Searches for HH production with the CMS detector

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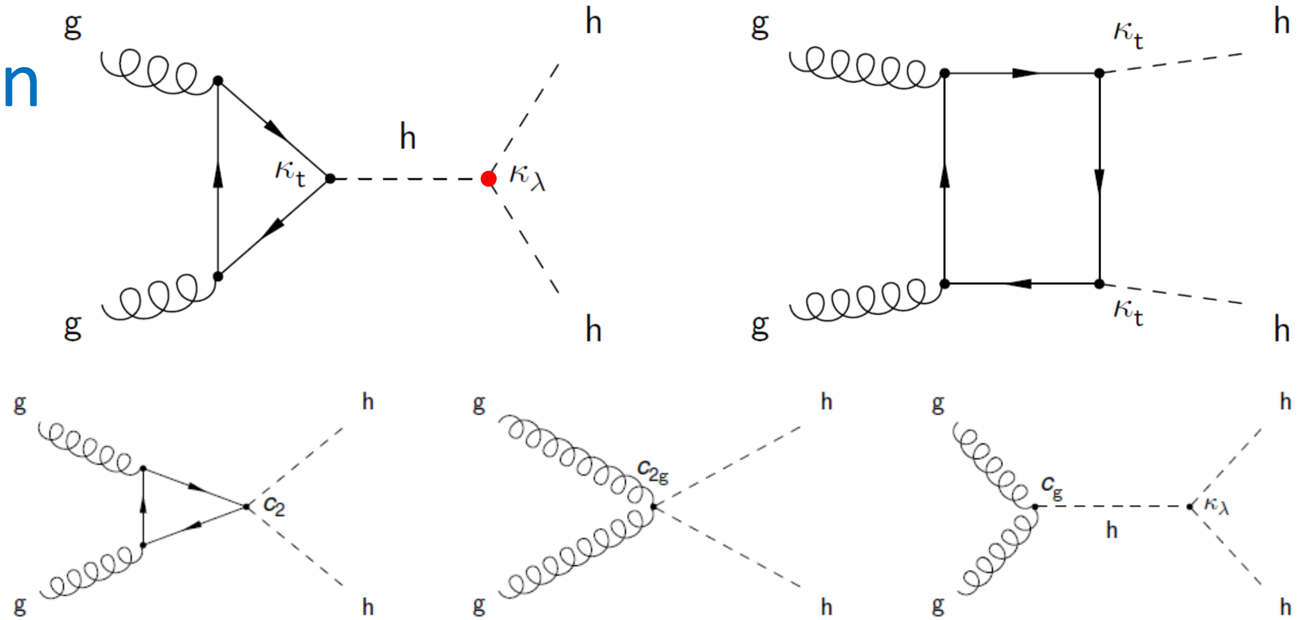
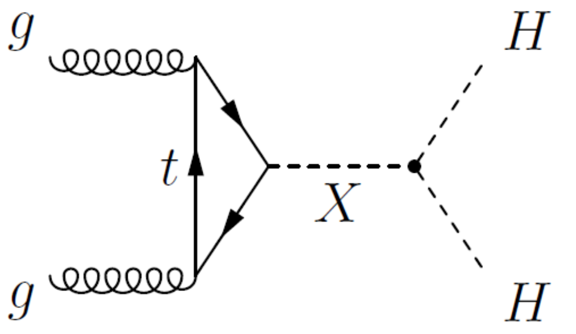
Pheno 2017 – Pittsburgh, 8-10 May

Physics motivations

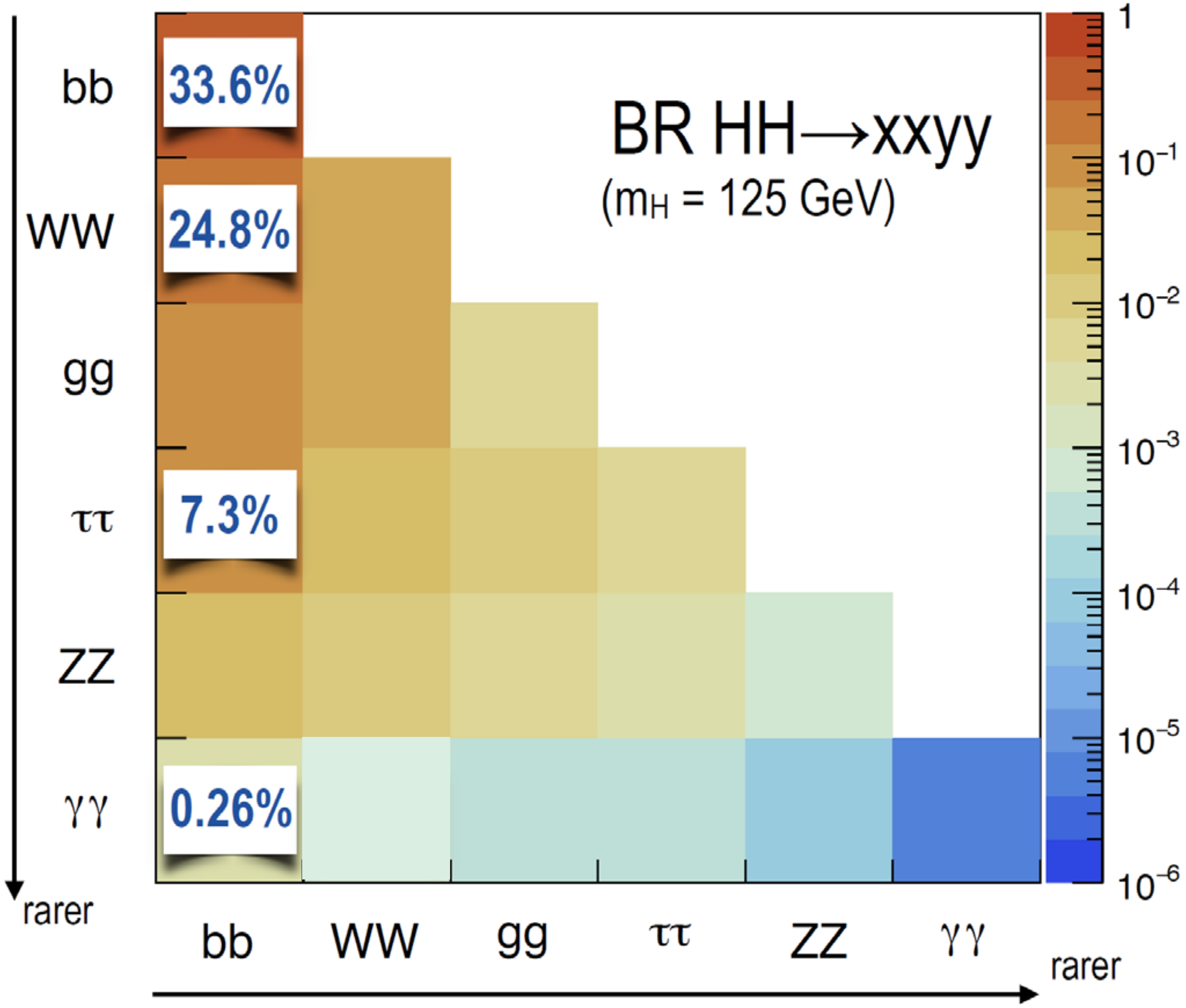


- Standard Model Double Higgs production
  - $\sigma_{HH} = 33.49\ fb$ @ $s = 13\ TeV$
  - access trilinear Higgs coupling λ_{hhh}
- Test non-resonant BSM effective models with anomalous couplings
  - c_2, c_{2g}, c_g.
- Model independent search of narrow width resonance + interpretations
  - Cover some part of the parameter space of hMSSM and low tanβ scenarios
  - Explore other models that predict a resonance that decays into two SM-like Higgses: Higgs singlet, 2HDM, warped extra dimensions, etc.



Final states

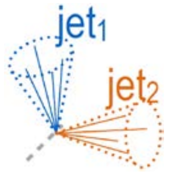
- Phenomenologically rich set of final states
- At least one $H \rightarrow b\bar{b}$ decay required to keep BR high enough
  - Common techniques across analyses (e.g. b-tagging) + channel-specific challenges
- Complementarity of the channels
  - similar sensitivity to non-resonant production
  - different coverage in m_X



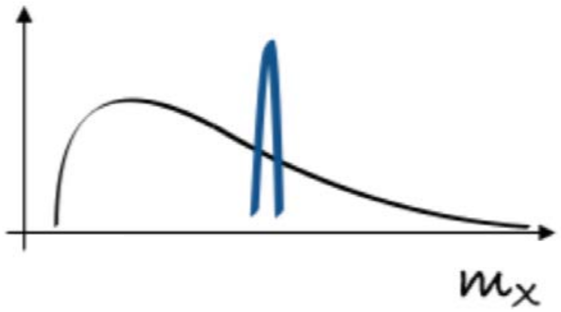
CMS PAS B2G-16-008 (2.7 fb^{-1})
CMS PAS HIG-16-002 (2.3 fb^{-1})
CMS PAS HIG-16-026 (2.3 fb^{-1})

$HH \rightarrow b\bar{b}b\bar{b}$

- Highest BR, large multijet background, estimated from data
- Two event topologies explored:
  - Resolved (non resonant & low m_X): four separate jets
  - Boosted (high m_X): jets from $H \rightarrow b\bar{b}$ decay overlap. Use substructure techniques



- Relies on b-tagging
  - Multi b-tag at trigger level for resolved analyses
  - Double b-tagging on 0.8 radius jet based on multivariate method for boosted analysis
- Invariant masses of selected jets used to search for a signal



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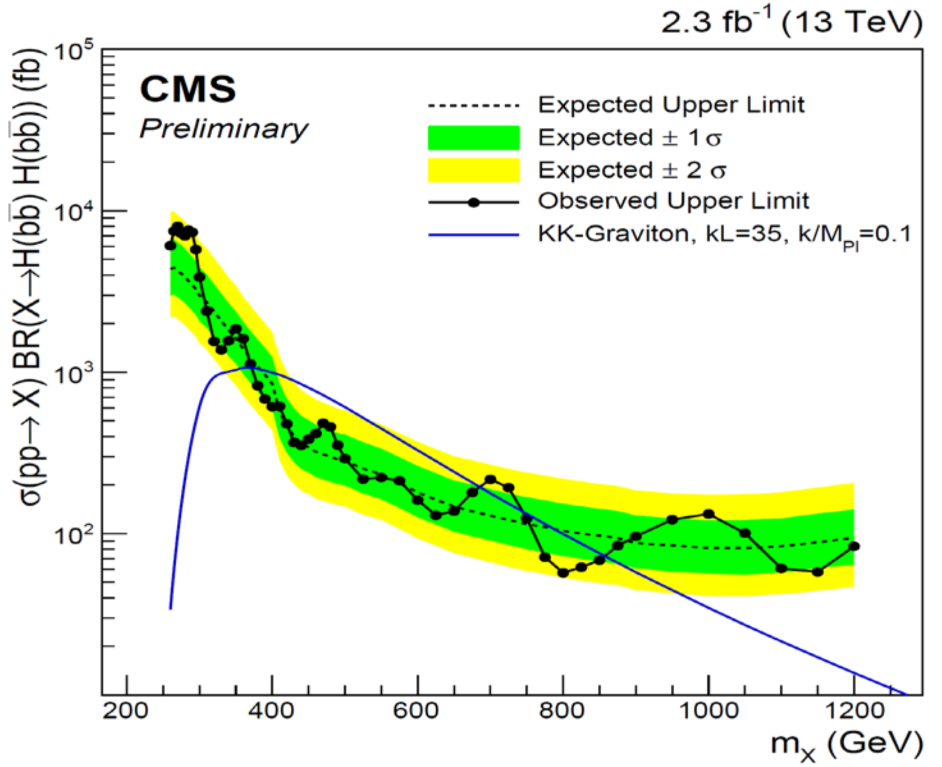
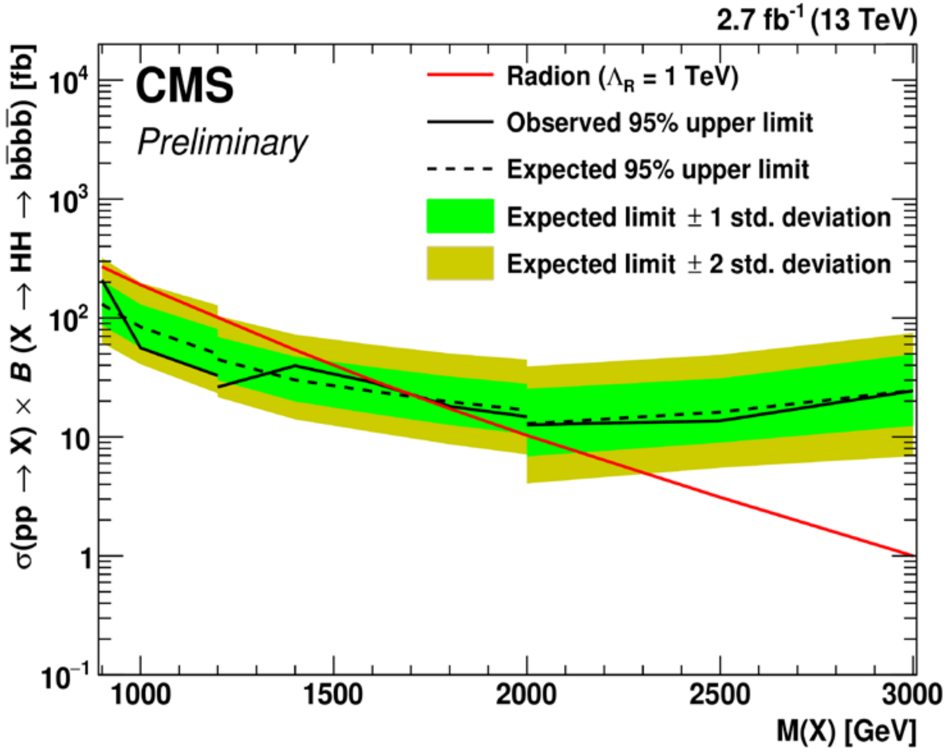
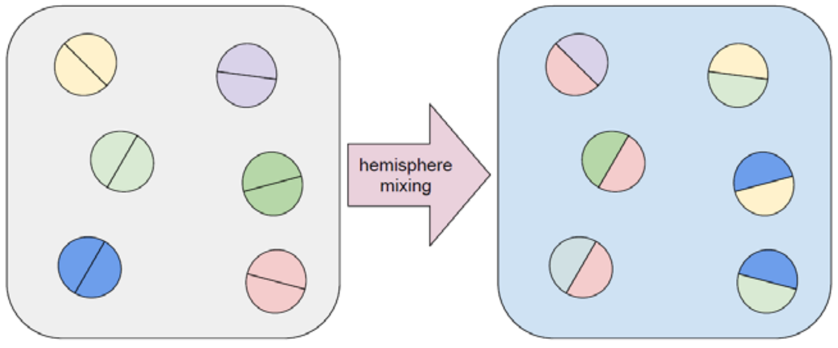
$HH \rightarrow b\bar{b}b\bar{b}$

- Resonant
  - Resolved regime: $M_X \in [0.26 - 0.9]TeV$
    - Multijet predicted from $m_{H_1}:m_{H_2}$ sidebands.
    - Exclude RS1 KK-Graviton (kL=35, $k/\overline{M_{Pl}}$=0.1) with $m_X \in [350 - 725]GeV \cup [775 - 850]GeV$
  - Boosted regime: double approach for optimal sensitivity in the $M_X \in [0.9 - 3.0]TeV$ range.
    - Data driven background predictions:
      - Smoothly falling background hypothesis, fit in situ.
      - “Alphabet” method to estimate the background in M_{jj}^{red}.
    - Exclude Radion (Λ_R=1 TeV) with $m_R < 1720\ GeV$
- Non resonant
  - “Hemisphere mixing” for background prediction.
    - Limits on SM hh: $342 \cdot \sigma_{SM}$







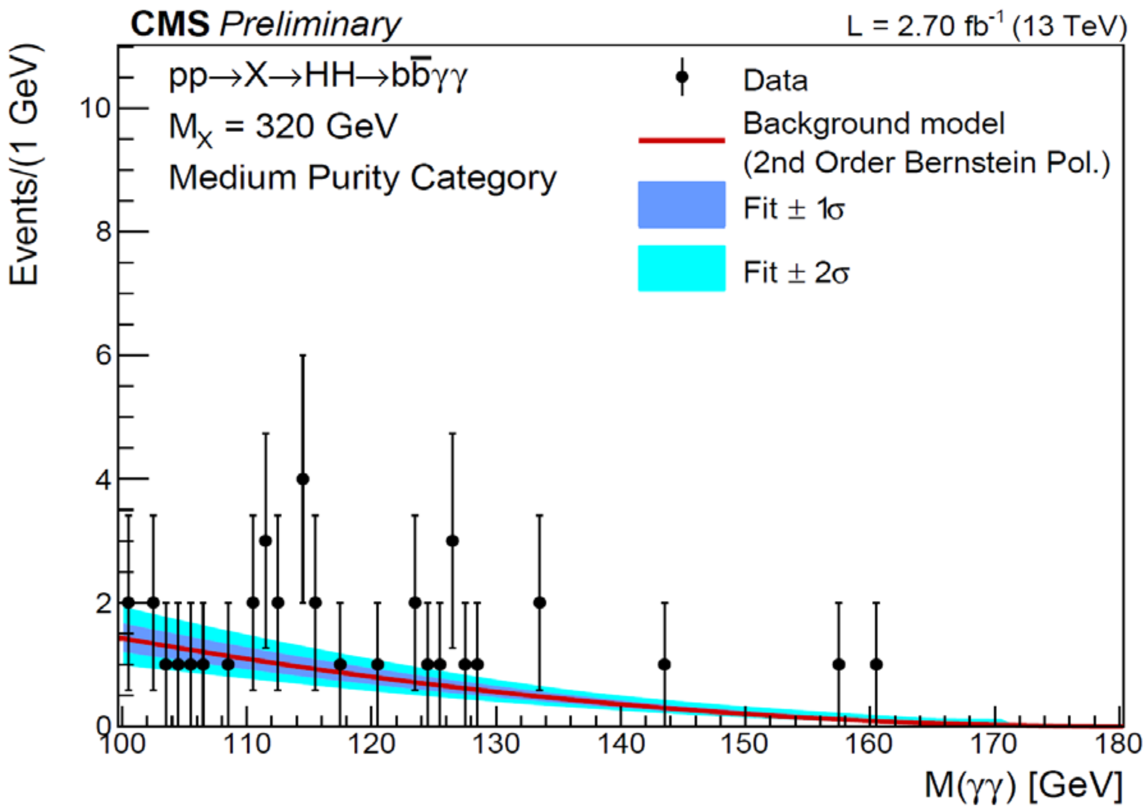
Original dataset: bkgs and potentially a small signal fraction

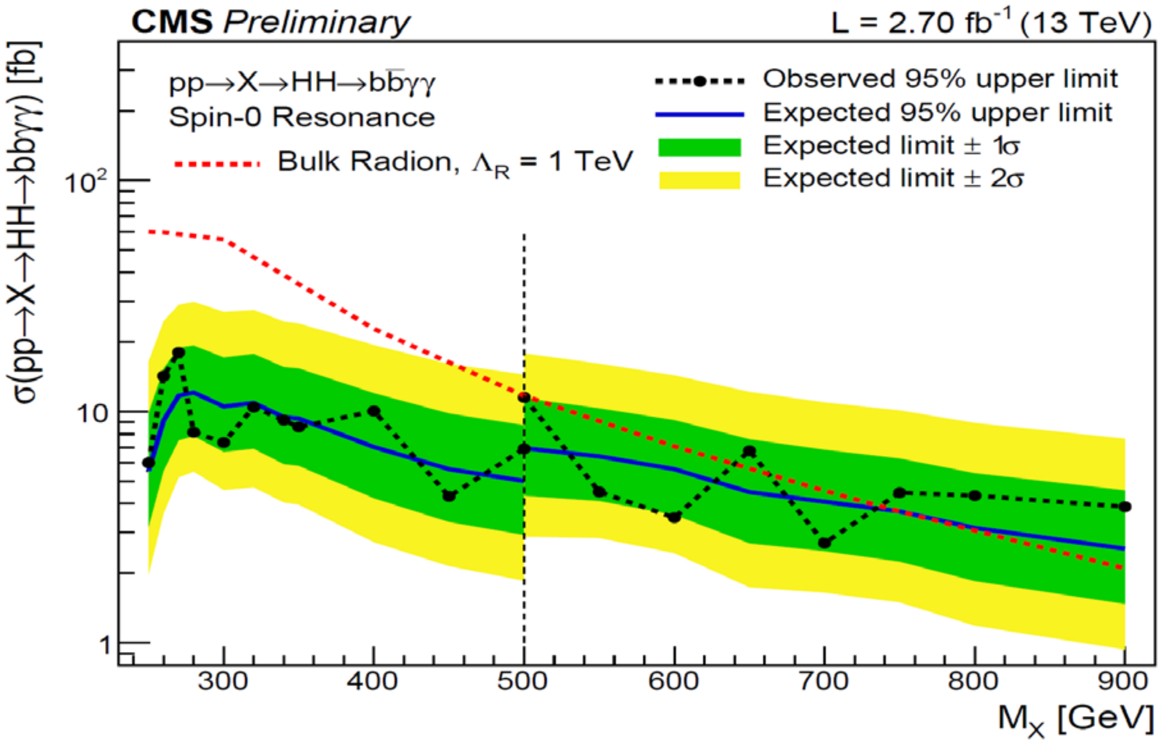
Mixed dataset: new composed event that represent bkg-only

CMS PAS HIG-16-032 (2.7 fb^{-1})

$HH \rightarrow b\bar{b}\gamma\gamma$

- The $H \rightarrow b\bar{b}$ provides a high BR (57.7%), the $H \rightarrow \gamma\gamma$ provides high S/B ratio and excellent mass resolution, BR=0.227%.
  - The total $Br(HH \rightarrow b\bar{b}\gamma\gamma) = 0.262\% \Rightarrow \sigma_{SM}(pp \rightarrow HH \rightarrow b\bar{b}\gamma\gamma) = 8.7 \cdot 10^{-2}\, fb$
- Main backgrounds: $jj + jets, \gamma j + jets, \gamma\gamma + jets$, estimated from data.
  - Signal fit in the 2D $M(\gamma\gamma){:}\,M(jj)$ plane. $M(\gamma\gamma)$ projection above.
- Exclude radion (spin-0) mass points below 750 GeV, assuming Λ_R=1 TeV
- Non resonant production: $UL(@95\%) = 7.9\, fb = 91 \cdot \sigma_{SM}$

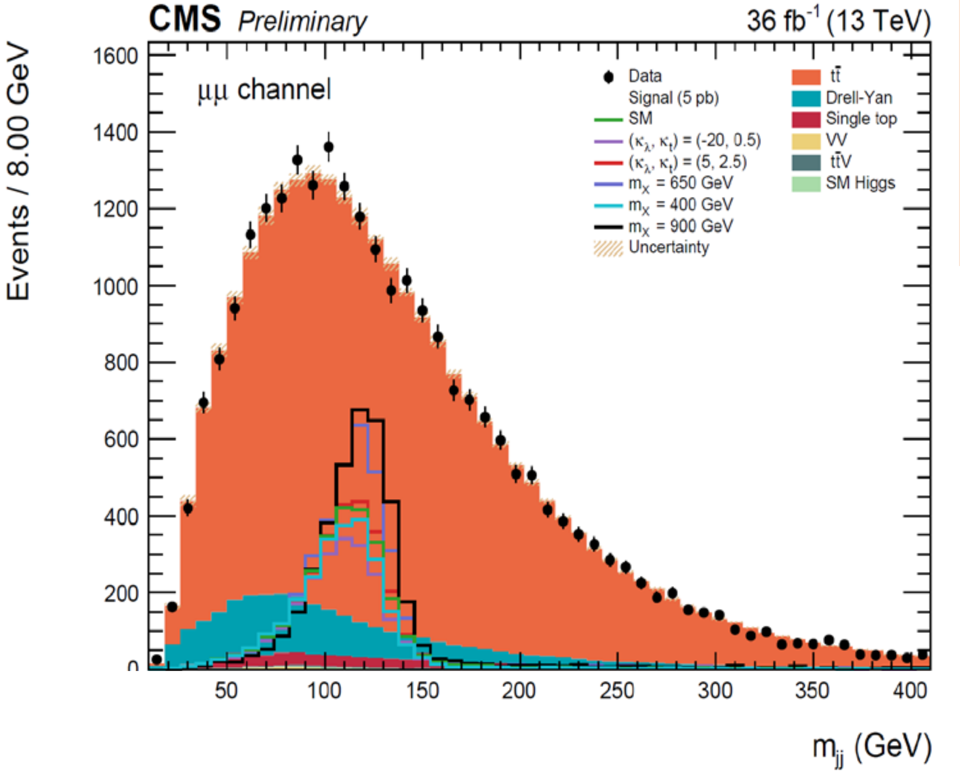


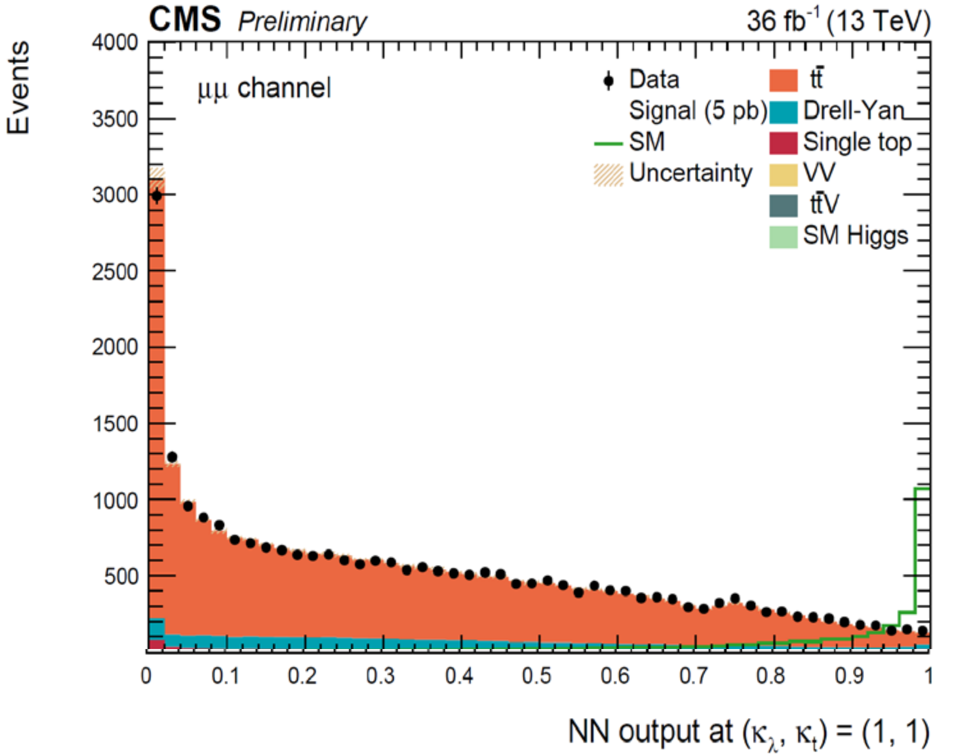


CMS PAS HIG-17-006 (35.9 fb^{-1})

$HH \to b\bar{b}\ell\nu\ell\nu$

- $h_1 \to b\bar{b}$, $h_2 \to VV \to \ell^+\nu\ell^-\nu$ with $V \in \{W, Z\}$, $(\ell \in \{e, \mu, \tau_{e,\mu}\})$
- Event selection:
  - Dilepton triggers, $e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$, ≥2 (medium) b-tagged jets, $12\ GeV < m_{\ell\ell} < m_Z - 15\ GeV$
- $t\bar{t}$ main background (estimated from MC simulation)
  - in the $e^+e^-, \mu^+\mu^-$ final states also Drell-Yan, (from data, in b-untagged region)
- 2 parameterized DNN to improve S/B separation
  - One for resonant hh production ($m_X = 260, \ldots, 900\ GeV$) one for non –resonant
  - $m_{\ell\ell}, \Delta R_{\ell\ell}, \Delta R_{jj}, \Delta\phi_{\ell\ell,jj}, p_T^{\ell\ell}, p_T^{jj}, \min(\Delta R_{\ell,j}), M_T$
- Use m_{jj} and DNN discriminant.

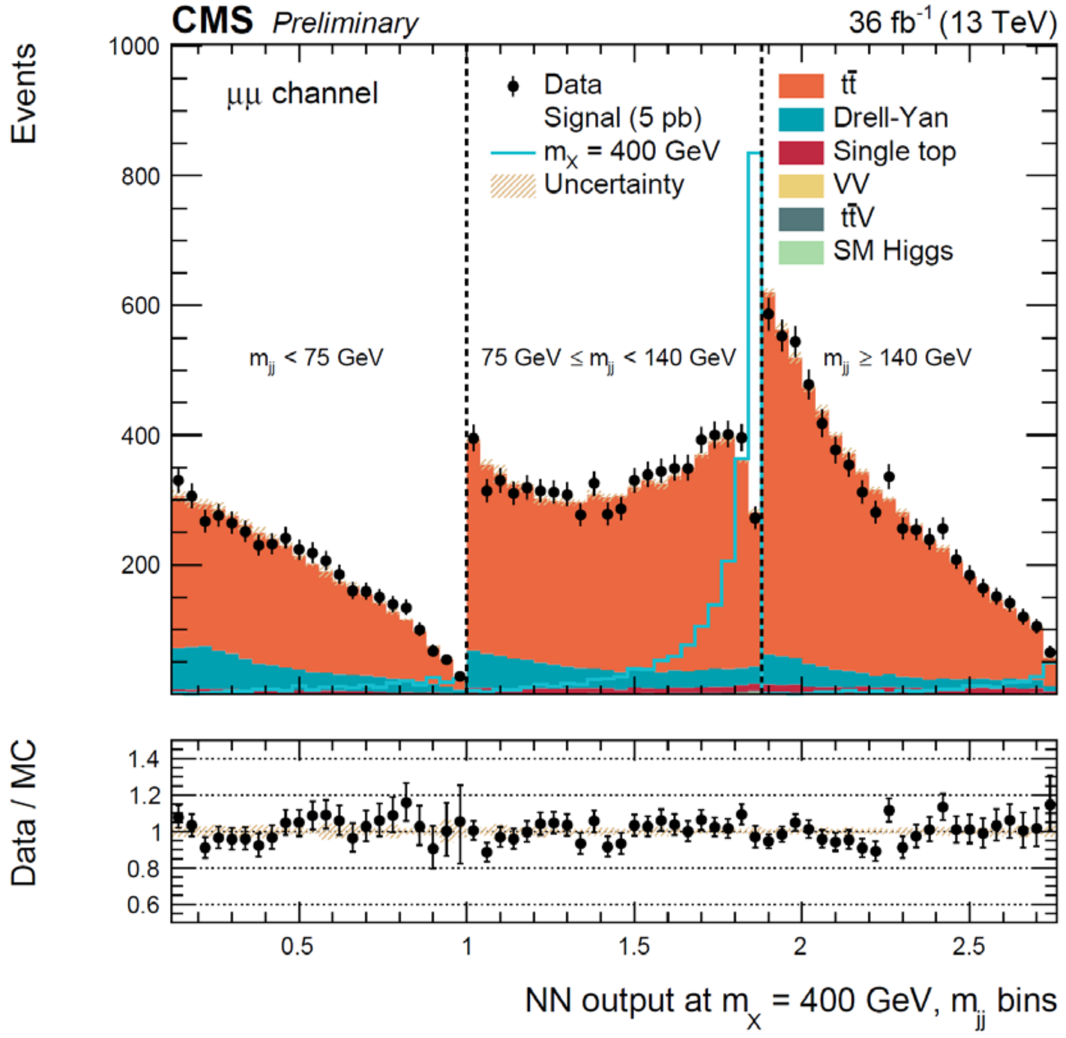


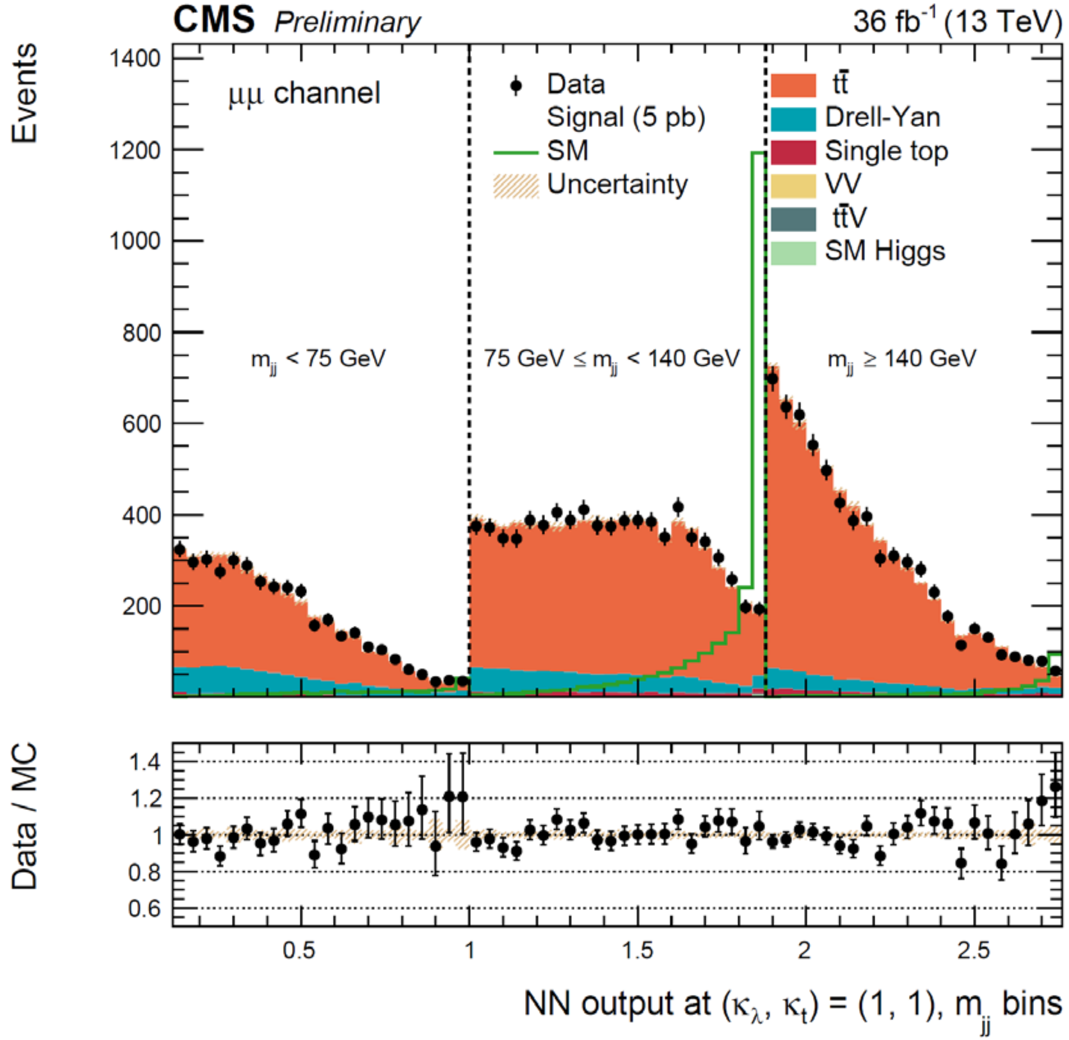


CMS PAS HIG-17-006 (35.9 fb^{-1})

$HH \rightarrow b\bar{b}\ell\nu\ell\nu$

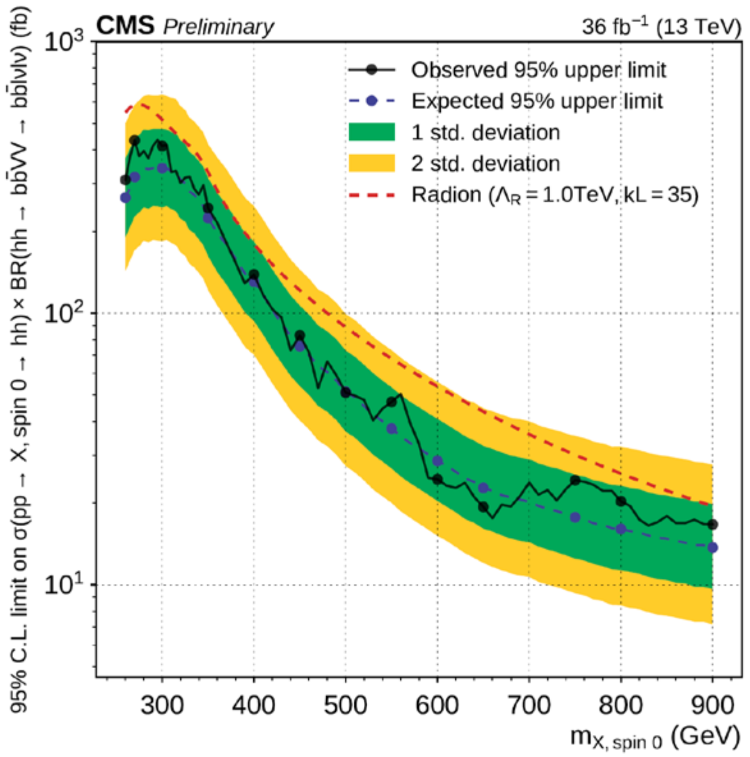
- 3 regions in m_{jj}:
  - $m_{jj} < 75\ GeV$, $75 < m_{jj} < 140\ GeV$ SIGNAL, $140\ GeV < m_{jj}$

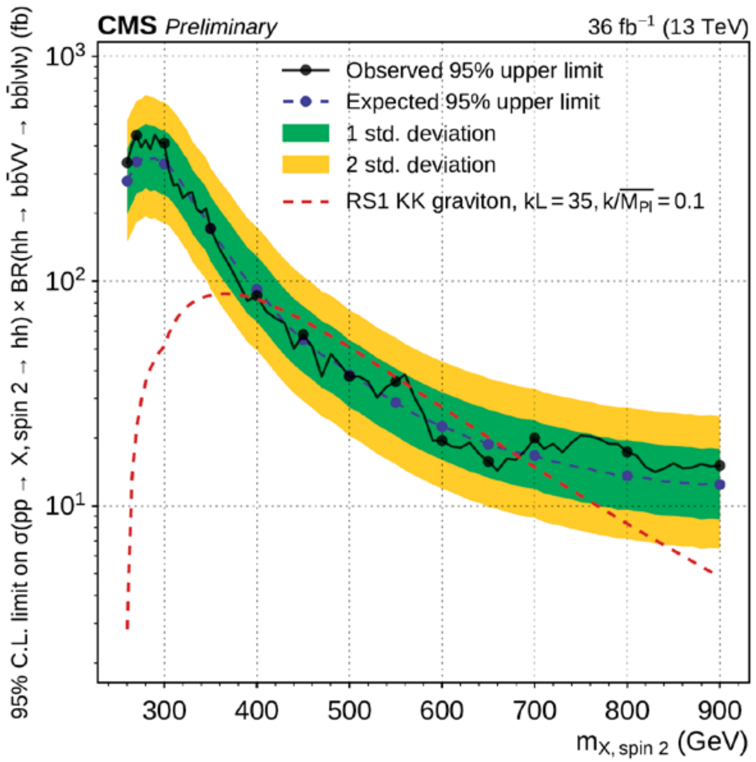


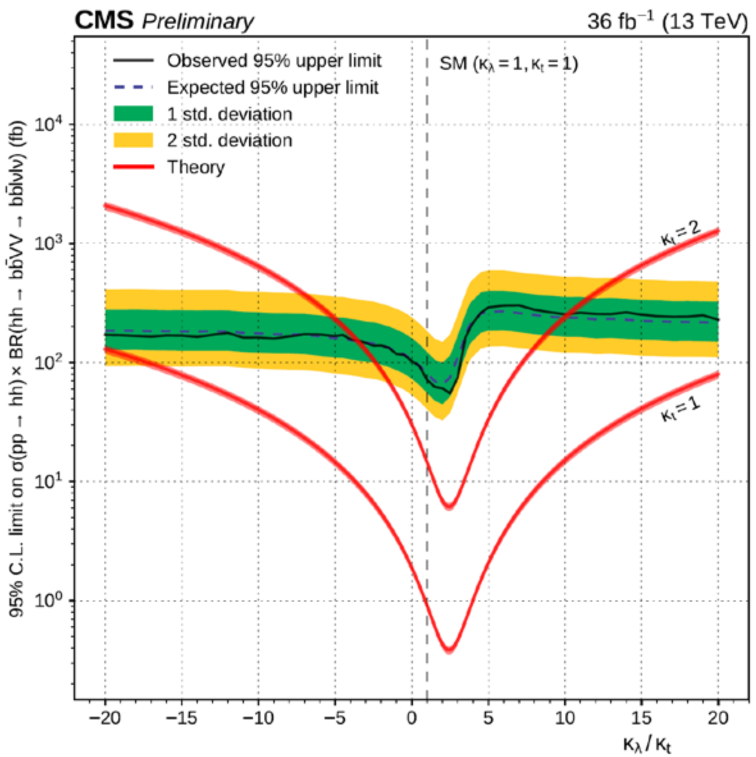


$HH \rightarrow b\bar{b}\ell\nu\ell\nu$

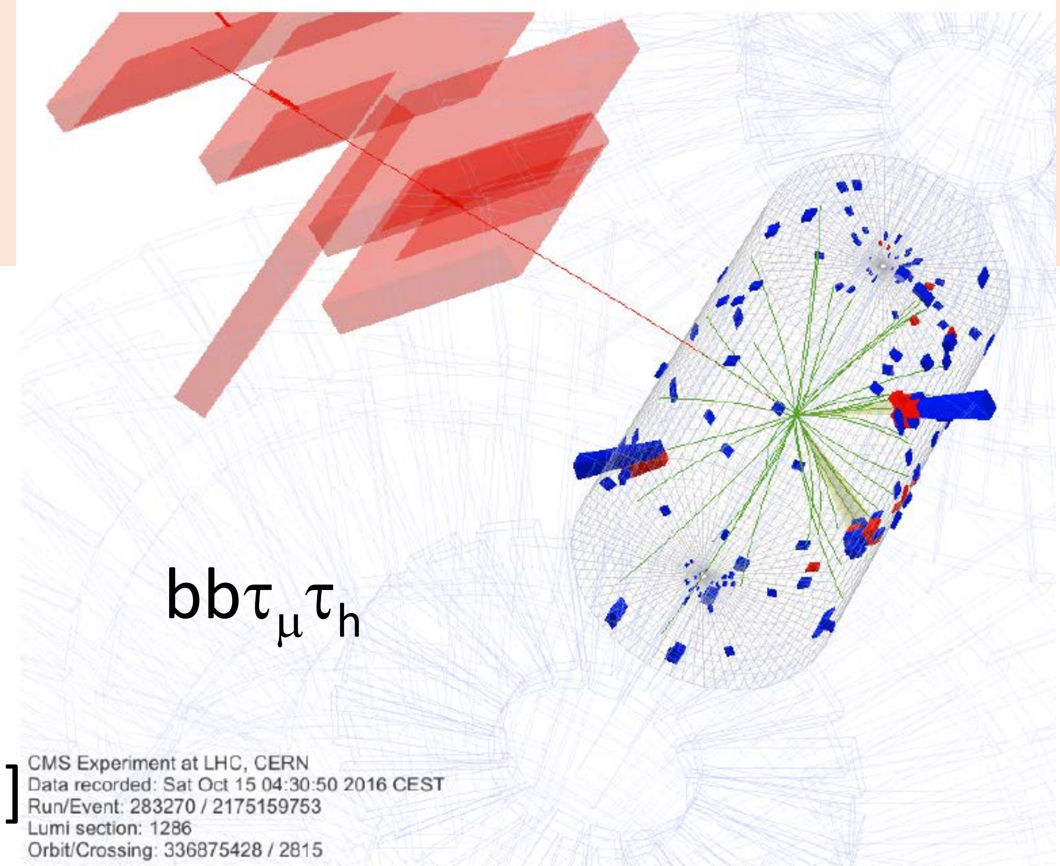
- Limits on resonant productions, $m_X \in [300, 900] GeV$:
  - Spin 0 (Λ_R=1 TeV, kL=35): $434 - 17\ fb$ (exp. $342^{+135}_{-97} - 14^{+6}_{-4}\ fb$)
  - Spin 2 (RS1 KK graviton, kL=35, $k/\overline{M_{Pl}} = 0.1$): $448 - 14\ fb$ (exp. $361^{+140}_{-102} - 13^{+5}_{-4}\ fb$)
  - Limits on SM hh: $72\ fb$ (exp. $81^{+42}_{-25}\ fb$) $\leftrightarrow$ 79 (exp. 89^{+47}_{-28}) times SM cross section



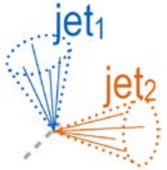


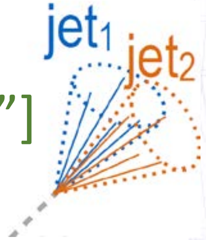


$HH \to b\bar{b}\tau\tau$

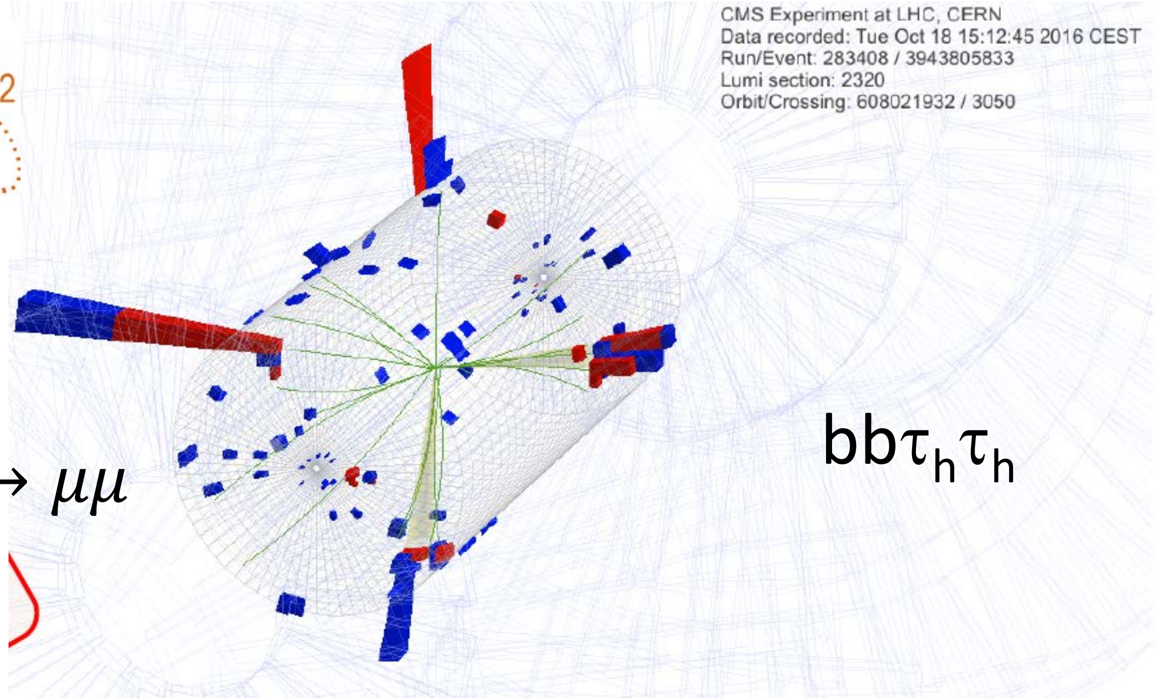


- Final states:
  - $bb\tau_\mu\tau_h$, $bb\tau_e\tau_h$. Triggered on the lepton
  - $bb\tau_h\tau_h$. Triggered on the 2 τs.
  - MET
- Selections:
  - 2 opposite charged leptons [No extra isolated leptons]
  - 2 jets
    - 2 ak$_T$(R=0.4) ="resolved"
    - [AND 1 ak$_T$(R=0.8) with substructures = "boosted"]
    - ≥ 1,2 medium (CSV) b-tags

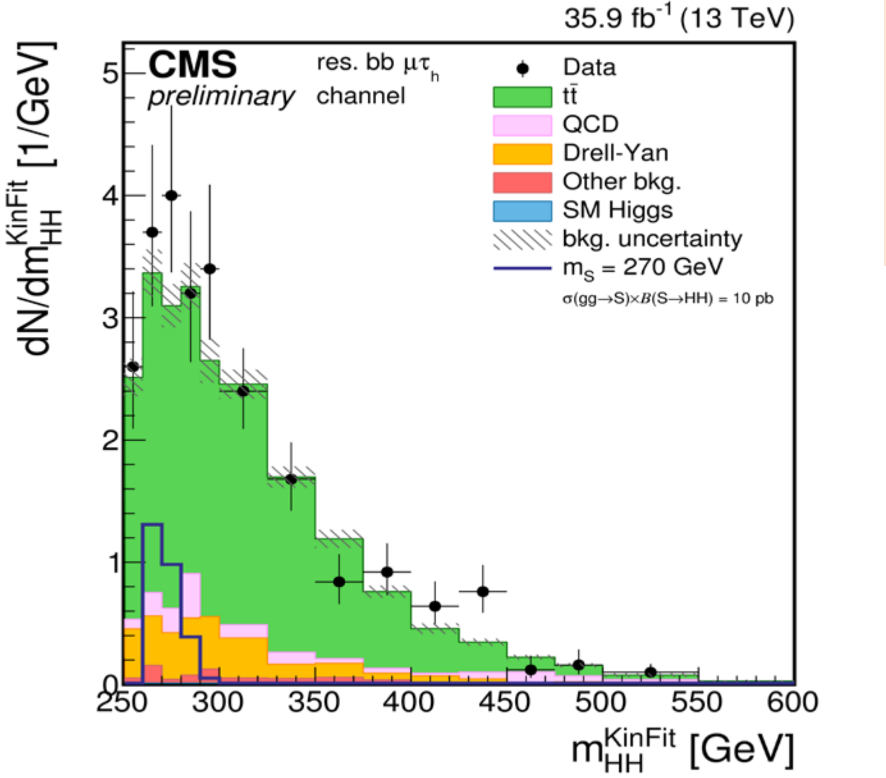




- Backgrounds and their estimations:
  - $t\bar{t}$. MC simulation
  - Drell-Yan: MC simulation with correction from $Z \to \mu\mu$
  - QCD: from data (SS→OS)



$HH \rightarrow b\bar{b}\tau\tau$

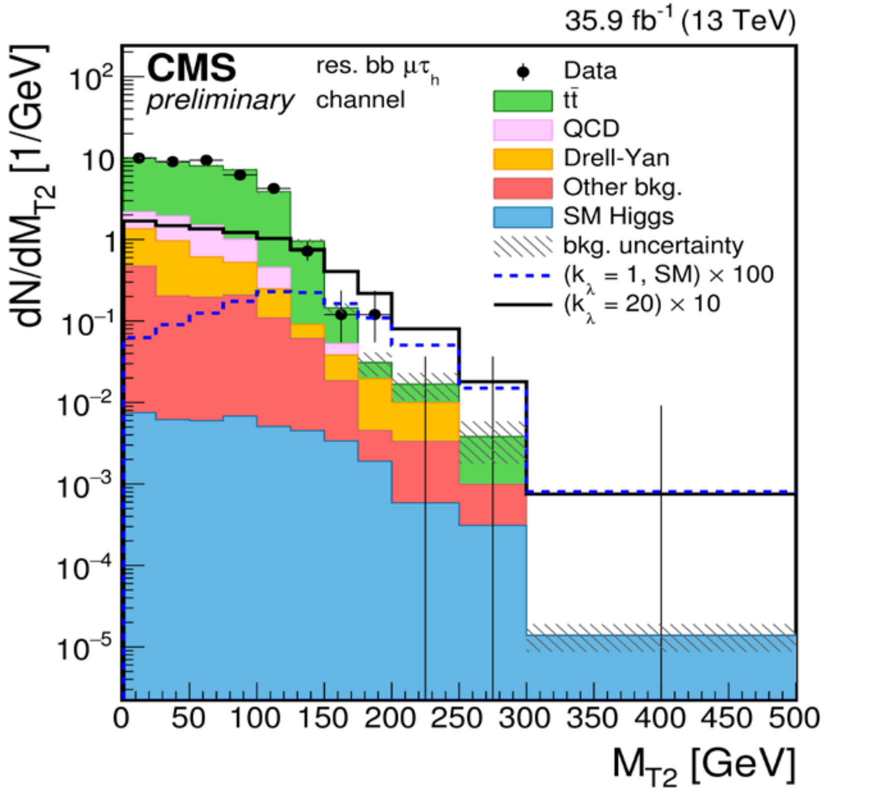


- $\tau_h\tau_h$
  - $m_{\tau\tau}$ (+MET) and m_{bb} must be compatible with m_h
- $\tau_{\mu,e}\tau_h$
  - $\tau_h\tau_h$ requirements + selection on a multivariate discriminant (BDT) to reject $t\bar{t}$.
    - Using angular separation btw leptons, h and m_T

Observables:

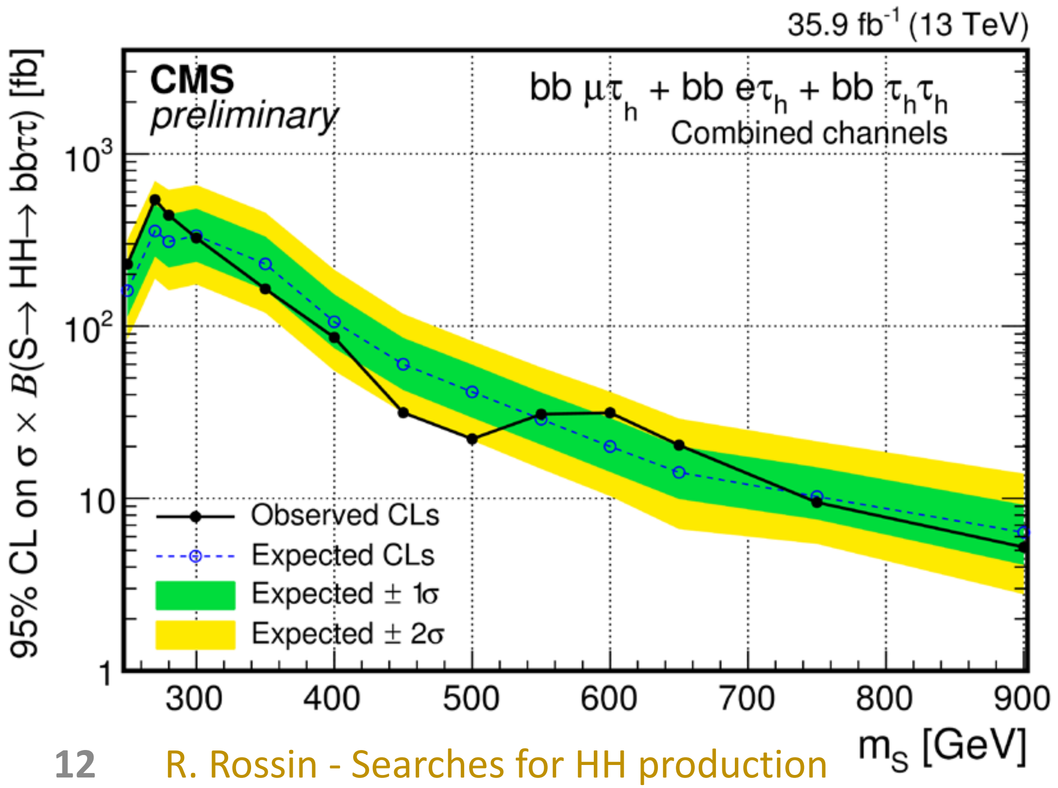
- Resonant search: the 2τ and 2b are combined with a kinematic fit to m_{hh}^{kinfit}
- Non resonant search: "stransverse mass" M_{T2}.

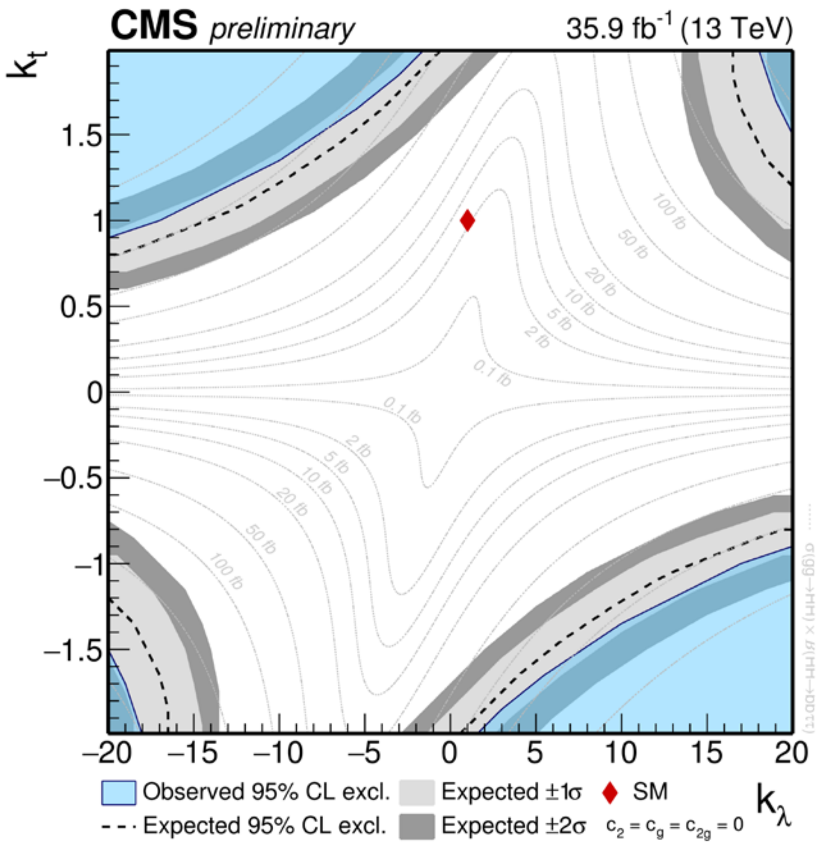
$$M_{T2} = \min_{p_{T1}+p_{T1}=p_T^{\tau\tau}}\{\max[m_T(m_{b1}, p_T^{b1}, m_{vis}^{\tau1}, p_{T1}), m_T(m_{b2}, p_T^{b2}, m_{vis}^{\tau2}, p_{T2})]\}$$

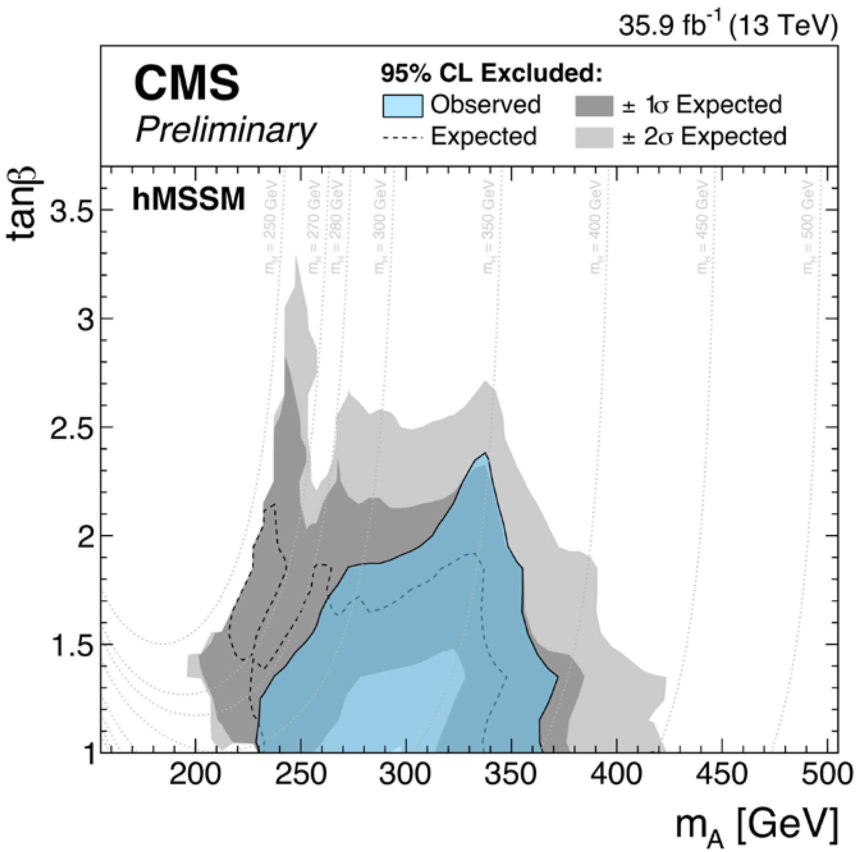


$HH \rightarrow b\bar{b}\tau\tau$

- Non-resonant search excludes 28 (exp. 25) times the SM .
  - Anomalous λ_{hhh} and y_t couplings tested
  - sensitive to the sign of y_t
- Resonant production tested up to m_X = 900 GeV, and interpreted in the hMSSM

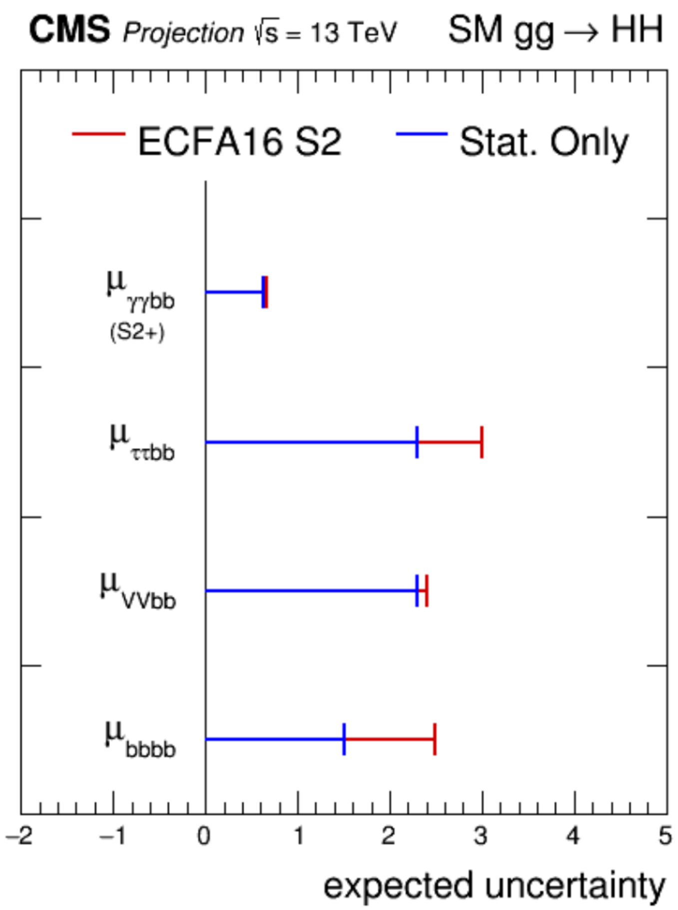






CMS-DP-2016-064 (~3 ab^{-1})

Conclusions and prospects



- Summary
  - several HH final states explored at 13 TeV by CMS
  - no sign of (B)SM HH production yet: best limit is $28 \cdot \sigma_{SM}$
- Near future
  - more updated results with full 2016 luminosity
  - new HH final states and a combination are coming soon
- Not so near:
  - Measurement of σ_{HH} and determination of λ_{HHH} are one of the main points of the physics programme at the HL-LHC (3 ab^{-1} of data)
    - See table for the extrapolation of results from 13 TeV, 2.3/2.7 fb-1, to HL-LHC

Channel	Z Value	
	ECFA16 S2	Stat. Only
$gg \to HH \to \gamma\gamma b\bar{b}$	1.6	1.6
$gg \to HH \to \tau\tau b\bar{b}$	0.39	0.53
$gg \to HH \to VVb\bar{b}$	0.45	0.47
$gg \to HH \to b\bar{b}b\bar{b}$	0.39	0.67