Di-Higgs production with CMS

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on behalf of the CMS collaboration

Northeastern

LHCP2017

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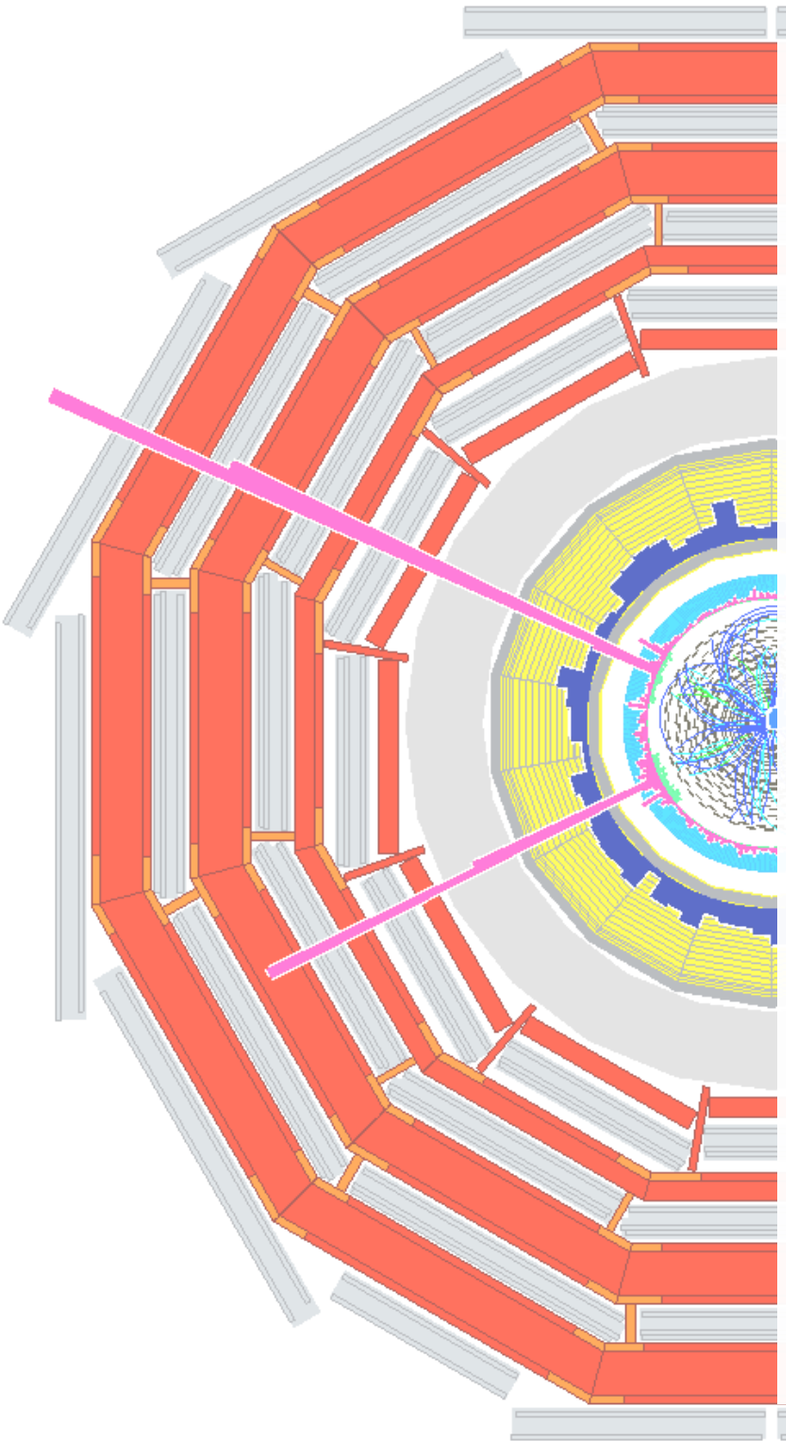
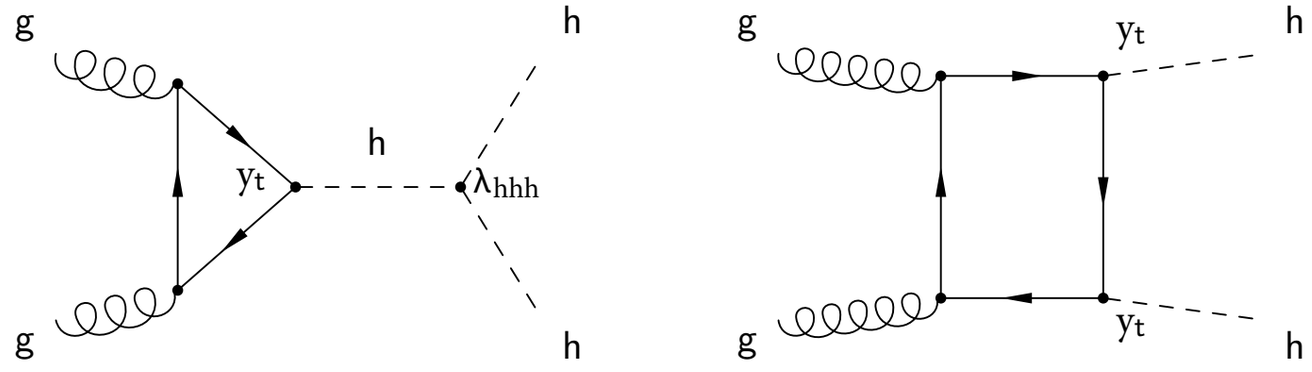
Outline



- Theoretical Motivation
  - Standard Model and BSM
- CMS Searches
  - Final states
  - Results
- Summary of Results
- Conclusion

Non-resonant HH production

- SM di-higgs production provides a crucial test of electroweak symmetry breaking
  - dominated by gluon-gluon fusion
  - Main production diagrams interfere destructively → reduces already small cross section
  - Access Higgs trilinear coupling λ_{hhh}



$$V = \frac{m_h^2}{2}h^2 + \lambda_{hhh}vh^3 + \frac{\lambda_{hhhh}}{4}h^4, \quad \lambda_{hhh} = m_h^2/(2v^2)$$

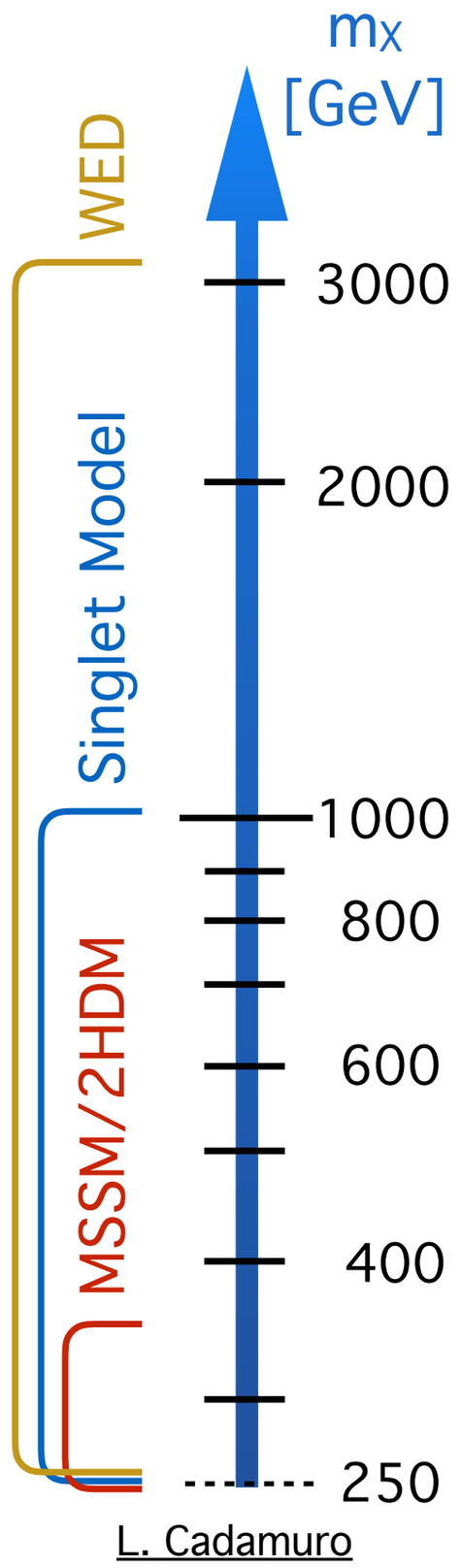
$$\sigma_{\mathrm{SM\ gg\to HH}} = 33.49^{+1.44}_{-2.01}(\mathrm{Scale}) \pm 0.70(\mathrm{PDF}) \pm 0.77(\alpha_s)\ \mathrm{fb}$$

arXiv:1610.07922

- BSM scenarios calculated via effective lagrangian
  - Anomalous couplings $\kappa_t = y_t'/y_t^{SM}$, $\kappa_\lambda = \lambda'_{hhh}/\lambda^{SM}_{hhh}$ and up to 4 new contact interactions can lead to large modifications in production cross section and kinematic shapes

Resonant HH production

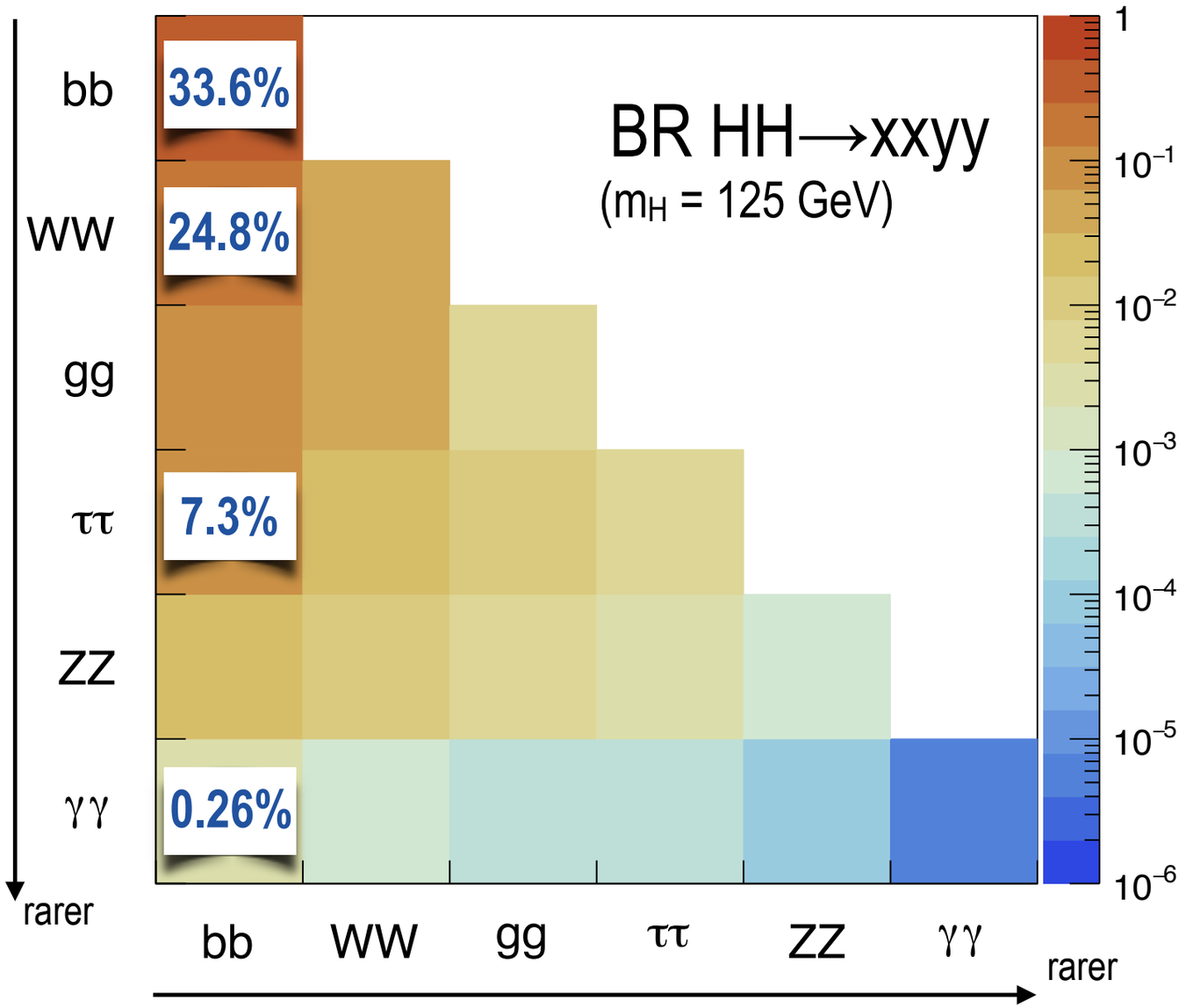
- New particle X→HH not present in SM
  - Many BSM models predict X→HH production
    - Singlet model, MSSM, 2HDM, warped extra dimensions....
    - m_X can range up to several TeV
      - Search sensitivity varies from channel to channel, and over mass range
      - Important to search in as many channels as possible
  - Benchmark models: Bulk Randall-Sundrum WED → spin-0 Radion, spin-2 Kaluza-Klein Graviton



L. Cadamuro

Final States

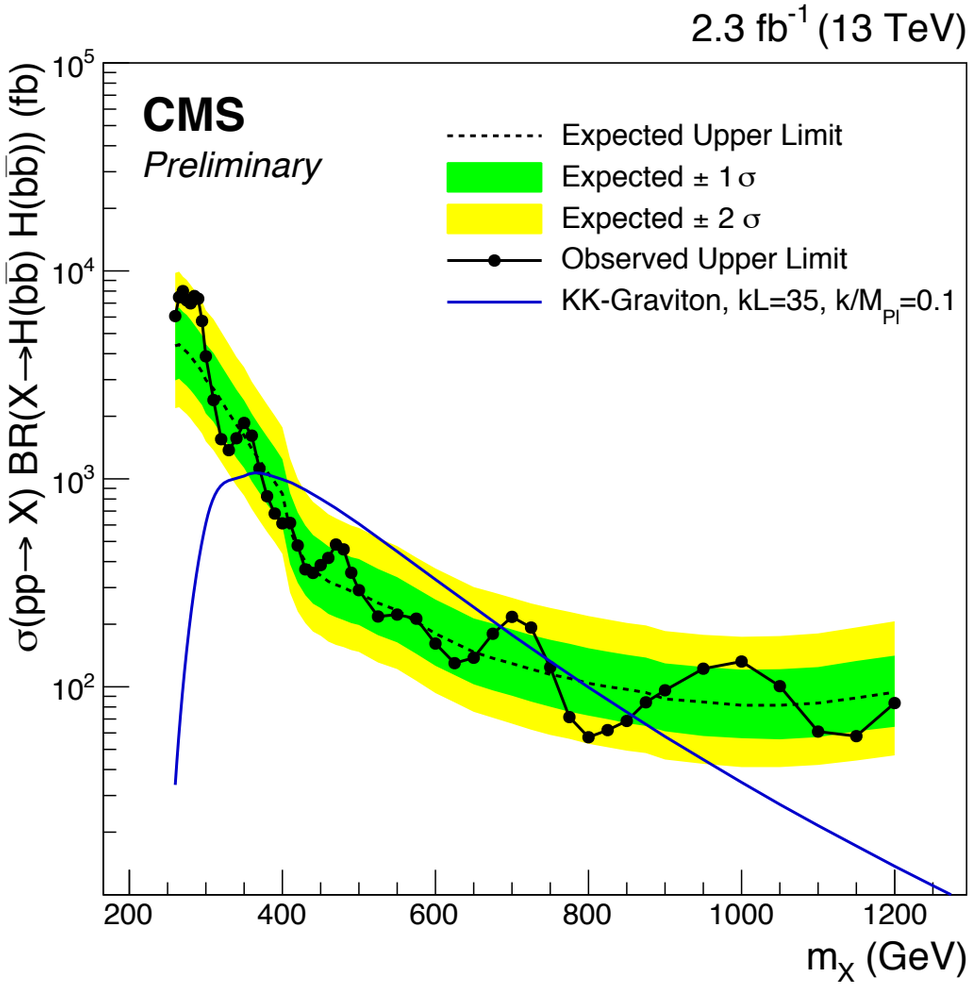
- Large number of possible final states
- Require one H→b$\bar{b}$ to keep final state BFs higher
  - H→b$\bar{b}$ provides kinematic handle, shared techniques
- Other H decay based on BF and event kinematics
  - Disjoint searches provide complementary sensitivity in M_X for resonant searches: b$\bar{b}$b$\bar{b}$, b$\bar{b}\gamma\gamma$, b$\bar{b}\ell\nu\ell\nu$, b$\bar{b}\tau\tau$



CMS-PAS-HIG-16-002
CMS-PAS-HIG-16-026

$b\bar{b}b\bar{b}$

- Highest BF of the searches
  - Large multijet background estimated with data-driven technique
- Resonant analysis separated into 4-jet resolved and high-mass 2-jet boosted topologies



Non-resonant limits (fb) 2.3 fb^{-1} (13TeV)

Category	Observed	Expected	-2σ [fb]	-1σ	$+1\sigma$	$+2\sigma$
SM $H(b\bar{b})H(b\bar{b})$	3880	3490	2140	2540	5350	8350

CMS-PAS-B2G-16-032

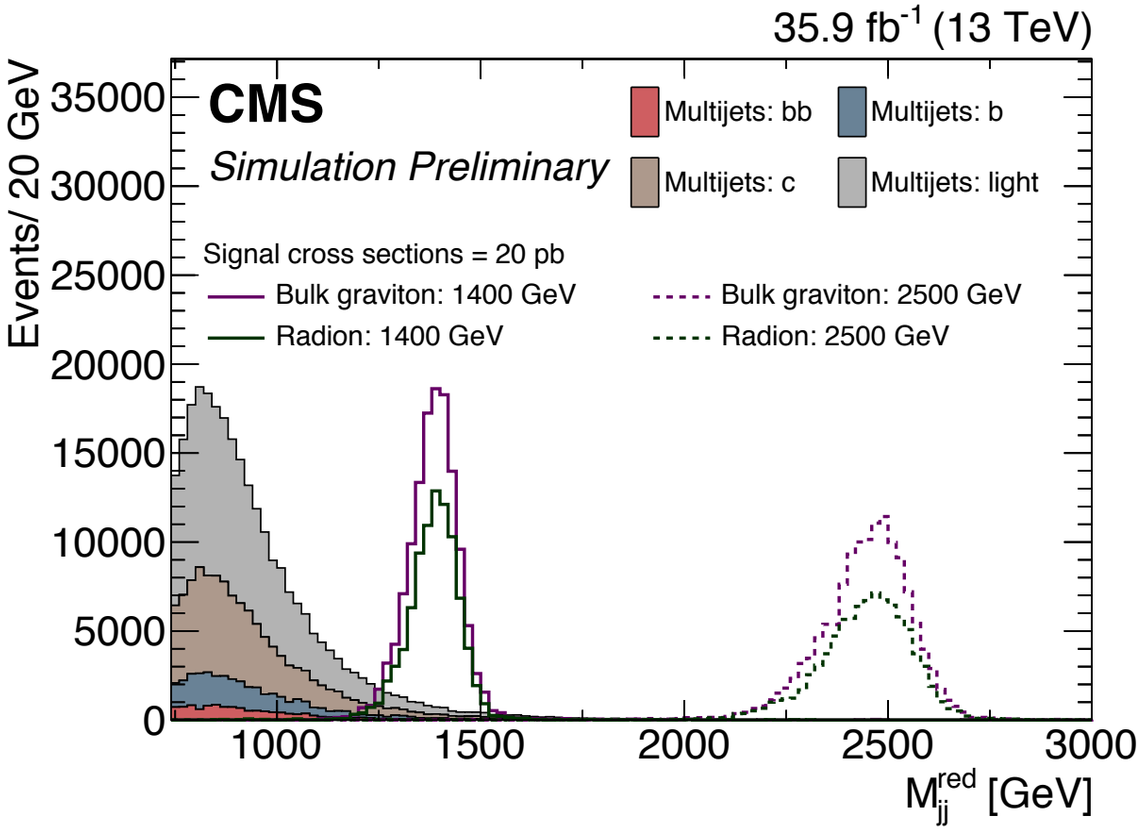
$b\bar{b}b\bar{b}$ high mass

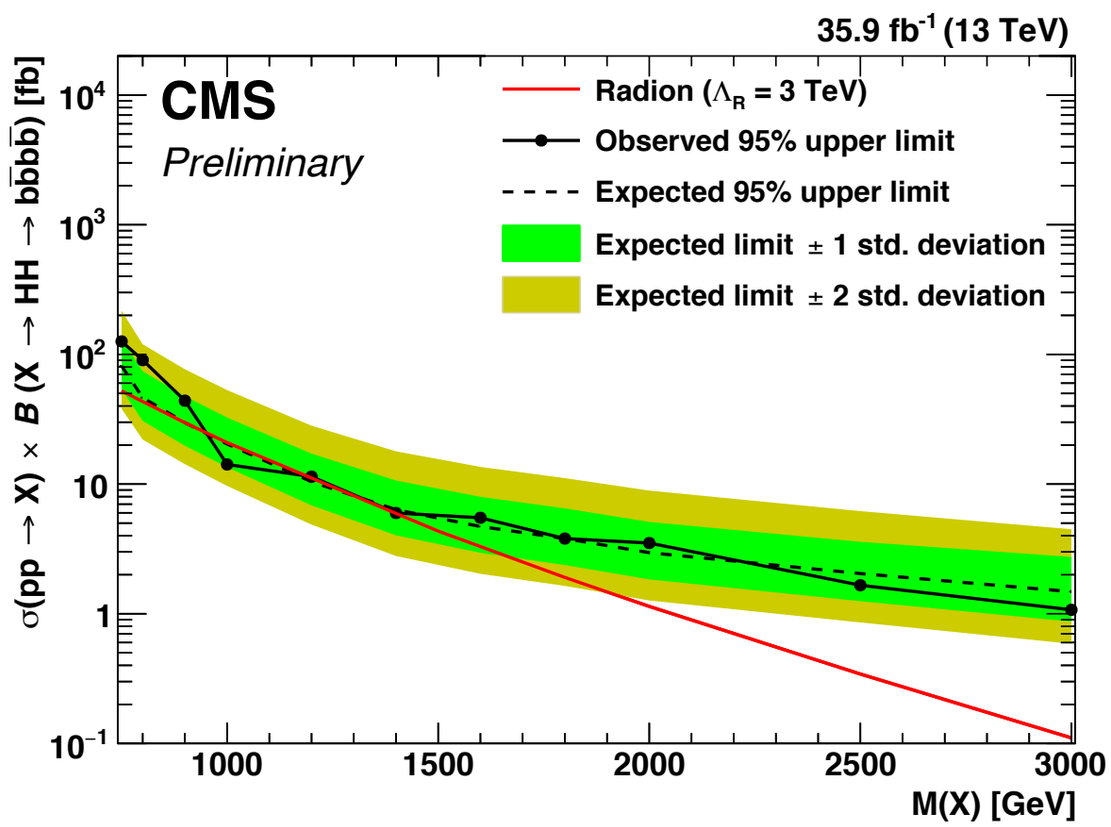
Full 2016 dataset

NEW!

- High mass 2-jet boosted topology
  - Each $H \to b\bar{b}$ system reconstructed as single high-p_T jet, $105 < M_j < 130$
  - Jet substructure techniques and double b-tagger MVA suppress backgrounds
  - Data-driven background estimate from sidebands in double b-tagger and M_{j_1}
  - Signal separation through increased-resolution reduced dijet mass:

$$M_{jj}^{\mathrm{red}} = M_{jj} - (M_{j_1} - M_H) - (M_{j_2} - M_H)$$





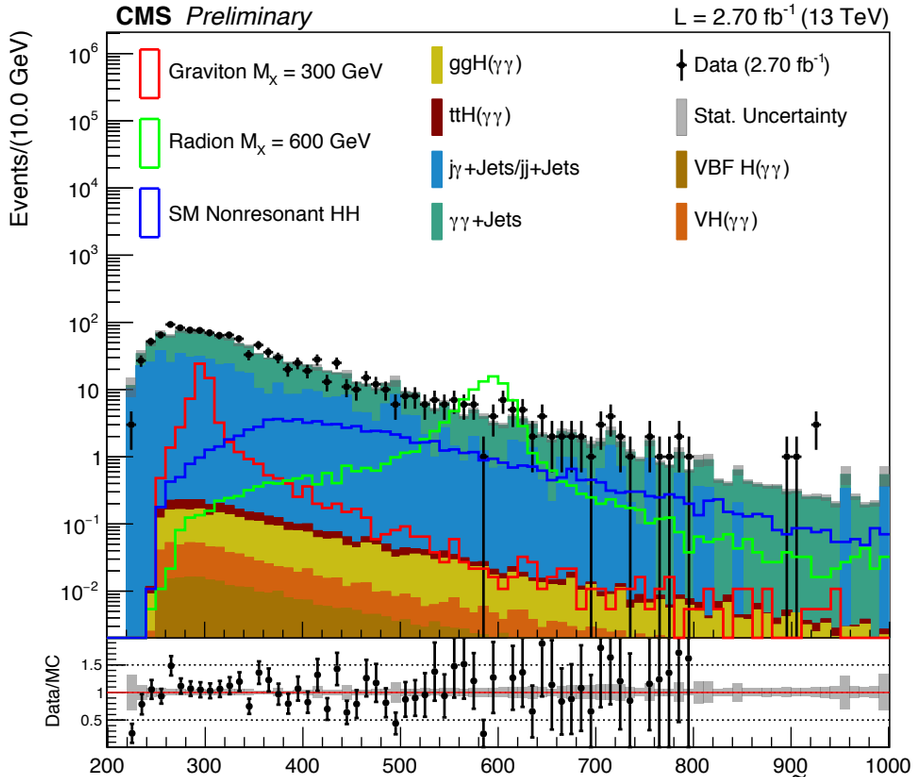
CMS-PAS-HIG-16-032

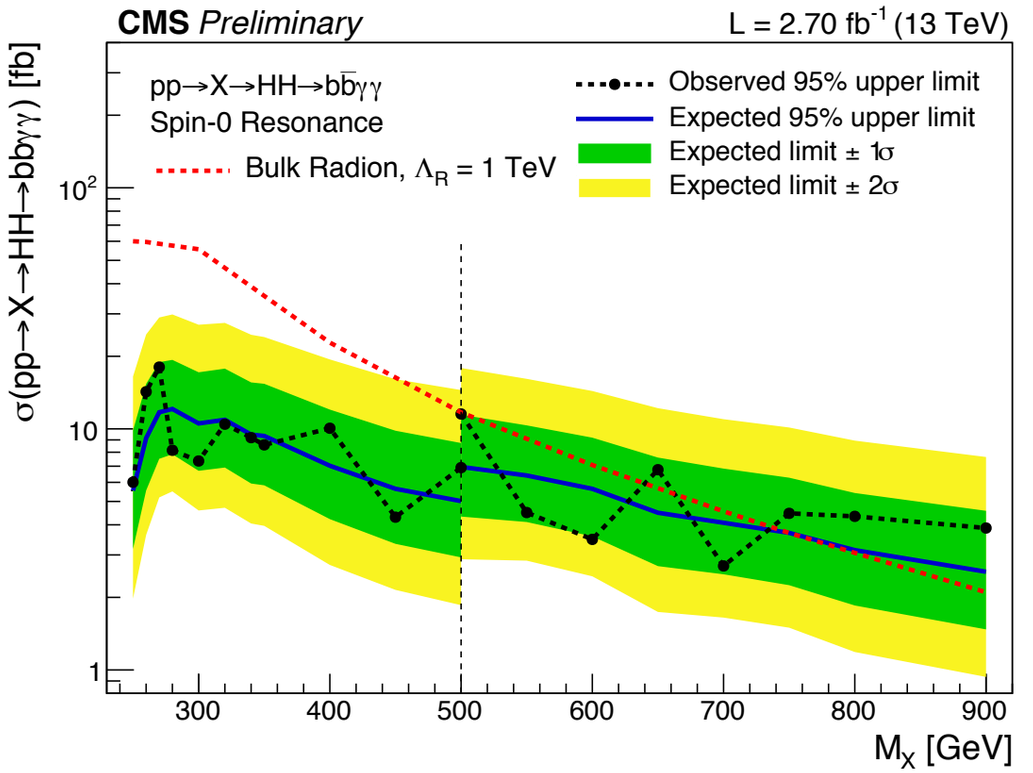
$b\bar{b}\gamma\gamma$

- Utilize high BF of $H\to b\bar{b}$ and excellent mass resolution of $H\to\gamma\gamma$
- Mixed b-tagging categorization gives medium and high purity categories
- Improve signal resolution using modified 4-body mass:

$$M_X = M(jj\gamma\gamma) - M(jj) + 125\text{GeV}$$

- Signal and background modeled in 2D m_{jj}:$m_{\gamma\gamma}$ space
  - Signal: Gaussian⊕Crystal Ball
  - Background: Bernstein polynomials
- Non-resonant obs.(exp.) limits: 7.90(7.85) fb



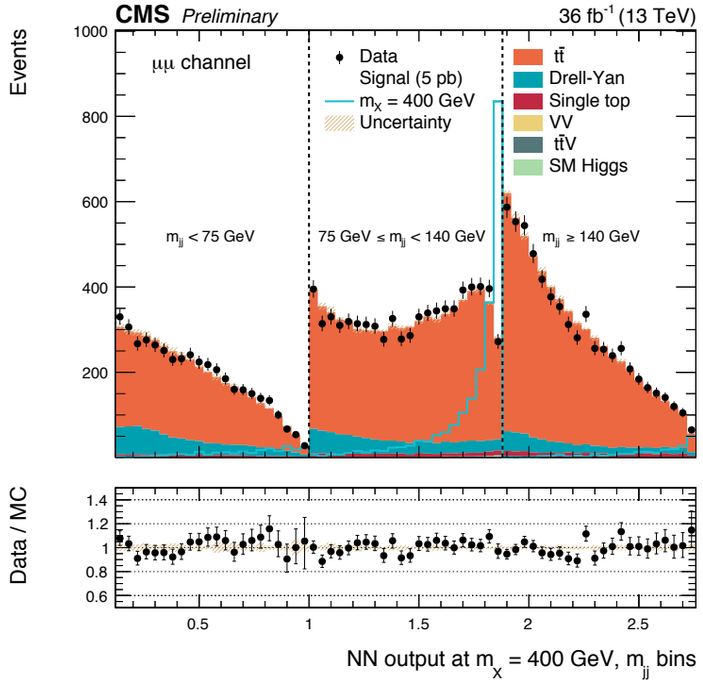


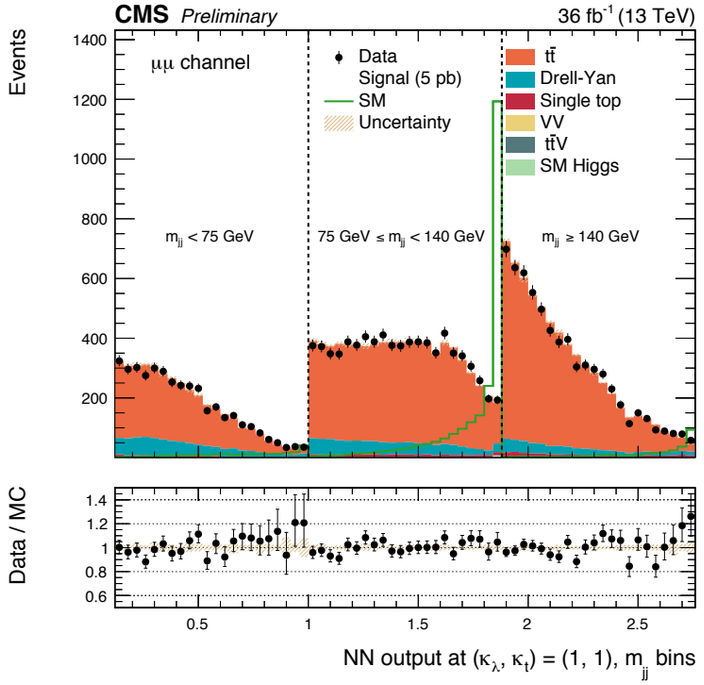
CMS-PAS-HIG-17-006

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

Full 2016 dataset

- $HH \rightarrow b\bar{b}VV \rightarrow b\bar{b}\ell\nu\ell\nu$
  - $\ell\ell$=ee, eμ, μμ
  - Require $12 < m_{\ell\ell} < 76$
- Most backgrounds estimated from simulation, including dominant $t\bar{t}$
- Exploit HH event kinematics with parametrized Deep Neural Net discriminant used for signal separation
  - 3 bins in m_{jj}



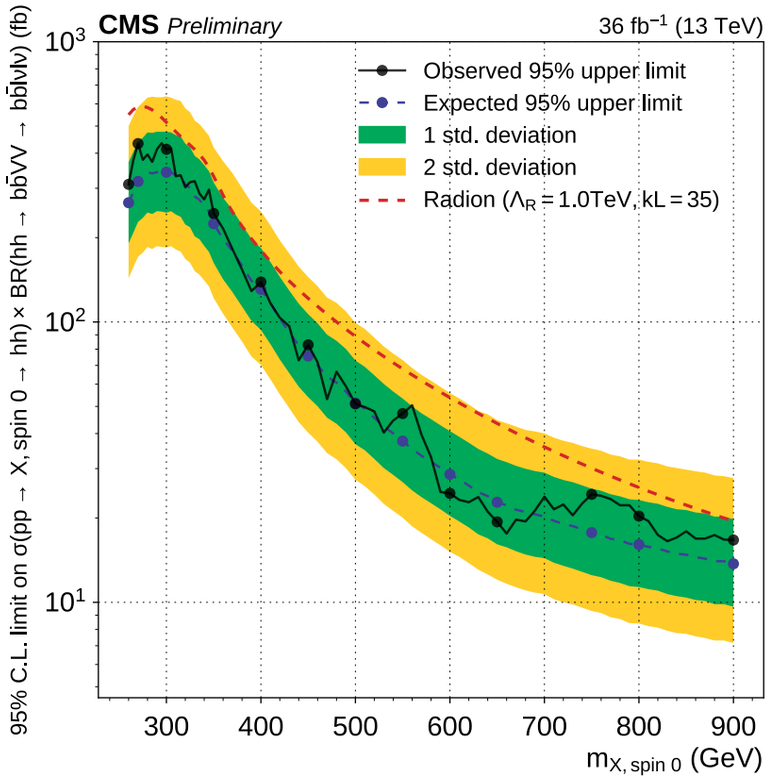


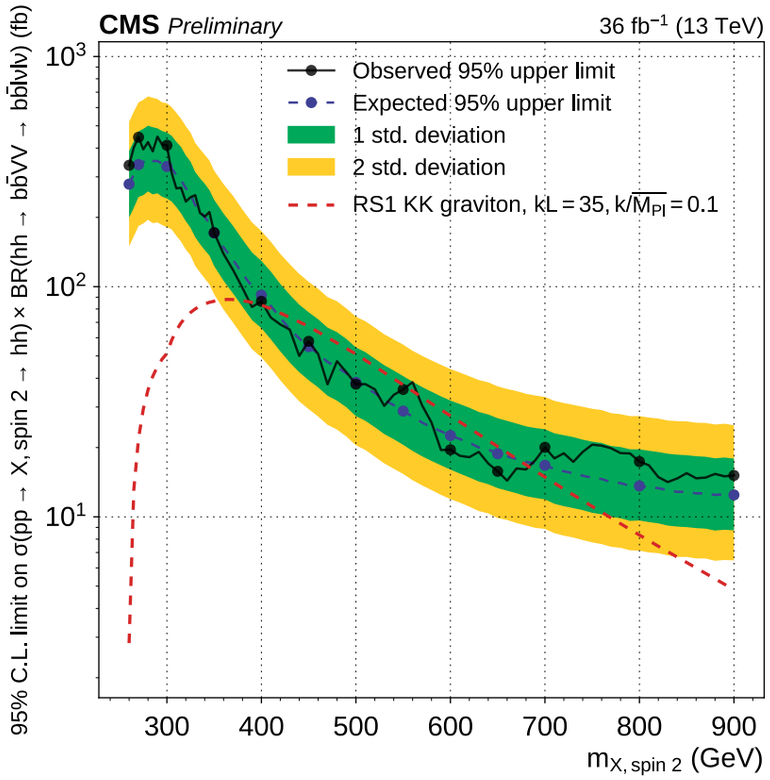
CMS-PAS-HIG-17-006

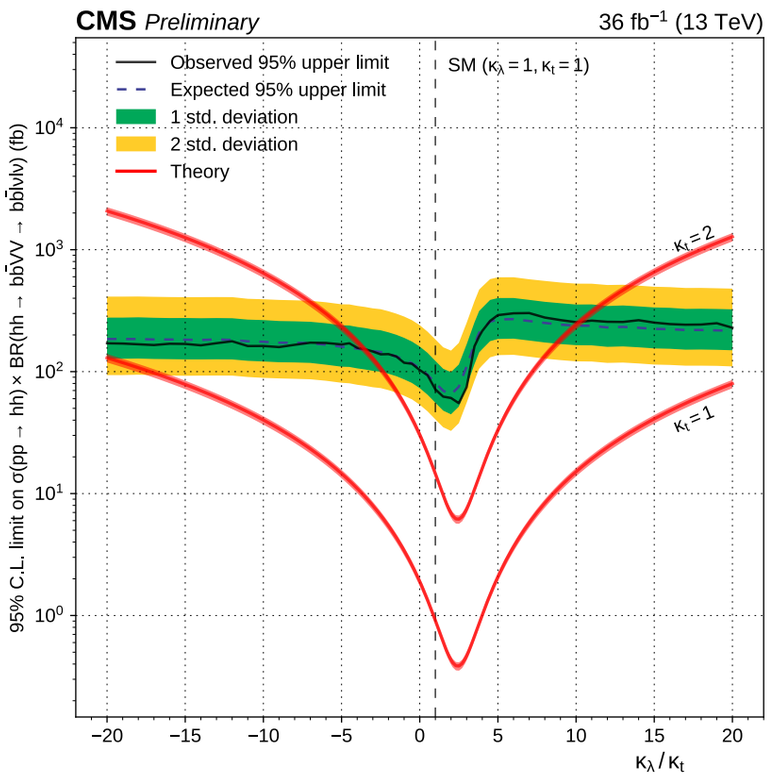
$b\bar{b}\ell\nu\ell\nu$ Results

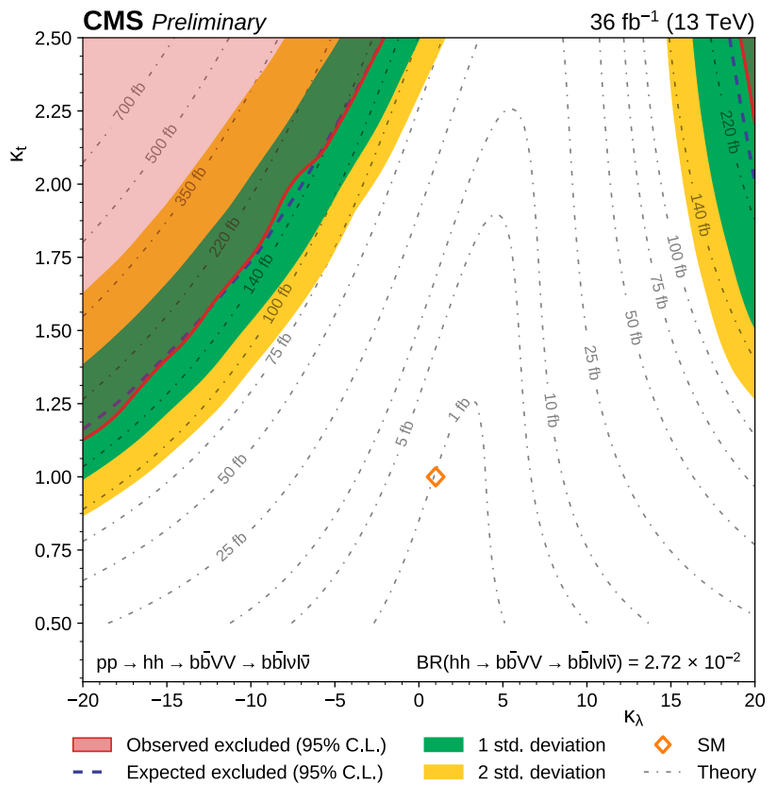
Full 2016 dataset

- Combine 3 m_{jj} bins and 3 $\ell\ell$ samples
- Data are compatible with no signal
- Non-resonant obs. (exp.) 95% CL limit set at $72(81^{+42}_{-25})$ fb









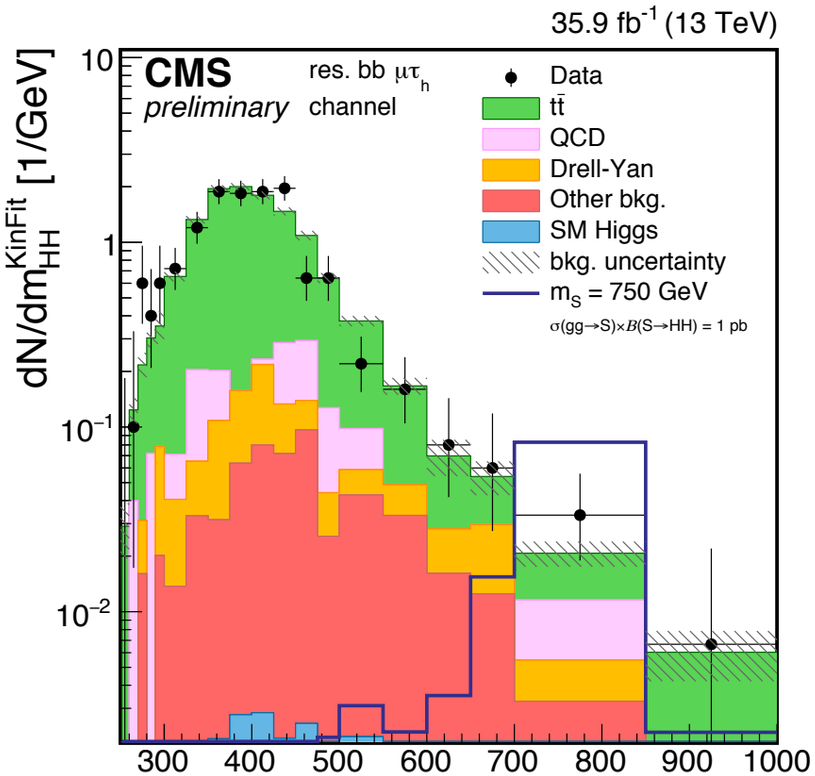
CMS-PAS-HIG-17-002

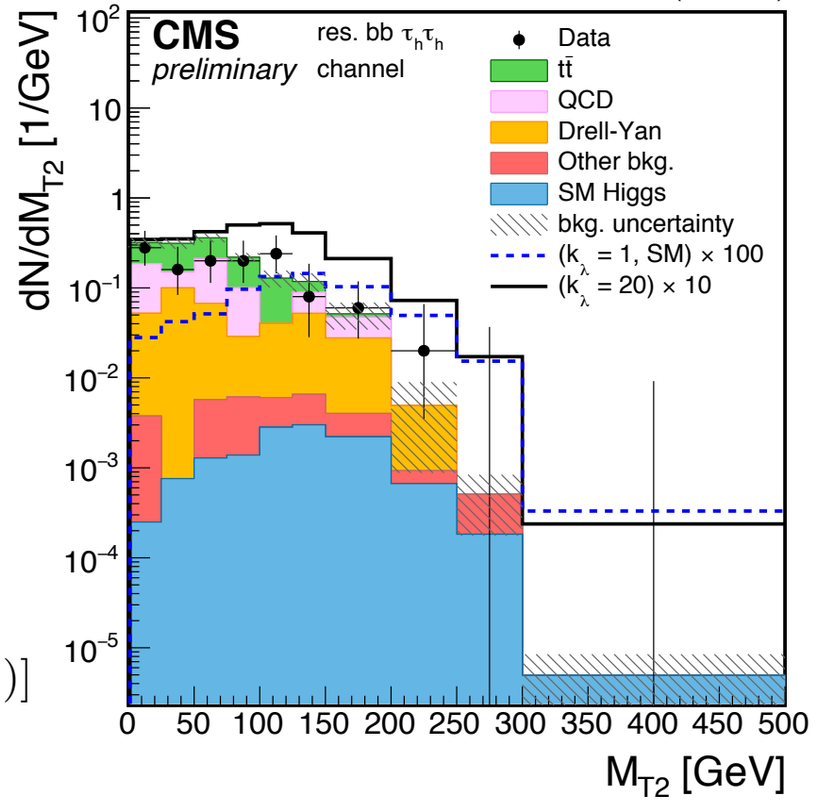
$b\bar{b}\tau\tau$

Full 2016 dataset

- 3 channels:
  $H\to\tau_h\tau_h$ / $\tau_h\tau_e$ / $\tau_h\tau_\mu$ >85% of $\tau\tau$ decays
- 3 categories: 2 b-tags, 1 b-tag, boosted (high mass)
- m_{bb} and $m_{\tau\tau}$ constrained to be consistent with m_H
- $\tau_h\tau_\ell$ final states reject $t\bar{t}$ background
  BDT trained with kinematic and angular variables
- Signal discrimination
  - Resonant: HH system kinematic fit m_{HH}^{KinFit} improves m_X resolution
  - Non-resonant: 'stransverse' mass m_{T2} designed for signal-background separation

$$m_{T2} = \min_{(p_{T_1}+p_{T_2}=p_T^{\tau\tau\ \text{system}})} \max[m_T(p_T^{b_1}, p_{T_1}, m_{b_1}, m_{\tau_1}^{vis}), m_T(p_T^{b_2}, p_{T_2}, m_{b_2}, m_{\tau_2}^{vis})]$$



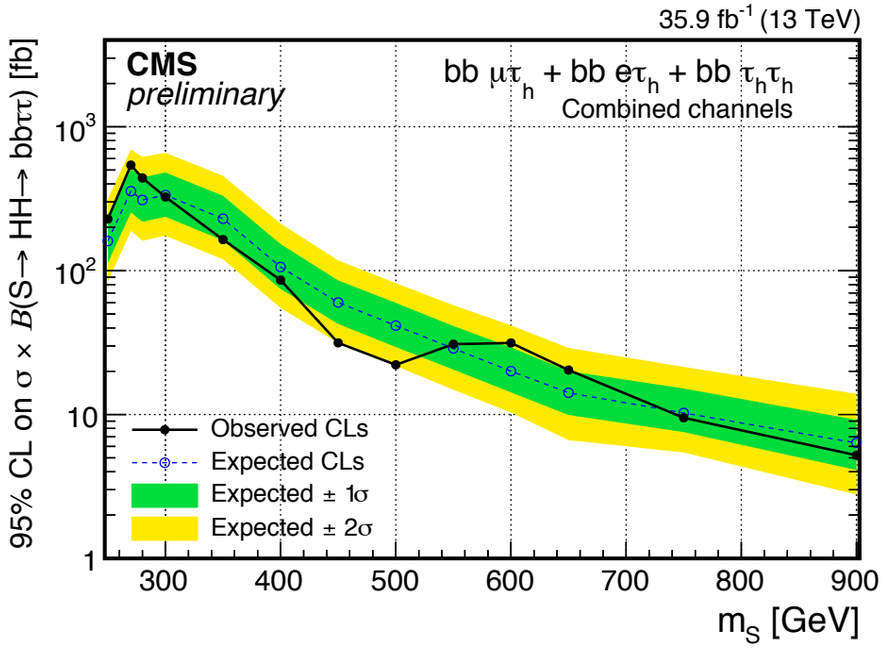


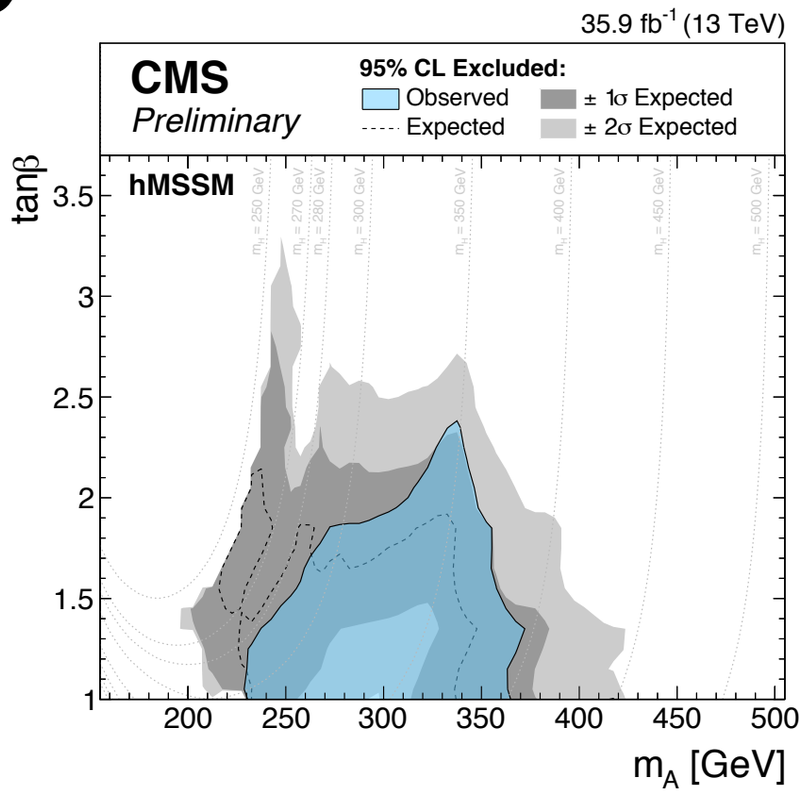
CMS-PAS-HIG-17-002

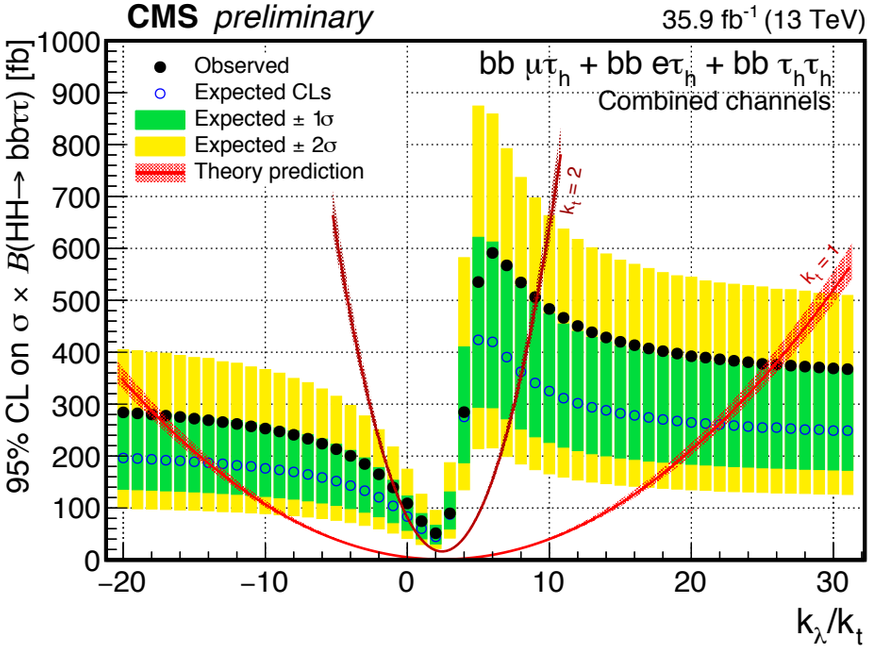
$b\bar{b}\tau\tau$ Results

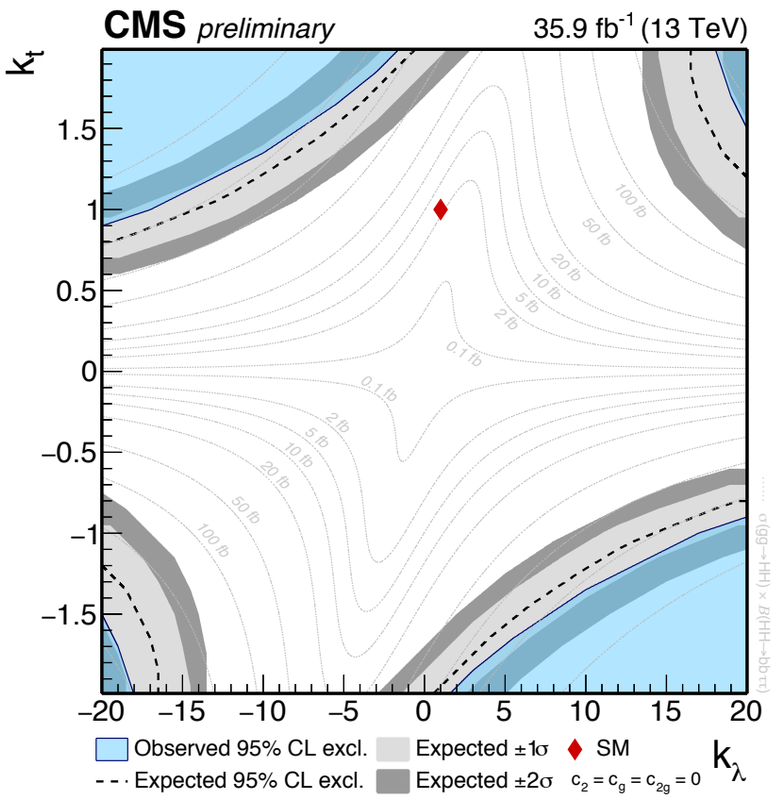
Full 2016 dataset

- 3 channels combined in limit setting
- Resonant analysis interpreted as model-independent narrow resonance and in hMSSM
- Non-resonant analysis obs. (exp.) 95% CL limit set at 28(25)*SM expectation







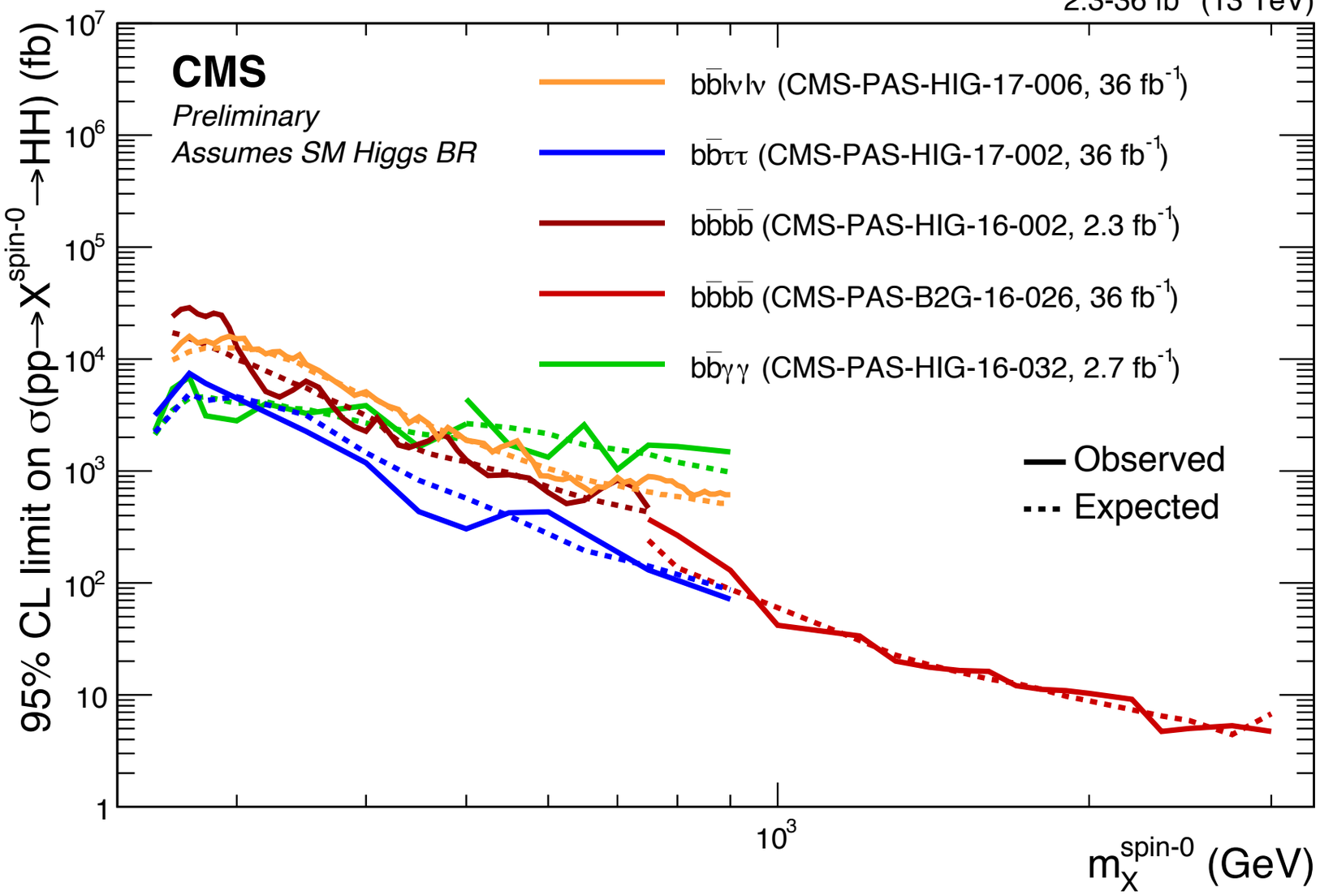


Summary of Results

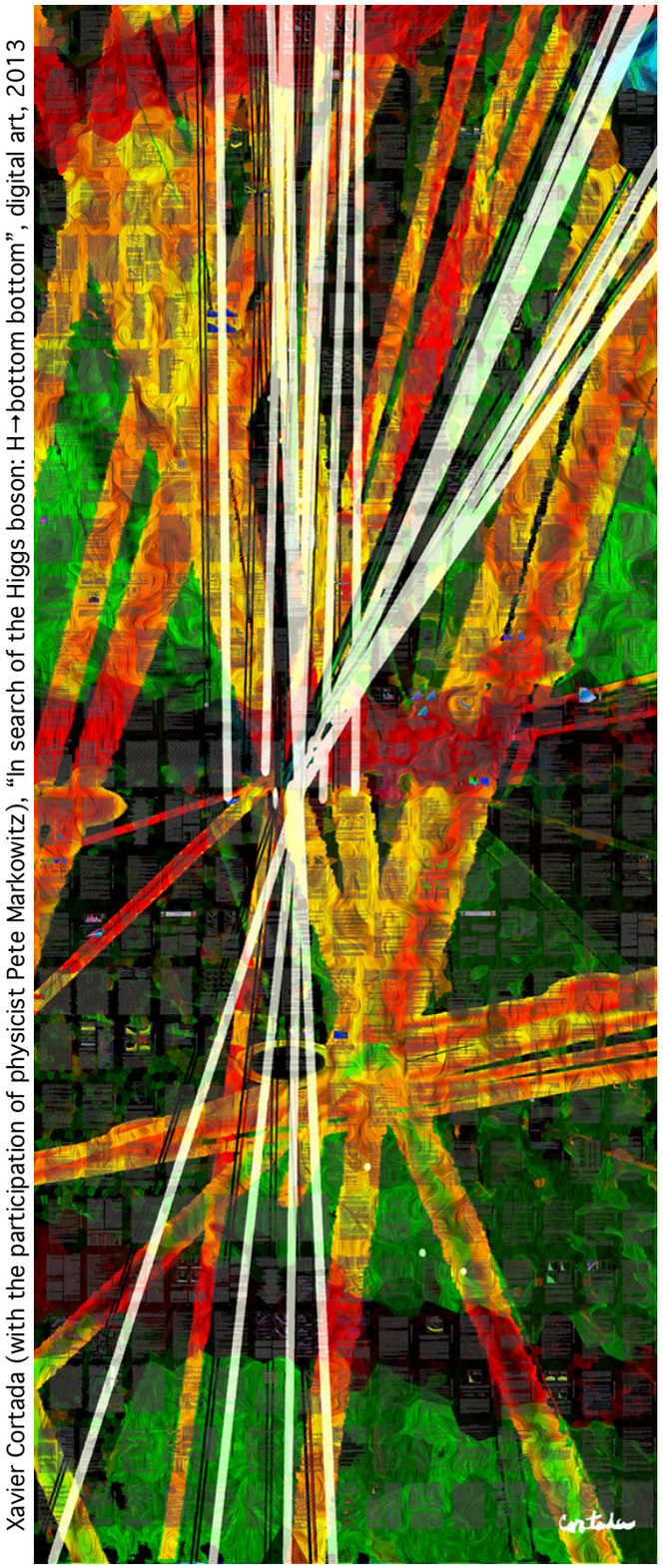
NEW!

13TeV non-resonant observed (expected) σ/σ_{SM} 95% CL limits		
$b\bar{b}\tau\tau$	28 (25)	35.9 fb^{-1}
$b\bar{b}\ell\nu\ell\nu$	79 (89)	35.9 fb^{-1}
$b\bar{b}\gamma\gamma$	91 (90)	2.7 fb^{-1}
$b\bar{b}b\bar{b}$	342 (308)	2.3-2.7 fb^{-1}

To be updated soon



Conclusion

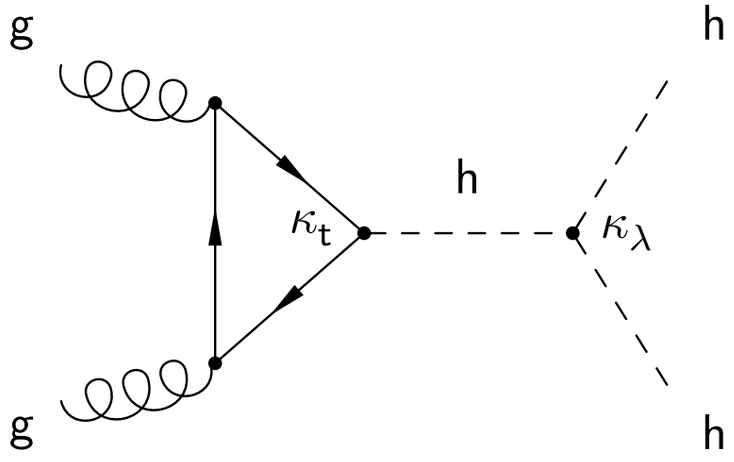


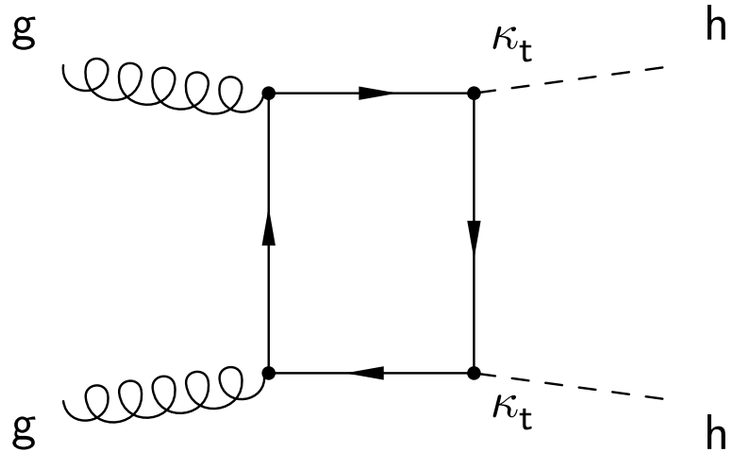
Xavier Cortada (with the participation of physicist Pete Markowitz), "In search of the Higgs boson: H→bottom bottom", digital art, 2013

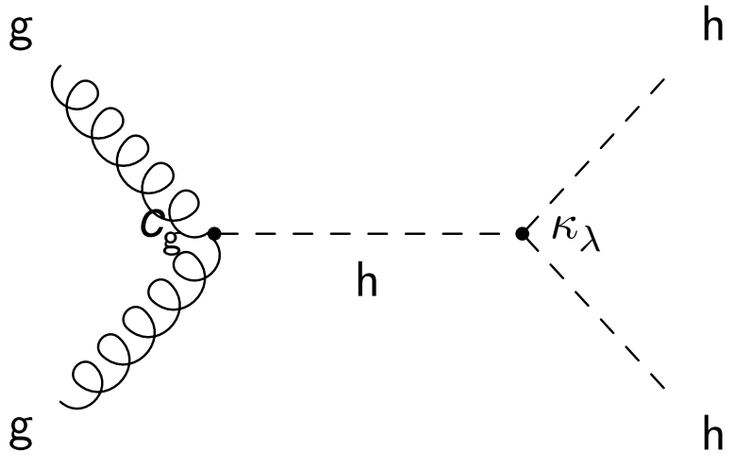
- Searches for HH production give both insight into the nature of electroweak symmetry breaking and searches for new physics
- CMS has a suite of HH searches which are disjoint and complementary across a large mass range
  - So far no sign of SM or BSM HH production. Current best limits: $28*\sigma_{SM}$
  - Multiple analyses still to update to full 2016 dataset
- (B)SM HH will be tested as we transition from energy-scaling regime to the luminosity-scaling era of the HL-LHC
  - Improving analyses, adding new final states and combining results will be crucial to success

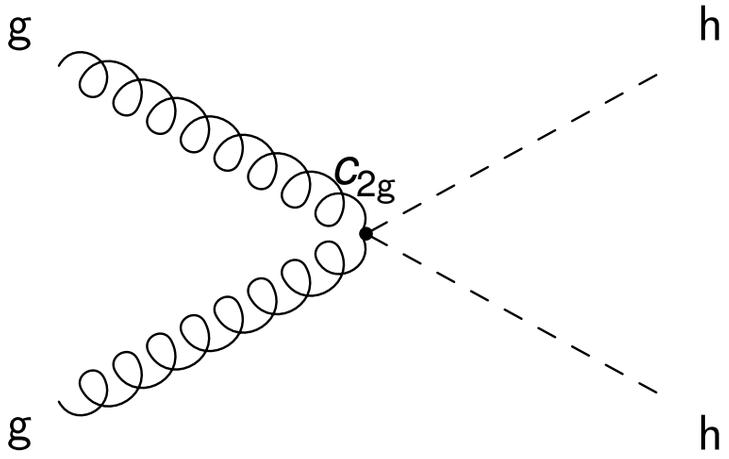
b($\bar{b}$)ackup

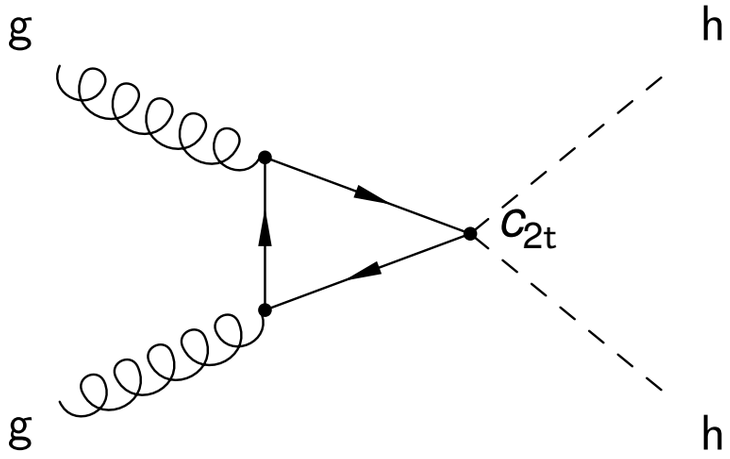
Non-resonant HH production



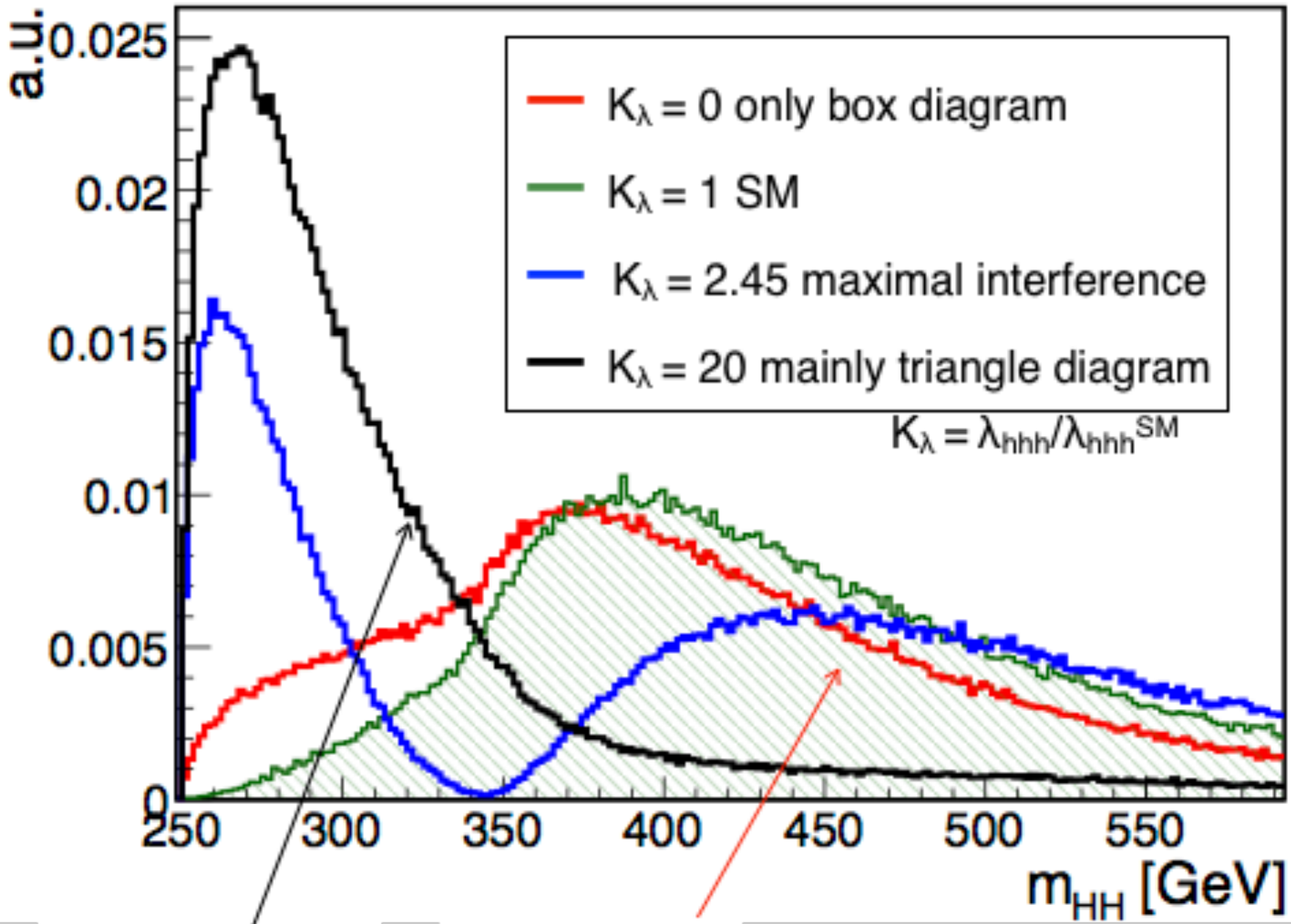








Non-resonant HH shape

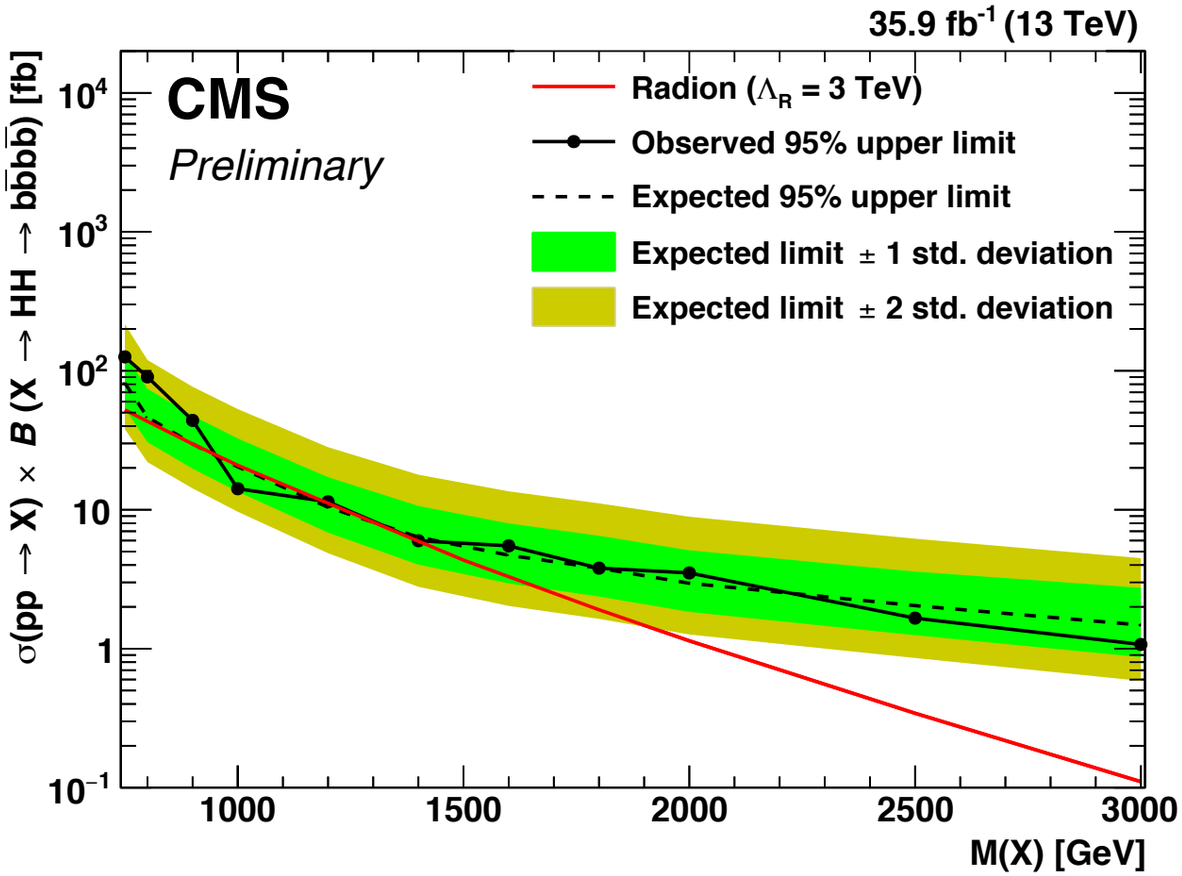


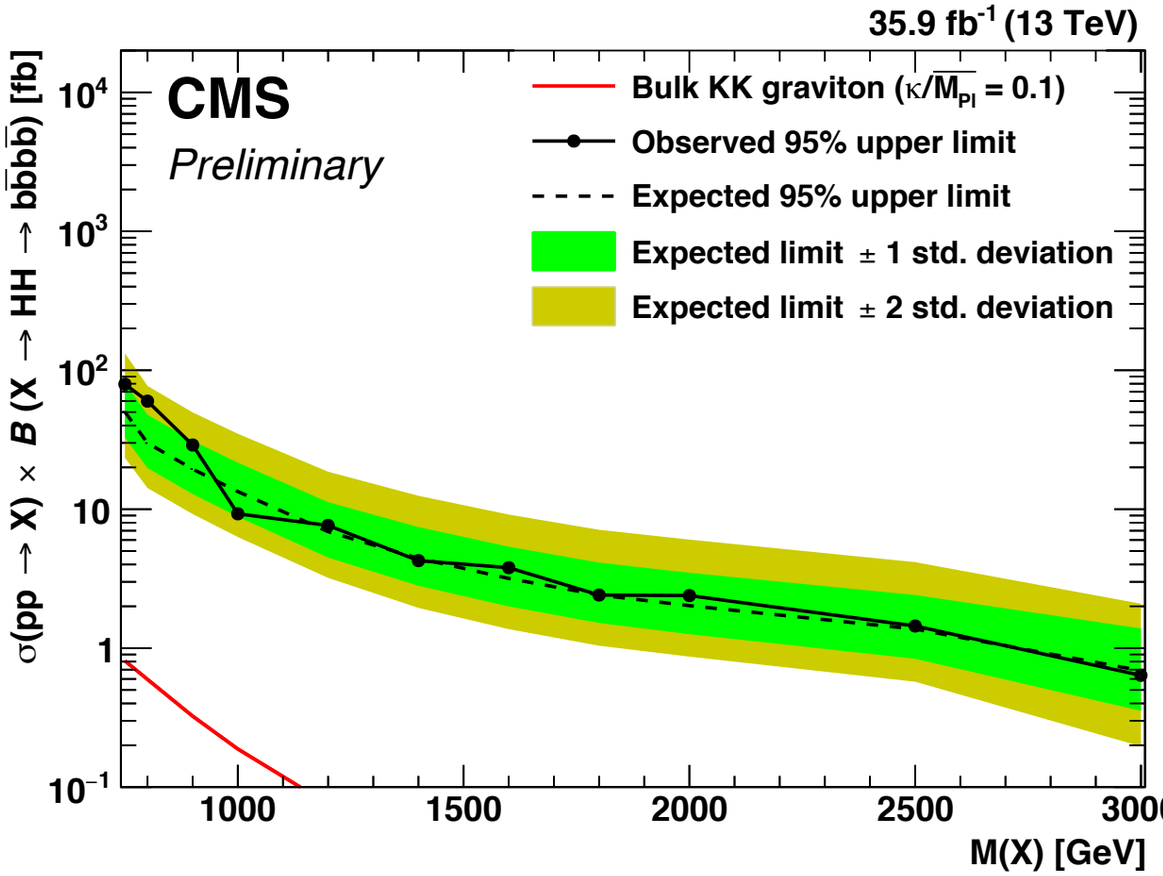
CMS-PAS-B2G-16-032

$b\bar{b}b\bar{b}$

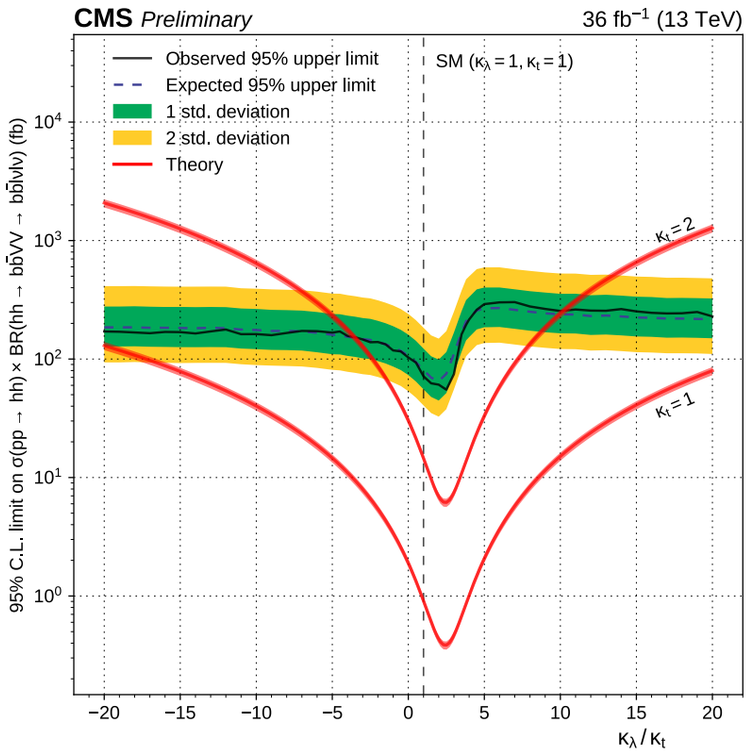
Full 2016 dataset

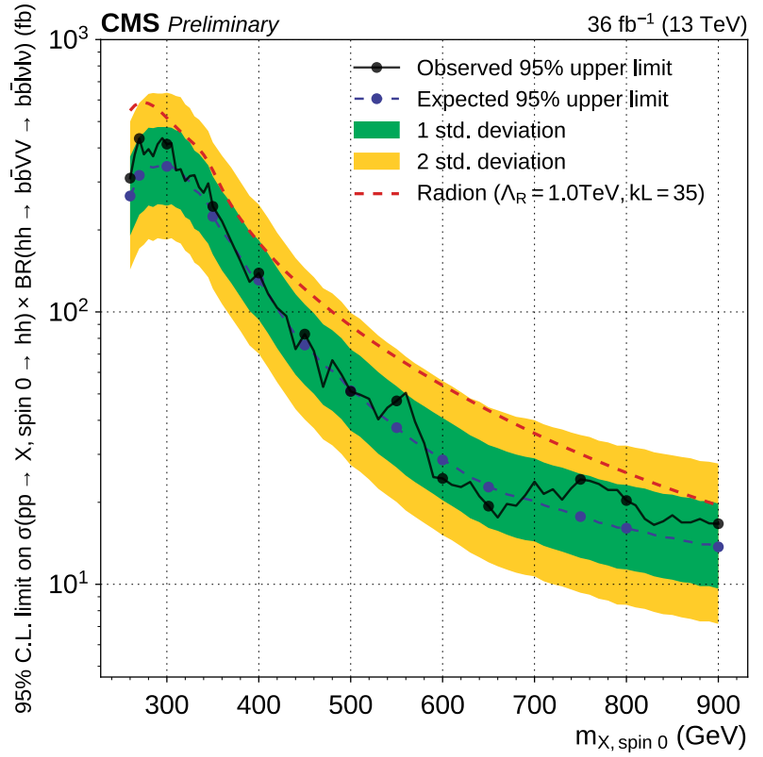
NEW!



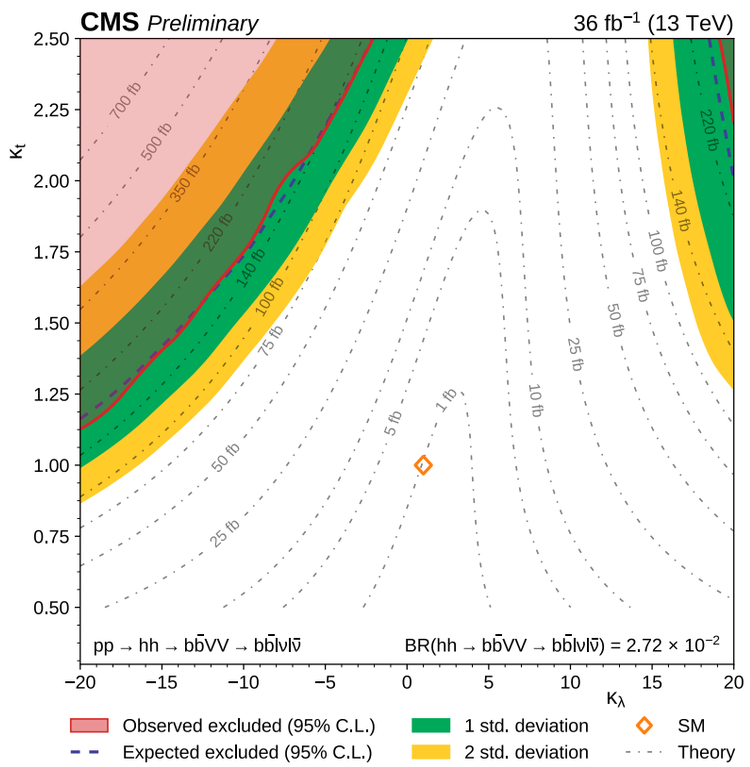


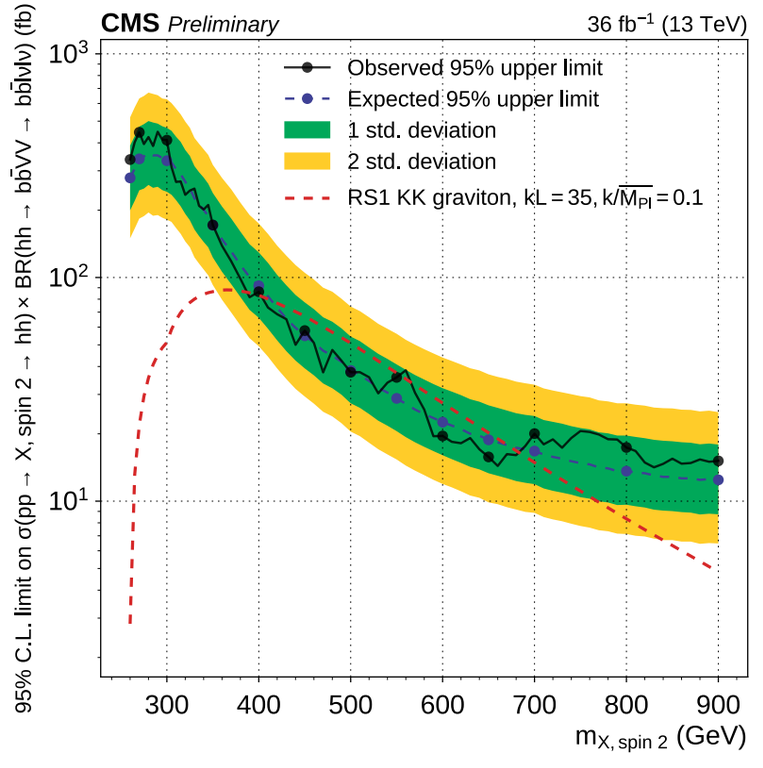
$b\bar{b}\ell\nu\ell\nu$





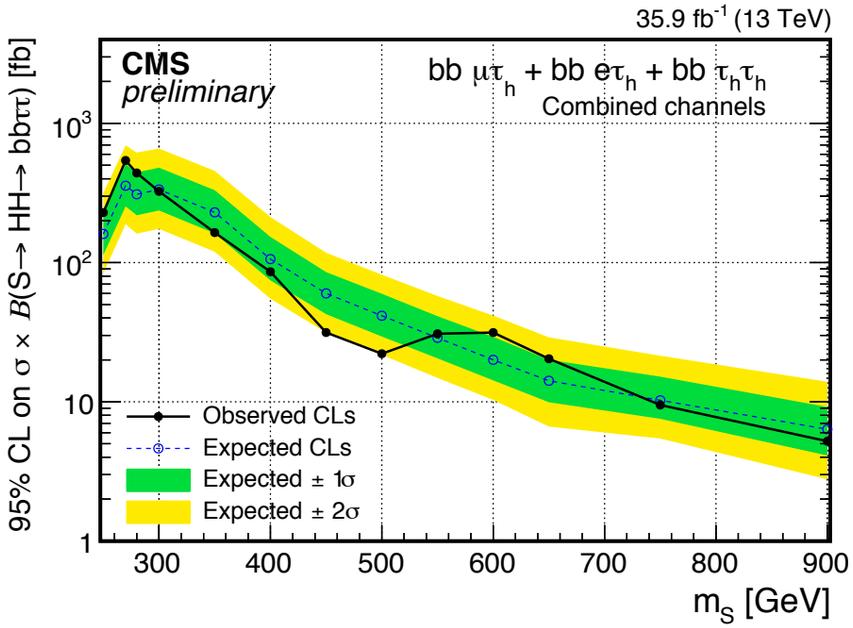
X = Radion



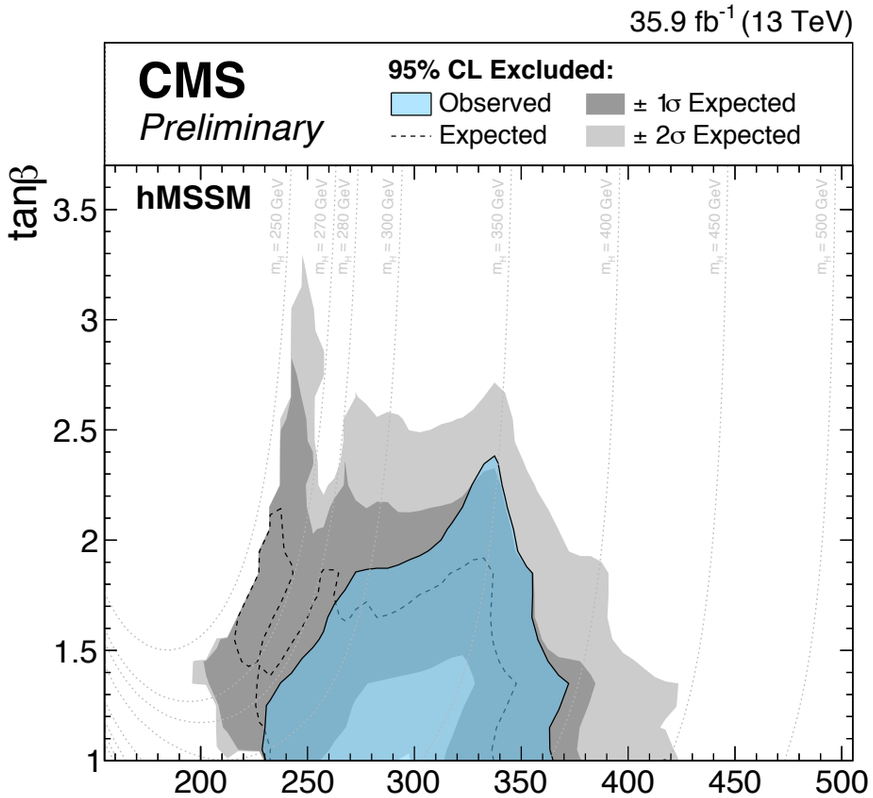


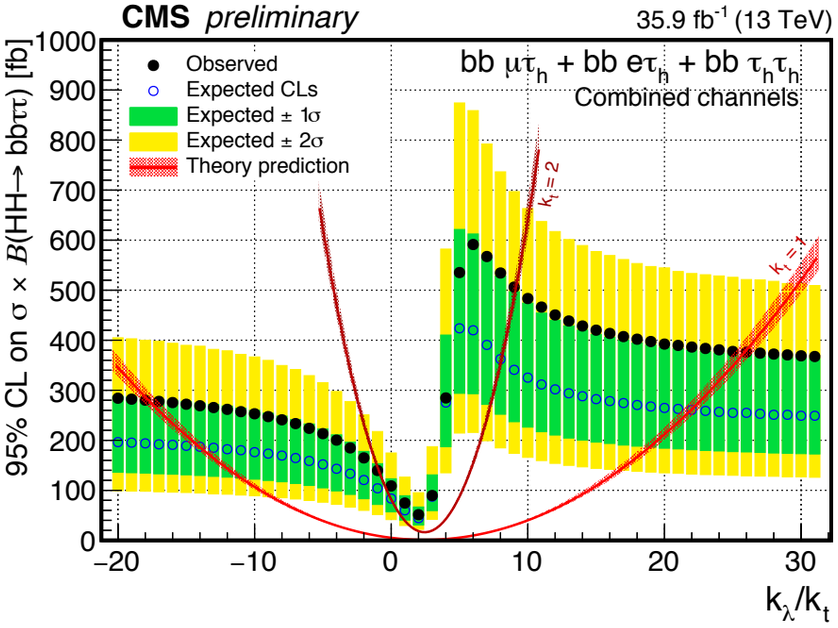
X = Kaluza-Klein Graviton

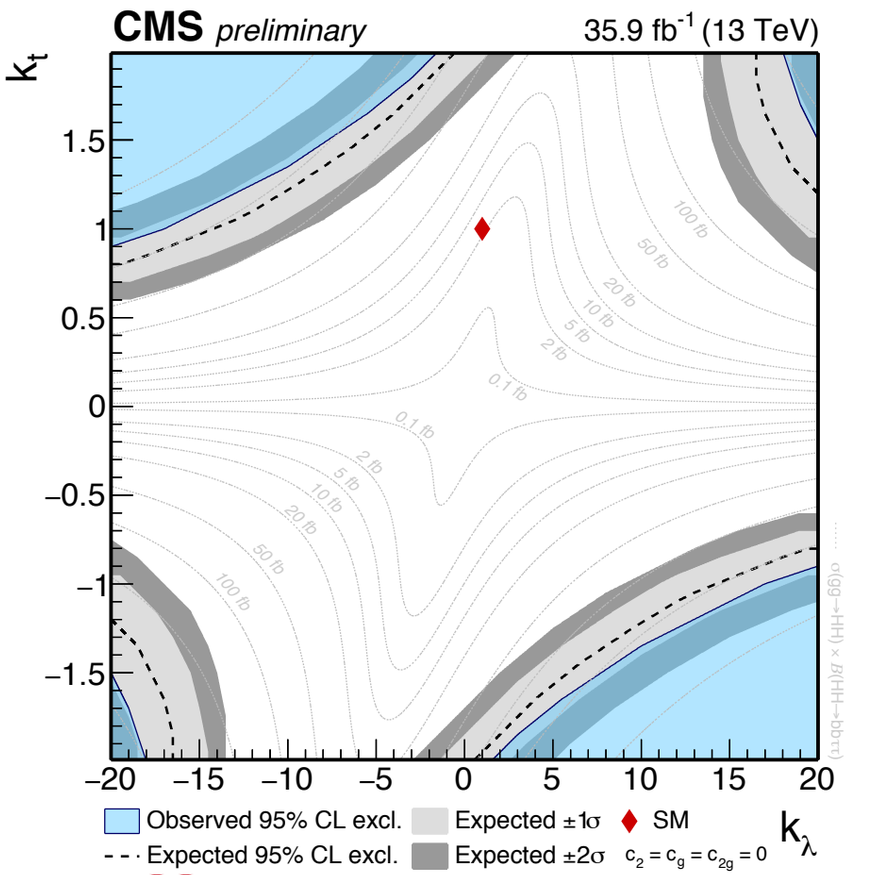
$b\bar{b}\tau\tau$



(a) Model independent limit

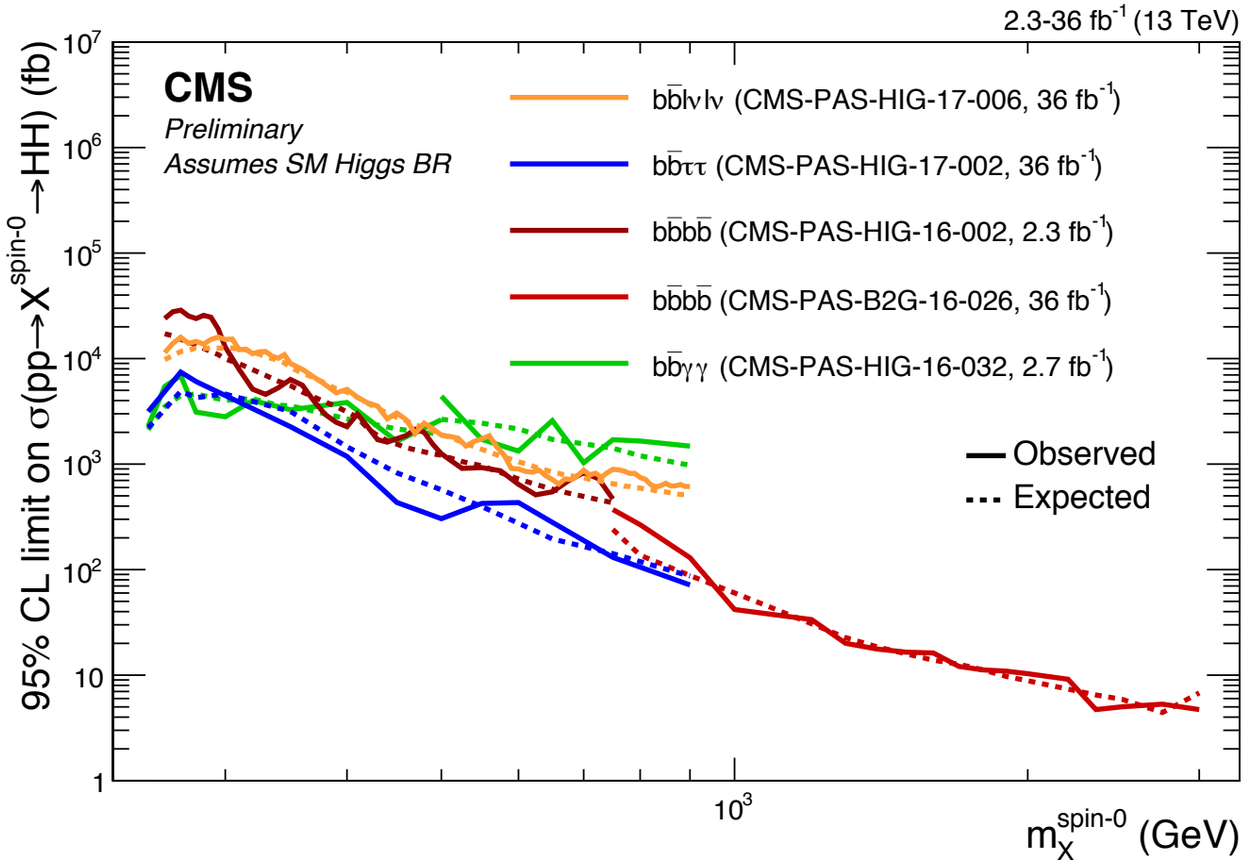


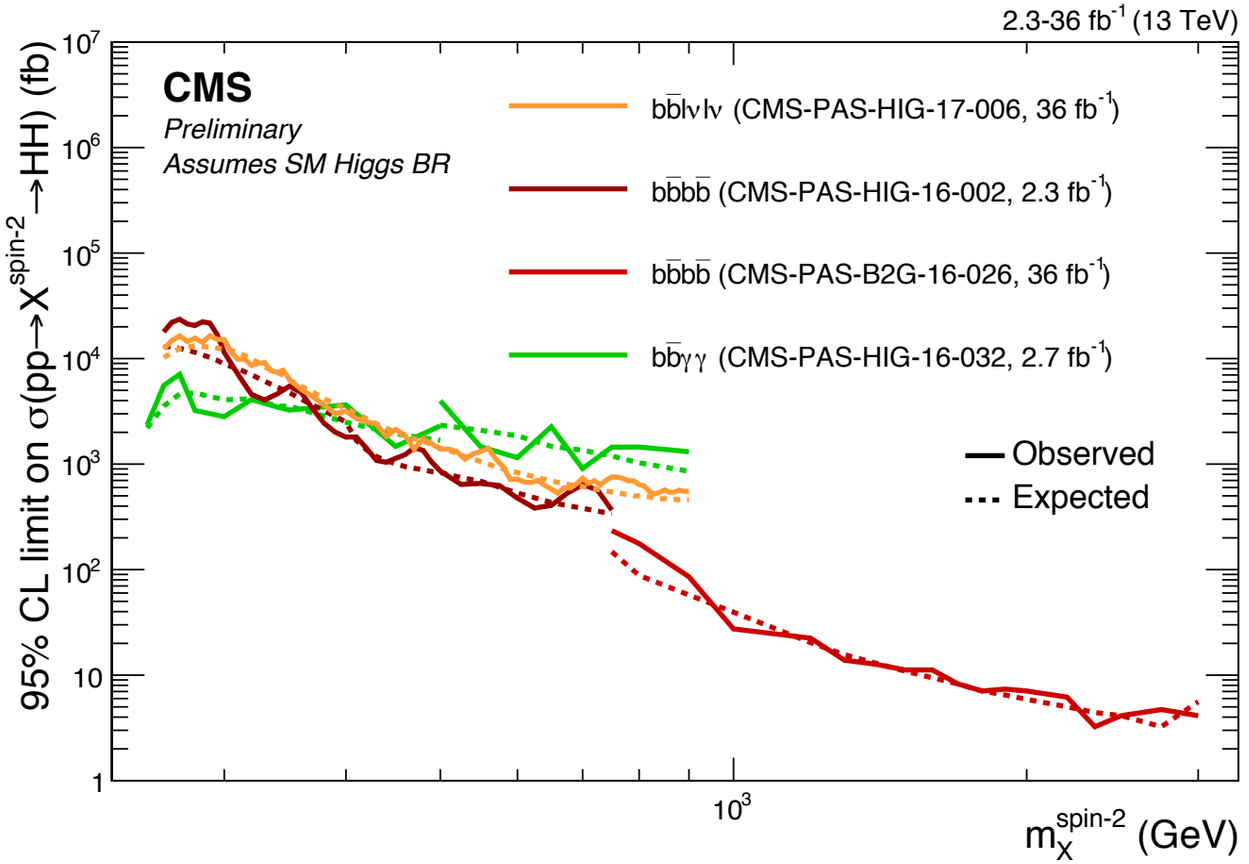




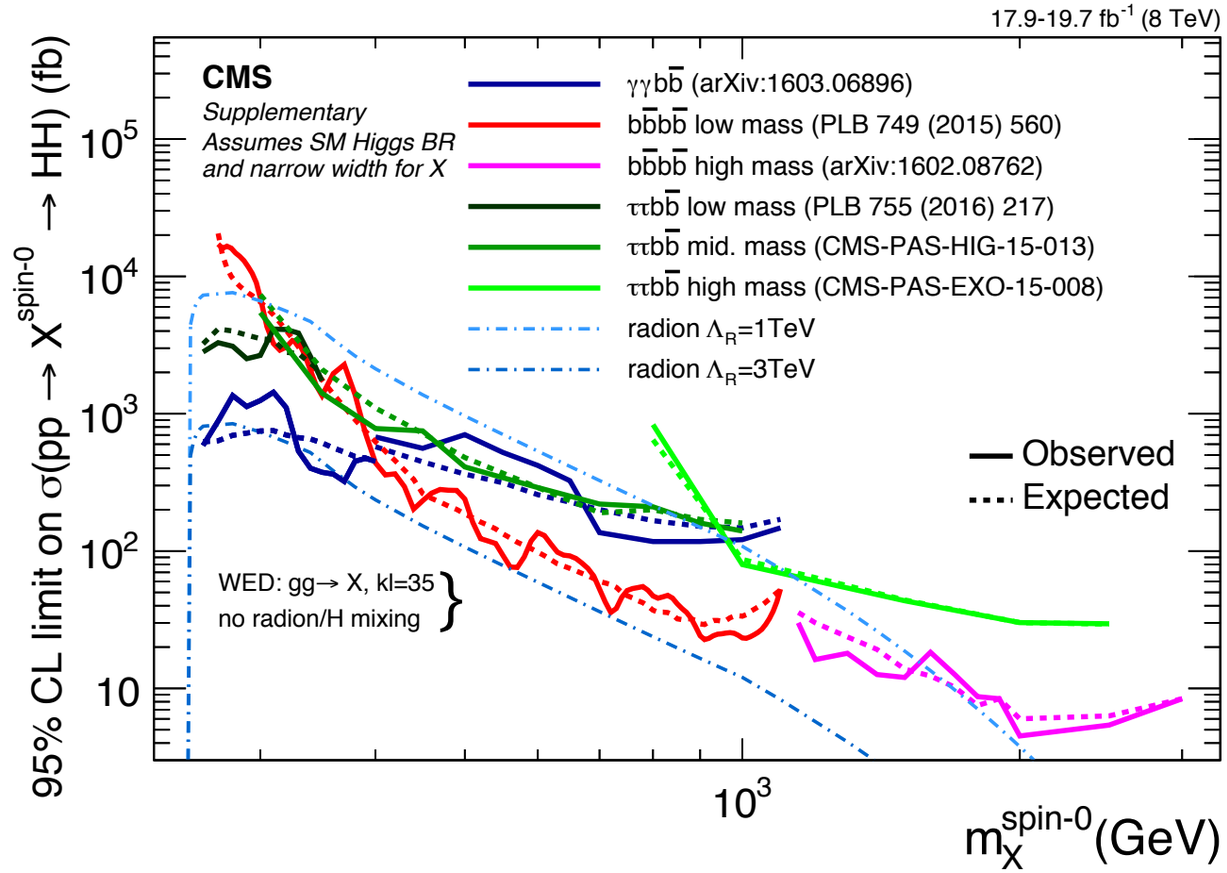
Summary of Results

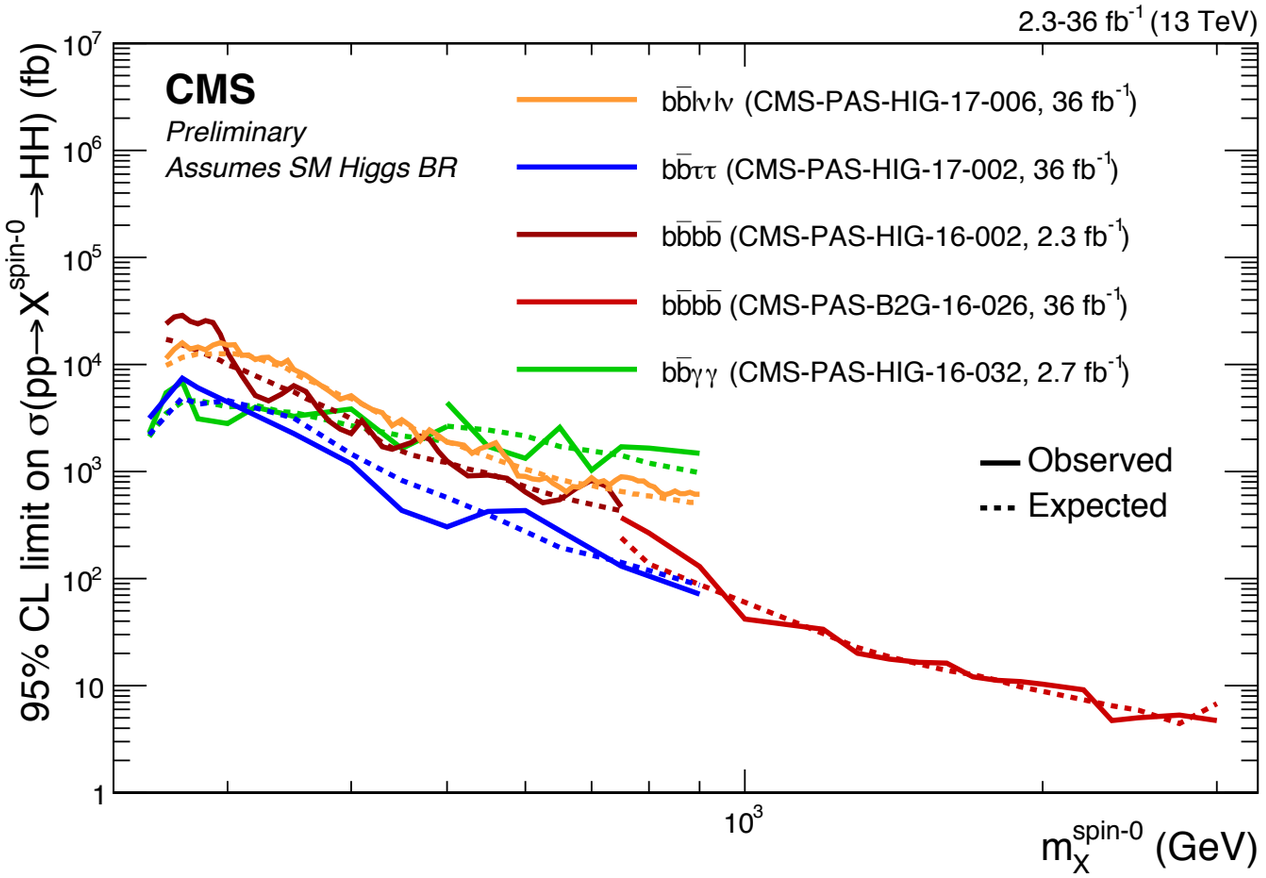
NEW!





Run1 Comparison





Run2 Comparison