Di-Higgs Searches at CMS

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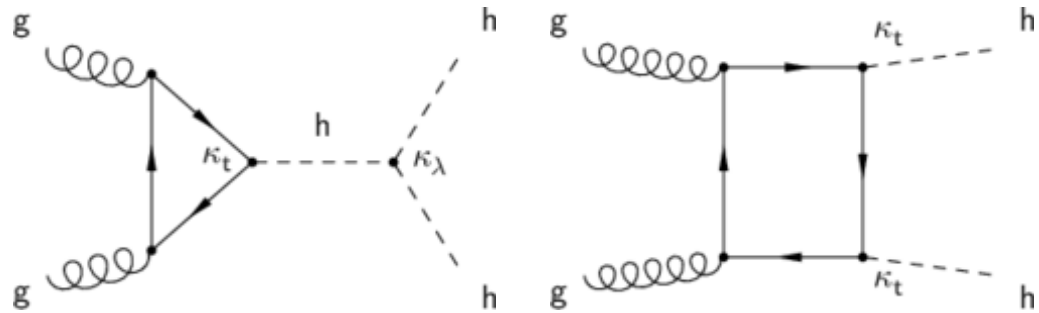
on behalf of the CMS collaboration

Non-resonant HH production

- Production is dominated by gluon fusion
- Measuring λ_{hhh} is a crucial test of electroweak symmetry breaking



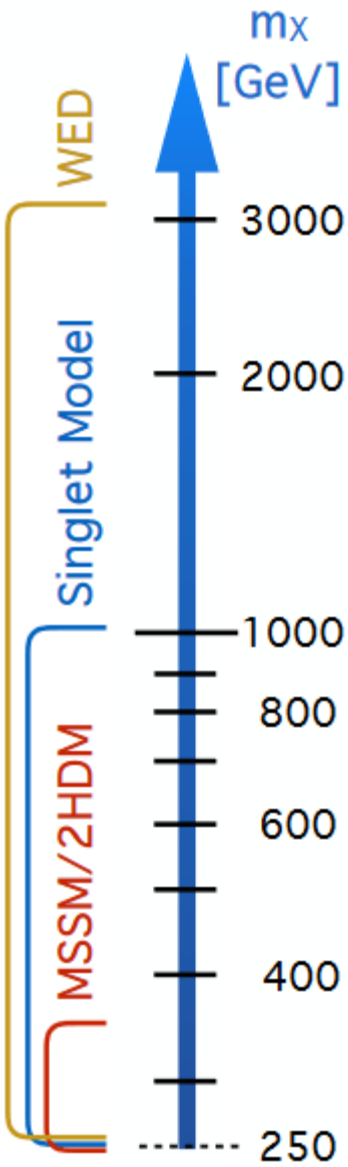
$$V = \frac{m_h^2}{2}h^2 + \lambda_{hhh} v h^3 + \frac{\lambda_{hhhh}}{4}h^4, \quad \lambda_{hhh} = \frac{m_h^2}{2v^2}$$

$\sigma_{gg\to HH} = 33.49^{+4.3}_{-6.0}(\text{Scale}) \pm 2.1(PDF) \pm 2.3(\alpha_s)$ fb, arXiv:1610.07922

- Diagrams interfere destructively – small σ_{HH}
- Effective lagrangian used to predict BSM scenarios
  - BSM physics could cause a substantial enhancement in the production cross section and a change to the event kinematics

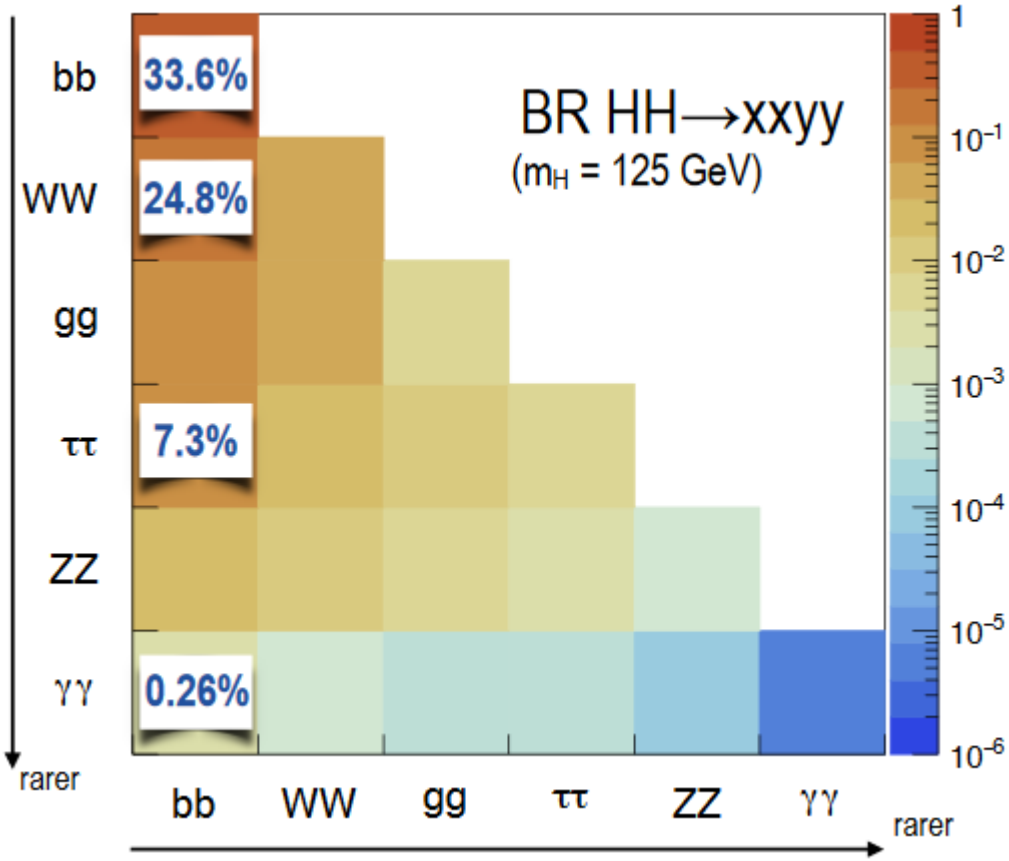
Resonant HH production

- Resonant HH production would be evidence of a new state, not predicted by the SM
- Many BSM models predict X → HH scenarios
  - Singlet model, MSSM, 2HDM, warped extra dimensions
  - Full coverage of broad m_X range over multiple channels is necessary to maximize the sensitivity to all models
- Benchmark model: Bulk Randall-Sundrum WED scenarios
  - Spin-0 Radion
  - Spin-2 Kaluza-Klein Graviton



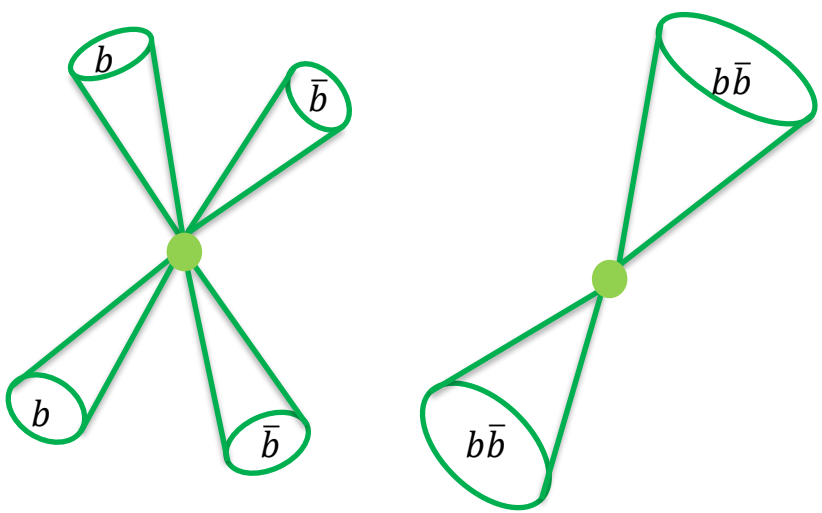
Which final state?

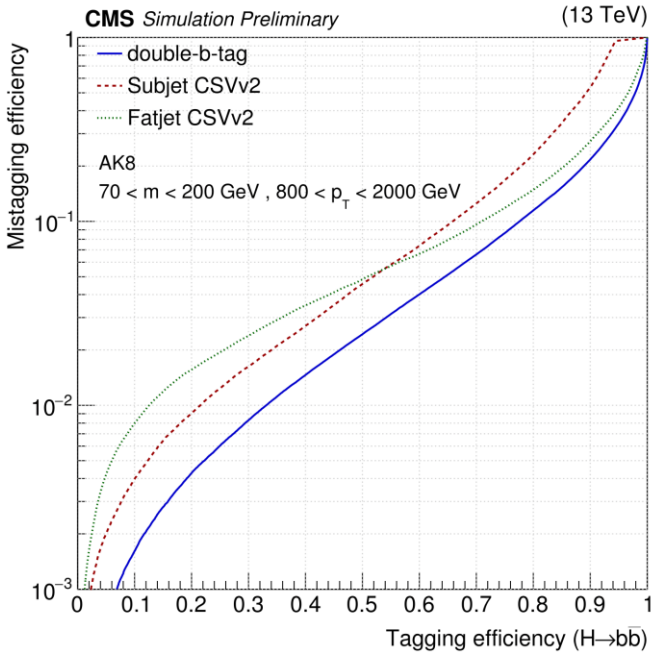
- One H→bb decay required to keep the branching fraction high
  - Identification of H→bb decays is well understood
- Other H decay depends on event kinematics
  - Channel specific challenges
  - Different coverage in m_X



HH → bbbb

- High BR, large multijet background
  - Estimated from data
- 2 event topologies
  - Resolved: each b quark is reconstructed as a separate jet
  - Boosted: the tracks from each b jet of a Higgs merge; each H reconstructed as a separate jet

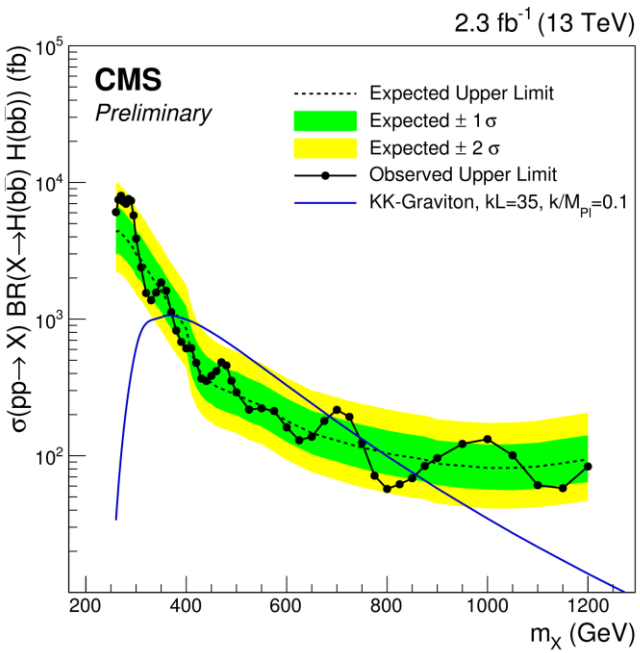




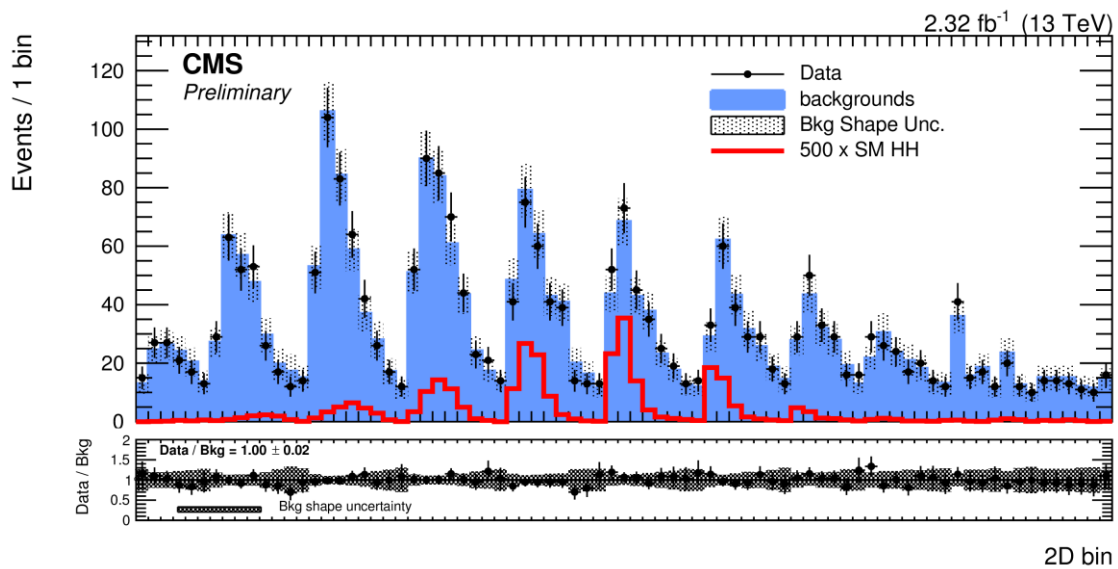
- b-tagging crucial to reduce large background
  - Resolved: b-tagging at trigger level and a multivariate discriminant
  - Boosted: multivariate discriminant used to find jets with 2 b quarks within

HH → bbbb (Resolved)

- Invariant masses of dijets used to search for signal
- Resonant
  - Different resonant mass categories use different selection criteria
- Non-resonant
  - Reject tt and QCD background with a BDT trained on dijet kinematics
  - Obs. upper limit at 95% CL is at 308 × σ_{SM} prediciton



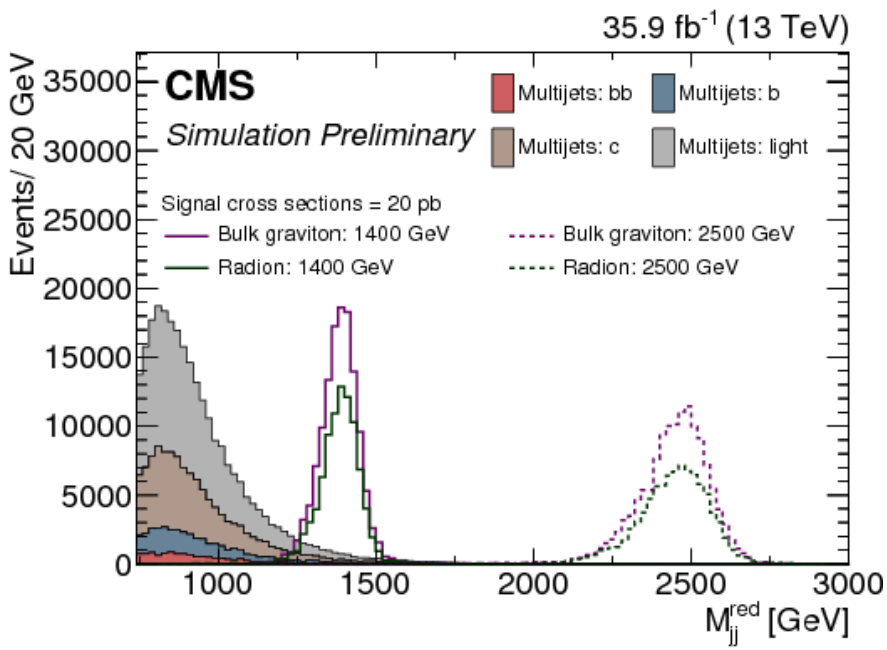
Category	Observed	Expected	-2σ	-1σ	$+1\sigma$	$+2\sigma$
			[fb]			
SM $H(b\bar{b})H(b\bar{b})$	3880	3490	2140	2540	5350	8350



HH → bbbb (Boosted)

Full 2016 dataset

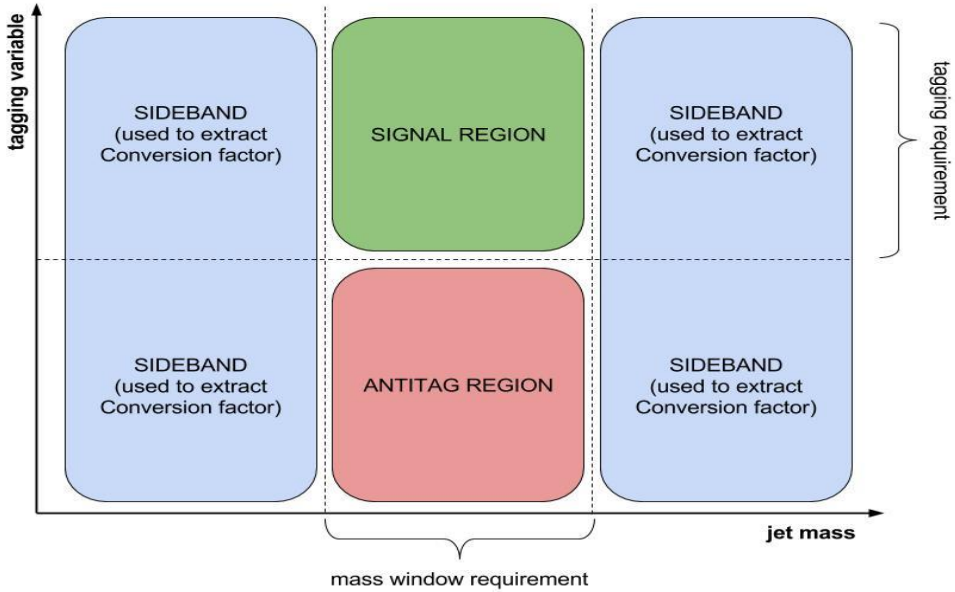
- Jet substructure, jet mass, and double b-tagger MVA used to reduce background
- Improved resolution from reduced dijet mass
  - $M_{jj}^{red} = M_{jj} - (M_{jet1} - M_H) - (M_{jet2} - M_H)$
- New data driven method for background estimate: Alphabet Assisted Bump Hunt (AABH)
  - Combines the Alphabet method and the classic Bump Hunt method

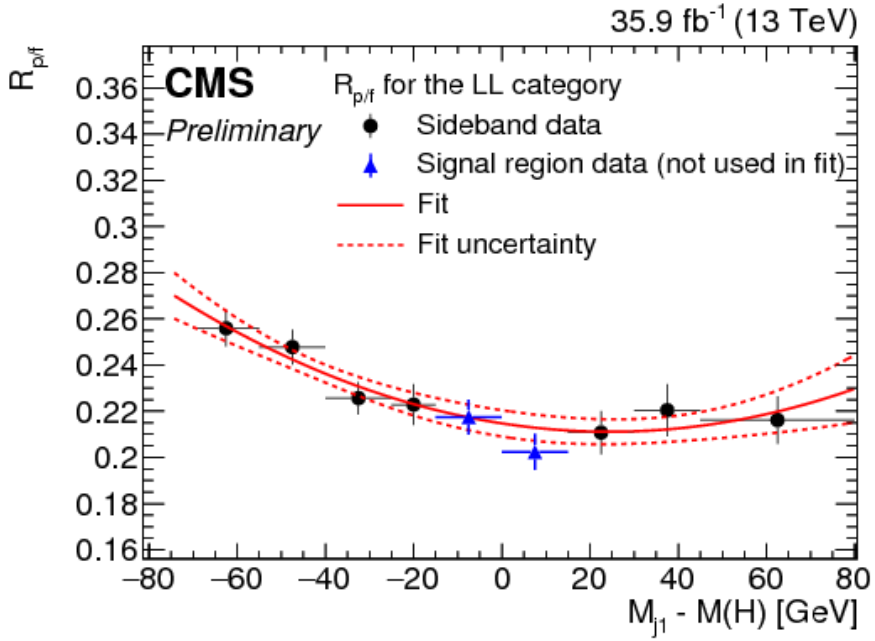


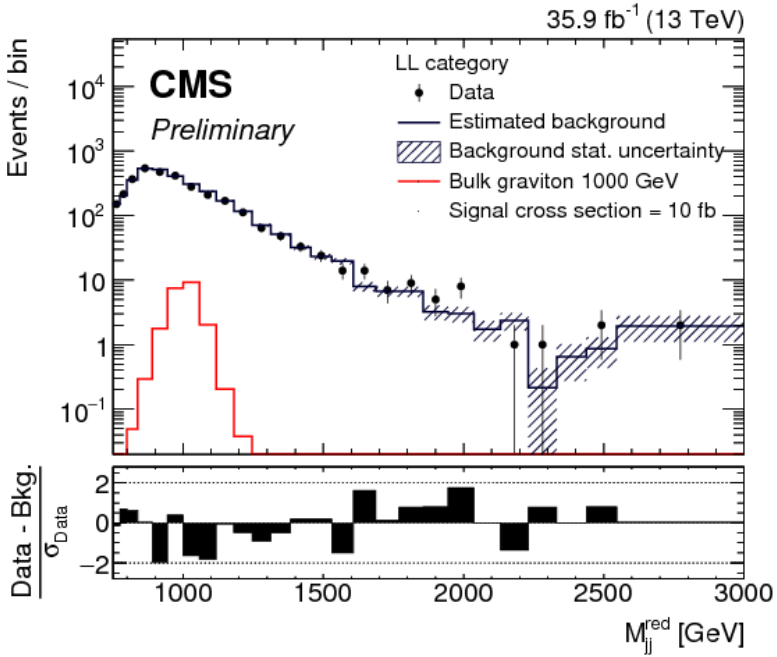
Alphabet Method

Full 2016 dataset

- Uses information from sidebands of the (leading) jet mass to predict some conversion factor: $R_{p/f}$
- $R_{p/f}$ scales Anti-tag region for bin by bin estimate of background
- Used below trigger turn-on



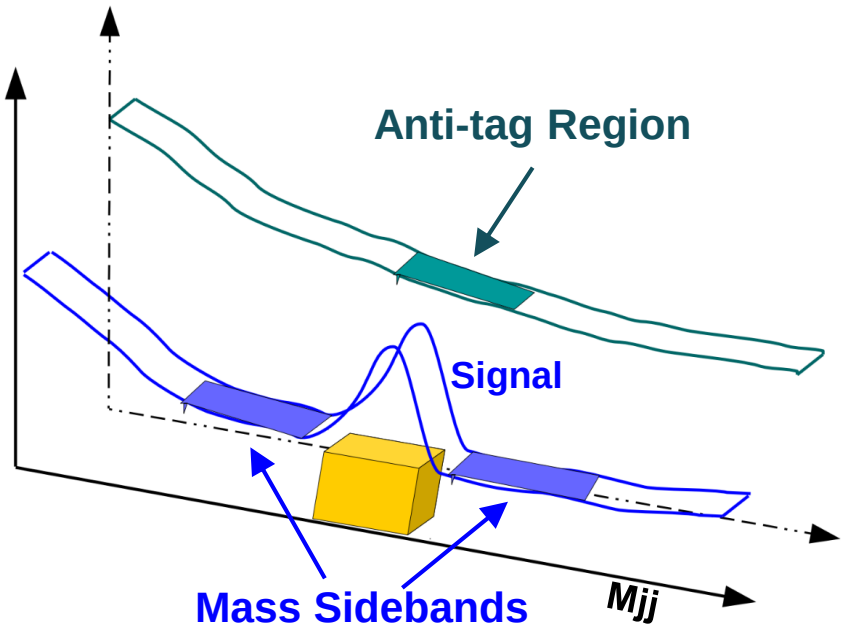


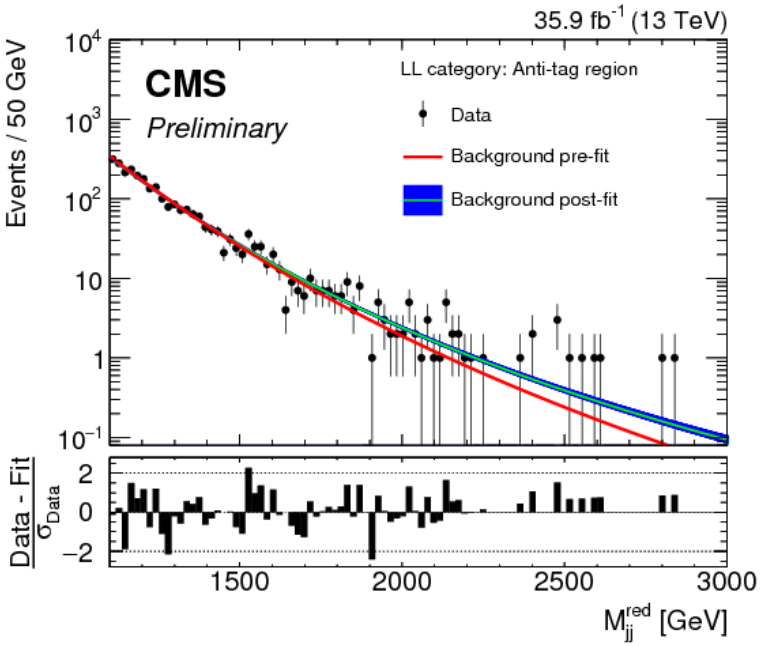


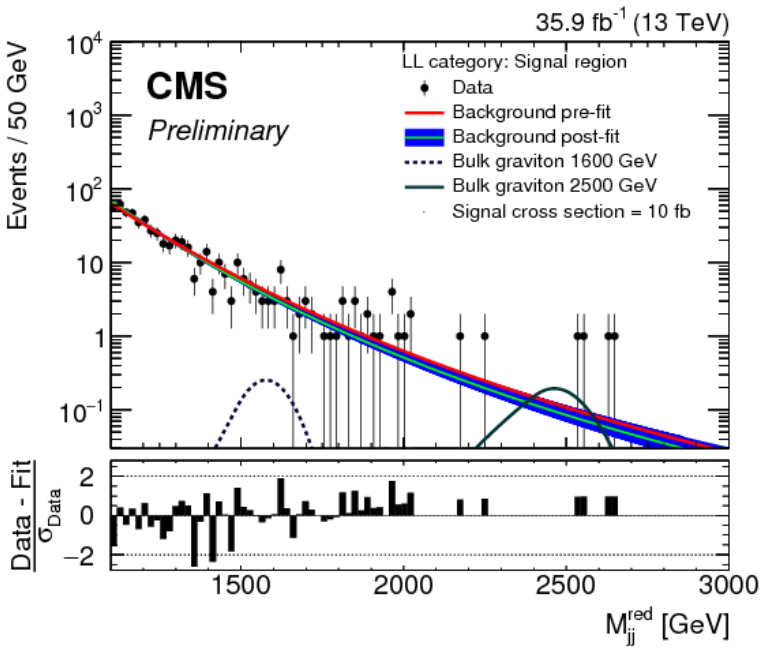
AABH Method

Full 2016 dataset

- Simultaneous fit of bkg in anti-tag region and signal region
  - Same parametric shape for both regions
  - Bkg normalization in signal region constrained by $R_{p/f}$
- Used above trigger turn-on



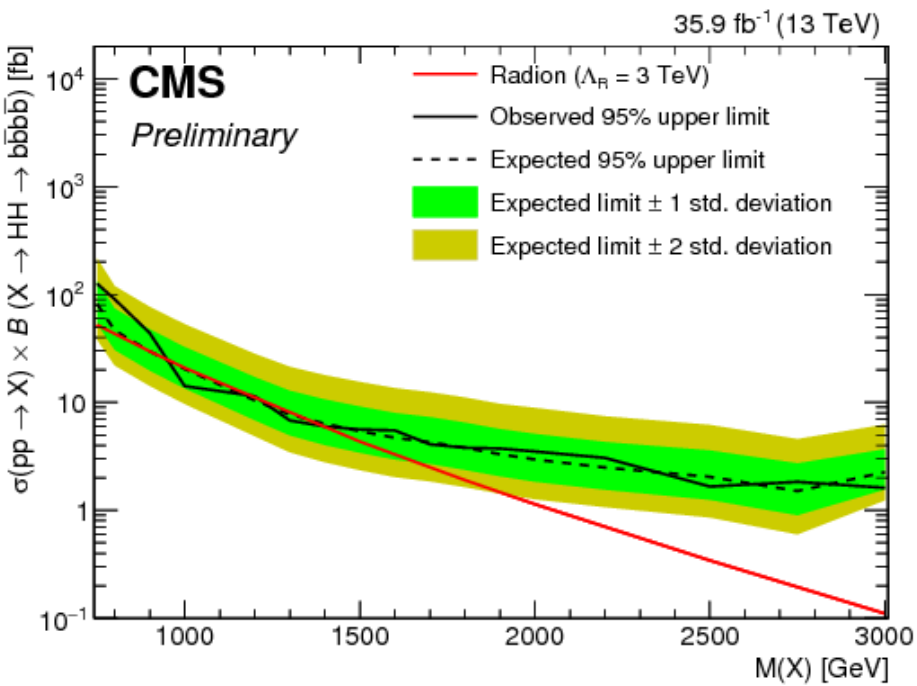


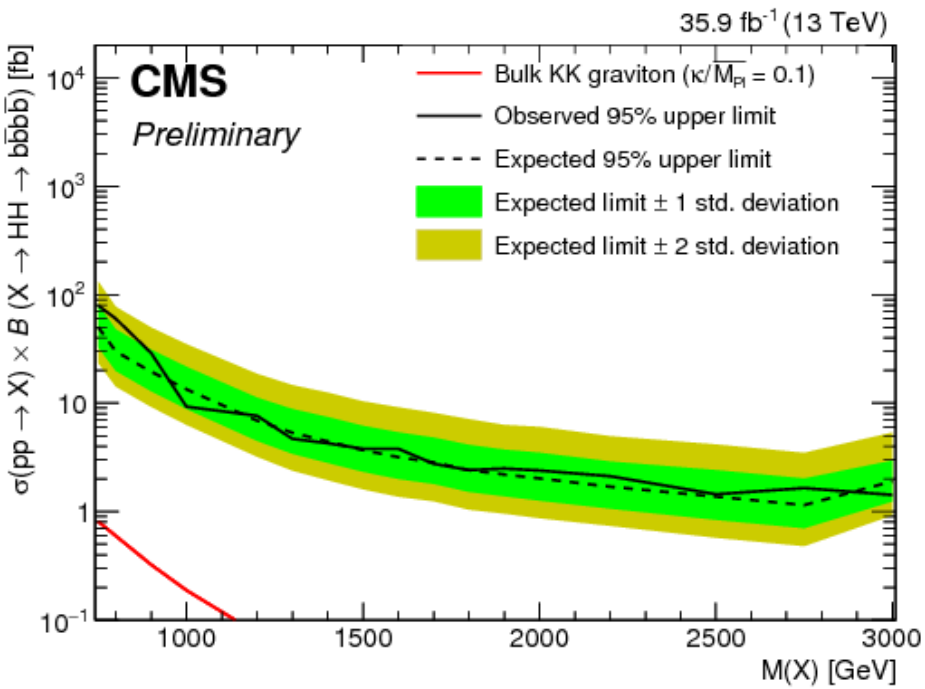


HH → bbbb (Boosted) Results

Full 2016 dataset

- Model independent limits interpreted in spin-0 and spin-2 searches

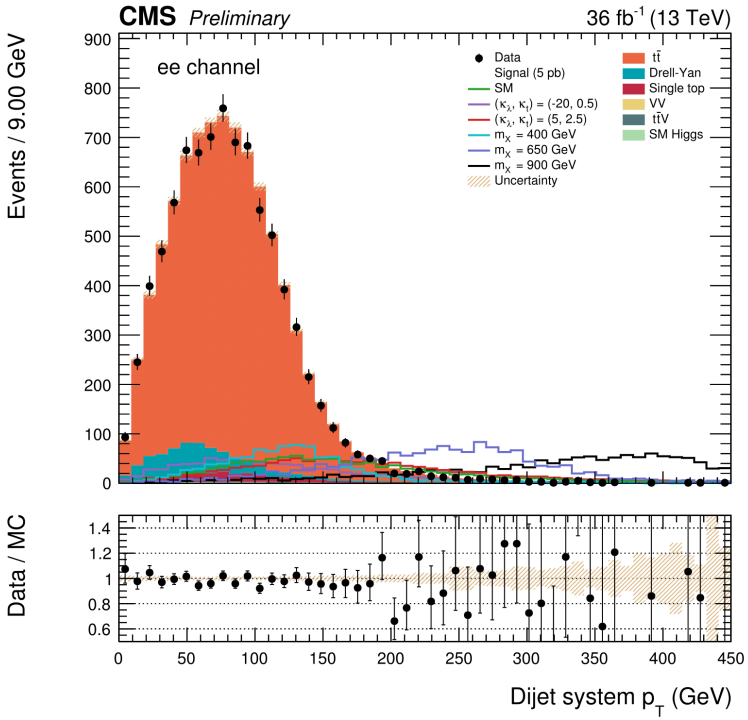


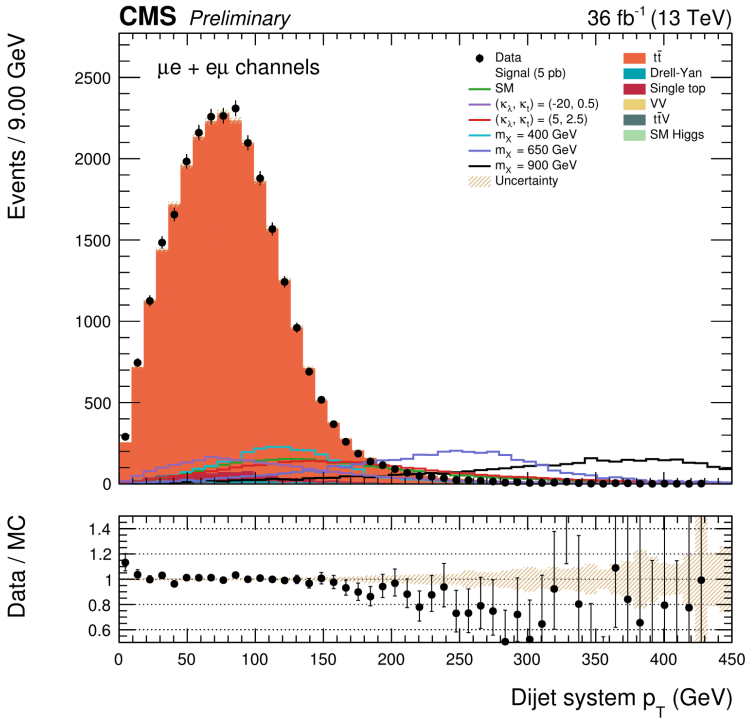


HH → bbVV

Full 2016 dataset

- HH → bbVV → bblνlν
  - ll = ee, eμ, μμ
- Dominant background: tt
  - Most backgrounds estimated from simulation
  - Drell-Yan production with two opposite-sign, same-flavor leptons and 2 b-tagged jets estimated from data

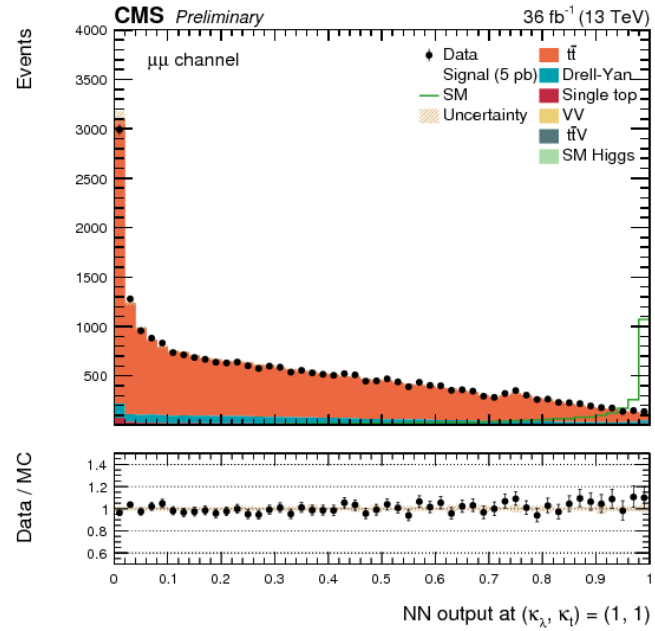


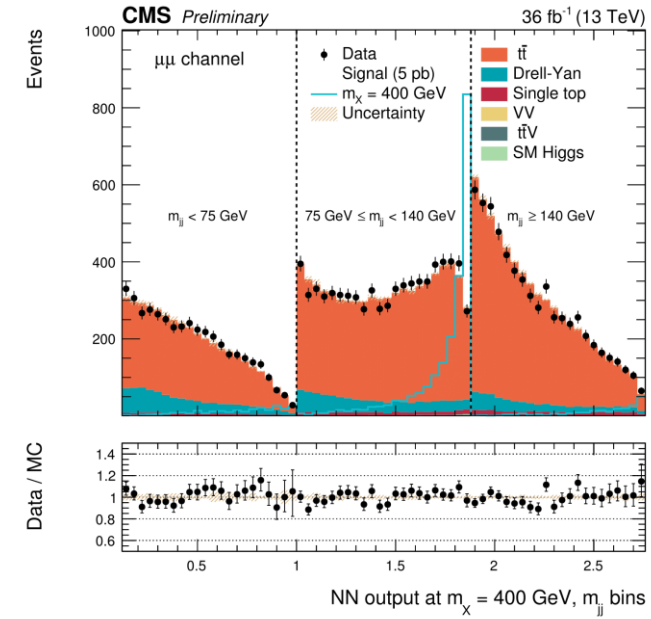


HH → bbVV

Full 2016 dataset

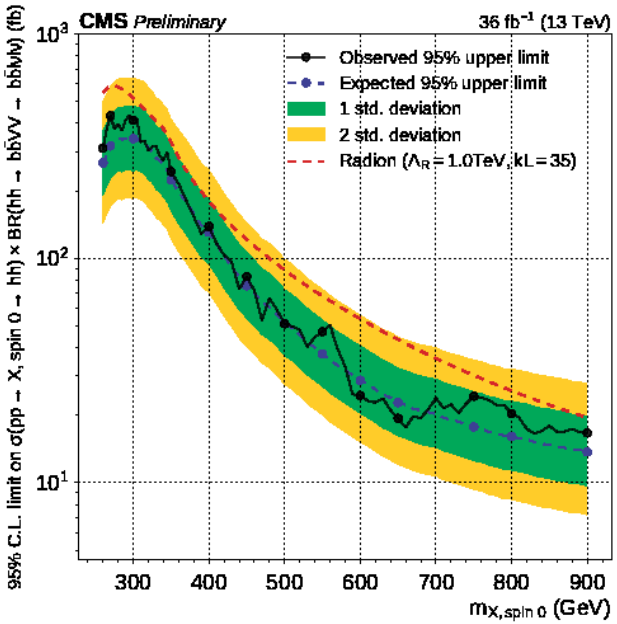
- Parameterized deep neural network (DNN) discriminant used to exploit event kinematics between signal and background events
  - Resonant: trained with different resonance masses as parameters and a variable indicating the di-lepton flavor
  - Non-resonant: used the coupling constants, κ_λ and κ_t, as parameters and the di-lepton flavor variable
  - 3 m_{jj} regions

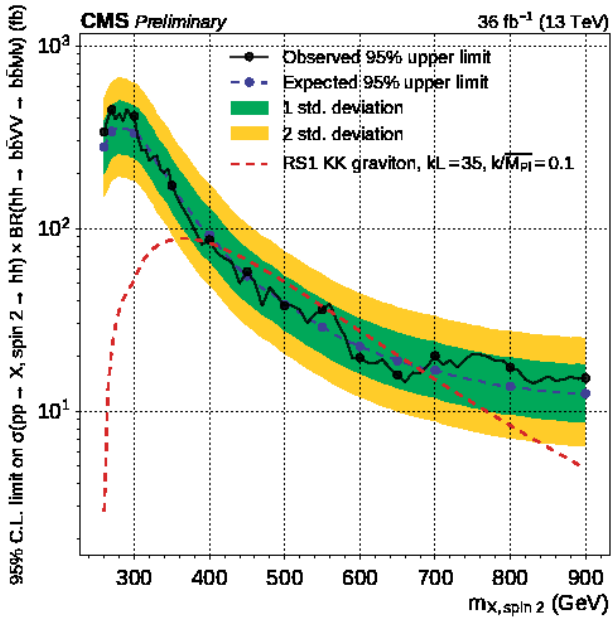




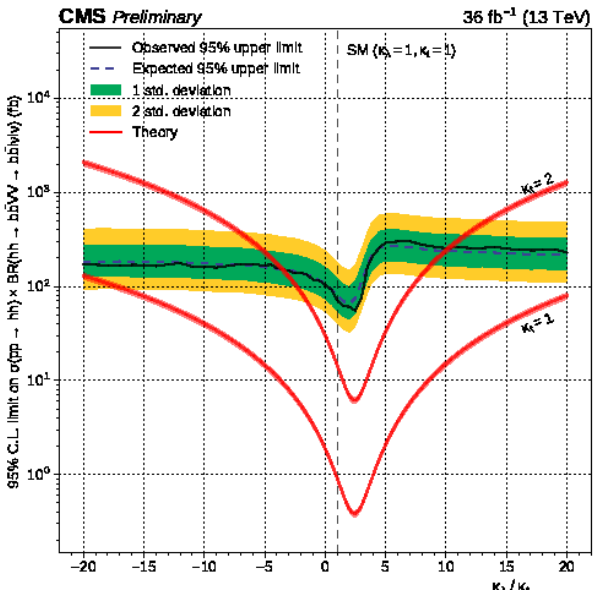
HH → bbVV

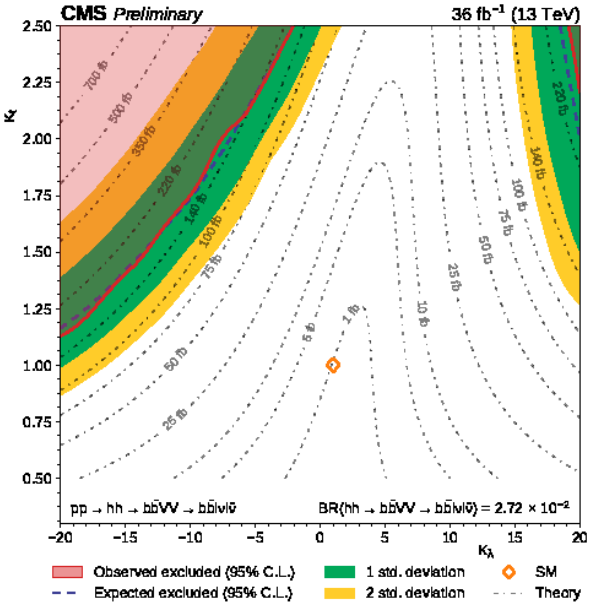
Full 2016 dataset





- Combine 3 m_{jj} and 3 ll categories
- In resonant search no significant excess above background prediction
- Non-resonant obs. (exp) upper limit at 95% CL is at $72(81^{+42}_{-25}) \times$ SM prediciton

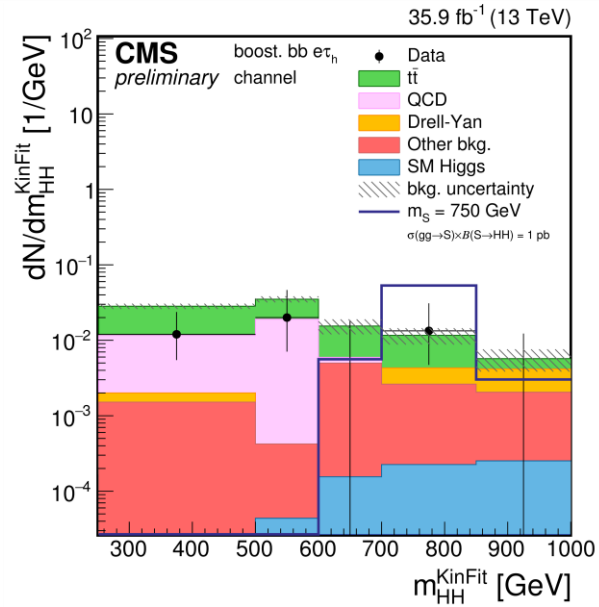


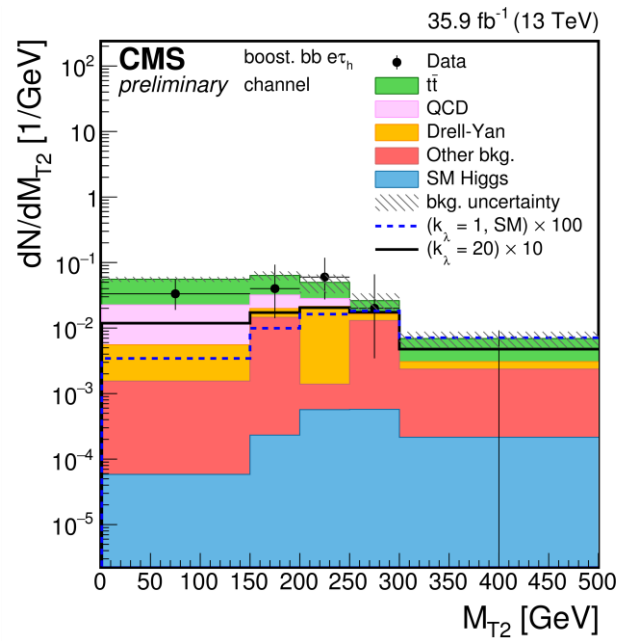


HH → bbττ

Full 2016 dataset

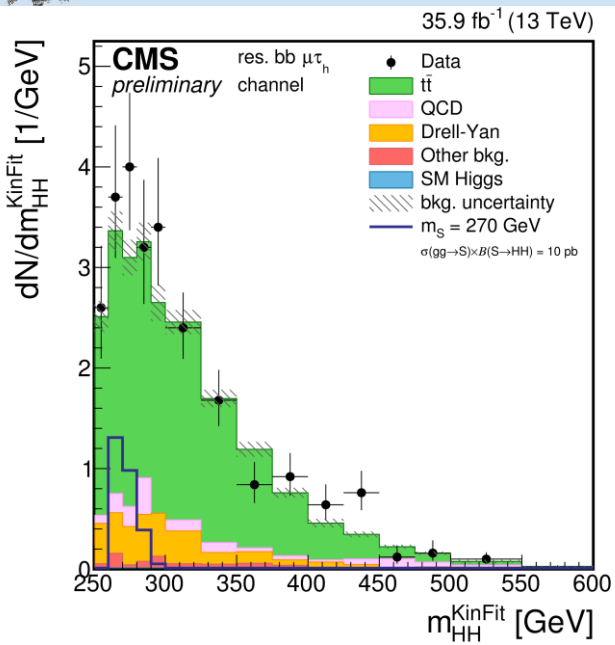
- 3 ττ final states: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ → 85% of decays
- Background
  - Drell-Yan → from simulation
  - tt → from simulation
  - multijet QCD → from same sign lepton sideband in data
- 3 categories:
  - 2 b-tagged jets
  - 1 b-tagged jet and 1 untagged jet
  - boosted category with an AK8 jet

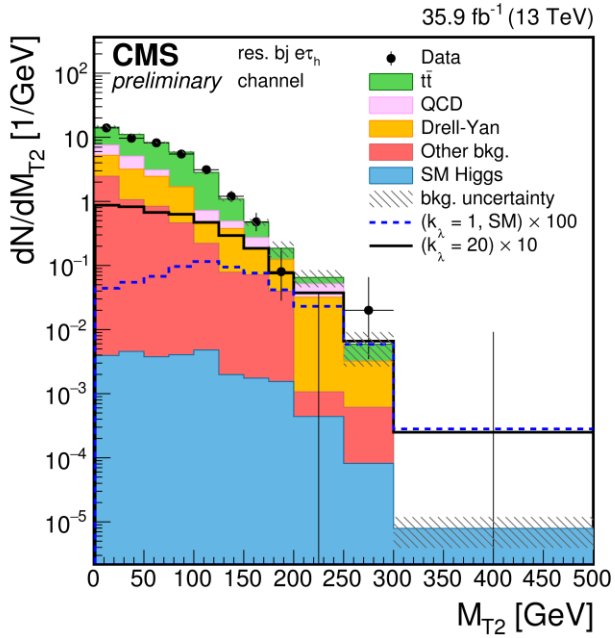




HH → bbττ

Full 2016 dataset





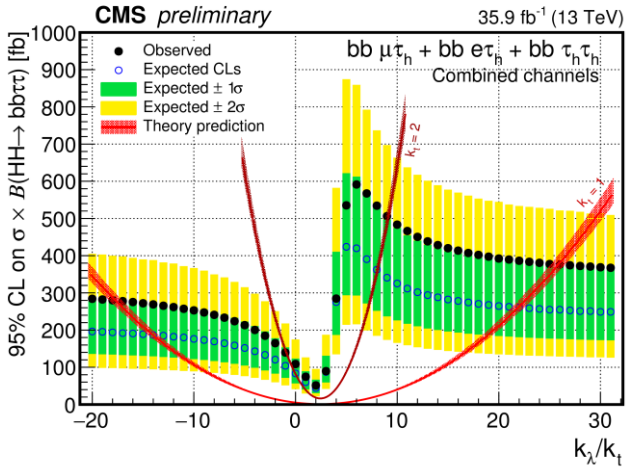
- tt is the largest background for $e\tau_h$ and $\mu\tau_h$ events, rejected with a boosted decision tree trained on kinematic variables
- Signal discrimination:
  - Resonant search: invariant mass reconstructed with a kinematic fit (m_{HH}^{KinFit}) in order to improve resolution
  - Non-resonant: stransverse mass, M_{T2}, has optimal discrimination of signal from background

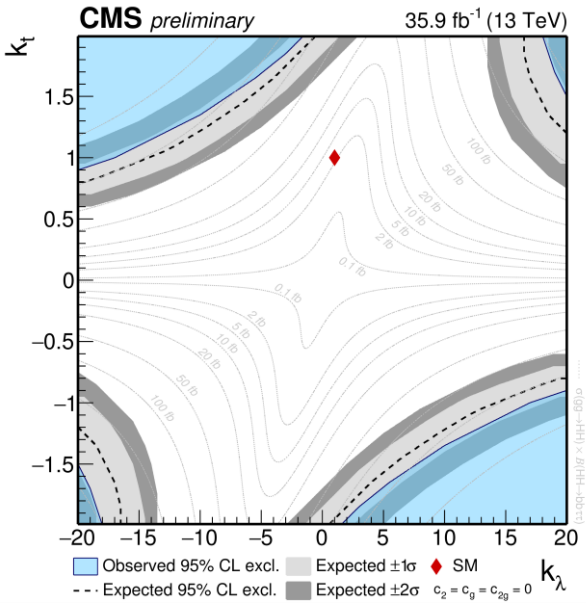
$$m_{T2} = \min_{p_{T1}+p_{T2}=p_T^{\tau\tau}} \{\max[m_T(m_{b1}, p_T^{b1}, m_{vis}^{\tau 1}, p_{T1}), m_T(m_{b1}, p_T^{b1}, m_{vis}^{\tau 1}, p_{T1})]\}$$

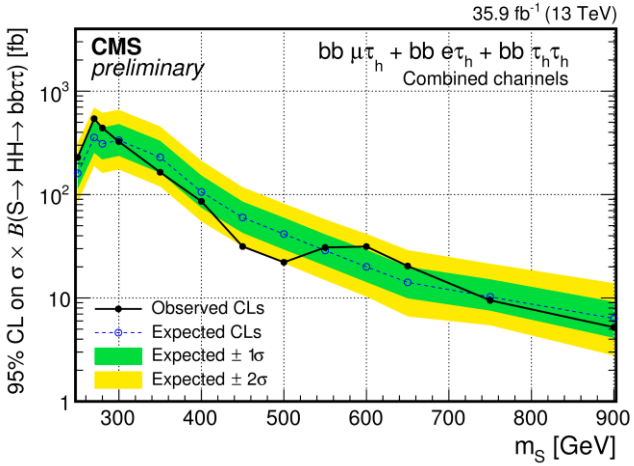
HH → bbττ

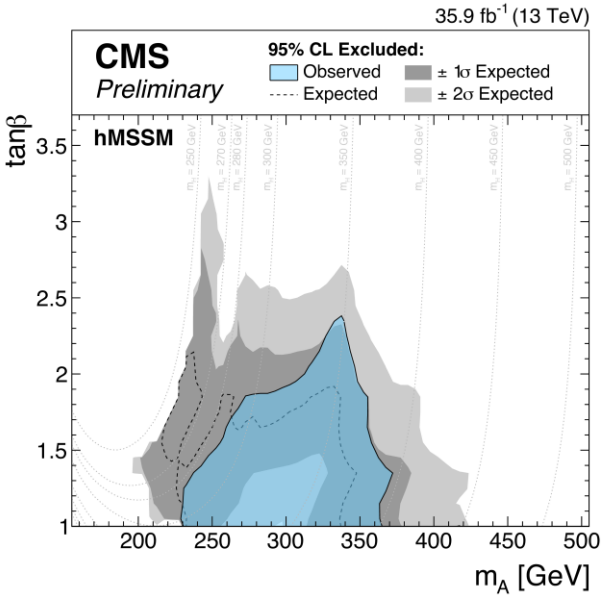
Full 2016 dataset

- Non-resonant obs. (exp) upper limit at 95% CL is at 28(25) × SM expectation
- Resonant model independent limits interpreted in the hMSSM



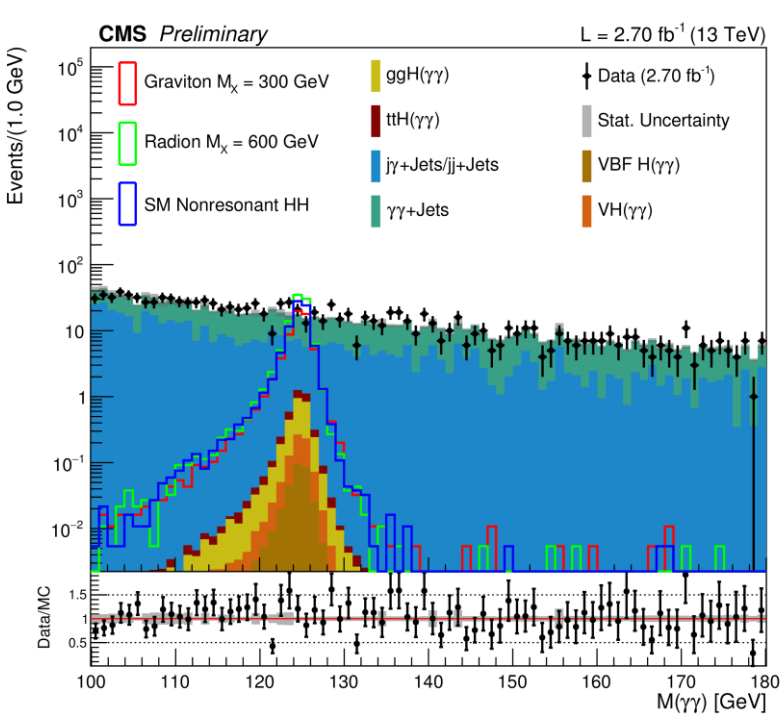






HH → bbγγ

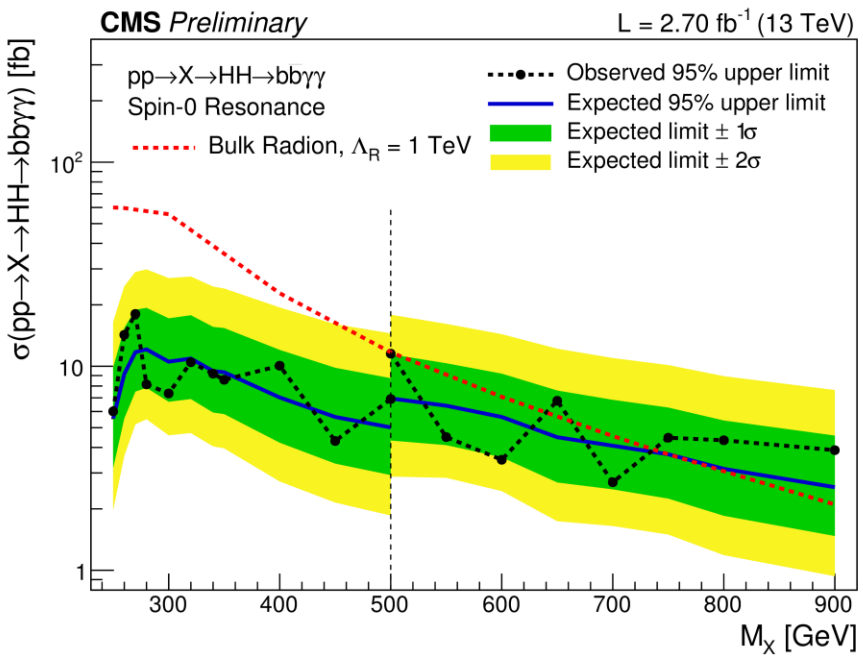
- Small branching fraction, but very clean final state
  - Excellent $m_{\gamma\gamma}$ resolution
- Signal extraction from parametric fit of 2D m_{jj}: $m_{\gamma\gamma}$ plane
- High and medium purity categories based on jet b-tagging for $M(jj\gamma\gamma) < 500$ GeV

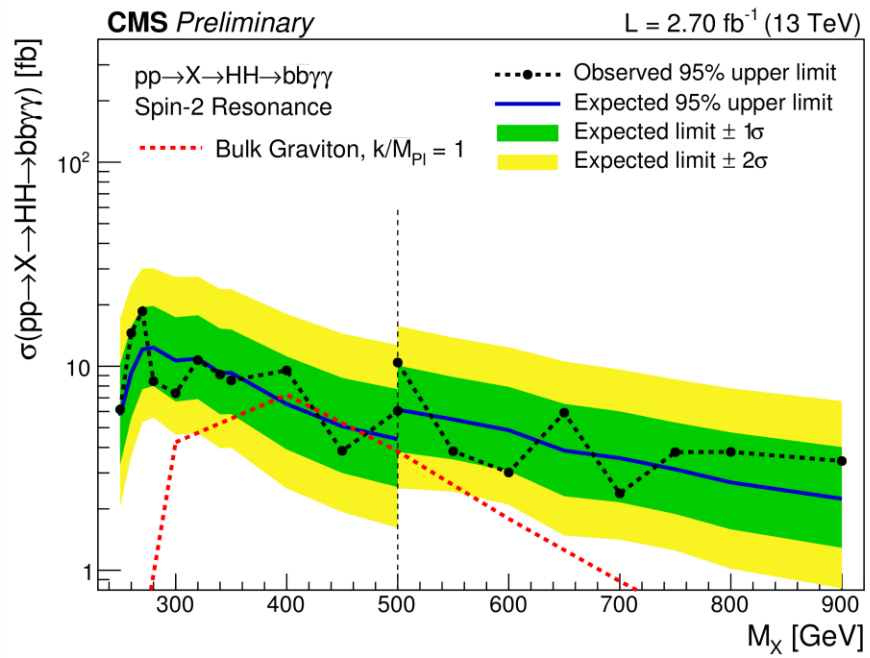


- Single category for $M(jj\gamma\gamma) > 500$ GeV
- Signal resolution improved with reconstructed 4-body invariant mass
  - $M_X = M(jj\gamma\gamma) - M(jj) + 125\ GeV$

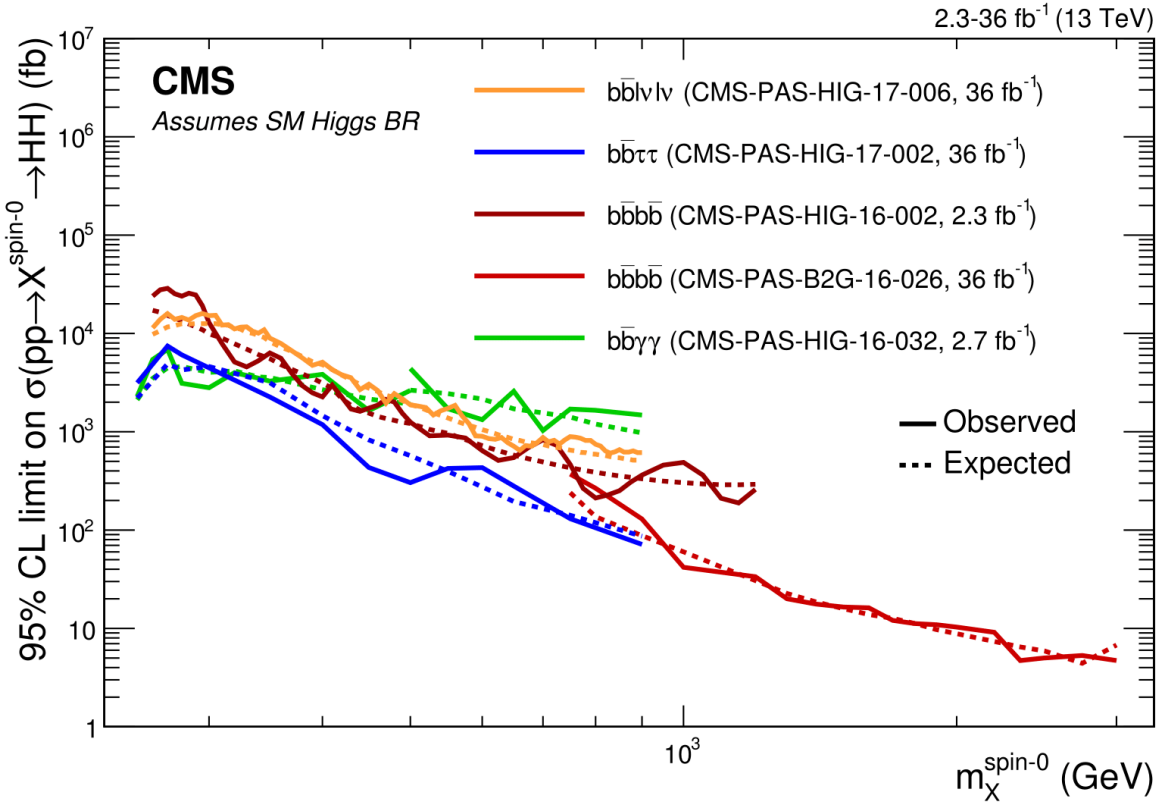
HH → bbγγ

- In resonant search no significant excess above background prediction
- Non-resonant obs. (exp) upper limit at 95% CL is at 7.90(7.85) fb





Summary of Results



13 TeV non-resonant observed(expected) 95% CL limits		
bbbb	342(308)	2.3-2.7fb^{-1}
bbVV	79(89)	35.9fb^{-1}
bbττ	28(25)	35.9fb^{-1}
bbγγ	91(90)	2.7fb^{-1}

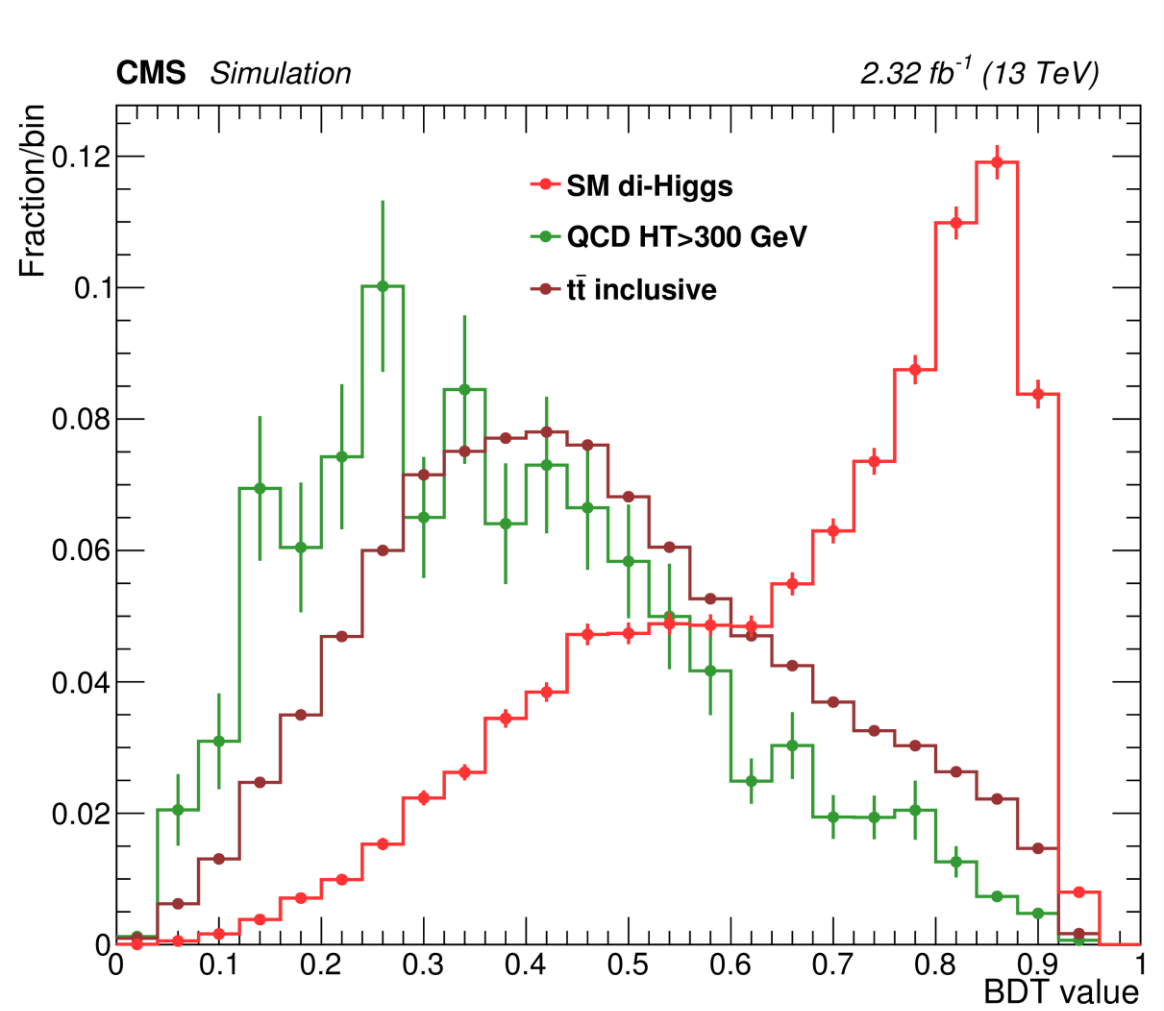
Conclusion

- Di-Higgs searches are good ways to test electroweak symmetry breaking and search for BSM physics
- Several final states searched for at 13 TeV at CMS using new methods
  - No sign of SM or BSM HH production thus far
  - Best limit: $28 * \sigma_{SM}$
  - Multiple results will soon be updated with 2016 data
- Expect to be sensitive to SM HH production at HL-LHC
  - Improve analyses
  - Combine results from different channels
  - Add new final states

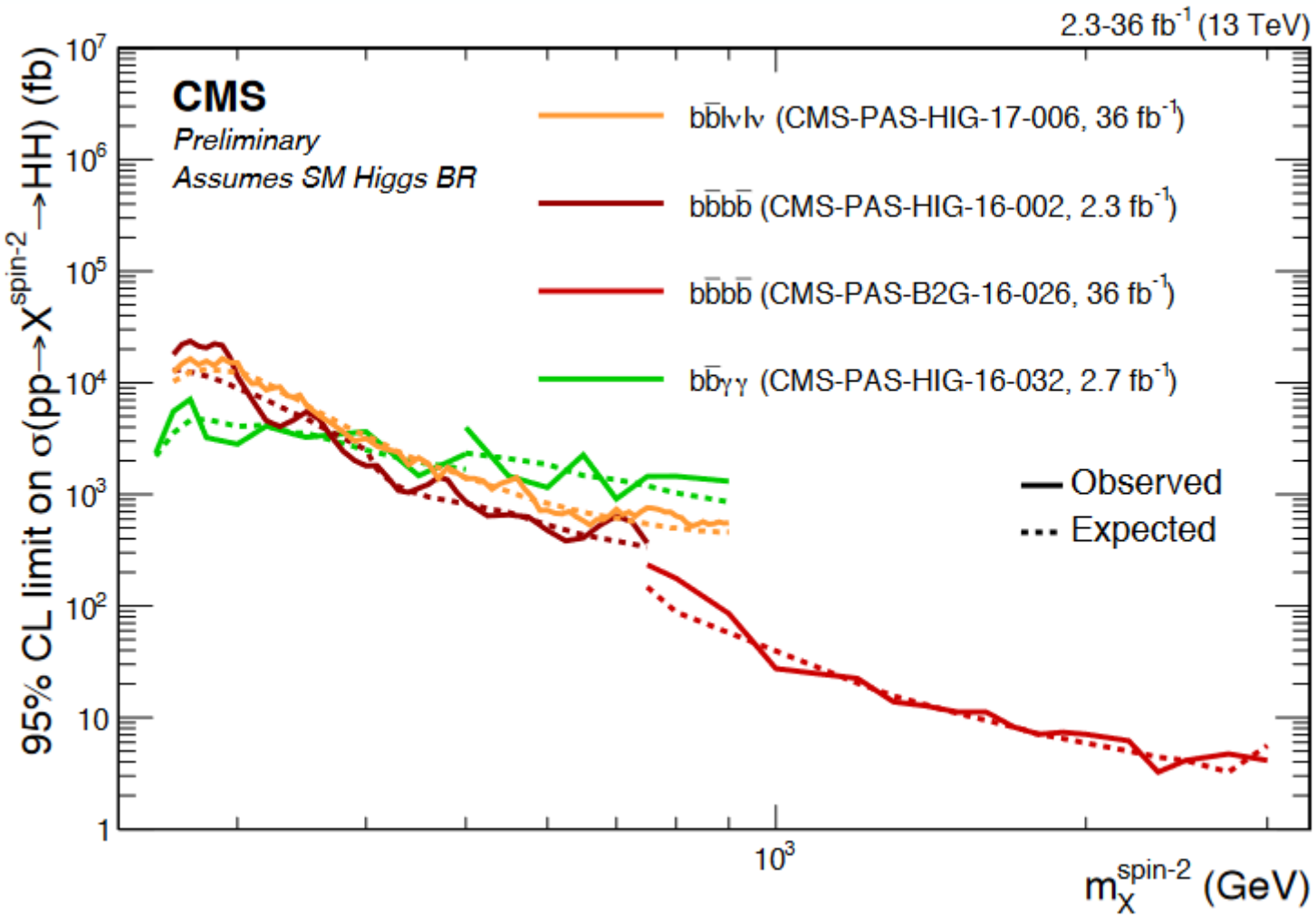
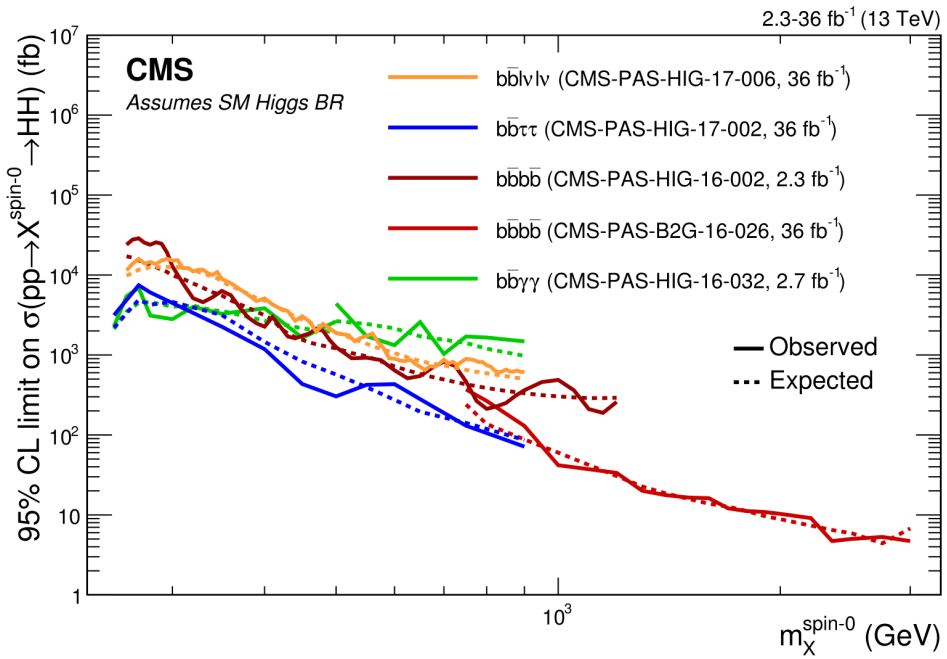
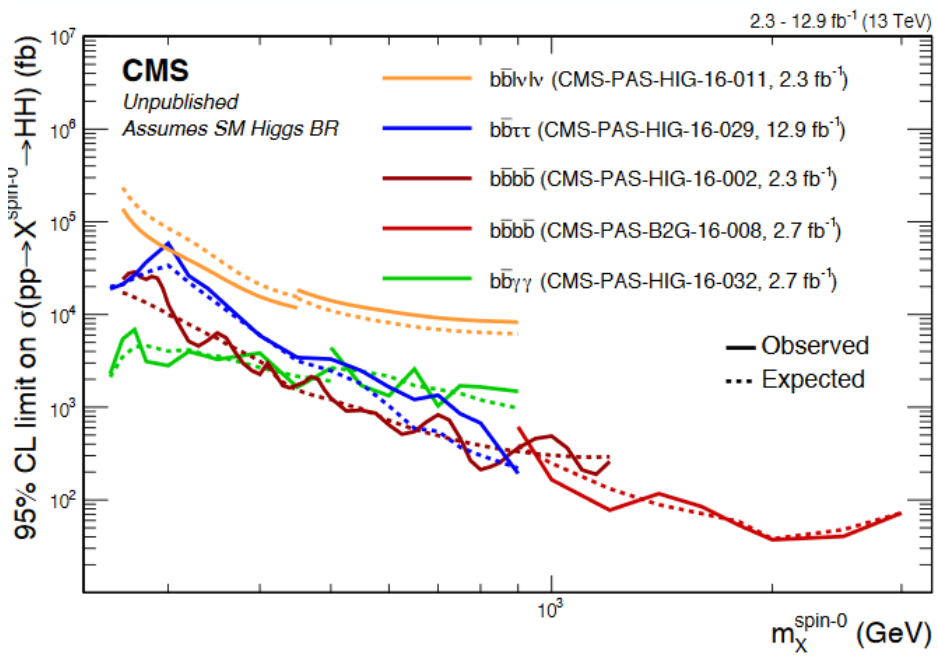
Backup Slides

HH → bbbb (Resolved)

- Working point 0.6
  - Rejects 85% of background
  - Retains 65% of signal



Spin-2 Limit


2.3-36 fb^{-1} (13 TeV)
CMS
Preliminary
Assumes SM Higgs BR
$b\bar{b}l\nu l\nu$ (CMS-PAS-HIG-17-006, 36 fb^{-1})
$b\bar{b}b\bar{b}$ (CMS-PAS-HIG-16-002, 2.3 fb^{-1})
$b\bar{b}b\bar{b}$ (CMS-PAS-B2G-16-026, 36 fb^{-1})
$b\bar{b}\gamma\gamma$ (CMS-PAS-HIG-16-032, 2.7 fb^{-1})
Observed
Expected
95% CL limit on $\sigma(pp \to X^{spin-2} \to HH)$ (fb)
m_X^{spin-2} (GeV)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^3

Run 2 Comparison