HH production in CMS

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Orthodox Academy of Science
Kolymbari, Island of Crete where Zeus was born

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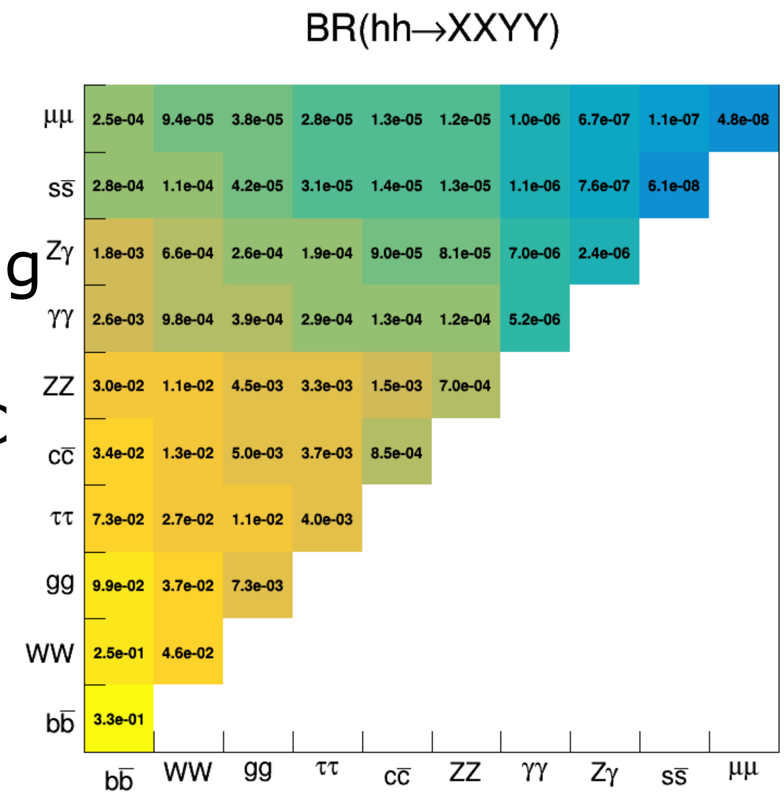
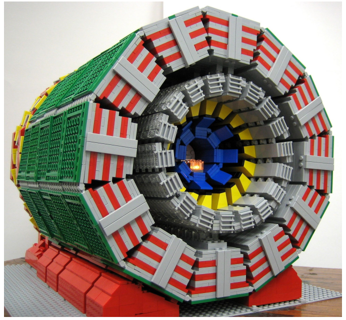
pp → X → HH

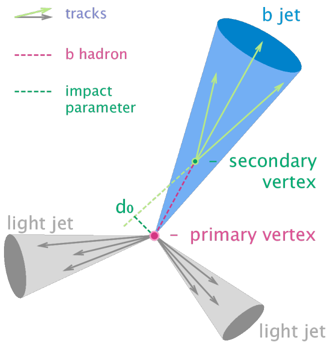
- We are all (in HEP) dreaming of new particles...
- Imagine something heavy decaying into two Higgses, **X → HH**
  - Well, we can search for that at LHC
- However, Higgses are rare, and their decays are hard to detect...
  - We do it anyway!
- In CMS, we search for these decays:
  - HH → bbbb
  - HH → bbWW
  - HH → bbττ
  - HH → bbγγ

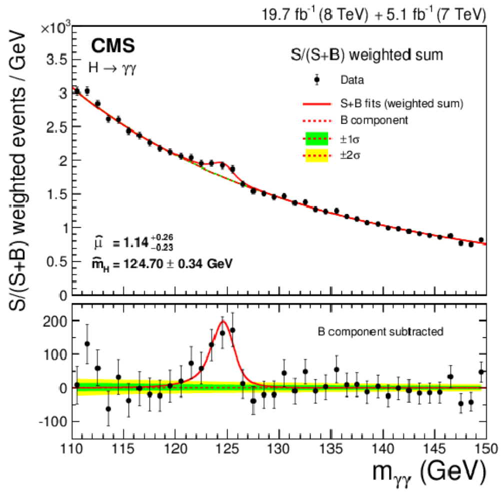


CMS

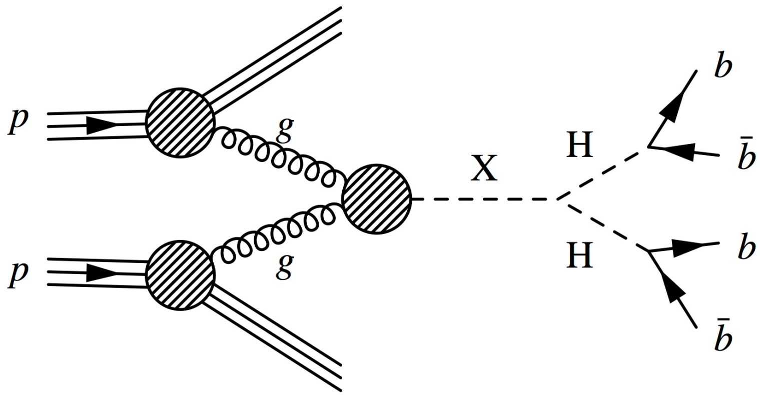
- CMS is maybe compact, but it is very powerful.
  - Fine granularity pixel, and tracker detectors around the interaction point, together with 4T magnetic filed, allow to measure tracks and verteces with high spacial and momentum resolution:
    - muons, electrons,
    - charged hadrons, b-tagging
  - Almost 4π coverage allows us to measure missing energy
    - we (almost) see neutrinos
  - Great electromagnetic calorimeter
    - nice peak in H → γγ







HH → bbbb



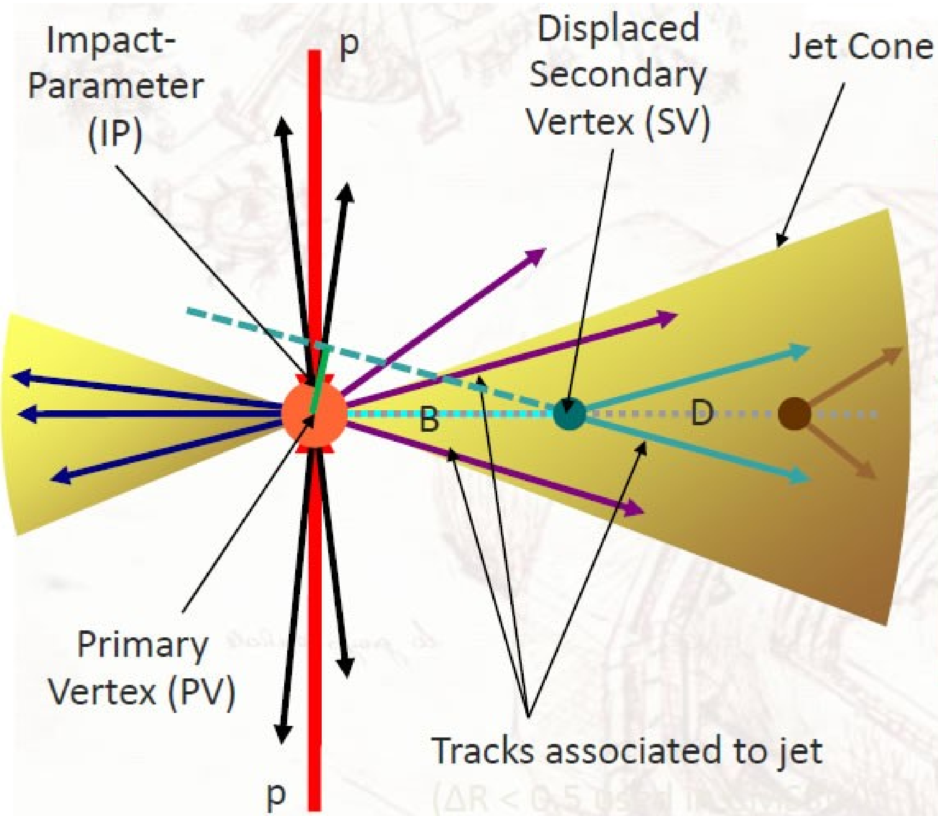
Challenges:

- Trigger selection. Need to record those data!
- Distinguish b-jets from light-jets
- Deal with multi-jet background of QCD(~85%), and ttbar(~15%)

Solutions

- At the trigger level: select events with:
  (**1**) 2 jets w/ p_T > 90 GeV and 2 jets w/ p_T > 30 GeV,
  at least 3 jets are b-tagged; and
  (**2**) 4 jets w/ p_T > 45, 3 are b-tagged
- B-jets are identified by secondary vertex from B-hadrons decays (b-tagging algorithm)
- Backgrounds have a smooth distributions of m(jj) and m(jjjj), while signals peaks at ~m_H and ~m_X

b-tagging



Tracker resolution of impact parameter: 15um

b-hadrons:

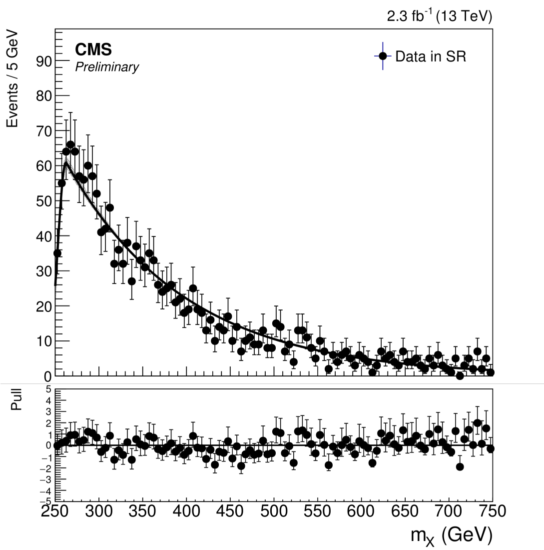
- $\tau \approx 1.5$ ps, $c\tau \approx 450\ \mu m$
- at p = 20 GeV → dist ≈ 1.8 mm
- $m_b \approx 4.2$ GeV
- high track multiplicity

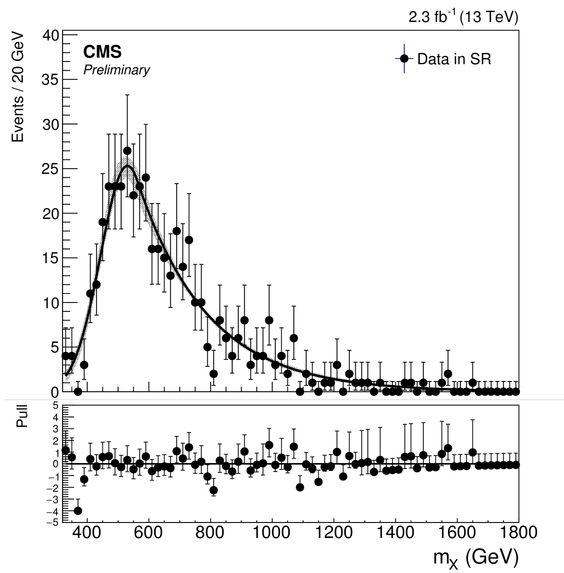
c-hadrons:

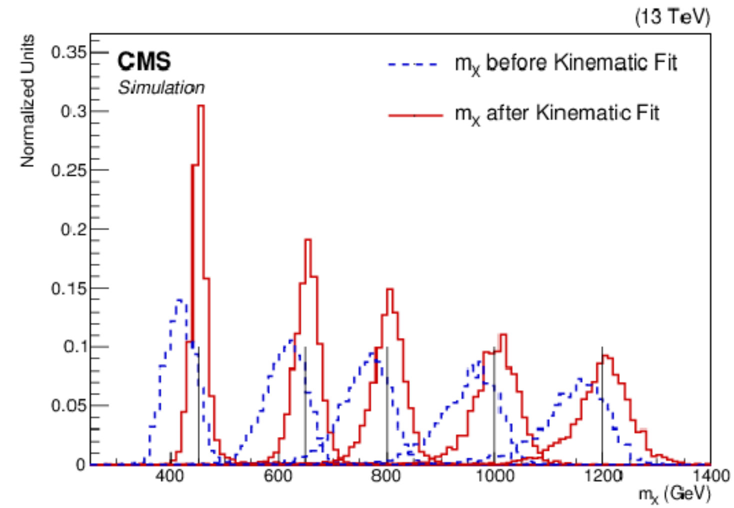
- D^+: ≈ 312 μm, D^0: ≈ 123 μm
- $m_c \approx 1.9$ GeV
- can produce a secondary vertex or an additional tertiary vertex in a b-jet

- In CMS we let computers find the best b-tag:
  - Train MVA discriminant with many input variables measured (IP, SV, jet's constituents, soft leptons, etc.)
  - Typically, get ~70% tag efficiency, with 1% mis-tag rate
- See talk by Ian Connelly on b-tagging, for Atlas.

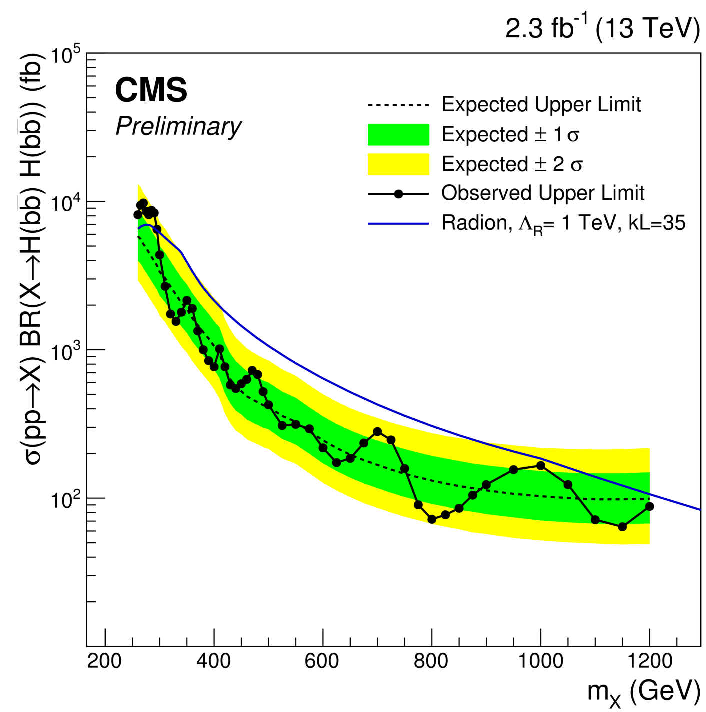
HH → bbbb details







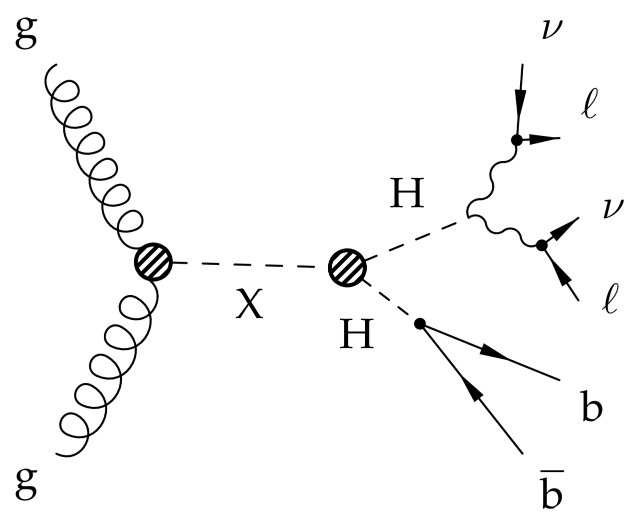
- Background is fit with a smooth function in m(jjjj) data.
- No peaks of signal are seen (yet)
  - The upper limit on the production cross section times the branching ratio is set



HH → bb WW → bb lνlν

Challenges

- B-jets ID, as usual.
- Missing energy form W → lν decays (l = μ or el)
- Large irreducible ttbar background (t → Wb), and DY+jets



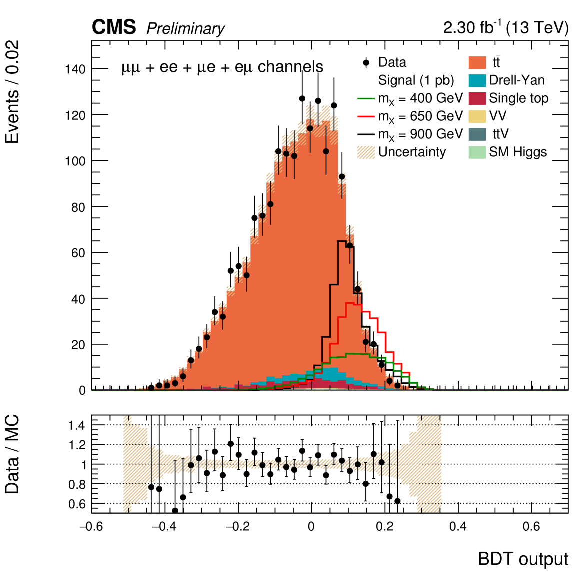
Solutions

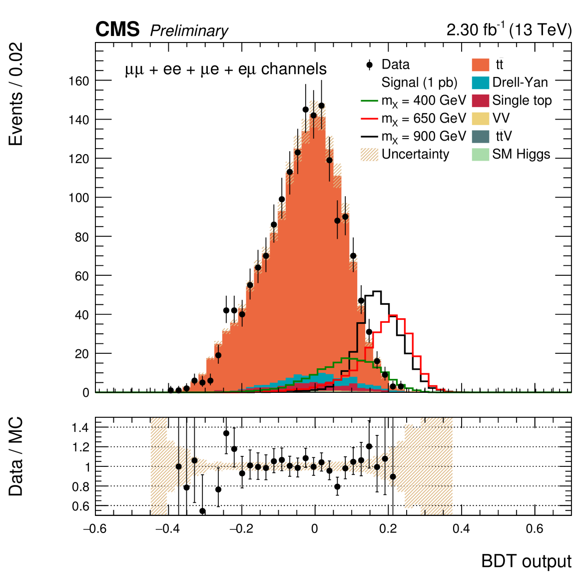
- Remove Z → ll background by rejecting Z → ll decay: $|m_Z - m(ll)| > 15$ GeV; and dR(ll), $\Delta\phi$(ll, jj)
- Model the rest of the background (ttbar dominated) in MC generators.
  - Note: there is no QCD background which is the hardest to model in MC
- Use MVA training (BDT) to separate signal from backgrounds (next slide)

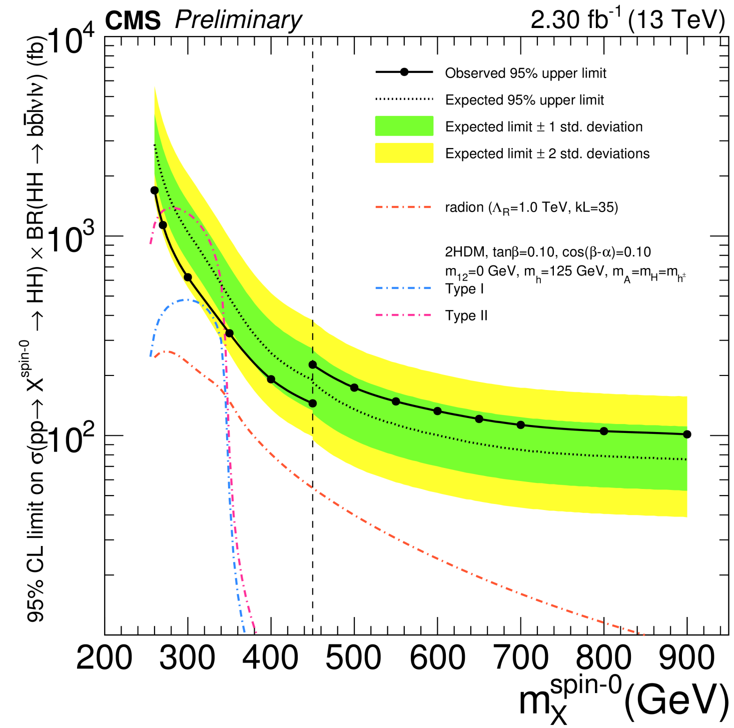
HH → bb WW, results

$$M_T = \sqrt{2p_T^{ll}E_T^{miss}(1-\cos(\Delta\Phi(ll, E_t^{miss})))}$$

- BDT training input variables:
  - p_T(ll), p_T(jj), dR(ll), dR(jj), dPhi(ll,jj), p_T(ll), min(DR(j,l)), m_T
  - 2 BDTs are trained, for signals with m_X = 400, 650 GeV
- Finally, the fit is performed simultaneously in four regions: (low BDT, high BDT) x (mjj-peak, mjj-sidebands), where:
  - Mjj-peak is defined as: 95 < m(jj) < 135 GeV;
  - Mjj-sideband is: m(jj) < 95 GeV and m(jj) > 135 GeV
  - Low/High BDT boundary is 0.1







CMS-PAS-HIG-16-011

HH → bb $\tau\tau$

$H \to \tau_{lep}\tau_{lep}$ (12%)
$H \to \tau_{lep}\tau_{had}$ (46%)
$H \to \tau_{had}\tau_{had}$ (42%)

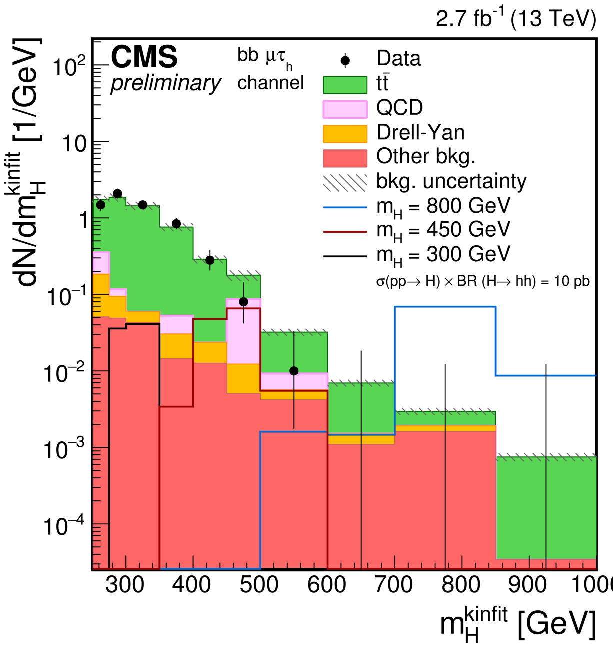
Challenges

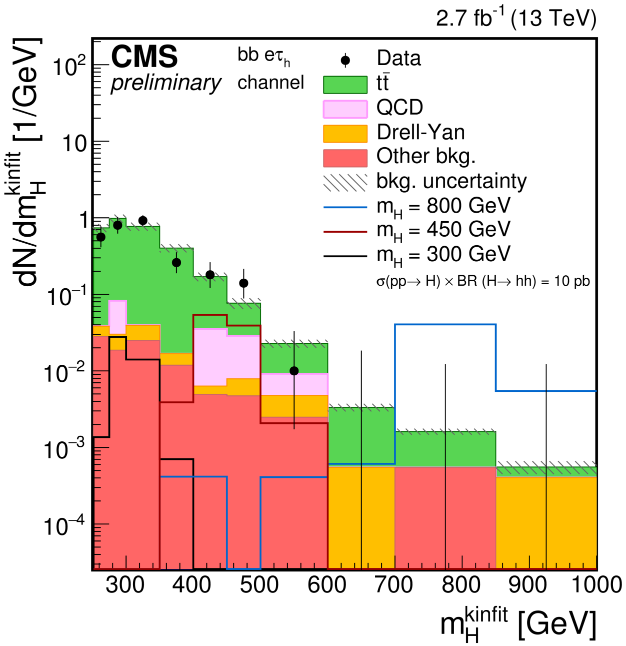
- Neutrinos from leptonic tau decays make up large missing energy
- Hadronic decays are difficult to distinguish from other hadrons
- QCD background is present

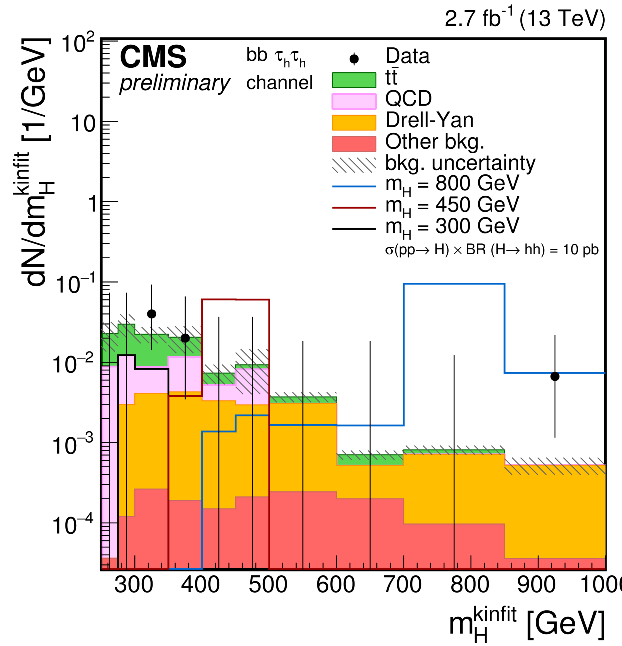
Solutions

- Trigger: single high-pT Electron/Muon for leptonic decay; special 2 τ_h trigger for hadronic channels
- Developed dedicated "hadrons plus strips" algorithm for τ_h reconstruction
- Reconstruction of the $m_{\tau\tau}$ mass from the visible products of tau decay is one of the key ingredient: CMS uses matrix element Likelihood Function
- Selecting Higgs boson candidates: 80 < m(bb), m($\tau\tau$)<160
- QCD background estimated from Data in control regions
  - Ttbar and the rest are taken from MC

HH → bb ττ, results

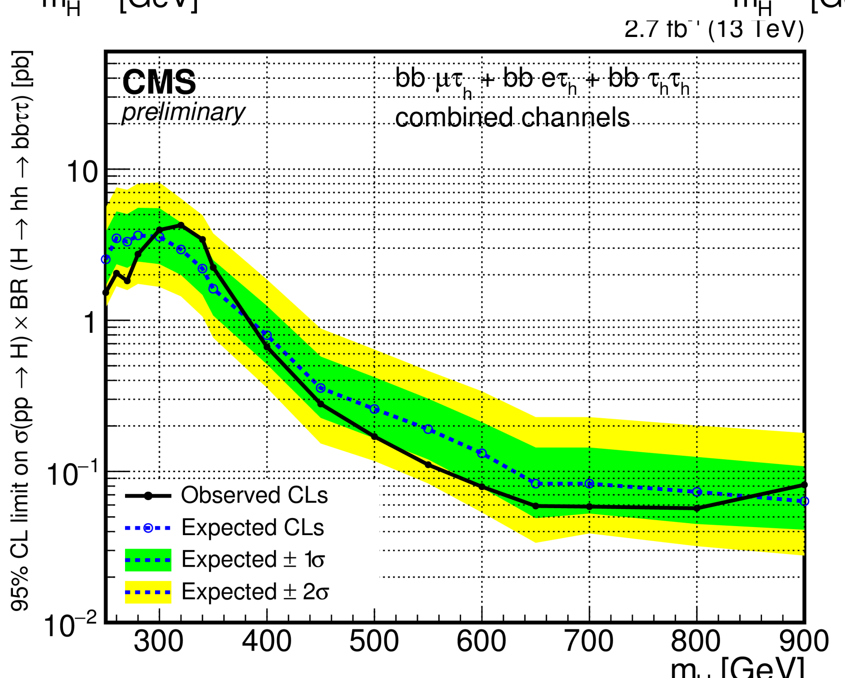






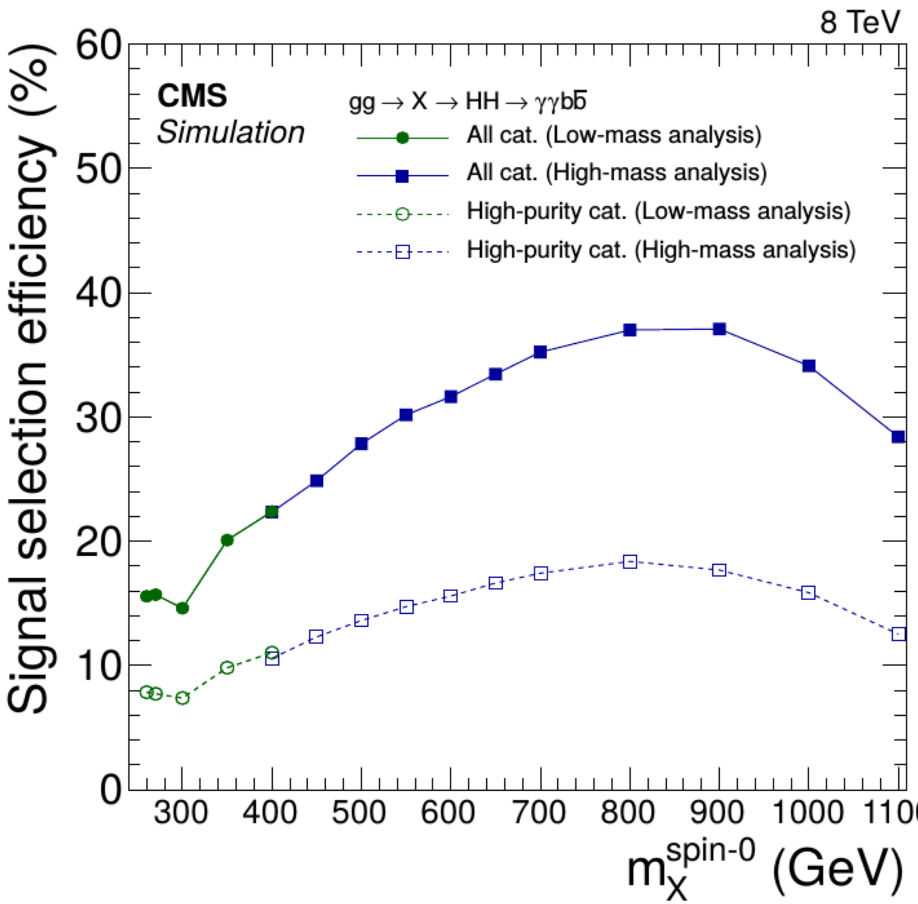
Note: redefined the variable names here: $m_H = m_X$

- Employ "kinematic fit" with constrains momenta of b-jets and taus with m_H = 125 hypothesis
- Search for access over background estimation, at each m_X
  - Non is found – set a limit



CMS-PAS-HIG-16-013

HH → bbγγ



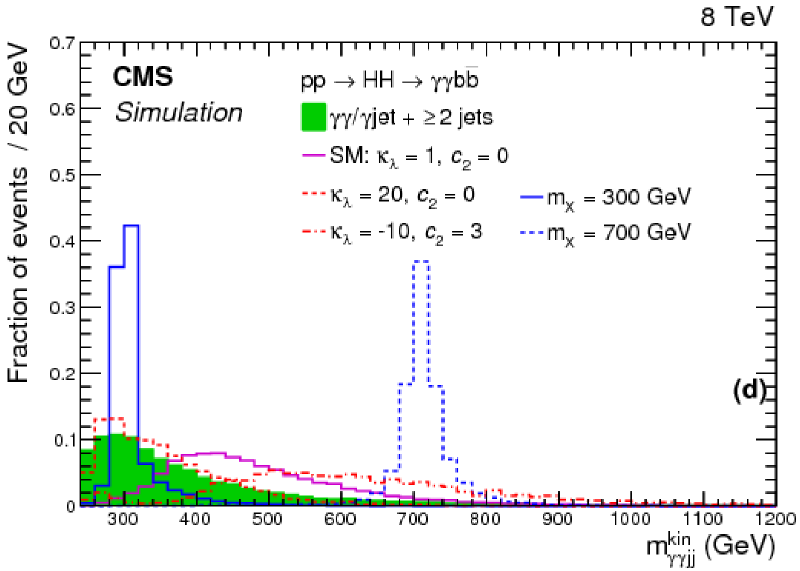
Challenges

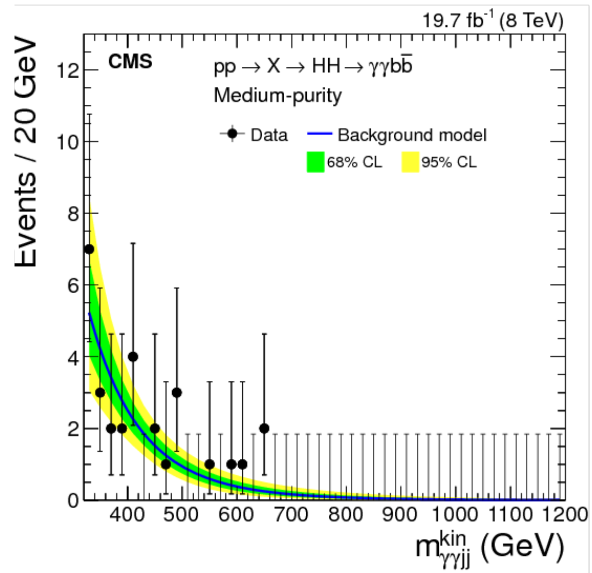
- Small signal

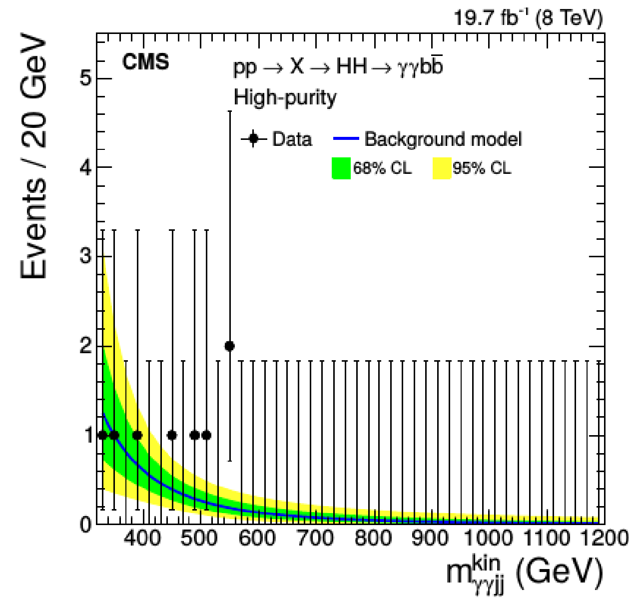
Solutions

- Being smart in event categorization
  - Low mass search and High mass search for m_X
  - High purity category with two b-tagged jets, but also add a category where just one jet is b-tagged
  - Employ kinematic fit to construct m(jj) to 125 mass
- Great resolution of the H → γγ peak helps.

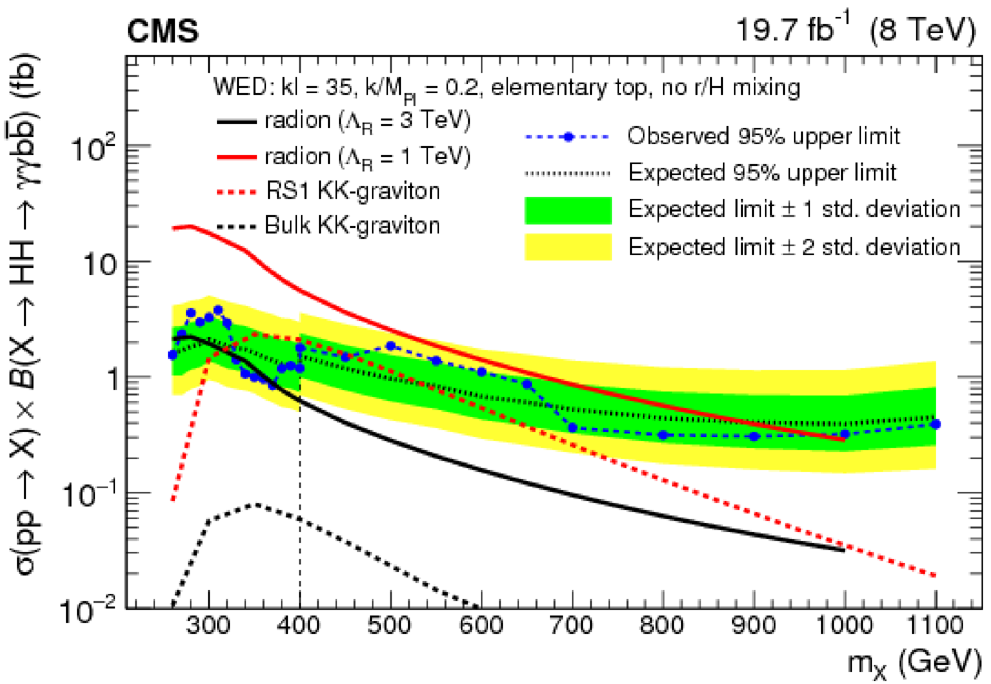
HH → bbγγ, resonant result





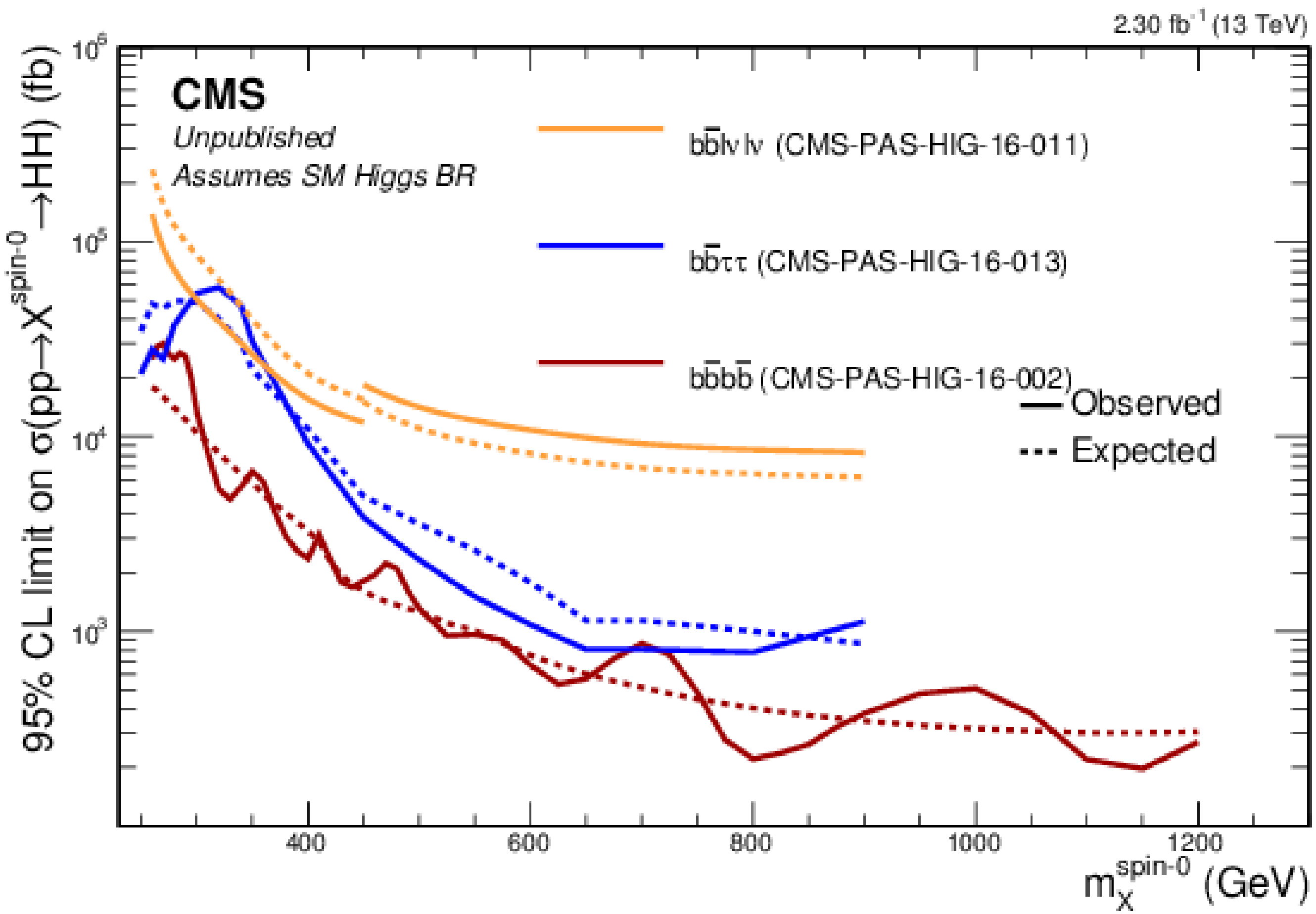


- Signal/background ratio is highest among all HH decay channels for low mass of m_X
- Results at 8 TeV are presented
  - We're limited by the amount of data – need more of it
  - First 13 TeV results are soon to be released



arXiv:1603.06896

Comparisons of channels

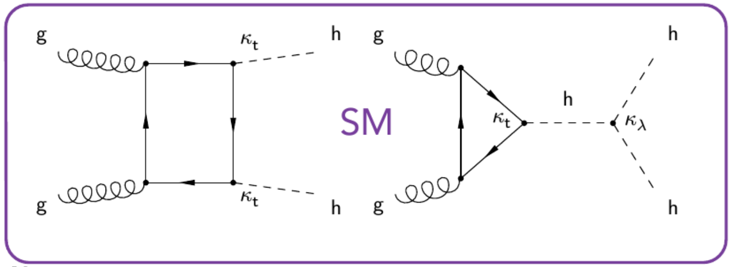


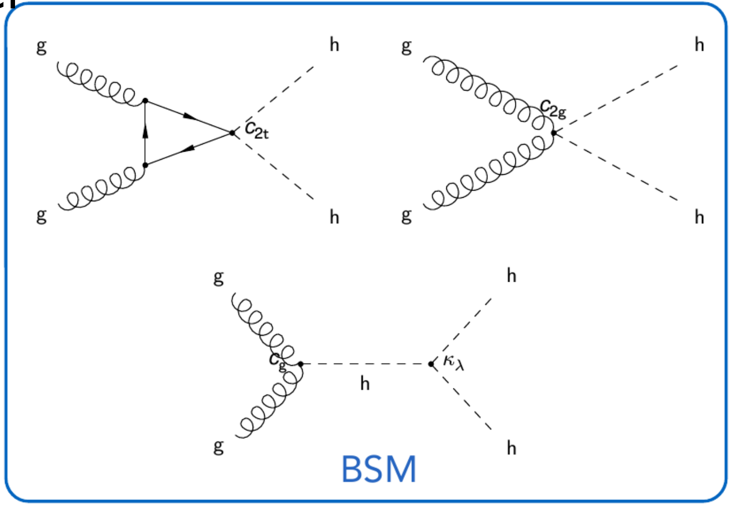
- Some channels vary in their sensitivity over the resonance mass, m_X

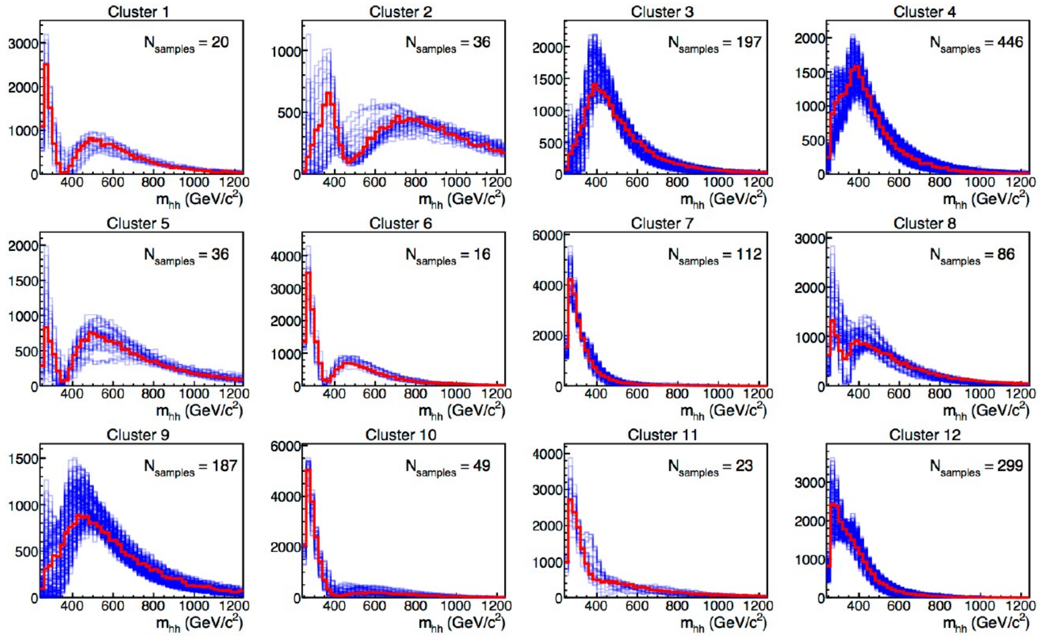
Non-resonant production

- SM is boring, let's go beyond.
  - There is no obvious BSM signatures found so far
  - HH is subtle way to get BSM – vary the couplings
- 5D parameter space can be used to describe the BSM deviation in HH production: λ/λ_{SM}, $c_t/c_{t,SM}$, c_{2t}, c_{2g} and c_g

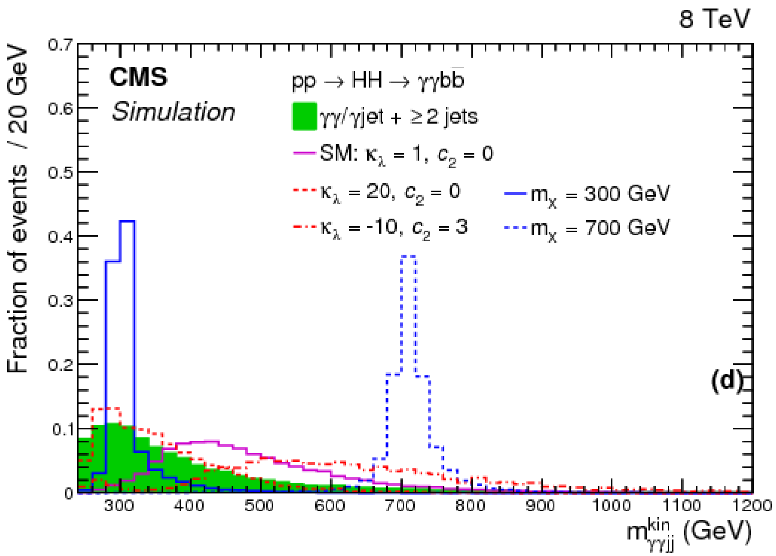
  [arxiv:1502.00539, 1507.02245, LHCHXSWG-INT-2016-001]
  - This results in different observed m_{HH} (and other variables)



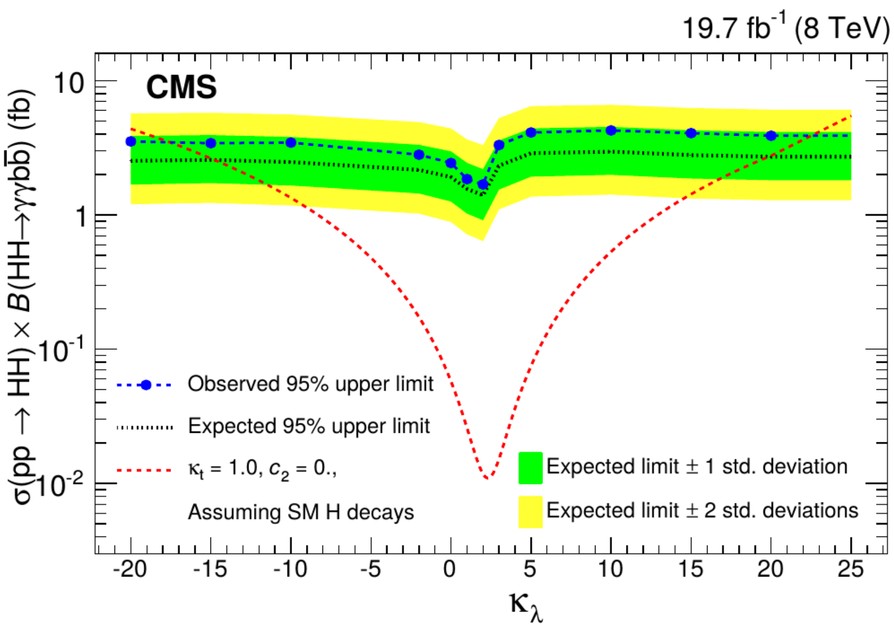


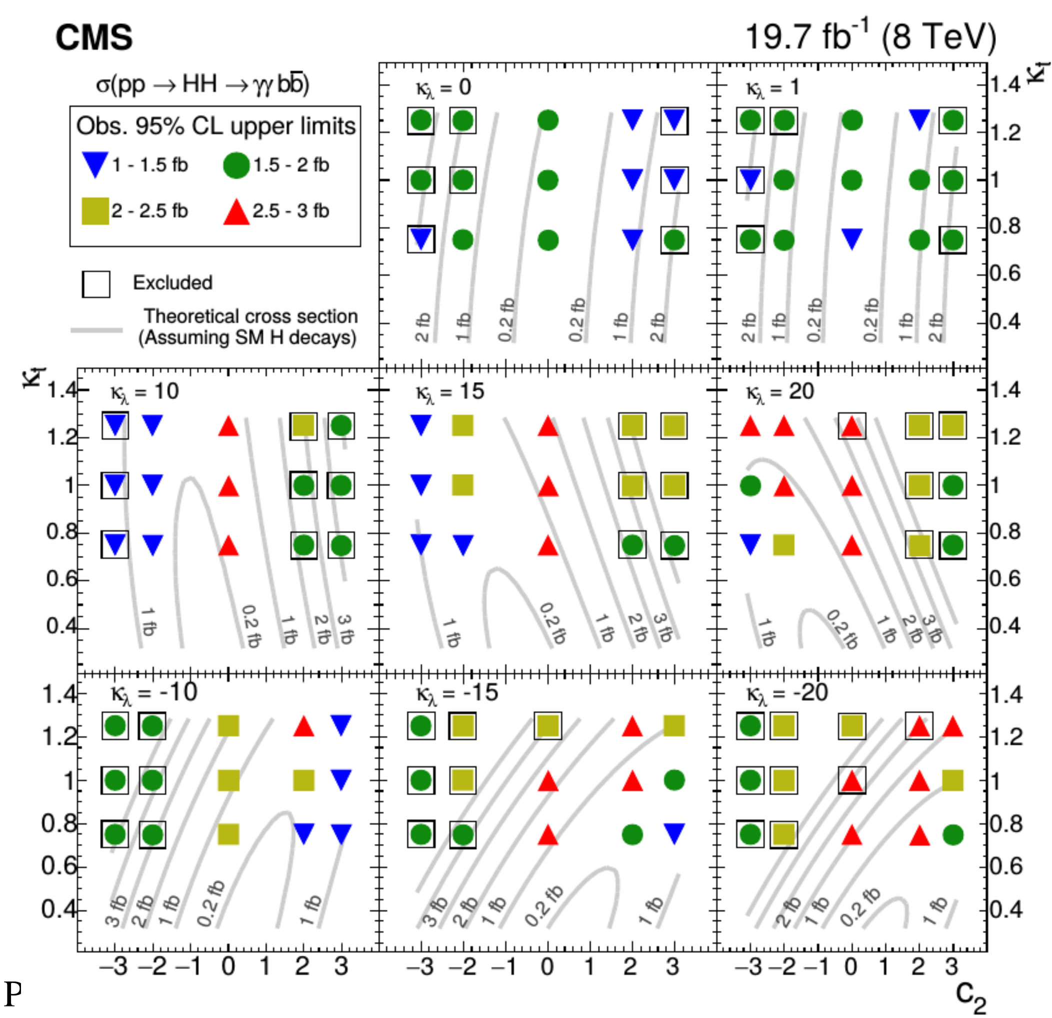


Non-resonant search in HH → bb gg



- We have first limits on HH production in the BSM parametrization space





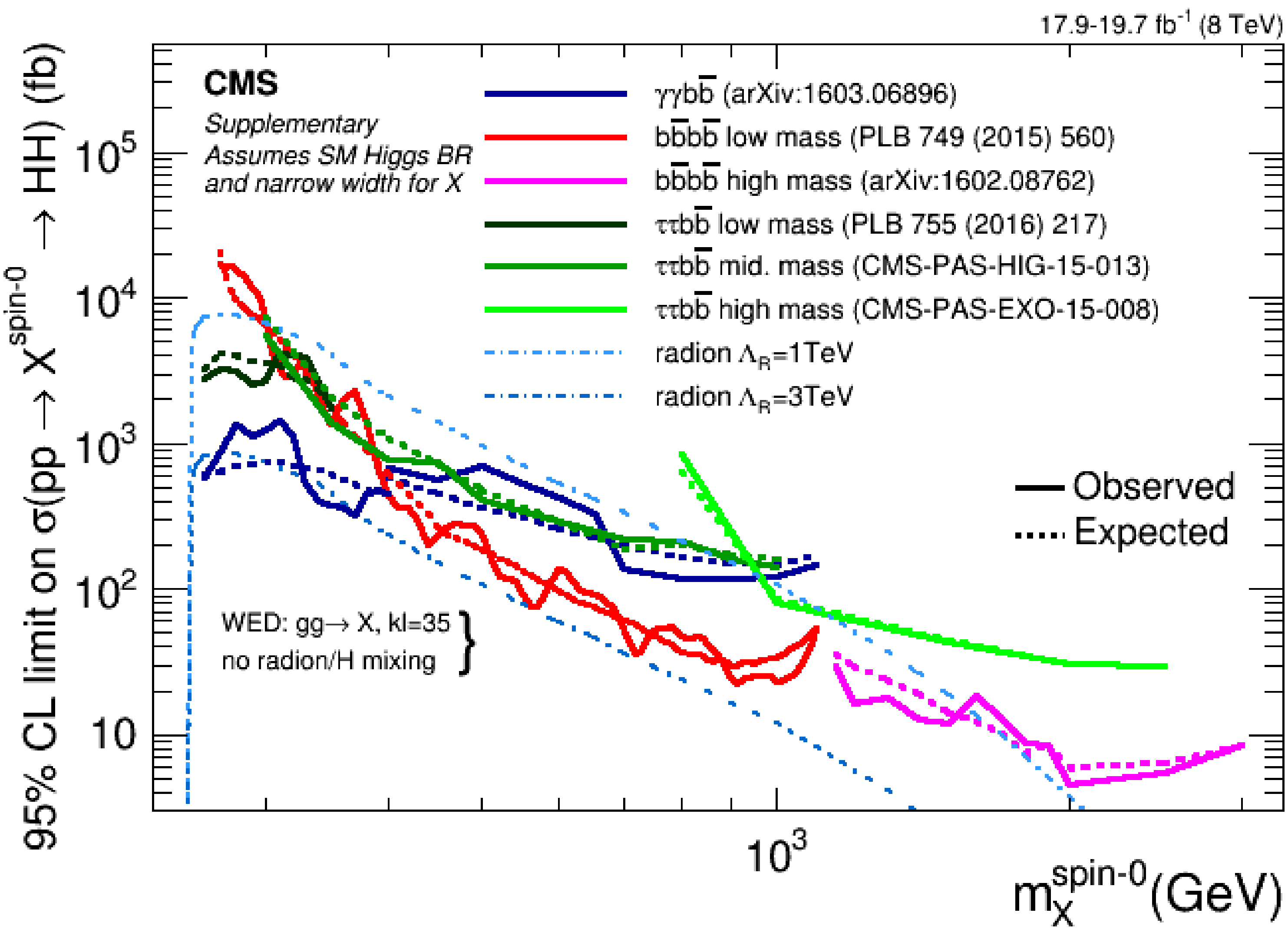
Summary

- Two Higgs bosons are better than one.
- But they are harder to find...
  - Haven't seen them so far, but we keep looking. One day we'll find them!

Backup

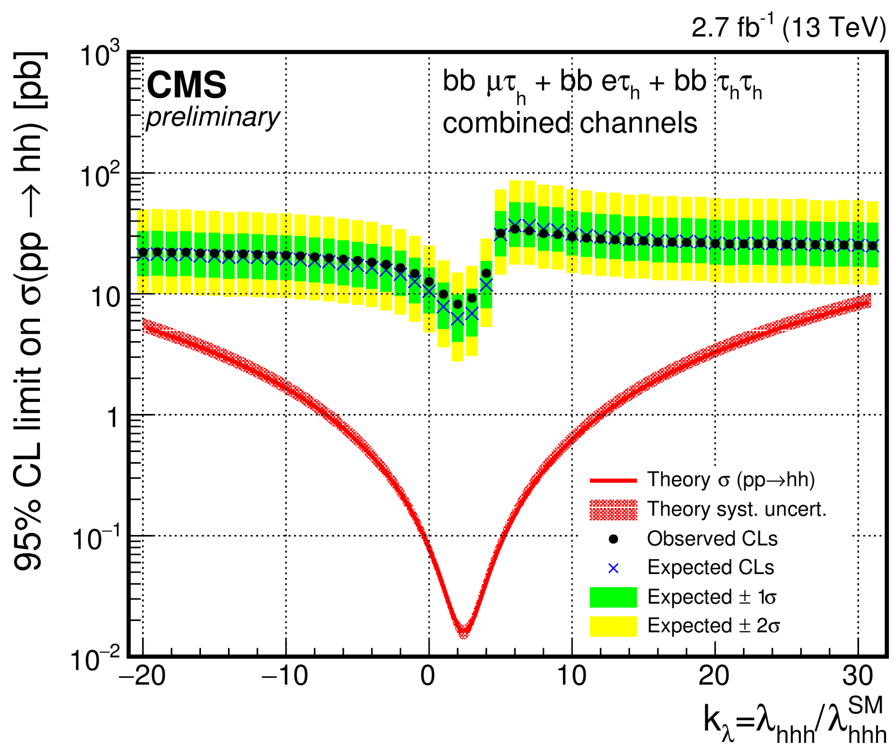
8 TeV results

- Summary limit of 8 TeV results



Non-resonant search in HH → bbττ

- Channels sensitive to the low m_X range in the resonant searches should also be the most sensitive in the non-resonant searches: HH → bbγγ (slide 15), HH → bbττ
- HH → bbττ non-res analysis is similar to the one for the resonant:
  - BDT trained for H → ττ component
  - m(jj) used for H → bb component
  - The limit vs k_λ is shown:



HH→ bbbb at High mass, at 8 TeV

- Merged jets, D = 0.8 – jet reco distance parameter
- m(jj) is the mass of the resonance
  - M_X > 1 TeV search
- Due to trigger:
  - m(jj) > 750 GeV
  - HT > 650 GeV
- Sub-jettiness, t_N - probability of a jet to contain N smaller jets inside
  - Cut on $t_{12} = t_2/t_1$
  - Low purity, High purity jets
- Categories: HPHP, HPLP, LPHP