Recent HH results

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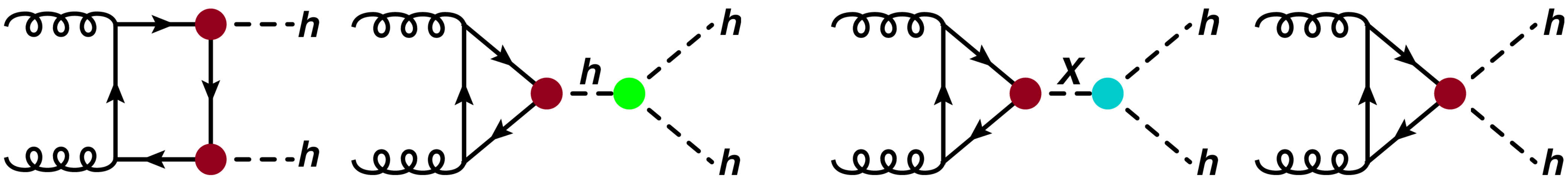
the Higgs trilinear coupling

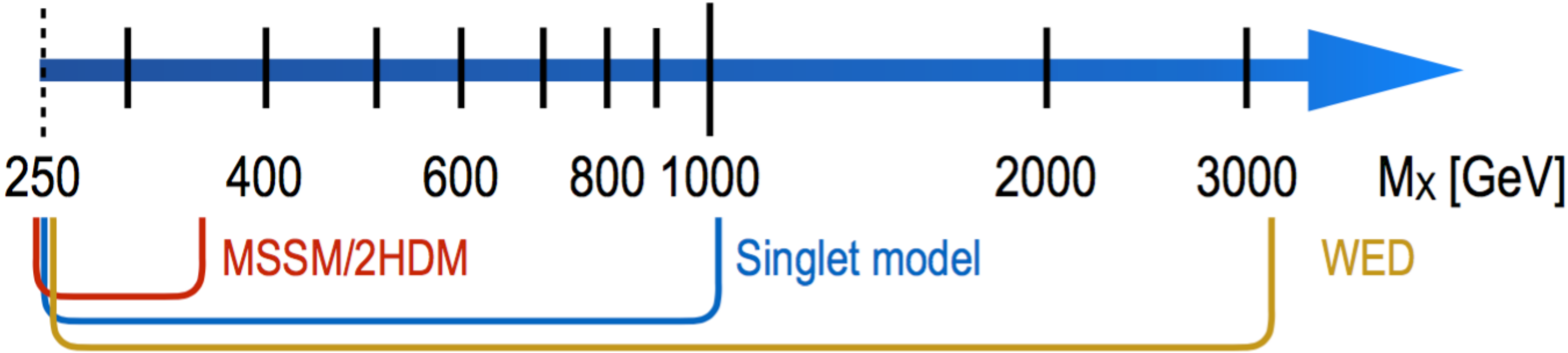
- Precision measurements of Higgs boson physics give us insights into the **nature of electroweak symmetry breaking**.
- **new Physics might affect the trilinear Higgs coupling**:
  - new resonances, new particles in loops, modified couplings
- trilinear coupling **could be measured at LHC from Higgs pair production**



SM production: very low cross-section because of large interference

BSM production: new couplings (hhtt, ggh, gghh) or resonances

models for new resonances



- **MSSM/2HDM**: additional Higgs doublet gives CP-even scalar H
  - probe the low m_H - low tanβ region of the MSSM plane where BR ($H \rightarrow hh$) is sizeable
- **Singlet model**: additional Higgs singlet gives an extra scalar H
  - sizeable BR beyond 2 x m_t, non negligible width at high m_H
- **Warped Extra Dimensions**: spin-2 (KK-graviton) and spin-0 (radion) resonances
  - different phenomenology if SM particles are allowed (bulk RS) or not (RS1 model) to propagate in the extra-dimensional bulk

BSM effects in non resonant production

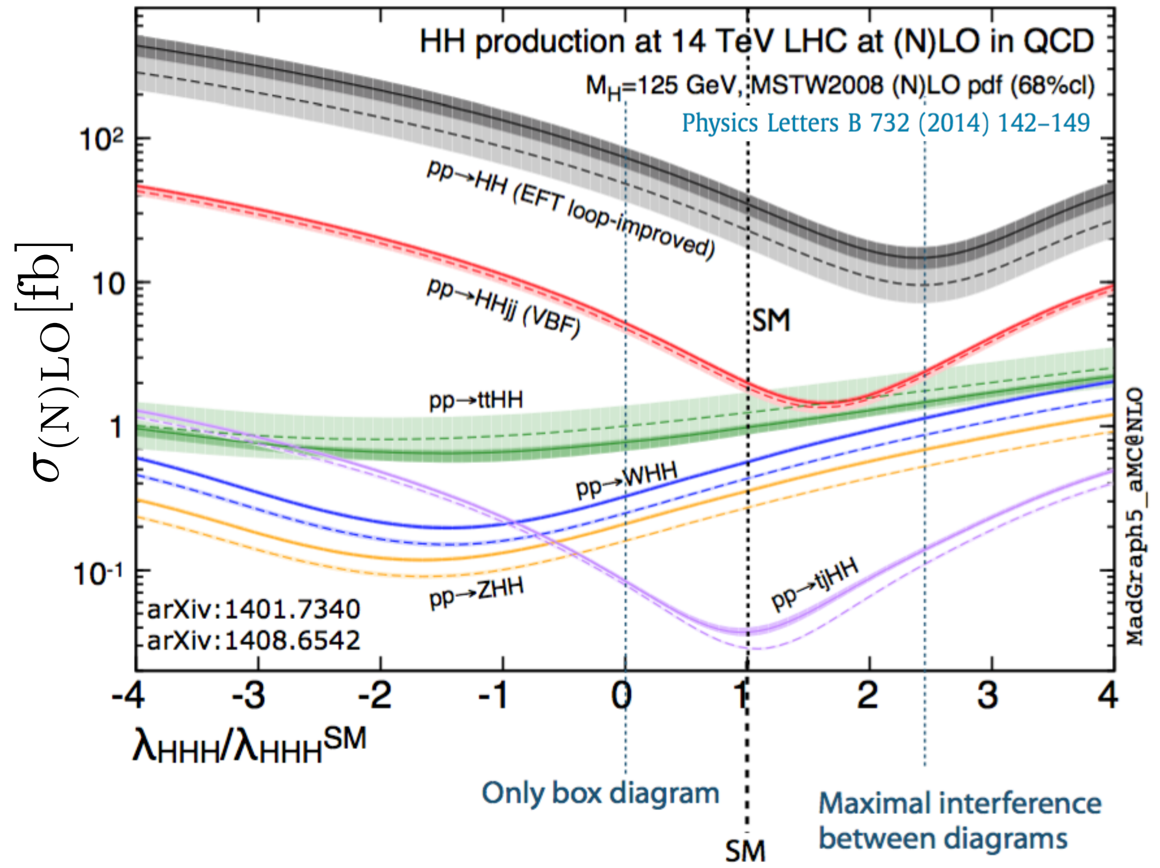
- SM cross-section at 13 TeV is at the order of **33.4 fb**
  - (gluon fusion Higgs production is ~44 pb)
- **BSM effects** modify existing vertices and add new diagrams
- **large enhancements** in the cross-section can happen

- **effective parameterisation** (EFT) of BSM effects:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i O_i}{\Lambda^2}$$

- five independent **parameters**:

$$\lambda_{hhh} \quad c_2 \quad c_{2g} \quad c_g \quad y_t$$

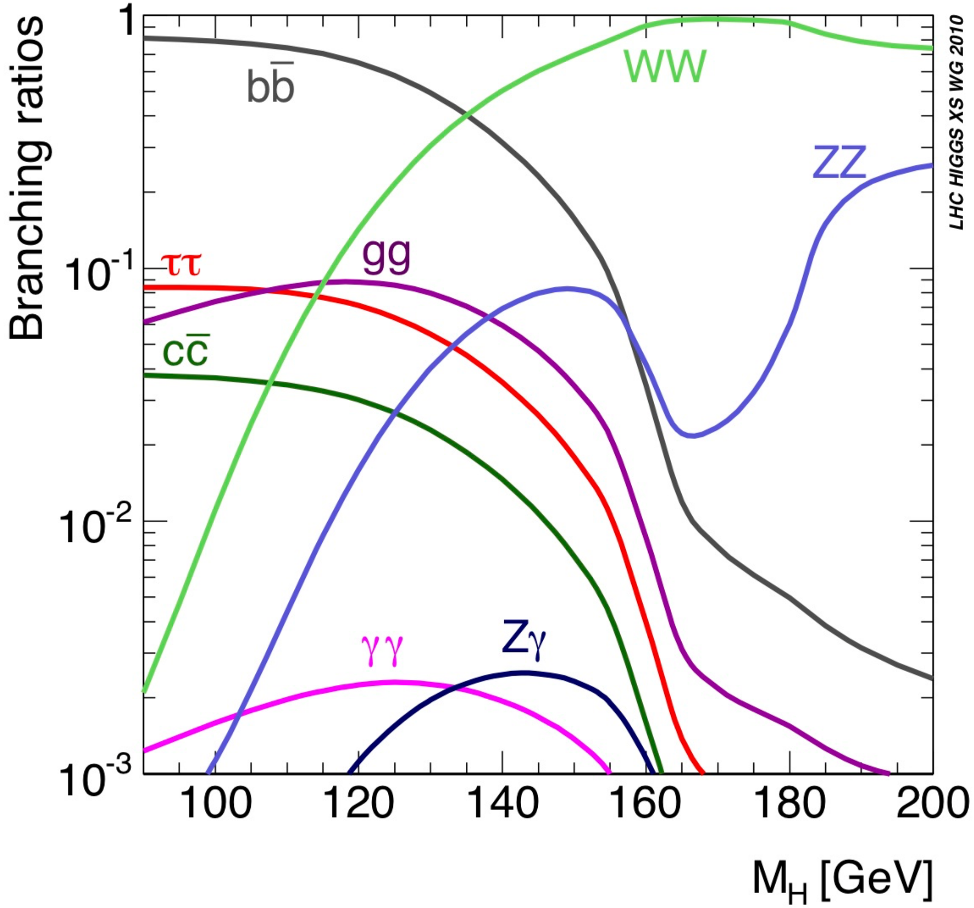


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGHH

the analysis final states

- given the low expected cross-sections, search for at least **one Higgs boson decaying into bb pairs**
- the second one is searched for in **several final states**

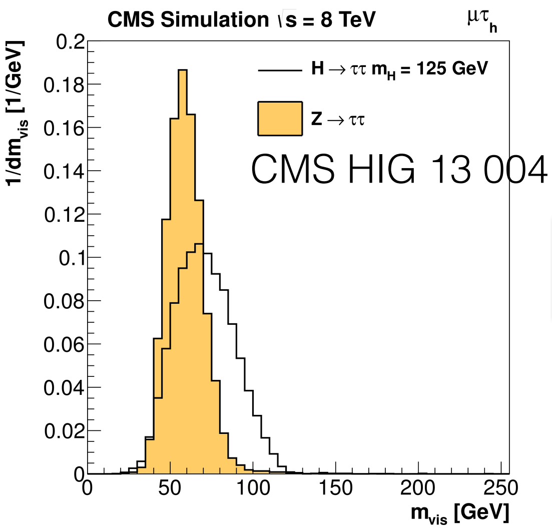
bb bb	large branching ratio, large QCD and tt bkg
bb WW	large branching ratio, large tt contamination
bb $\tau\tau$	tradeoff between purity and branching ratio
bb $\gamma\gamma$	high purity, low branching ratio



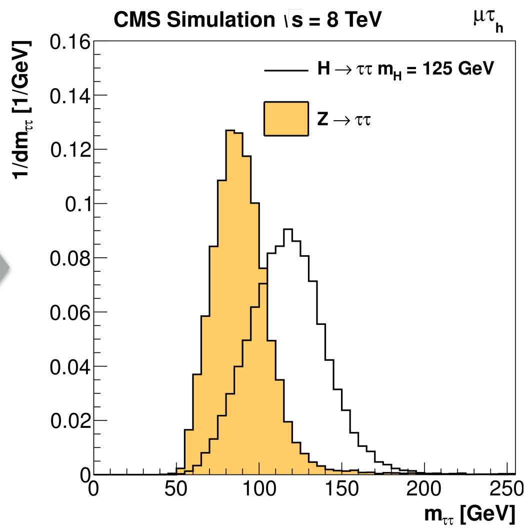
(the SM branching ratios are assumed)

experimental challenges: invariant masses

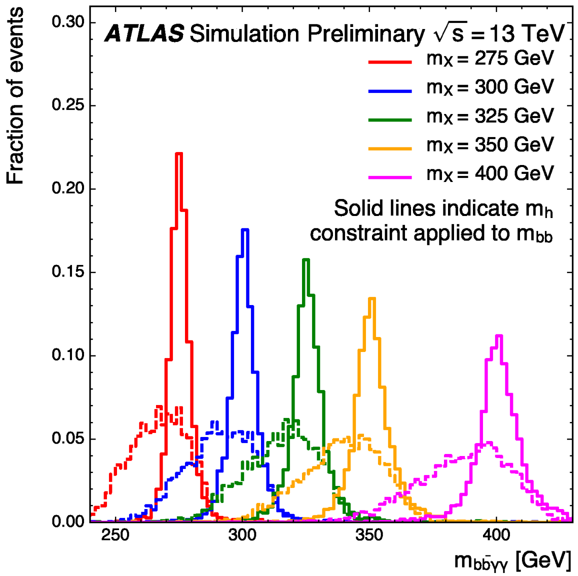
- tau leptons and b quarks are **not reconstructed with good resolution**
- use kinematic constraints to improve the invariant mass resolution of the **single Higgs resonances**



CMS HIG 13 004



effect on the CMS likelihood fit in the **di-tau invariant mass** reconstruction

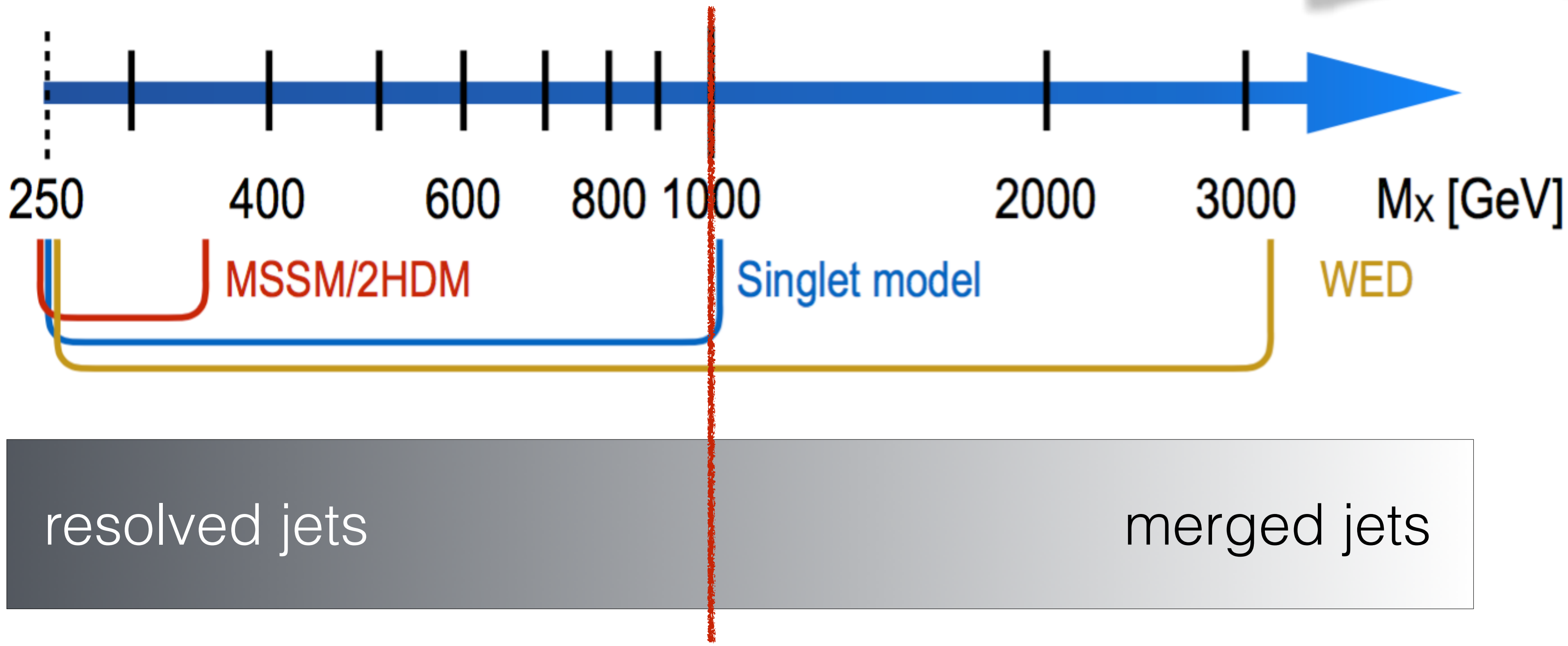


effect of **m_h/m_{bb} rescaling** on the high-mass resonance resolution in ATLAS

experimental challenges: the boosted regime

- highly boosted Higgs bosons produce **collimated pairs of objects**
- for new resonances of very large invariant mass they are reconstructed as **single large jets**
  - for b pairs and tau pairs
  - **b-tagging and tau-identification** need to be performed within the large jet (see C. Collard talk)

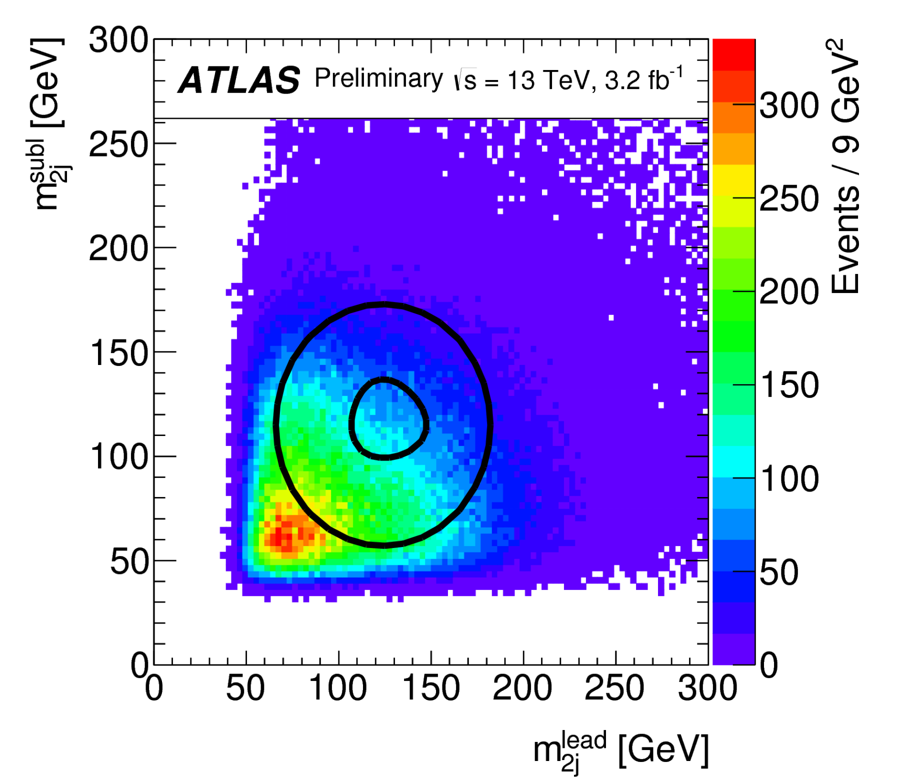
$$R < \frac{2 \cdot m_h}{p_T^{(h)}}$$

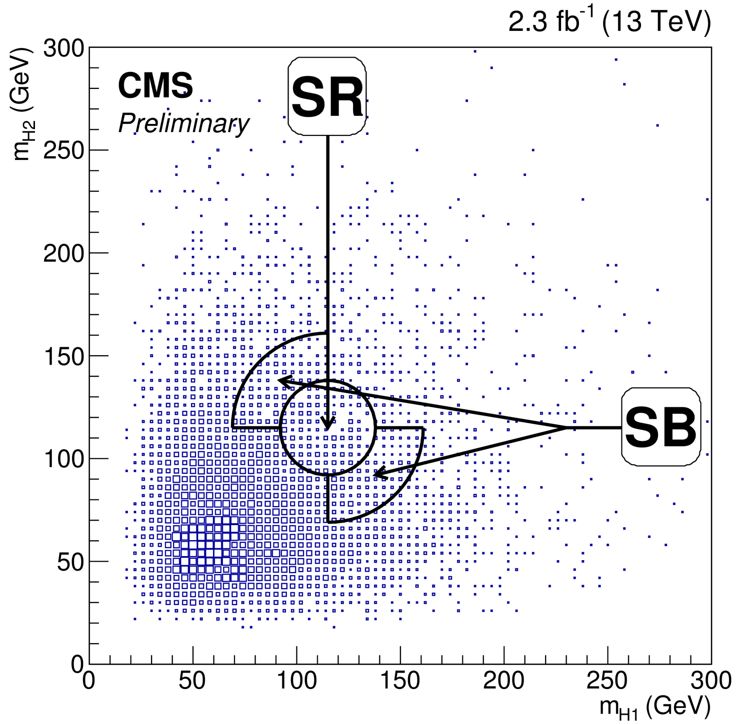


hh → bb bb

- **dominant QCD multi-jet background**, to be measured in data
- 4 jets at **trigger level** (minimal p_T of at least 30 GeV),
  - some b-tagged (1-2 for ATLAS, 3 for CMS)
- **signal region** defined with a chiSquared:

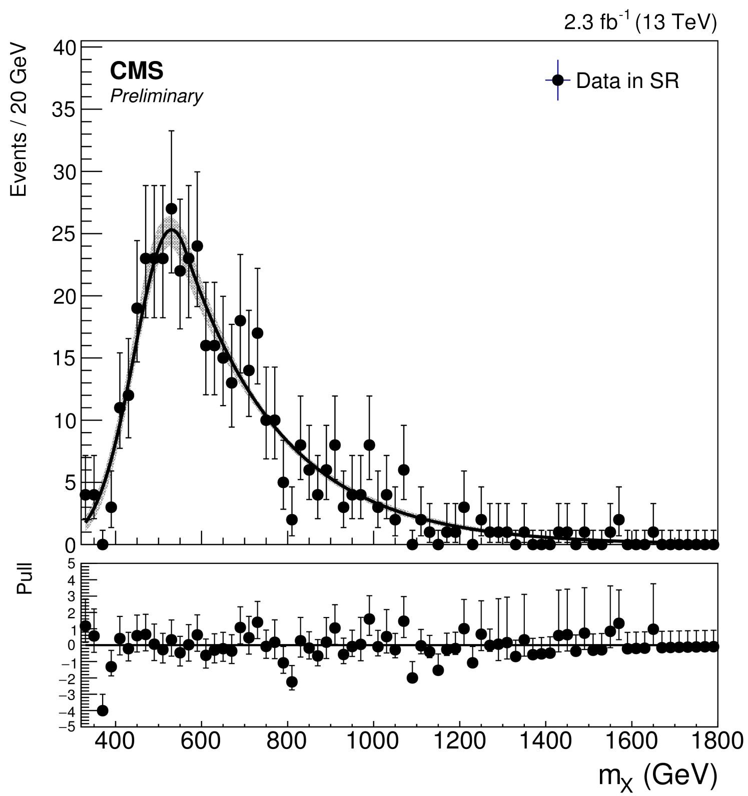
$$\chi^2 = \left(\frac{m_{jj} - m_{h_1}}{\sigma_h}\right)^2 + \left(\frac{m_{jj} - m_{h_2}}{\sigma_h}\right)^2$$

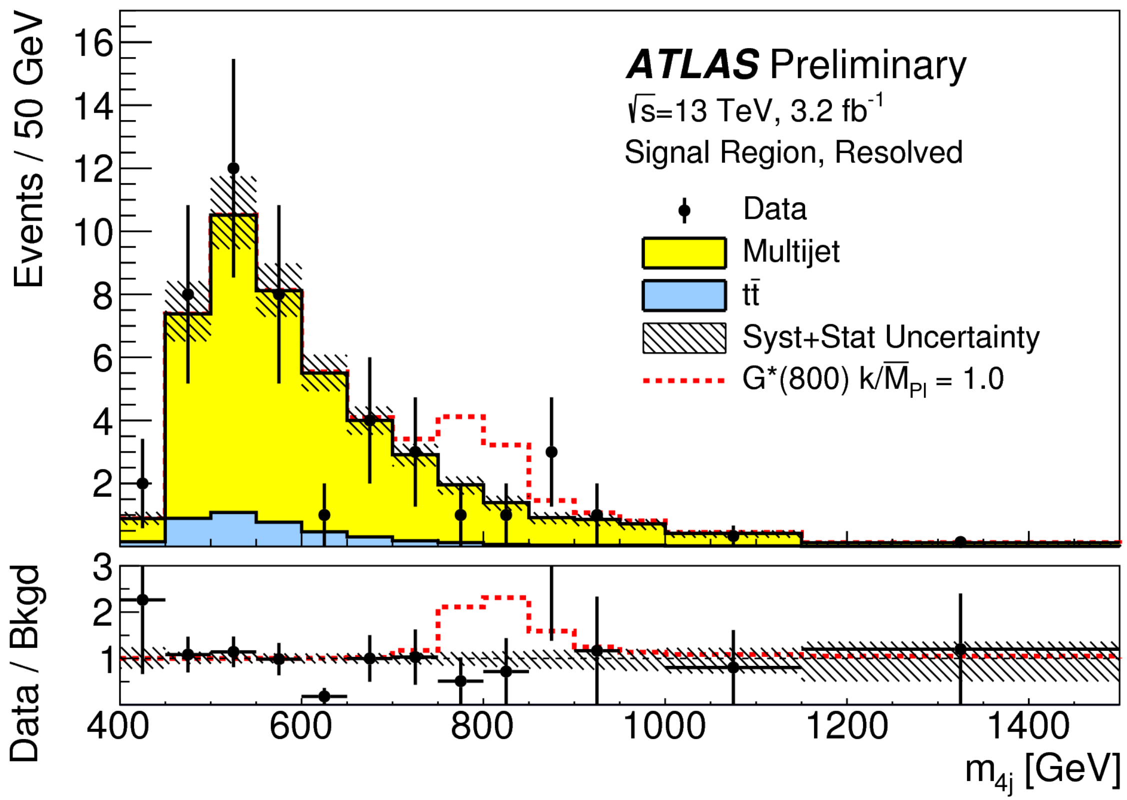




final distributions

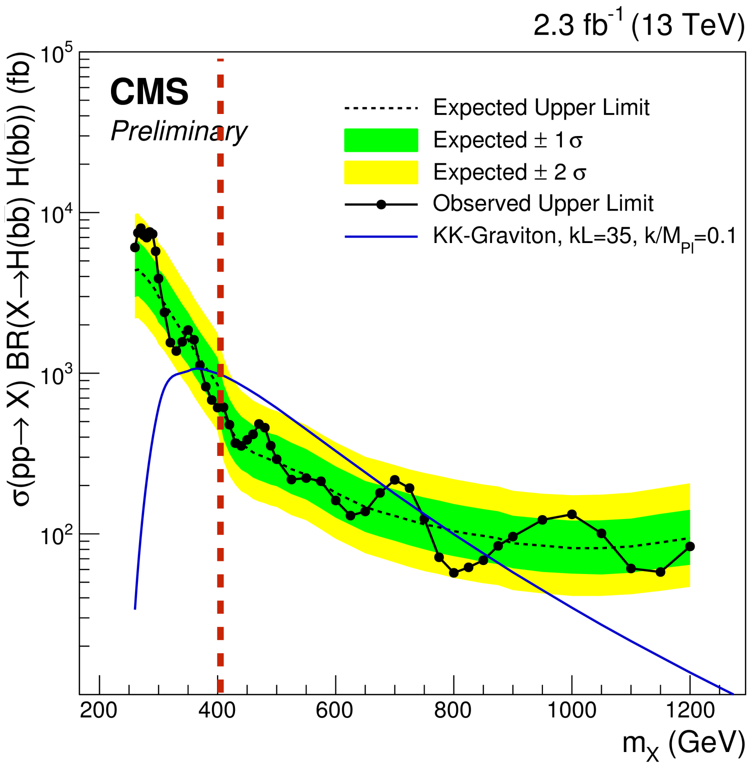
- jets forming H boson candidates required to be **nearby in η**
- **QCD background shape** determined in sidebands and free to float in the signal region fit
- **no significant deviations** from the SM have been observed

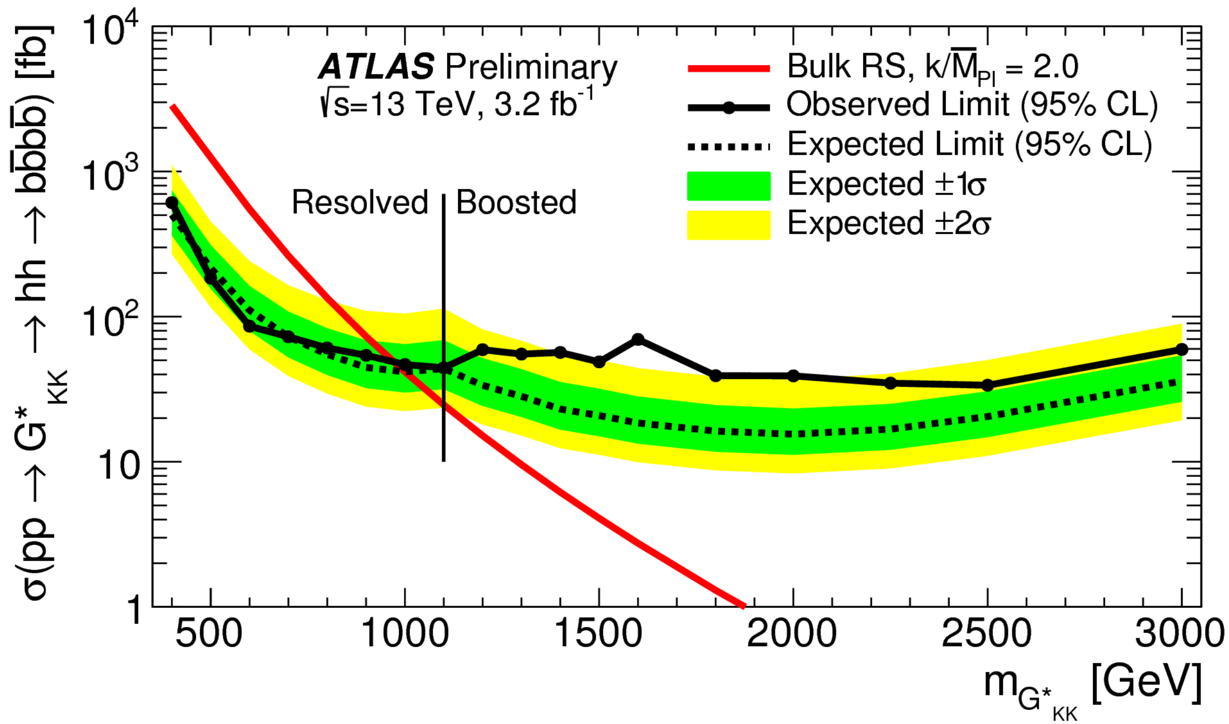




exclusion limits

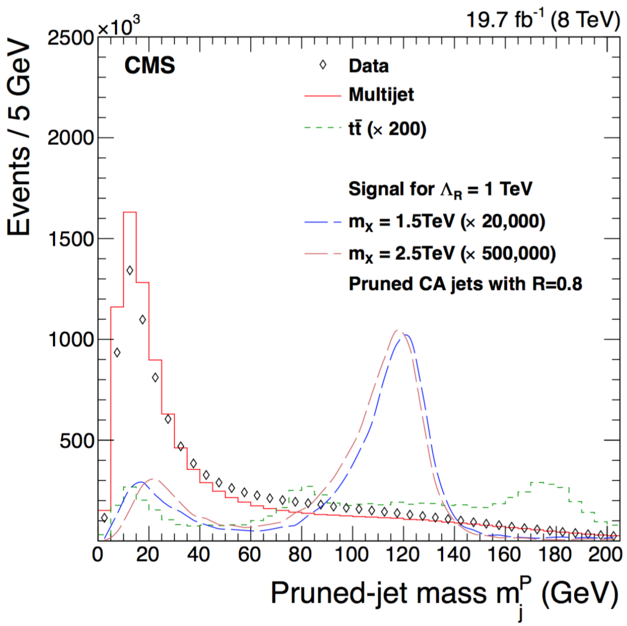
- CMS analysis divided into **two mass regions** (threshold at 400 GeV)
- ATLAS analysis features **boosted jets for m_h > 1100 GeV**
  - the analysis in the boosted regime is similar to the resolved one
- exclusion limits presented for **some benchmark models**
  - graviton, Higgs-like resonance (ATLAS)
- ATLAS excludes at 95%CL anomalous **non resonant production** with 1.22 pb of cross-section (SM one is ~13 fb)

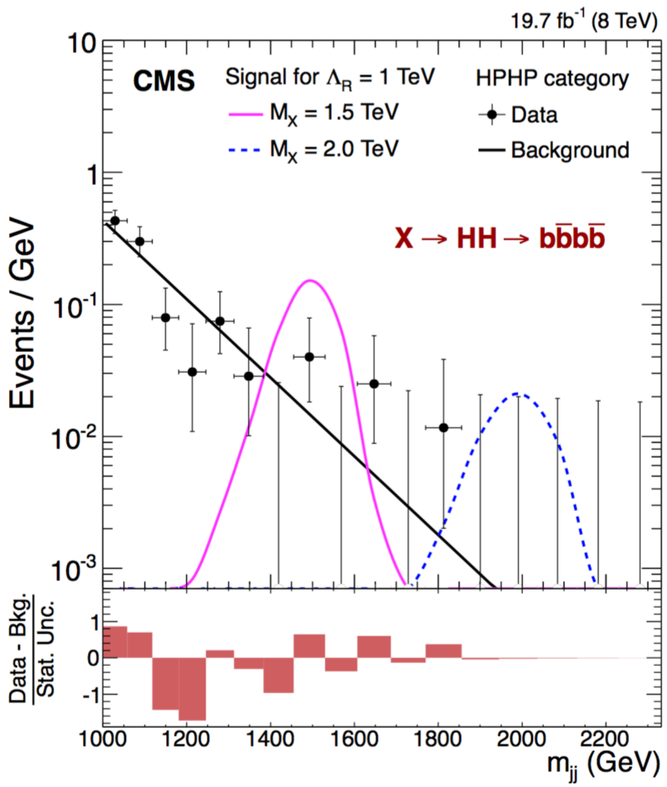


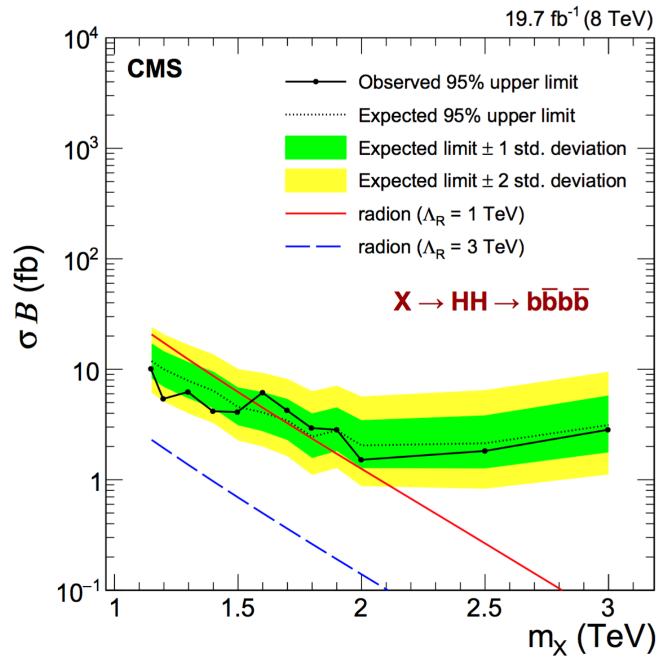


boosted case in CMS

- **trigger** on hadronic activity in the event (m_{JJ} or HT)
- main backgrounds due to **QCD multijet and tt**
- **data-driven fit of backgrounds**
  - several closure tests on MC and sidebands
- final result in three different event **categories of purity**, defined by the kinematics of jets constituents

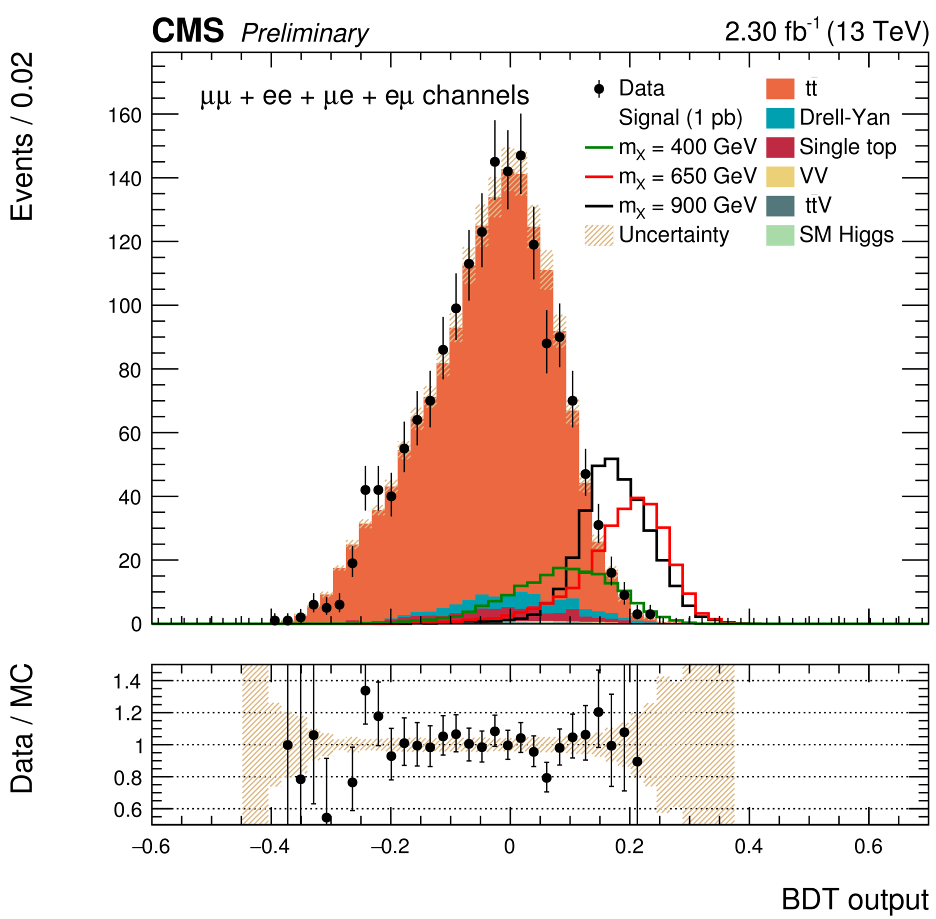


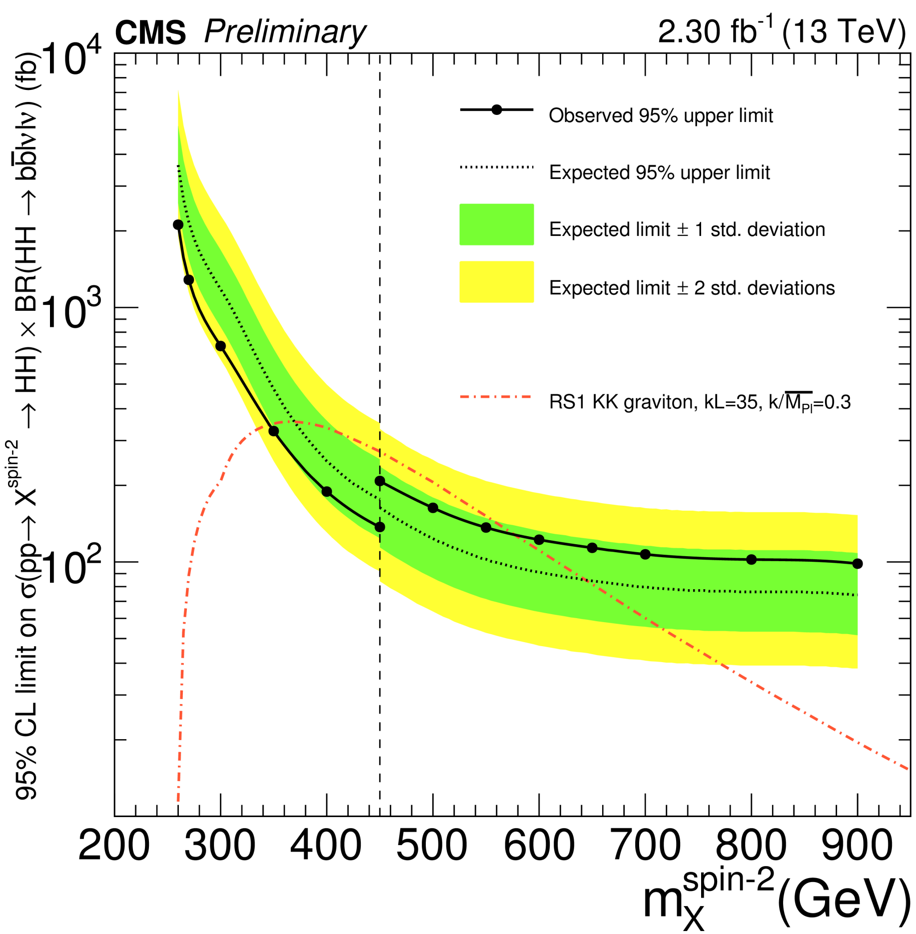




hh → bb WW → bb ℓν ℓν (ℓ = e, μ)

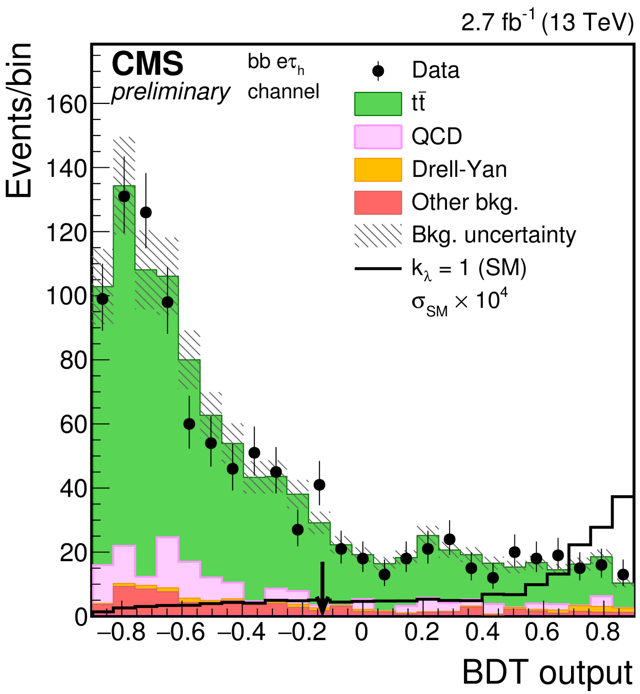
- **preselections + BDT** trained to separate signal from main bkg (tt, t, DY)
- training in two mass intervals
- limit extracted for spin-0 and spin-2 hypothesis
- **simultaneous fit of signal and sideband regions** to constrain the background normalisation

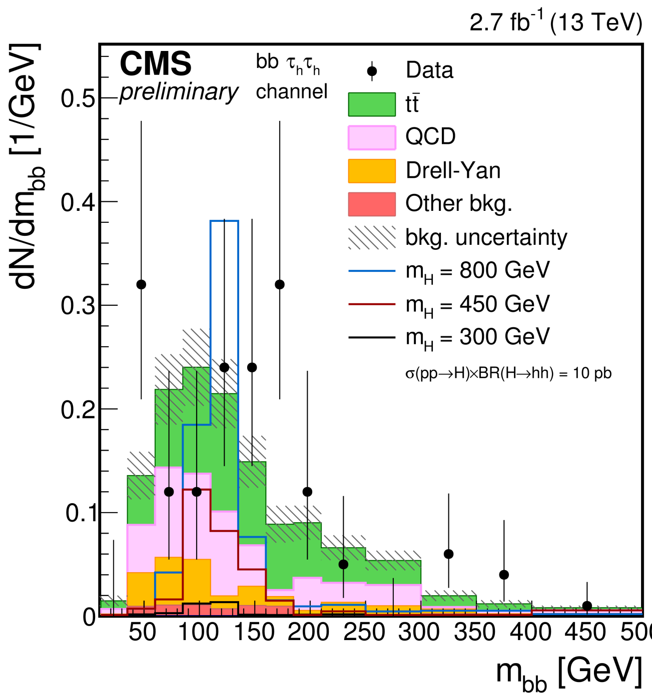


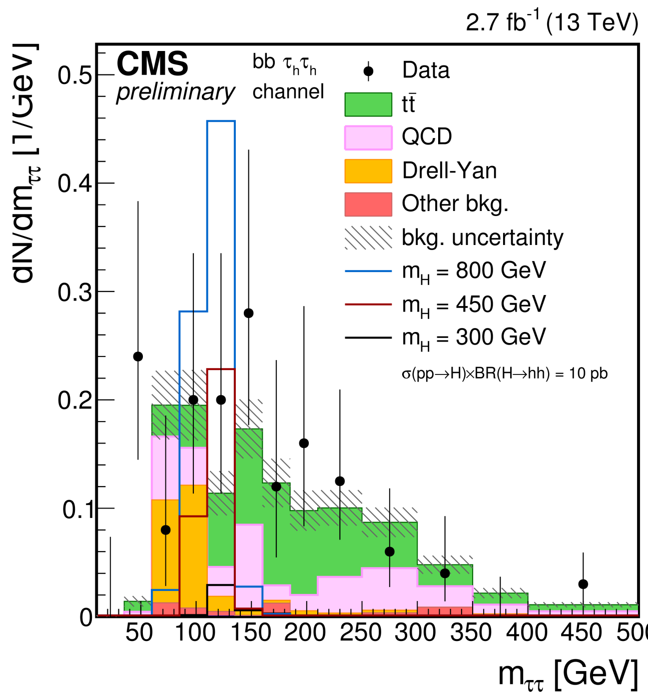


hh → bb ττ

- **3 final states**: bb $e\tau_h$, bb $\mu\tau_h$, bb $\tau_h\tau_h$
- **trigger** selections based on electrons, muons and hadronic taus
- **leptons** should have a minimal p_T (~20 GeV) and be isolated
- BDT trained **against ttbar** for the non-resonant analysis
- backgrounds:
  - **tt**: from MC with kinematic p_T reweighing to data
  - **Z→ττ**: MC yield corrected for b-tagging efficiency
  - **QCD** shape and yield from same-sign anti-isolated τ_h region

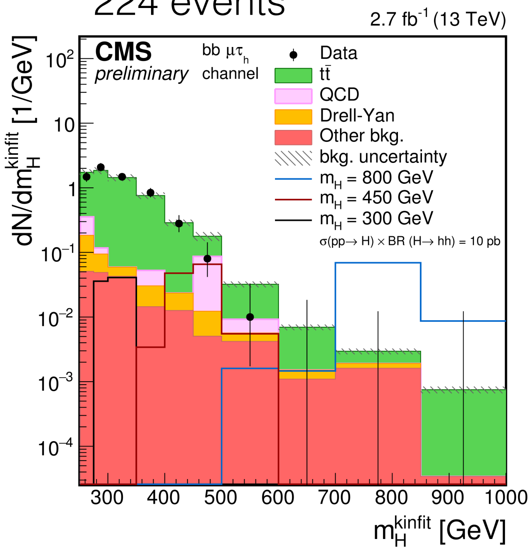




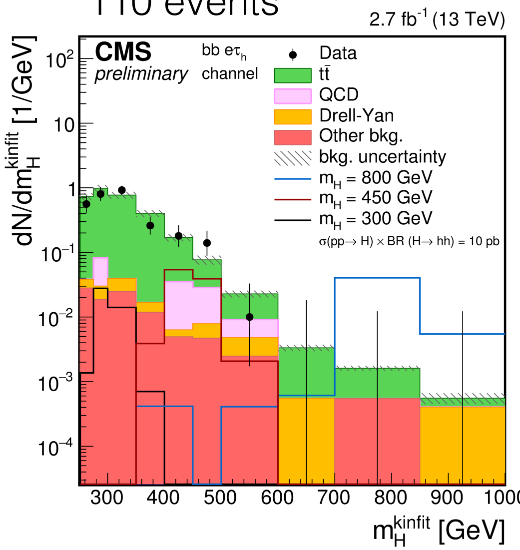


the resonant result

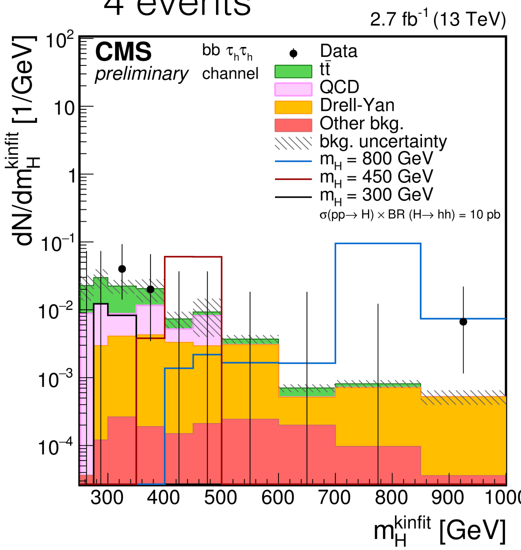
224 events



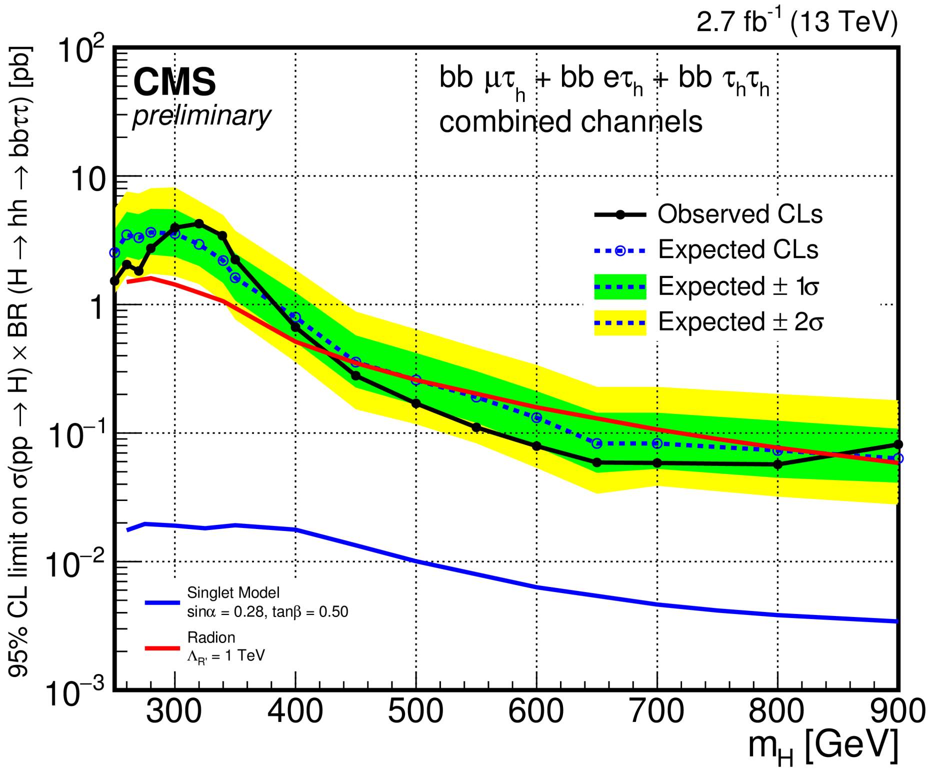
110 events



4 events

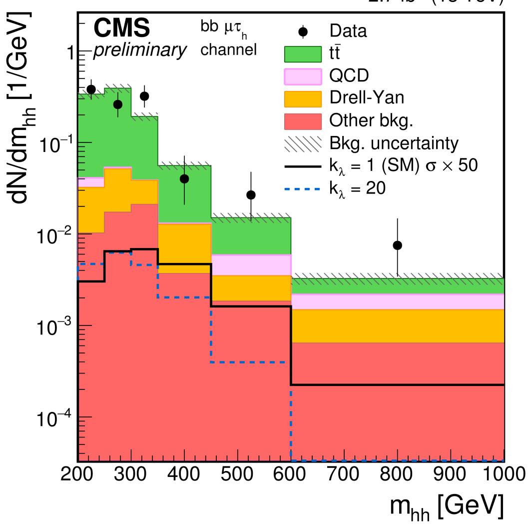


- **no significant excess** observed up to 900 GeV
- limit presented for a **model-independent narrow H**
- **bb $\tau_h\tau_h$ channel** with best S/B but low statistics
- At high mass, **close to Run I sensitivity** already

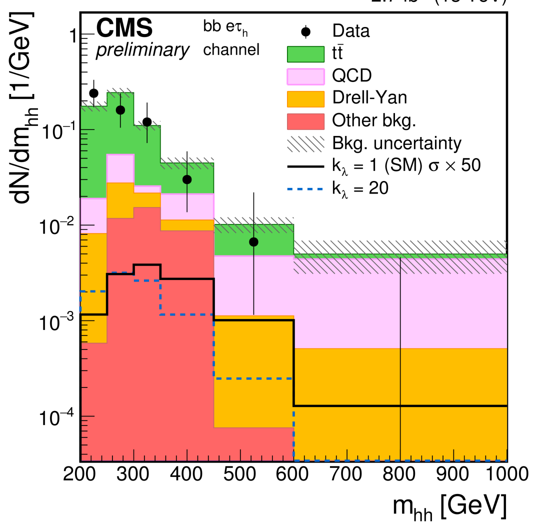


the non-resonant result

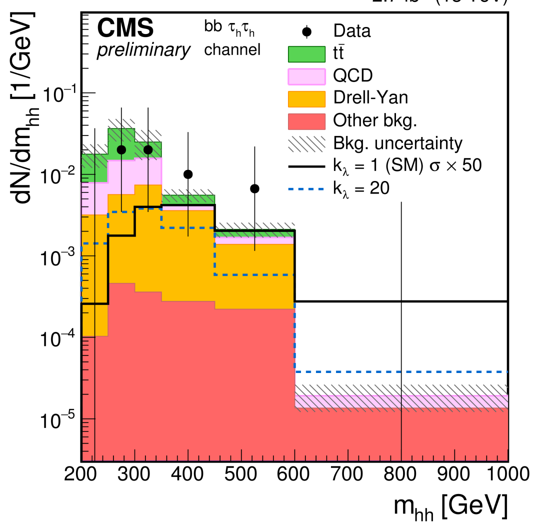
59 events



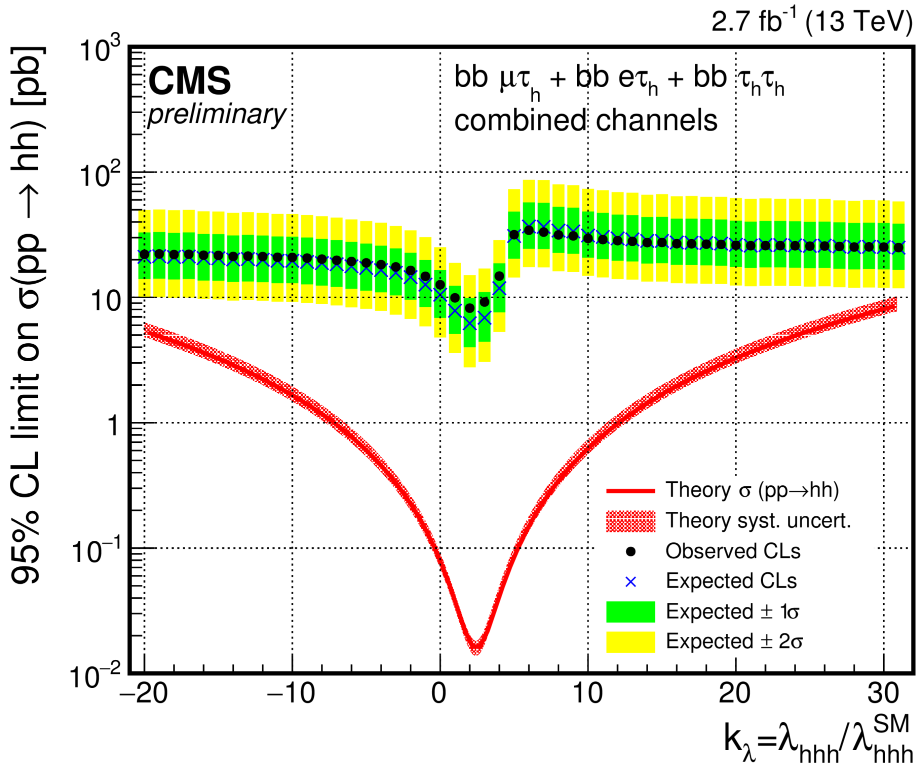
30 events



4 events

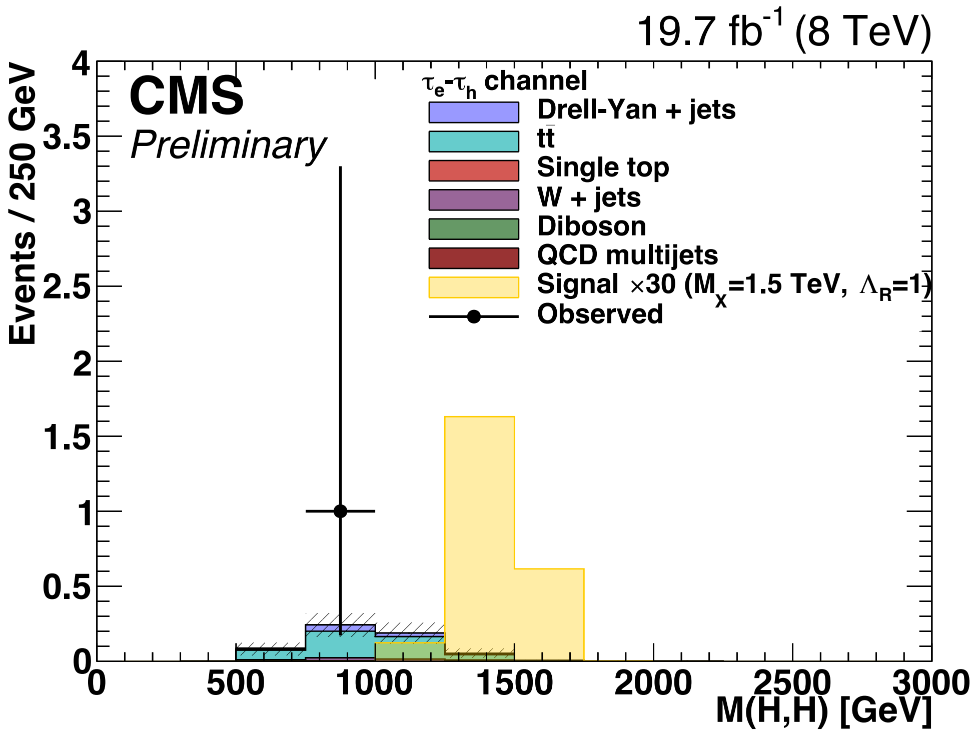


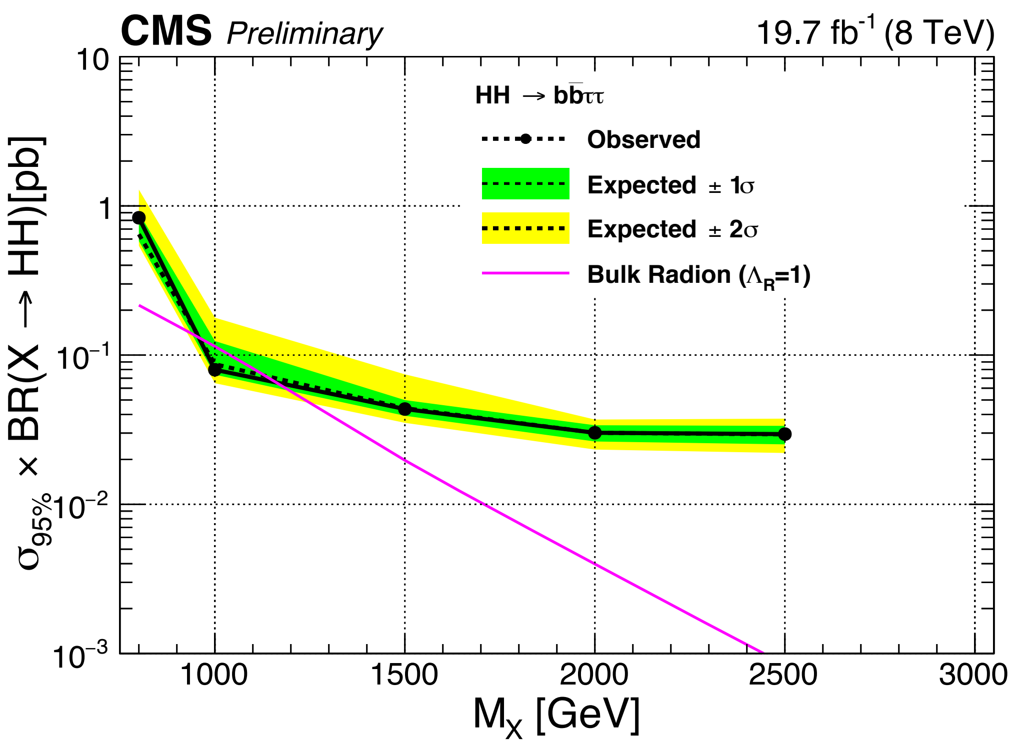
- fit performed on the $\mathbf{m_{bb\tau\tau}}$ **variable**
- Analysis dominated by the statistical uncertainties
- Observed (expected) limits of 8.8 (7.2) pb at λ = 1, corresponding to **200 x SM expectations**



the boosted case

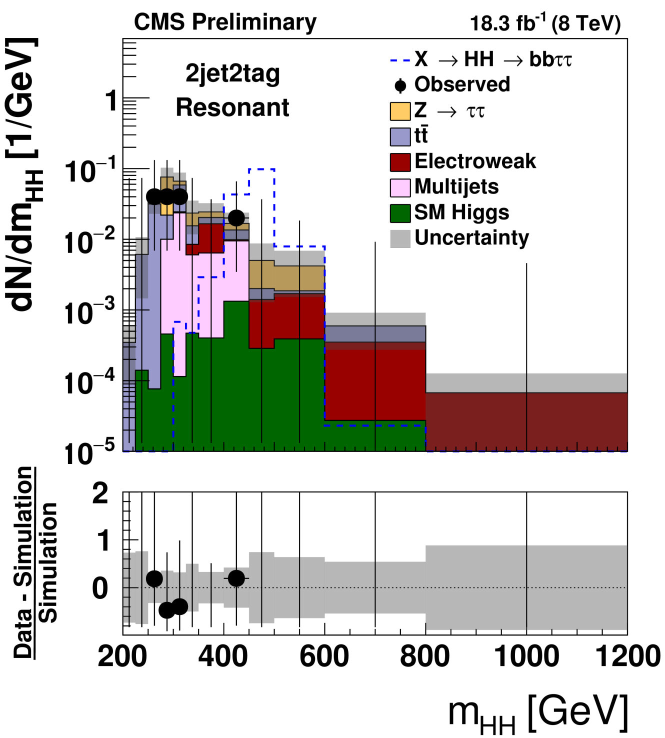
- event **trigger** based on a high-p_T jet (320 GeV) or large H_T (650 GeV)
- b-quark pairs are identified **inside single Cambridge-Aachen jets** with size ΔR=0.8
- **background** shapes from MC with loose selections, normalisation from data sidebands
  - anti b-tagged, loosened and inverted τ_h isolation, m_{bb} sideband

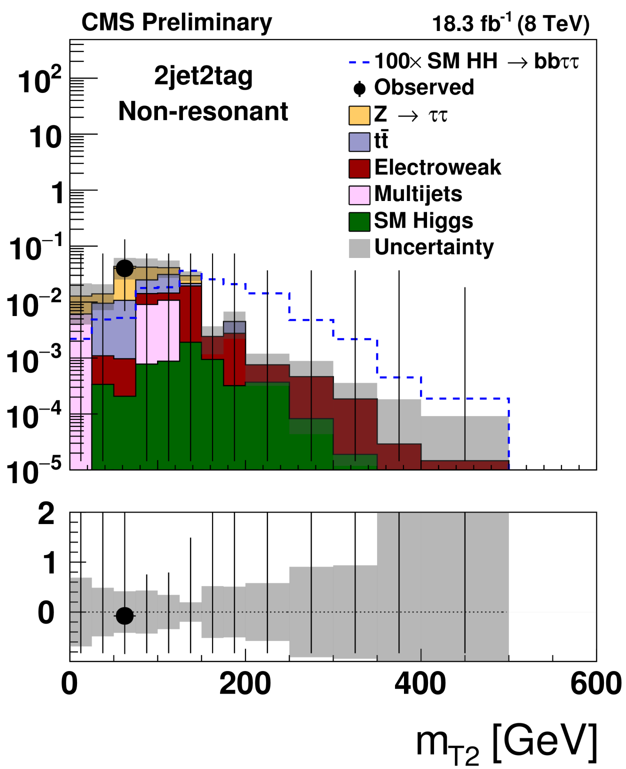


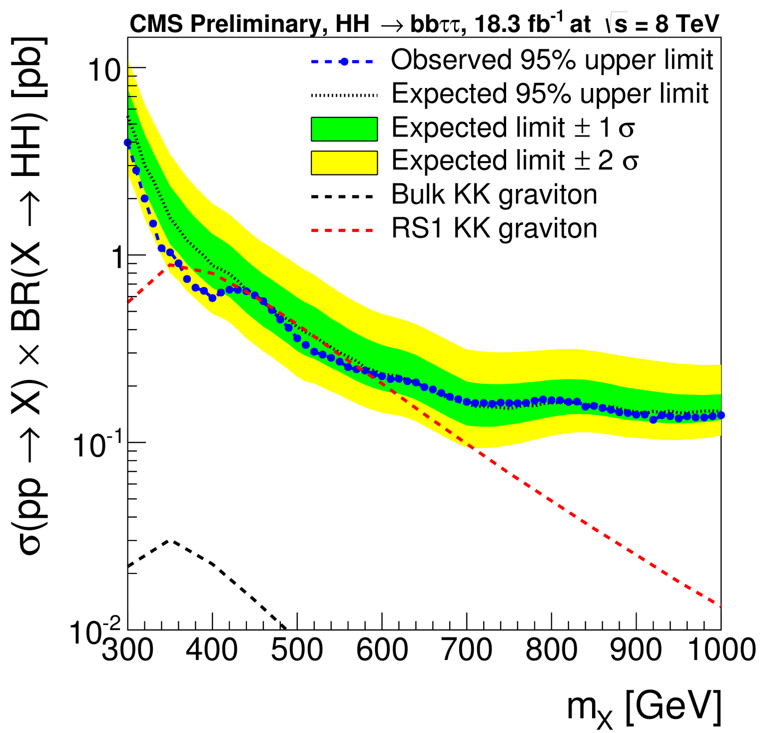


run 1 CMS results: bb $\tau_h \tau_h$

- trigger selection based on **one or two hadronic taus**
- **QCD** bkg from sidebands (same-sign + relaxed isolation)
- **Drell-Yan** bkg from substitution of μ in data with simulated τ
- **binned maximum likelihood fit** on m_{hh} for the resonant case
- fit on M_{T2} for the **non-resonant case**: a limit of 160 (130) times the SM cross section is observed (expected)

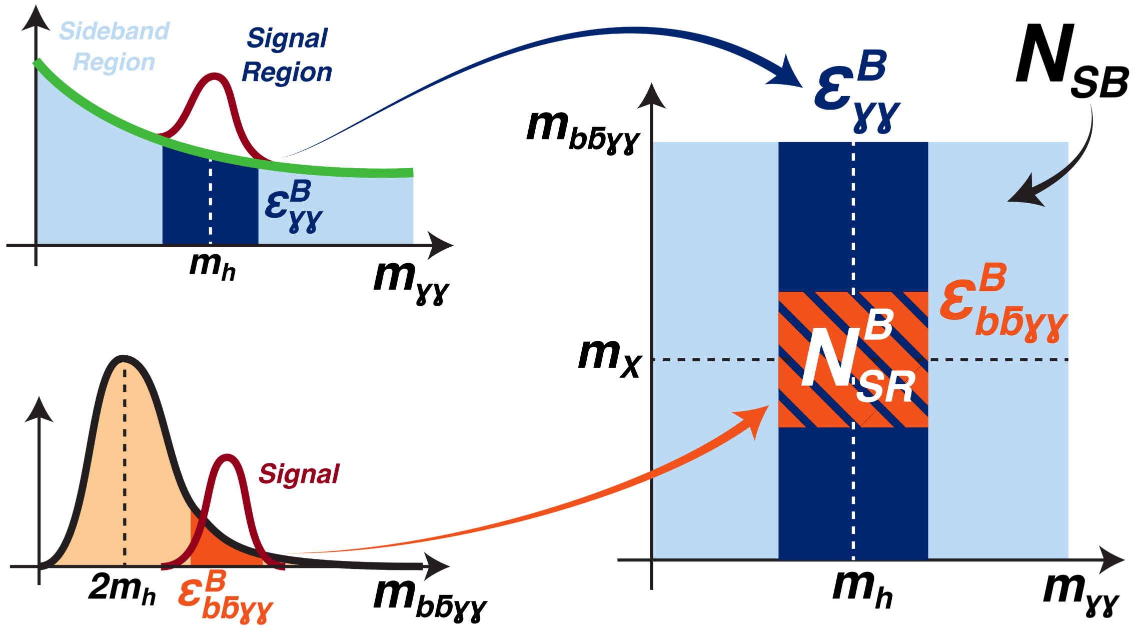


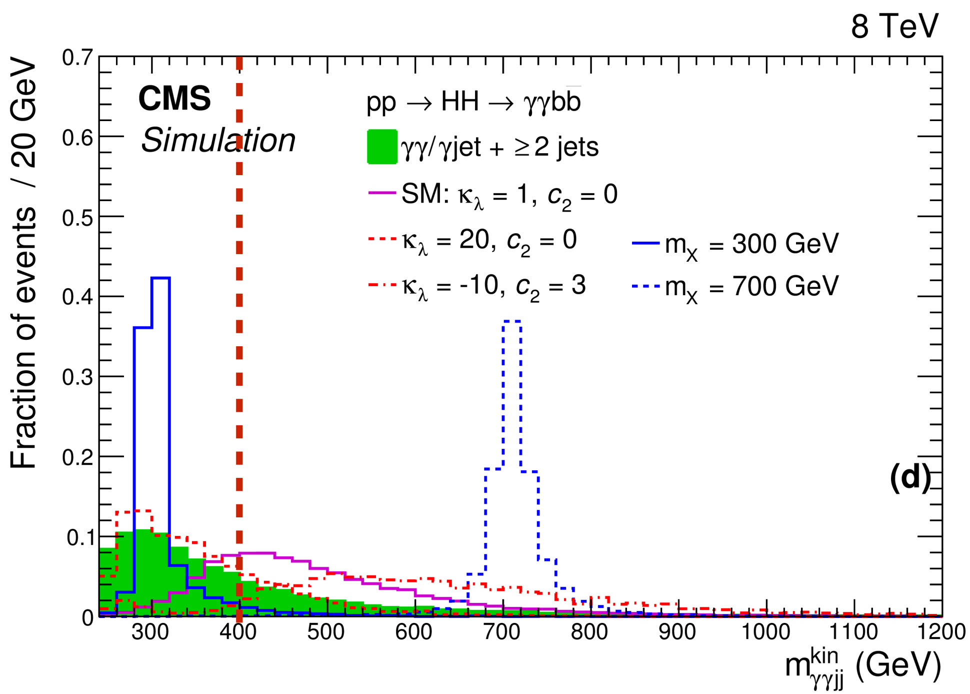




hh → bb γγ

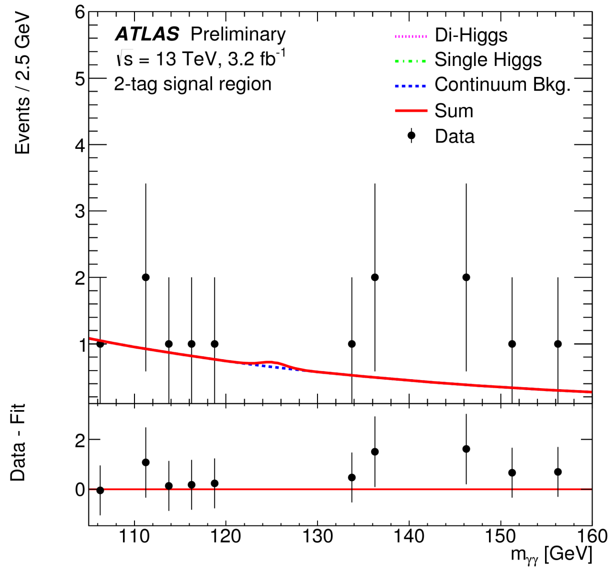
- main background: **di-photon production** in association with jets
- **data-driven** with simultaneous fit of functional models on data
  - check in sidebands
- **number of b-jets** used to define categories and sidebands
- **specific final selections** for each analysis target
- ATLAS first results at 13 TeV, CMS paper at 8 TeV

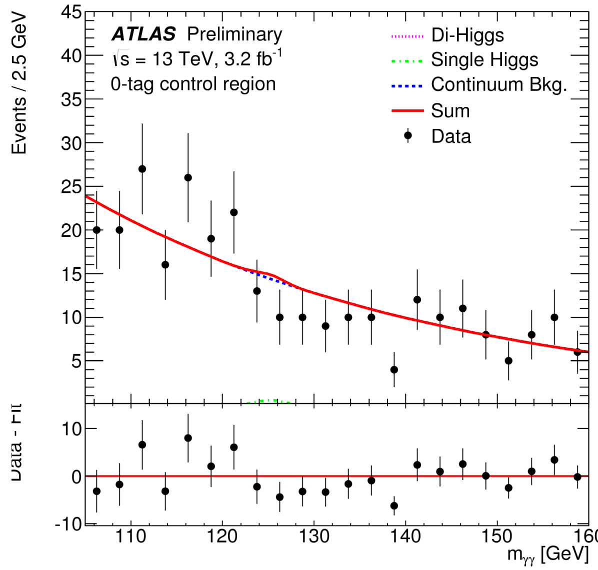




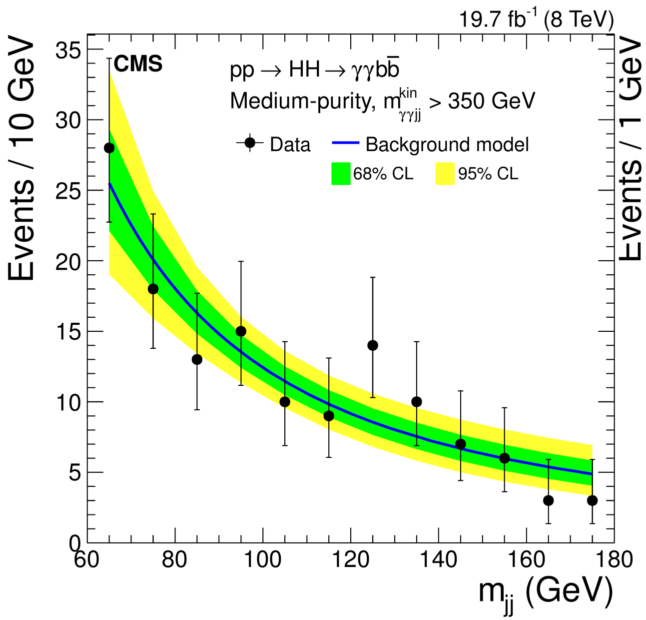
invariant mass distributions

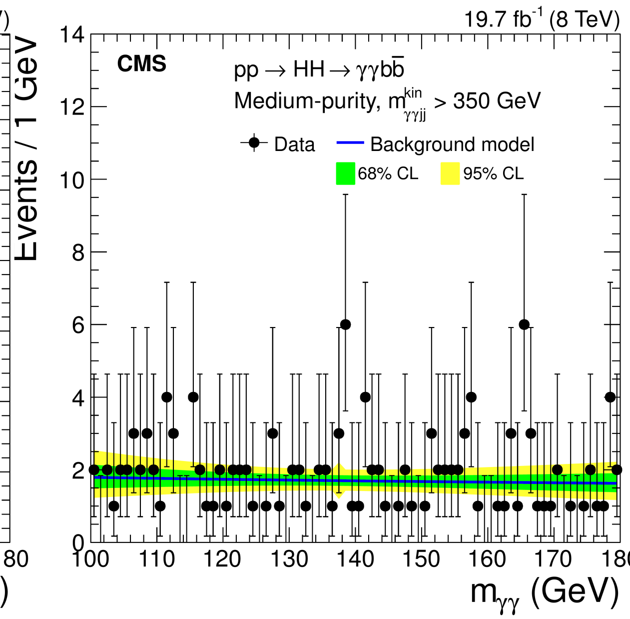
- **non-resonant**: fit the $m_{\gamma\gamma}$ spectrum in signal and sideband
- **resonant**: cut & count
- **no events** in the signal region





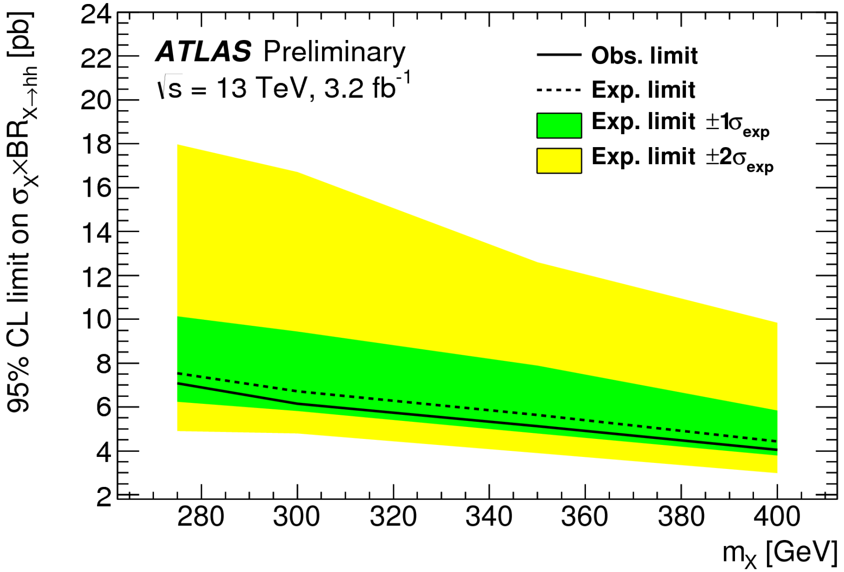
- several **event categories**
- different **fit regions** depending on the kinematics of the signals
- **fit in m_{hh} or (m_{bb}, $m_{\gamma\gamma}$)**, depending on the kinematic region

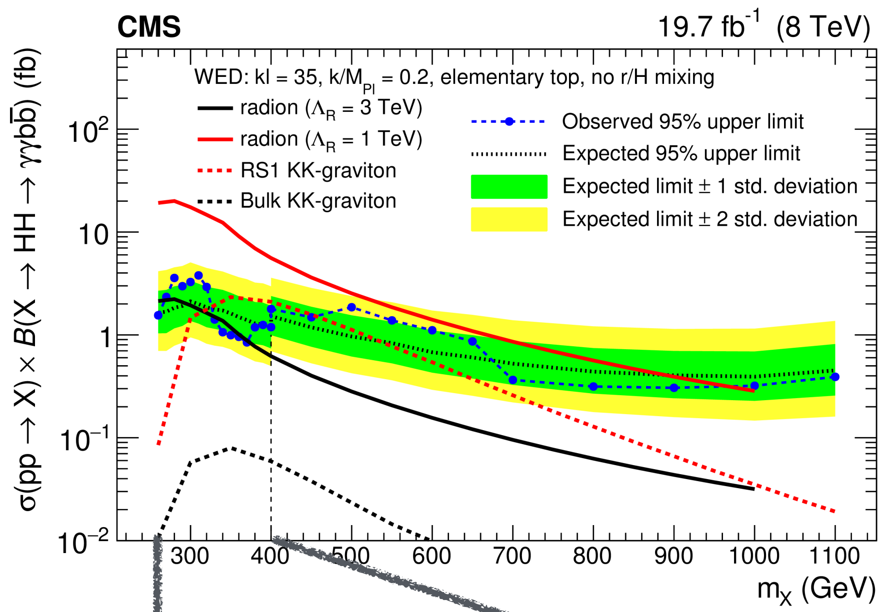




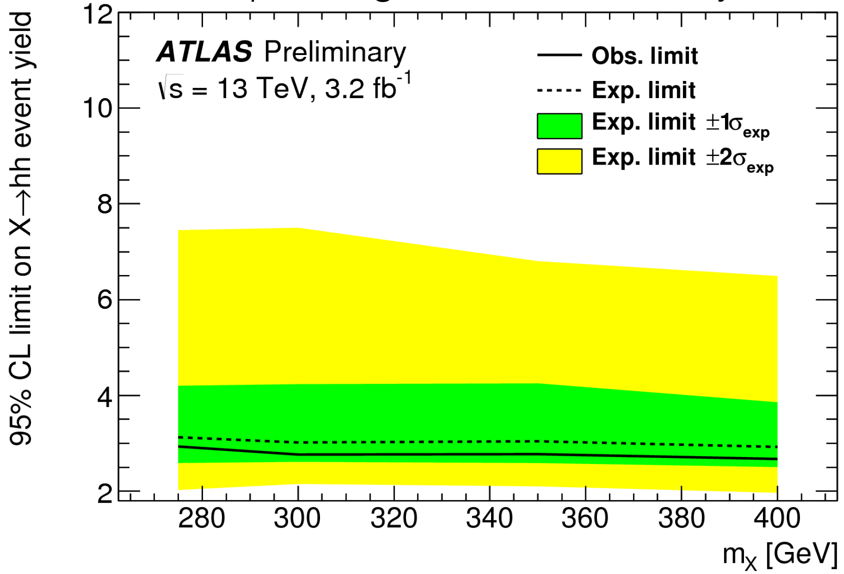
results of the resonant analyses

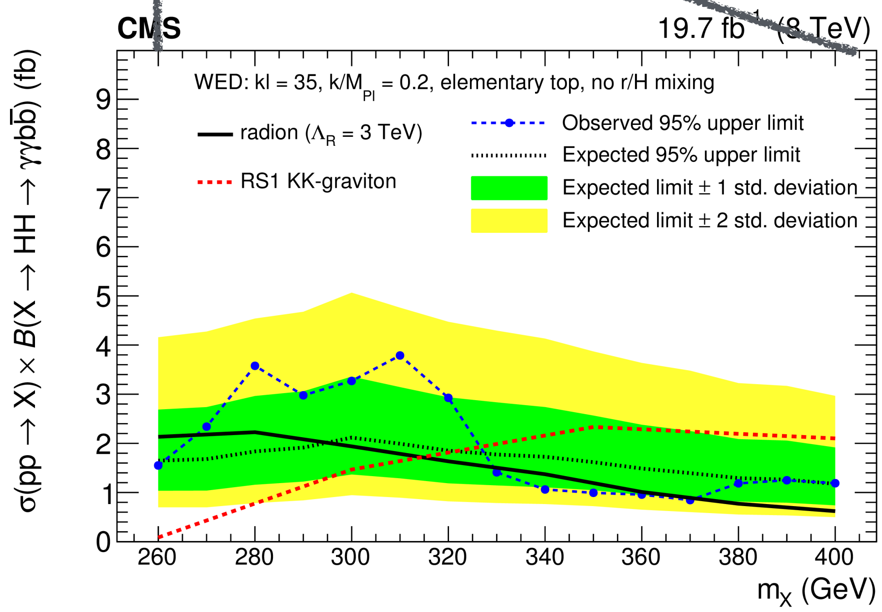
narrow resonance search limit



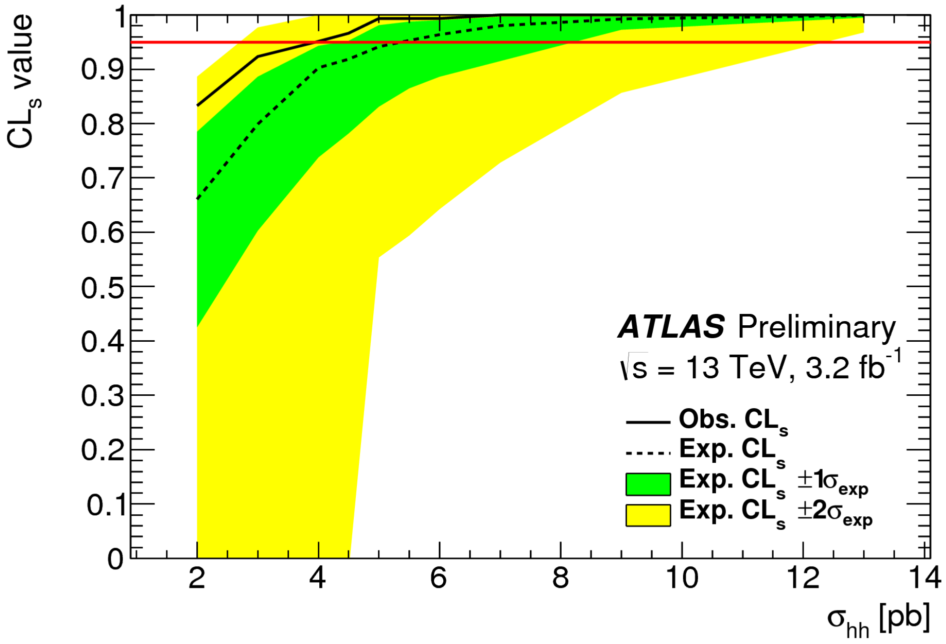


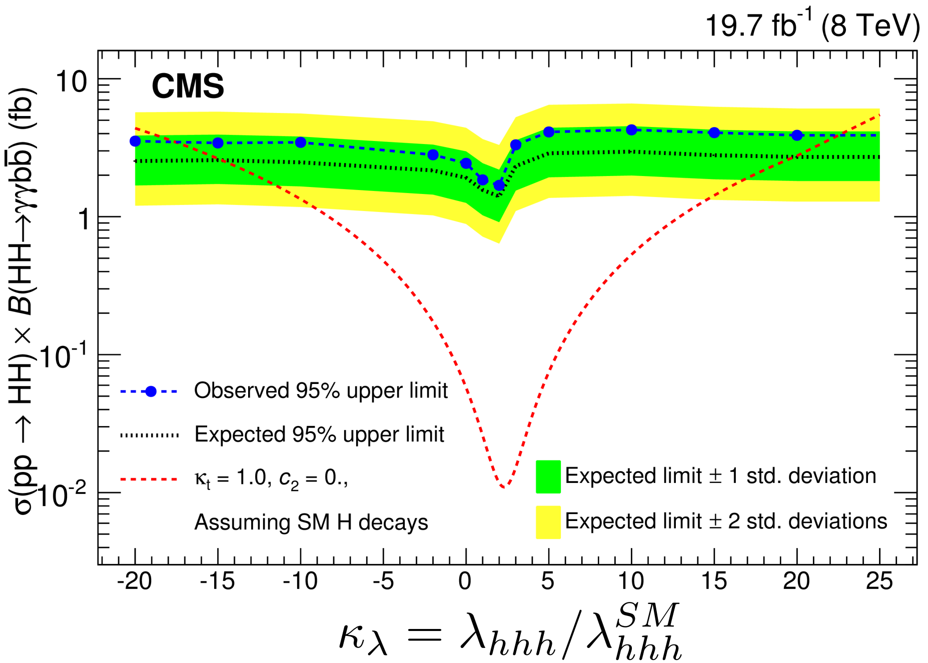
corresponding limit on the event yield

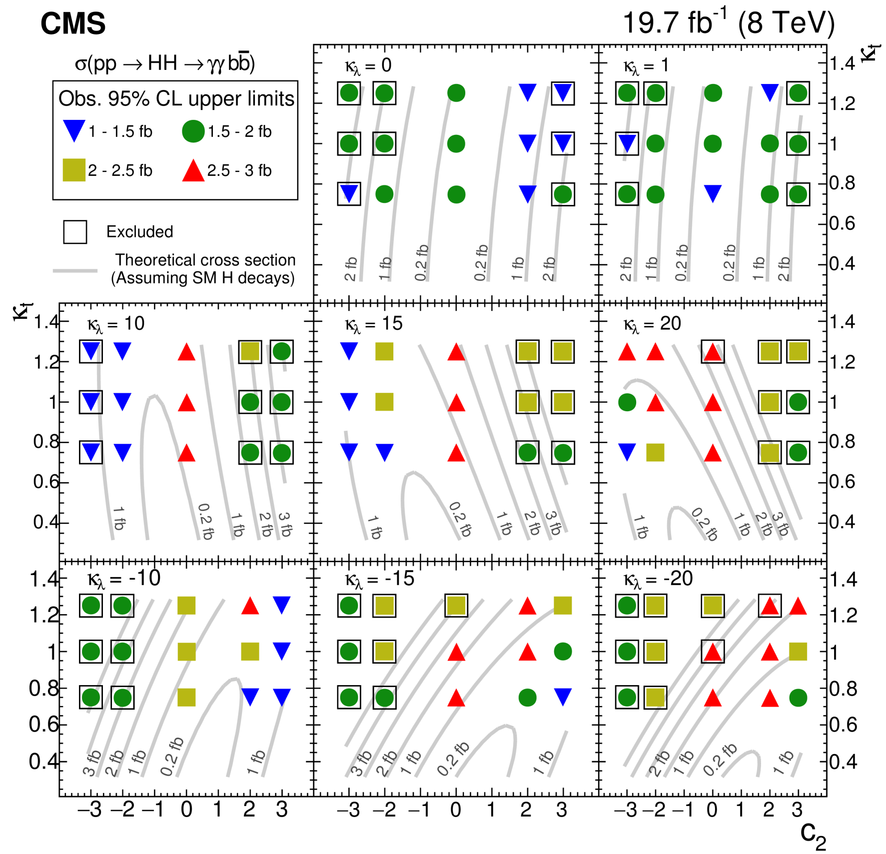




results of the non-resonant analyses





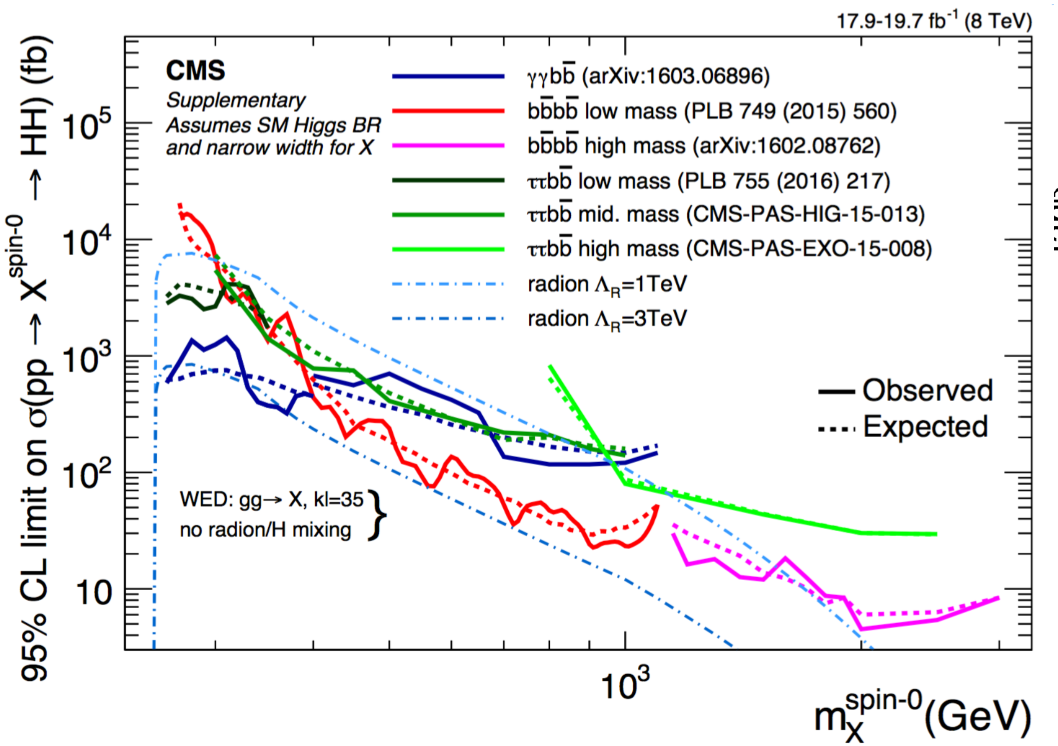


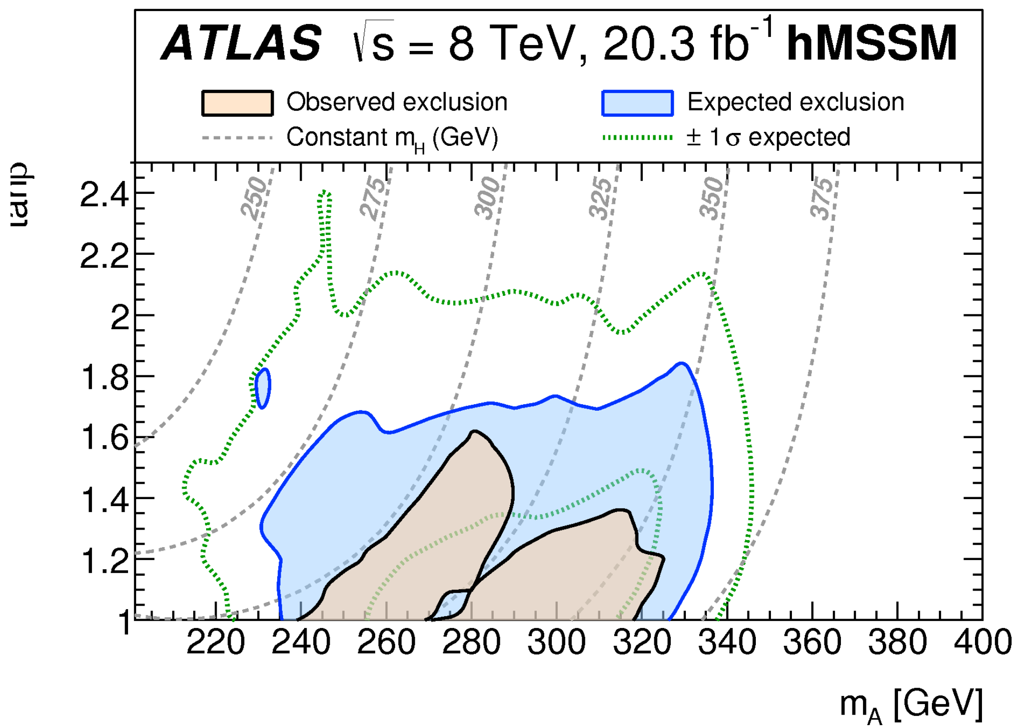
Scan of the EFT Lagrangian as a function of κ_t, c2, for various values of κ_λ.

Gray lines show the theoretical prediction for the hh production cross-section, the markers show the CMS sensitivity, the boxes indicate excluded points

putting the pieces together

- what we can expect, in light of the results of run1
- hunt for **narrow resonances**: bb $\gamma\gamma$ most sensitive channel at low mass, bb bb at high mass
- **hMSSM**: hh contributes significantly in the low mA - low tanβ region





conclusions

- the Higgs boson opens a new window on the **electroweak symmetry breaking**
- CMS and ATLAS experiments are studying final states with two Higgs bosons hunting for **resonant and non-resonant anomalies** in several final states, over a wide range of m_{hh}
- so far **no evidence for BSM signals** have been found
- despite the small luminosity (< 3 fb-1), Run II analyses start to be competitive with Run I, and will supersede it with 2016 data
- **13 TeV data analyses** are relying on very small statistics, 2016 data will grant a big leap forward