Search for resonant di-Higgs production with the CMS detector

40th International conference on High Energy Physics

28 July — 6 August 2020

Alessia Saggio[1]

On behalf of the CMS Collaboration

[1]Deutsches Elektronen-Synchrotron DESY
Email: alessia.saggio@cern.ch

Di-Higgs production: a portal to new physics

- Our efforts are focused on **looking for physics beyond the Standard Model**
- The **Higgs sector** is a **portal to new physics**
- **Di-Higgs production** is of special interest
- Why? And how does it manifest itself?

Di-Higgs in a nutshell

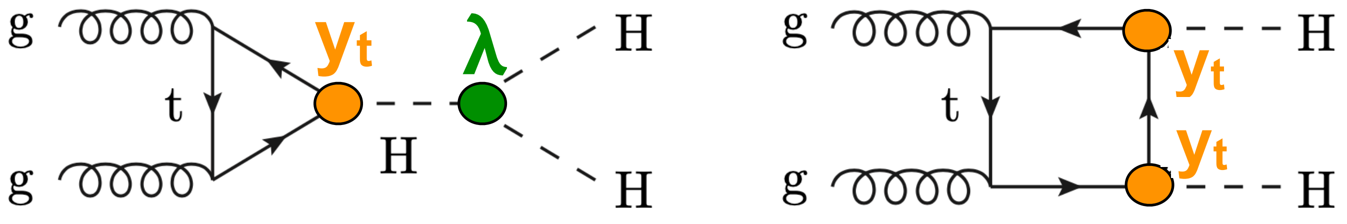
NON-RESONANT

- HH production cross section at 13 TeV at the LHC =~ 33 fb (NNLO in QCD)
- However, BSM models predict rate enhancement
- **BSM physics can appear via**

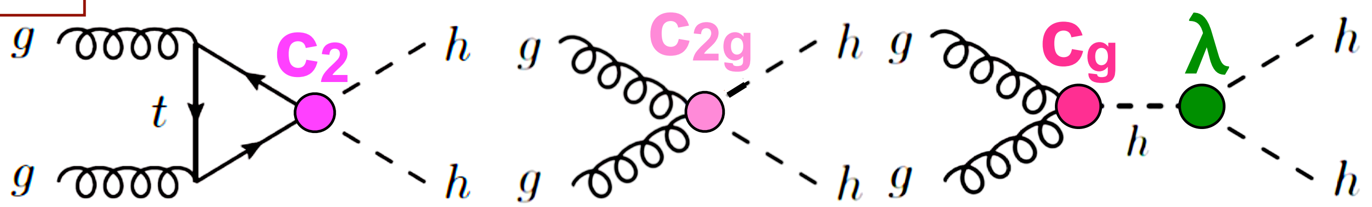
Anomalous couplings of the Higgs

New particles that decay to a Higgs pair

SM-like



BSM



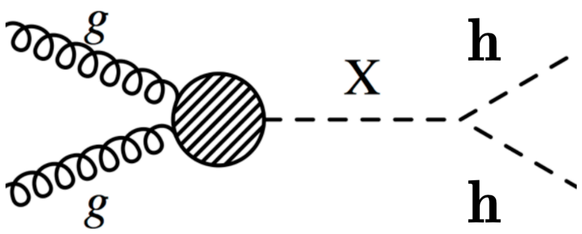
- **Non-resonant di-Higgs golden channel** to study the **Higgs potential**
- **Probe the Higgs trilinear coupling** (λ)
- **BSM effects** can be added through **dim-6 operators** in the Lagrangian

Di-Higgs in a nutshell

- HH production cross section at 13 TeV at the LHC =~ 33 fb (NNLO in QCD)
- However, BSM models predict rate enhancement
- **BSM physics can appear via**

RESONANT

Anomalous couplings of the Higgs



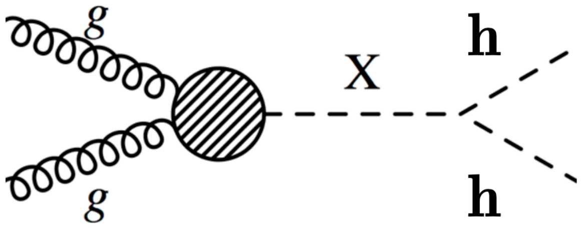
New particles that decay to a Higgs pair

- **Higgs pair** can be a **decay product of a new heavy particle**
- **Predicted by different BSM models**:
  - Randall-Sundrum Warped Extra Dim **(**scalar **radion/** spin-2 **graviton)**
  - Higgs singlet model
  - 2HDM, MSSM
- **Large mass range** probed: 250 GeV to (currently) 3 TeV

Di-Higgs in a nutshell

- HH production cross section at 13 TeV at the LHC =~ 33 fb (NNLO in QCD)
- However, BSM models predict rate enhancement
- **BSM physics can appear via**

Anomalous couplings of the Higgs



If m_X too large to be observed

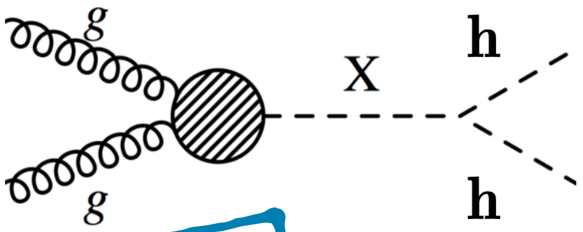
New particles that decay to a Higgs pair

- **Higgs pair** can be a **decay product of a new heavy particle**
- **Predicted by different BSM models**:
  - Randall-Sundrum Warped Extra Dim **(**scalar **radion/** spin-2 **graviton)**
  - Higgs singlet model
  - 2HDM, MSSM
- **Large mass range** probed: 250 GeV to (currently) 3 TeV

Di-Higgs in a nutshell

- HH production cross section at 13 TeV at the LHC =~ 33 fb (NNLO in QCD)
- However, BSM models predict rate enhancement
- **BSM physics can appear via**

~~**Anomalous couplings of the Higgs**~~



Talk focused on resonant di-Higgs searches

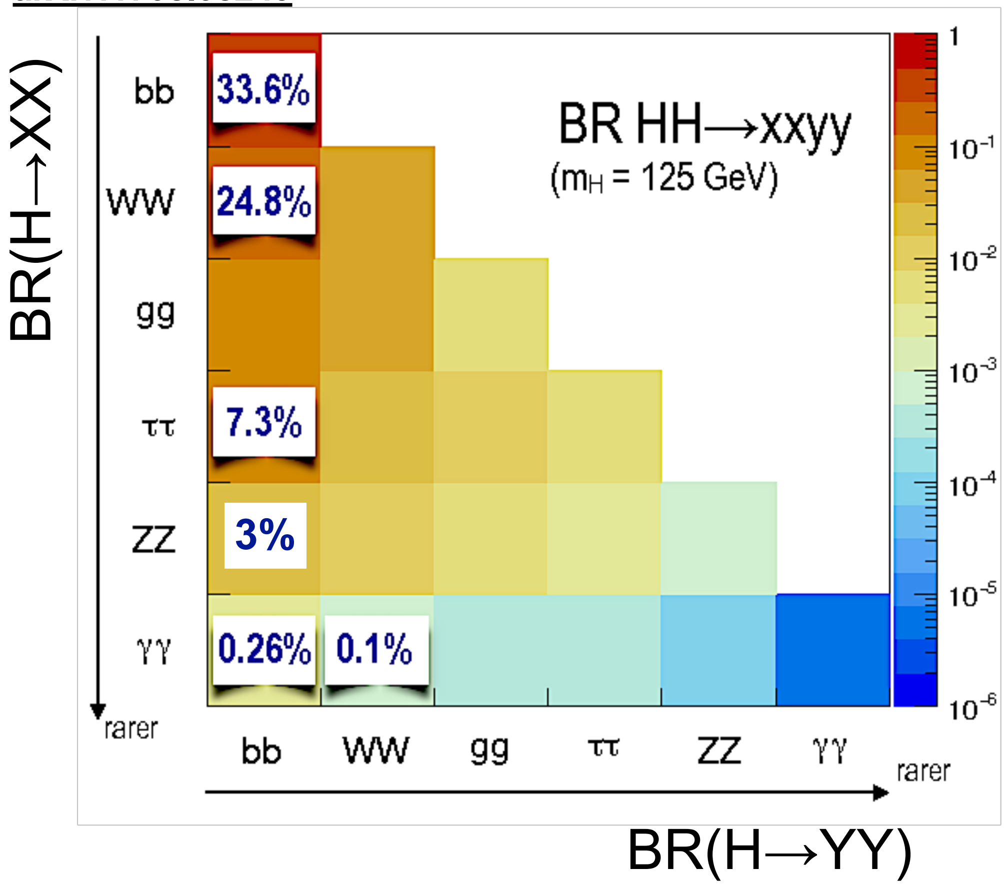
(See Ivan Ovtin's talk for non-resonant!)

New particles that decay to a Higgs pair

- **Higgs pair** can be a **decay product of a new heavy particle**
- **Predicted by different BSM models**:
  - Randall-Sundrum Warped Extra Dim **(**scalar **radion/** spin-2 **graviton)**
  - Higgs singlet model
  - 2HDM, MSSM
- **Large mass range** probed: 250 GeV to (currently) 3 TeV

A large variety of final states

arXiv:1708.08249



- **Large variety of final states** possible
- **Decay channels** chosen based on **BR** and **purity**
- The main ones are:
  - **bb bb**: highest BR, high QCD/tt contamination
  - **bb WW**: high BR, large irreducible tt
  - **bb** $\tau\tau$: relatively low background
  - **bb ZZ**
  - **bb** $\gamma\gamma$

  small BR, low background level

Next slides: overview of recent results on 2016 dataset

X→HH→bbbb

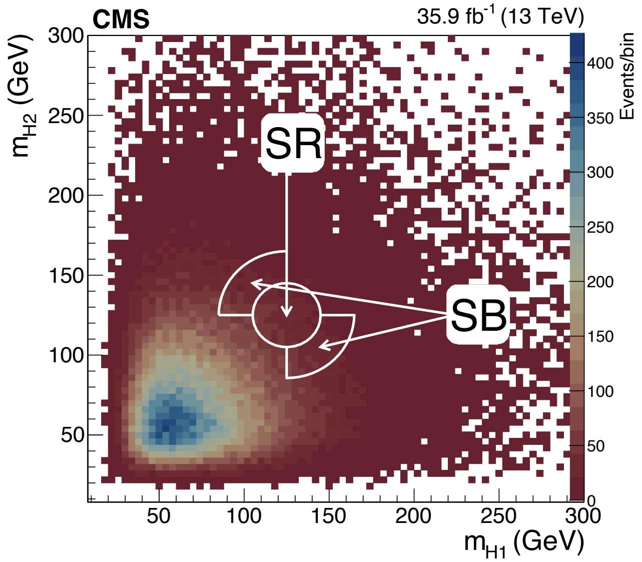
Topology dependent on the mass range probed

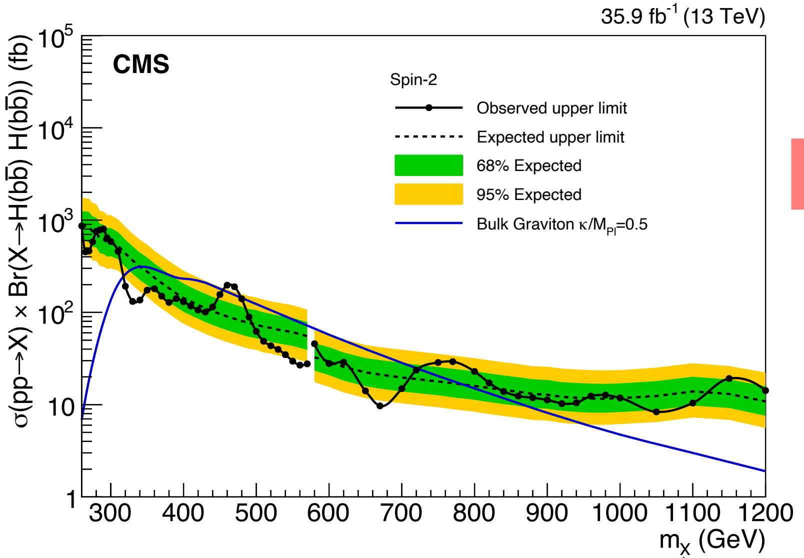
- **Low m_X**: bb pairs can be **resolved**
- **Intermediate m_X** (up to 2000 GeV): **one** pair treated as **resolved**, **one** as **merged**
- **High m_X**: pairs cannot be resolved, **two fully-merged**

X→HH→bbbb

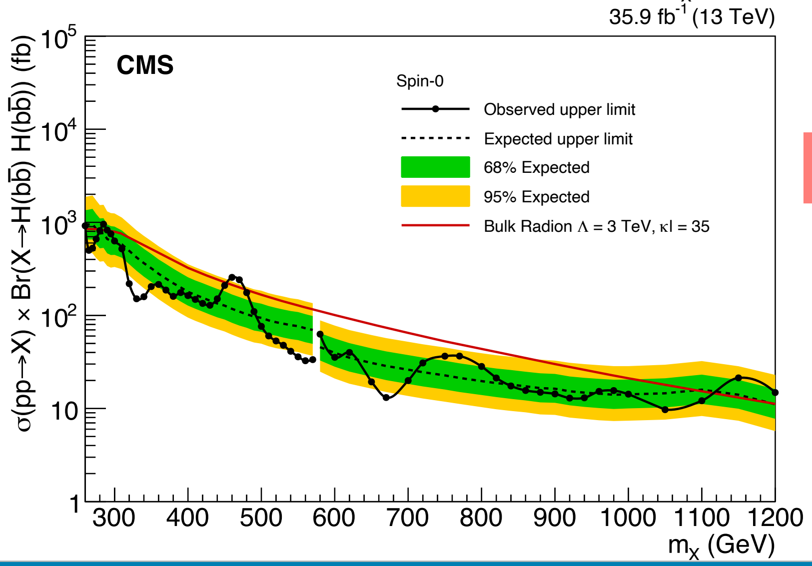
JHEP08(2018)152

- **Two main kinematic regions**:
  - **Low mass region**: 260 GeV to 620 GeV
  - **Medium mass region**: 550 GeV to 1200 GeV
- **4 jets**, of which at least **3 b-tagged**
- **BDT for b-jet energy regression**
- **Multijet background modelled from data** by parametric fits in sideband regions



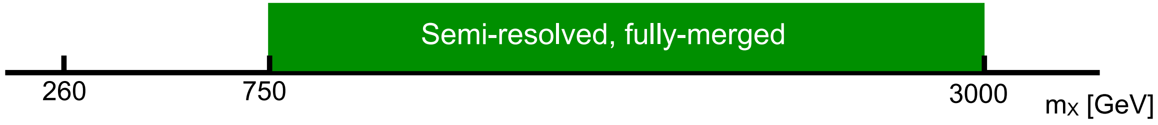


Bulk graviton



Radion

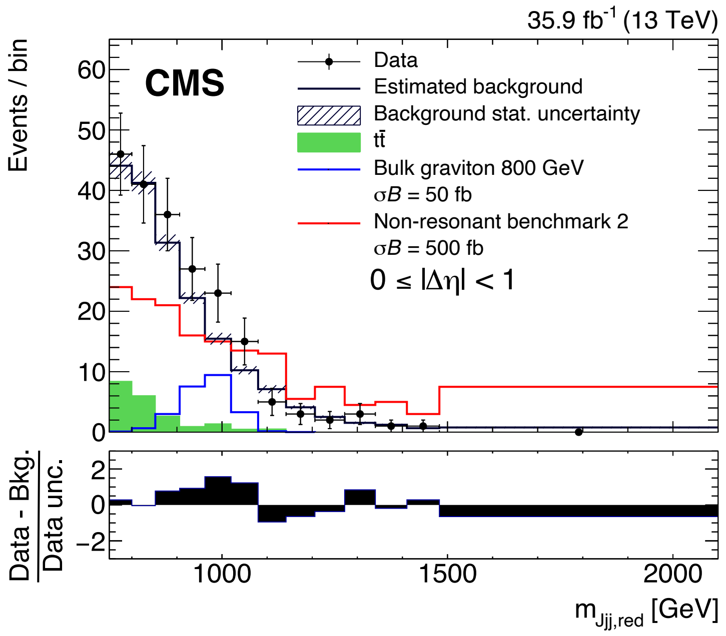
X→HH→bbbb



Semi-resolved

JHEP01(2019)040

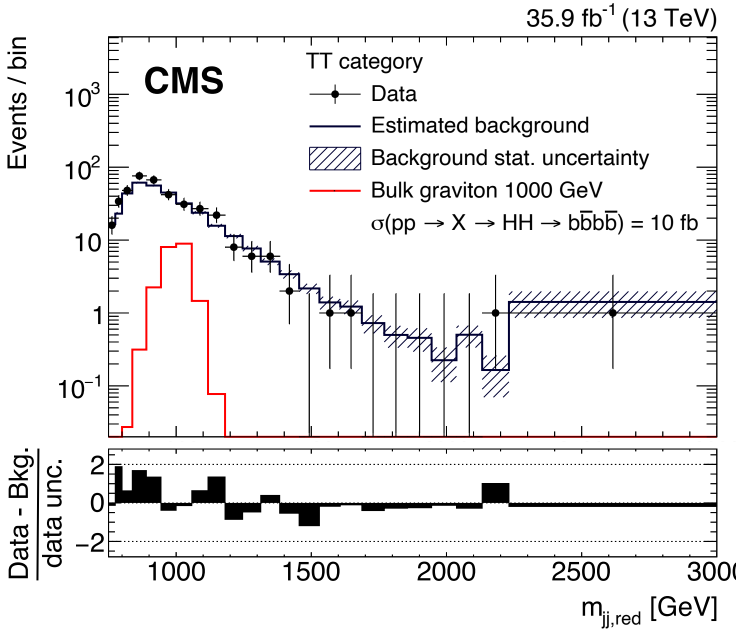
- 1 b-tagged fat-jet
- 2 b-tagged jets
- Two categories according to $\Delta\eta$ between the two jet structures (low is more signal-like)



Fully-merged

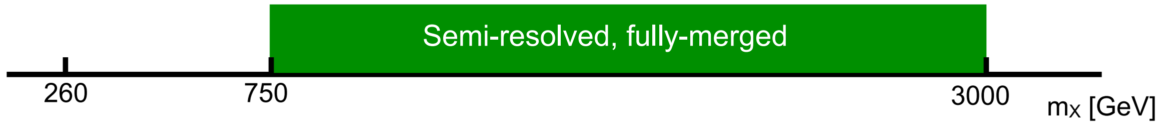
Phys.Lett.B 781 (2018)

- 2 b-tagged fat-jets
- Central jets selected
- Two categories according to double b-tagger value

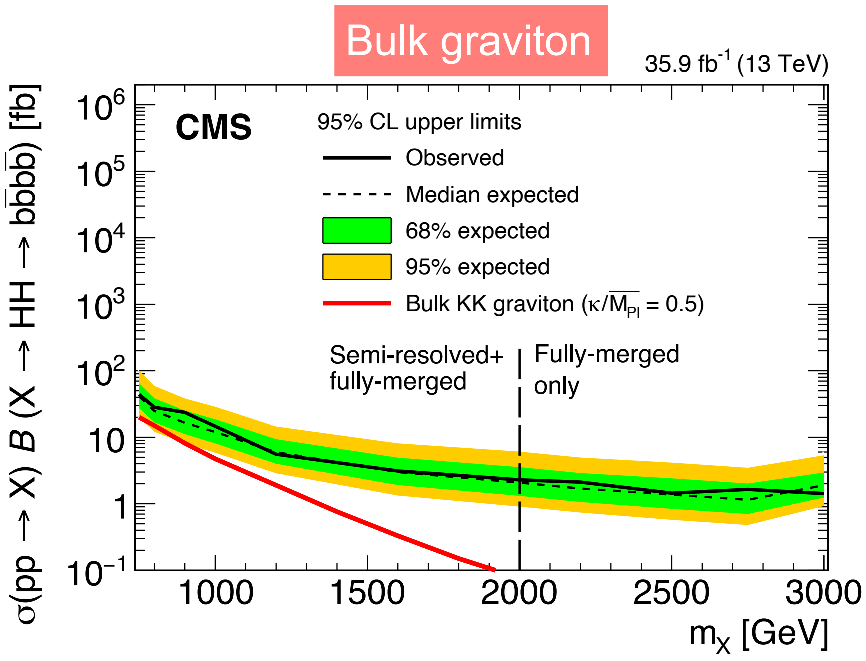


- **Discriminating variable** is **reduced di-Higgs invariant mass**
- **Main backgrounds**: **multijet** (data-driven), **tt+jets**

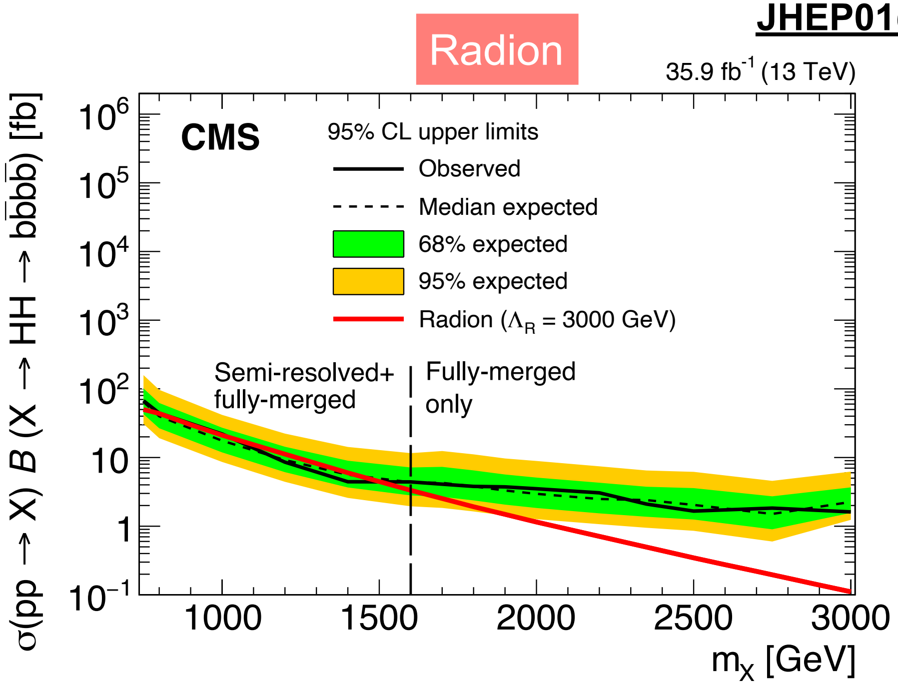
X→HH→bbbb



- **Results** from the two searches are **combined**



JHEP01(2019)040

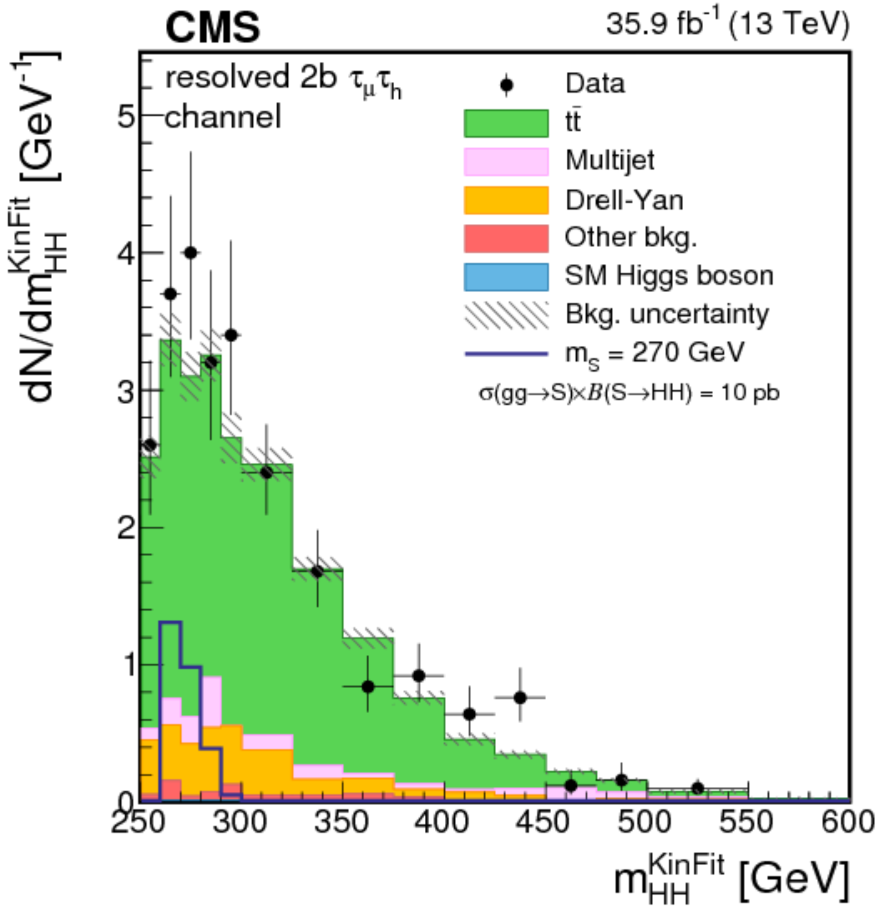


- Below 2 TeV, the sensitivity improves up to 18% (55%) for graviton (radion) w.r.t. fully-merged analysis
- Above 2 (1.6) TeV for graviton (radion), no sensitivity gain from semi-resolved analysis

X→HH→bb $\tau\tau$

- Select events with **one isolated** τ_{had} and a **second lepton** of opposite charge (**e, μ,** τ_{had})
- **Events categorised** according to **number of b-jets**
- **Main backgrounds: tt, DY** (from sim.), **multijet** (data-driven)
- **BDT** used to **discriminate against tt**
- Search for excess in m_{HH} **from kinematic fit**

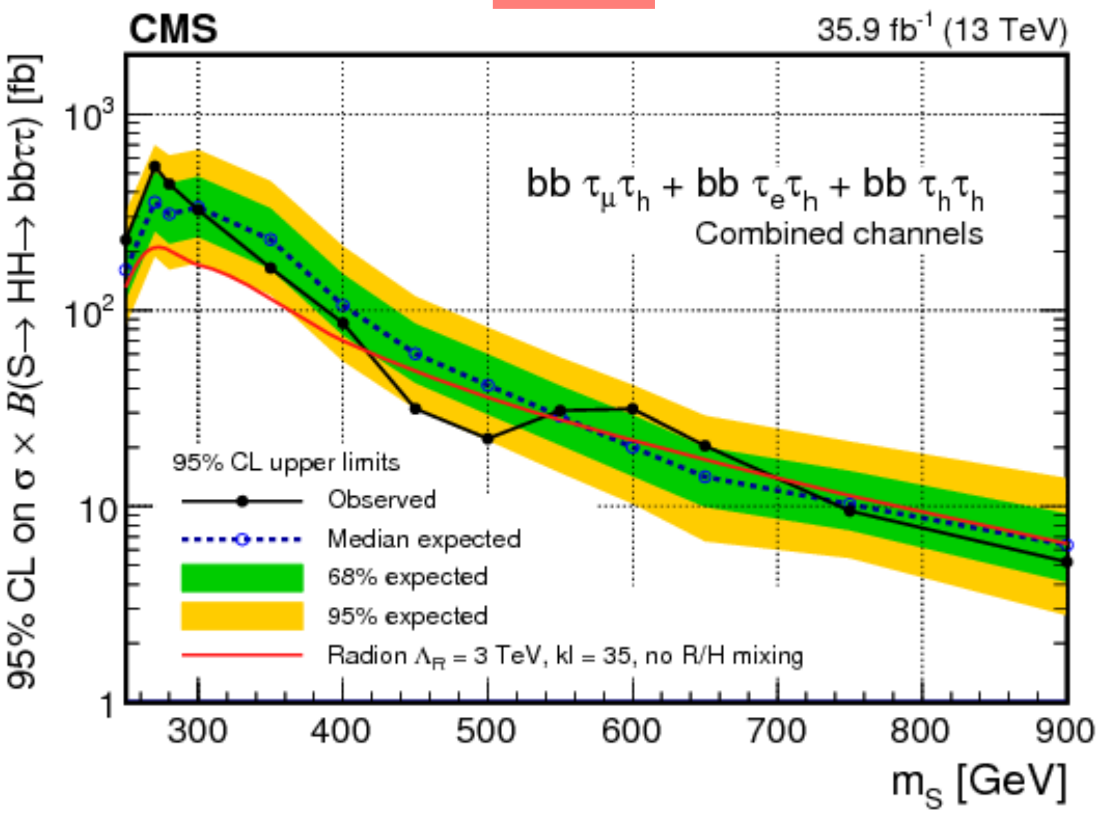
Phys. Lett. B 778 (2018) 101



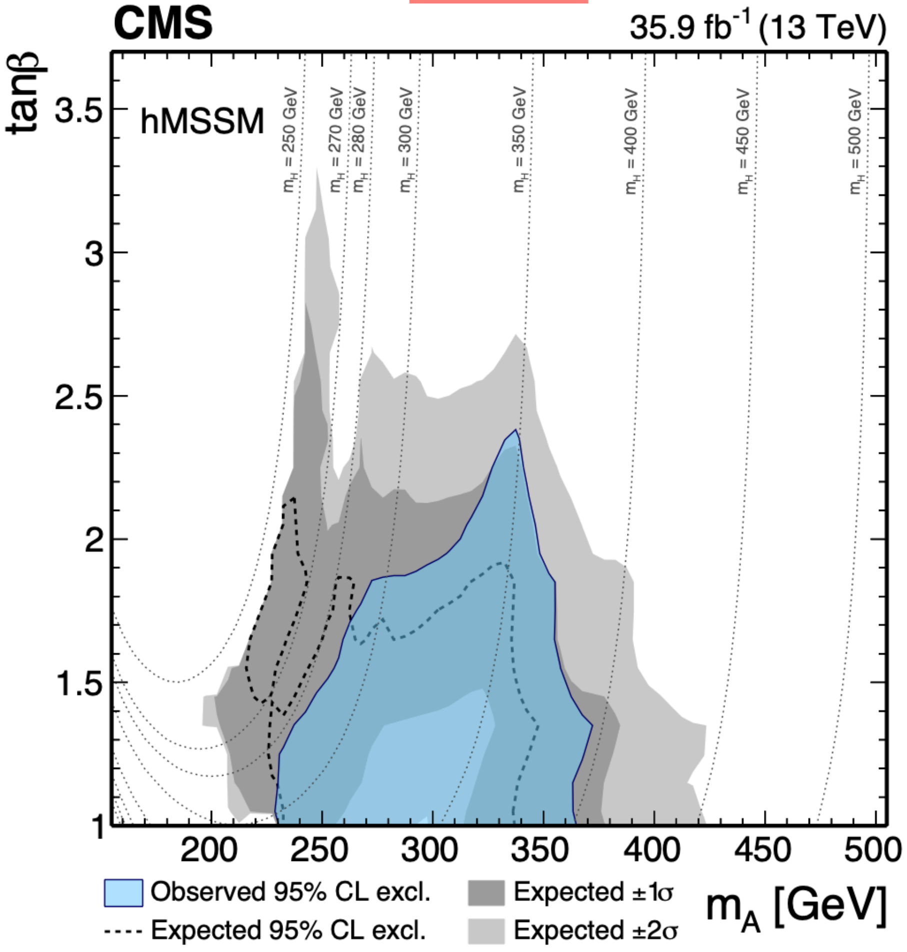
X→HH→bb $\tau\tau$

Phys. Lett. B 778 (2018) 101

Radion



hMSSM



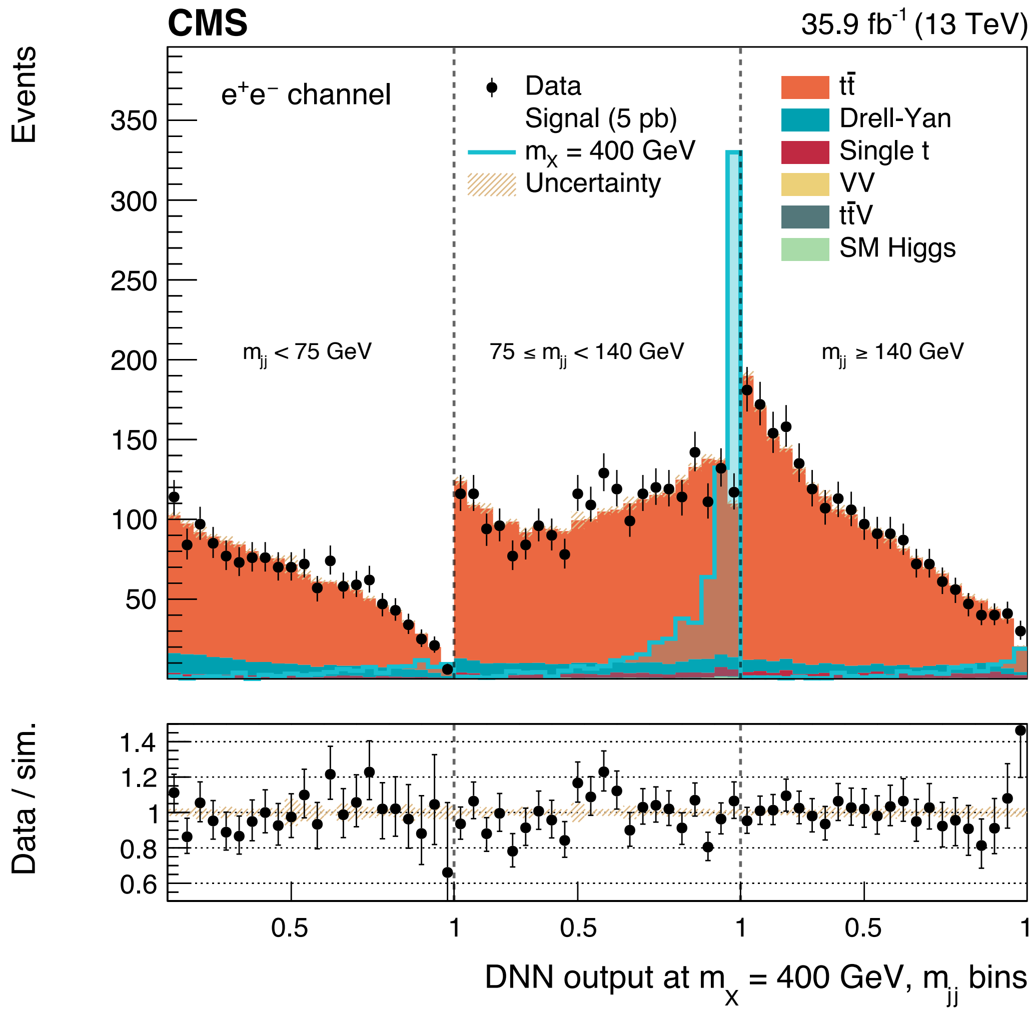
m_A in 230—360 GeV and up to tanβ ~ 2 excluded at 95% CL

X→HH→bb VV

VV→2ℓ2ν, V=Z,W

JHEP01(2018)054

- Events can come from **WW***→ℓν ℓν or **ZZ***→νν ℓℓ
- Require **two isolated and opposite-sign leptons** and **two b-tagged jets**
- Categorisation according to lepton flavours and m_{jj}
- **Backgrounds: tt** (from sim.), **DY** (data-driven)
- **Parametric DNN** to scan over different m_X
- **DNN output** as **final discriminant**

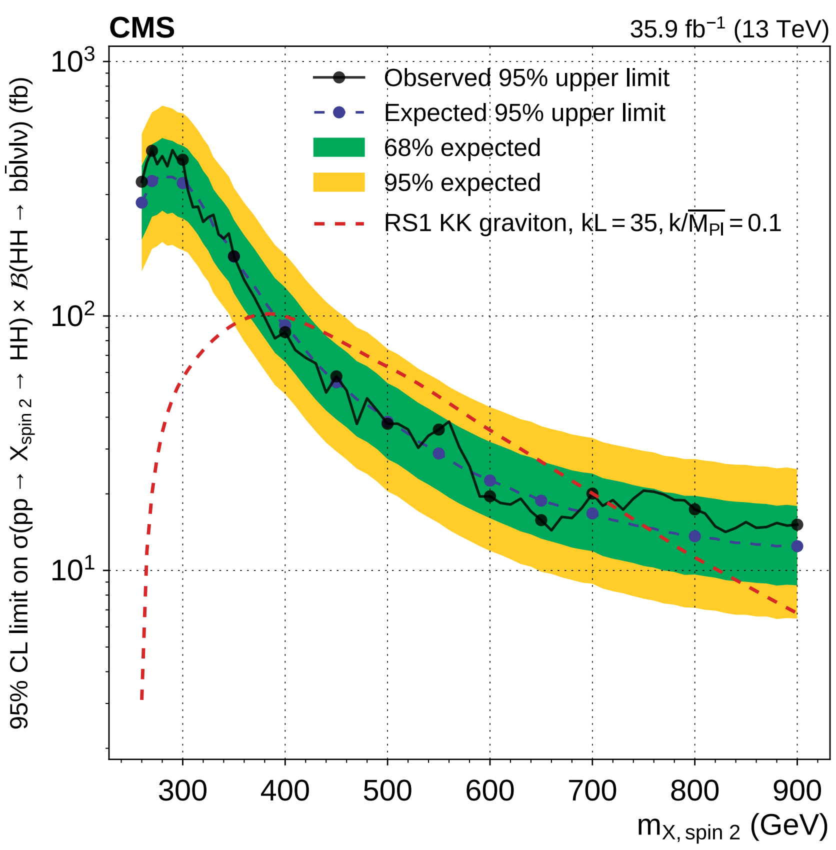


X→HH→bb VV

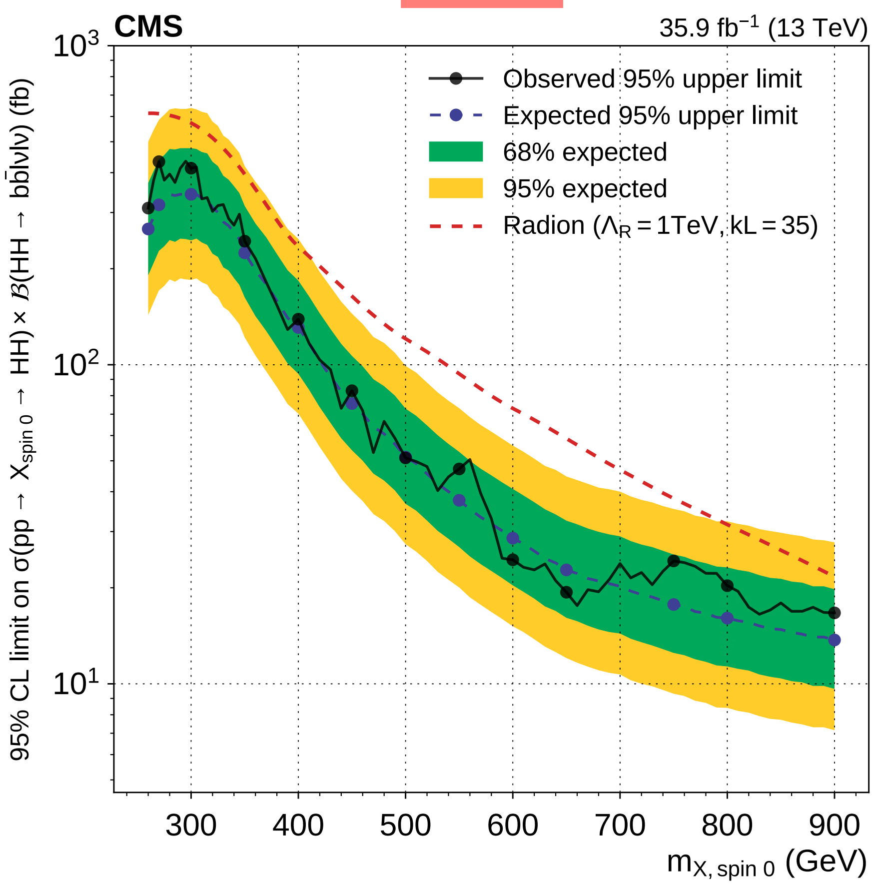
VV→2ℓ2ν, V=Z,W

JHEP01(2018)054

Bulk graviton



Radion

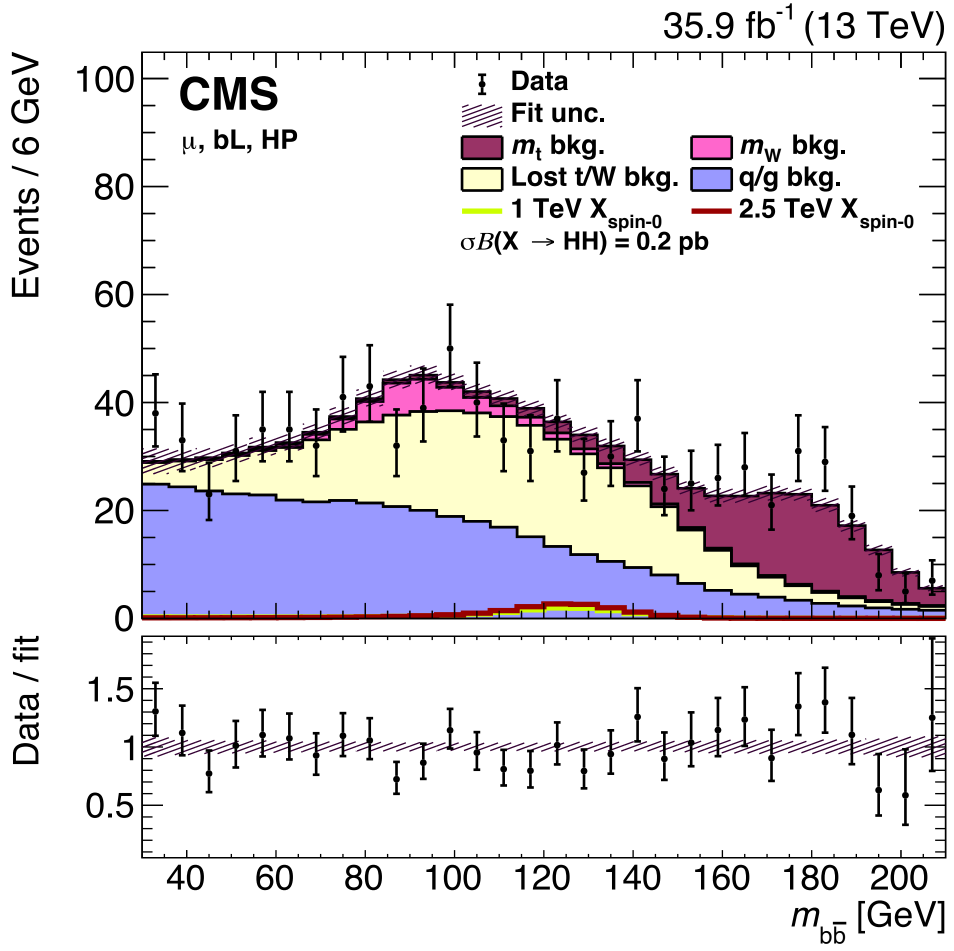


X→HH→bb VV

WW*→qq'ℓν

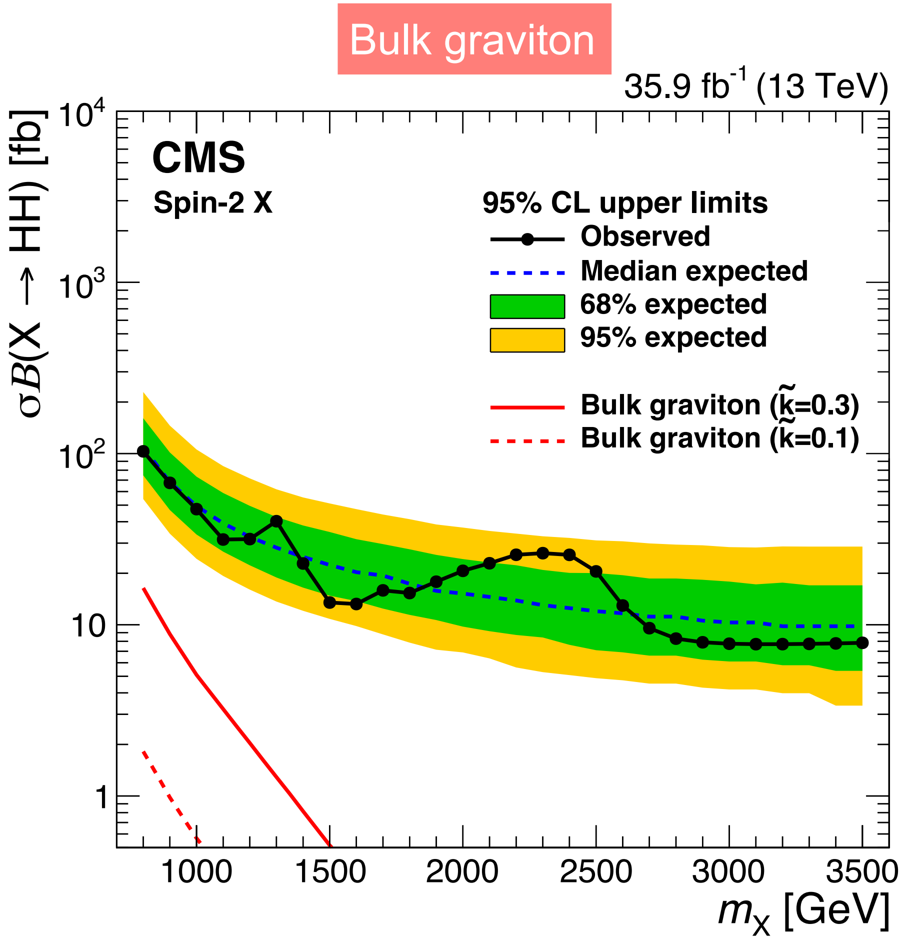
JHEP10(2019)125

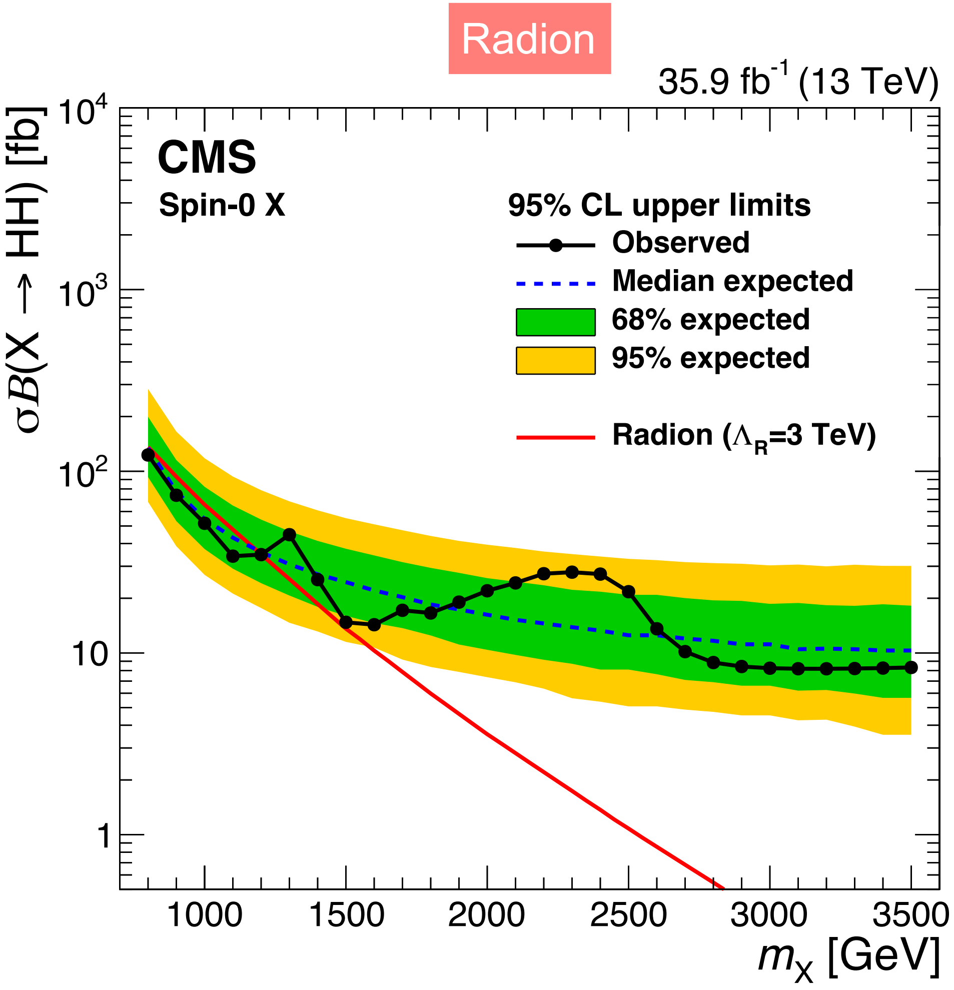
- **b-quark pair** reconstructed as **single jet**
- Require **one isolated lepton nearby** jet of **merged W→qq'** decay products
- Main background: tt, suppressed by reconstructing the HH decay chain and applying mass constraints
- **2D distribution of m_{bb} and m_{HH} used to extract limits**



X→HH→bb VV

WW*→qq'ℓν



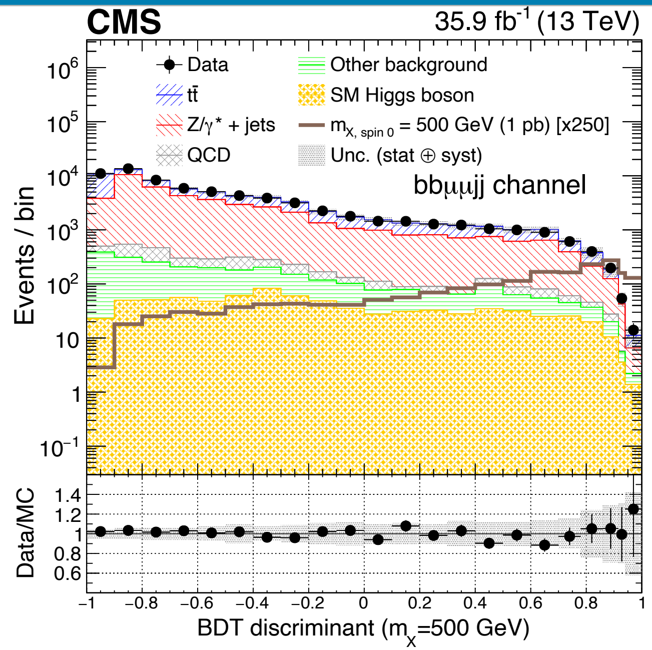


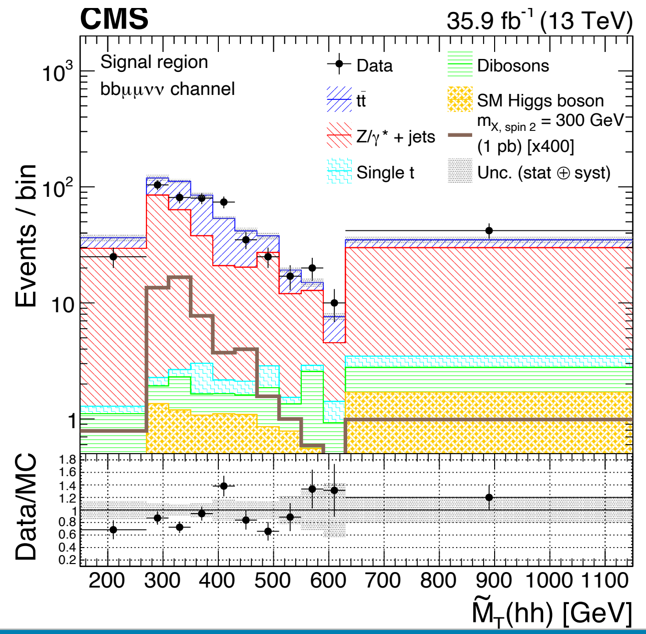
X→HH→bb VV

ZZ*→ℓℓ qq,νν

arXiv:2006.06391

- **First search where Z decays hadronically**
- **Main backgrounds**: **DY+jets** and **tt (multijet)** (data-driven)
- **bbℓℓqq**
  - assign jets to Z and H according to b-tag discriminant and H mass constraint
  - **BDT to discriminate against multijet background**
  - Search for excess in **BDT discriminant distribution**
- **bbℓℓνν**:
  - $m_{\ell\ell}$ > 76 GeV to reduce contribution from bbWW search
  - Search for excess in **HH transverse mass distribution**





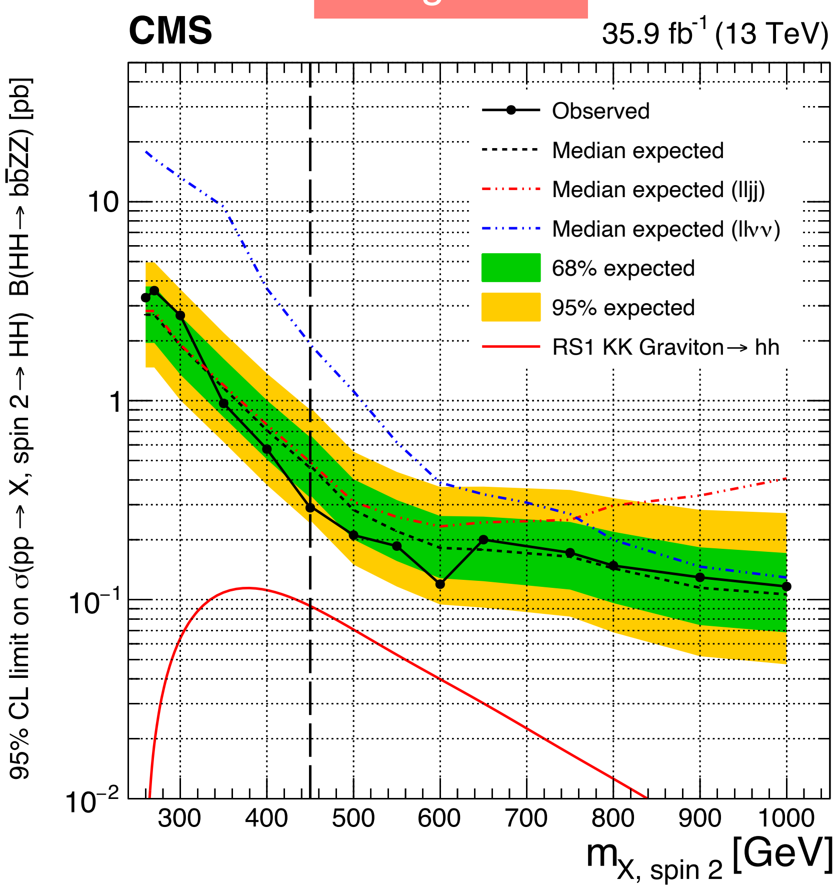
X→HH→bb VV

ZZ*→ℓℓ qq,νν

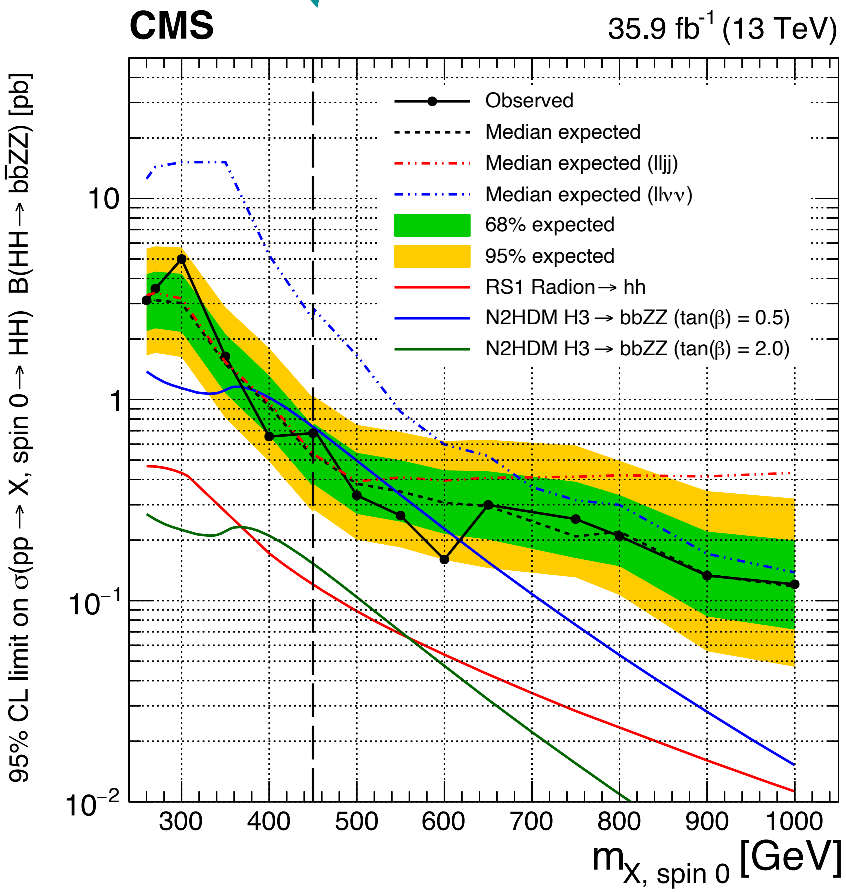
bbℓℓqq and bbℓℓνν combined

arXiv:2006.06391

Bulk graviton



Radion and N2HDM!

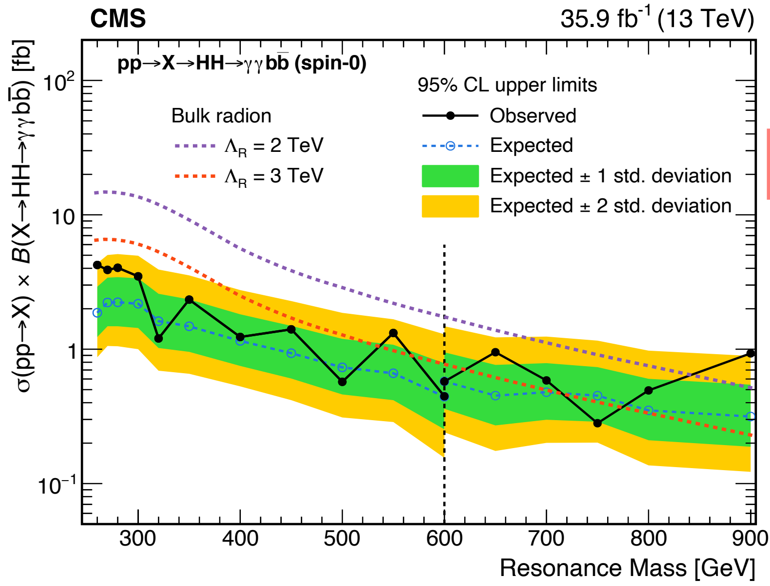


Interpretation also in Exotic Higgs scenario, first time in this analysis!

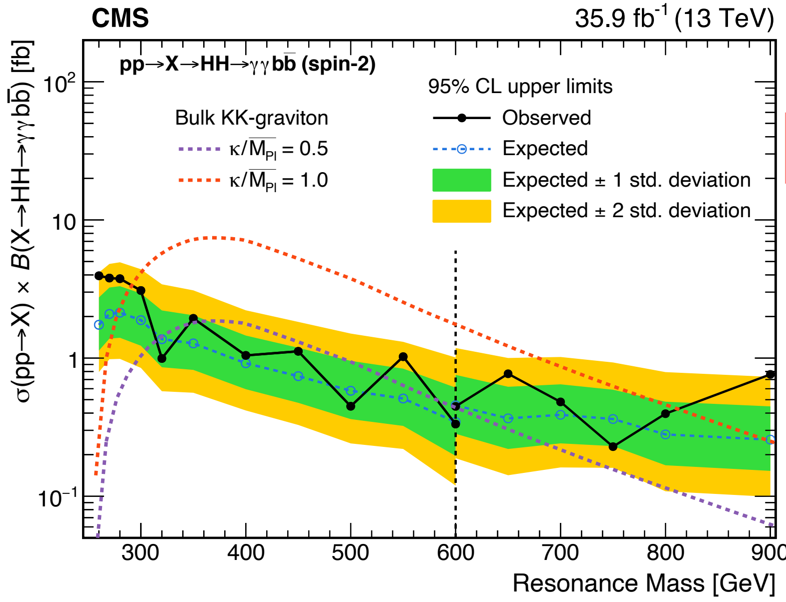
X→HH→bb γγ

- Select events with **two identified photons** and **two b-jets**
- **Categorisation** according to **BDT discriminant** and **HH reduced mass**
- **2D signal extraction** from parametric fit of m_{jj} and $m_{\gamma\gamma}$
- Main **background**: **(γ)γ + jets**, data-driven

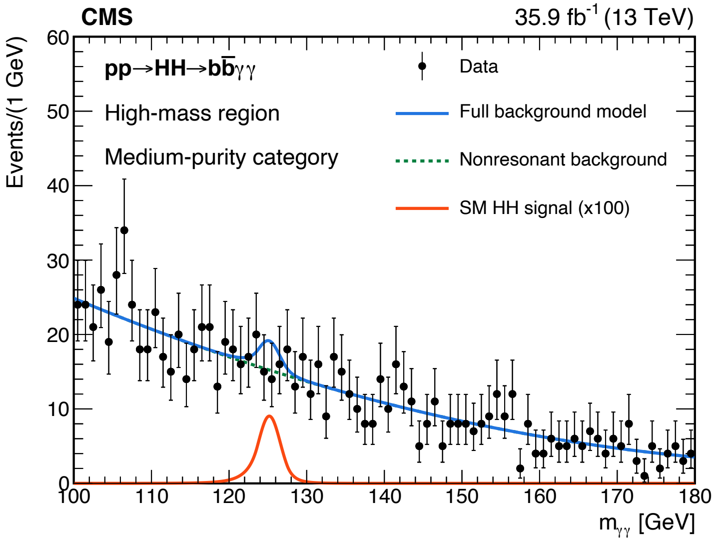
Phys. Lett. B 788 (2019) 7

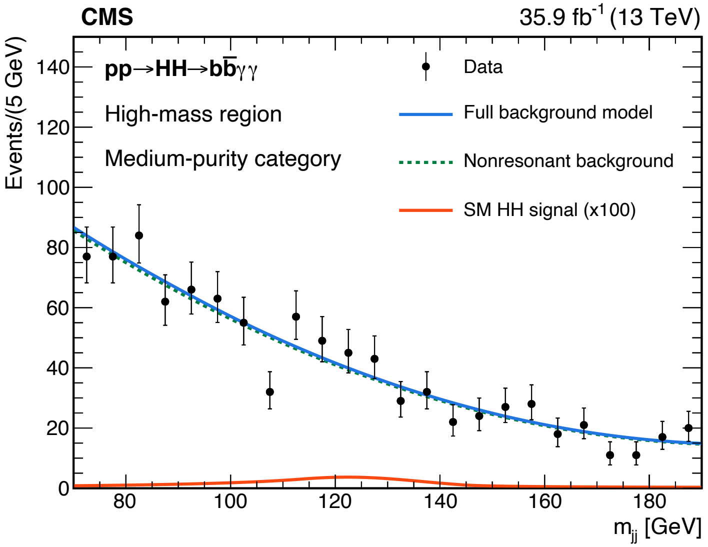


Radion



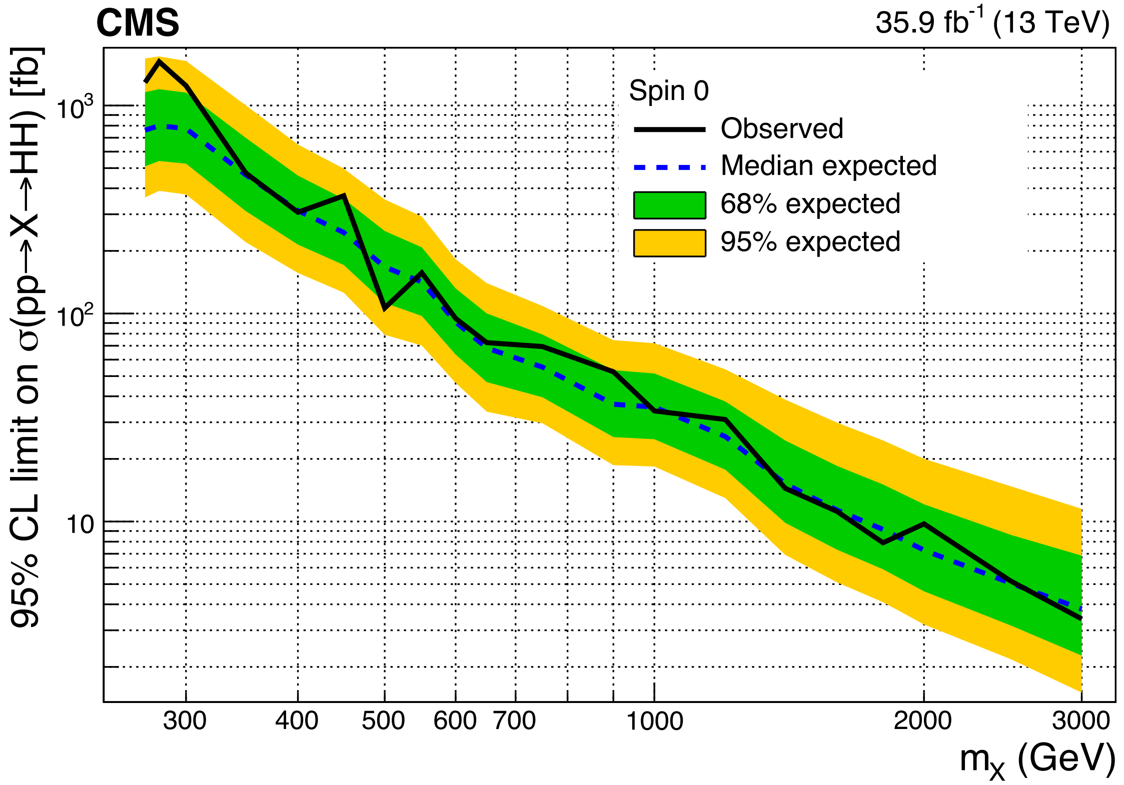
Bulk graviton





X→HH combination

Combination performed on bb bb, bb WW/ZZ → bb $\ell\nu\ell\nu$, bb $\tau\tau$, bb $\gamma\gamma$



Phys. Rev. Lett. 122, 121803

Conclusions

- **Resonant di-Higgs** production is **fundamental** in search for new physics
- **BSM** models predict **cross section enhancement**
- **Large variety of final states investigated**: trade-off between BR and purity
- **Important to explore** and **combine** many decay channels
- The **CMS** Collaboration has delivered **excellent results with 2016 data**
- We all look forward to **more results** from searches on **full Run II** data
- Stay tuned!

Conclusions

- **Resonant di-Higgs** production is **fundamental** in search for new physics
- **BSM** models predict **cross section enhancement**
- **Large variety of final states investigated**: trade-off between BR and purity
- **Important to explore** and **combine** many decay channels
- The **CMS** Collaboration has delivered **excellent results with 2016 data**
- We all look forward to **more results** from searches on **full Run II** data
- Stay tuned!

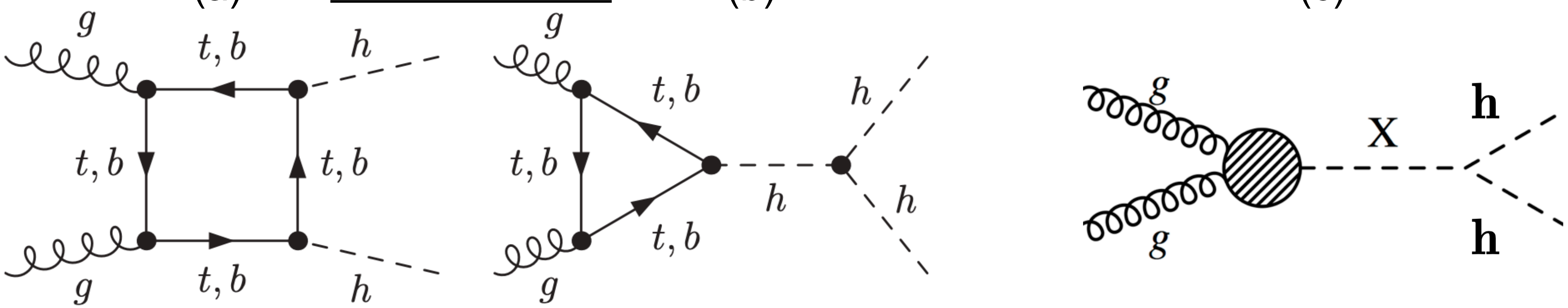
THANK YOU FOR YOUR ATTENTION

Backup slides

HH production

- Production dominated by gluon-fusion

(a) arXiv:1610.07922 (b) (c)



- Destructive interference between the heavy-quark square loop (a) and the Higgs self-coupling (b) production modes
- BSM Higgs boson pair production could proceed through changes to the Higgs couplings, for example the $t\bar{t}H$ or HHH couplings which contribute to (a) and (b), or through an intermediate resonance, X, which could, for example, be produced through a quark loop (c)

Channel	$\mathcal{B}$ [%]
bbbb	33.6
$bb\tau\tau$	7.3
$bbWW(\ell\nu\ell\nu)$	1.7
$bb\gamma\gamma$	0.26
$bbZZ(\ell\ell\ell\ell)$	0.015

Warped Extra Dimension formulation

- One small spacial extra dimensions where the SM particles are not allowed to propagate through it
- Resonant particle produced can be
  - **radion** (spin-0): production cross section proportional to $1/\Lambda_R$, Λ_R=interaction scale parameter of the theory; other free parameter: kL, with k constant appearing in the metric of the theory and L size of the extra dimension
  - **graviton** (spin-2): free parameter is k
- Main process is gluon-gluon fusion

X→HH→bbbb

JHEP08(2018)152

- b-jets randomly paired, then choose Higgs candidates:
  - **Low mass region**: $|m_H - 120\ \text{GeV}| < 40$ GeV
  - **Medium mass region**: $\Delta R < 1.5$
- Circular SR around Higgs mass in 2D phase space
- Di-jet inv. mass resolution for mH1 and mH2 is up to 13%
- Further improved by applying regression to estimate a correction for the jet energy, computed for individual b-jets
  - BDT trained on simulated b-jets from tt events
- Average improvement in the Higgs boson mass resolution, measured with simulated signal samples, is 6–12%, depending on the p_T of the reconstructed Higgs boson.
- Improves sensitivity up to 20%, depending on the mass hypothesis
- Local p-value of most significant excess (deficit) is 2.6 (-3.6) std. dev.
  - LEE -> global p-value in percent range

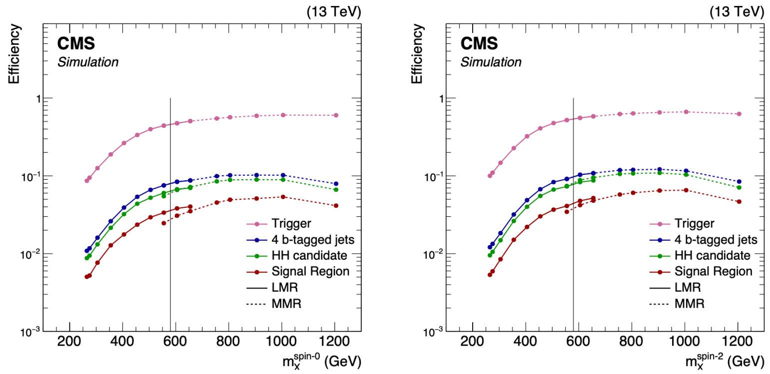
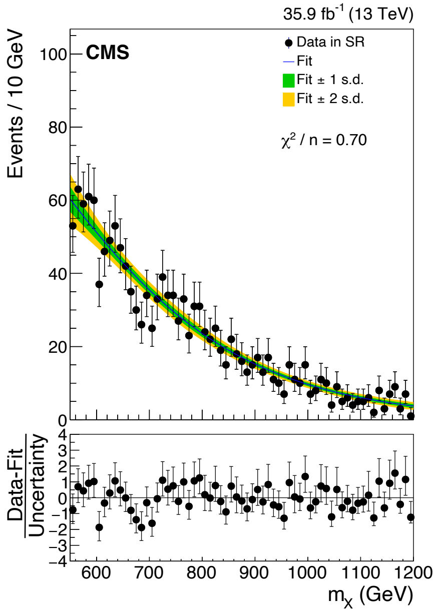
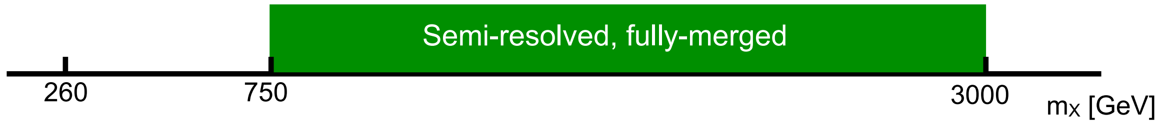


Figure 1: The selection efficiency for simulated $X \to H(b\bar{b})H(b\bar{b})$ events for a spin-0 radion (left) and a spin-2 bulk KK-graviton (right), at different stages of the event selection for each mass hypothesis, for the low-mass region (solid) and the medium-mass region (dashed). The vertical line at 580 GeV corresponds to the transition between the LMR and MMR regions.

m_X in MMR



X→HH→bbbb



Semi-resolved

JHEP01(2019)040

- 1 b-tagged AK8 jet J
- 2 b-tagged AK4 jets j_1, j_2
- $105 < m_J < 135$ GeV, $90 < m_{j1,j2} < 140$ GeV
- Two categories according to $|\Delta\eta(J, j_1+j_2)|$ (low is more signal-like)

Fully-merged

Phys.Lett.B 781 (2018)

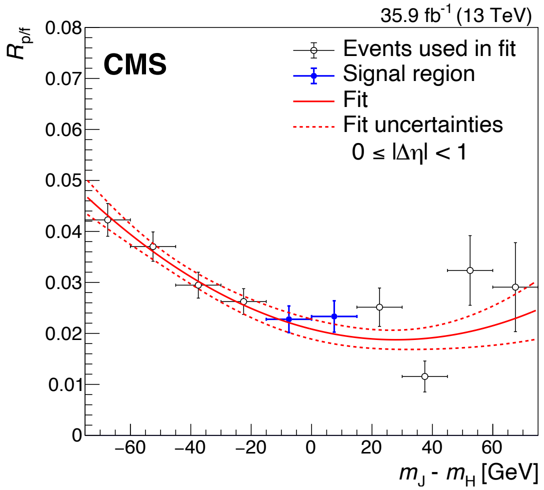
- 2 b-tagged AK8 jets J_1, J_2, highest p_T
- Central jets: $|\Delta\eta(J_1, J_2)| < 1.3$
- $105 < m_{J1}, m_{J2} < 135$ GeV
- Two categories according to double b-tagger value

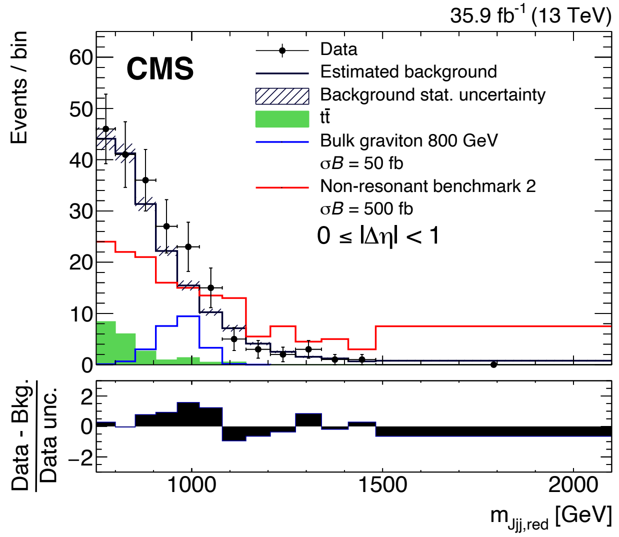
Main backgrounds:

- **multi-jets (90%)**, estimated from data
- **tt+jets (10%)**, estimated from MC

Reduced di-Higgs invariant mass to correct for fluctuations from jet mass resolution -> improvement of up to 10% in HH mass resolution:

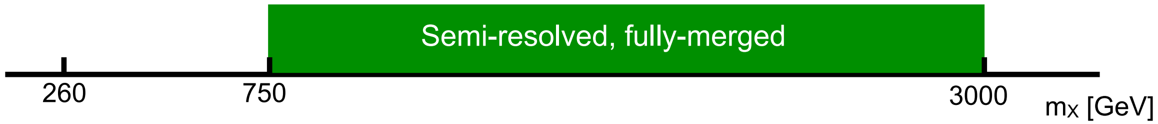
- $\mathbf{m_{Jjj,red} = m_{Jjj} - (m_J - m_H) - (m_{jj} - m_H)}$ — semi-resolved
- $\mathbf{m_{JJ,red} = m_{JJ} - (m_{J1} - m_H) - (m_{J2} - m_H)}$ — fully-merged



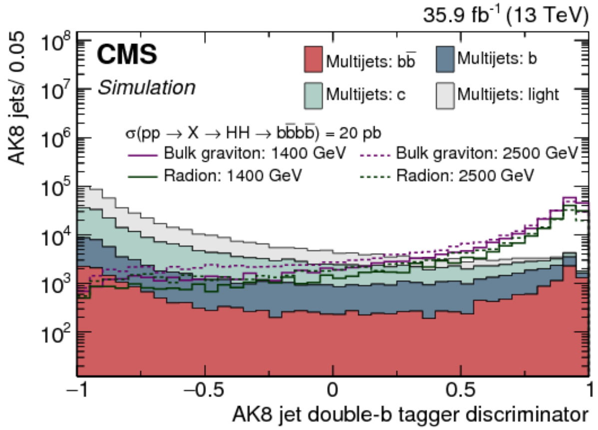


Radion has higher S/N in low DeltaEta because of the angular distribution of its decay products —> improvement up to 55% w.r.t. fully-merged

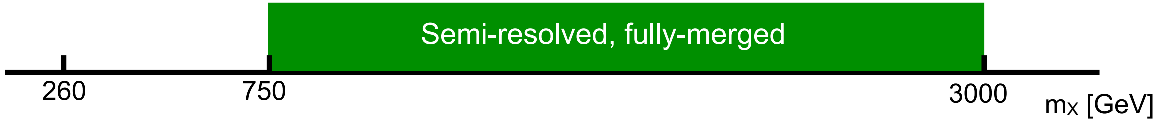
X→HH→bbbb



- Semi-resolved events passing fully-merged criteria are dropped to ensure statistical independence
- Reduced di-Higgs mass **corrects fluctuations** from jet mass resolution —> **10% improvement** in HH mass resolution
- Below 2 TeV, the sensitivity improves up to 55% for radion w.r.t. fully-merged analysis thanks to the DeltaEta categorisation: radion has higher S/N in low DeltaEta because of the angular distribution of its decay products



X→HH→bbbb



JHEP01(2019)040

Bulk graviton

Mass (GeV)	Obs. lim. (fb)	Exp. lim. (fb)	+Exp (68%) (fb)	-Exp (68%) (fb)	+Exp (95%) (fb)	-Exp (95%) (fb)
750	43.9	41.0	27.4	64.8	19.6	101
800	28.2	24.9	16.7	38.5	12.1	59.2
900	23.6	16.4	11.1	25.2	8.1	38.4
1000	14.6	11.9	8.0	18.6	5.9	28.8
1200	5.5	5.9	3.9	9.3	2.9	14.5
1600	3.1	3.0	1.9	4.9	1.3	8.1
2000	2.2	2.0	1.3	3.5	0.9	6.1
2500	1.4	1.4	0.8	2.4	0.5	4.2
3000	1.4	1.9	1.2	3.0	0.9	5.3

Table 4. The observed and expected upper limits on the products of the cross sections and branching fraction $\sigma(\mathrm{pp} \to \mathrm{X})B(\mathrm{X} \to \mathrm{HH} \to \mathrm{b\bar{b}b\bar{b}})$ for a bulk graviton from the combination of the fully-merged and semi-resolved channels (where the events used in the fully-merged analysis are not considered in the semi-resolved analysis). Results above 2000 GeV are taken directly from the fully-merged analysis [39].

Radion

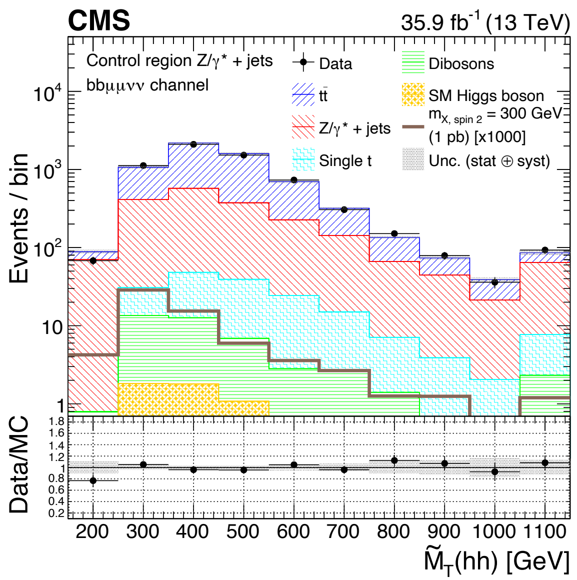
Mass (GeV)	Obs. lim. (fb)	Exp. lim. (fb)	+Exp (68%) (fb)	-Exp (68%) (fb)	+Exp (95%) (fb)	-Exp (95%) (fb)
750	67.0	64.5	42.8	101	30.9	158
800	44.3	39.8	26.6	62.2	19.1	96.8
900	31.2	28.6	19.8	43.1	15.9	65.1
1000	22.0	17.5	11.8	27.1	8.6	41.8
1200	8.5	9.1	6.1	14.3	4.4	22.3
1600	4.4	4.3	2.8	7.1	1.9	11.6
2000	3.5	3.0	1.8	5.1	1.3	8.9
2500	1.7	2.0	1.3	3.6	0.8	6.1
3000	1.6	2.3	1.6	3.7	1.2	6.2

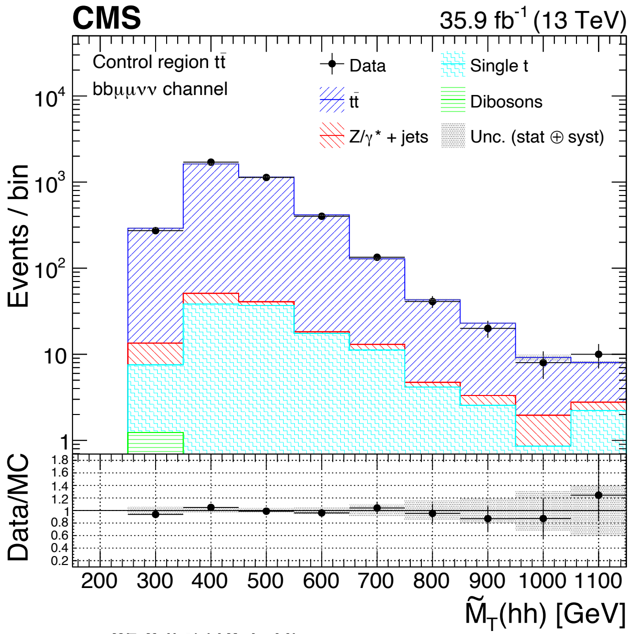
Table 5. The observed and expected upper limits on the products of the cross sections and branching fraction $\sigma(\mathrm{pp} \to \mathrm{X})B(\mathrm{X} \to \mathrm{HH} \to \mathrm{b\bar{b}b\bar{b}})$ for a radion from the combination of the fully-merged and semi-resolved channels (where the events used in the fully-merged analysis are not considered in the semi-resolved analysis). Results above 1600 GeV for the radion are taken directly from the fully-merged analysis [39].

HH->bbZZ

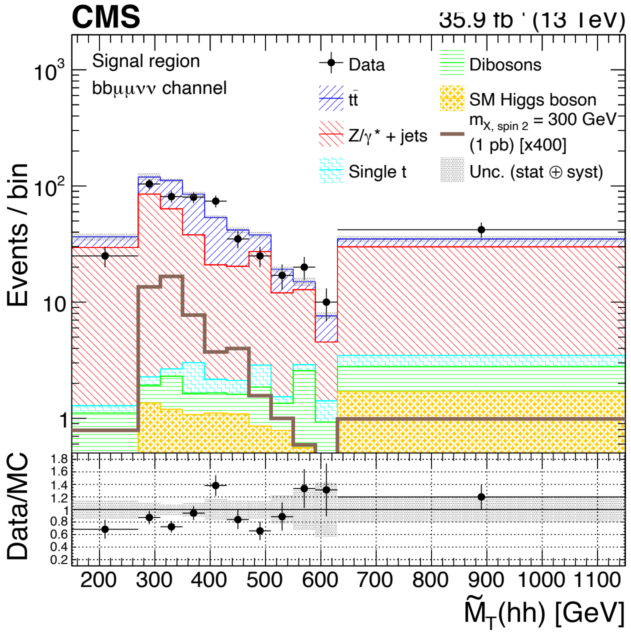
$ZZ^* \to \ell\ell\ \nu\nu$

arXiv:2006.06391

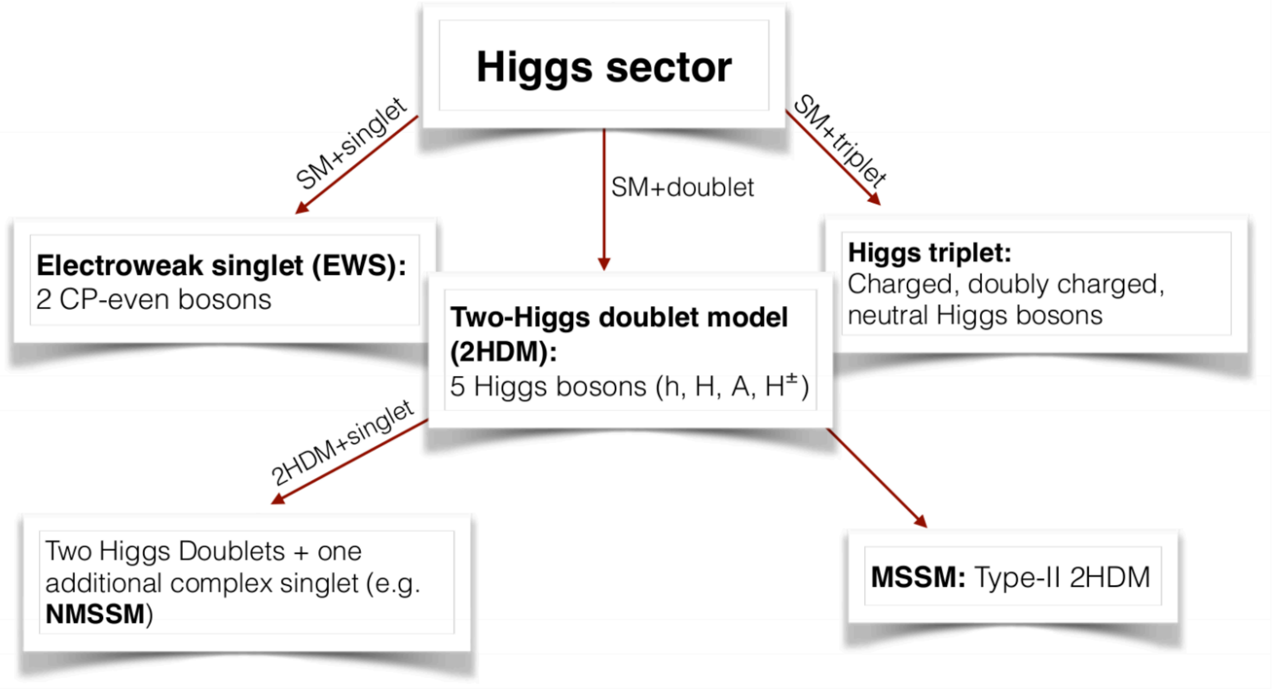




- mll > 76 GeV to reduce contribution from HH->bbWW, search is orthogonal to previous one
- **SR**: 70 < mll < 106 GeV && 90 < mbb < 150 GeV
- **DY-enriched CR**: 70 < mll < 106 GeV && (mbb < 90 GeV OR mbb > 150 GeV)
- **tt-enriched CR**: mll > 106 GeV && 90 < mbb < 150 GeV
- First Higgs reconstructed from b-jets, second from leptons and MET
- Mass-dependent cut on pTmiss to reduce contribution from DY+jets, QCD, ZH
- For further discrimination: BDTs trained in each lepton channel, spin hypothesis and mass range (250–450GeV, >450GeV)
  - Minimum BDT value required for candidates in the signal region
- DY+jets (tt): estimated from simulated events normalised to data in Z-(tt-)enriched region
- Transverse mass: $\widetilde{M}_{\mathrm{T}}(\mathrm{hh}) = \sqrt{E^2 - p_z^2}$ with E and pz of Lorentz-vector of HH candidate



Higgs sector extension: N2HDM



- Enhancement of HH cross section can be produced in the N2HDM: 2HDM + real singlet
- Broken phase: both the Higgs doublets and the singlet acquire vev
- Mixing between these states produces 3 *CP*-even Higgs bosons H_1, H_2, and H_3, with masses that are free parameters of the model
- Consider the nearly mass-degenerate case: masses of H_1 and H_2 are constrained to the experimental measurements of the h125 mass, but may give rise to manifestly non-SM-like rates in the case of hh production
- Higgs boson cascade decays: H_3 can decay to any combination of bosons H_1 and H_2, which then both can have different decay branching fractions compared to the SM Higgs boson.
- The model spectrum depends on:
    - the ratio of the vevs of the two Higgs doublets tan β, low values of which enhance H_3 production
    - the vev of the singlet, which affects the decay branching fractions of H_3 to H_1 and H_2
    - three mixing angles, which determine the decay branching fractions of H_1 and H_2

X→HH→bb γγ

Phys. Lett. B 788 (2019) 7

- Reduced mass: $\widetilde{M}_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$
- BDT trained to increase discrimination power of signal-like events
- To make BDT output independent of $m_{\gamma\gamma}$ and m_{jj}, trained with ensemble of signal samples
- SM single Higgs background estimated from simulation (ggF, VBF, tt/bb associated)
- Categorization:

Table 3: Definition of high-purity category (HPC) and medium-purity category (MPC) for the resonant and nonresonant analyses.

Analysis	Region	Classification MVA	$\widetilde{M}_X$
Nonresonant	High-mass	HPC: MVA > 0.97 MPC: 0.6 < MVA < 0.97	$\widetilde{M}_X > 350$ GeV
	Low-mass	HPC: MVA > 0.985 MPC: 0.6 < MVA < 0.985	$\widetilde{M}_X < 350$ GeV
Resonant	$m_X > 600$ GeV	HPC: MVA > 0.5 MPC: 0 < MVA < 0.5	Mass window
	$m_X < 600$ GeV	HPC: MVA > 0.96 MPC: 0.7 < MVA < 0.96	Mass window

- Double-sided Crystal Ball used for parametrisation of 2D mass plane
- Ngamma+jets background estimated from mass sidebands
- Very sensitive analysis thanks to excellent diphoton mass resolution of the CMS experiment for this channel (1.6 GeV)