Searches for pair-production of Higgs bosons using with the CMS detector at the LHC

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On behalf of the CMS Collaboration

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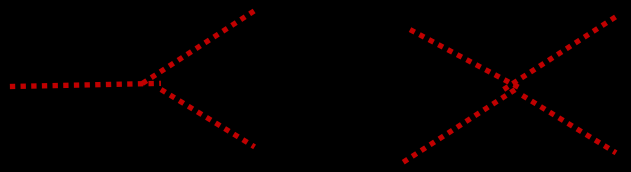
KU THE UNIVERSITY OF KANSAS

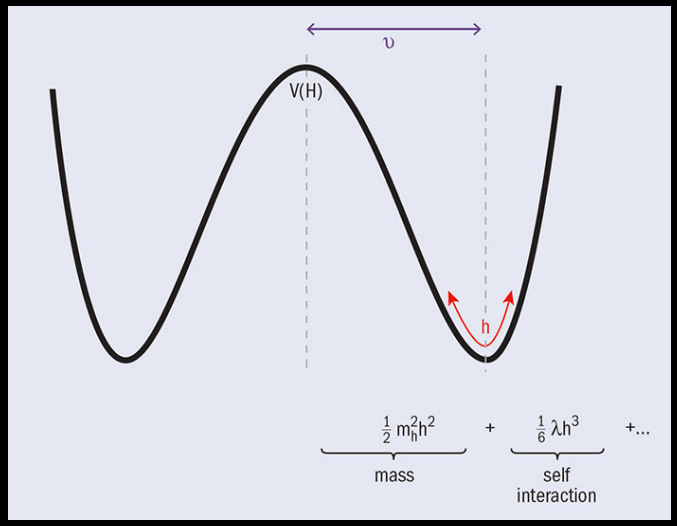
CMS Compact Muon Solenoid

HH in the SM

- $V(\phi) = -\mu^2\phi^2 + \lambda^2\phi^4$
- $= V_0 + \frac{1}{2}m_h^2h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$

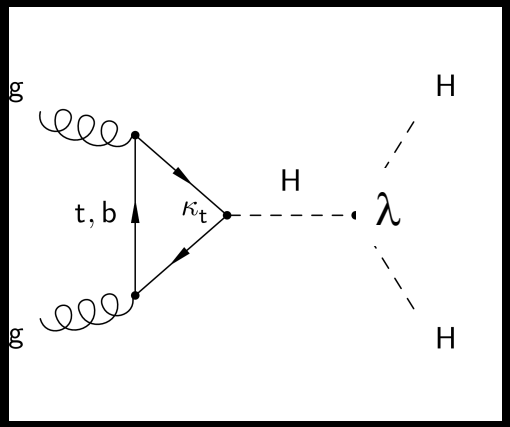


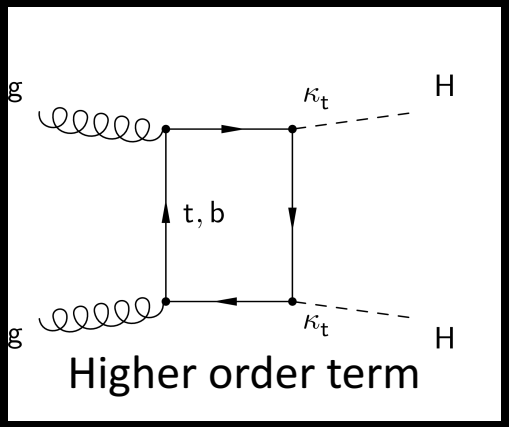
Trilinear coupling Quartic coupling



- Measurement of λ is a test of the standard model
- Can be measured using hh production

Di-Higgs non-resonant production





- Non-resonant production
  - Negative interference leads to low cross section

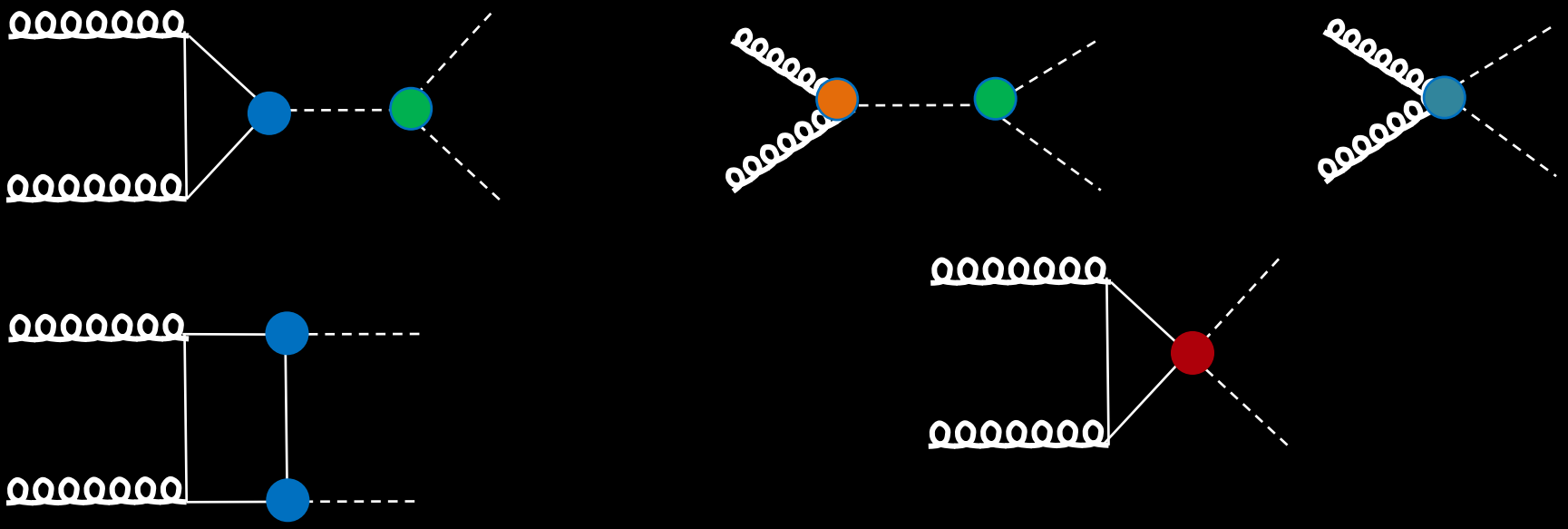
- $\sigma(pp \to hh)_{SM} = 33.45^{+4.3\%}_{-6.0\%}(scale) \pm 3.1\%\ (PDF)$
  - (LHC Higgs cross section WG yellow report)

- BSM contribution to non-resonant production: Composite Higgs, Little Higgs, etc.
  - Can modify the HH vertex

Di-Higgs non-resonant with BSM contribution

- EFT approach (doi:10.1103/PhysRevD.91.115008)

$$L_{hh} = \frac{1}{2}\partial_\mu \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3$$
$$- \frac{m_t}{v}\left(v + k_t h + \frac{c_2}{v} hh\right)(\bar{t_L} t_R + h.c.)$$
$$+ \frac{\alpha_S}{12}\left(c_{1g} h - \frac{c_{2g}}{2v} hh\right) G^A_{\mu\nu} G^{A\mu\nu}$$

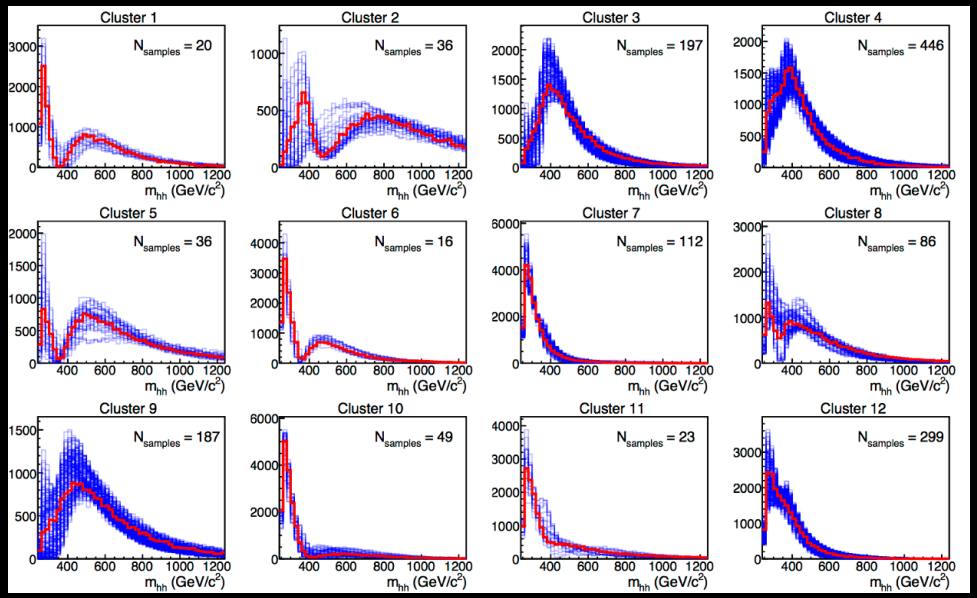


Interpreting non-resonant results

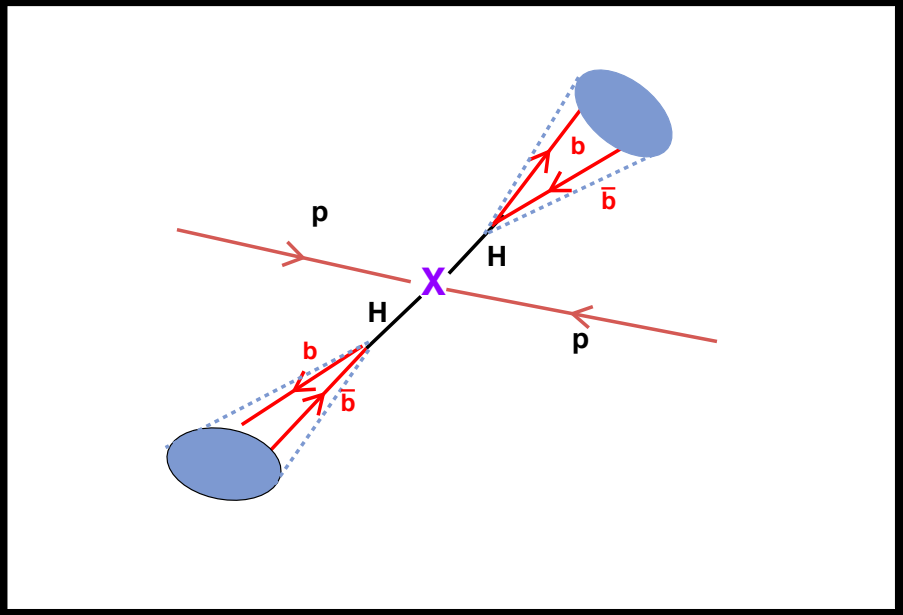
EFT parameters	κ_Λ	k_t	c_2	c_{1g}	c_{2g}
SM values	1	1	0	0	0

- **Connecting L_{hh}** to observables at the experiments
- Clusters in parameter space with similar Higgs boson kinematics (doi:10.1007/JHEP04(2016)126)

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	−1.0	0.0	0.0
2	1.0	1.0	0.5	−0.8	0.6
3	1.0	1.0	−1.5	0.0	−0.8
4	−3.5	1.5	−3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	−1
6	2.4	1.0	0.0	0.2	−0.2
7	5.0	1.0	0.0	0.2	−0.2
8	15.0	1.0	0.0	−1	1
9	1.0	1.0	1.0	−0.6	0.6
10	10.0	1.5	−1.0	0.0	0.0
11	2.4	1.0	0.0	1	−1
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

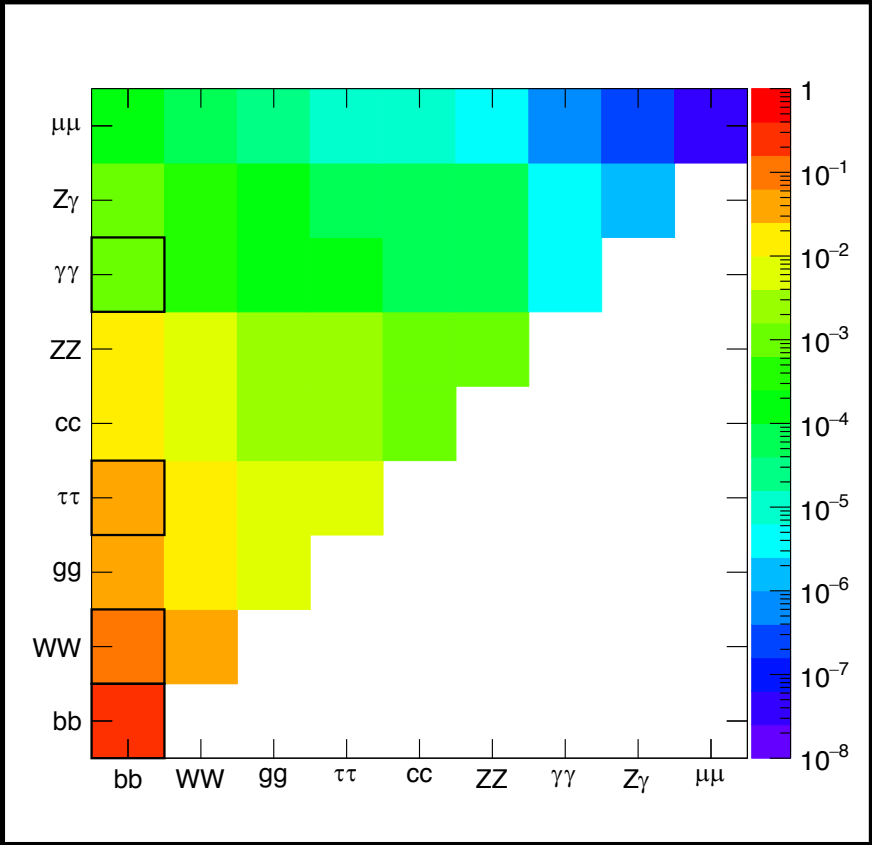


Di-Higgs resonant production



- Resonant production
  - BSMs with new contributions
  - KK graviton, radion, heavy higgs
  - Enhanced cross section

Explored final states

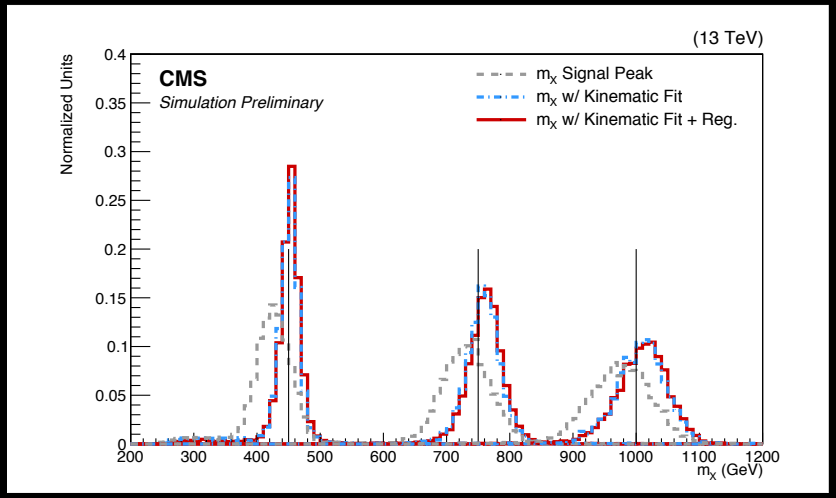


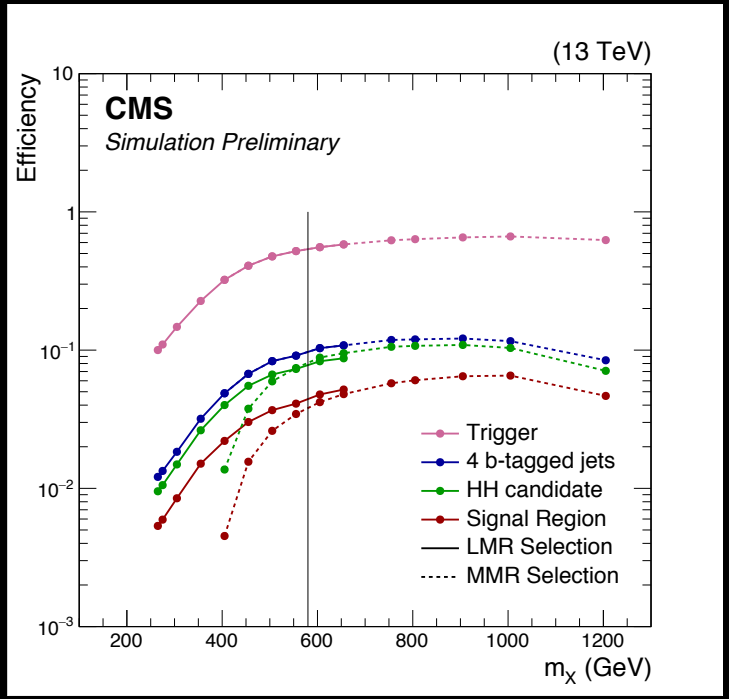
- bbbb:
  - Resolved
  - Boosted
- bbWW
- bbττ
  - Resolved
  - Boosted - Lisa's talk
- bbγγ

HH->4b resonant

HIG-17-009

- Low mass range: 260-1200 GeV
- High mass range: 750-3000 GeV
- H->bb mass resolution improved using a regression technique applied to the b jets.

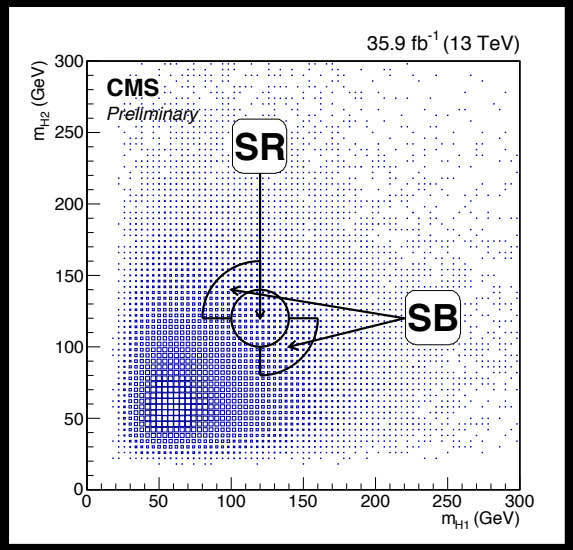




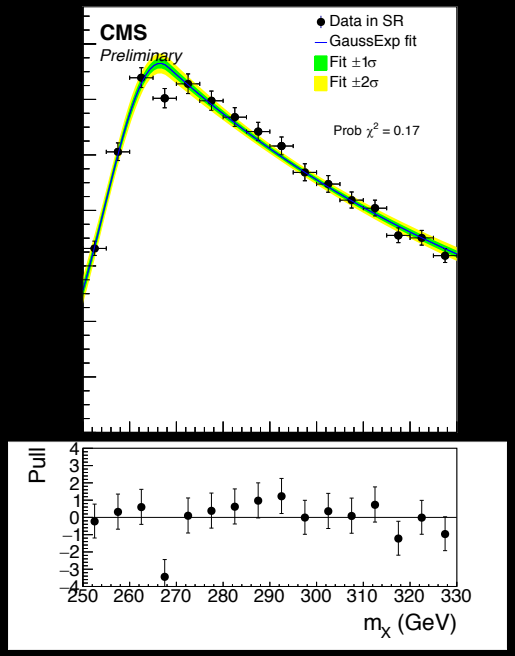
HH->4b resonant

HIG-17-009

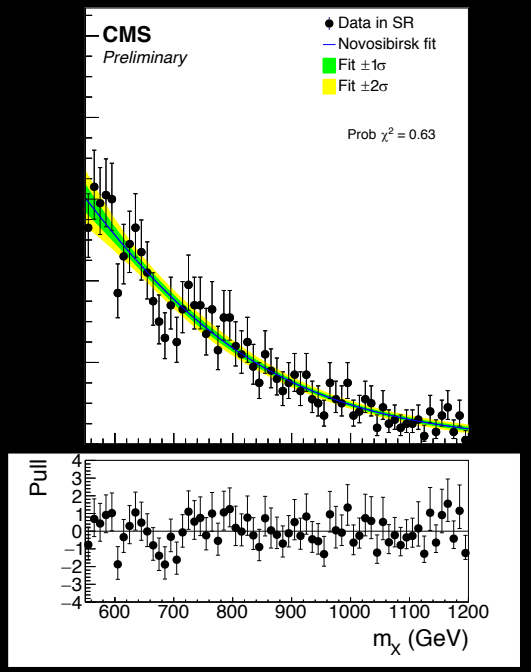
- Signal modelled using a sum of two Gaussians or Gaussian+exponential tails using MC simulations
- Background uses parametric fits derived from sideband regions in the m_H mass spectrum.



Low mass



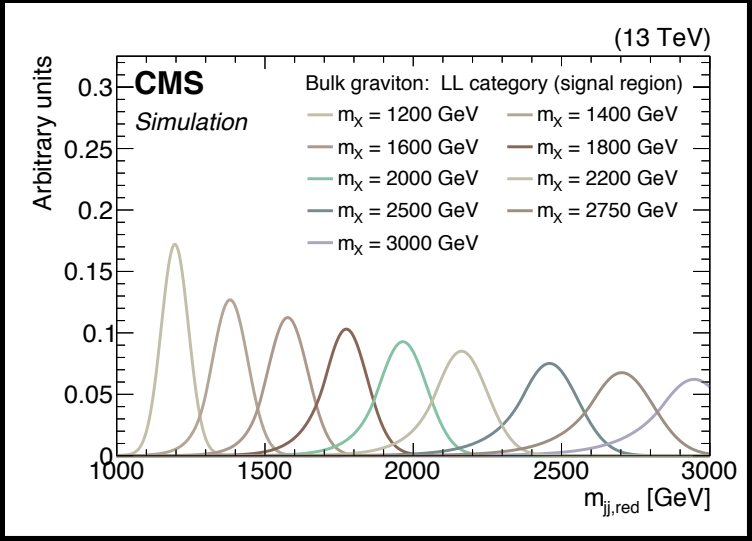
Medium mass

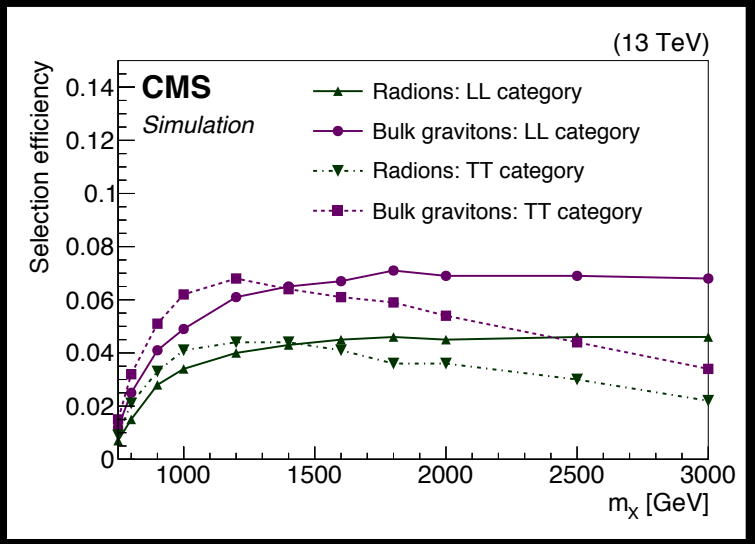


HH->4b resonant

B2G-16-026

- High mass range: 750-3000 GeV
- H->bb have a large transverse momentum w.r.t. the Higgs boson mass
- H->bb decay reconstructed using a fat jet (AK8)
- Jet substructure and double-b tagging applied to jets

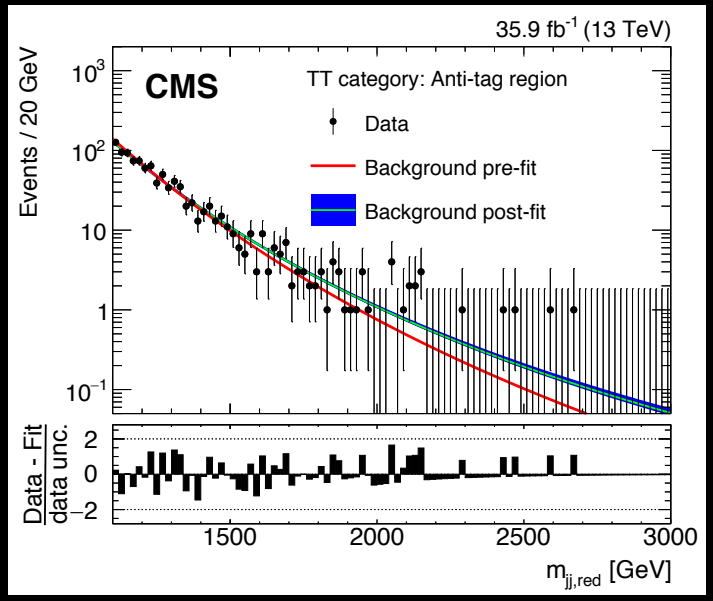


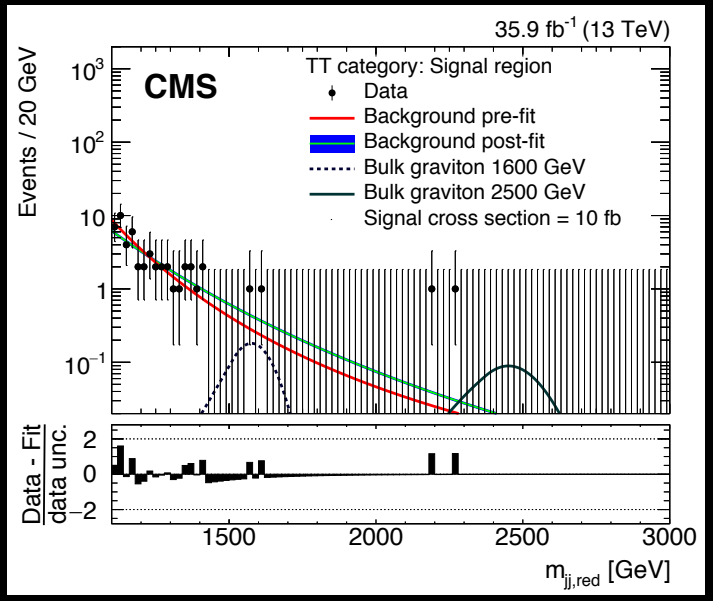


HH->4b resonant

B2G-16-026

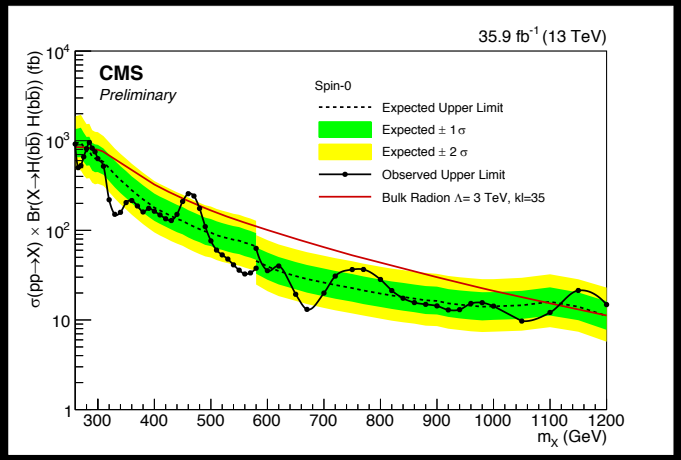
- Search performed as “bump hunt” over all falling background
  - Estimated using sidebands only (750 < M_X < 1200 GeV)
  - Estimated using a combined fit of sidebands and signal regions (M_X > 1200 GeV)

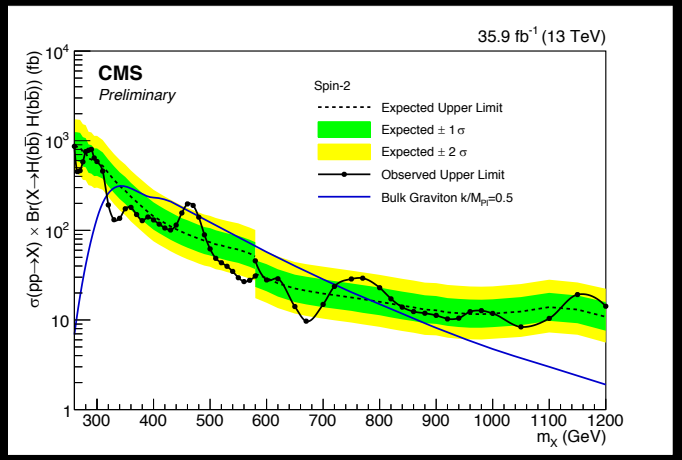




HH->bbbb resonant

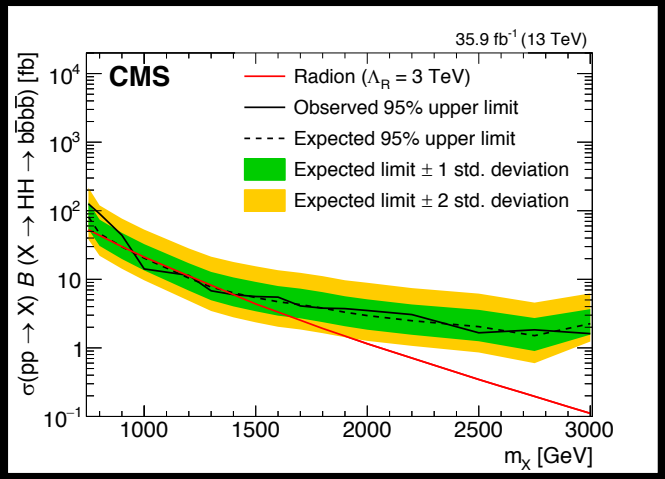
HIG-17-009

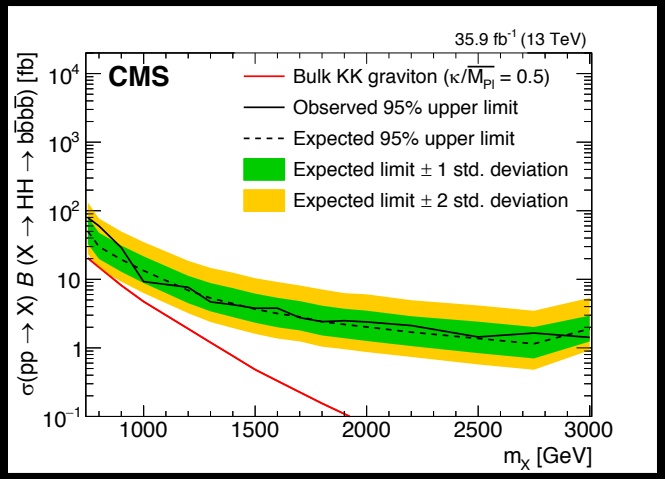




Low mass

B2G-16-026





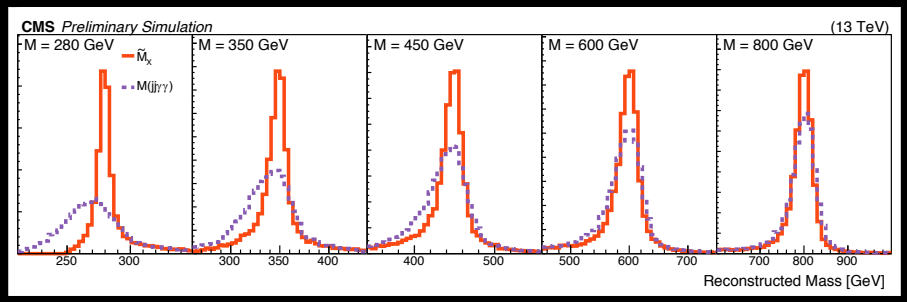
High mass

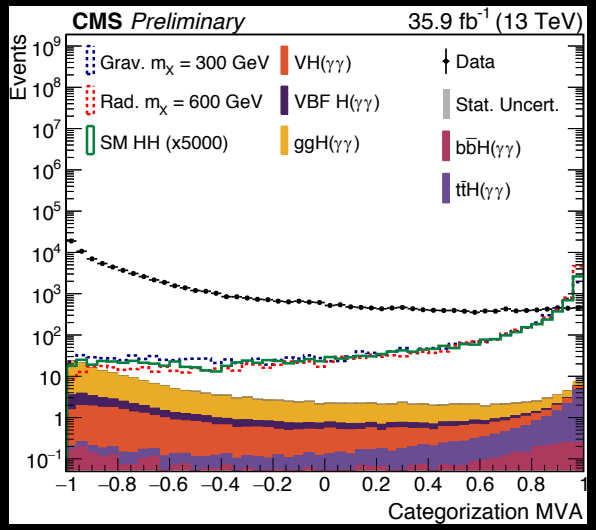
- Upper limits set on the cross section of bulk gravitons and radions in the warped extradimensional models

HH->bbγγ resonant

HIG-17-008

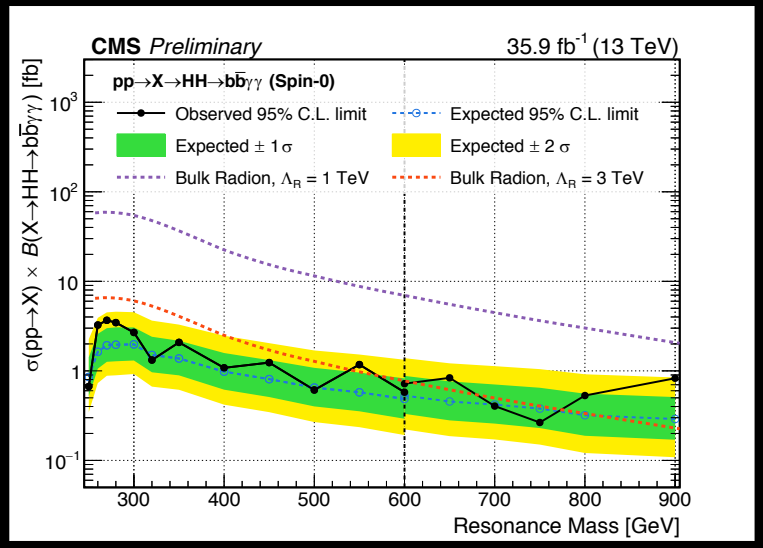
- Small BR (0.26%) but clean signature
- 2 photons+2 b-tagged jets (triggering using 2 photons)
- Resonant mass
- $\widetilde{M_X} = M(jj\gamma\gamma) - M(jj) - M(\gamma\gamma) + 250$
- MVA categorization
- Signal searched for using a parametric fit to M(jj) and M(γγ)

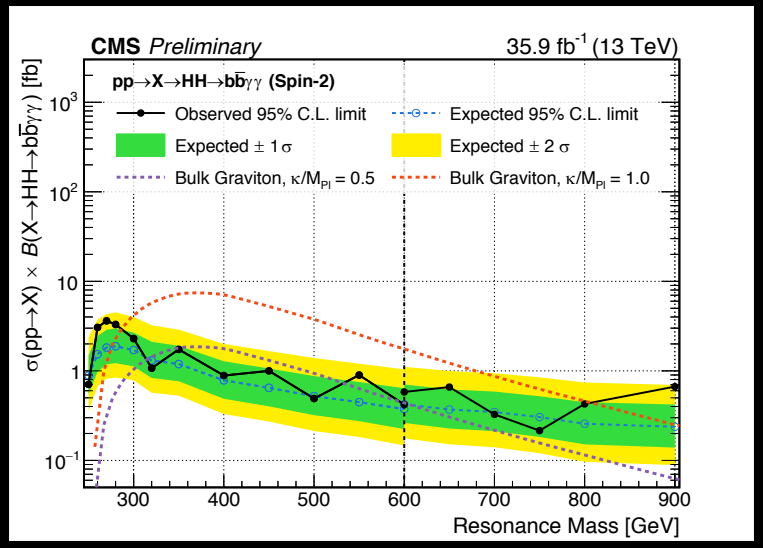




HH->bbγγ resonant

HIG-17-008

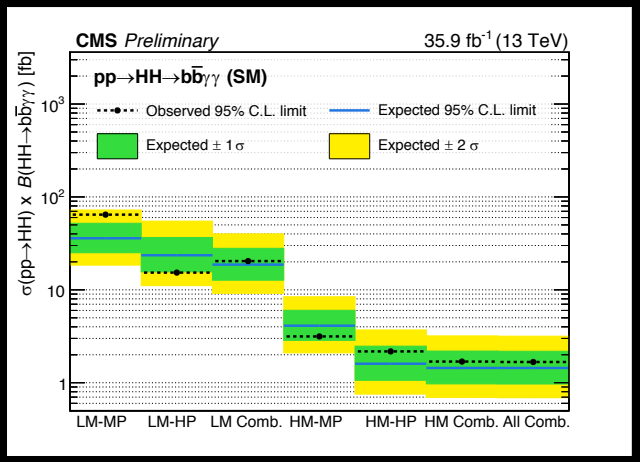


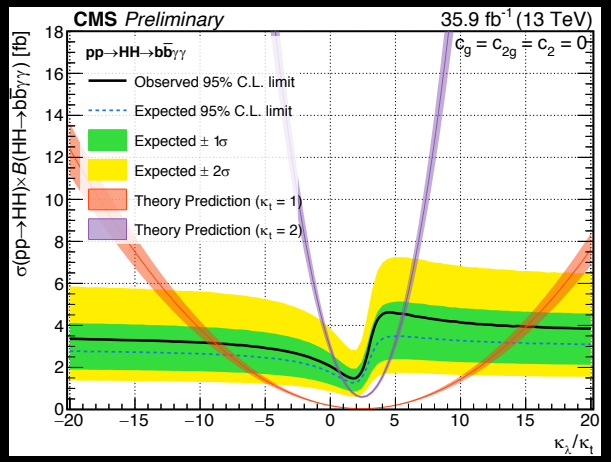


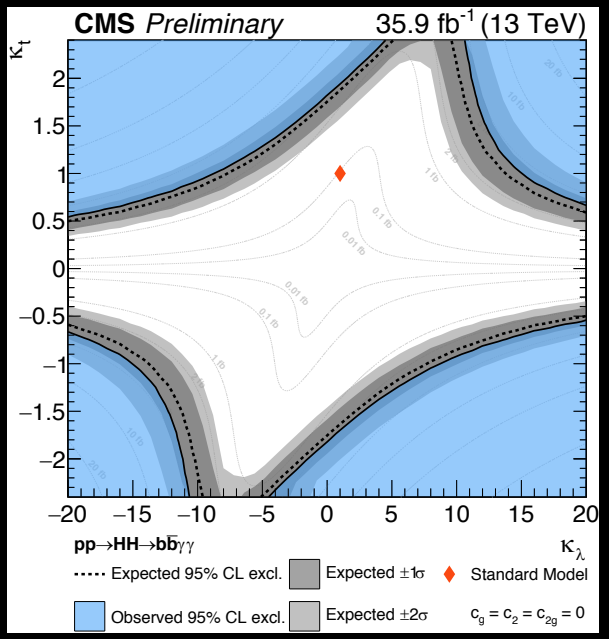
- Limits computed on the cross section of bulk gravitons and radions in the warped extradimensional models

HH->bbγγ non-resonant

HIG-17-008







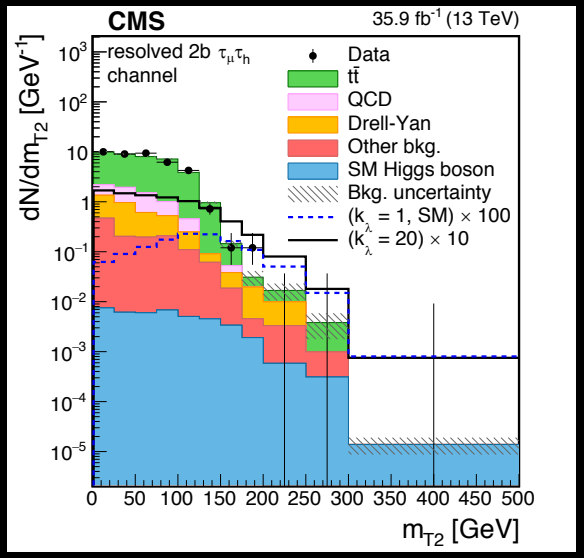
- Cross section observed (expected) upper limits are at 30(25) times SM.
- μ_{HH} < 19.2 (observed) and < 16.5 (expected).
- Limits also set for the BSM models varying κ_Λ parameter.

HH->bbττ

arXiv:1707.02909
HIG-17-002

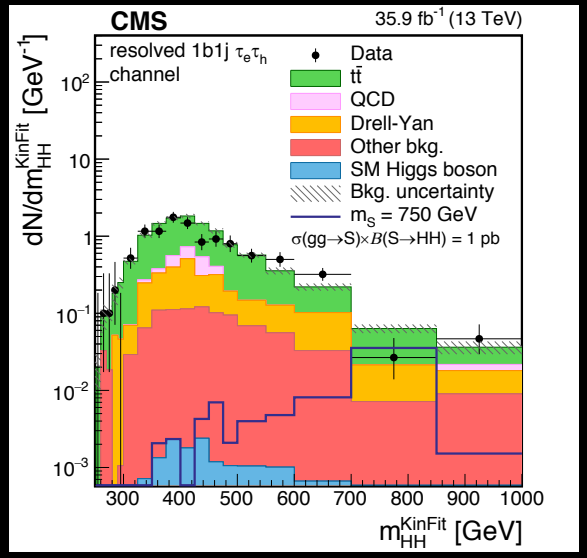
- >= 1 hadronic tau decay τ_h
- Resolved H decay: 1 or 2 b jet
- Boosted H decay: Fat jet (AK8) with subjets matched to AK4 jets
- MVA discriminator for $\tau_\mu\tau_h$/ $\tau_e\tau_h$ to reject ttjets

Stransverse mass M_{T2} for non-resonant

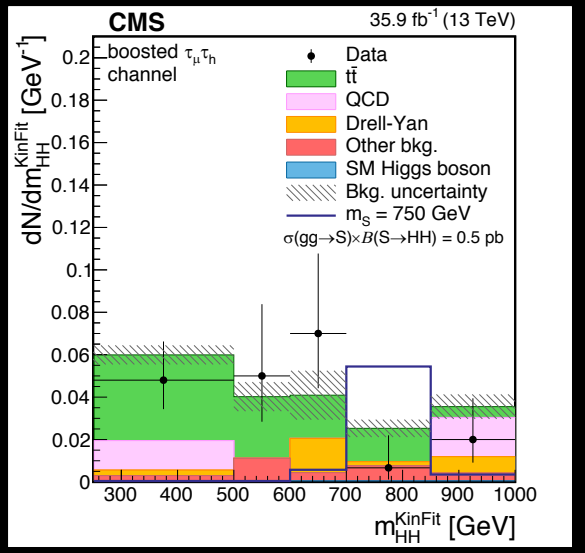


m_{HH} for resonant search

Resolved

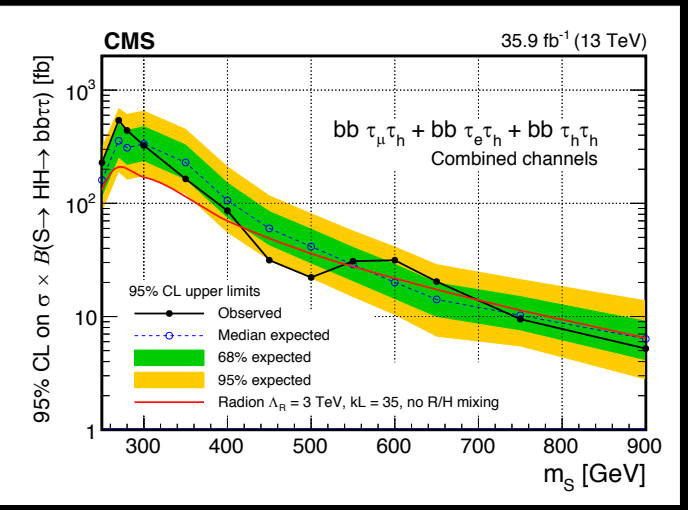


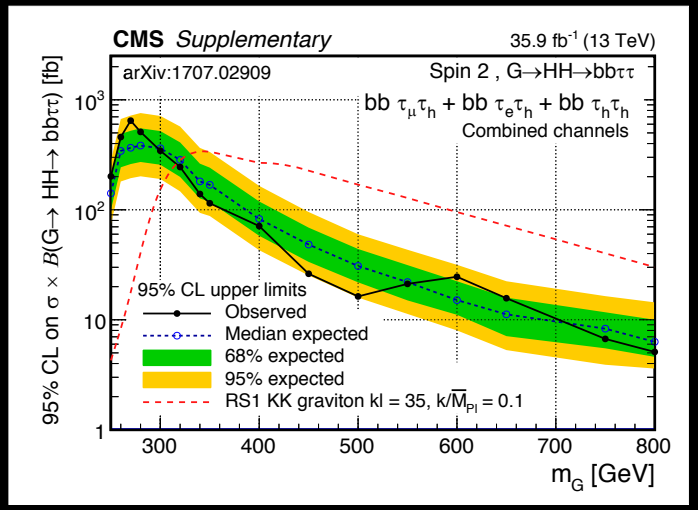
Boosted

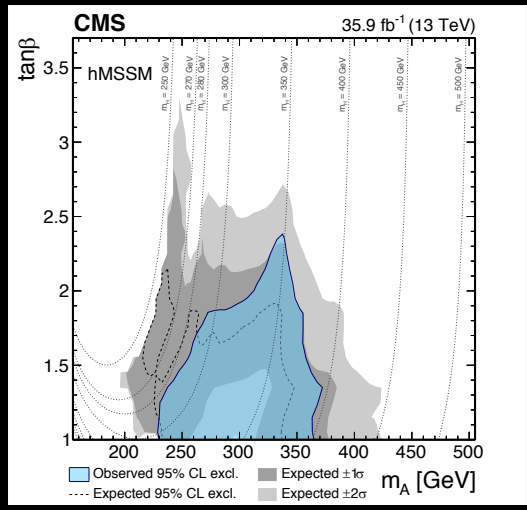


HH->bbττ resonant

arXiv:1707.02909
HIG-17-002





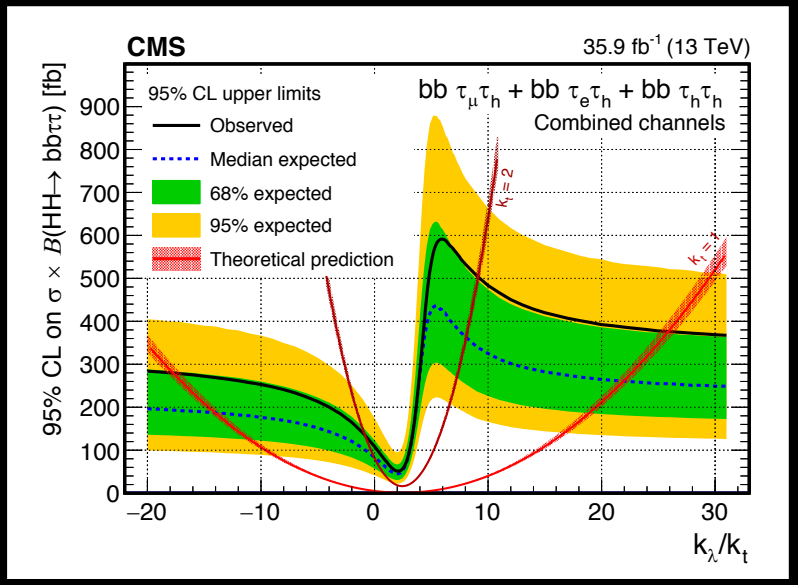


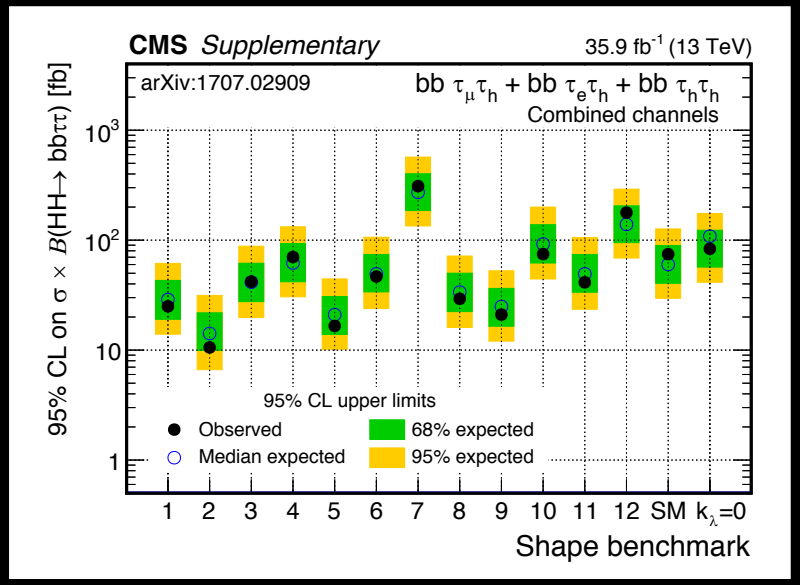
NMSSM Interpretaton

- BSM interpretation using radions and bulk gravitons
- Also interpreted as limits in the NMSSM parameter space in the low tanβ range.

HH->bbττ non-resonant

arXiv:1707.02909
HIG-17-002



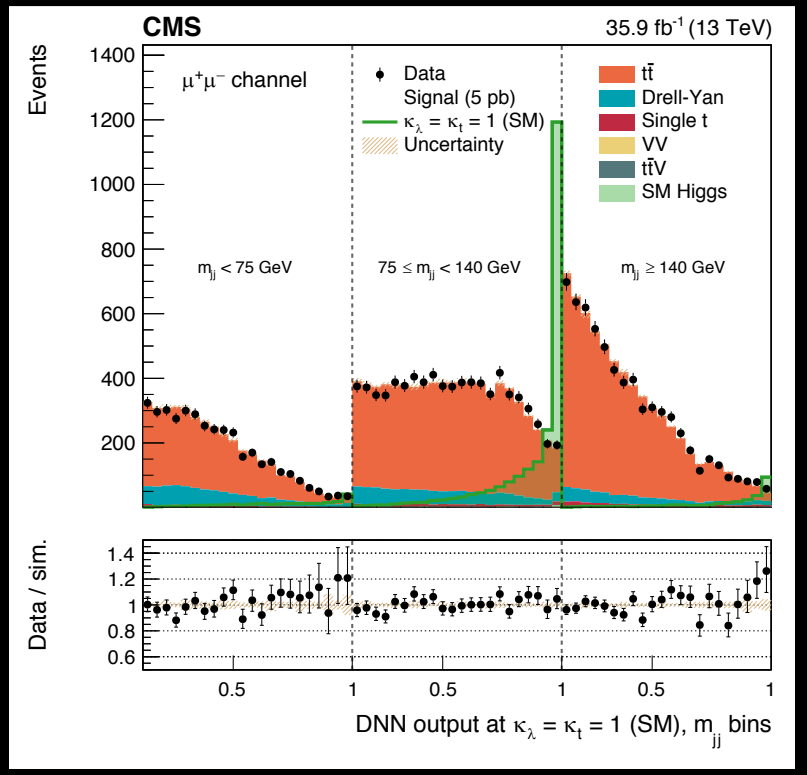


- Non-resonant HH cross section limit at 30 times SM.
- Cross section limits also set for different benchmarks for the Higgs boson coupling.

HH->bbVV

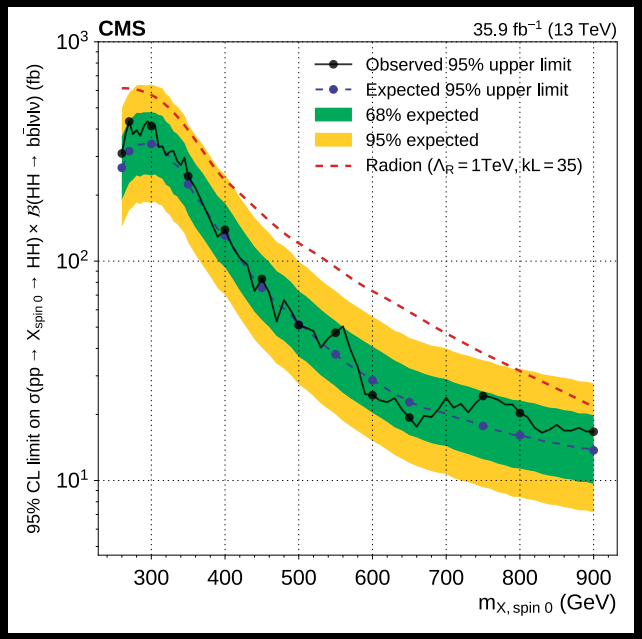
arXiv:1708.04188
HIG-17-006

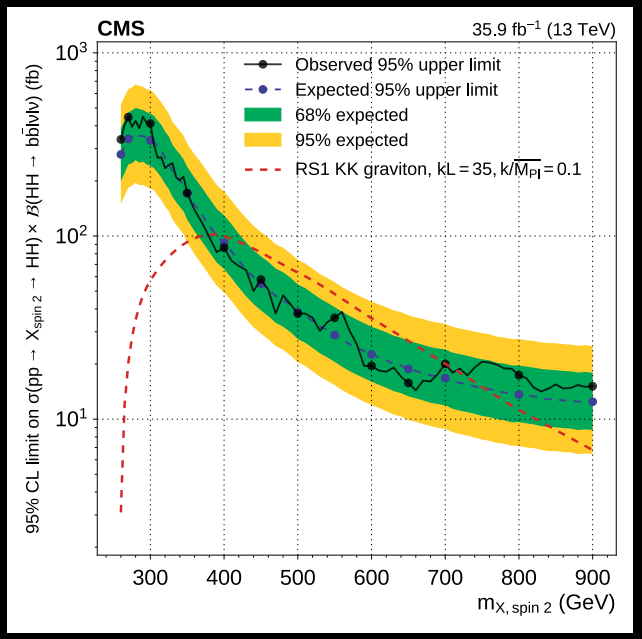
- Dilepton triggers
- Event categories: e^+e^- , $\mu^+\mu^-$, $e^{\pm}\mu^-$
- $12 < m_{ll} < m_Z - 15$ GeV: Reject quarkonia and Z->ll
- 2 b-tagged jets
- BDT to reject Z(bb/ cc)H production
- 3 m_{jj} categories
- Deep neural network training is used to improve signal-background separation.



HH->bbVV resonant interpretation

arXiv:1708.04188
HIG-17-006

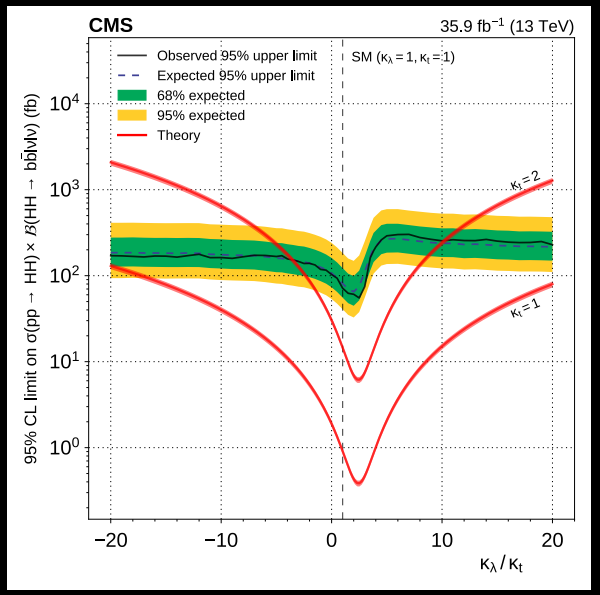


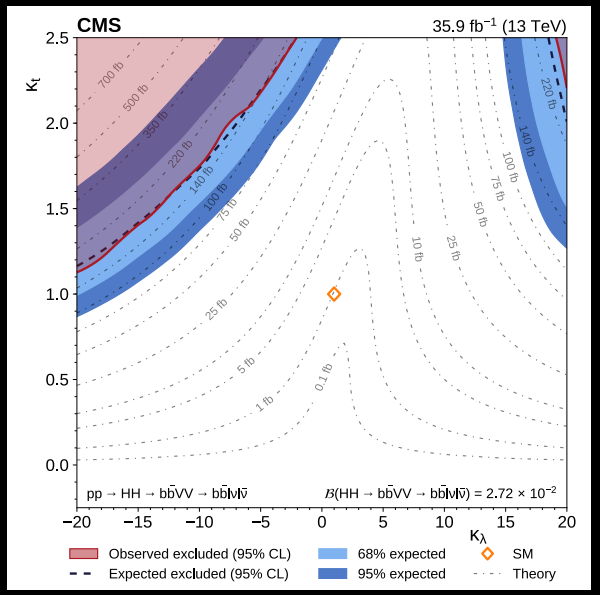


- Limits set on spin-0 radion and spin-2 bulk graviton

HH->bbVV non-resonant interpretation

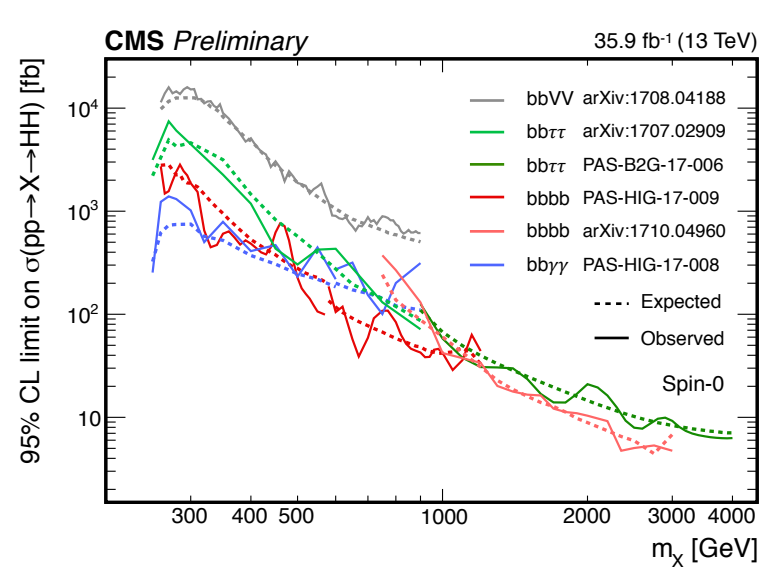
arXiv:1708.04188
HIG-17-006

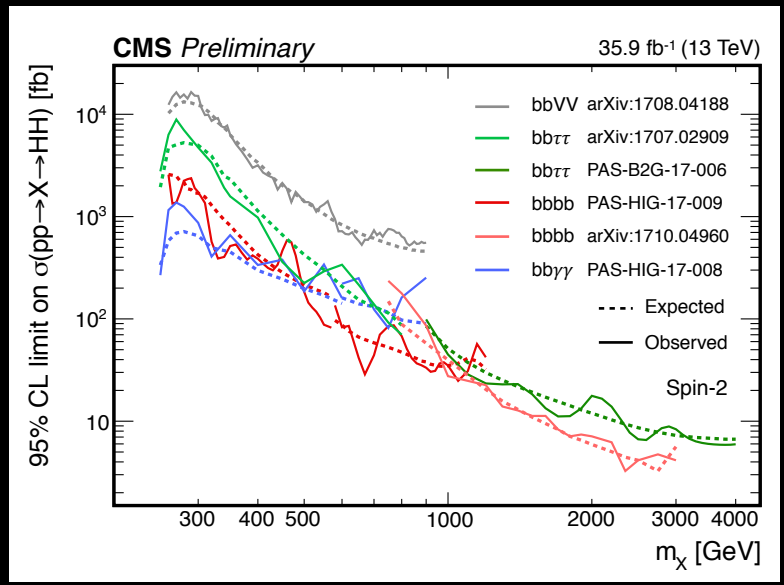




- Non-resonant HH cross section limit at 79 times SM.

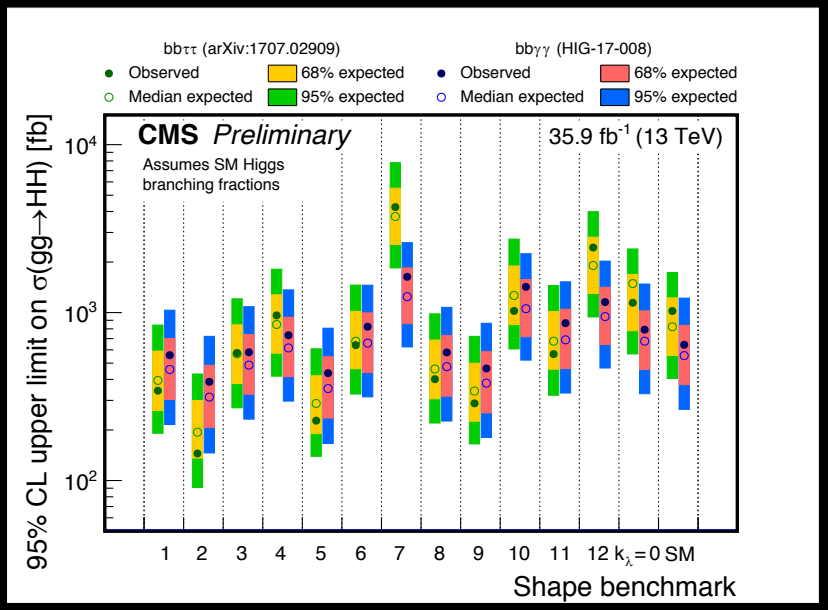
Summary of resonant searches





https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

Summary of non-resonant searches



- Using the EFT approach with 12 benchmark points

Final state	σ/σSM Obs (Exp) at 95% CL	Lumi (fb^{-1})
bbγγ	19.2 (16.5)	35.9
bbττ	30 (25)	35.9
bbWW	79 (89)	35.9
bbbb	342 (308)	2.3

Summary

- CMS searches for HH production presented
- Several analyses broken up by
  - Decay channels: bb$\tau\tau$, bb$\gamma\gamma$, bbWW, bbbb
  - HH mass range: Low mass, high mass
- All results consistent with SM backgrounds so far
  - Upper limits on resonance cross sections, anomalous couplings
- Combination in progress using all measurements done up to now
- Analyses under way using new data.

BACKUP

References

- http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-006/index.html
  - Res and non-res bbW(lv)W(lv) 13 TeV 35.9 fb−1
- http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-002/index.html
  - Res and non-red bbtautau 13 TeV 35.9 fb-1
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-17-008/index.html
  - Res and non-res bbgamgam 13 TeV 35.9 fb-1
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-17-009/index.html
  - Res bbbb 13 TeV 35.9 fb-1
- http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-16-026/index.html
  - Res high mass bbbb 13 TeV 35.9 fb-1
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-026/index.html
  - Non-res bbbb 13 TeV 2.3 fb-1

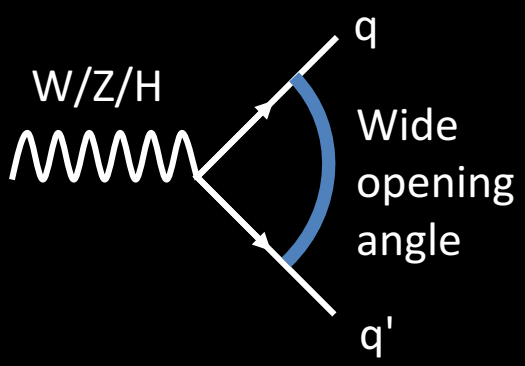
HH->bbbb non-res

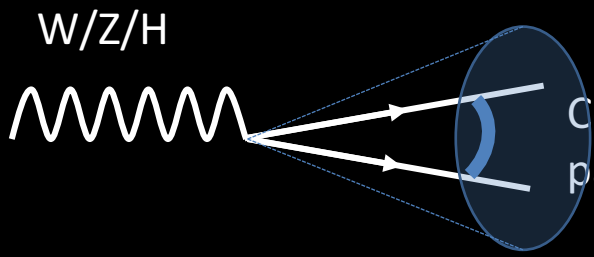
HIG-16-026

- 2015 analysis. Work in progress

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

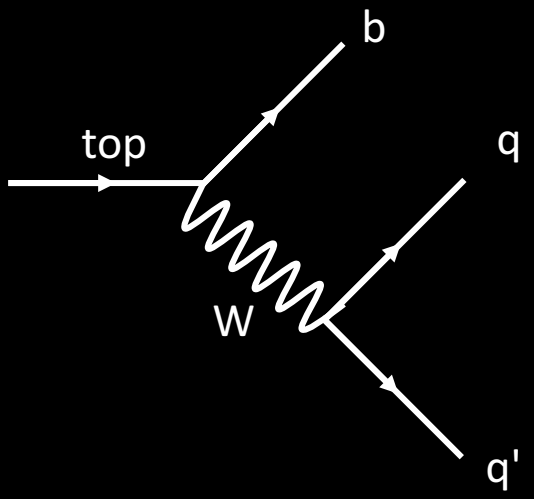
Jets

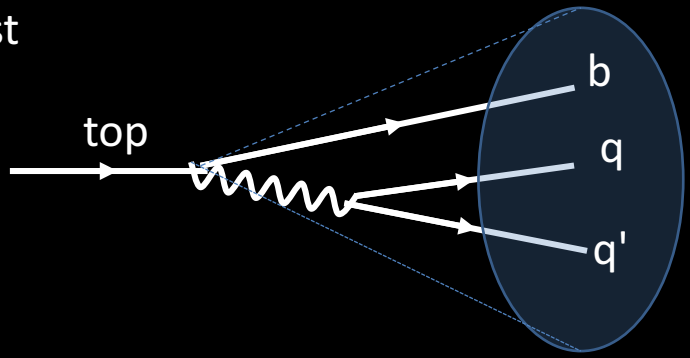




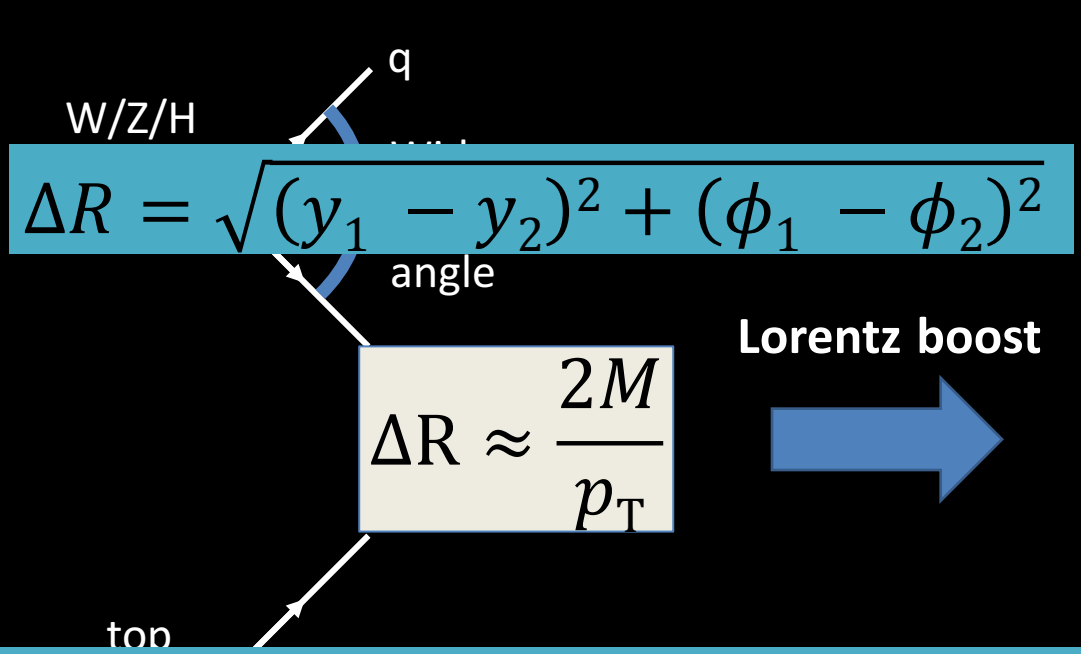
High mass decaying parent particle

Lorentz boost





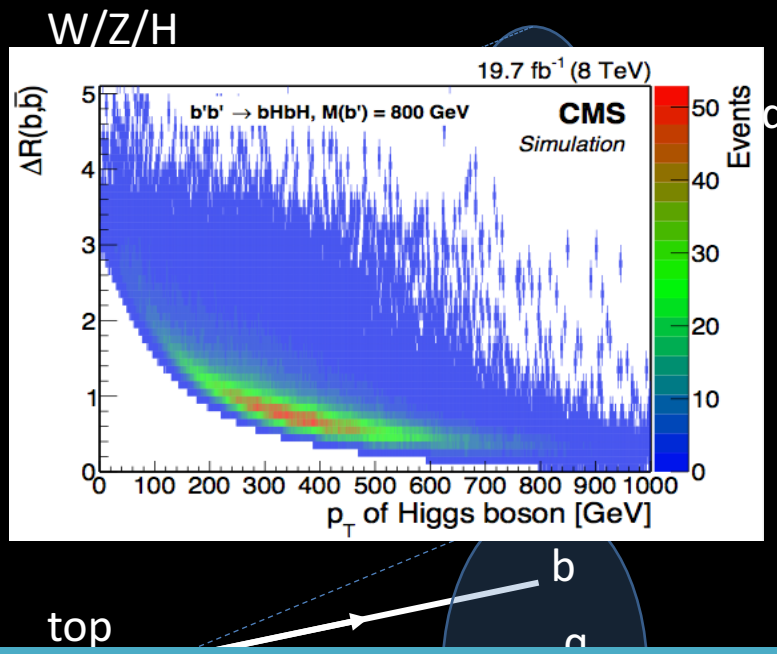
Jets



$$\Delta R = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}$$

$$\Delta R \approx \frac{2M}{p_T}$$

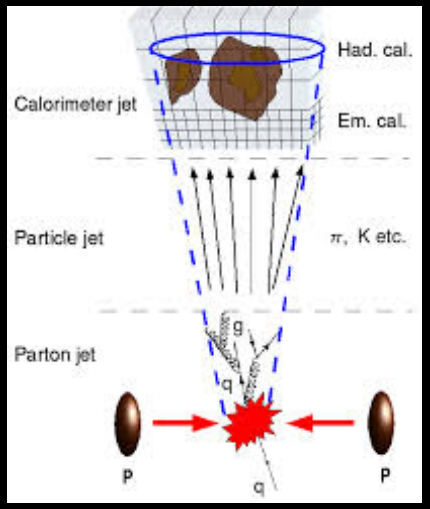
Lorentz boost



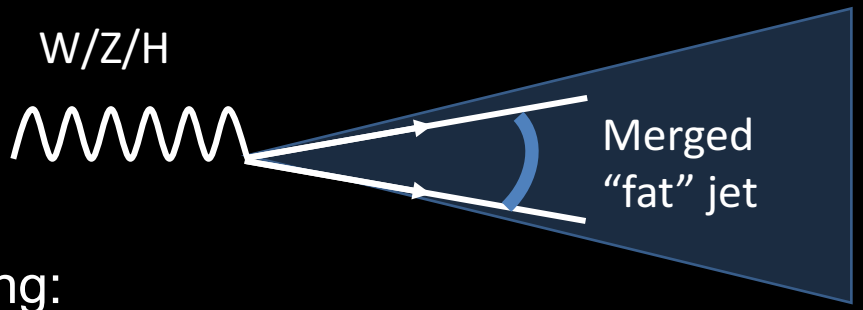
- Boosted SM particles can be reconstructed as a single jet.
  - Intrinsic jet mass
  - Internal substructure
  - Flavour content

Search toolbox: tagging

Jets



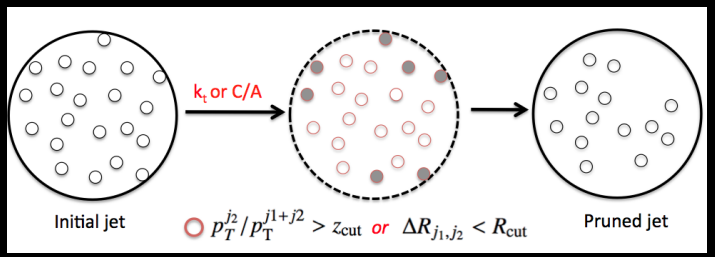
W/Z/H



$$\Delta R \approx \frac{2M}{p_T}$$

- Pruning:
  - $\Delta R(j_1, j_2) > 0.5\frac{m}{p_T}$
  - $z_{cut} = p_T j_2/(p_T j_1 + p_T j_2)$

    > 0.1

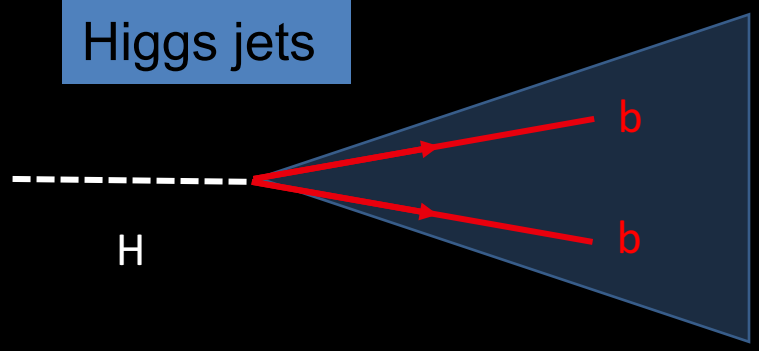


- Soft drop: $\frac{\min(p_{T1},p_{T2})}{P_{T1}+p_{T2}} > z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$
  - Angular exponent parameter $\beta = 0$
    Soft radiation parameter $z_{cut} = 0.1$

  } Modified mass drop

- N-subjettiness $\tau_N = \frac{1}{d_o}\sum_k p_{T,k}\min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}$
  - τ_2/τ_1 for W/Z/ Higgs tagging
  - τ_3/τ_2 for top tagging

B-tagging in boosted topologies



- Double b-tagging:
  - Holistically tag jets with two B hadrons.

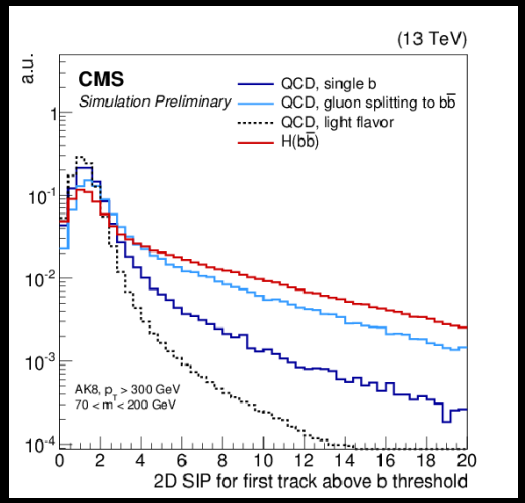
Fully hadronic decay exploited

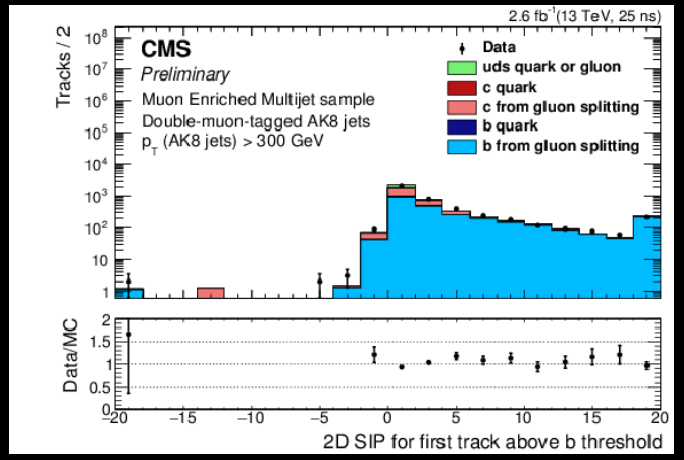
→ **Branching ratio advantage**

$$BR(\mathrm{H} \to \mathrm{b\bar{b}}) = 58\%$$

- **Uses track and secondary vertex info.**
- **Commissioned using AK8 jets tagged with two soft muons: Enriched in gluon -> bb**

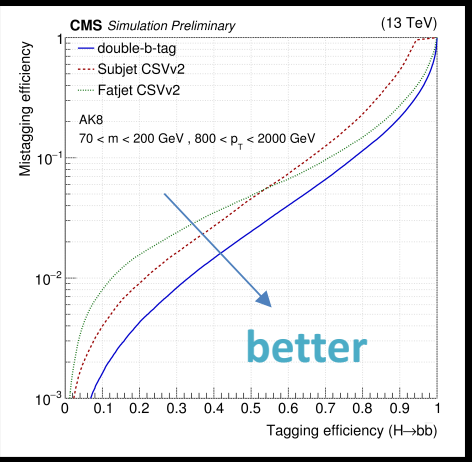
CMS-PAS-BTV-15-002



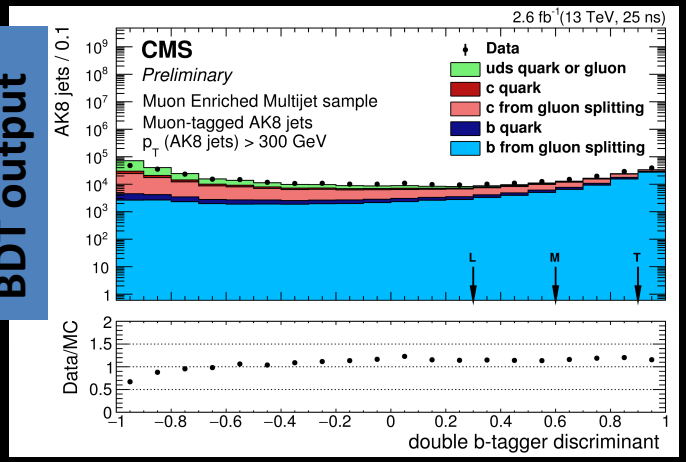


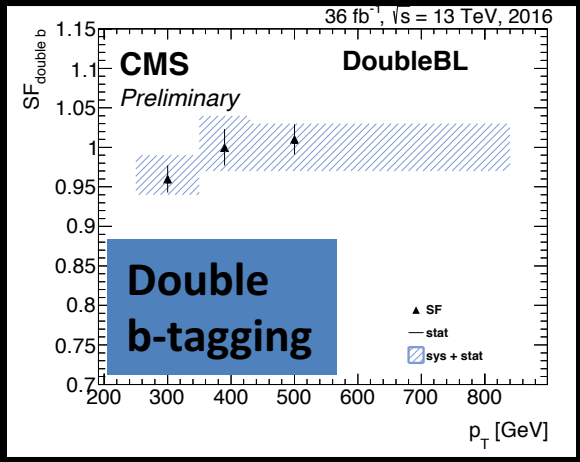
Boosted b-tagger performances

Aim is to distinguish signal (H -> bb) from multijet background.



BDT output





Data/ MC efficiency scale factors measured using double-mu tagged AK8 jets to enrich them in bb flavour (mostly gluon splitting to bb).

BTV-15-001/ BTV-15-002