Searches for new resonances decaying to HH at CMS

Higgs2020, 26-30 Oct 2020

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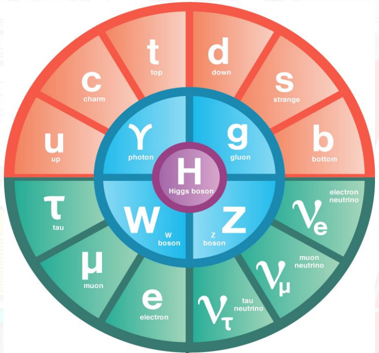
On behalf of the CMS Collaboration

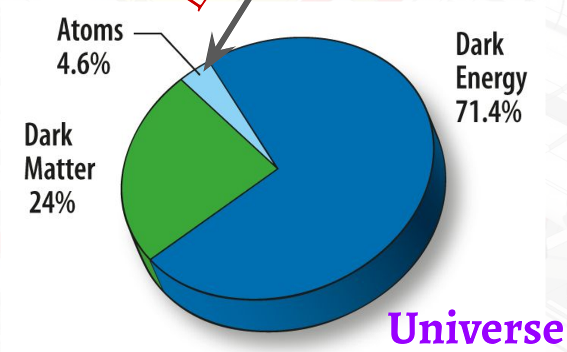
THE HIGGS BOSON

2012: discovery of Higgs-like particle

Completes SM



Explains 5%



Universe Pie chart

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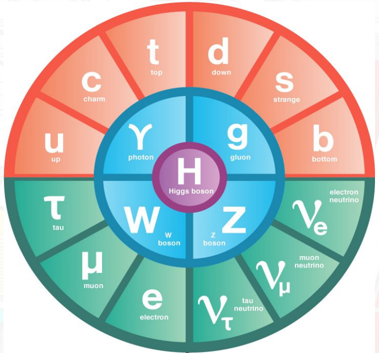
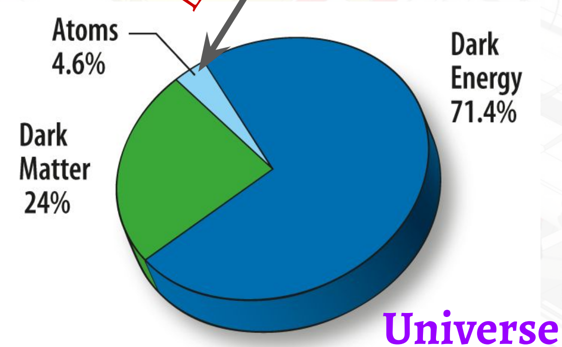


What about Gravity, Dark matter, neutrino oscillation ?

Explains 5%



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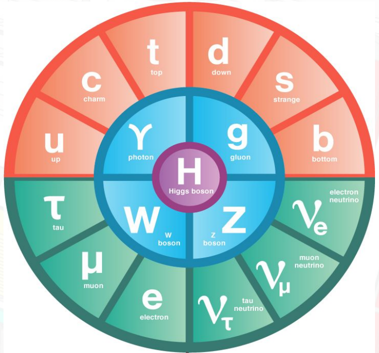

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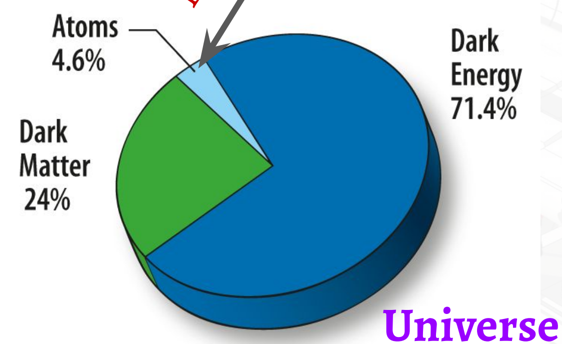
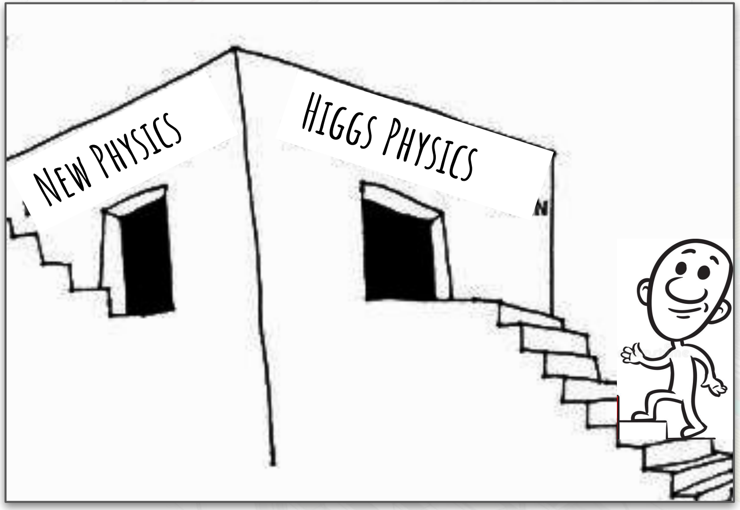


Universe Pie chart

Let's start from Higgs

Di-Higgs Production: a step towards new physics



Higgs Physics ⇒ staircase for new physics

Di-Higgs production is of special interest

- **non-resonant production:** probe for Higgs self coupling, EFT searches (Soumya's talk)
- **resonant production:** Many BSM models predict resonances with higher cross-section, it is easier to observe with direct detection searches

Di-Higgs Production: a step towards new physics

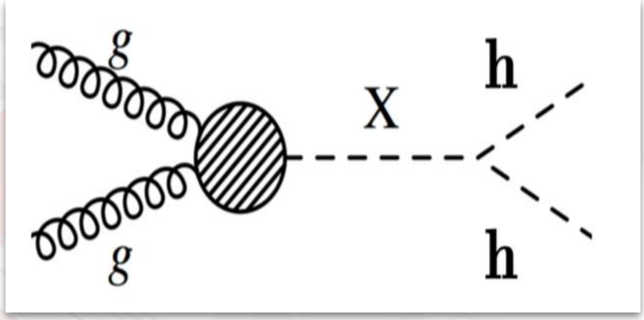
Talk focuses on Resonant di-Higgs searches

- **Warped extra dimension** (Spin-0 Radion and Spin-2 Graviton)
  - Explains SM hierarchy problem
- **2HDM (2 Higgs-Doublet Model) and MSSM (Minimal SuperSymmetric model)**
  - Provide candidate for dark matter searches

Mass range: 260 GeV to 3 TeV

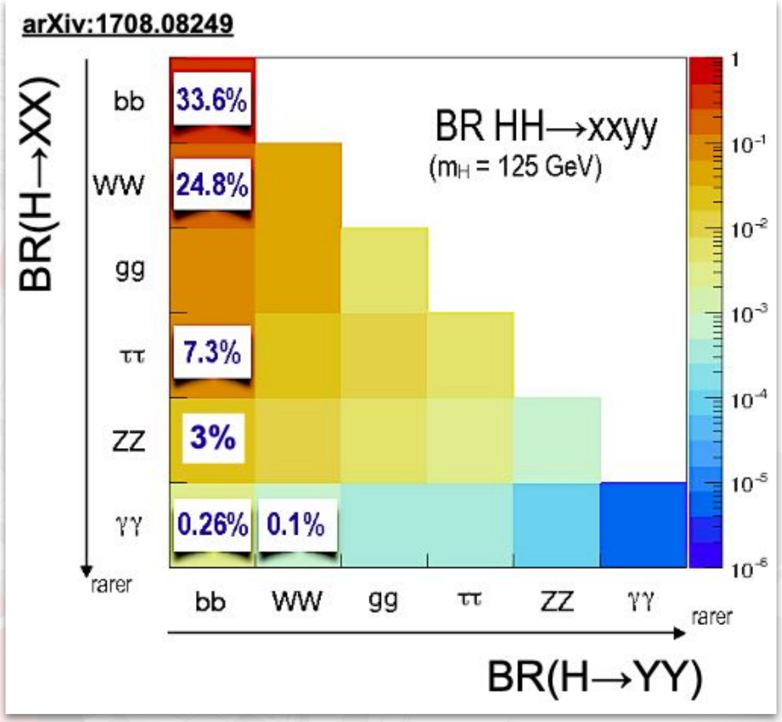
Di-Higgs production is of special interest

- **non-resonant production:** probe for Higgs self coupling, EFT searches (Soumya's talk)
- **resonant production:** Many BSM models predict resonances with higher cross-section, it is easier to observe with direct detection searches



Di-Higgs decay modes

- Explore according to branching fraction (BR) and purity of the channel
  - **bbbb/bbWW** ⇒ large BR, high QCD/ ttbar contamination
  - **bbττ** ⇒ relatively lower BR, tau-tagging increases S/√B
  - **bbγγ/bbZZ** ⇒ small BR, good selection efficiency



From next slide: Overview of all resonant HH searches at CMS with 2016 dataset

X→ HH→ bbbb

Analysis strategy depends on the probed mass range.

Resolved
m_X = [260, 1200] GeV

→ 4 isolated b-tagged AK4 jets
→ Study in low and medium mass region

Semi-resolved
m_X= [750, 2000] GeV

→ one bb pair treated as collimated ⇒ 1 AK8 jet and 2 AK4 jets

Fully-merged
m_X= [750, 3000] GeV

→ bb pairs are collimated⇒ 2 AK8 jets

AK4(8) jet = jet clustered with anti-k_t algorithm with D = 0.4 (0.8)

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Results are combined from both

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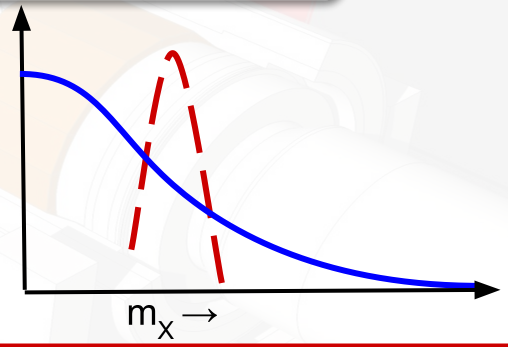
Results are combined from both

- Bump-hunt searches on m_X observable
- Multijets background is modeled using data for m_X side-bands



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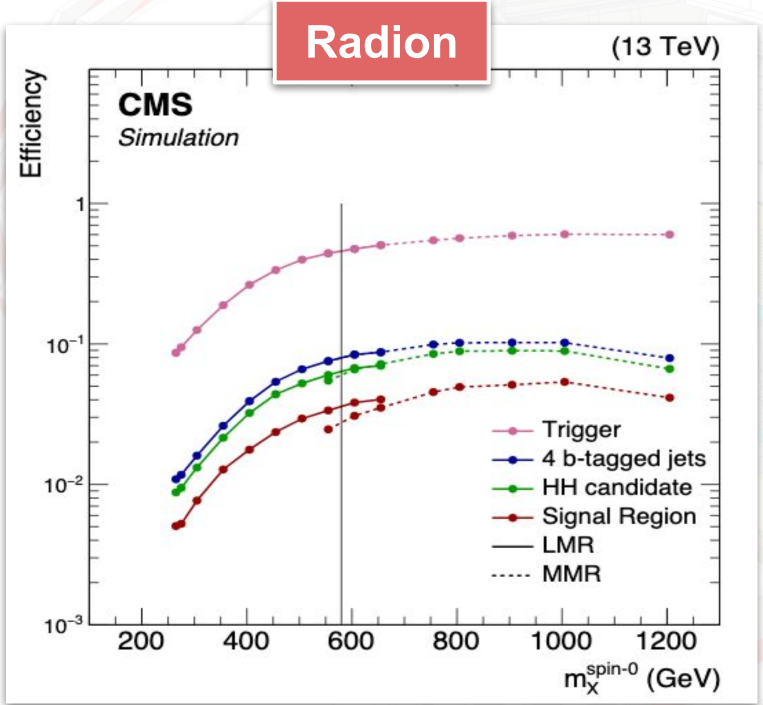
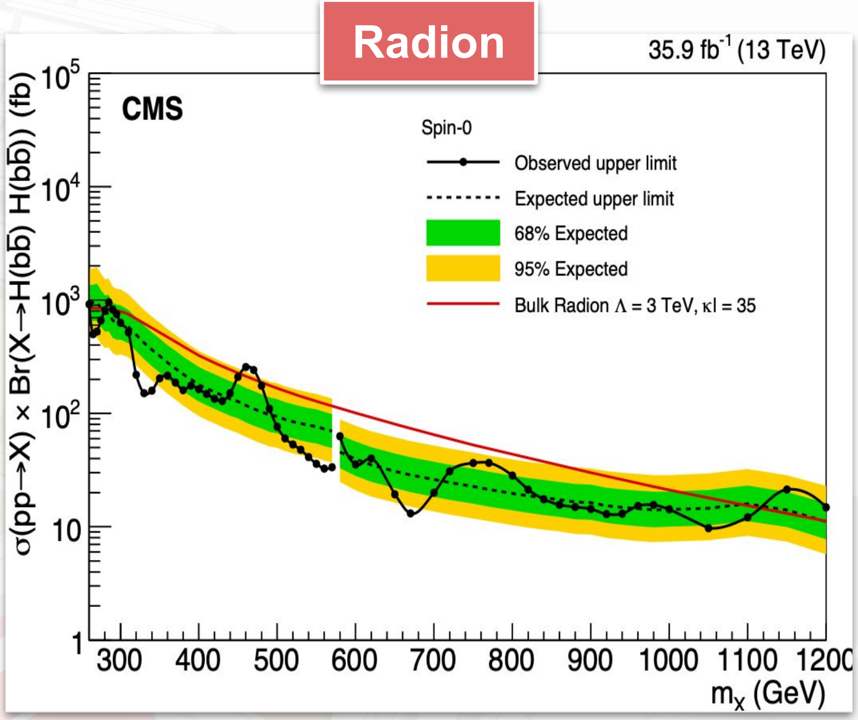
X→ HH→ bbbb (resolved)





Signal efficiencies for different m_X (spin-0)

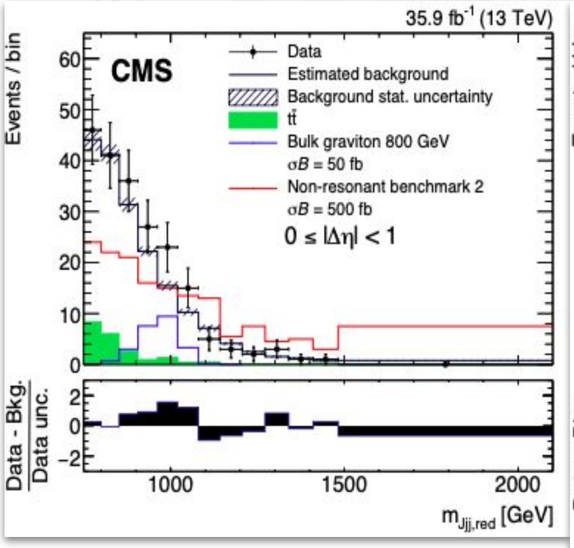
Model independent UL on HH production cross-section

NOTE: Results for Spin-2 in the backup

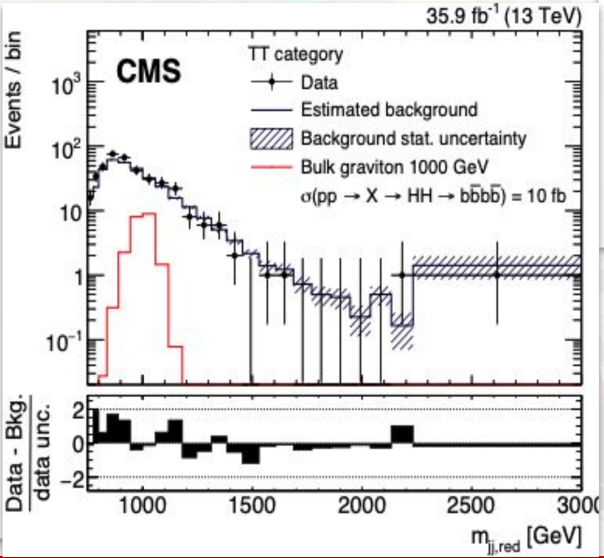
X→ HH→ bbbb (semi-resolved, fully-merged)

- Adding semi-resolved results improves sensitivity 55% Spin-0 w.r.t. Fully-merged
- For high masses, use only fully-merged analysis

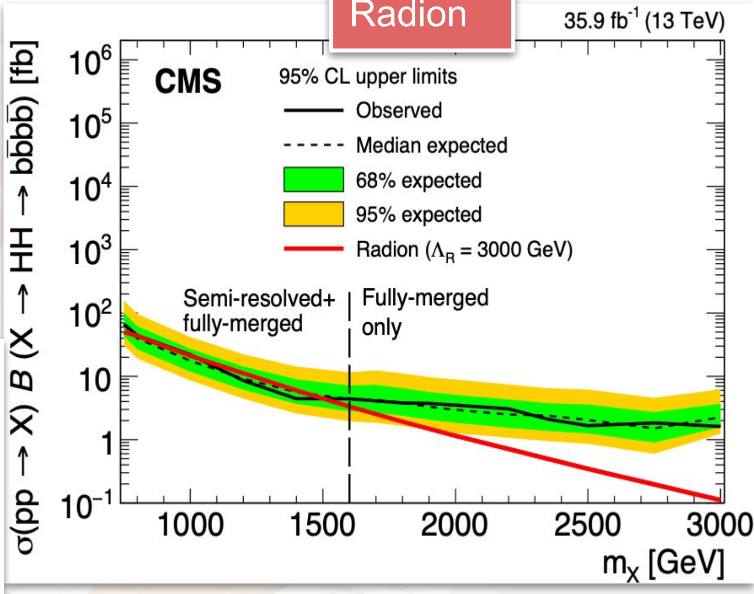
Semi-resolved



Fully-merged



Radion



Model independent UL on HH production cross-section

NOTE: Results for Spin-2 in the backup

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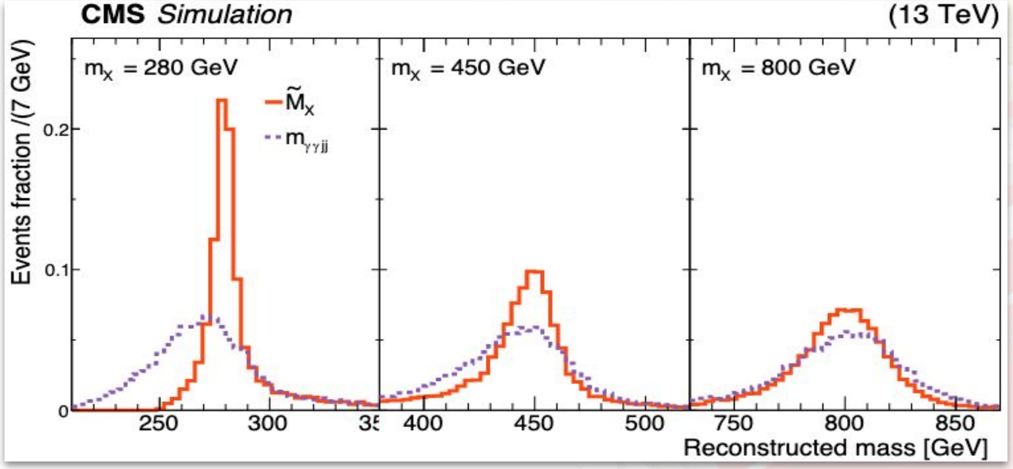
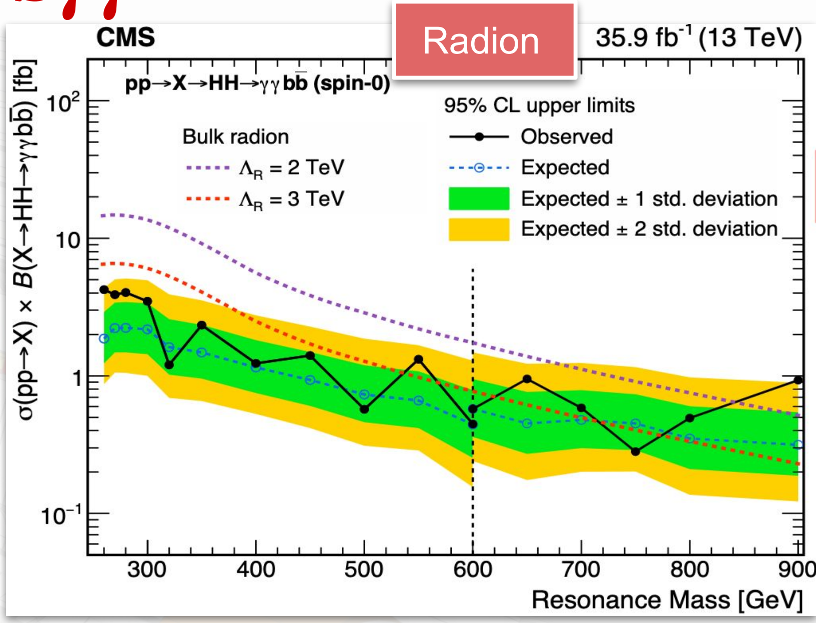
$X \rightarrow HH \rightarrow bb\gamma\gamma$

- 2 photons and 2 b-tagged AK4 jets
- MVA based Categorization in low and medium mass regions
- **2D-signal extraction method** ⇒ fit on m_{jj} and $m_{\gamma\gamma}$ in a $\tilde{M}_X$ window
- Background modeling ⇒ data-driven method





NOTE:

$\tilde{M}_X = m_{HH} - (m_{jj} + m_{\gamma\gamma}) + 250$

Results for Spin-2 in the backup

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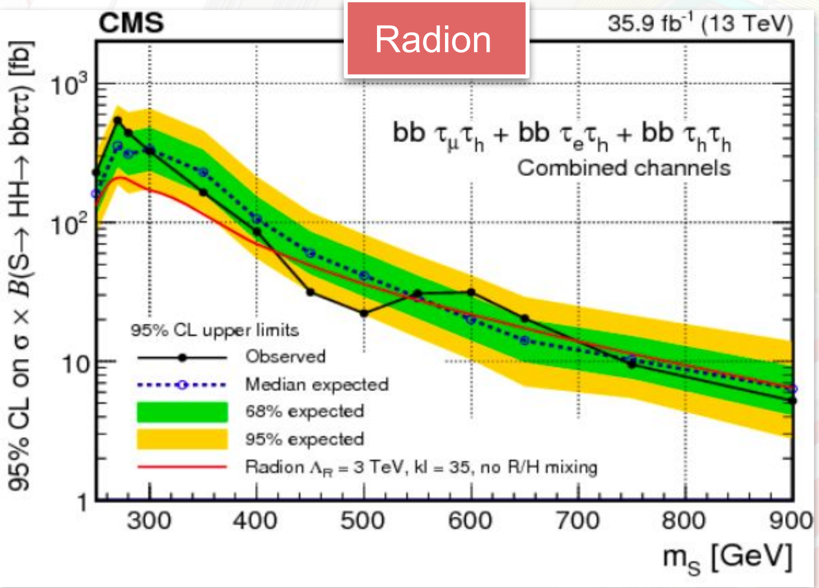
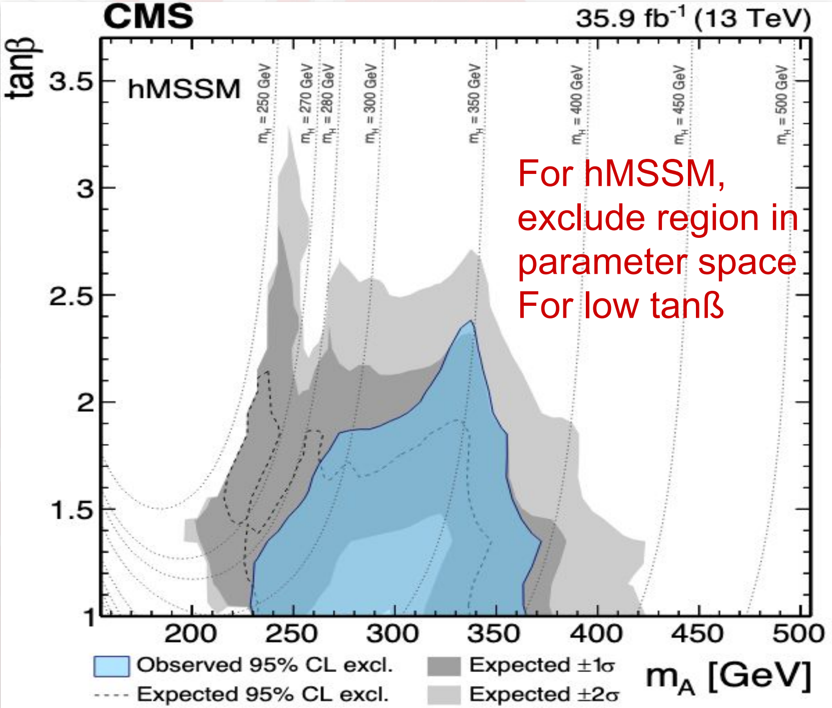
$X \to HH \to bb\tau\tau$

- Low (resolved bb) and high (merged bb) mass analyses
- 3 channels: (τ_h,$\tau_{e/\mu}$/ τ_h) along with 2 b-tagged AK4 jets (high mass: 1 b-tagged AK8 jet)
- Main backgrounds: ttbar (MC), multijets (data)
- Limit extraction using fit on m_X observable

Radion





For hMSSM, exclude region in parameter space For low tanß

JHEP01(2018)054

$X \to HH \to bbll\nu\nu$

- Events from **W(lν)W(lν)** and **Z(ll) Z($\nu\nu$)** final state along with bb final states
  - two isolated and opposite sign leptons along with 2 b-tagged AK4 jets

bbWW

- 3 channels: μμ, ee, μe/eμ
- Parametric DNN to scan different m_X values.
- DY from data-driven method
- final discriminant: DNN output in different mass bins

JHEP01(2018)054

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- Parametric DNN to scan different m_X values.
- DY from data-driven method
- final discriminant: DNN output in different mass bins

bbZZ

- 2 channels: μμ, ee
- Main background : DY and ttbar
- Low and medium mass region BDT discriminant to increase $S/\sqrt{B}$

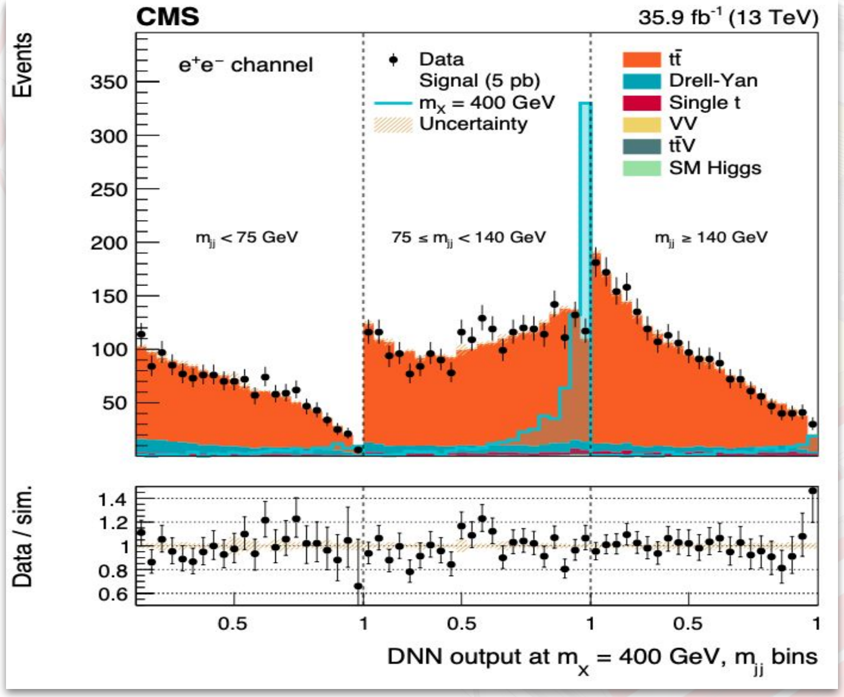
NOTE: bbZZ analysis is also used in combination with $X \rightarrow HH \rightarrow bbZZ \rightarrow bbllqq$ analysis (upcoming slide)

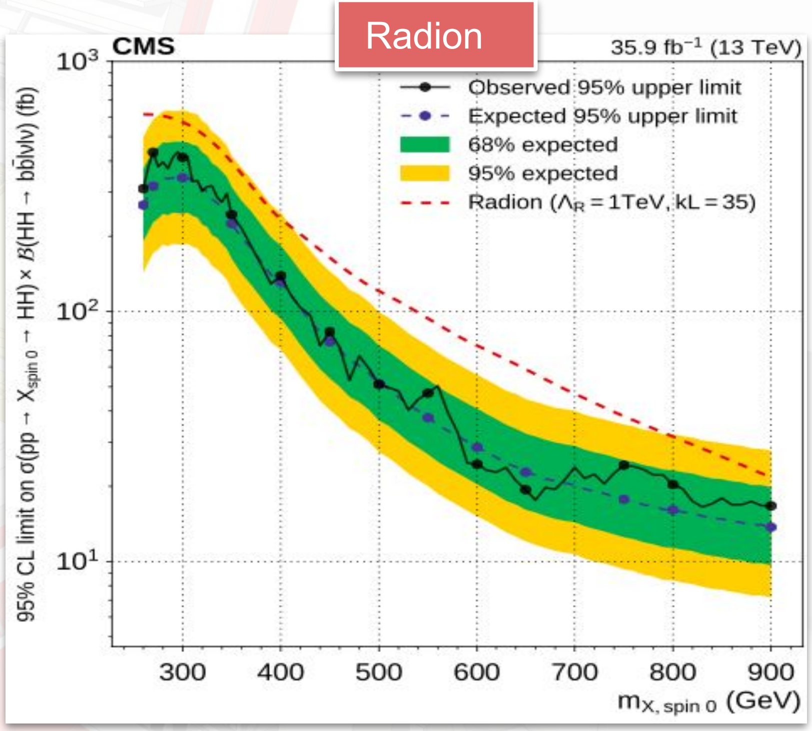
Additional constraints are used in the analyses to have statistical independence for combined results

JHEP01(2018)054

X→HH→bbll$\nu\nu$

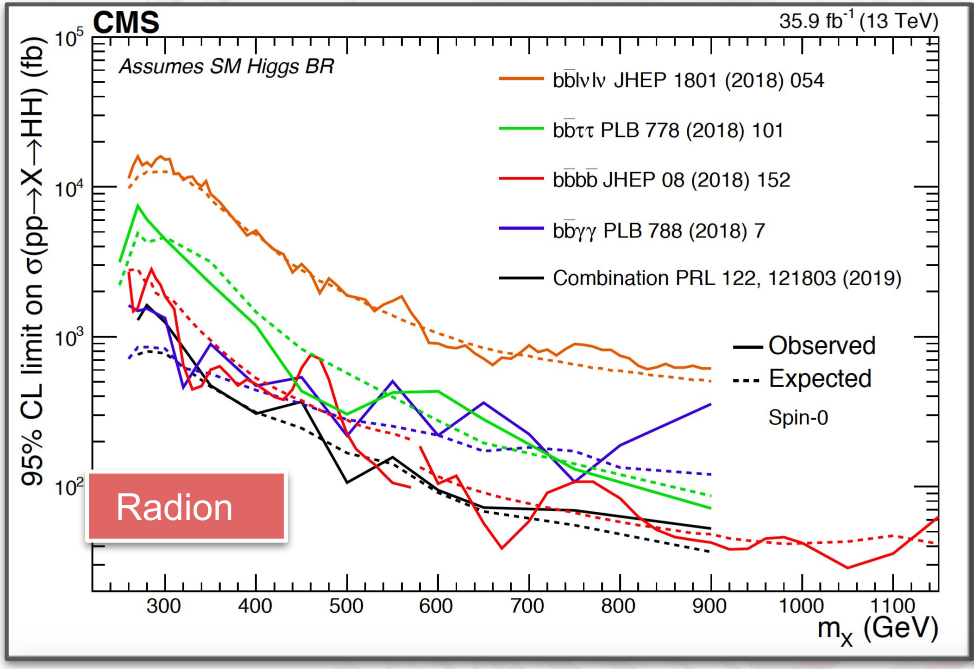
- **Results are combination of both bbWW and bbZZ analyses keeping the orthogonality**

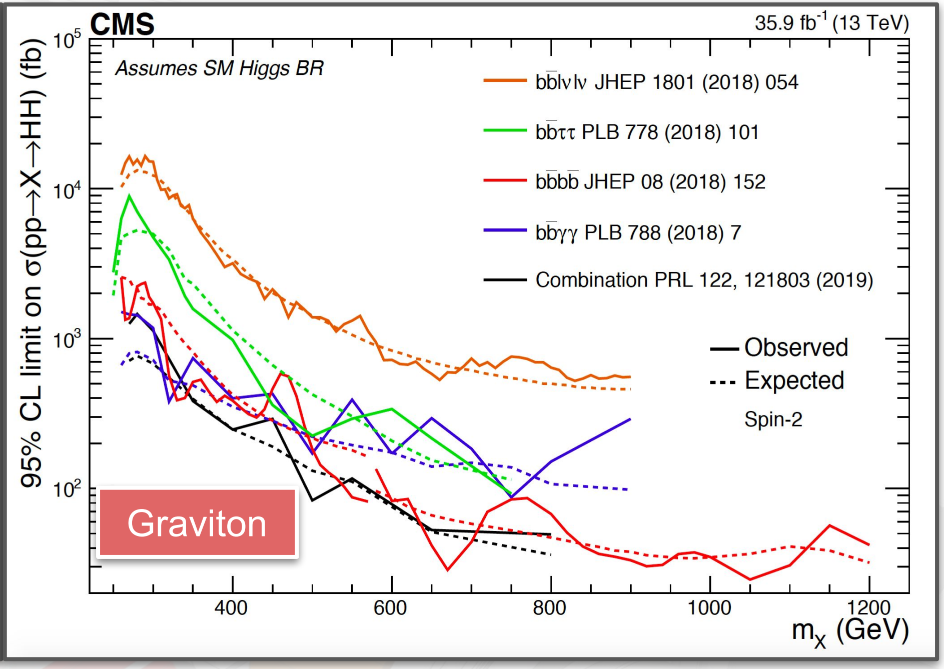




reference

X→ HH Combination results



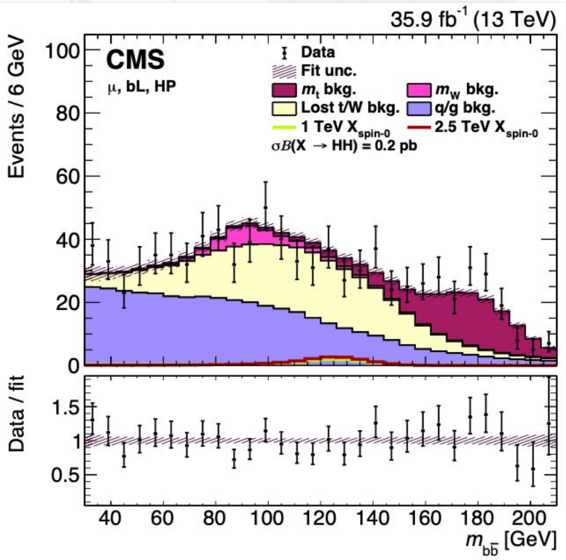


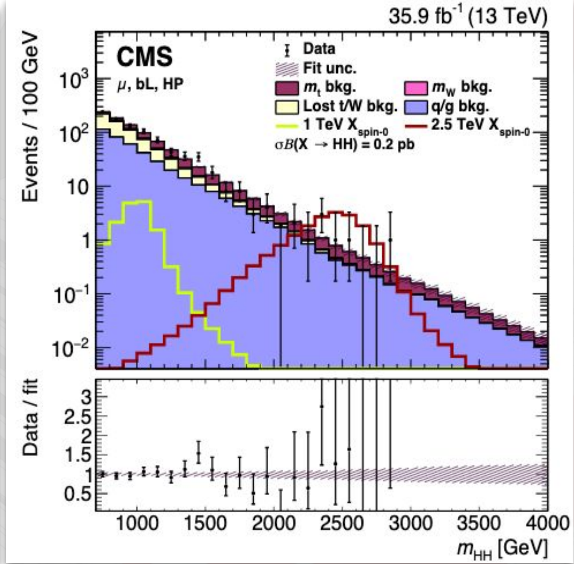
- Results are from combination of bbbb, bbll$\nu\nu$, bbττ, bb$\gamma\gamma$ final states
- No deviation is observed from standard model background expectation
- **Next 2 slides:other resonant HH search at CMS⇒ not part of combination**

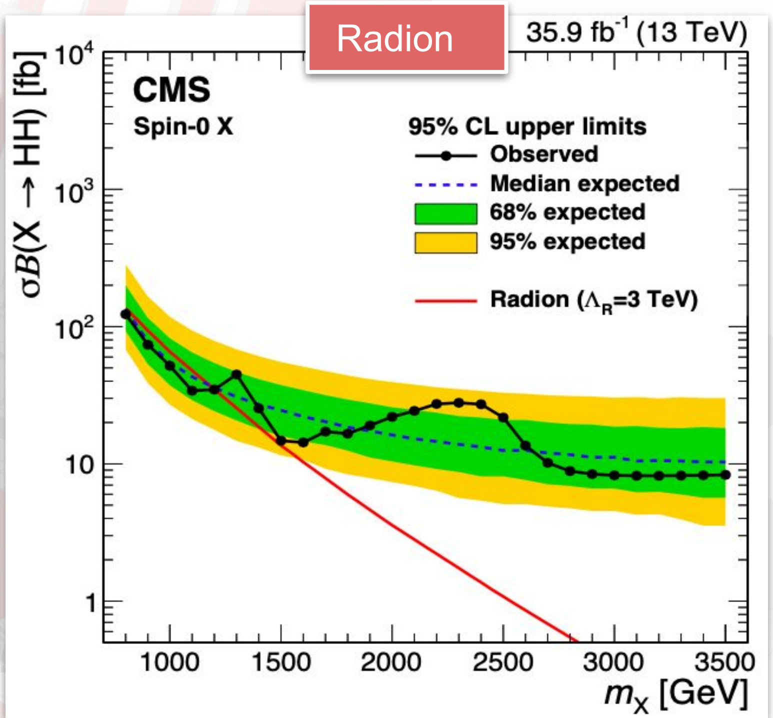
JHEP10(2019)125

X→HH→bbW*W → (bblνqq')

- bb pair: subject b-tagging to tag as H-jet (AK8 jet) and qq': jet substructure to tag as W-jet (AK8 jet)
- one isolated lepton near a W-jet
- ttbar main background
- Limit extraction: 2D-fit in m_{jj}-m_{HH} plane



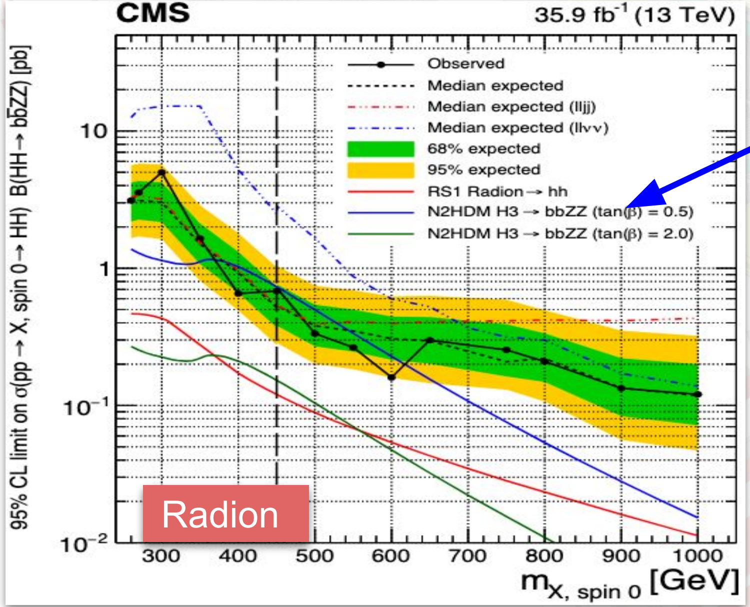




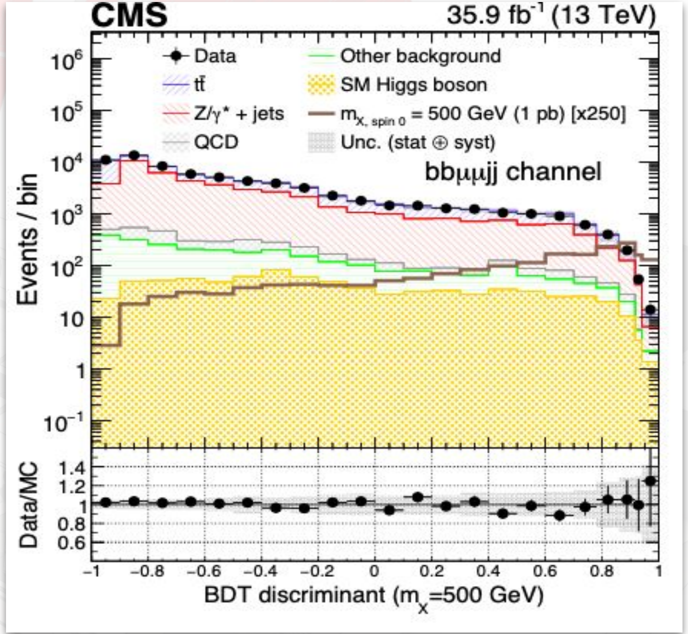
Phys. Rev. D 102, 032003

X→HH→bbZZ → (bbllqq)

- same flavour and opposite sign isolated leptons.
- b-tagging helps to tag b-jet pair; jet pair is selected to have mass (lljj)~m_H
- BDT discriminant to suppress background contribution
- Limit extraction: fit on BDT distribution (bbllqq) & hh pseudo transverse mass (bbll$\nu\nu$)



Interpretation in Exotic Higgs scenario⇒ Exclude [360-610] GeV for tanß = 0.5



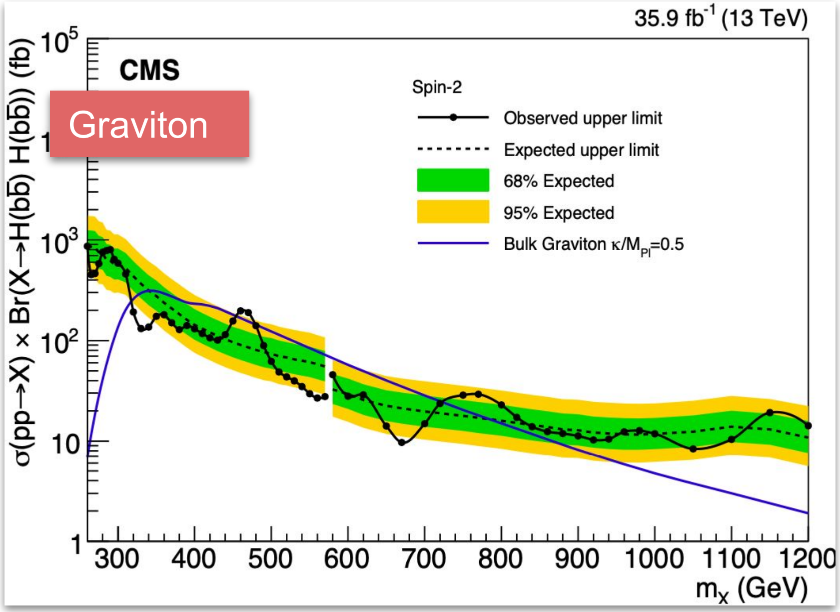
Summary and Conclusion

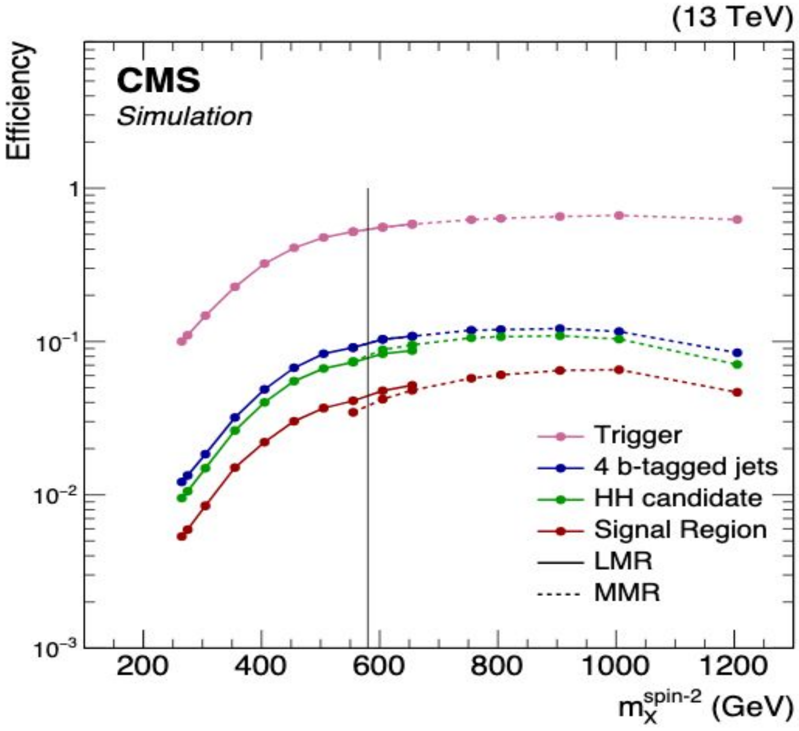
- Resonant di-Higgs production is important for new physics searches
- At CMS, we study these signatures in various final states based upon its branching fraction and purity
  - Machine learning tools and object identification algorithms are used to enhance the analysis sensitivity
  - Results are consistent with the SM background expectations.
  - Provided stringent bounds set on large part of BSM parameters space using resonant HH searches with 2016 data
- We look forward to have more results using full RunII data. Stay tuned!

Thanks for your attention!

Backup

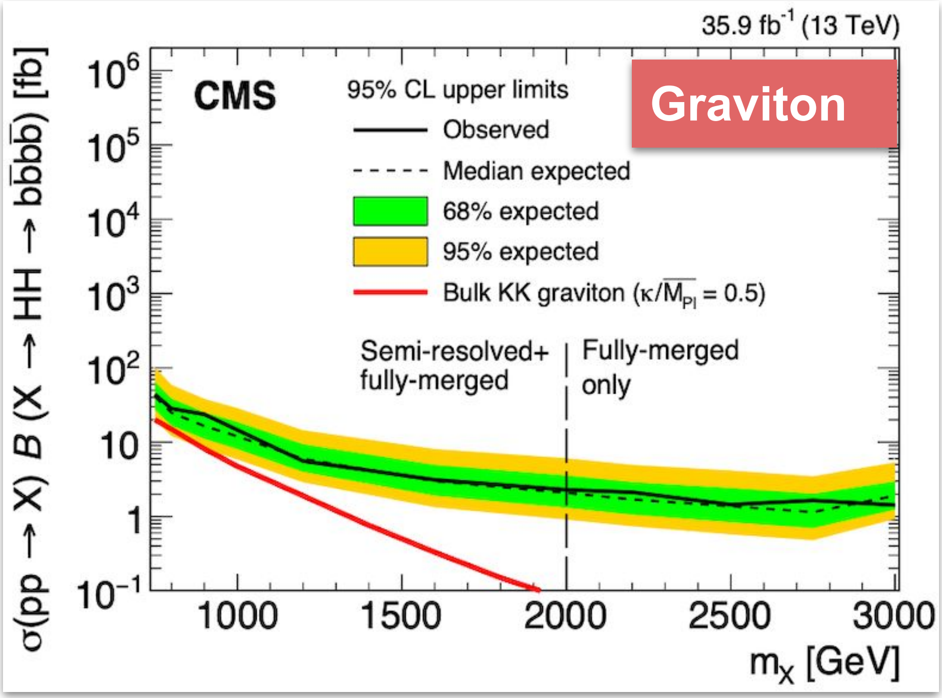
X→ HH→ bbbb





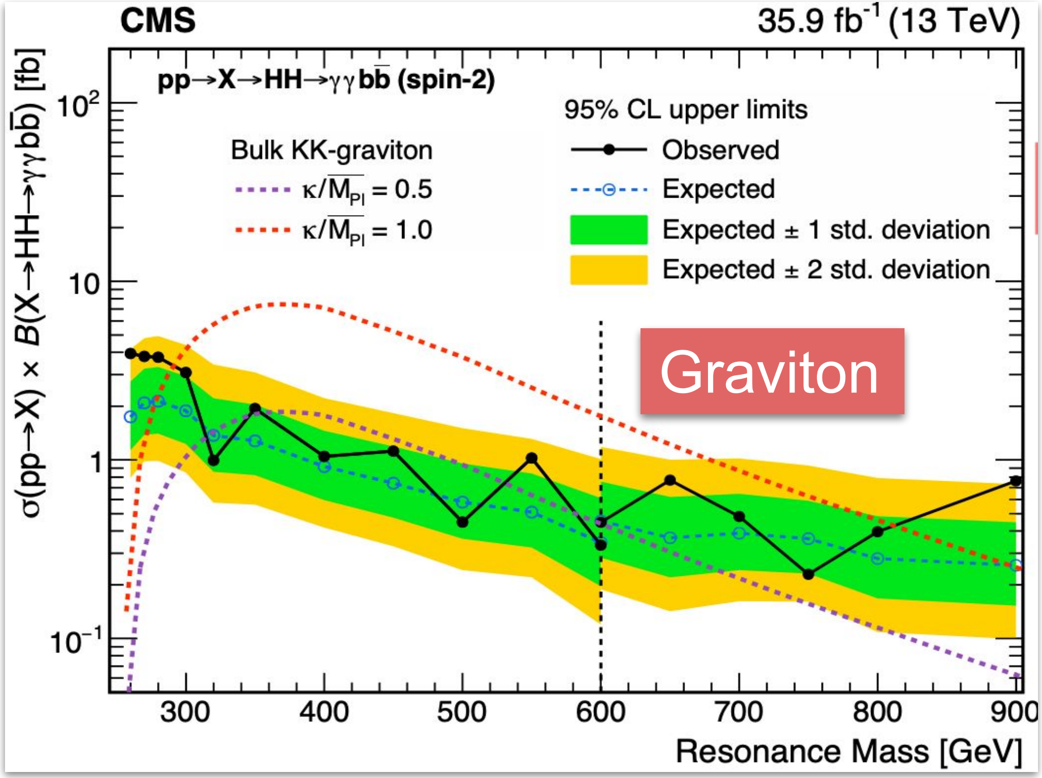
Resolved

$X \to HH \to bbbb$



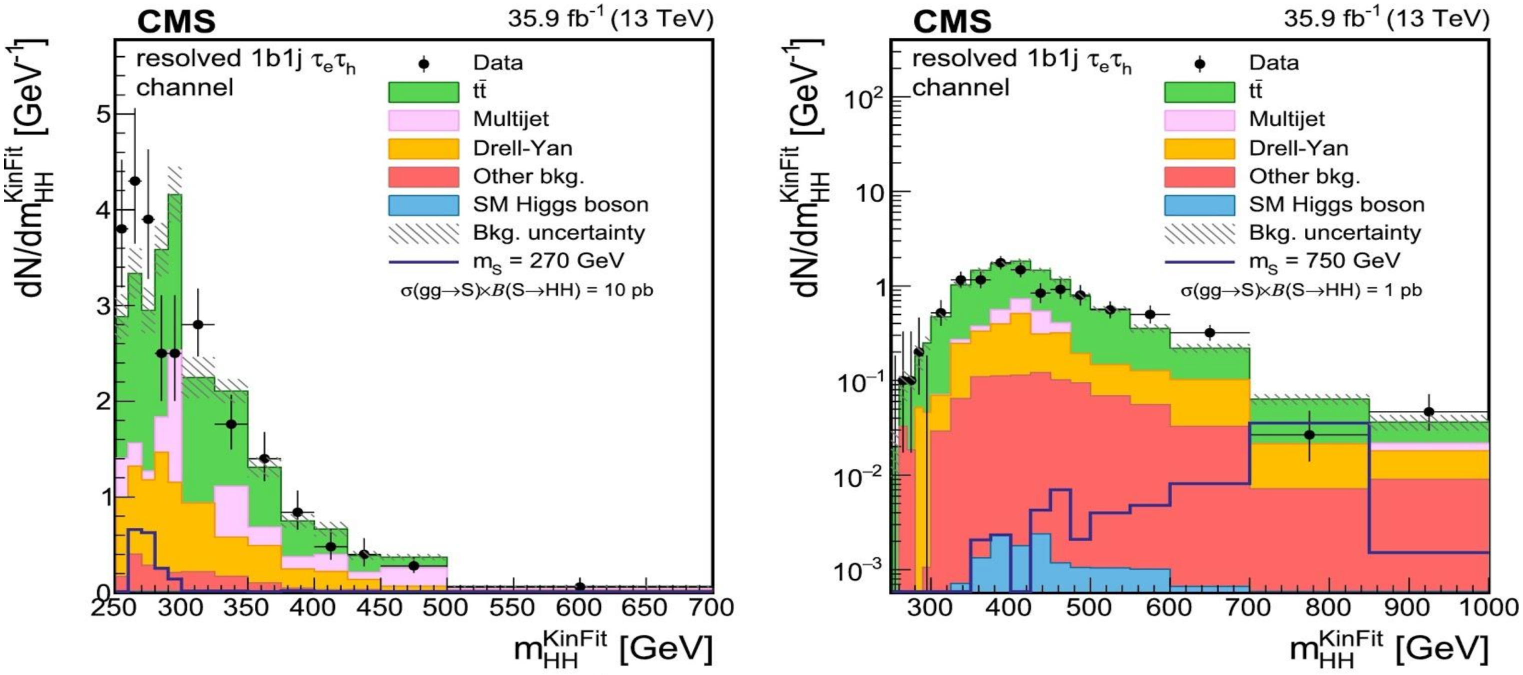
Semi-resolved + fully merged

X→ HH→ bbgg



CMS
35.9 fb-1 (13 TeV)
pp→X→HH→γγbb̄ (spin-2)
Bulk KK-graviton
κ/M̄Pl = 0.5
κ/M̄Pl = 1.0
95% CL upper limits
Observed
Expected
Expected ± 1 std. deviation
Expected ± 2 std. deviation
Graviton
σ(pp→X) × B(X→HH→γγbb̄) [fb]
Resonance Mass [GeV]

X→ HH→ bb$\tau\tau$



m_X with kinematic fit, used for limit extraction, resolved and semi resolved

$X \rightarrow HH \rightarrow bbll\nu\nu$

- Events can come from **W(lν)W(lν)** and **Z(ll) Z(νν)** final state along with bb final states
- Required to have two isolated and opposite sign leptons along with 2 b-tagged jets

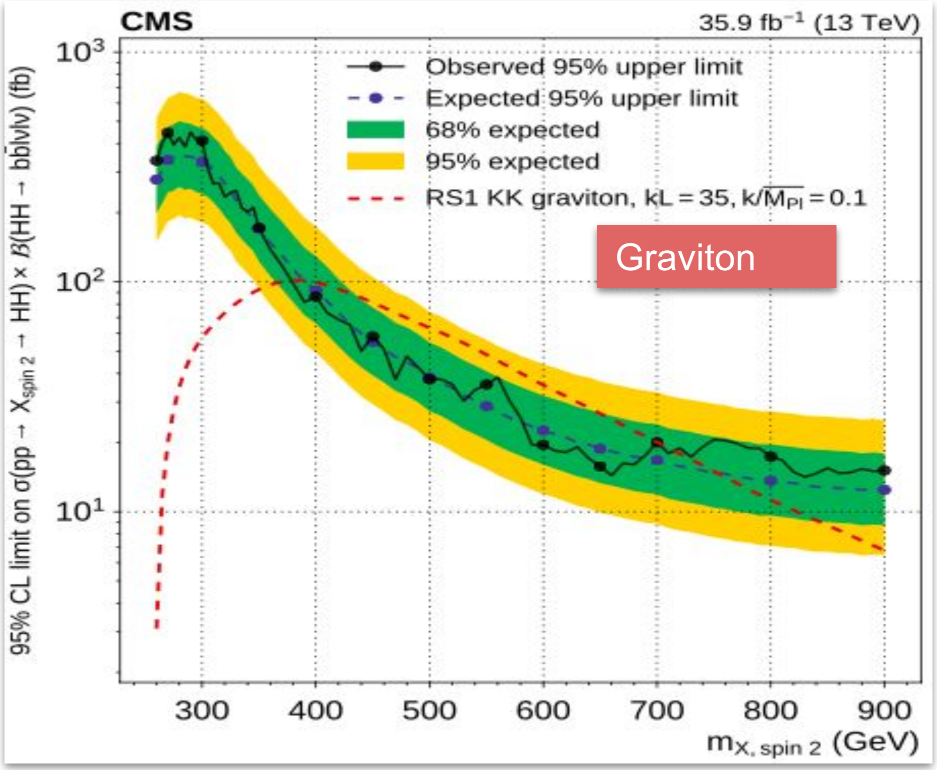
bbWW

- 3 channels: μμ, ee, μe/eμ
- Constraint not to select m_{ll} from Z-decay ⇒ $m_{ll} < m_Z$ - 15 GeV
- Parametric DNN is used to scan over different m_X values.
- DY from data-driven method, other background contribution from MC
- DNN output is used as final discriminant in different mass bins

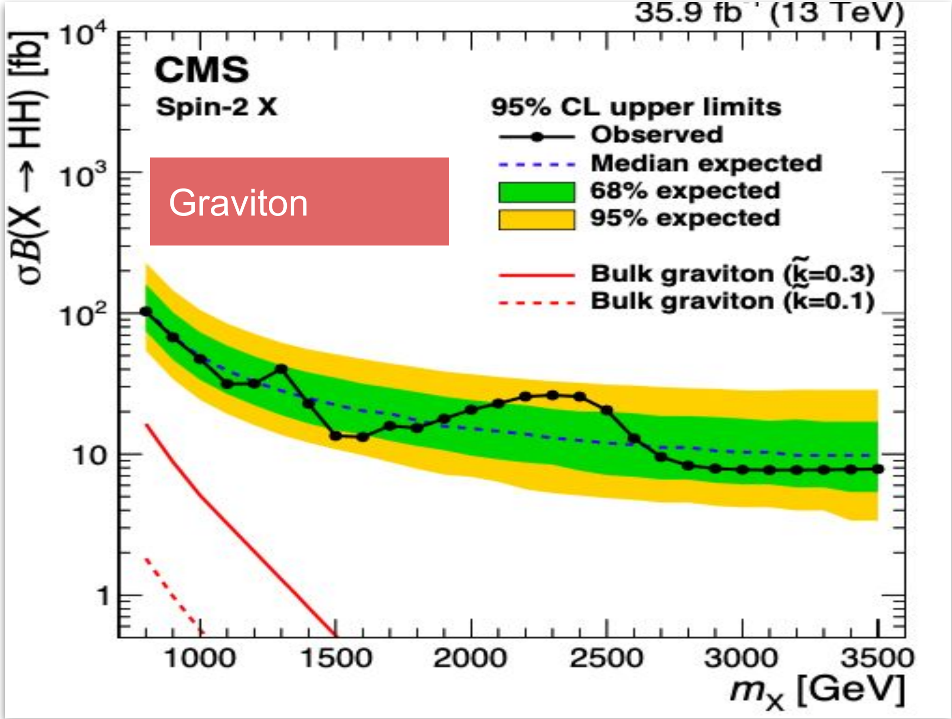
bbZZ

- 2 channels: μμ, ee
- Completely orthogonal to bbWW analysis by keeping constraint of $m_{ll} > 76$ GeV
- MET selection thus m_{ll} + MET + $m_{jj} \sim m_X$
- Main background : DY and ttbar
- Cut on BDT discriminant to increase $S/\sqrt{B}$
  - BDT training is performed in two mass regions: [250, 450] and [500, 900] GeV

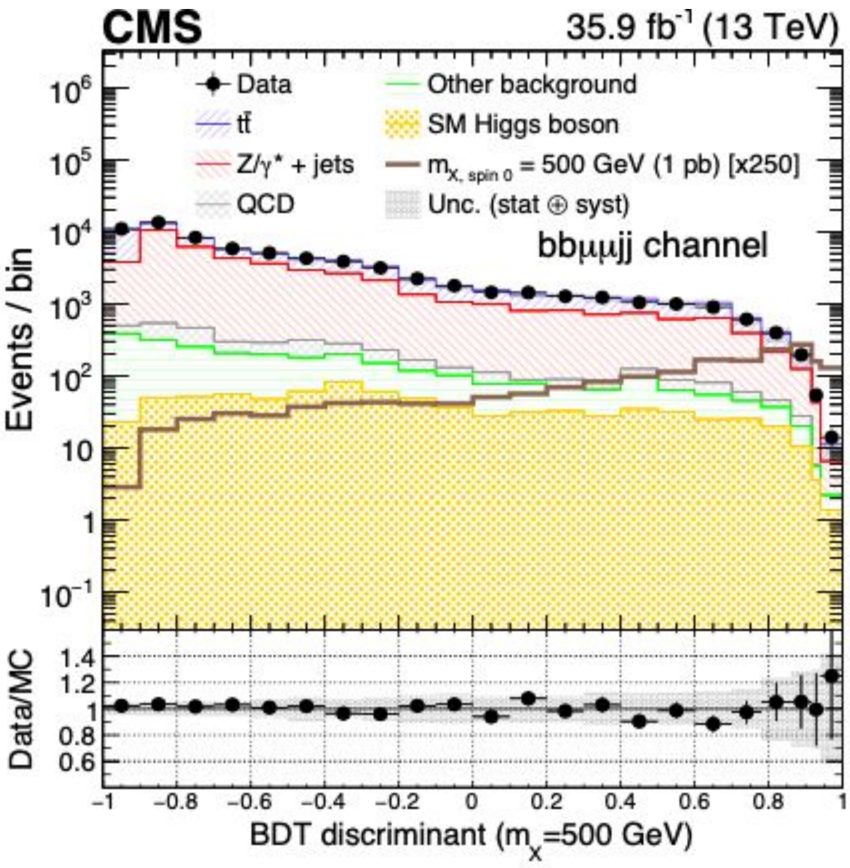
X→ HH→ bbll$\nu\nu$

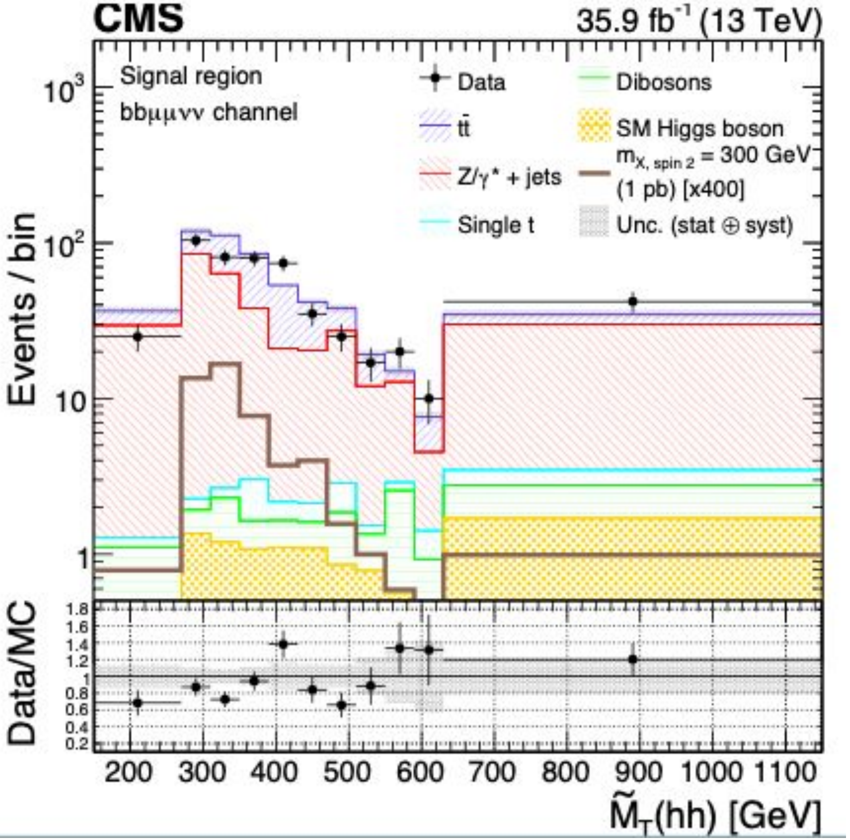


X→ HH→bbWW*→ bblνqq’



X→ HH→bbZZ*→ bbllqq





$M_T(hh) = \sqrt{E^2 - p_z^2}$, where E and p_z are the energy and the z component of the combined four-vector (bbll)

X→ HH→bbZZ*→ bbllqq