Multilepton searches for resonant *HH* production with CMS

T. Lange[1] on behalf of the CMS collaboration

[1] KBFI, Estonia

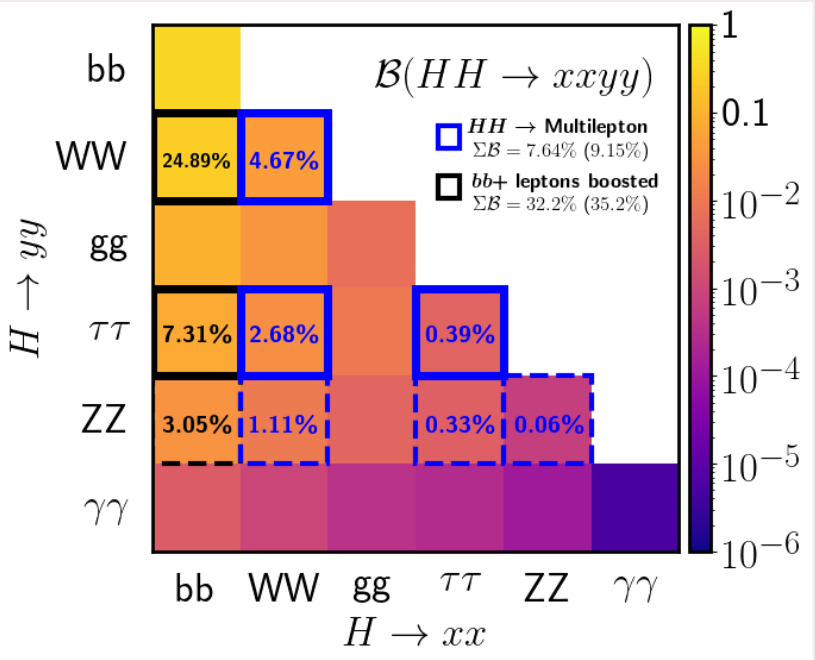
01.06.2022 — Higgs pairs workshop – Dubrovnik

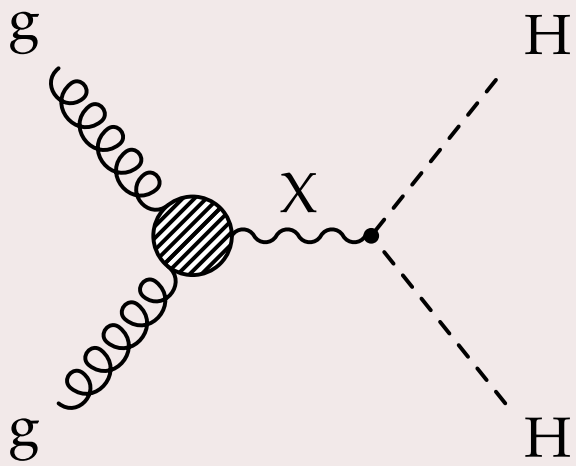
Introduction

Two lepton centered analysis looking for spin−0/spin−2 resonances (Radion/Graviton) decaying into Higgs Pairs:

HH Multilepton CMS PAS HIG-21-002

- First CMS analysis covering $HH \to VVVV$, $HH \to VV\tau\tau$ and $HH \to \tau\tau\tau\tau$ final states
- Covers resonant masses (m_X) $250\ GeV < m_X < 1000\ GeV$
- Very good at low m_X





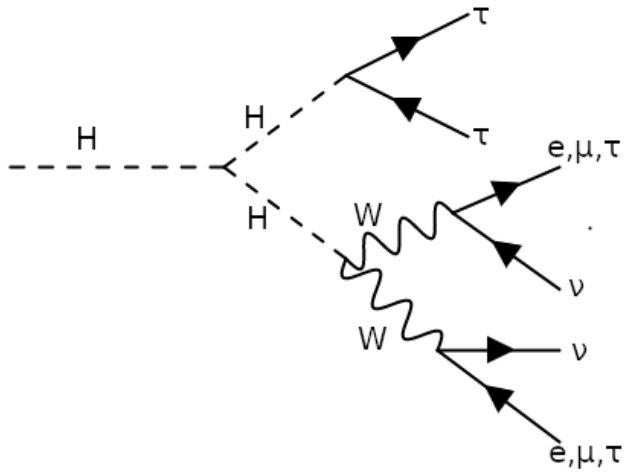
HH *bb*+leptons boosted
doi:10.1007/JHEP05(2022)005

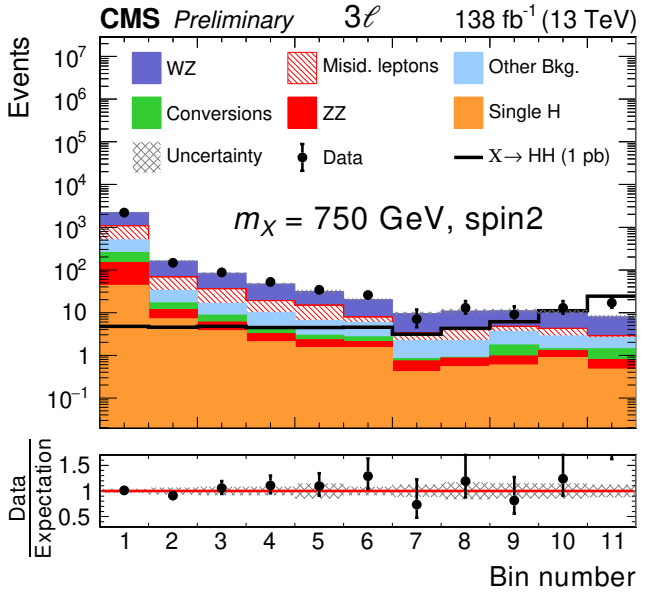
- Expansion of 2016 CMS $HH \to bb\ell\nu qq$ analysis
- Covers $0.8\ TeV < m_X < 4.5\ TeV$
- Strongest leptonic *HH* limits at high m_X

$HH \rightarrow$Multilepton – Strategy

Multilepton strategy:

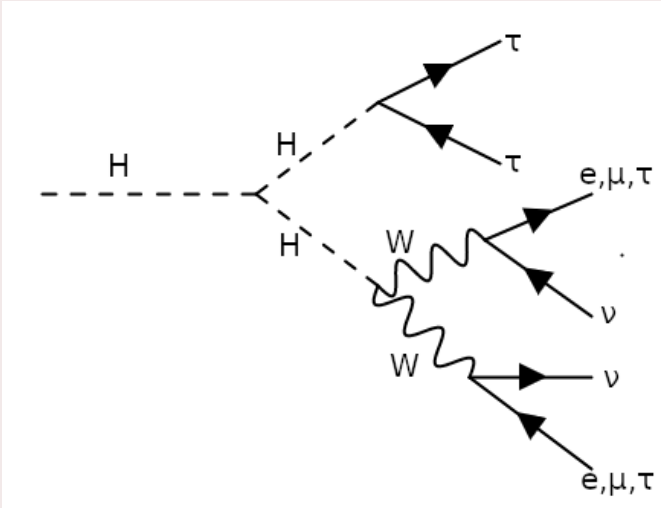
- Seven channels with multiple $\ell = e, \mu/\tau_h$:
  - 2ℓ (SS)
  - 3ℓ
  - 4ℓ
  - $3\ell + 1\tau_h$
  - $0\ell + 4\tau_h$
  - $1\ell + 3\tau_h$
  - $2\ell + 2\tau_h$
- Background both simulation + data-driven
- **Signal extraction on BDTclassifier output:**
  - Parametrized BDT on resonant mass for spin−0/spin−2 scenarios
  - 19 resonant masses $250 - 1000\ GeV$
  - Also non-resonant analysis on dedicated BDT
    (See talks by Allessandra/Julian and Xanda yesterday)





$HH \rightarrow$Multilepton – Event selection

- Combination of lepton and tau triggers
- $n\ \ell + m\ \tau_h$ $(n + m < 4)$
- e / μ: leptonMVA [doi:10.1140/epjc/s10052-021-09014-x]
- τ_h: deepTau [arXiv:2201.08458]
- Charge requirements: i.e. $Q(3\ell + 1\tau_h) = 0$
- AK4/AK8 jets in 2ℓ(ss) and 3ℓ ($W \rightarrow q\bar{q}$)
- b – jet veto:
  (deepJet [doi:10.1088/1748-0221/15/12/P12012])

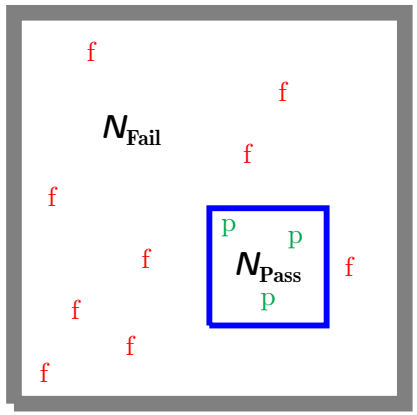


$\rightarrow$ Low yield categories $O(1) - O(10k)$ events $\rightarrow$ Misidentfied ℓ/τ_h, genuine ZZ and genuine WZ (3ℓ) as dominant backgrounds

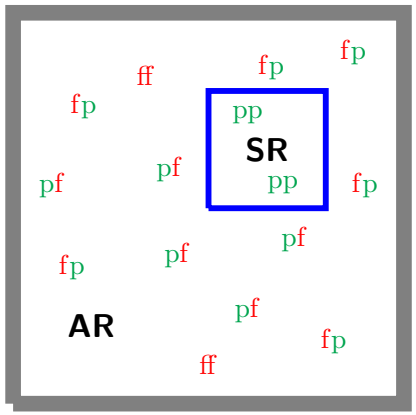
$HH \rightarrow$Multilepton – Background Estimation

Missidentification background: data driven

- Measurement region (MR): $f = \frac{N_{\text{pass}}}{N_{\text{pass}}+N_{\text{fail}}}$
- e/μ MR: QCD multijet
- τ_h MR: $Z/\gamma^* \rightarrow \mu\mu + jets$
- Application region: SR with Fakable Id ℓ/τ_h
- $F_i = \frac{f_i}{1-f_i}$



Measurement Region



Relaxed Signal Region

p := passing Tight ID

f := failing Tight ID but passing Fakable ID

$$N_{\text{pp}}^{\text{fake}} = \sum_{\text{fp}} F_1 + \sum_{\text{pf}} F_2 - \sum_{\text{ff}} F_1 F_2$$

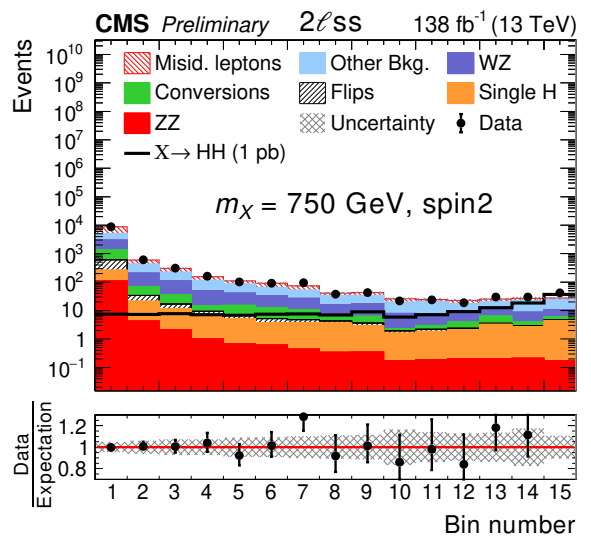
Charge flip background: data driven ($Z/\gamma^* \rightarrow ee$)
Other background + signal: simulation

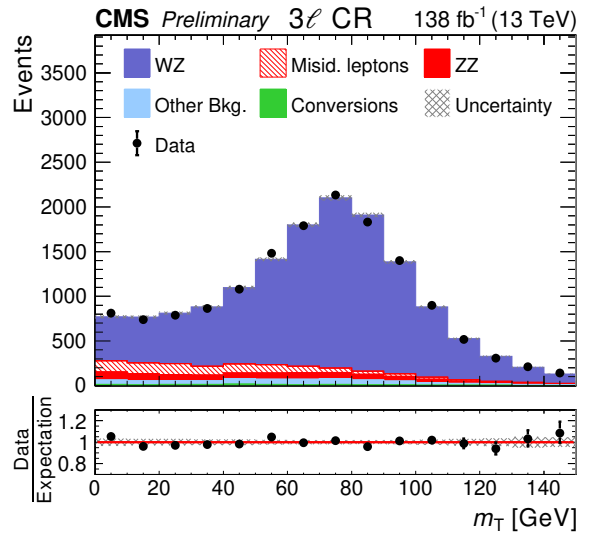
BDT training

- Separate training for each category
- Kinematic variables like angular separation of $\ell/\tau_h/j$, visible di-Higgs mass, missing transverse energy
- Variables decorrelated from m_X

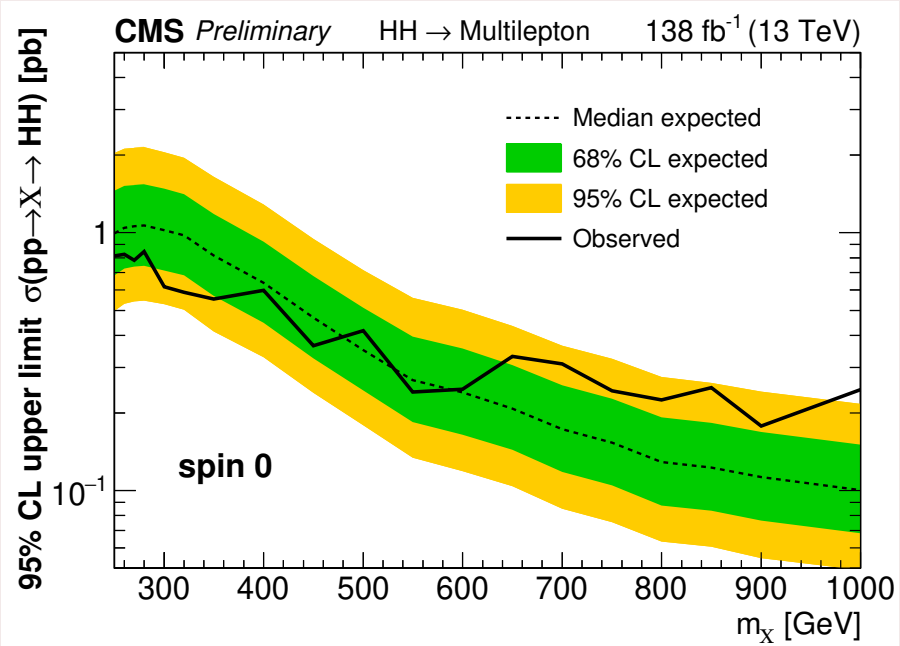
Signal extraction

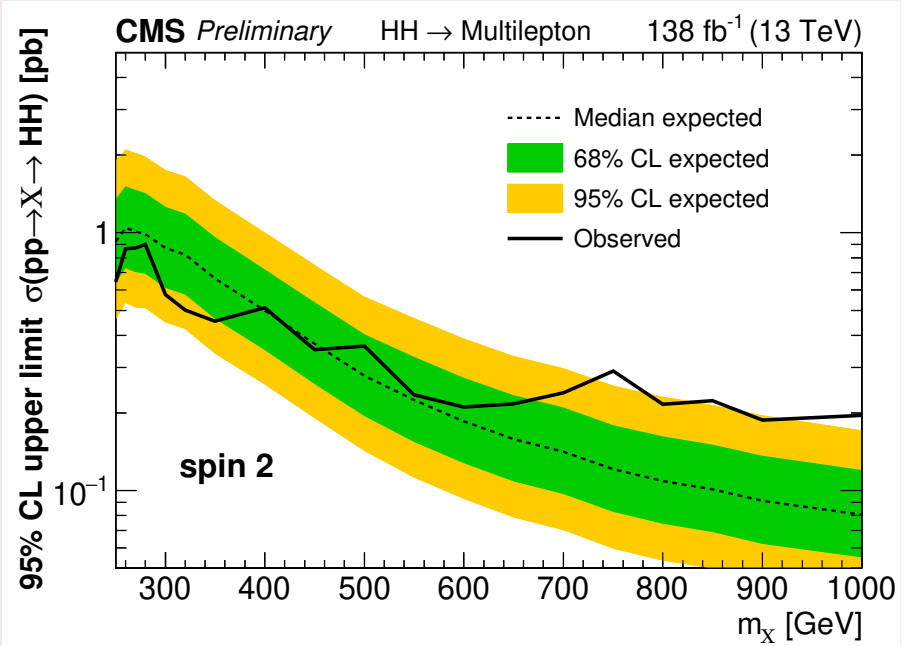
- Fit to 7 BDT outputs/year for given mass
- Two control regions/year for genuine WZ/ZZ included
- No signal yet $\rightarrow$ Asymptotic limits





$HH \rightarrow$Multilepton – Results

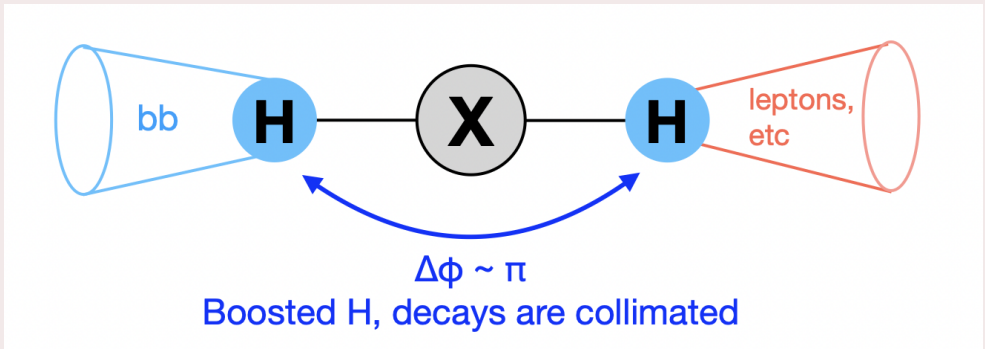


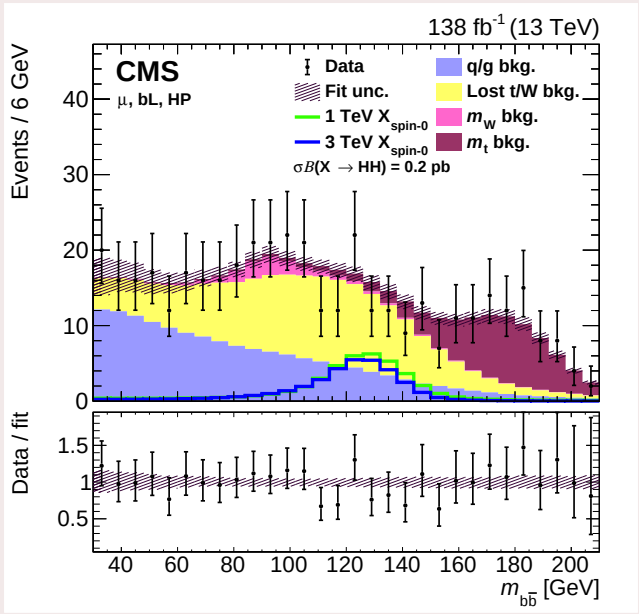


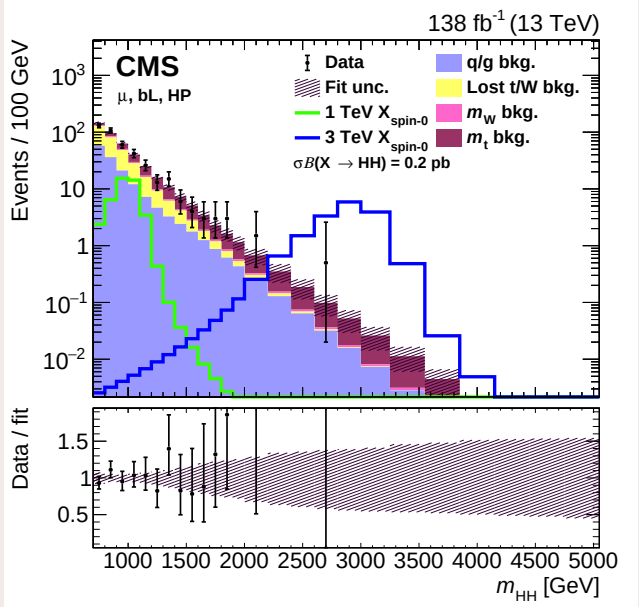
- No statistically significant excess
- Overall (expected) limits on $\sigma(pp \rightarrow X \rightarrow HH)$: 0.18 to 0.90 (0.08 to 1.07) pb

HH bb+leptons – boosted Strategy:

- Single lepton (SL) and (NEW!) Di-Lepton (DL)
- Reconstructs $m_{b\bar{b}}$ and m_{HH}
- 4 background templates ($m_{b\bar{b}}$ shape) + 1 signal template
- 2D template fit to m_{bb}, m_{HH} in 12 = 8 (SL) + 4 (DL) categories

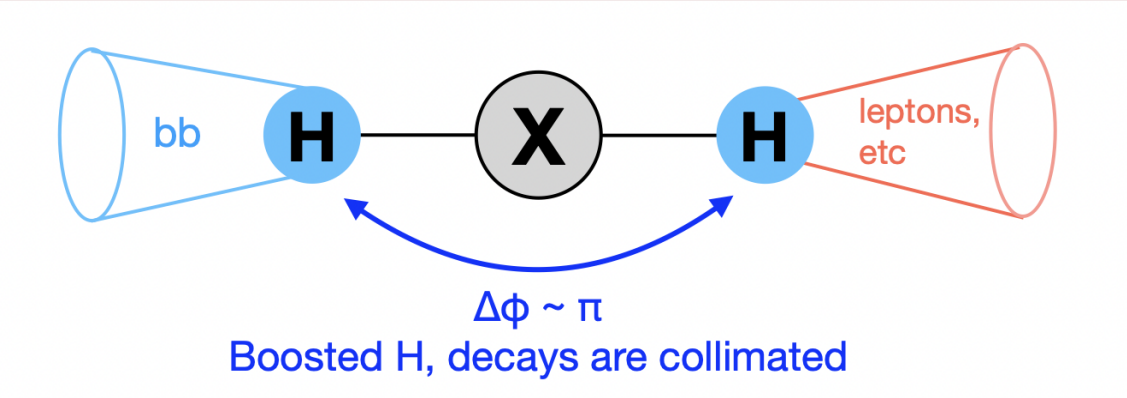






HH bb+leptons – boosted – Event selection

- Single lepton and H_T triggers



- $H \to b\bar{b}$:
  - AK8 jet with $p_T > 200\ GeV$
  - $b-$tagged
    DeepAK8 $Z/H \to b\bar{b}$ tagger [doi:10.1088/1748-0221/15/06/P06005]
  - No additional $b-$tagged AK4 jets (deepJet [doi:10.1088/1748-0221/15/12/P12012])
- $H \to W^*W$ / $H \to \tau\tau$:
  - SL: e/μ + additional AK8 jet ($W \to q\bar{q}'$)
  - DL: 2 e/μ
  - 2nd. Higgs decay products opposite $b\bar{b}$ jet

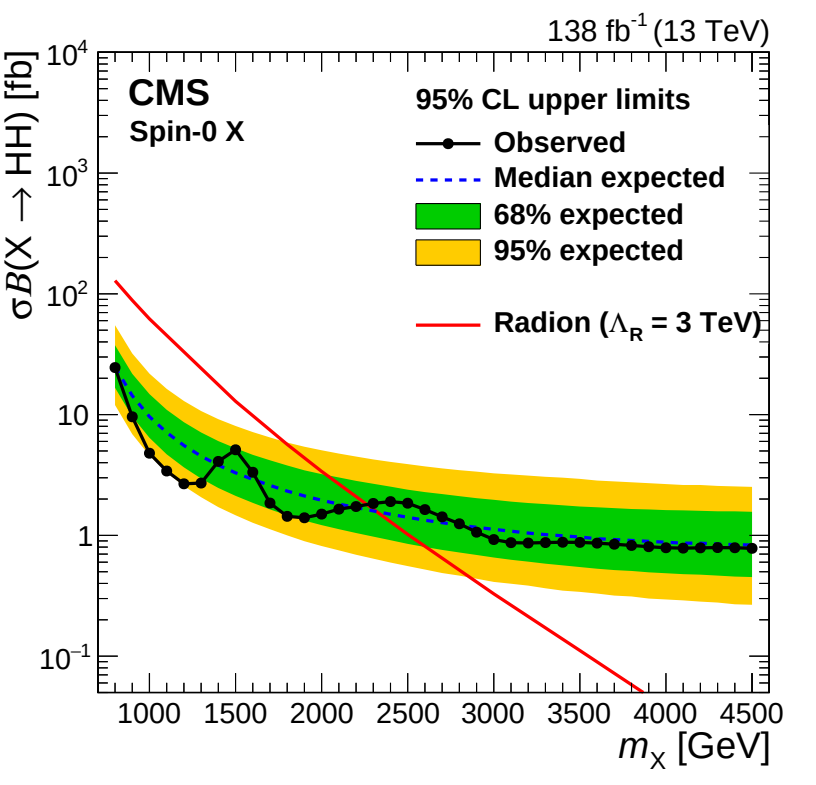
SL: $H \to W^*W \to \ell\nu q\bar{q}'$

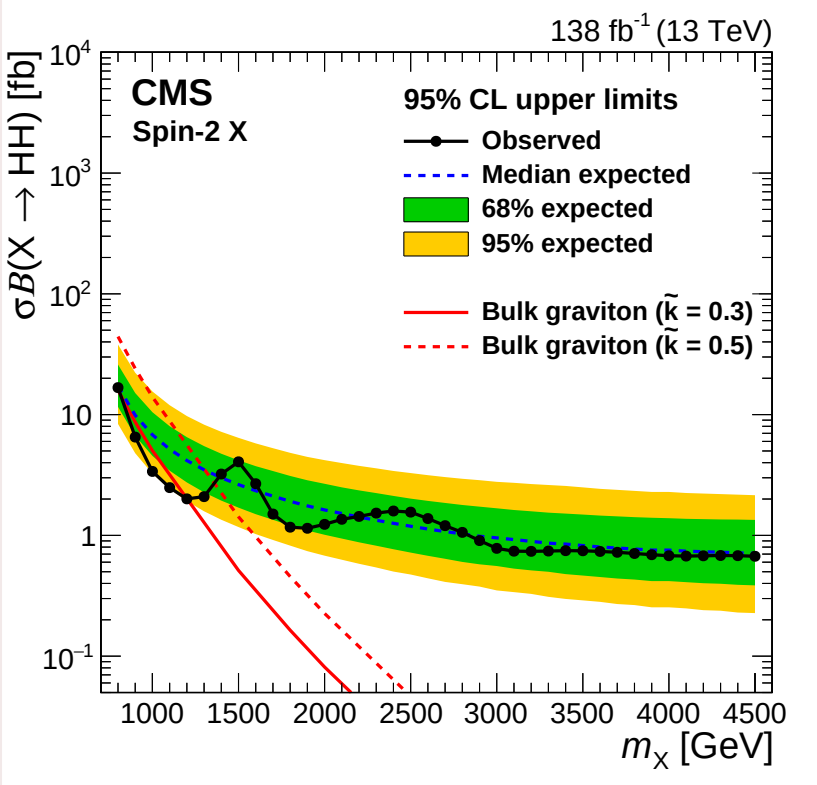
- Likelihood fit on $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} + q\bar{q}'$ jet
- 5 parameters:
  - $\vec{p}_{\nu}$: Neutrino momentum components
  - $R_{q\bar{q}'}$: Jet response correction
  - $V_{q\bar{q}}$: boolean W^* or W?
- $\to$ Full $H \to W^*W$ four momentum
- $p_{b\bar{b}}$ / $m_{b\bar{b}}$: $b\bar{b}$ sub-jets

DL: $H \to W^*W \to \ell\nu\ell\nu'$ / $H \to \tau\tau \to \ell\nu\ell\nu'$

- Boosted: p_{inv} (ν) from $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ and $\ell\ell$ direction
  - $p_{\mathrm{T}}^{\mathrm{inv}} = p_{T}^{\mathrm{miss}}$, $\theta_{\mathrm{inv}} = \theta_{\ell\ell}$
  - $m_{\mathrm{inv}} = 55\ GeV$ (mean from simulation)
- $p_{b\bar{b}}$ / $m_{b\bar{b}}$: $b\bar{b}$ sub-jets

HH *bb*+leptons – boosted – Results





- Overall limits on $\sigma(pp \to X \to HH)$: 24.5 fb to 0.67 fb
- 6 – 14 $\times$ more sensitive than previous result
- Main gain: DL channel, 70% more sensitive than SL at low mass and similar at high mass

Summary

- Two new lepton focused HH analysis with strong limits!
- New $HH \rightarrow$Multilepton covers new HH final states
  - ML fit on parametrized BDT discrimminant for seven sub-categories and 2 control regions
  - Data driven backgrounds for misidentified ℓ/τ_h and charge flip ℓ + simulation for WZ/ZZ and other genuine backgrounds
  - Covers 250 $GeV < m_X <$ 1000 GeV with strong limits at very low m_X!
- Optimized HH bb+leptons – boosted analysis:
  - Template fit to $m_{b\bar{b}}$ and m_{HH}
  - New: di-lepton channel with more sensitivity than single lepton
  - Covers 800 $GeV < m_X <$ 4.5 TeV, strongest limits for leptonic HH searches!

Thank you!

Backup

$HH \rightarrow$Multilepton – Event selection (Detailed)

- Combination of single–/double–/triple lepton trigger + lepton+tau cross trigger and double tau triggers
- Require $n\ \ell + m\ \tau_h$ $(n + m < 4)$
- Three Ids (deepTau [arXiv:2201.08458] + leptonMVA [doi:10.1140/epjc/s10052-021-09014-x]):
  - Loose: Z–boson and low $m_{\ell\ell}$ veto + orthogonality/cleaning
  - Medium/Fakable: Background estimation (next Slide)
  - Tight: Signal region requirement
- Charge required to fit hypothesis i.e. $Q(3\ell + 1\tau_h) = 0$
- AK4/AK8 jets in 2ℓ(ss) and 3ℓ ($W \rightarrow q\bar{q}$)
- Veto b – jets (deepJet [doi:10.1088/1748-0221/15/12/P12012])

$\rightarrow$ Low yield categories $O(1) - O(10k)$ events $\rightarrow$ Misidentfied ℓ/τ_h, genuine ZZ and genuine WZ (3ℓ) as dominant backgrounds

HH bb+leptons – boosted – Event selection (Detailed)

- Single lepton / H_T / multi-object + H_T triggers
- $H \to b\bar{b}$: AK8 jet with $p_T > 200\,GeV$
  - 2 sub-jets $p_T > 20\,GeV$
  - $b-$tagged
    DeepAK8 $Z/H \to b\bar{b}$ tagger [doi:10.1088/1748-0221/15/06/P06005]
- Veto on additional $b-$tagged AK4 jets (deepJet [doi:10.1088/1748-0221/15/12/P12012])
- SL channel:
  - e/μ $p_T > 30/27\,GeV$ + additional AK8 jet $(q\bar{q}')$ $p_T > 50\,GeV$
  - Close to lepton: $\Delta R(\ell, q\bar{q}') < 1.2$
  - Opposite bb: $\Delta R(b\bar{b}, q\bar{q}') > 1.6$, $\Delta\phi(\ell, b\bar{b}) > 2$
  - QCD supression: $|\eta_\ell| < 1.479$ (ECAL boundary)
  - Additional criteria on $H \to W^*W$ purity
- DL channel:
  - 1 e/μ $p_T > 30/27\,GeV$ + 1 e/mu $p_T > 10 GeV$
  - Opposite $b\bar{b}$: $\Delta\phi(\ell\ell, b\bar{b}) > 2$
  - Additional criteria on $p_T^{miss}/m_{\ell\ell}$

Categorization:

- SL categories:
  - Lepton Flavor: e or μ
  - $b\bar{b}$ tagging: loose (bL) or tight (bT)
  - $H \to W^* W$ purity:
    low purity (LP) or high purity (HP)
    (τ_2/τ_1 subjetiness + Likelihood discriminant)
- DL categories:
  - Lepton flavor: $ee/\mu\mu$ (SF) or $e\mu$ (OF)
  - $b\bar{b}$ tagging: loose (bL) or tight (bT)

Signal extraction templates:

- m_t bkg: 3 gen lvl quarks from t decay in $m_{b\bar{b}}$
- m_W bkg: 2 gen lvl quarks from W decay in $m_{b\bar{b}}$ (both from W)
- lost W/t bkg: 1/2 gen lvl quarks from t/W decay in $m_{b\bar{b}}$
- q/g bkg: No gen lvl quarks from t/W decay in $m_{b\bar{b}}$
- HH signal