Di-Higgs Searches

from the experimental view

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Di-Higgs Day @ Konkuk University, 27 Jun 2019

Hot Issue

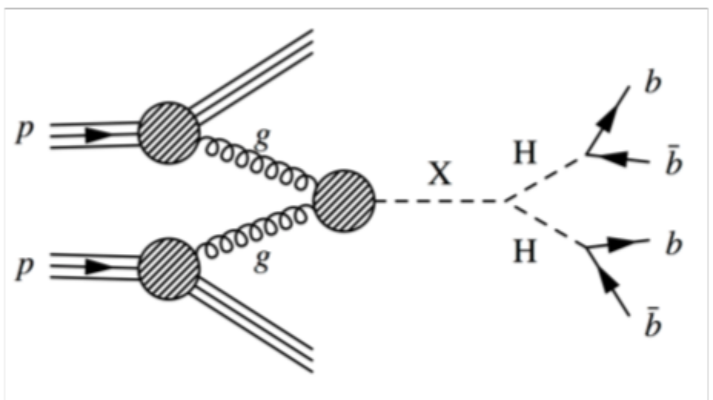
- Di-Higgs production is one of hot topics in Higgs physics group in consideration of SM or BSM
- Interesting final states from two Higgs bosons: bbbb/bbWW/bb$\tau\tau$/bb$\gamma\gamma$/bbZZ/WW$\gamma\gamma$/WWWW
- Higgs self-coupling measurement predicted in the SM is challenging at LHC in 10 years : σ_{ggF}(pp→HH)=33.5 fb @ 13 TeV in NLO QCD
- Currently searches have been performed for both SM & BSM scenarios
    - LHC run2 (pp@$\sqrt{s}$=13 TeV with $\int\mathscr{L}$~150 fb^{-1})
    - HighLuminosity LHC (2026~2035, $\int\mathscr{L}$~3 ab^{-1})

Subdecays (CMS)

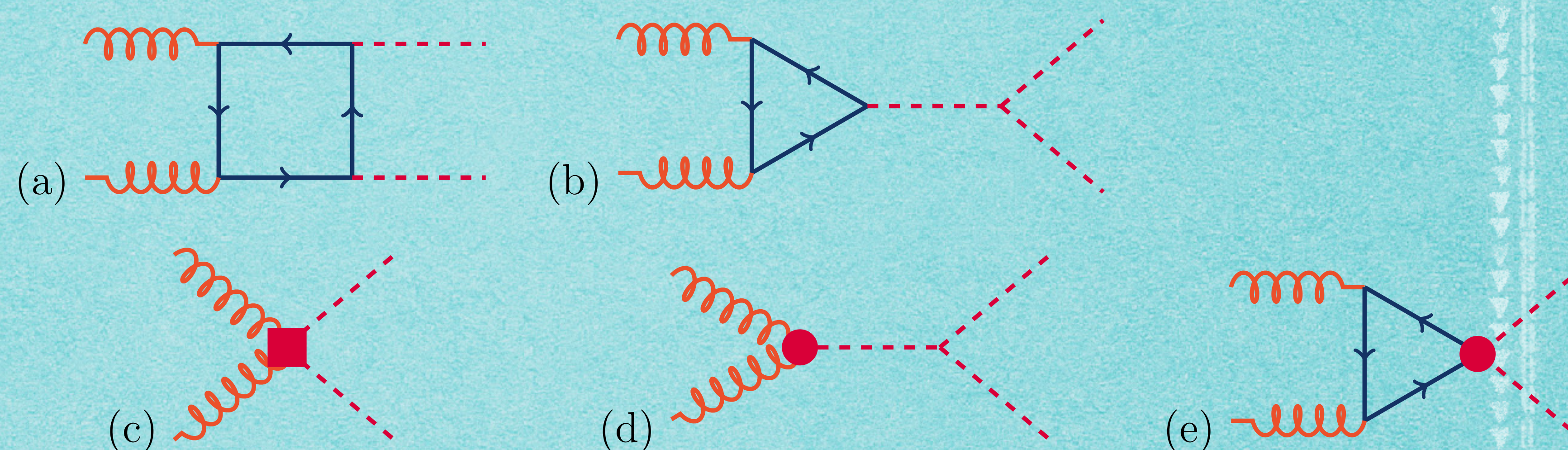
- HIG-16-002: Search for H(bb)H(bb) decays using the 2015 data sample
- HIG-16-011: Search for H(WW)H(bb) decays using the 2015 data sample
- HIG-16-012: Search for H(bb)H($\tau\tau$) decays from non-resonant production
- HIG-16-013: Search for H(bb)H($\tau\tau$) decays from resonant production
- HIG-16-024: Search for the non resonant HH process with Webb decays using 2015 data
- HIG-16-026: Search for non-resonant pair production of Higgs bosons in the bbbb final state with 13 TeV CMS data
- HIG-16-028: Search for H(bb)H($\tau\tau$) decays from non-resonant production (2016)
- B2G-16-008: Search for HH in the 4b final state
- B2G-16-026: Search for HH resonances in the 4b final state - PLB
- HIG-16-029: Search for H(bb)H($\tau\tau$) decays from resonant production (2016)
- HIG-16-032: Search for H(bb)H($\gamma\gamma$) decays at 13 TeV
- HIG-17-002: HH(bb$\tau\tau$) with 2016 dataset - PLB
- HIG-17-006: HH(bbWW) with 2016 dataset - JHEP
- HIG-17-008: HH(bb$\gamma\gamma$) with 2016 dataset - PLB HIG-17-009: HH(bbbb) resonant with 2016 dataset - JHEP
- HIG-17-017: Non resonant HH in 4b - JHEP
- HIG-17-030: Combination of HH analyses with 2016 dataset - PRL
- HIG-17-032: Search for resonant double Higgs production with bbZZ decays in the bbll$\nu\nu$ final state
- B2G-17-019: Search for resonant and non resonant production of HH to 4b in boosted topologies - JHEP
- B2G-18-008: Search for HH in the qqbblnu final state - JHEP

Quick Reminder

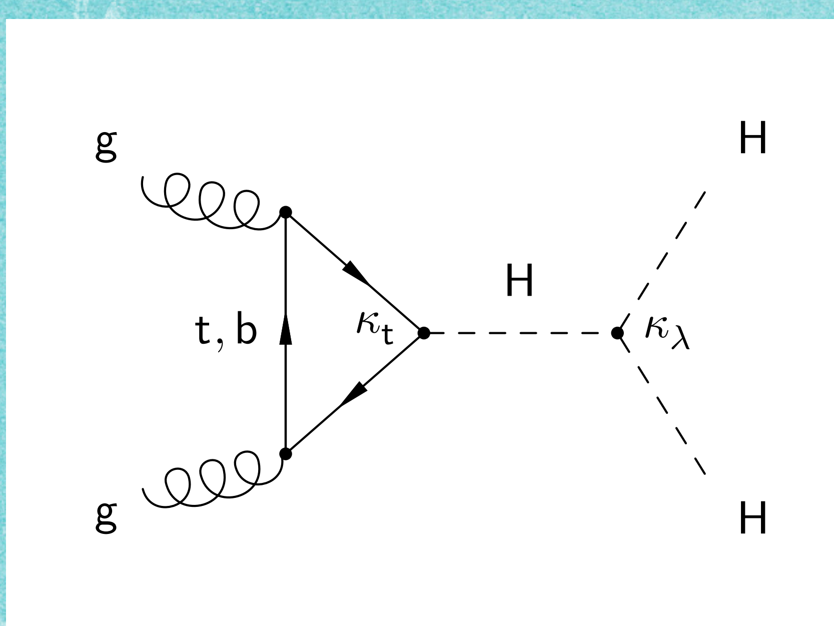
Resonant

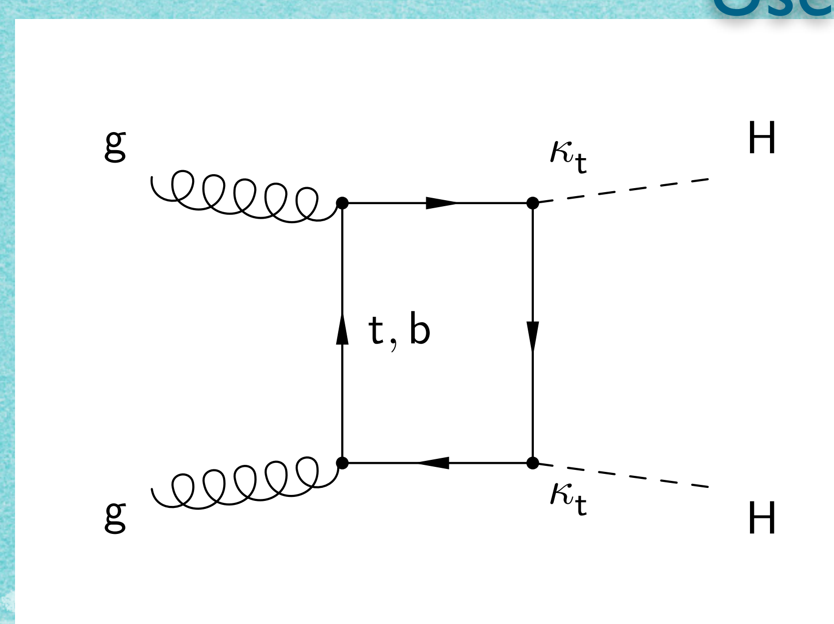


non-Resonant LO



Use various interpolation method to fill between samples





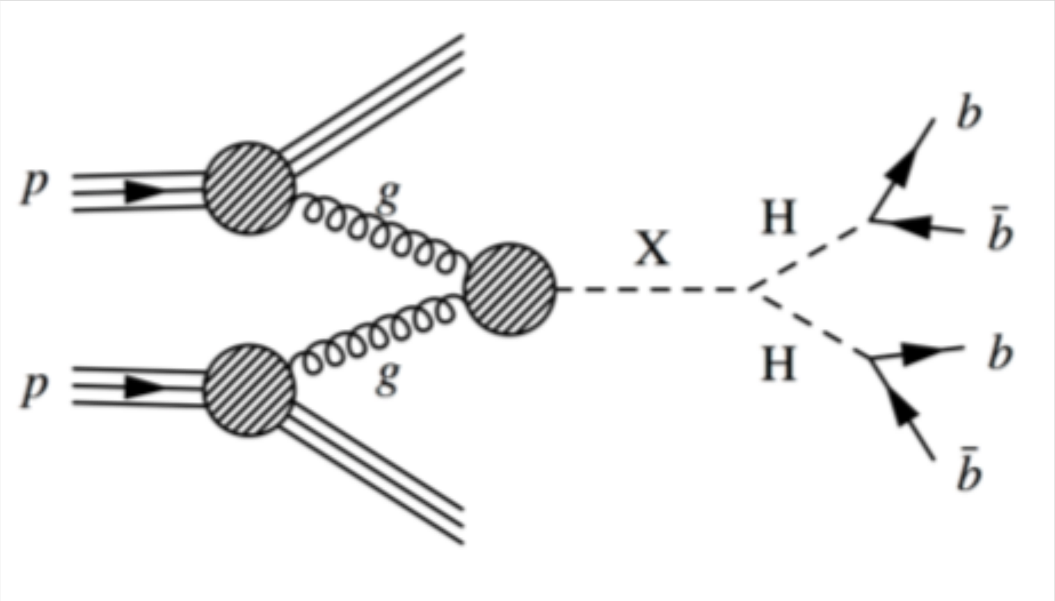
$\kappa_\lambda = \lambda_{HHH} / \lambda_{SM}$

$\kappa_t = y_t / y_{SM}$

B(HH→4b)=33.9%

Resonant HH→bbbb

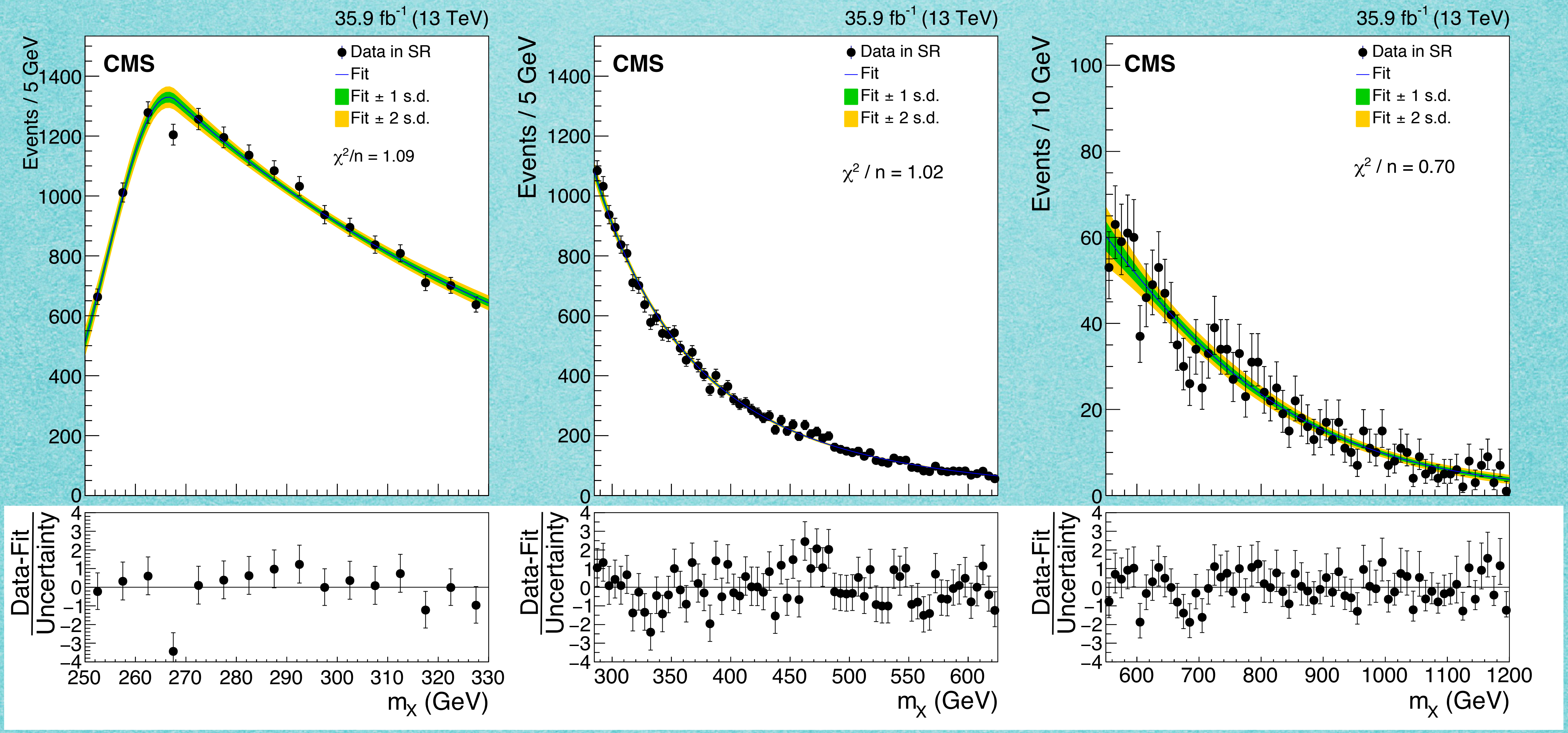
JHEP 08 (2018) 152, arXiv: 1806.03548



- 1000 times smaller xsec than the single H production
- 300<m(X)<500 GeV: (N)MSSM
- m(X)>500 GeV: spin-0 Radion and spin-2 KK-Graviton in warped extra dimensions
- 4 b-tagged jets : two di-jet pairs consistent with Higgs mass
- Looking in 260GeV—1.2TeV m(X) range
- m(X) resolution improved by kinematic constraint
  - B-tagged jet energy regression & m(H1)=m(H2) constraint
- QCD background estimation done by fit the data m(X) distribution

Resonant HH⟶bbbb (cont'd)

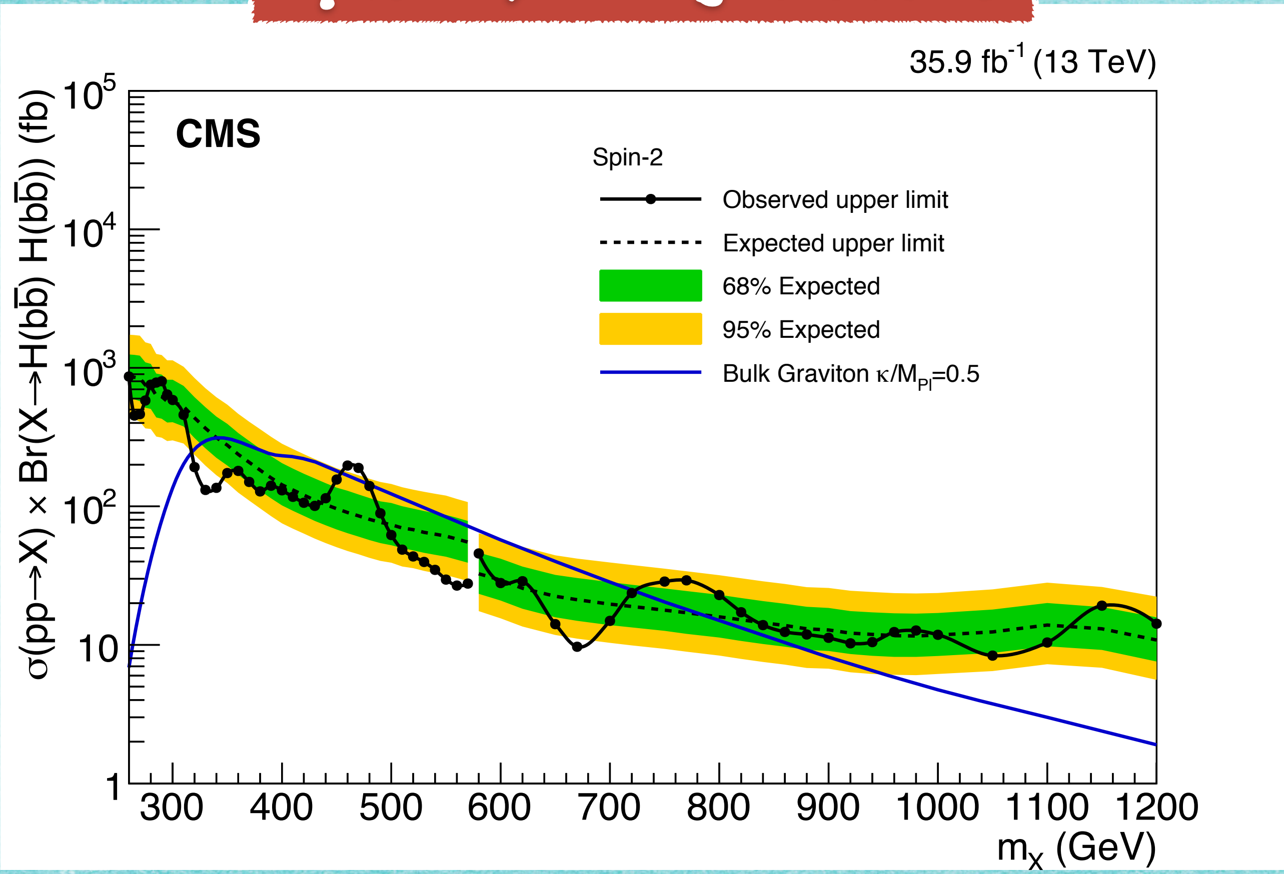
m(X→HH→4b) distribution



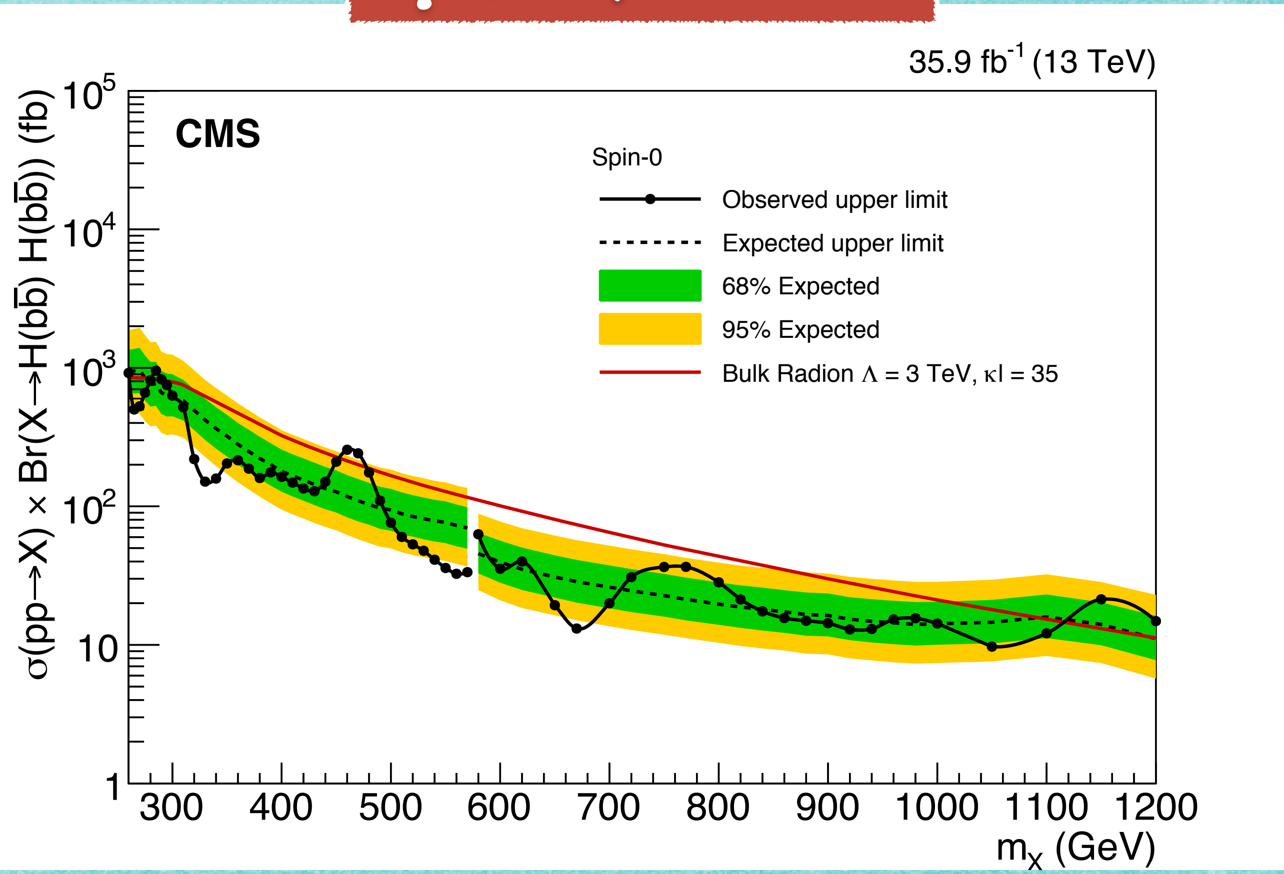
Resonant HH→bbbb (cont'd)

Cross section limits vs. m(X)

Spin-2, KK-graviton



Spin-0, Radion

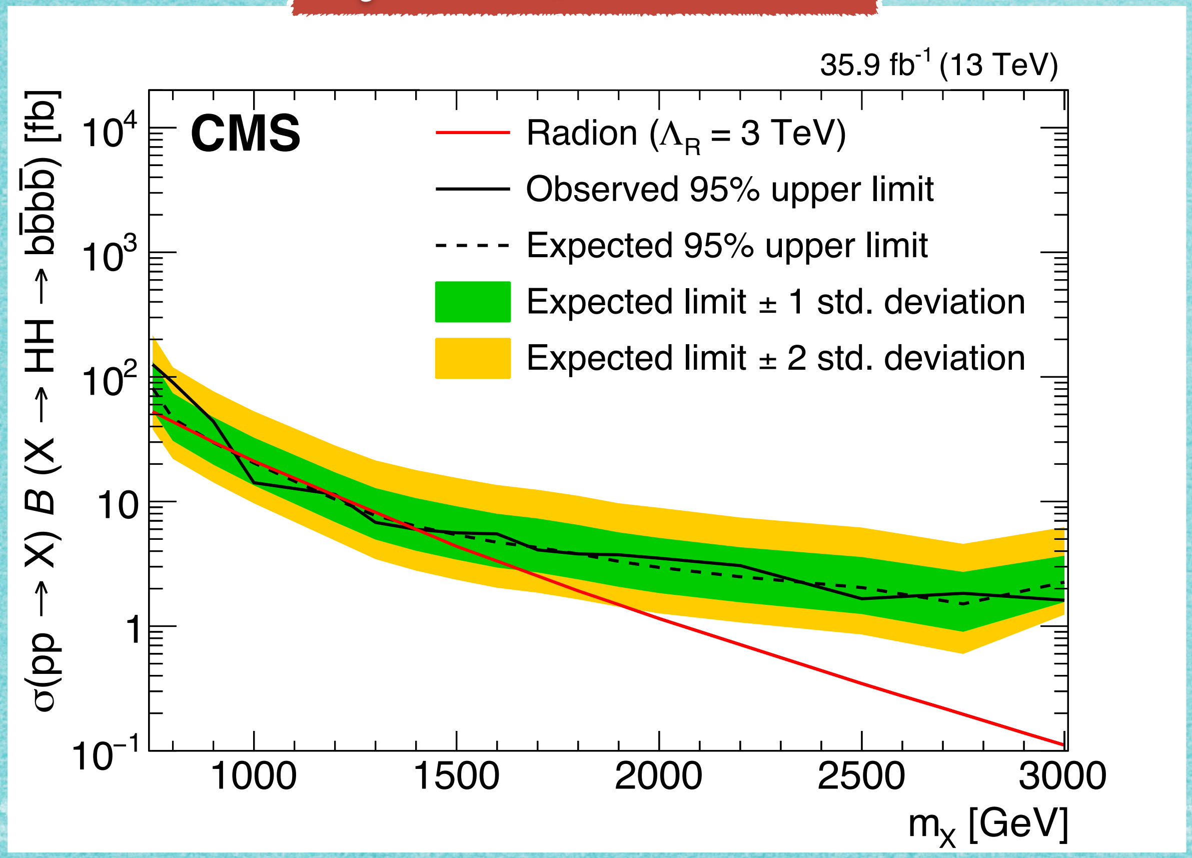


Resonant HH→bbbb Boosted

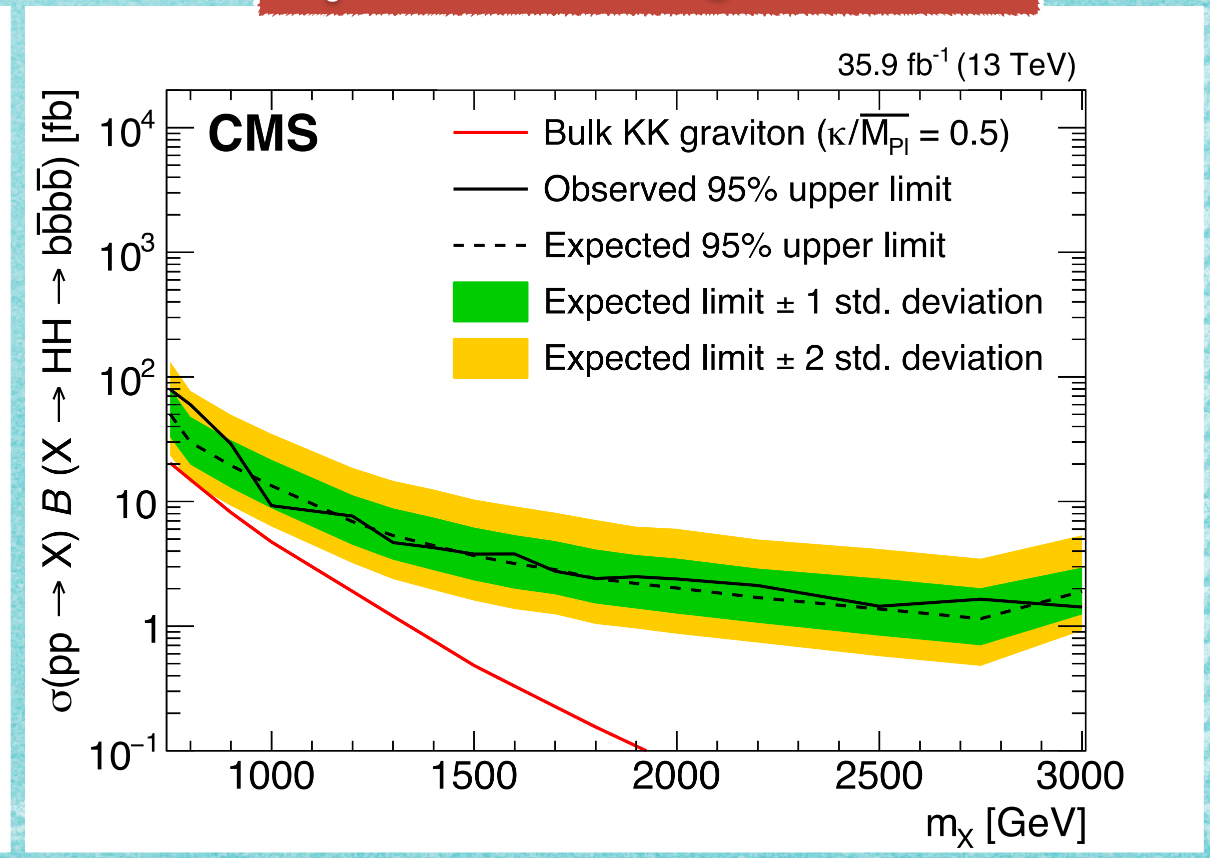
Phys. Lett. B 781 (2018) 244, arXiv:1710.04960

- Use fat-jet with R=0.8, p_T>300 GeV, $|\eta|$<2.4
- Leading two jets are Higgs tagged (double b requirement in the jet) & $|\Delta\eta(j1,j2)|$<1.3
- Results obtained by the fit on a reduced mass ($=m_{jj}-(m_{j1}-m_H)-(m_{j2}-m_H)$) distribution

Spin-0, Radion

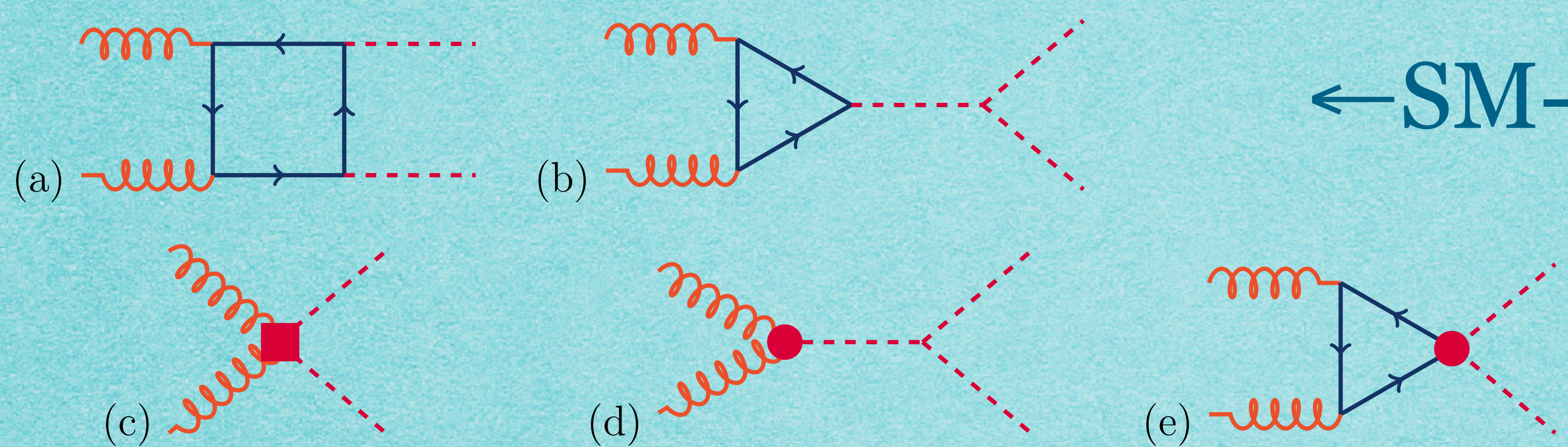


Spin-2, KK-graviton



NonResonant HH⟶bbbb

JHEP 04 (2019) 112 ,arXiv: 1810.11854



←SM-like

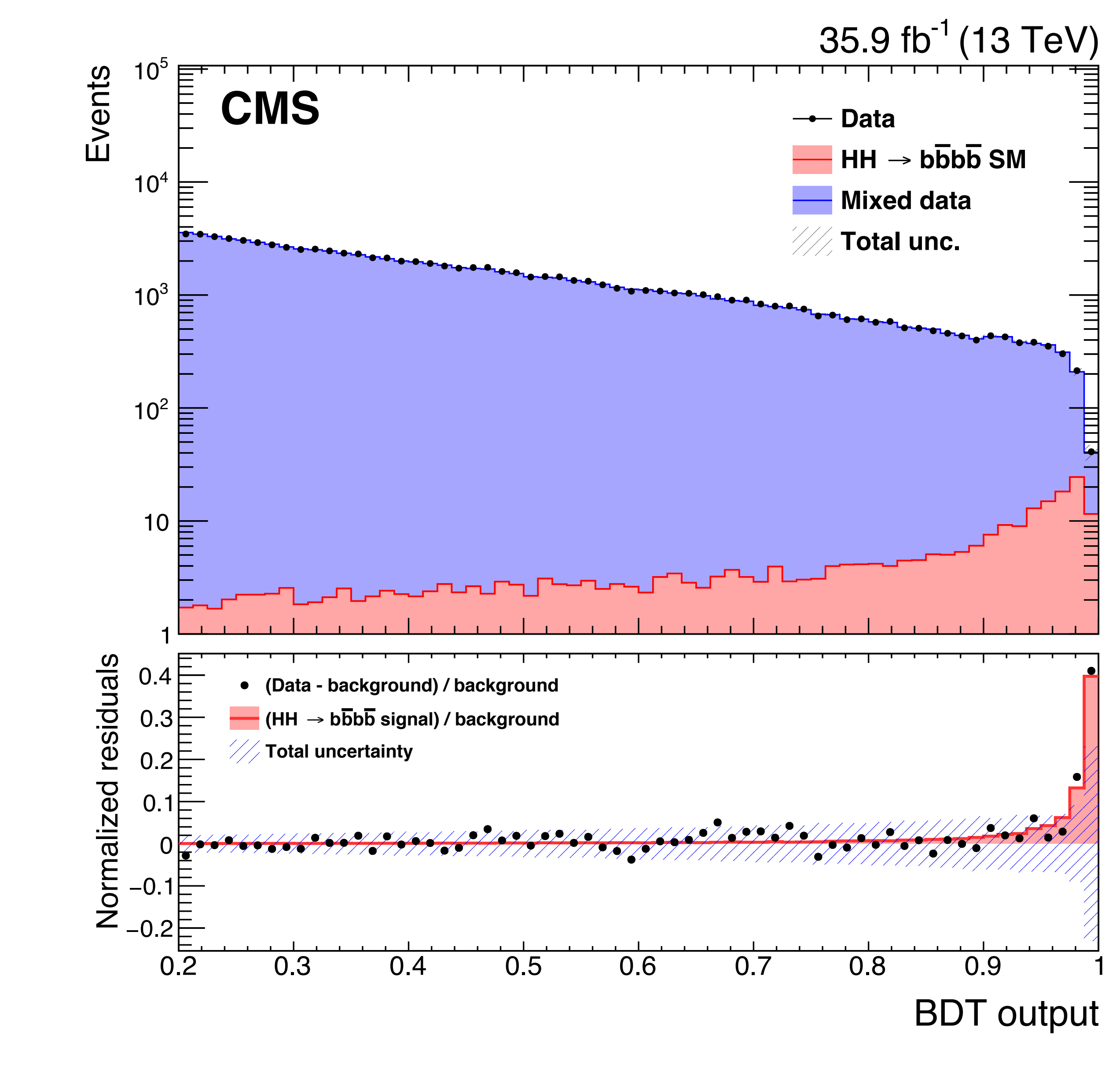
←BSM effects

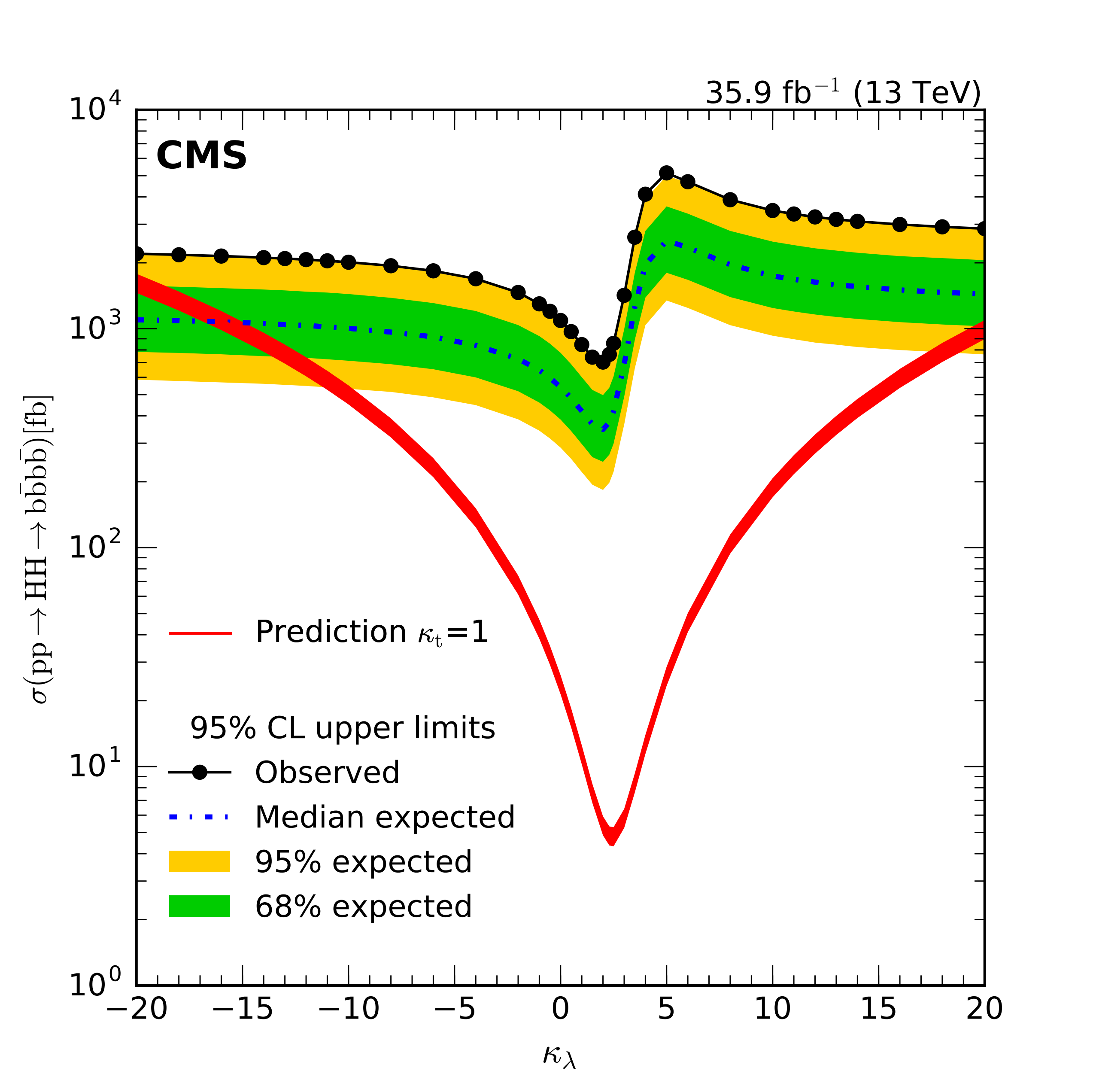
- Selection: 4 jets with highest b-tag score & pT>30 & $|\eta|<2.4$
- 4 jets pairing with minimum Δm(H1,H2)
- After careful checks on the data-driven background estimation, fit on a BDT output to find the signal

NonResonant HH→bbbb (cont'd)

Category	Observed	Expected	-2 s.d.	-1 s.d.	+1 s.d.	+2 s.d.
SM HH → $b\bar{b}b\bar{b}$	847	419	221	297	601	834

(fb)



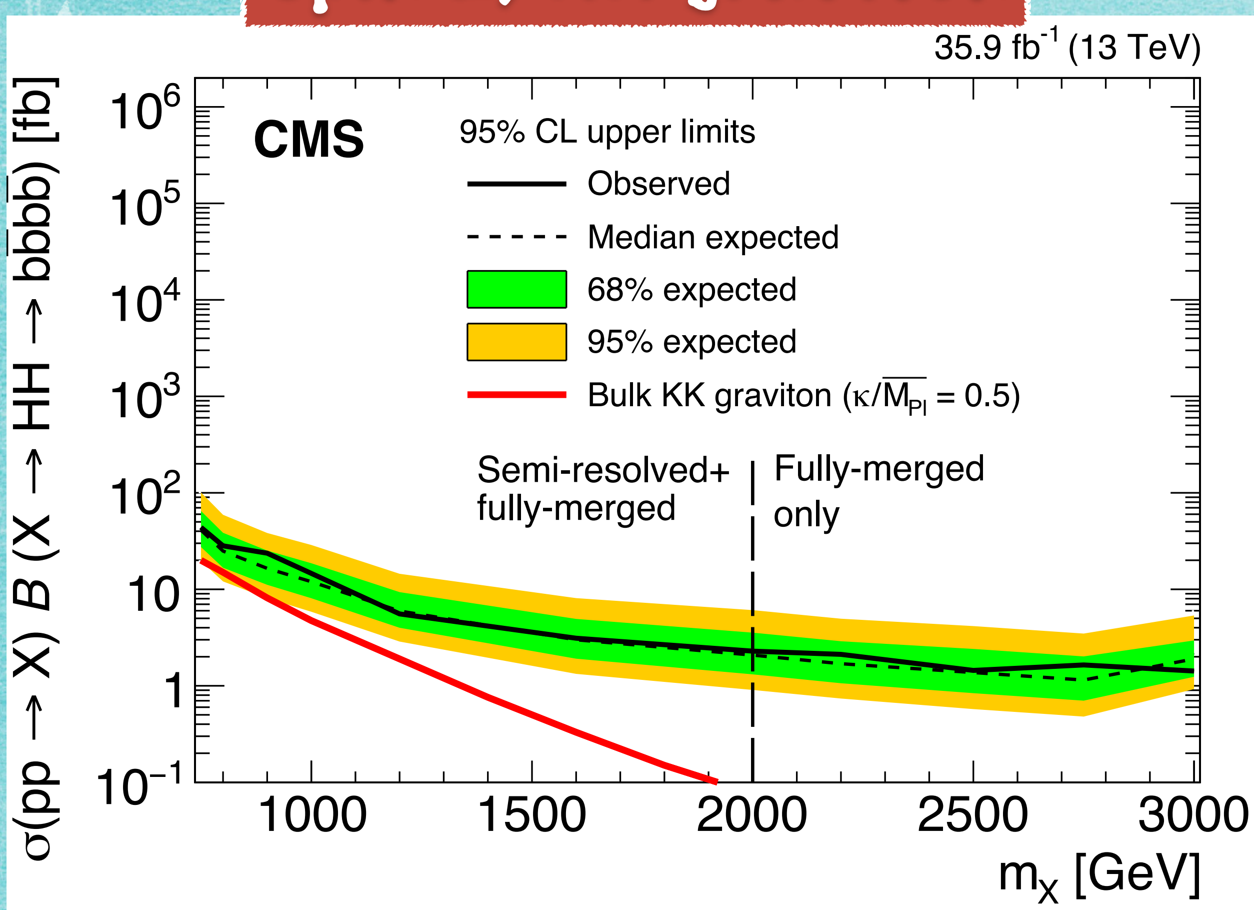


(H→)HH→4b

JHEP 01 (2019) 040, arXiv:1808.01473

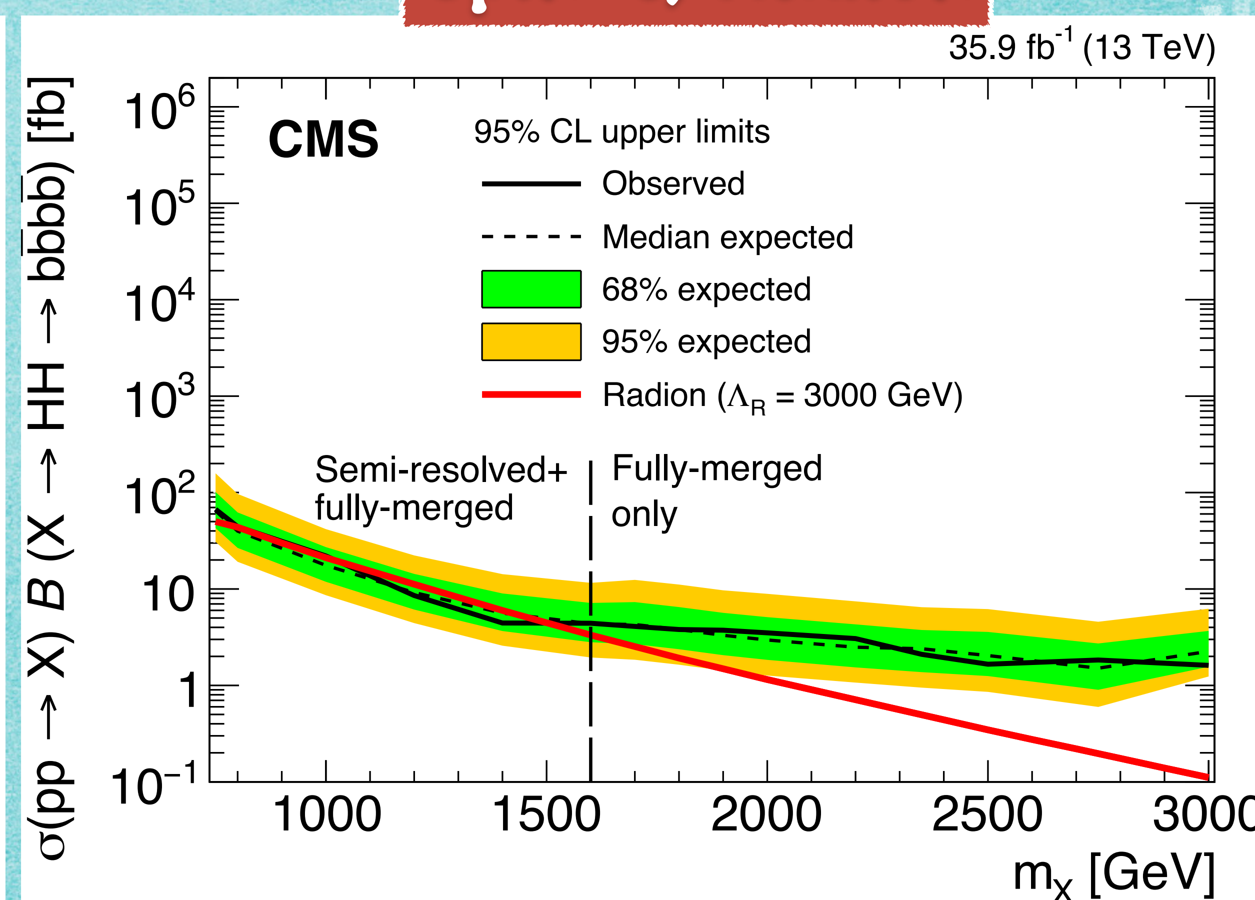
- Search performed requiring one AK8 jet (boost) and two b-tagged jets (resolved)

Spin-2, KK-graviton



18—7% improved

Spin-0, Radion



55—8% improved

Analysis strategy in a nutshell $HH \to bbVV \to bbl\nu l\nu$

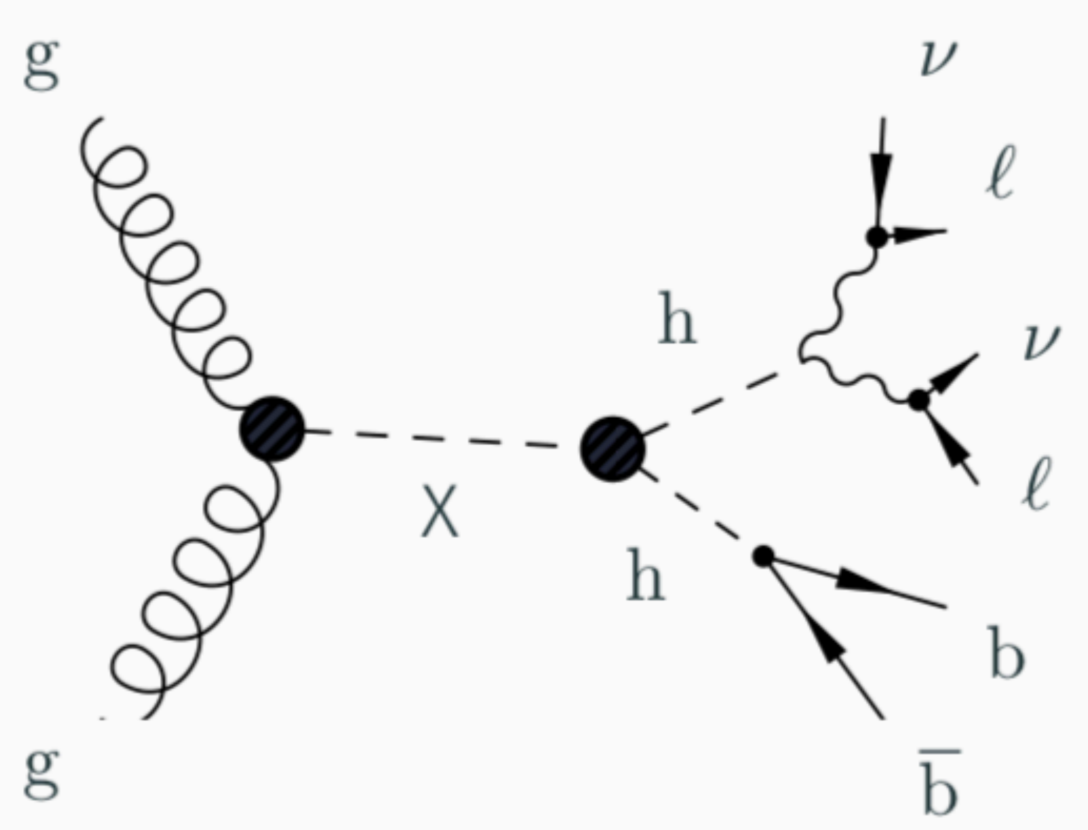
JHEP 01 (2018) 054, arXiv:1708.04188

Signal features

- $h(b\bar{b})$ side: resonant in m_{jj}
- $h(WW)$ side: $\not{E}_T$ (not fully reconstructible)

Background situation

- leading irreducible background: $t\bar{t}$
- subleading background: DY ($\sim$ 10%)
- subsubleading: single top, VV, ttV, SMHiggs, etc.



Overall strategy, for both resonant and nonresonant analyses

1. Select two leptons and two b-jets, below Z peak: $m_{ll} < m_Z - 15$ GeV
2. Estimate all bkg but DY (in *ee* and $\mu\mu$) from MC (rely on good understanding of $t\bar{t}$)
3. Train MVA on kin. variables (without m_{jj}) to discriminate signal and bkg
4. Final discriminant: m_{jj} vs MVA

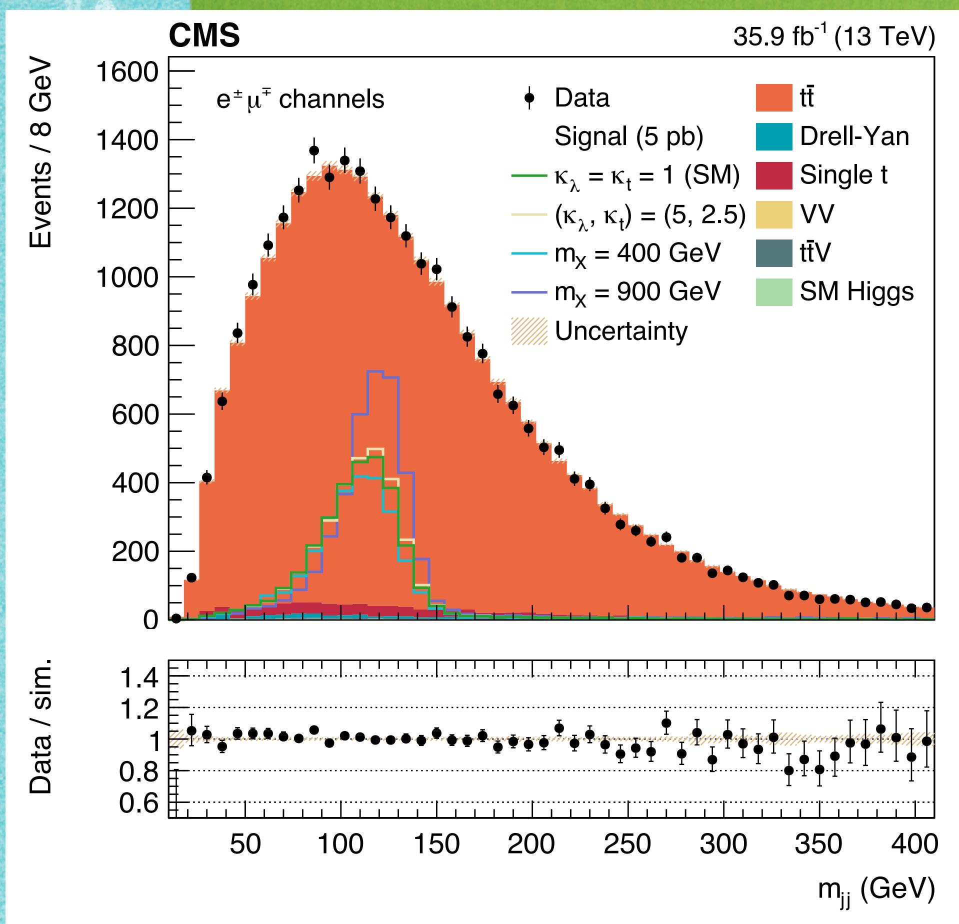
$HH \to bbVV \to bbl\nu l\nu$ (cont'd)

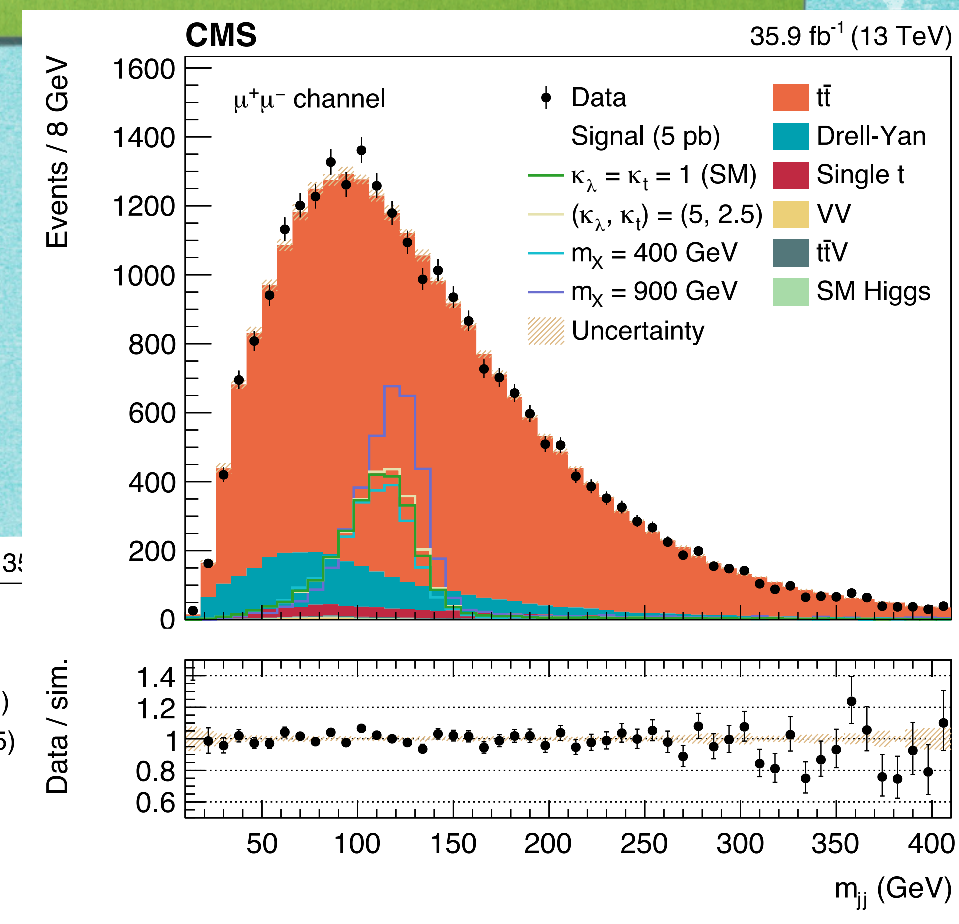
- Event Selection
  - p_T-leading and OS lepton pair (ee/eμ/$\mu\mu$)
  - 12 GeV < m_{ll} < m_Z - 15 GeV
  - Two jet pair with highest b-tag score sum & each jet satisfying p_T>20 GeV and $|\eta|$<2.4
- Main background tt - rely on the tt MC
- Drell-Yan background suffer from low MC stat - use data-driven method
  - DY+HF fraction among entire DY events obtained using BDT

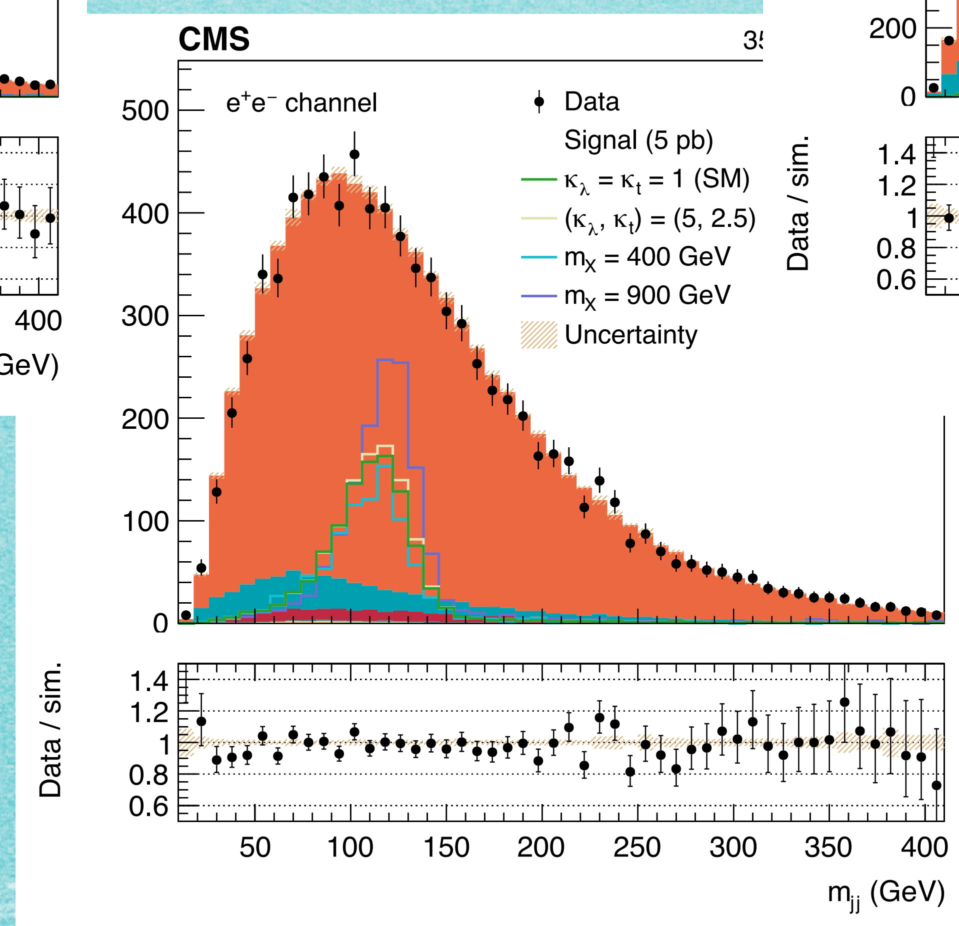
HH→bbVV→bblνlν (cont'd)

- Deep Neural Network discriminators based on Keras with TensorFlow
  - Inputs: m_{ll}, ΔR_{ll}, ΔR_{jj}, $\Delta\varphi(ll,jj)$, p_T^{ll}, p_T^{jj}, $\min(\Delta R_{jl})$ and transverse mass (ll,MET)
  - Parameterized network used for resonant and non resonant case separately
    - Resonant case: mass of resonance (260—900 GeV), SF vs. OF
    - Nonresonant case: κ_λ, κ_t, and SF vs. OF

$HH \rightarrow bbVV \rightarrow bbl\nu l\nu$: BDT input m_{jj}





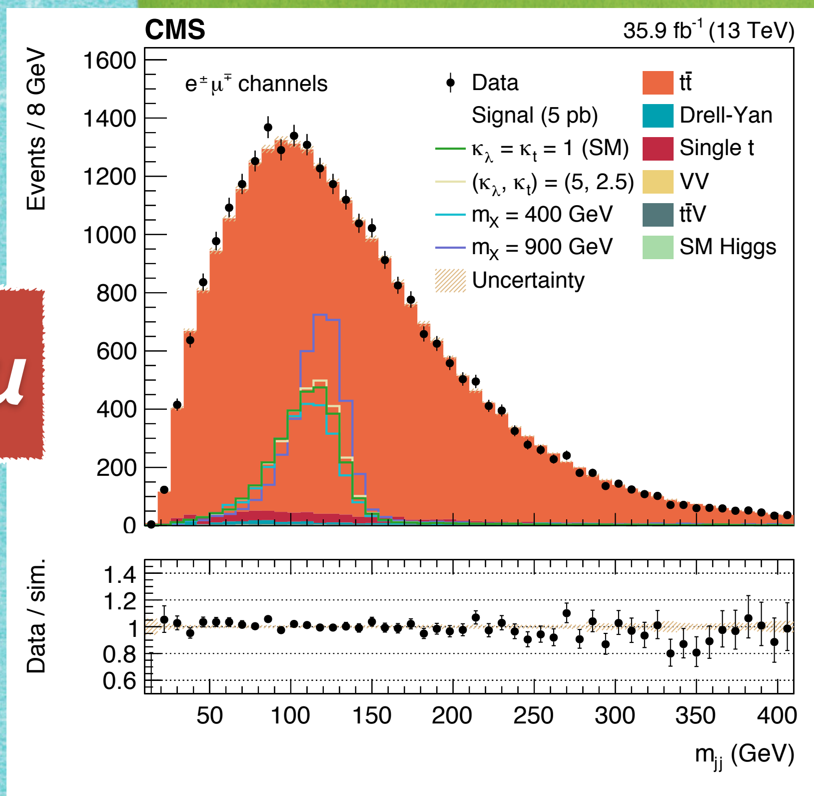


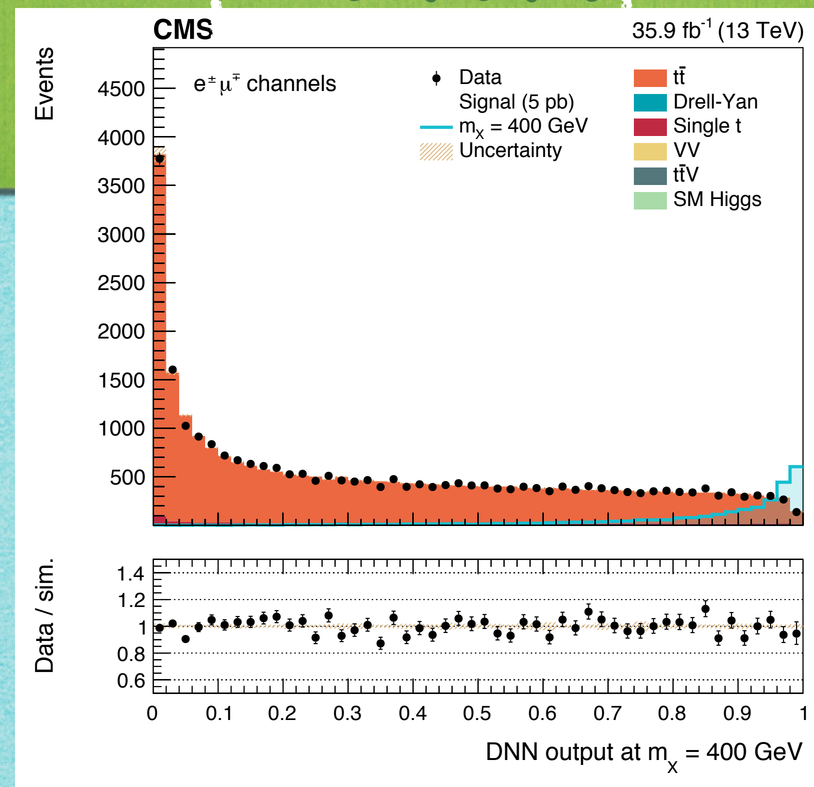
HH→bbVV→bblνlν (cont'd): BDT output

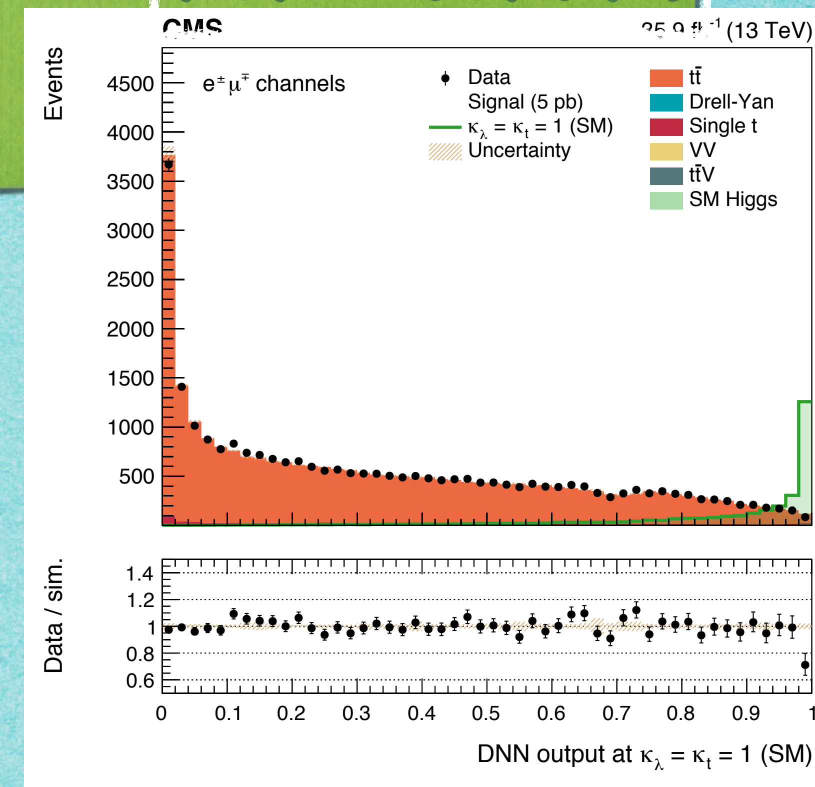
Resonant

nonResonant

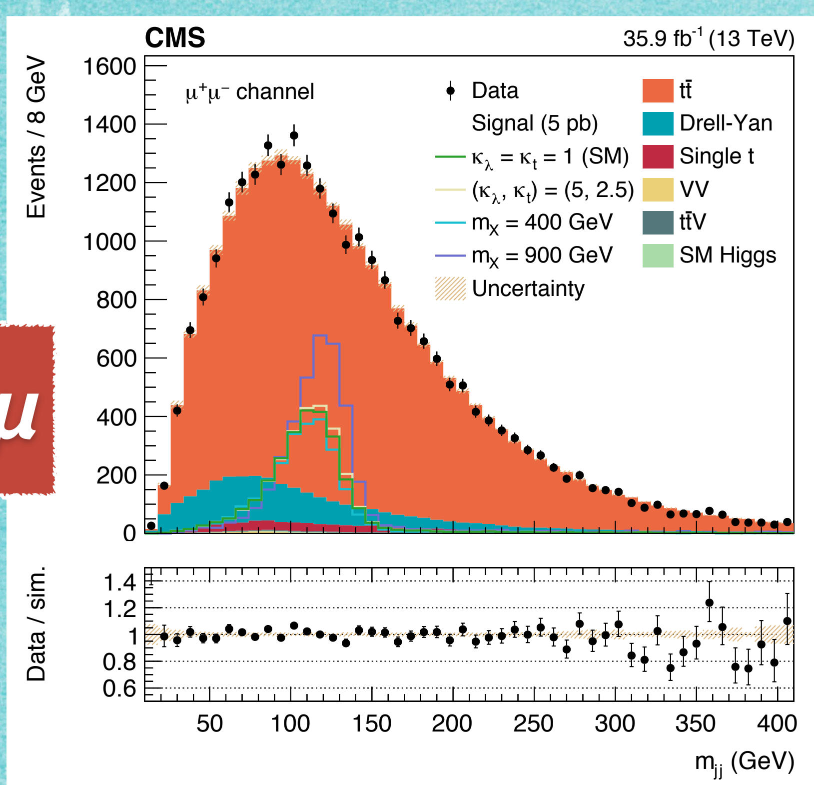
eμ

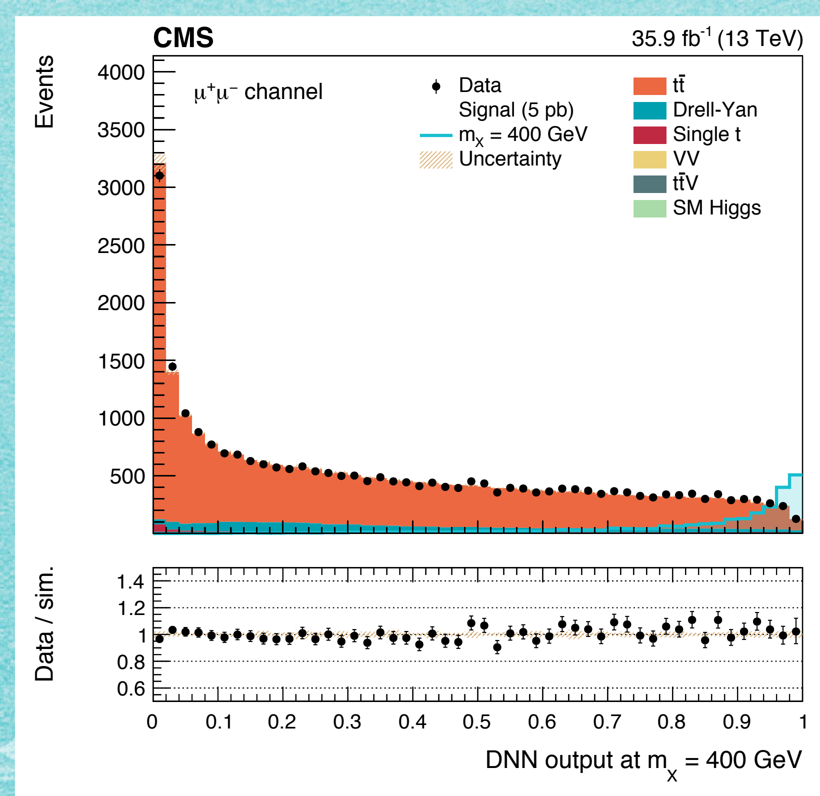


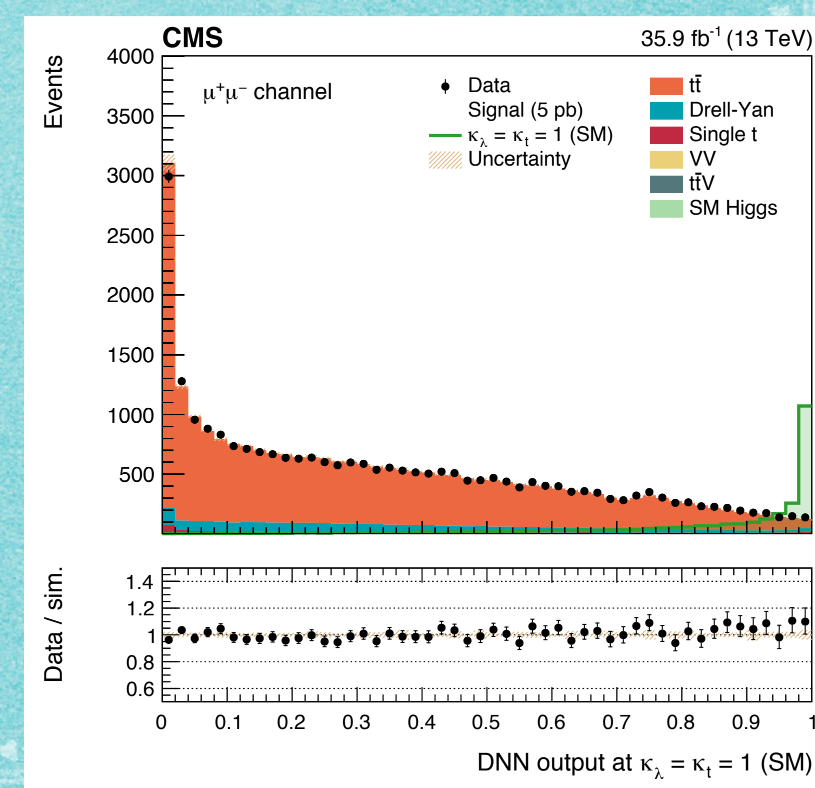




μμ

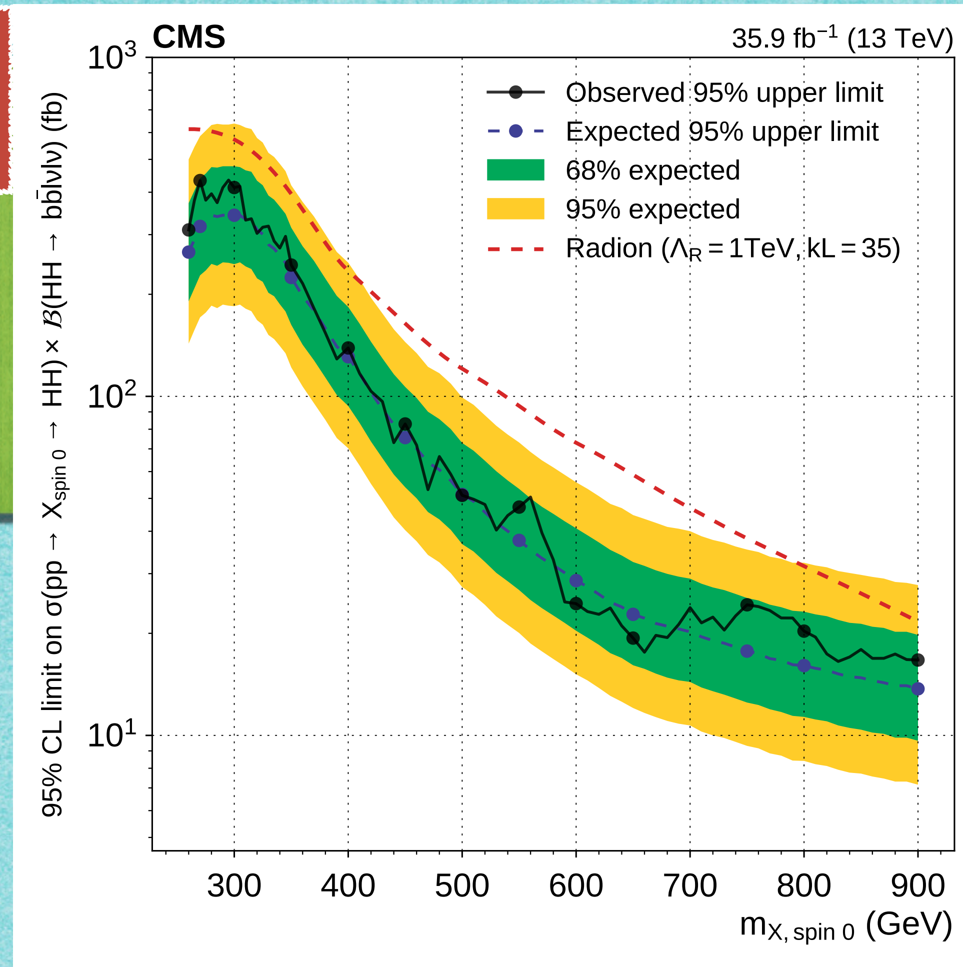


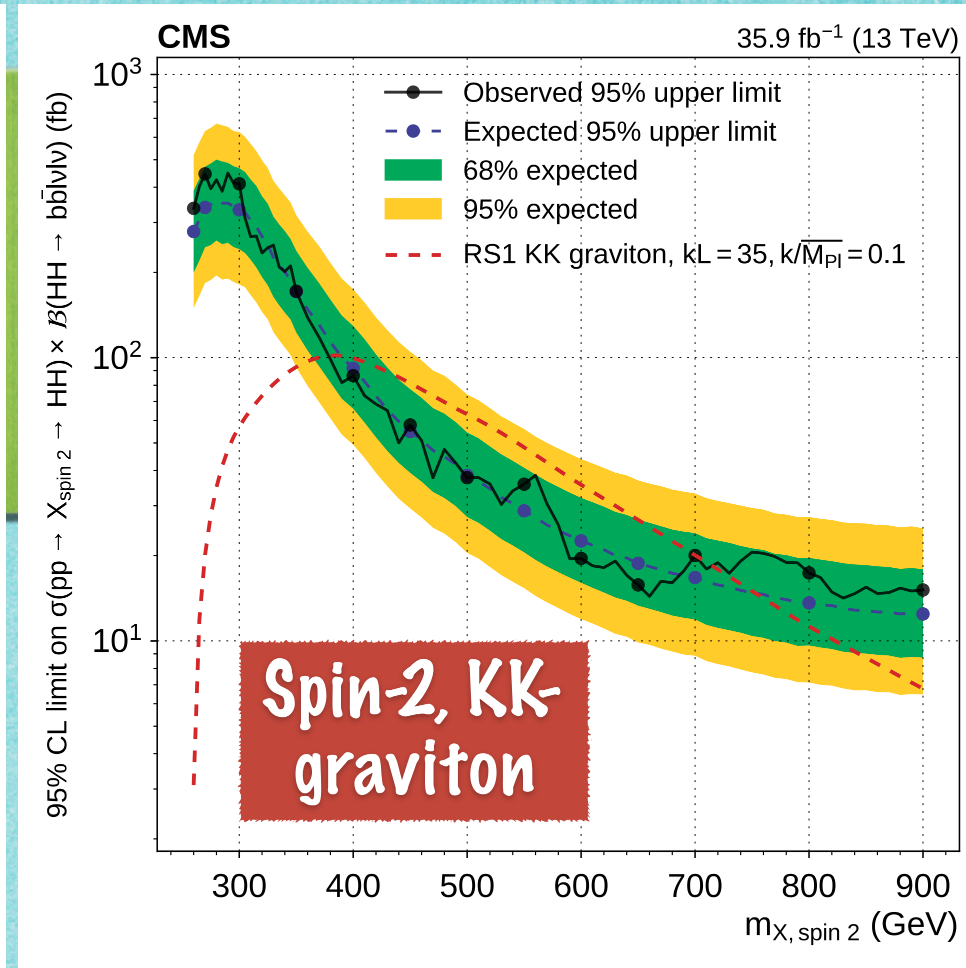


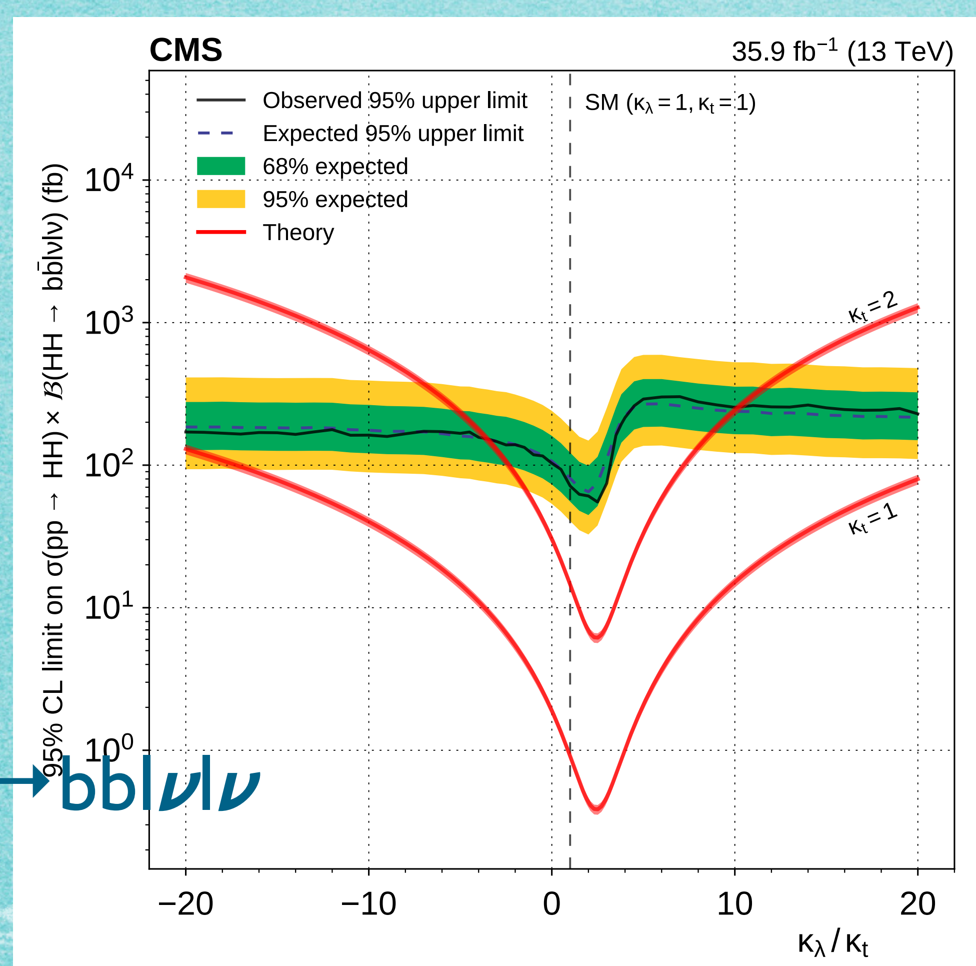


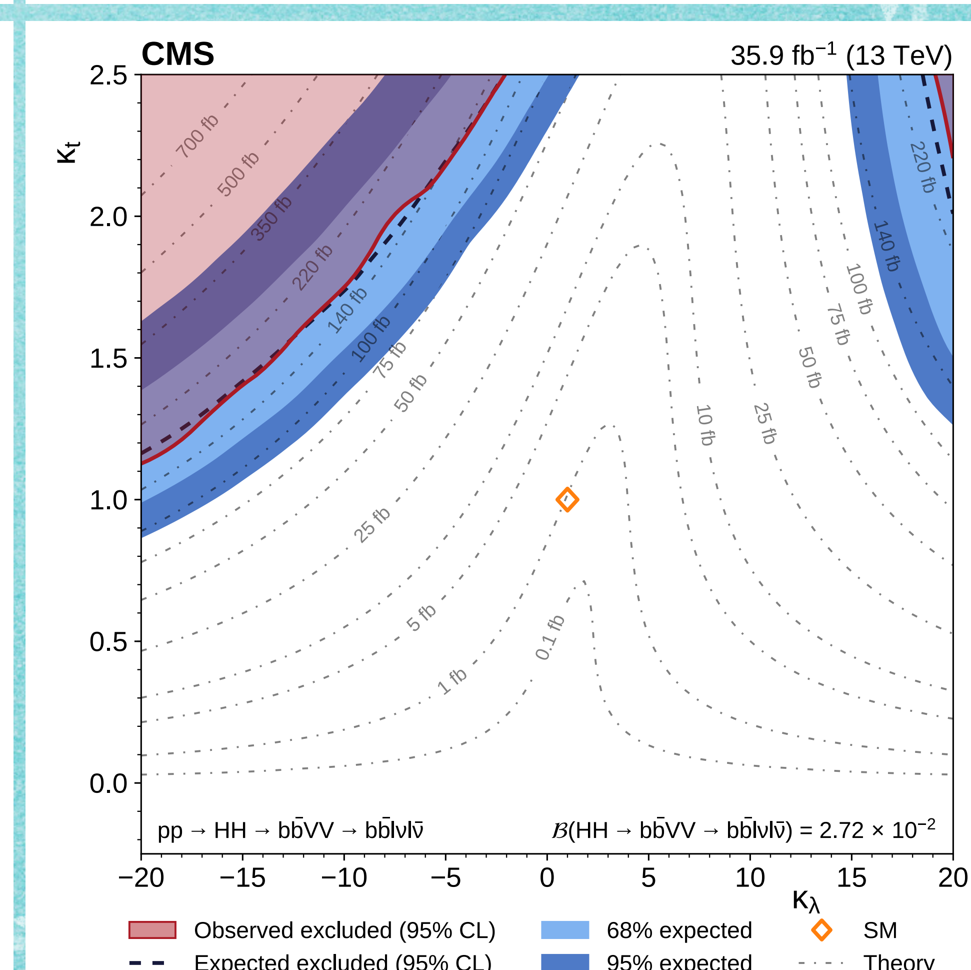
Spin-0, Radion

HH→bbVV →bblνlν : Result









SM xsec HH→bbVV→bblνlν

Observed: 72 fb

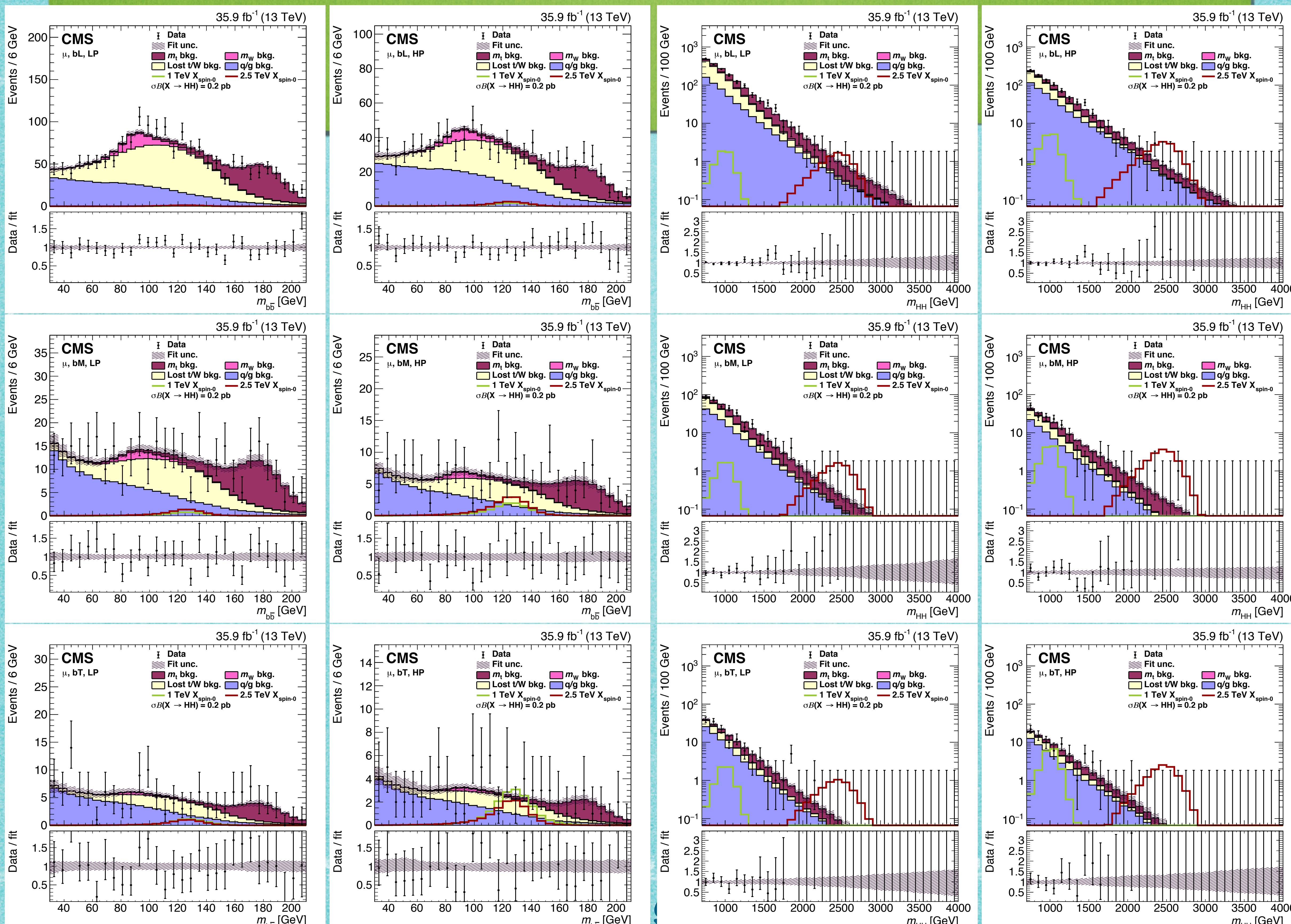
Expected: 81 fb

$X \to HH \to bbWW^*(\to bbql\nu)$: Boost

Submitted to JHEP, arXiv:1904.04193

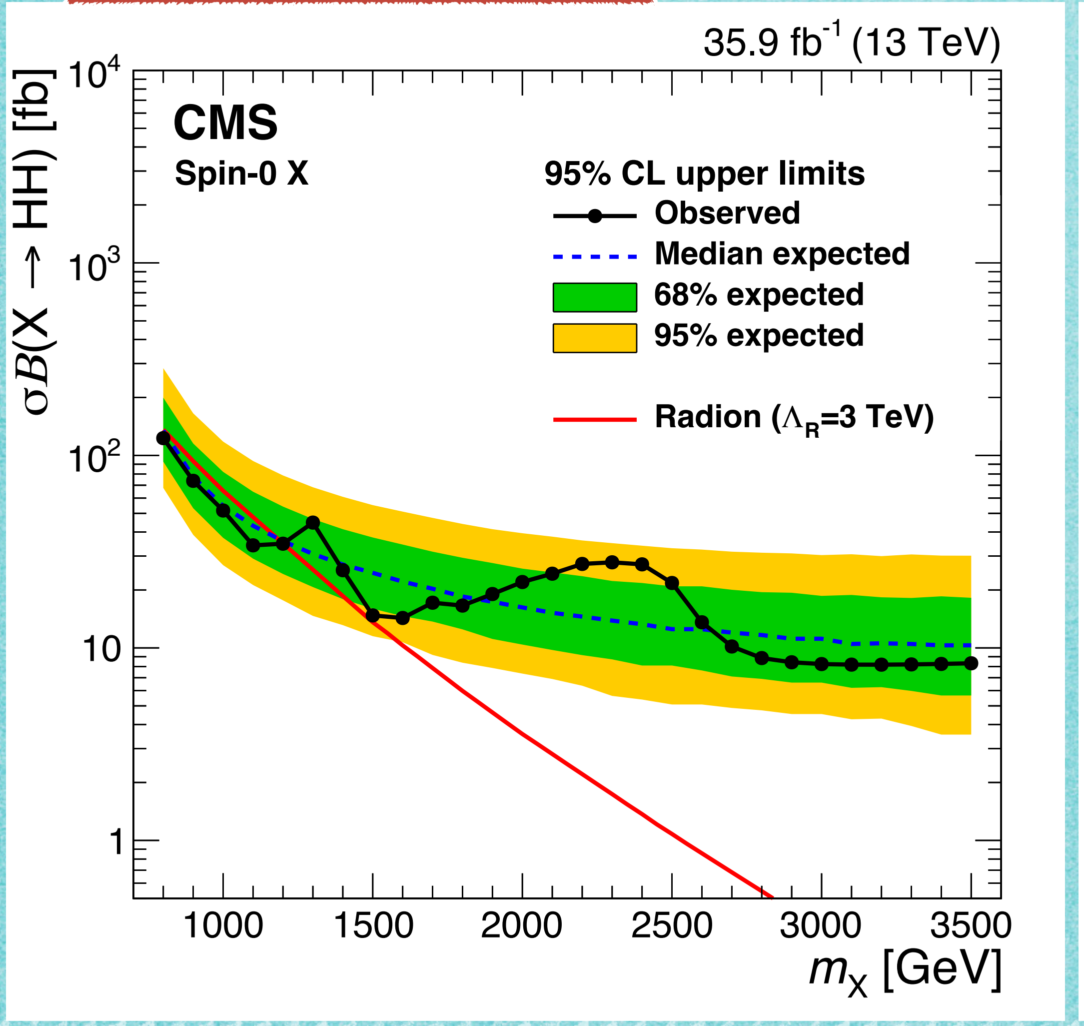
- Search for X with m(X)=0.8—3.5 TeV
- Events selection:
  - H_T>400 GeV, only one e/μ
  - A single bb jet with high p_T and a single qq jet with a nearby e/μ
  - Veto events with ΔR(AK4jet(R=0.4),bb jet)>1.2 to reject tt background
- Events categorized by the lepton flavor, number of b-tag subjetness in the bb jet, and qq jet substructure to increase signal purity and background estimation
- 2D maximum likelihood fit on m(bb) & m(HH)

X→HH→bbWW*(→bbqqlν): template

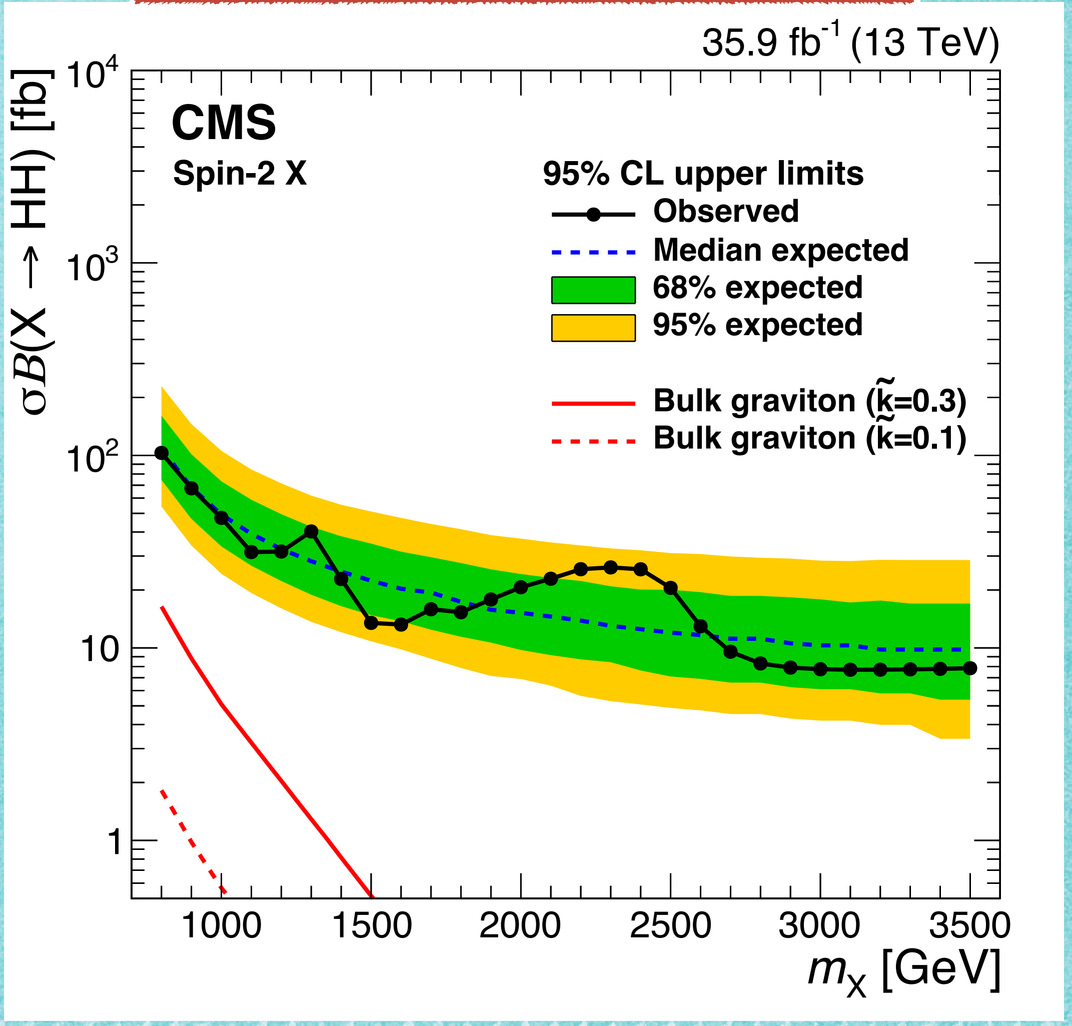


X→HH→bbWW*(→bbqqlν): Limits

Spin-0, Radion



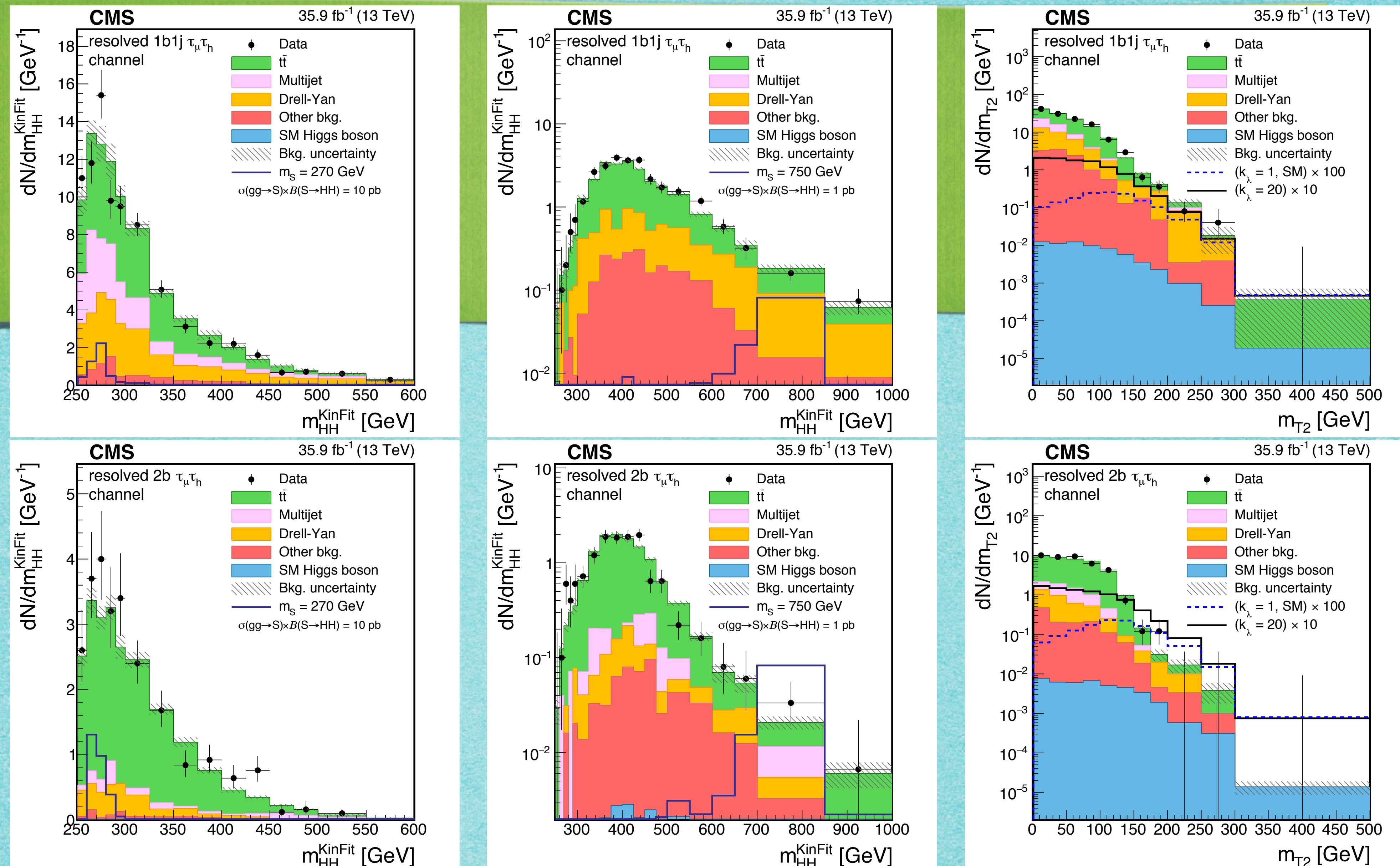
Spin-2, KK-graviton

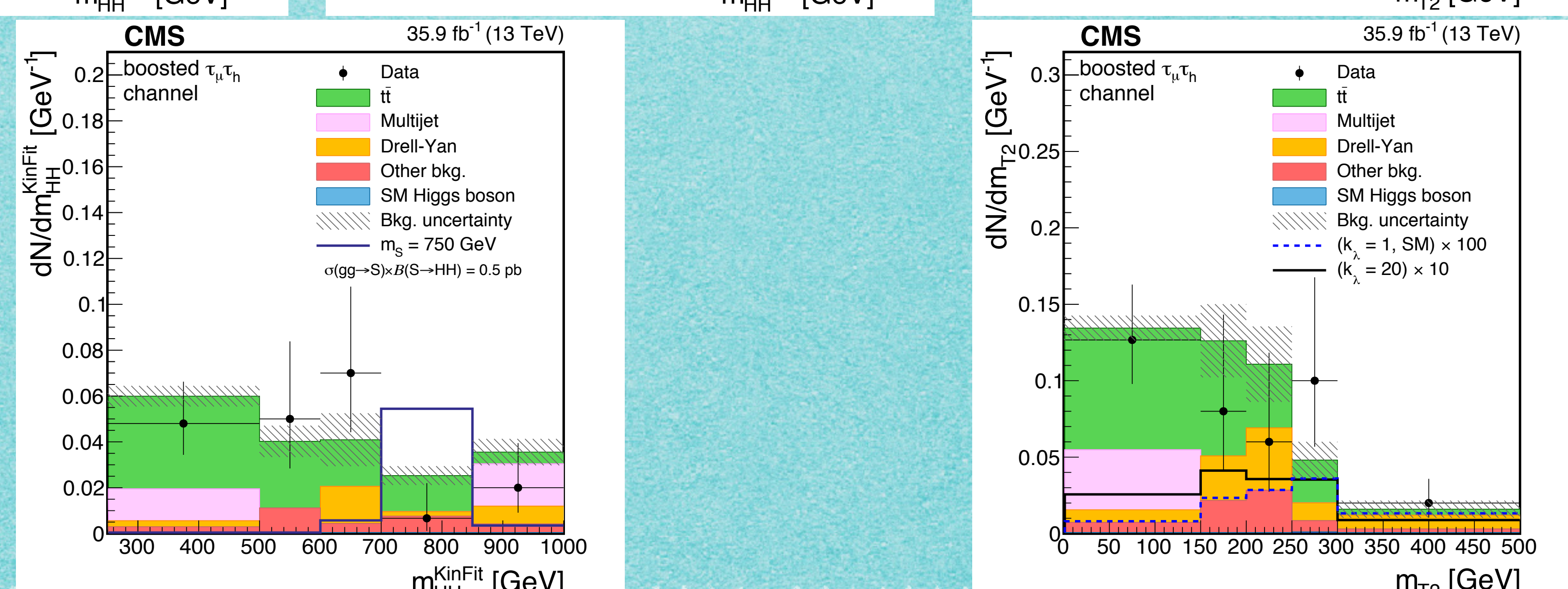


$HH \to bb\tau\tau(\tau_e\tau_h/\tau_\mu\tau_h/\tau_h\tau_h)$

Phys. Lett. B 778 (2018) 101, arXiv:1707.02909

- Select events:
  - OS τ pair: $\Delta R(\tau,\tau)>0.1$ and $m(\tau\tau)$ reconstructed using SecondaryVertex fit algorithm
  - Two jets with highest b-tag score
  - Categorization: resolved 1/2 b-tag, and boosted
  - Mass window cuts for m(bb) and $m(\tau\tau)$ within 45 and 35 GeV, respectively
- BDT discriminant $e/\mu+\tau_h$ vs. tt
- Limit extraction based on:
  - Resonant: Fitted HH mass
  - Nonresonant: MT2

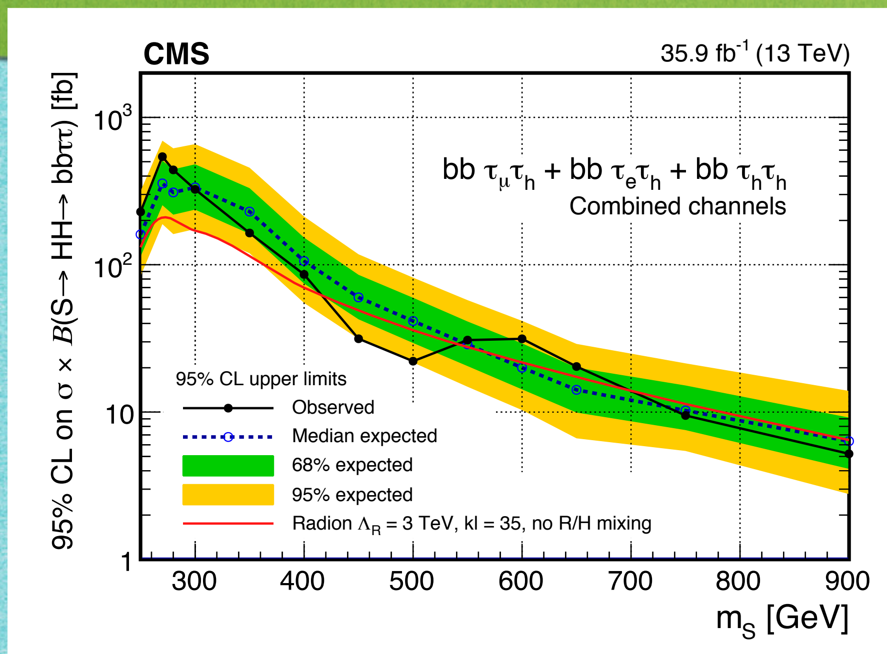


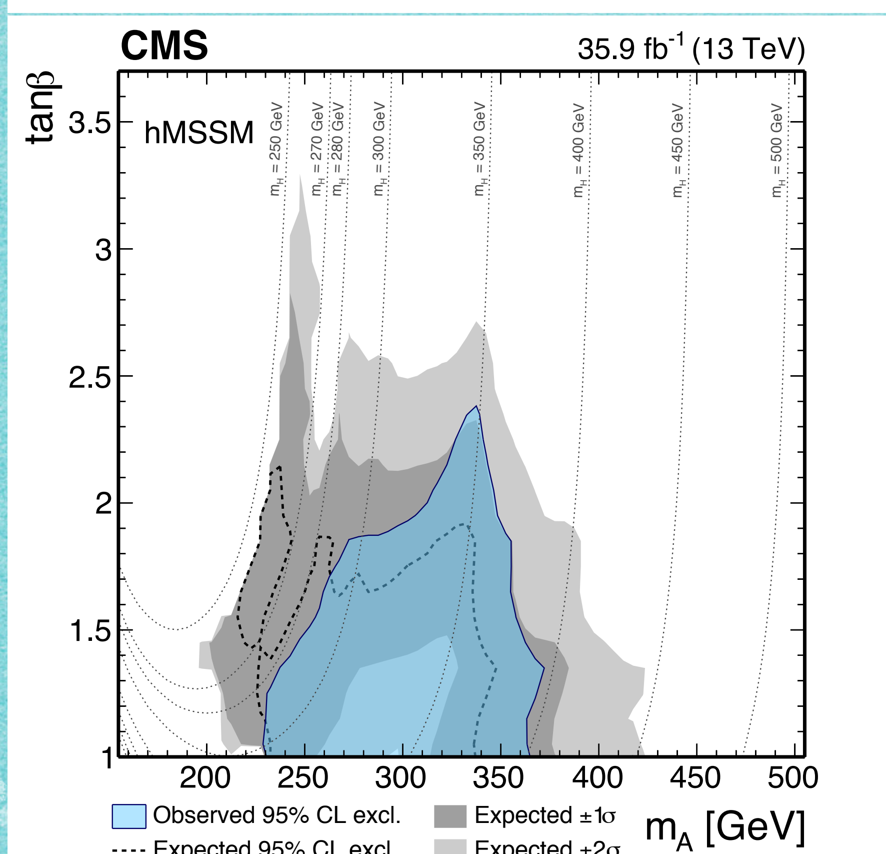


HH→bb$\tau\tau$: Signal extraction

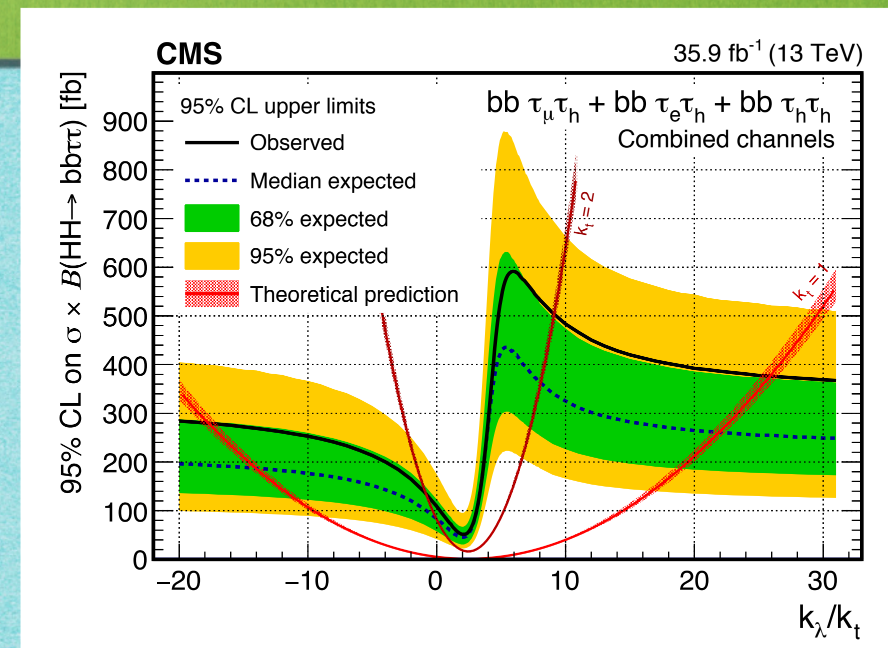
HH→bbττ: Limits

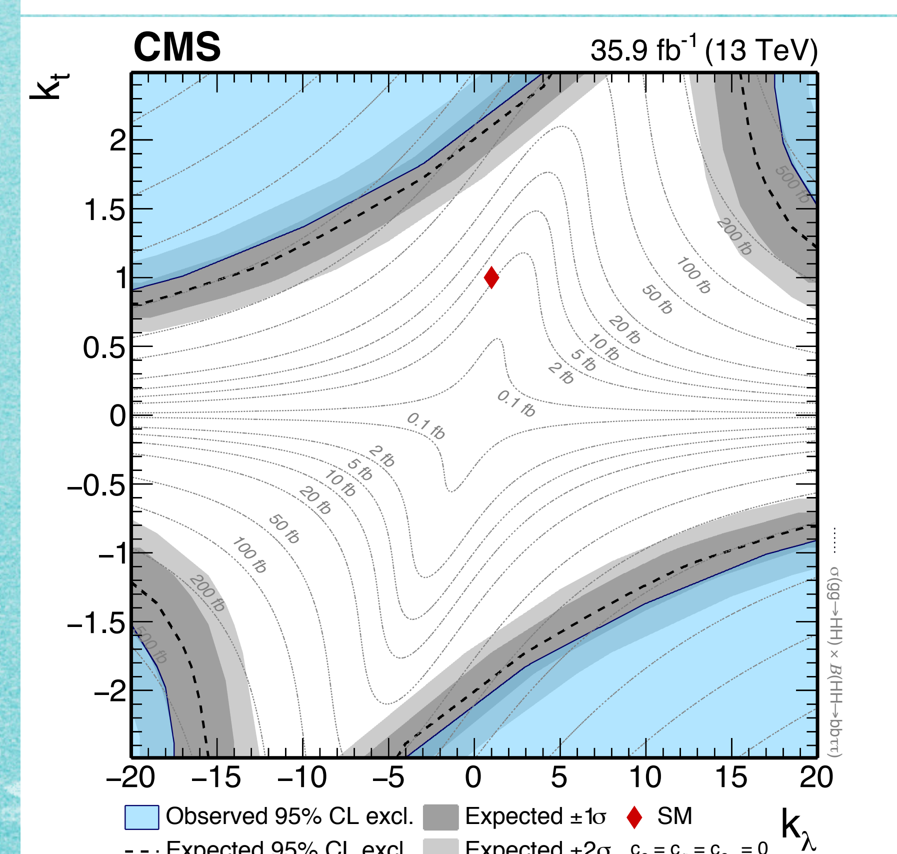
Model-independent limit on X





Limits on κ_λ & κ_t





HH→bb$\gamma\gamma$

Phys. Lett. B 788 (2019) 7, arXiv:1806.00408

ANALYSIS STRATEGY

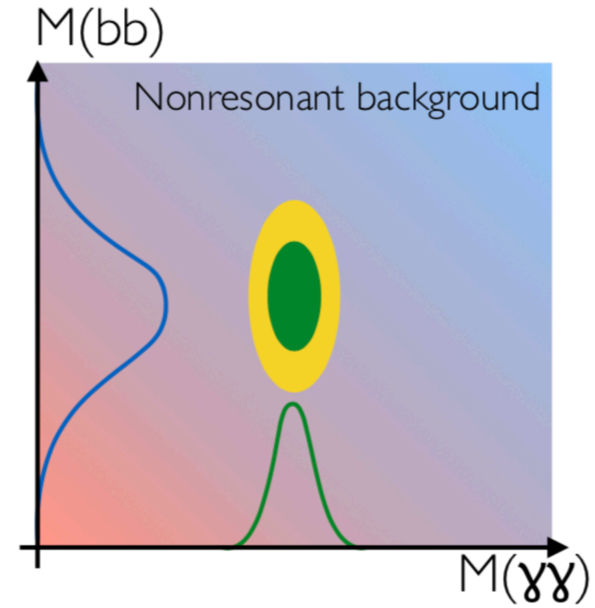
Online Selection → Photons Selection → Jets Selection

Non-resonant sig. hypothesis → 4-body Mass Categories → MVA-based Categories → 4-categories combined limit

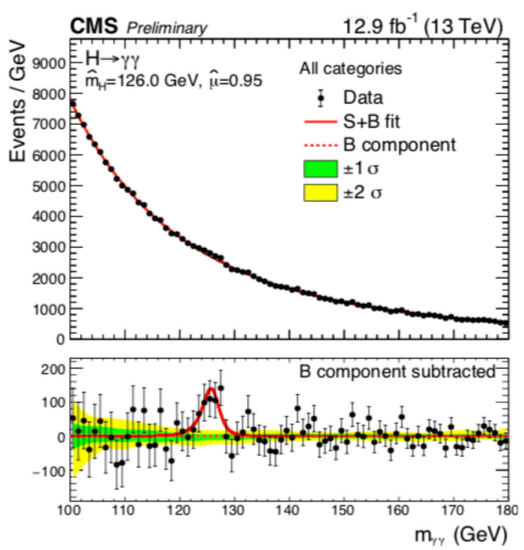
Resonant sig. hypothesis → 4-body Mass Window → MVA-based Categories → 2-categories comb. limits for separate mass intervals

Signal extraction via parametric fit on 2D plane M(jj):M(ɣɣ)

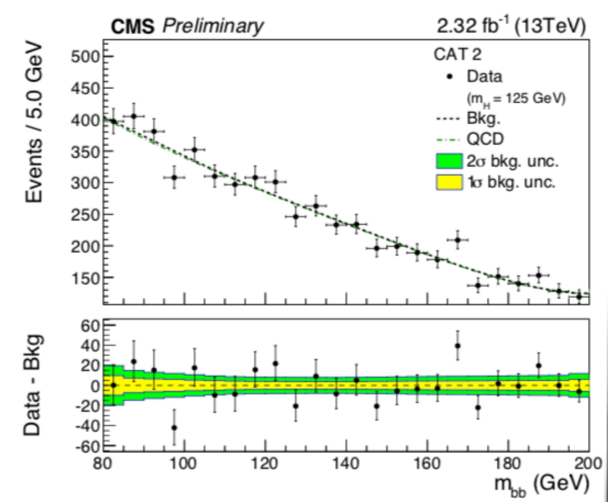
M(jj) and M(ɣɣ) = 1D parametric signal shapes



Analysis backgrounds:
non-resonant photons produced via QCD
Single Higgs



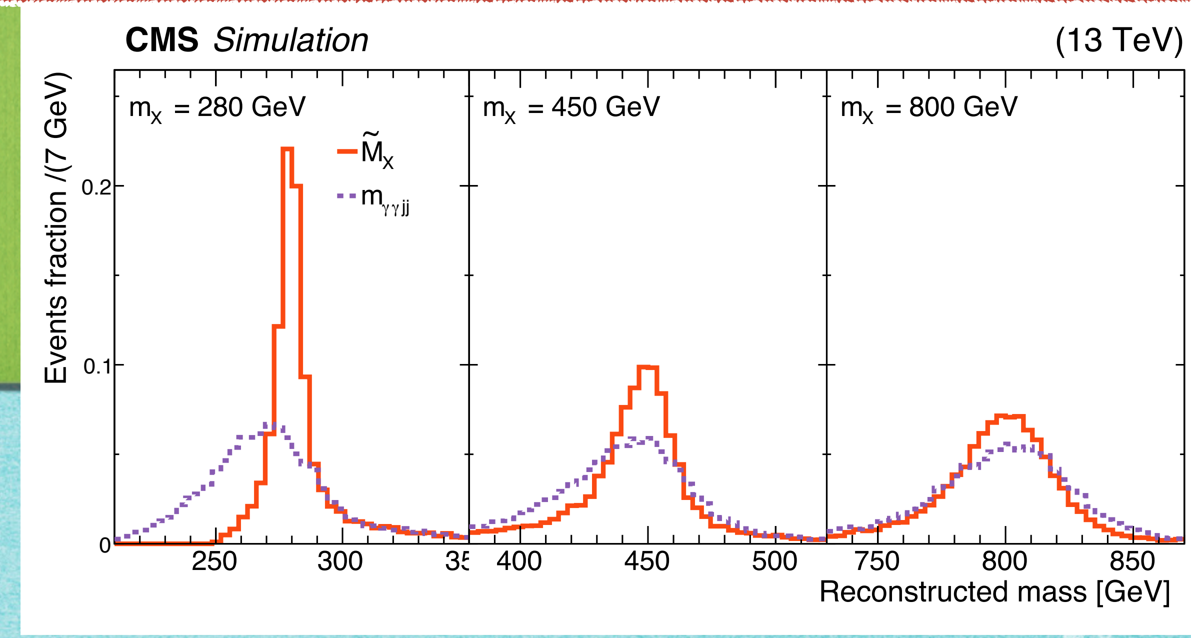
CMS SM H→ɣɣ



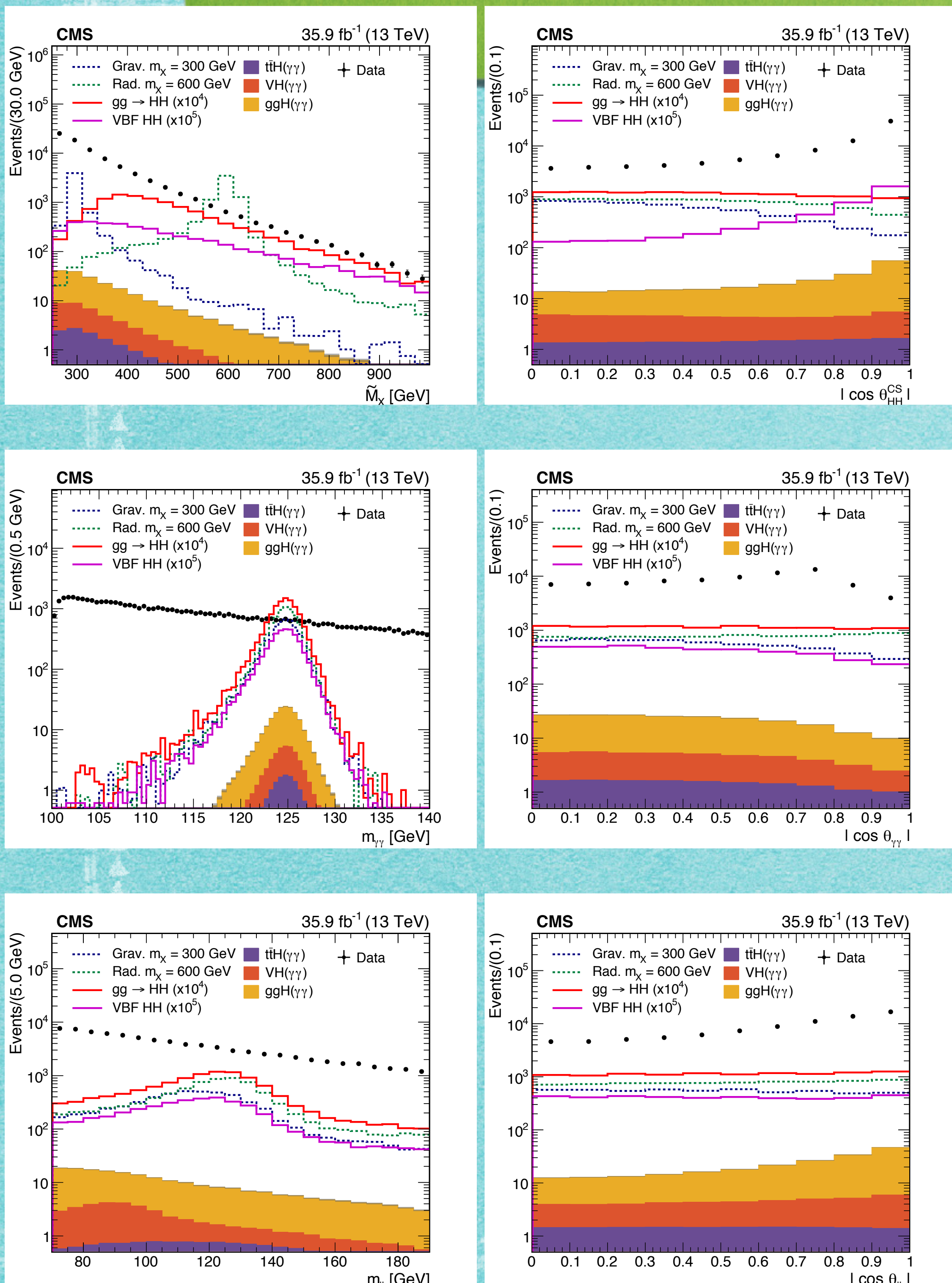
CMS SM H→bb

HH→bbγγ

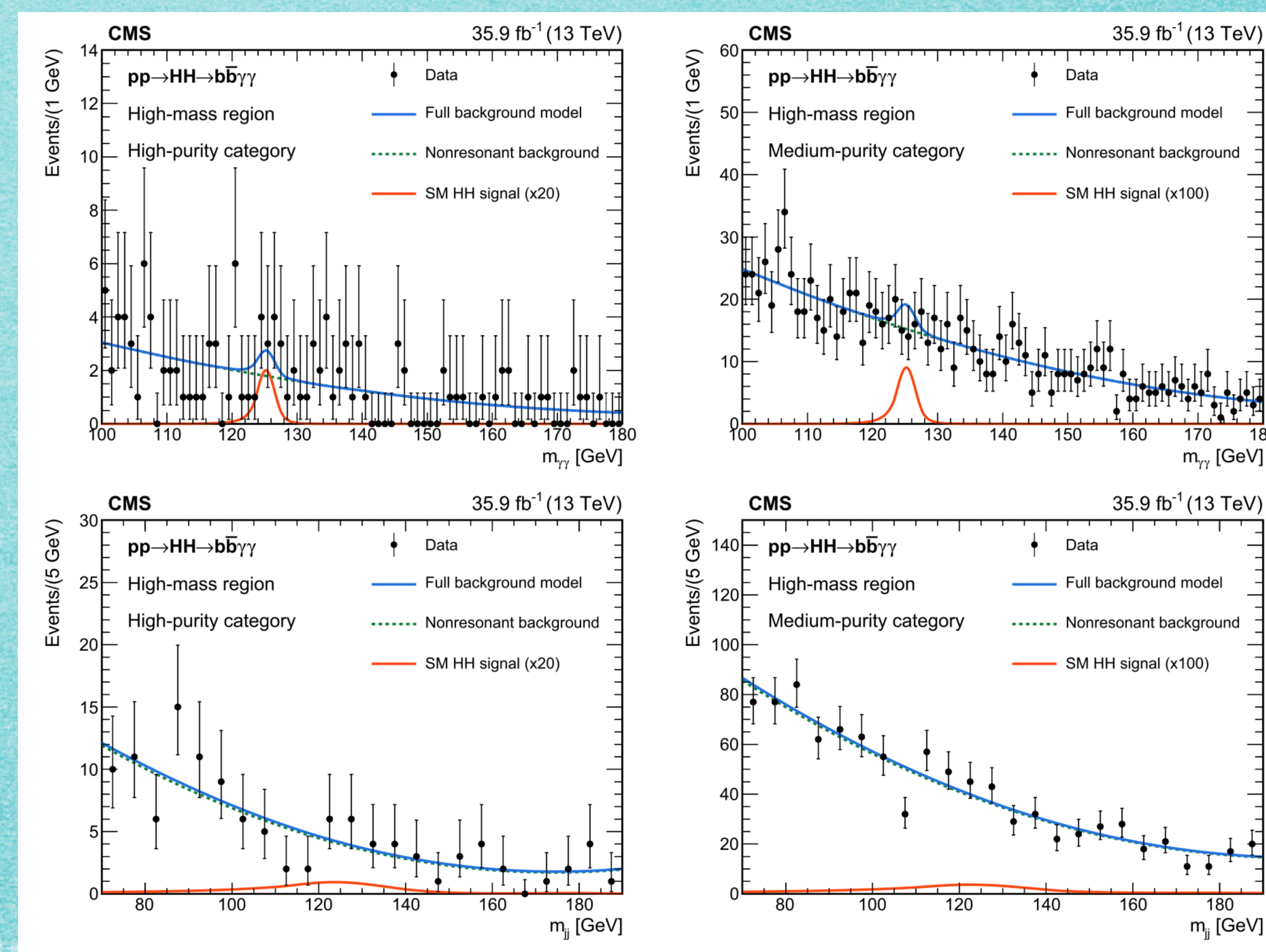
Use effective mass = m(X) =m(jjγγ)-m(jj)-m(γγ)+250



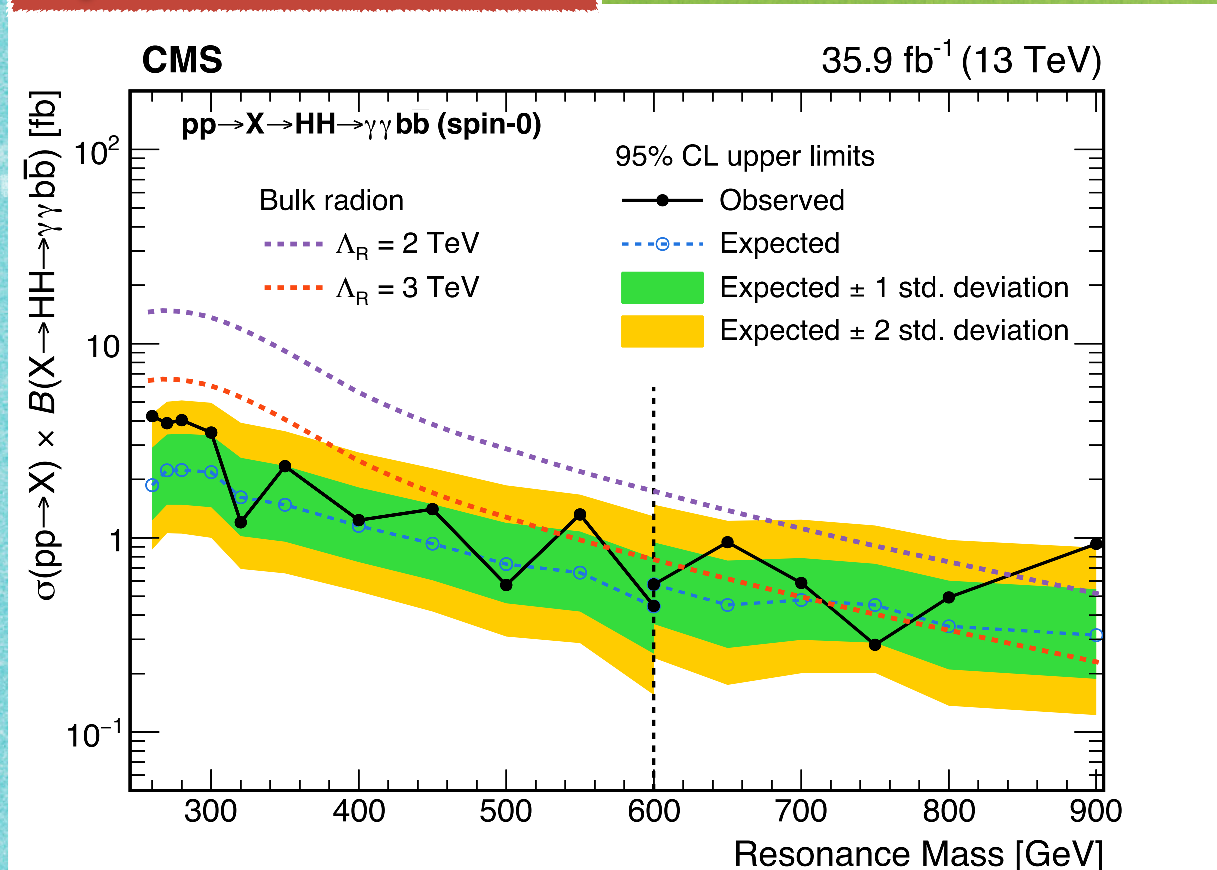
Resonant: Data vs. expectation



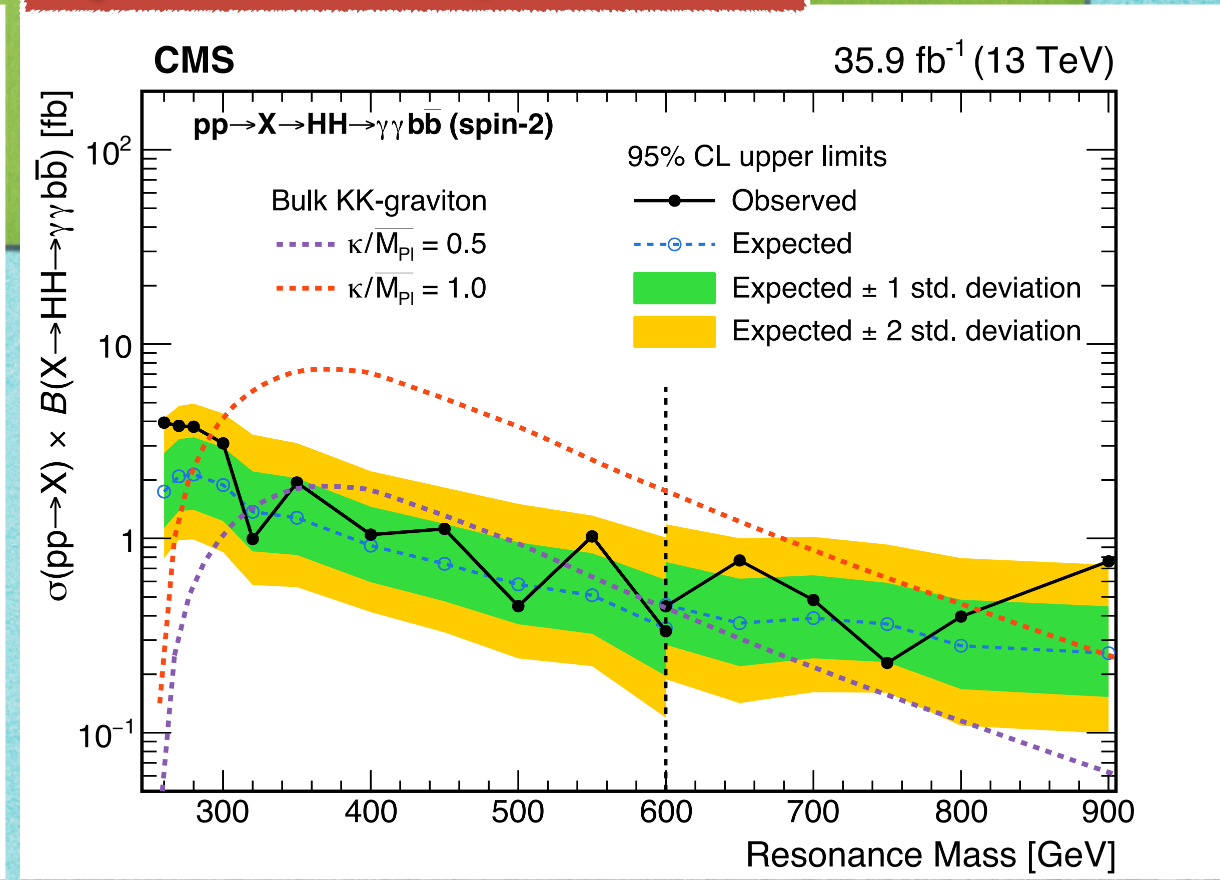
NonResonant background fits



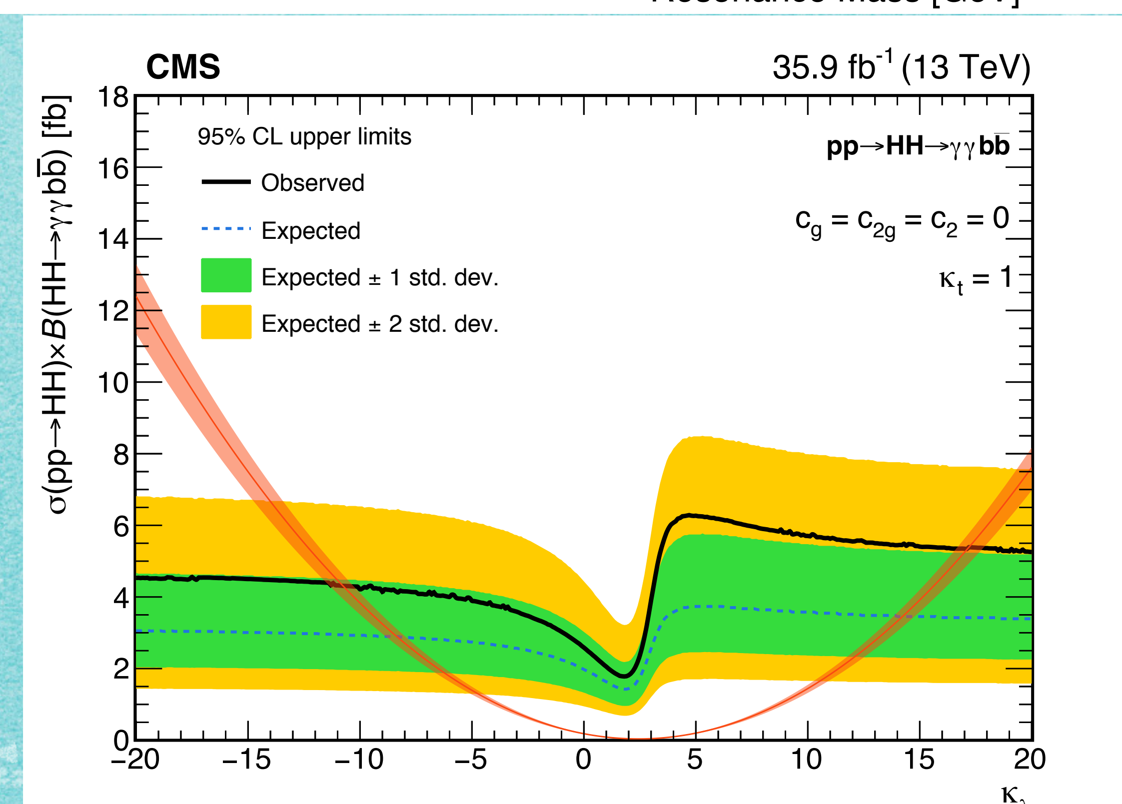
Spin-0, Radion



Spin-2, KK-graviton



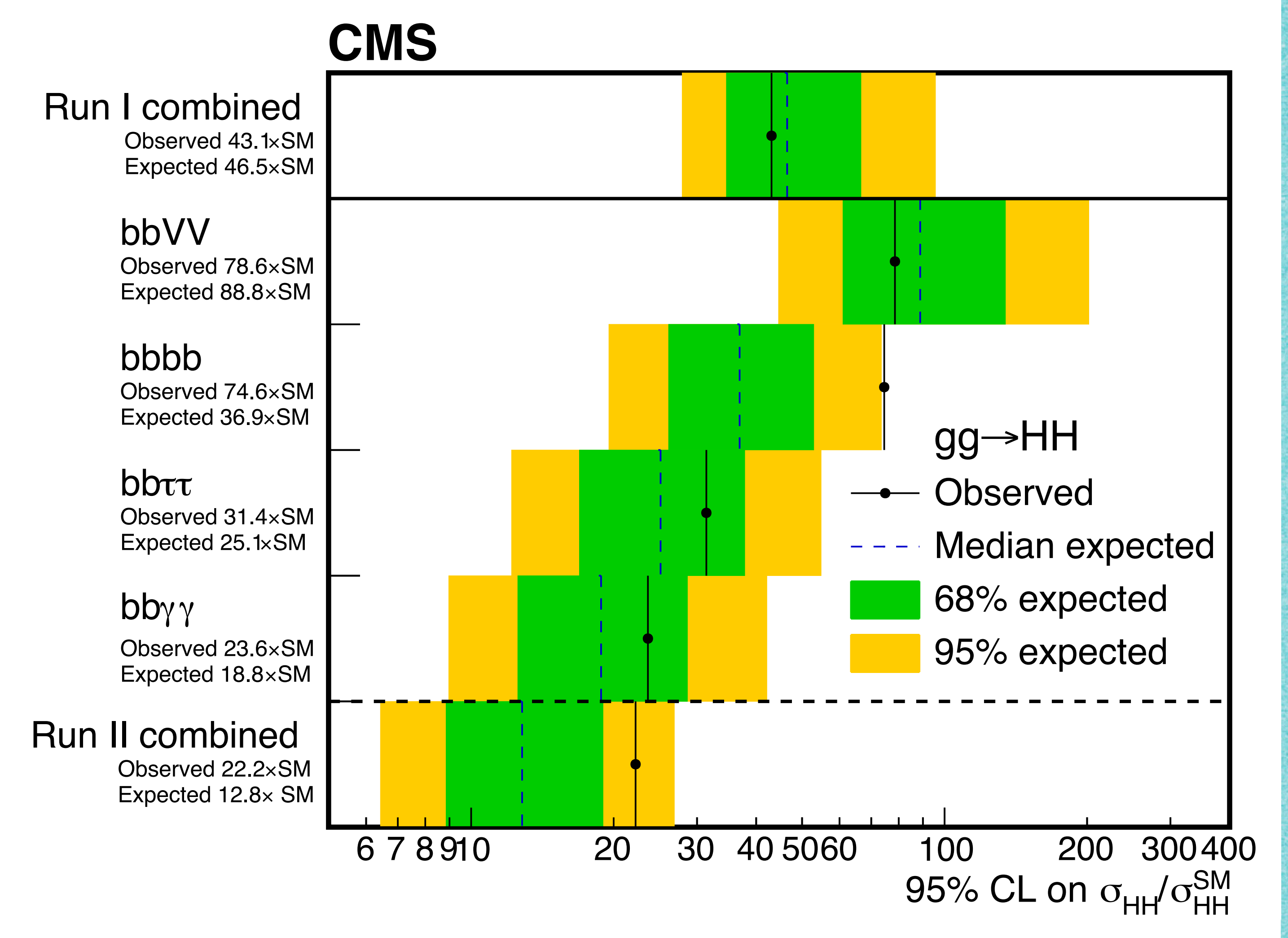
HH⟶bb$\gamma\gamma$: Limits

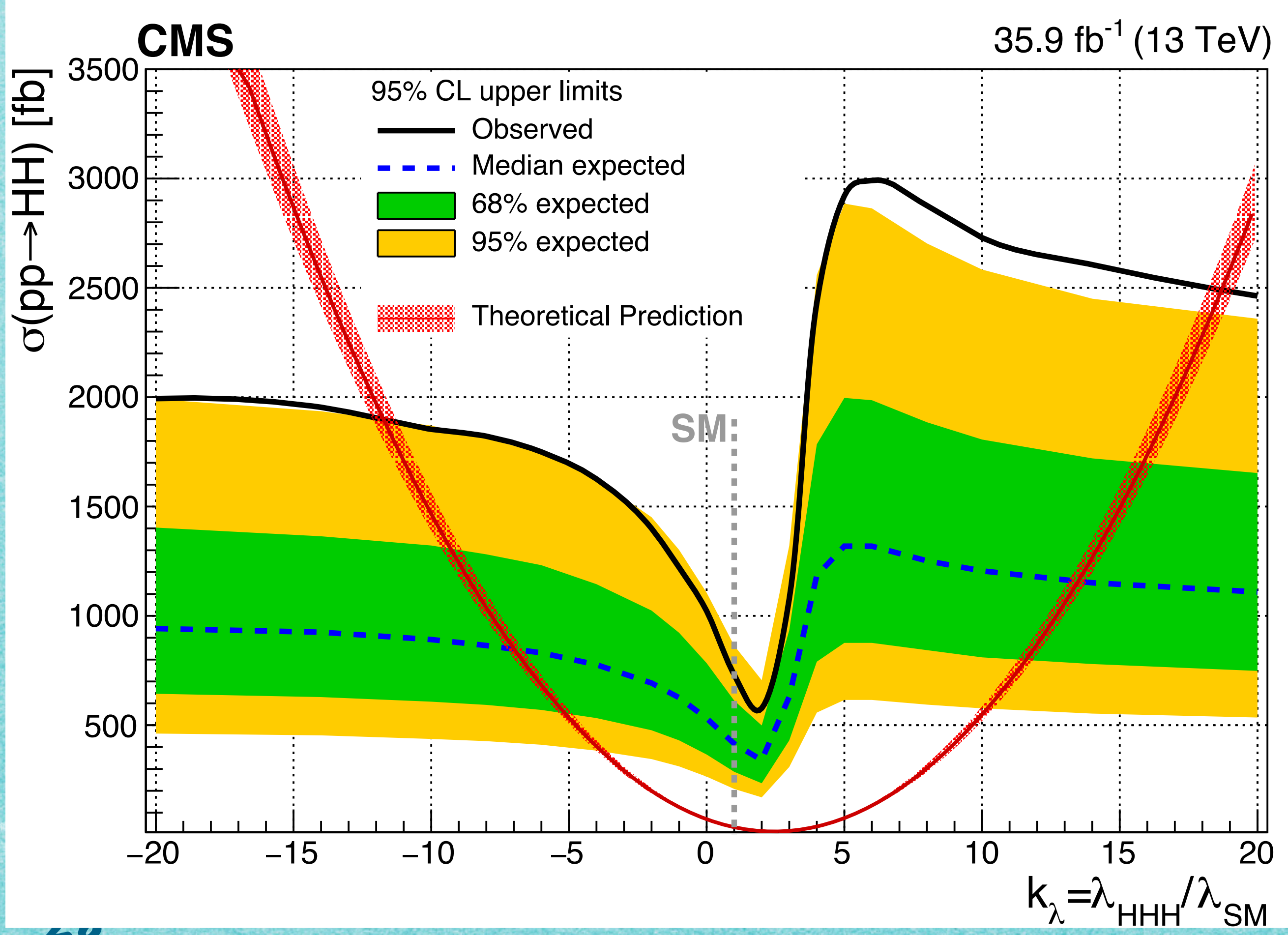


Combination of Higgs Boson Pair Production in pp @ 13 TeV CMS experiment

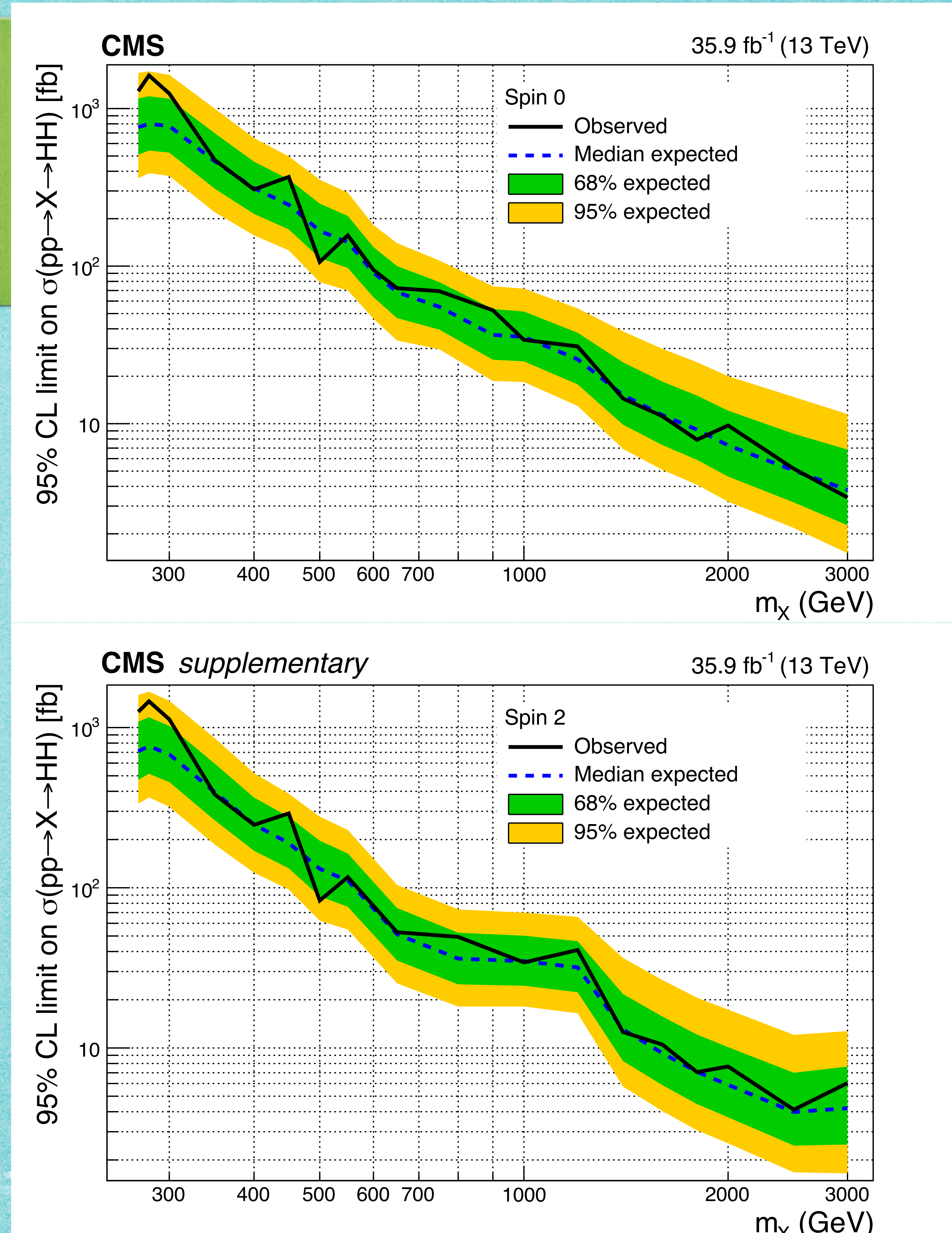
- Using 35.9 fb^{-1} 2016 CMS data
- PRL **122** (2019) 121803, arXiv:1811.09689
- Subdecays: bbbb/bb$\tau\tau$/bb$\gamma\gamma$/bbVV (V=W or Z)
- Observed (expected) upper limit on the non resonant production xsec = 22.2 (12.8) $\times\sigma_{SM}$
- No evidence for narrow resonances in the mass range 250—3000 GeV

Combined CMS HH @ 13TeV Limits





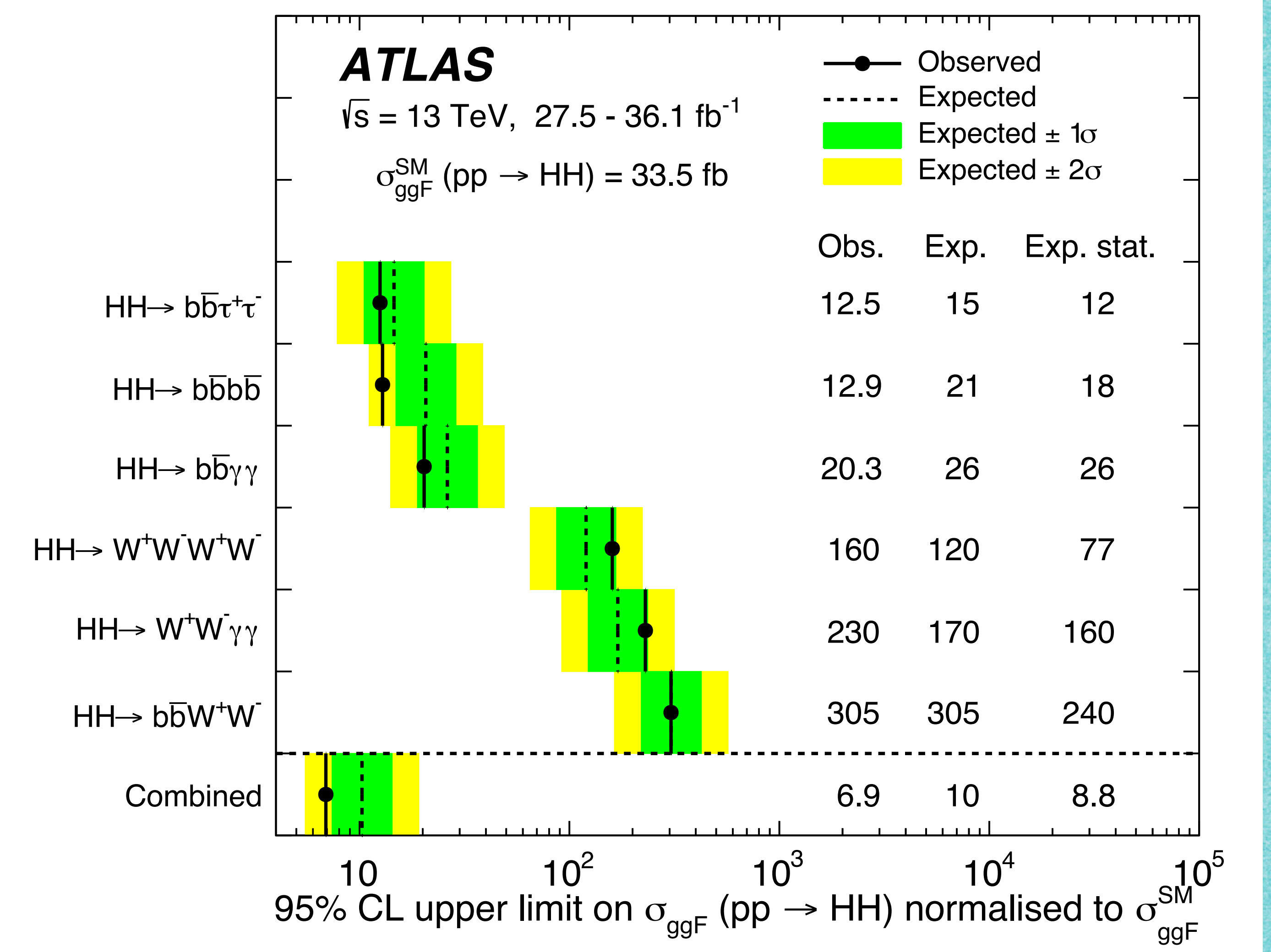
Combined CMS HH @ 13TeV Limits

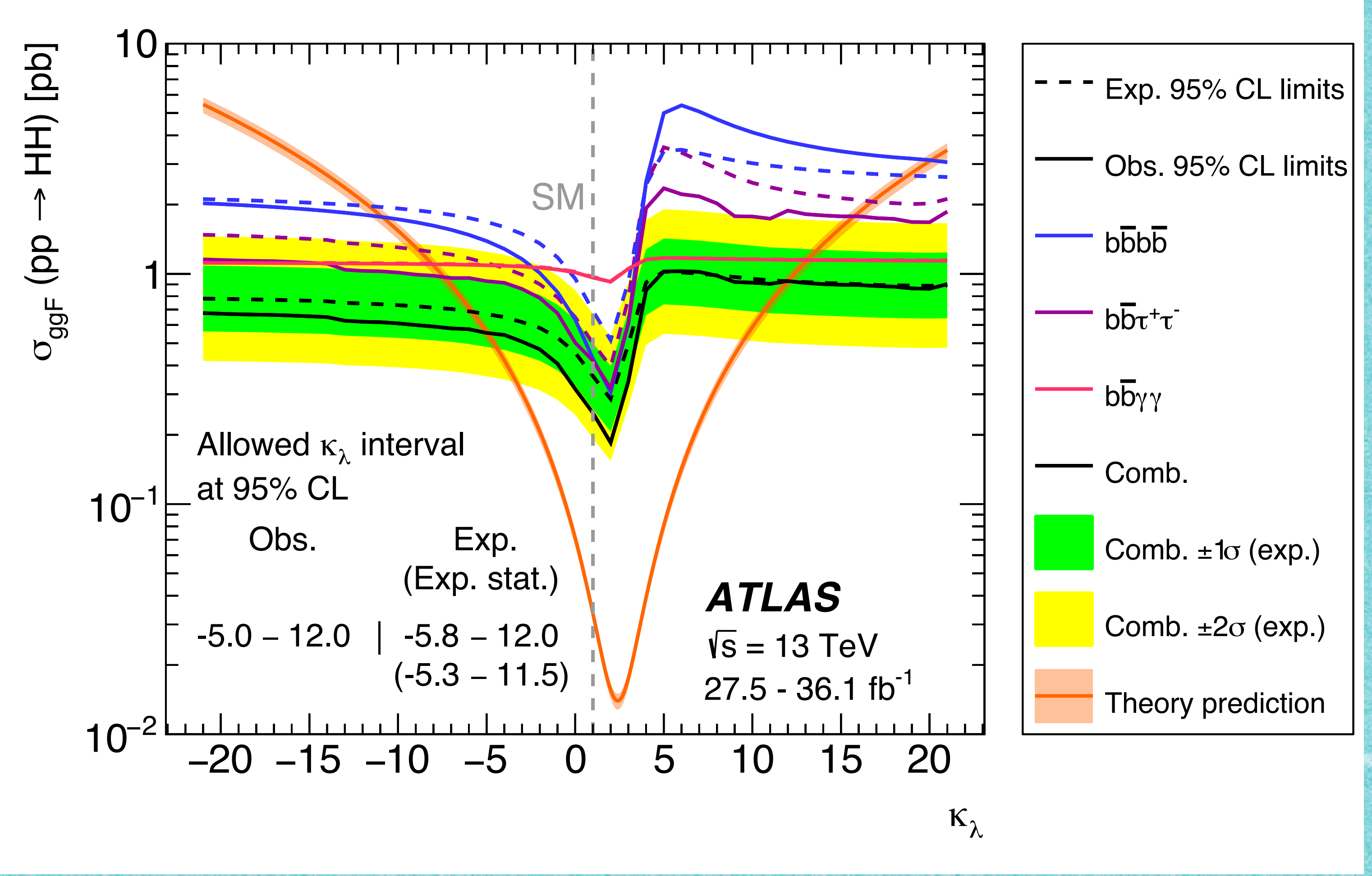


Combination of h(125)h(125) ATLAS experiment

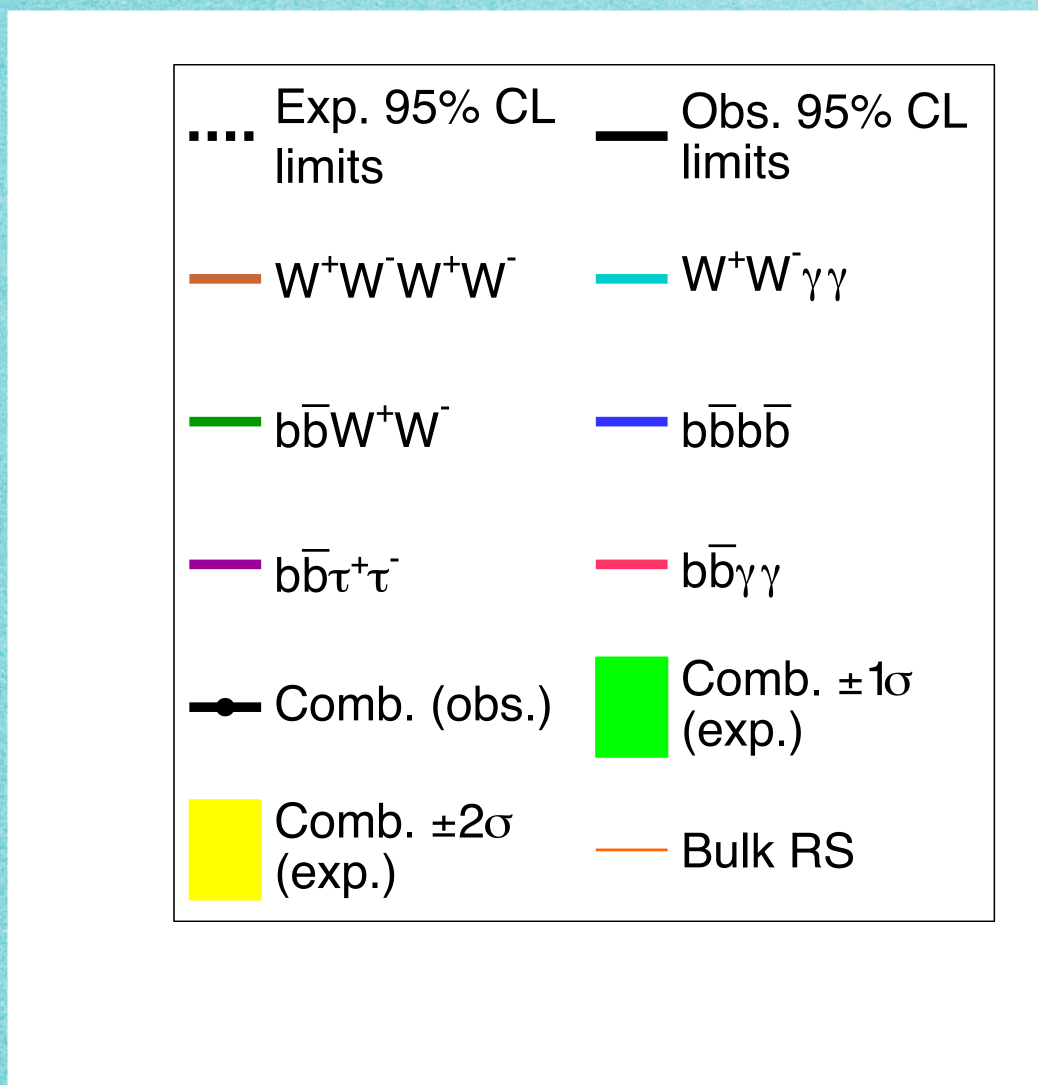
- Using 36.1 fb^{-1} 2016 ATLAS data
- Submitted to PLB, arXiv:1906.02025
- Subdecays: bbbb/bbWW($l\nu qq$)/bb$\tau\tau$/WWWW($ll\nu\nu 4q$/$lll\nu\nu\nu 2q$/$4l4\nu$)/bb$\gamma\gamma$/ WW($l\nu qq$)$\gamma\gamma$
- Results are presented for non-resonant and resonant Higgs boson pair production modes
- Combined observed limit @ 95% CL on the non-resonant HH xsec = $6.9\times\sigma_{SM}$
- Limits set on the ratio (κ_λ) of the Higgs boson self-coupling to SM value: $-5.0 < \kappa_\lambda < 12.0$ @ 95% CL
- Limits set on the production of narrow scalar resonances in BSM

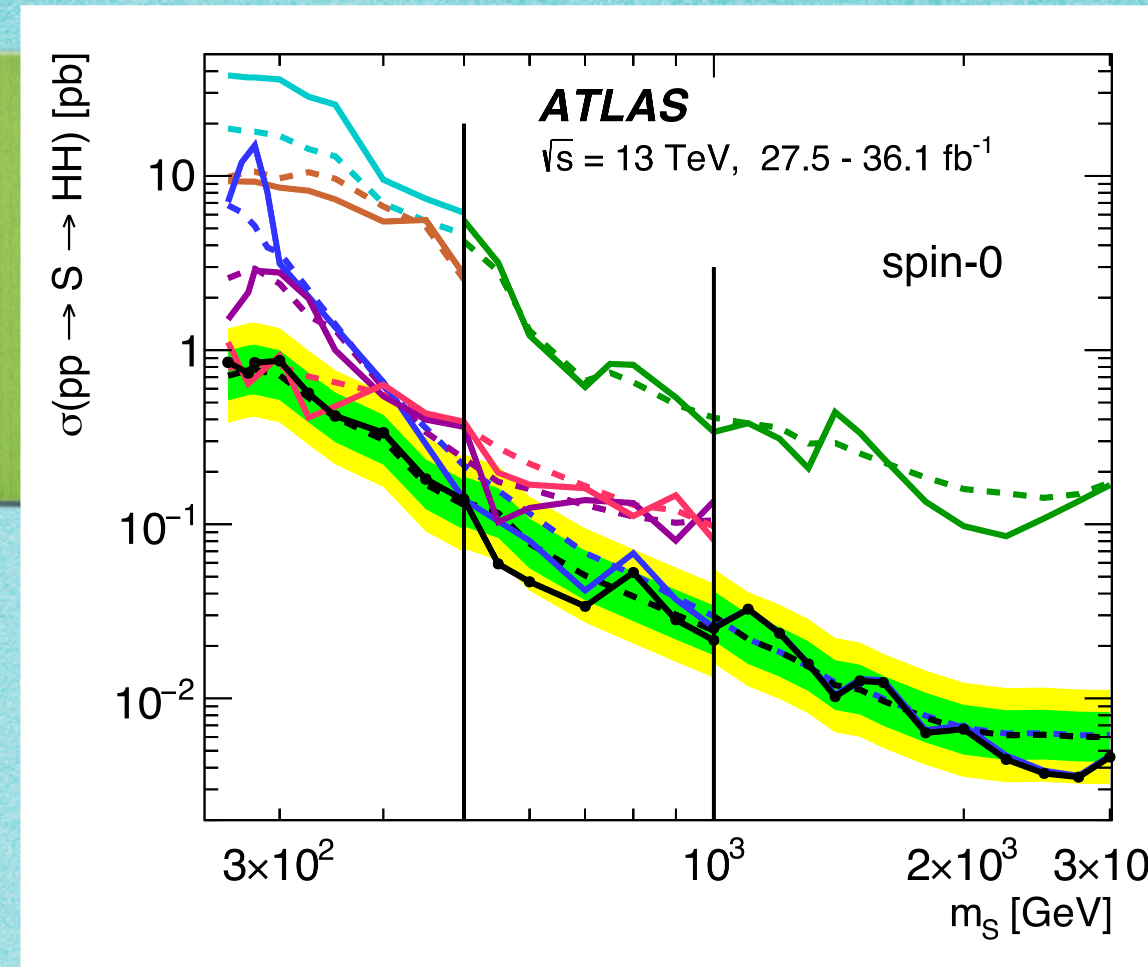
Combined ATLAS HH @ 13TeV Limits

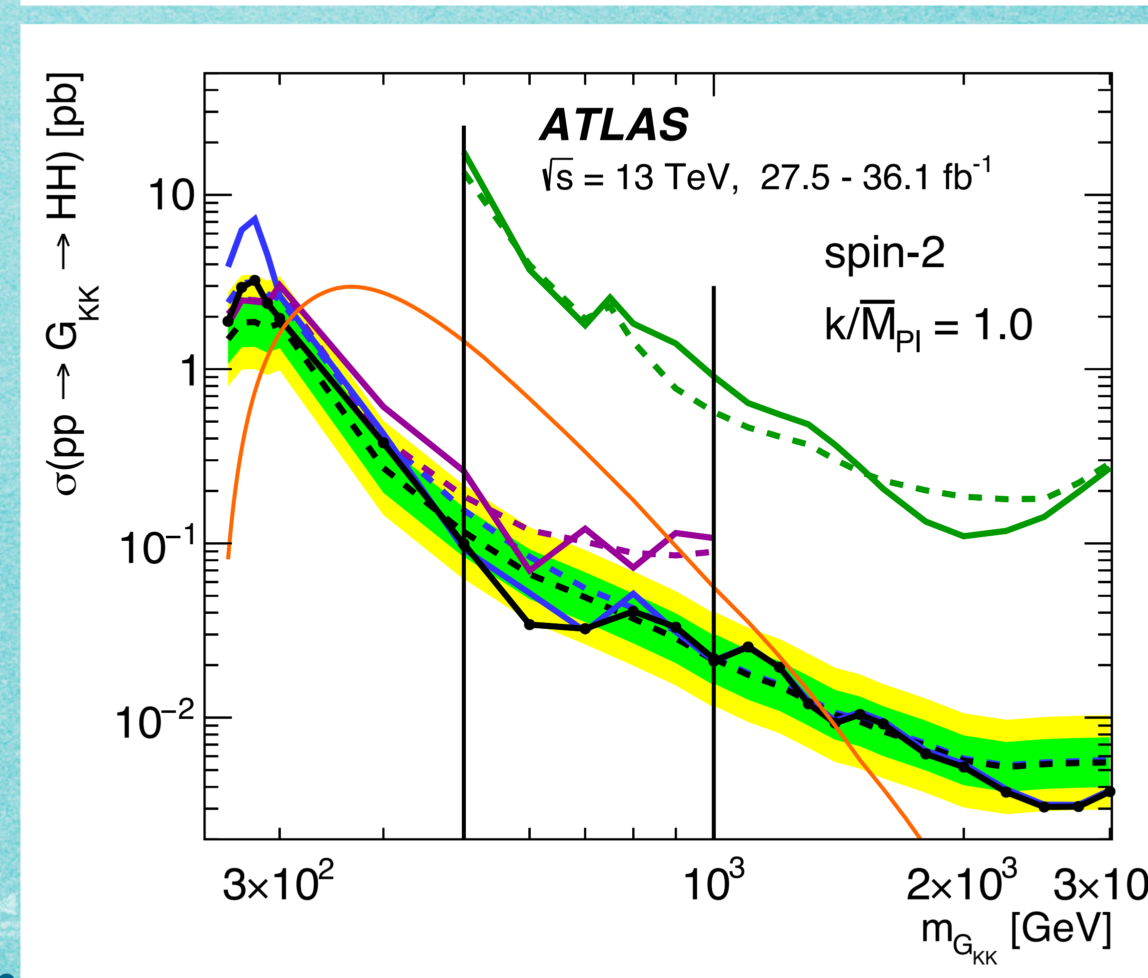




Combined ATLAS HH @ 13TeV Limits







HH @ HighLuminosity-LHC

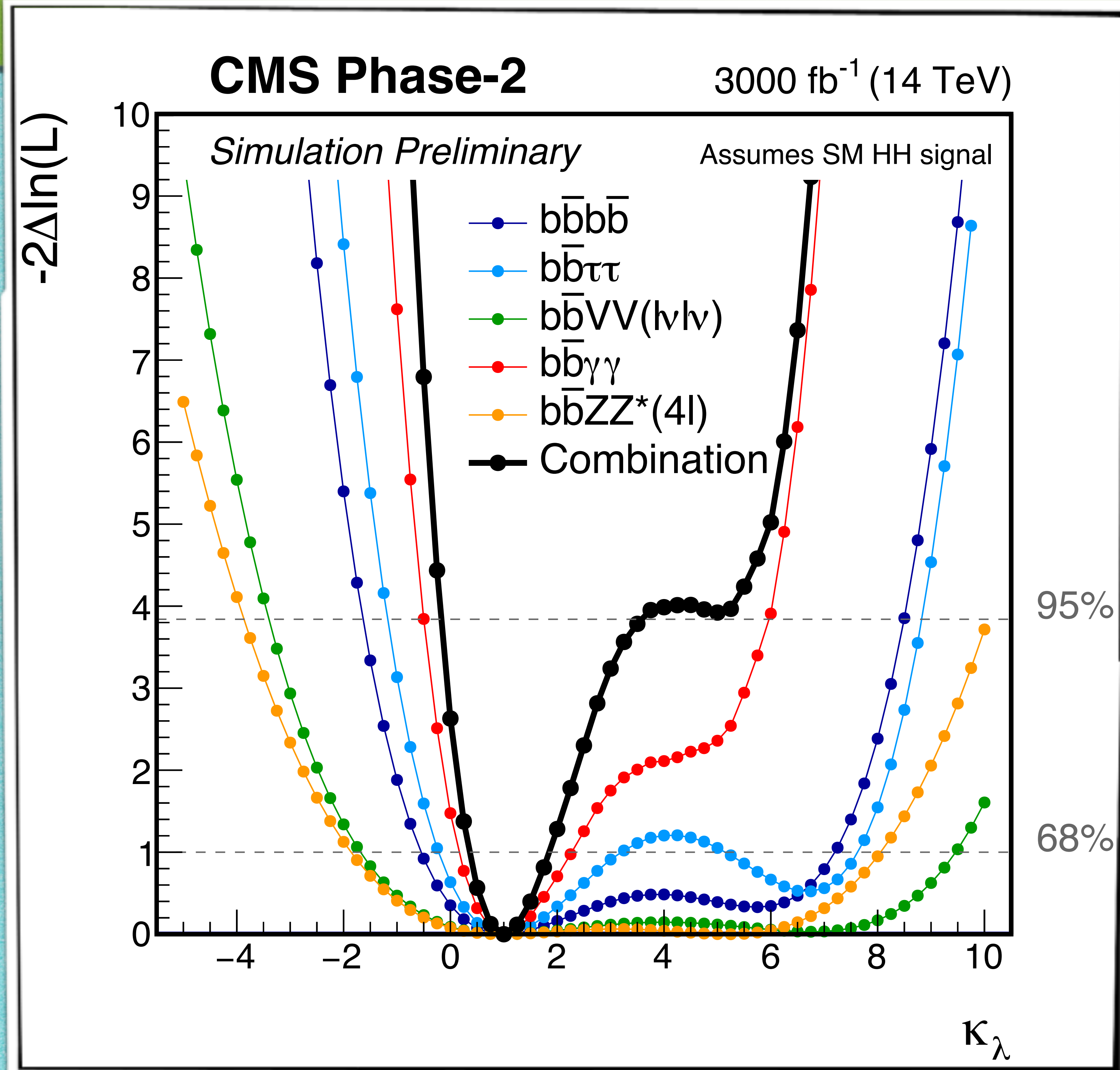
- CMS-FTR-18-019: HH measurements at the HL-LHC (pp @ 14 TeV, 3 ab^{-1})
- Subdecays: bbbb/bbWW(ll$\nu\nu$)/bb$\tau\tau$/bb$\gamma\gamma$/bbZZ(4l)
- Analyses developed using parametric simulation of upgraded detector response and optimized for 3 ab^{-1}
    - Expected significance of SM HH signal with 2.6σ

HH @ HL-LHC

Table 6: Upper limit at the 95% confidence level, significance, projected measurement at 68% confidence level of the Higgs boson self coupling λ_{HHH} for the five channels studied and their combination. Systematic and statistical uncertainties are considered.

Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	1.8	1.8	1.1	1.1
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

HH @ HL-LHC



CMS Phase-2
3000 fb^{-1} (14 TeV)
Simulation Preliminary
Assumes SM HH signal
-2ΔIn(L)
$b\bar{b}b\bar{b}$
$b\bar{b}\tau\tau$
$b\bar{b}VV(l\nu l\nu)$
$b\bar{b}\gamma\gamma$
$b\bar{b}ZZ^*(4l)$
Combination
95%
68%
κ_λ
0 1 2 3 4 5 6 7 8 9 10
−4 −2 0 2 4 6 8 10

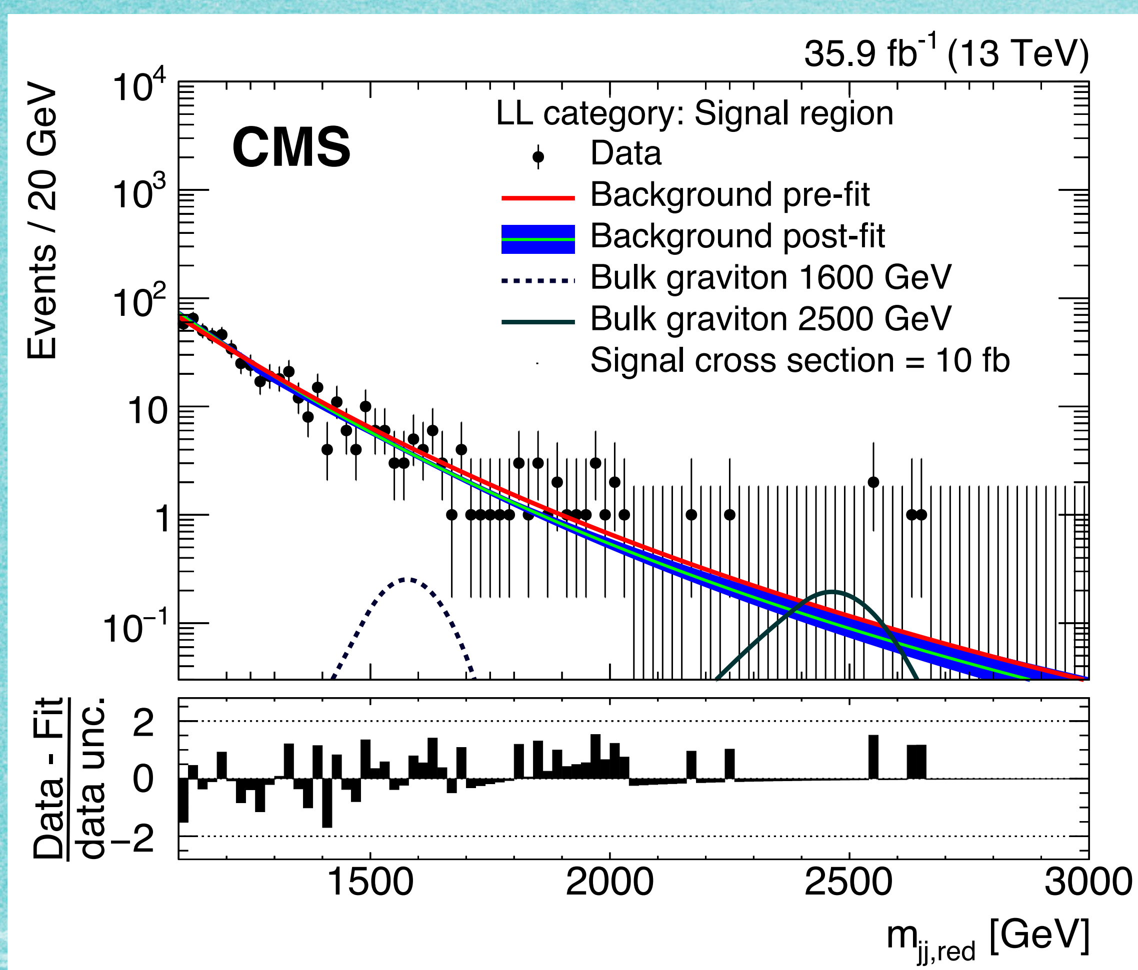
Summary

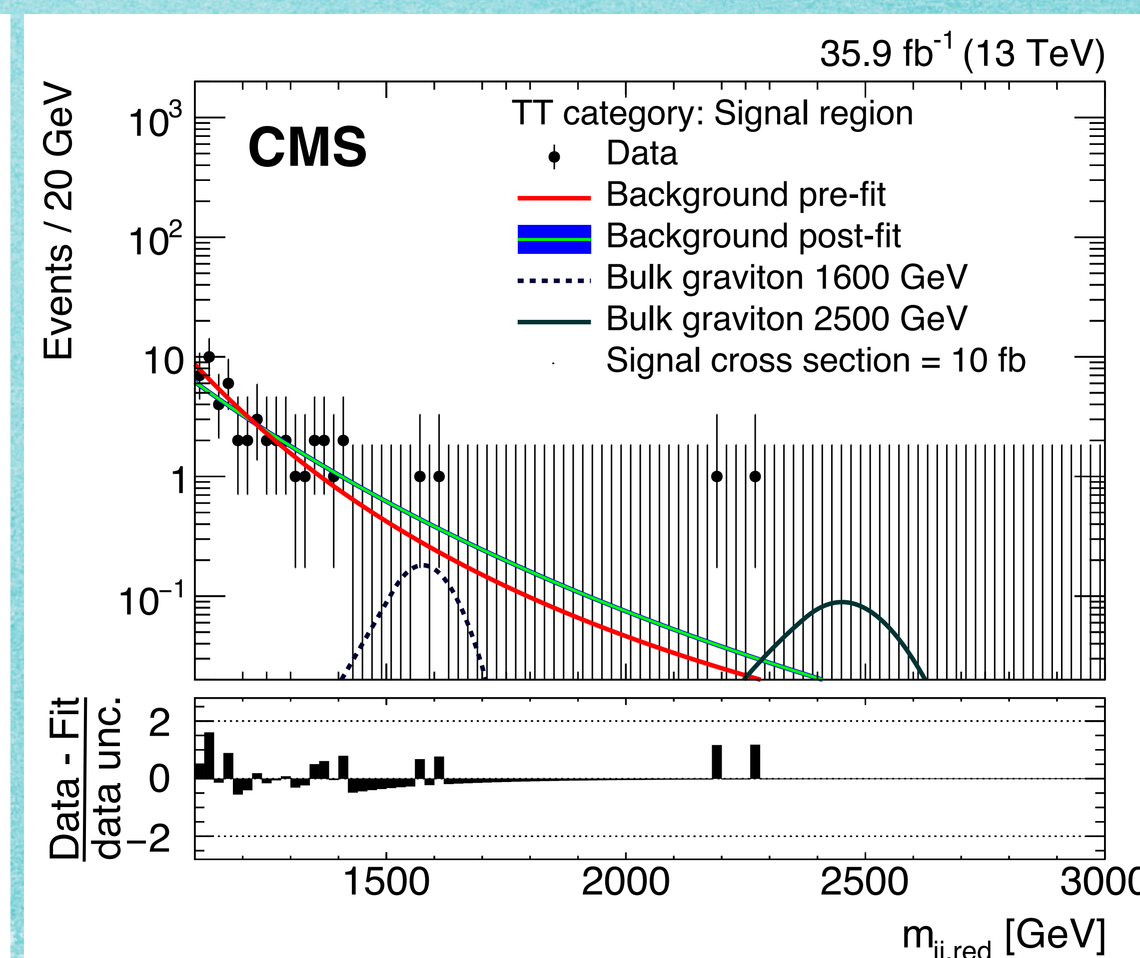
- The SM HH production is expected to have a cross section ~31 fb at 13 TeV and 40 fb at 14 TeV
  - Negative result of the SM HH measurement using 2016 dataset (~36 fb^{-1})
  - before High Luminosity LHC operation
  - Expect to confirm it at the end of HL-LHC with $>2\sigma$
- It is interesting because the HH production search would be a hint for BSM
  - Many searches have been performed not only for the HH production but also for any BSM di-Higgs signals such as H^+H^-/aa/....
- Stay tuned for the LHC run2 results (~150 fb^{-1}) and next

Resonant HH→bbbb Boosted

Phys. Lett. B 781 (2018) 244, arXiv:1710.04960

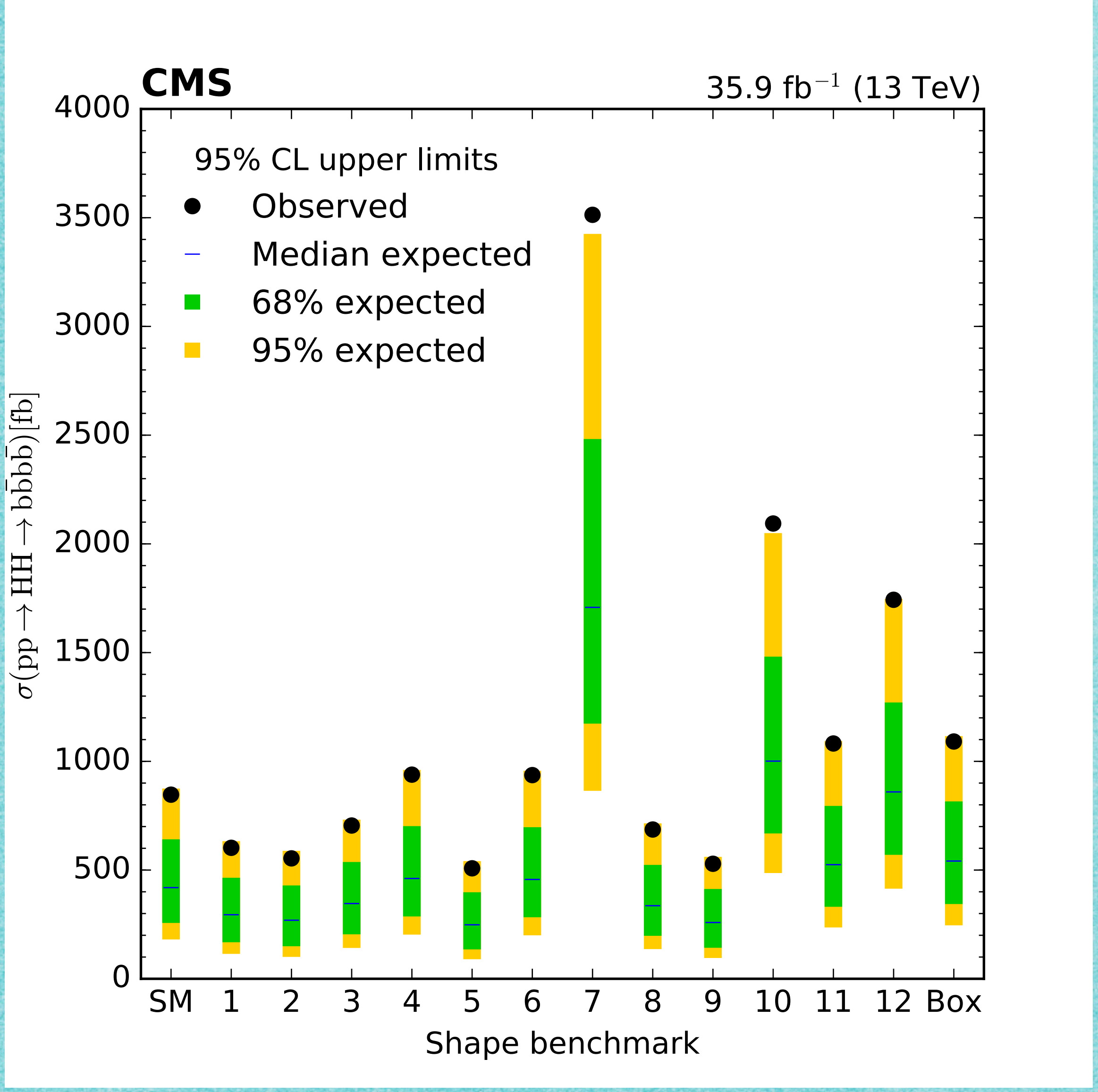
- Use fat-jet with R=0.8, p_T>300 GeV, $|\eta|$<2.4
- Leading two jets are Higgs tagged (double b requirement in the jet) & $|\Delta\eta(j1,j2)|$<1.3
- Results obtained by the fit on a reduced mass ($=m_{jj}-(m_{j1}-m_H)-(m_{j2}-m_H)$) distribution



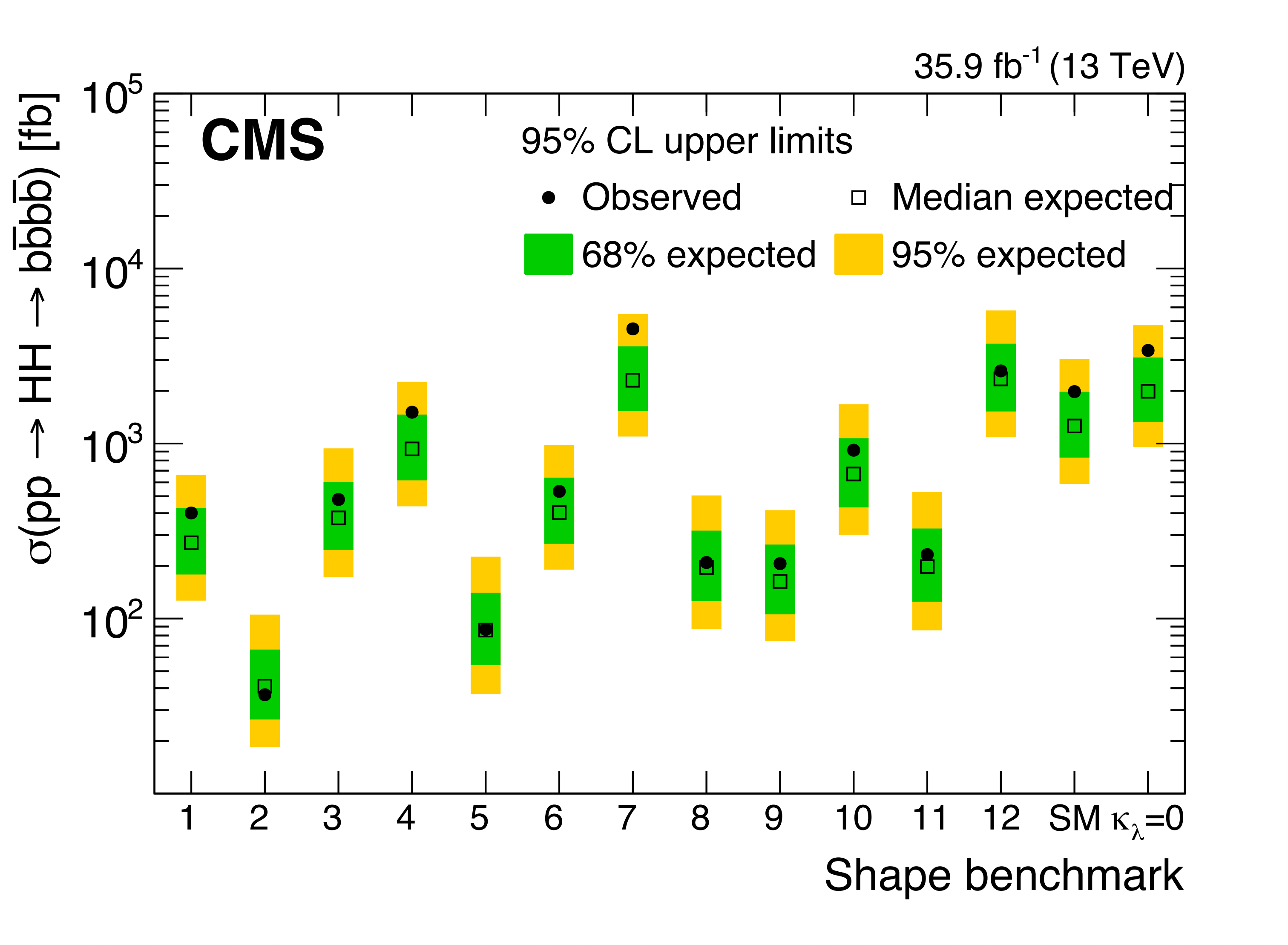


Non resonant limits from HH→4b

Resolved



semi-resolved+fully merged



HH→bbZZ→bbll$\nu\nu$

CMS-PAS-HIG-17-032

ATLAS

HH→WW*$\gamma\gamma$

Eur. Phys. J. C (2018) 78:1007, arXiv:1807.08567

ATLAS

HH→WW$^{(*)}$WW$^{(*)}$

JHEP 05 (2019) 124, arXiv:1811.11028