Overview of searches for resonant HH production and associated signatures at the LHC

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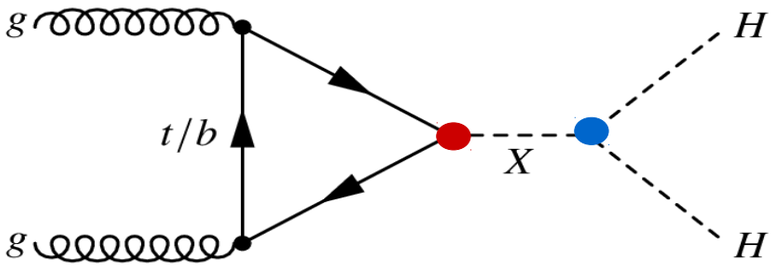
University of Florida
on behalf of the CMS and ATLAS Collaborations

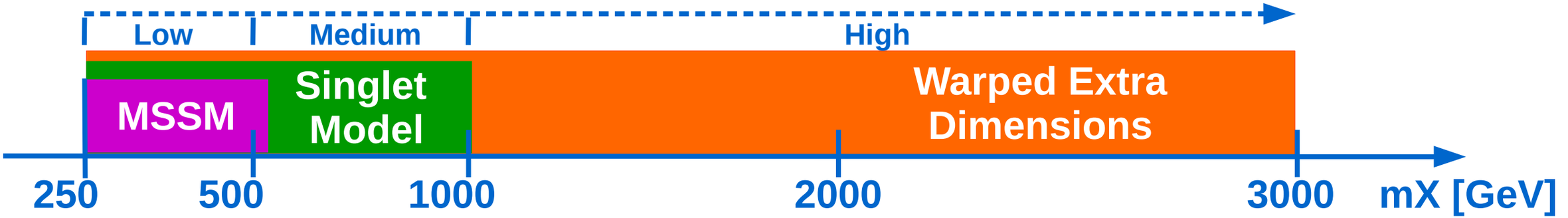
16th Workshop of the LHC Higgs Cross Section Working Group
CERN, October 17th, 2019

HH resonant production at the LHC

Several BSM models can be proved via heavy particle decaying into a pair of Higgs bosons



- Warped Extra Dimensions → Gravitons & Radions
- MSSM → Heavy boson $\tilde{H}$
- Singlet model → Heavy boson S



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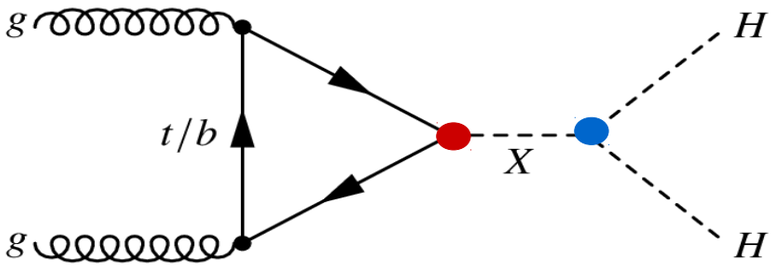

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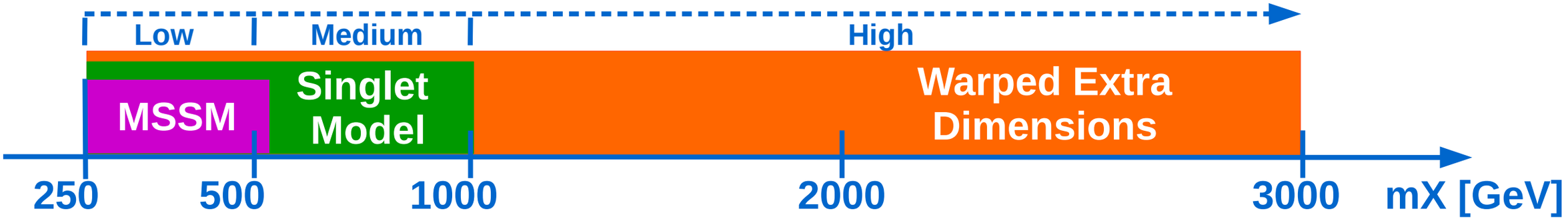
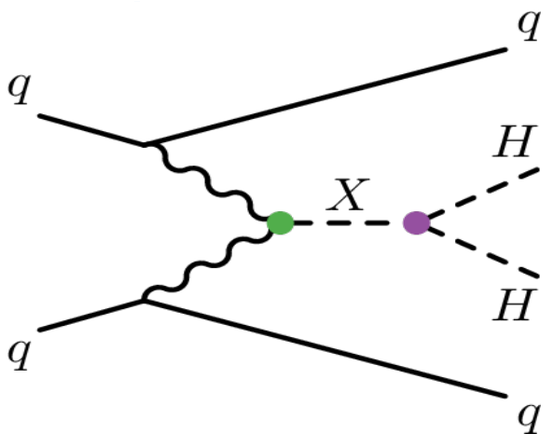


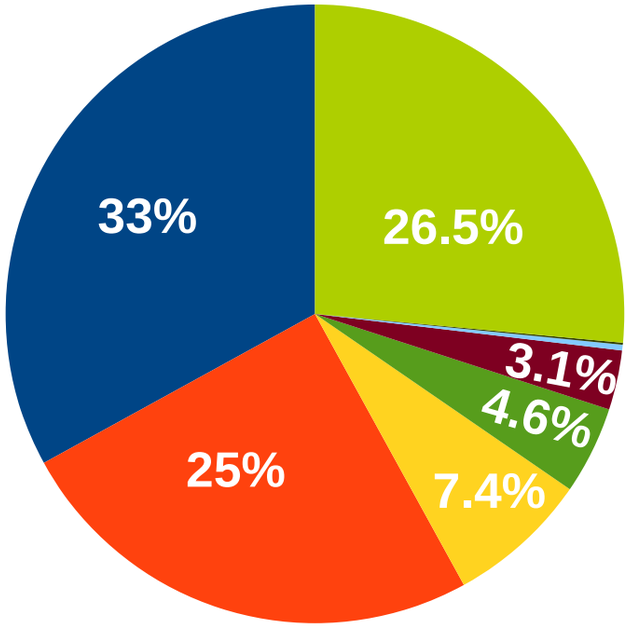
Very rich phase space to explore

- Production modes:
  - Gluon fusion
  - Vector boson fusion (VBF)
- Mass range: 250 GeV – 3 TeV
- Spin-2 & Spin-0 hypotheses
- Narrow- & broad-width



Overview of HH resonant searches

HH Branching ratios



Search challenges by final state

$b\bar{b}b\bar{b}$: Large multijet background & challenging trigger

$b\bar{b}WW$: Large & irreducible top quark pair background

$b\bar{b}\tau\tau$: Incomplete reconstruction (neutrinos)

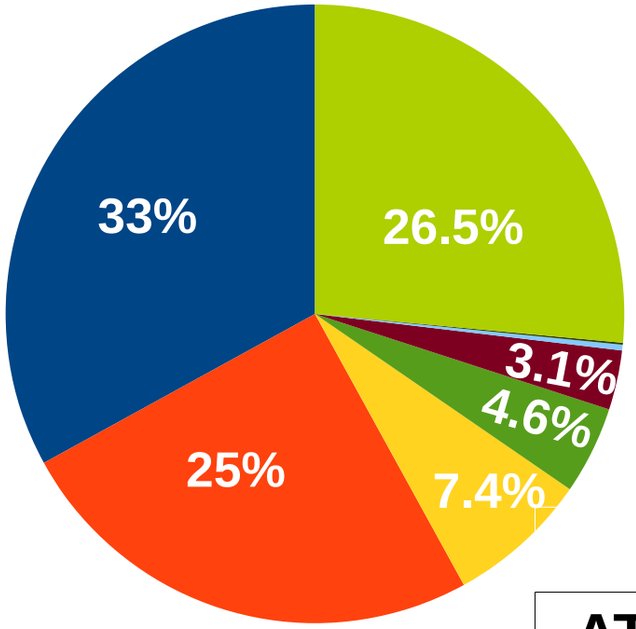
WWWW: Poor resolution and large background

$b\bar{b}ZZ$ / $b\bar{b}\gamma\gamma$ / WWyy : Statistically limited

Others (e.g. bbμμ): Not feasible/accessible at the LHC

Overview of HH resonant searches

HH Branching ratios



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13 TeV experimental program coverage until date

	$b\bar{b}b\bar{b}$	$b\bar{b}WW$	$b\bar{b}\tau\tau$	WWWW	$b\bar{b}ZZ$	$b\bar{b}\gamma\gamma$	WW$\gamma\gamma$
ATLAS	**X*,#**	**X***	**X**	**X**		**X**	**X**
CMS	**X***	**X***	**X***		**X**	**X**	

*Includes dedicated analysis with highly Lorentz-boosted Higgses

#Includes dedicated analysis of the VBF production mode

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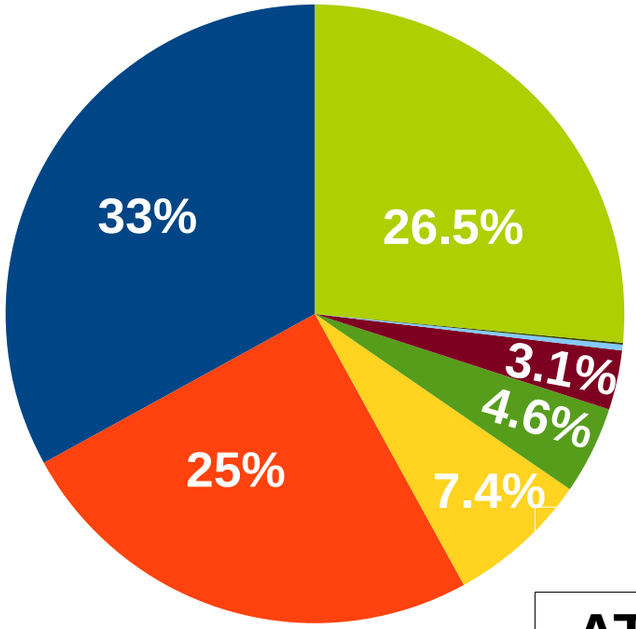

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ATLAS	**X*,#**	**X***	**X**	**X**		**X**	**X**
CMS	**X***	**X***	**X***		**X**	**X**	

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#Includes dedicated analysis of the VBF production mode

Multivariate methods are used in most final states to improve search sensitivity

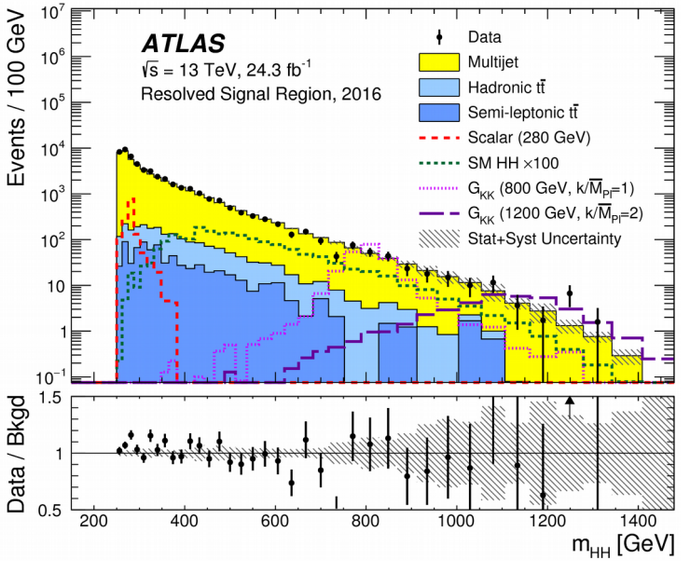
- Background discriminators, b-quark jet identification algorithms, etc

A resonant HH combination of final states maximizes the sensitivity to new physics

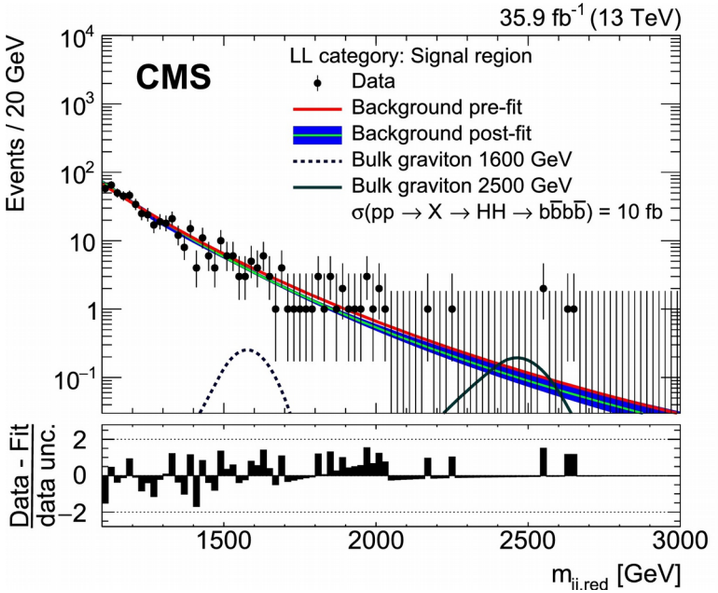
ATLAS and CMS performed their own combination using 2015-2016 data

X(HH) → bb̄bb̄

Phys. Lett. B 781 (2018) 244 JHEP01(2019)030
JHEP01(2019)040 JHEP08(2018)152



- Data-driven multijet bkg. model
- Mass range: 260 GeV - 3 TeV
- Spin-2 and Spin-0 hypotheses
  - W.E.D. interpretations



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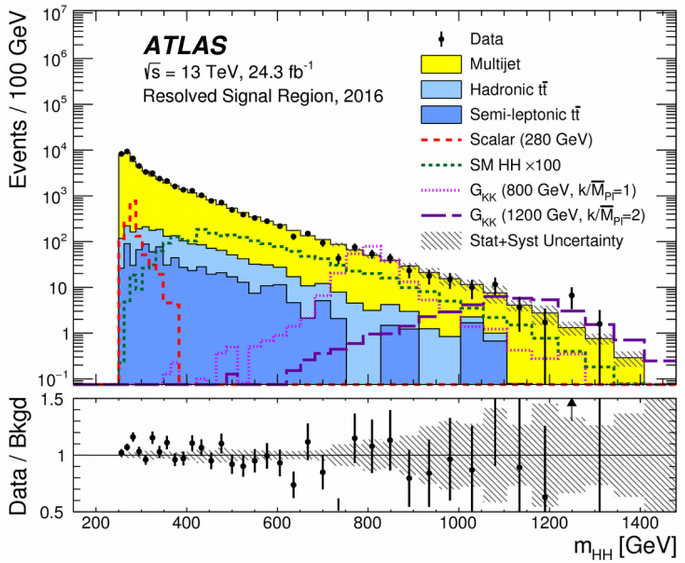

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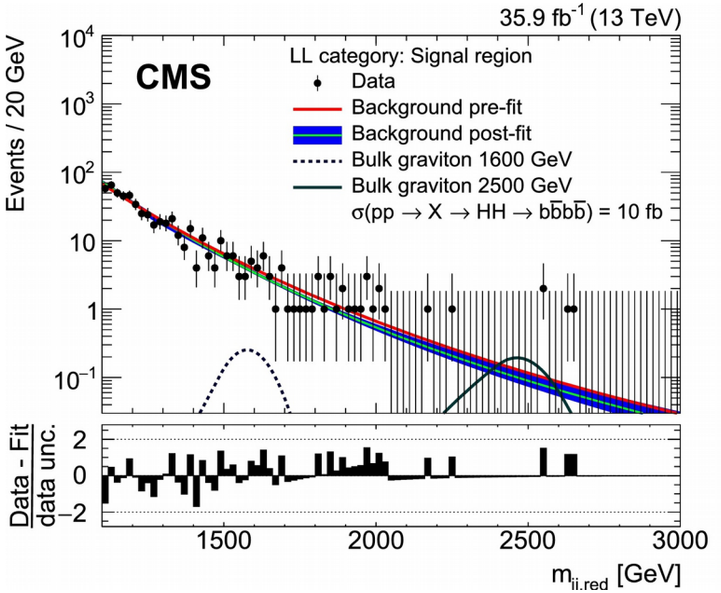
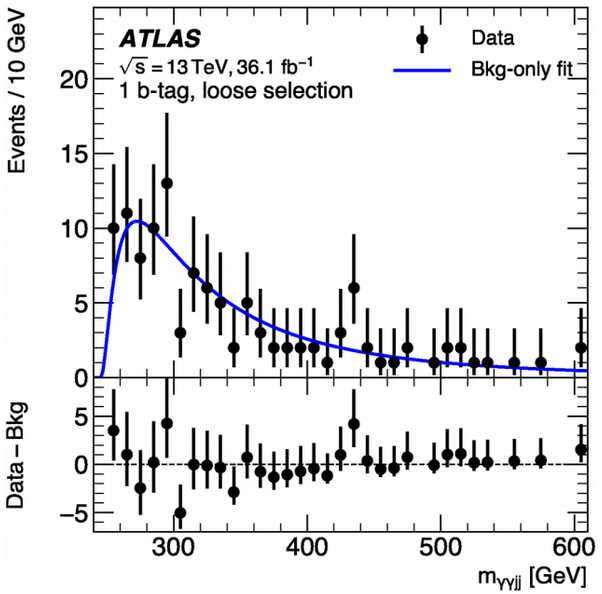
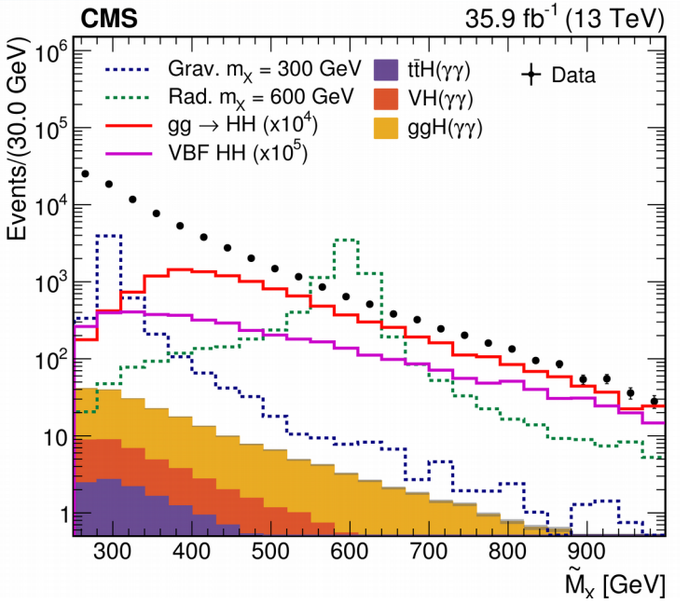


X(HH) → bb̄γγ

JHEP 11 (2018) 040
Phys. Lett. B 788 (2018) 7

- Clean channel:
  - Myy resolution ~ 1%
- Mass range: 260 GeV - 1 TeV
- Spin-2 and spin-0 hypotheses
  - W.E.D. interpretations

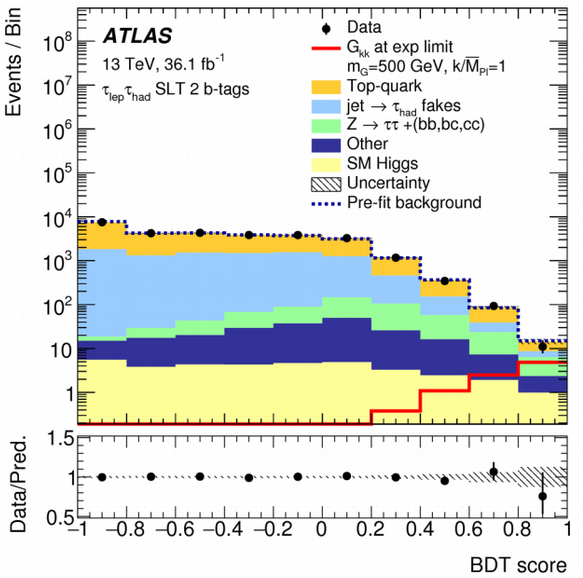


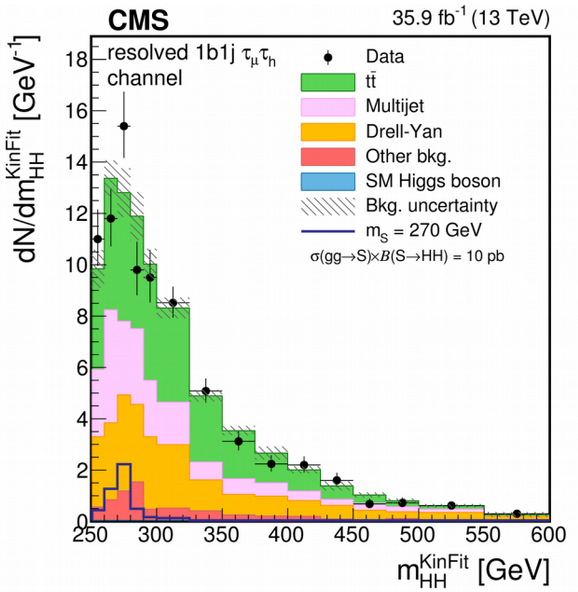


X(HH) → bb̄ττ

Phys. Rev. Lett. 121 (2018) 191801
JHEP01(2019)051 Phys. Lett. B 778 (2018) 101

- Mass range: 250 GeV – 3 TeV
- Combination:
  - $\tau_l\tau_{had}$ + $\tau_{had}\tau_{had}$ (l = e, μ)
- Spin-2 and spin-0 hypothesis:
  - hMSSM & W.E.D. interpretations





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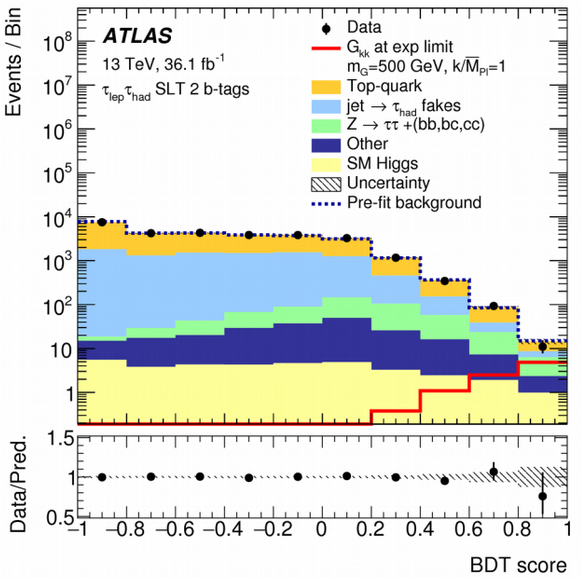
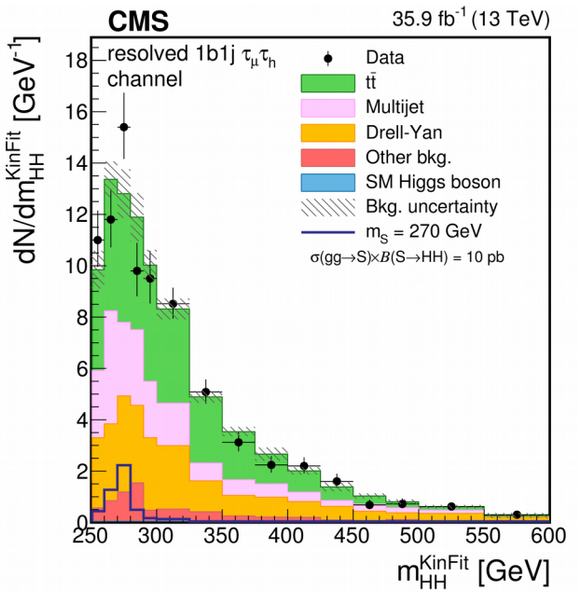
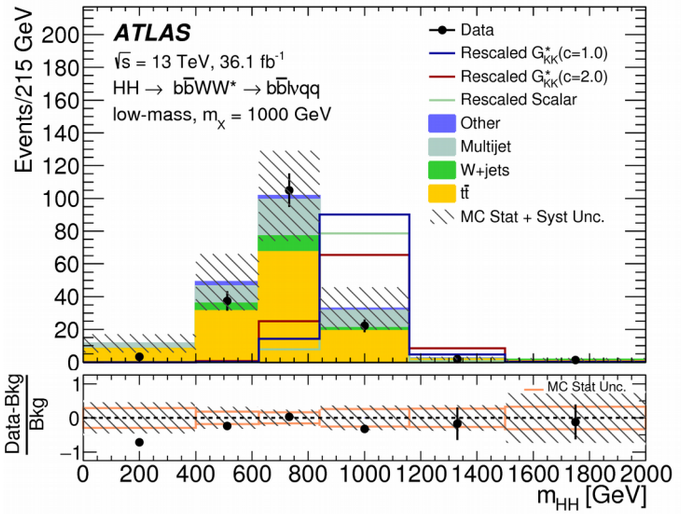
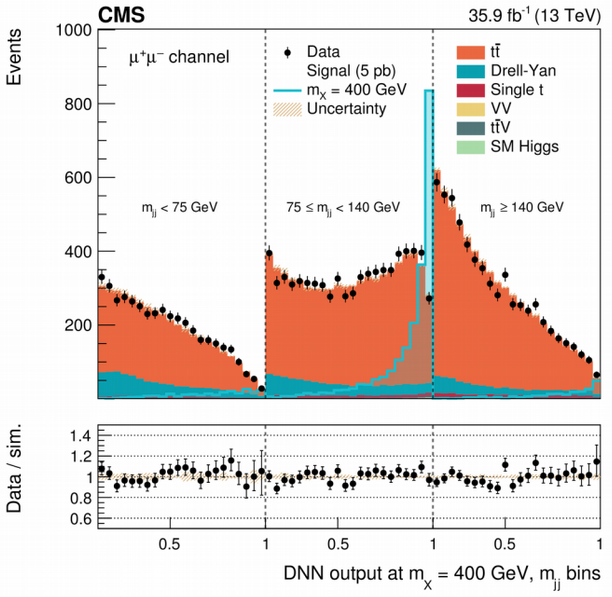




X(HH) → bb̄WW(*)

JHEP 04 (2019) 092
JHEP 01 (2018) 054



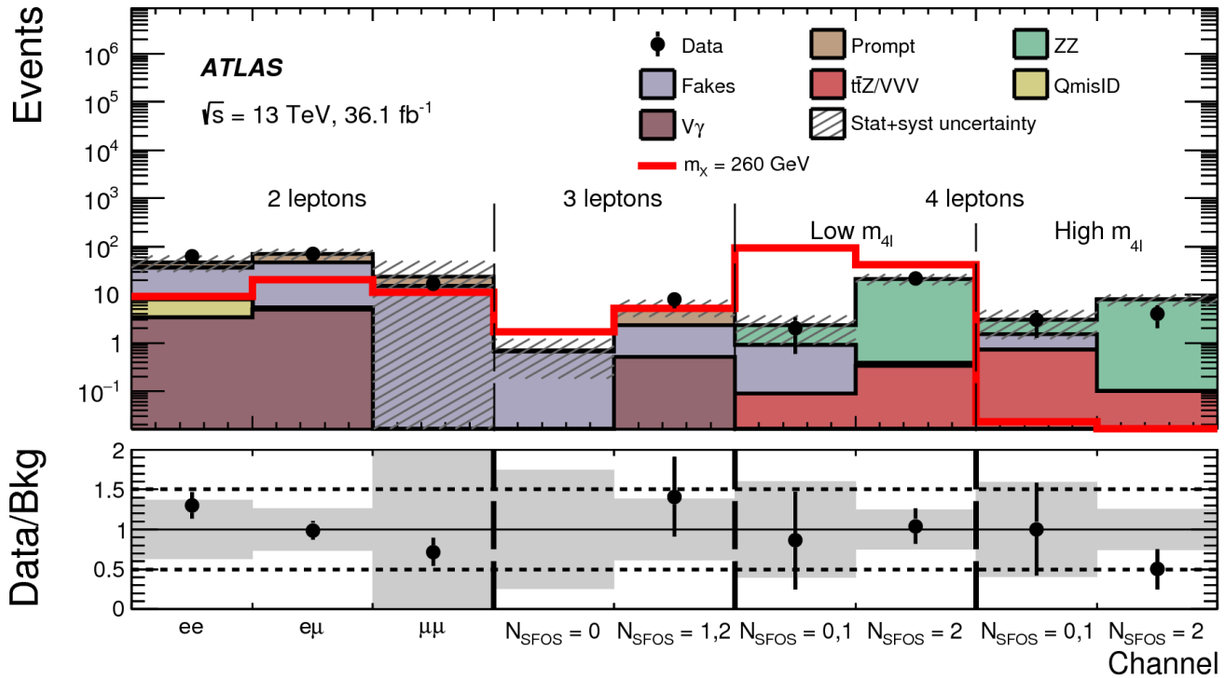


- Mass range in ATLAS (CMS)
  - 500 (260) GeV – 3 (0.9) TeV
- Channel:
  - bblνqq (bblνlν) with l=e,μ
- Spin-2 and spin-0 hypotheses
  - W.E.D. interpretations

X(HH) → WW(*)WW(*)

JHEP05(2019)124

- Spin-0 and mass range: 260 - 500 GeV
- Combination of event categories:
  - 2, 3, & 4 leptons (+ MET + jets)



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JHEP05(2019)124

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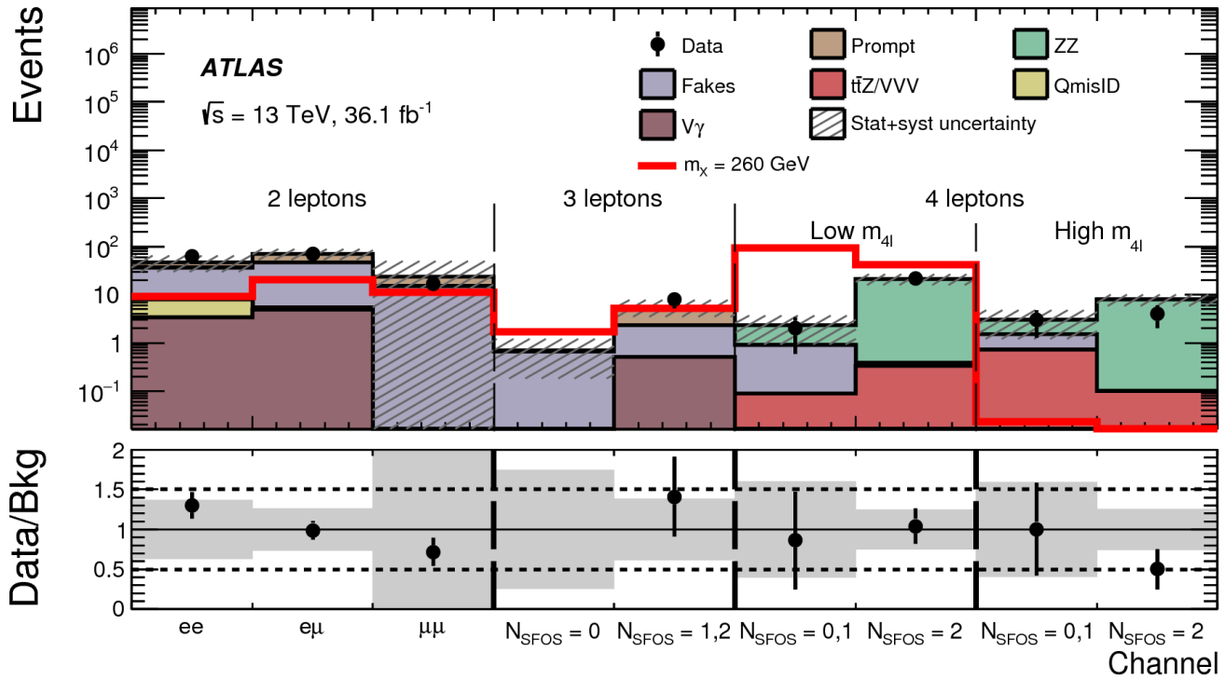
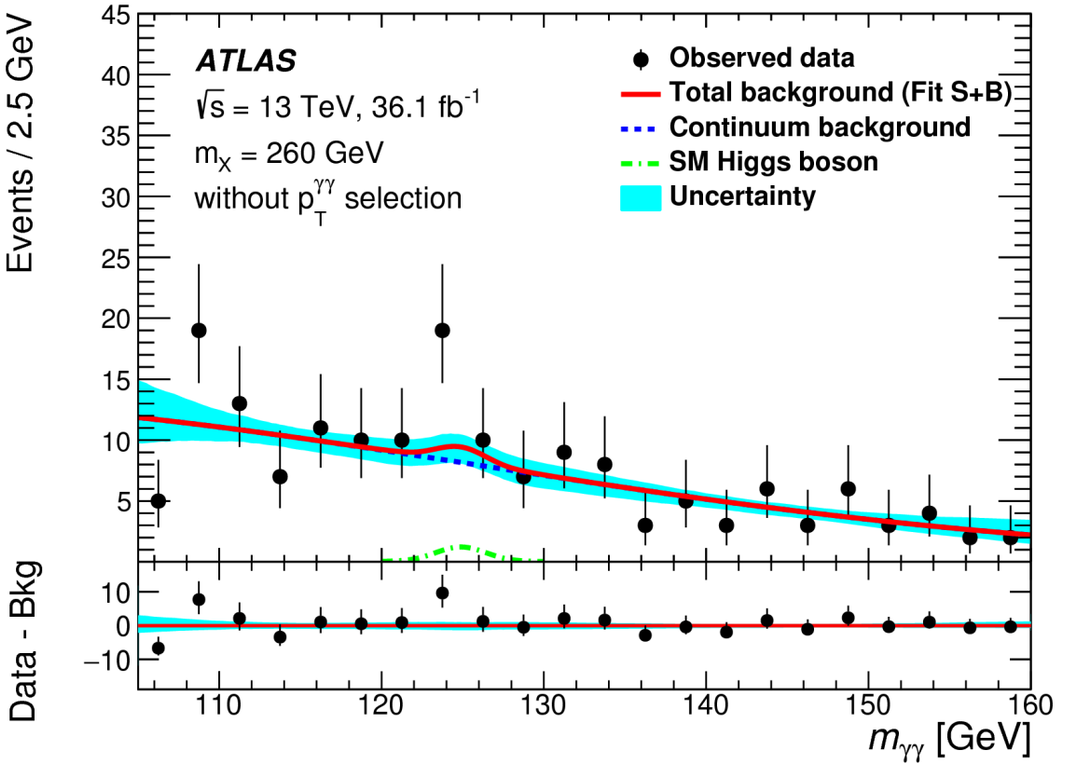


$X(HH) \rightarrow WW^{(*)}\gamma\gamma$

Eur. Phys. J. C 78 (2018) 1007

- Spin-0 and mass range: 260 - 500 GeV
- Channel: γγlνjj (l=e,μ, τ-leptonic)
- Discriminant: Di-photon mass distribution

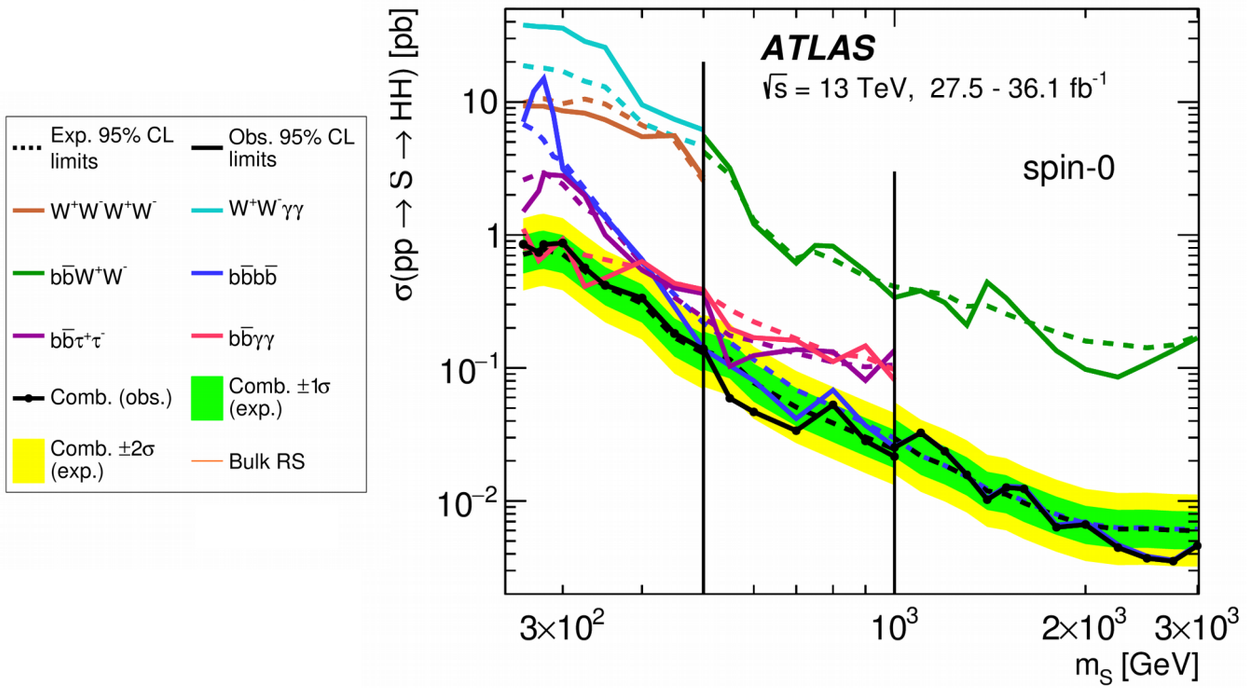


Resonant HH Combination

ATLAS

arXiv:1906.02025

- Narrow-width spin-0 (S)
  - hMSSM and EWK-singlet interpretations
- Spin-2 Bulk graviton (G)
  - W.E.D. Interpretations
- Mass range: 260 GeV to 3 TeV



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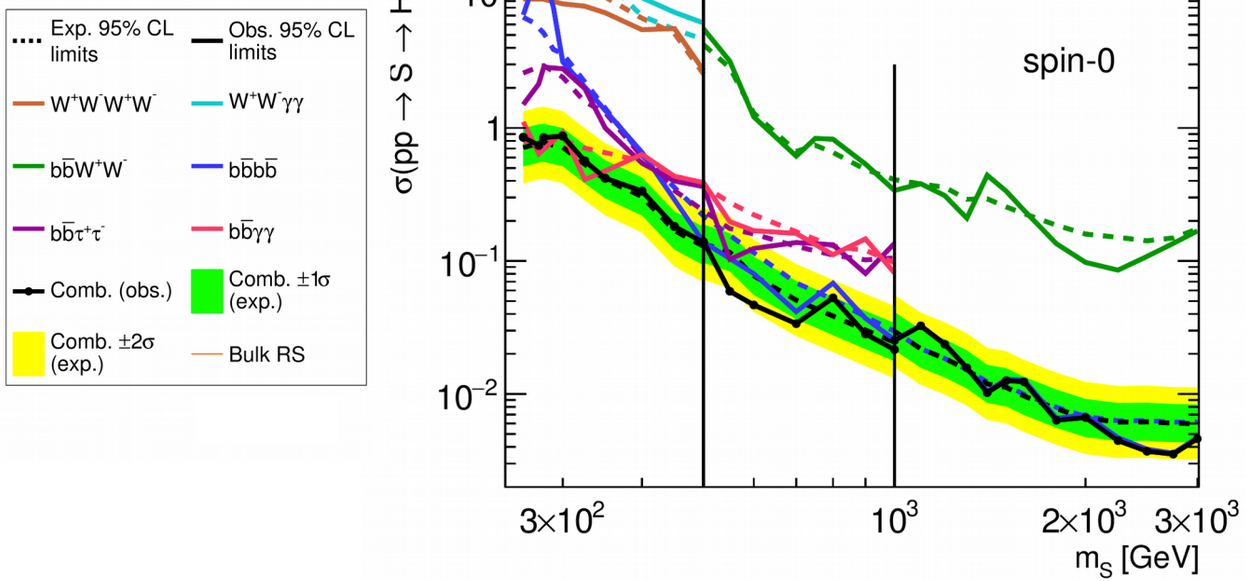
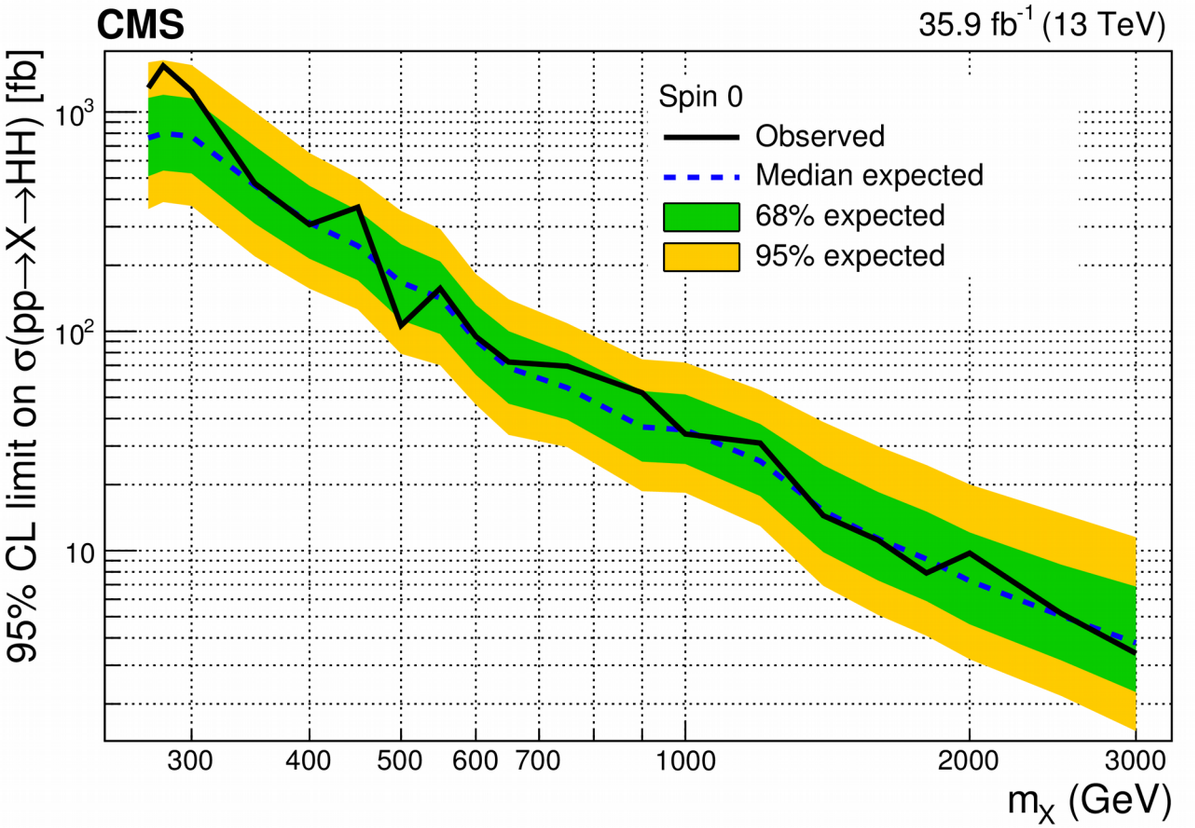


CMS

PRL 122, 121803 (2019)

- Narrow-width Spin-0 and Spin-2 (X)
- Mass range: 250 GeV to 3 TeV



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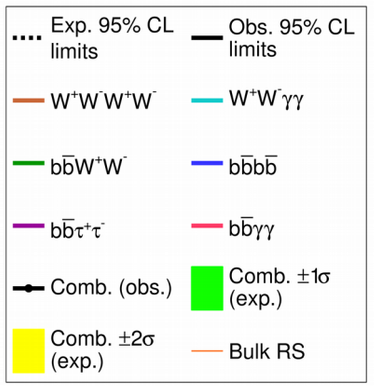

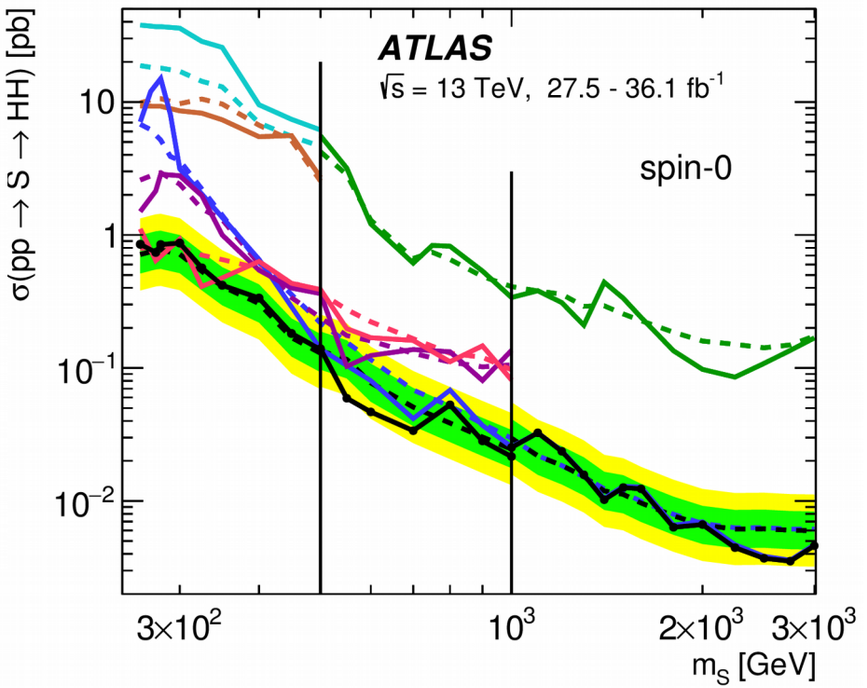

PRL 122, 121803 (2019)

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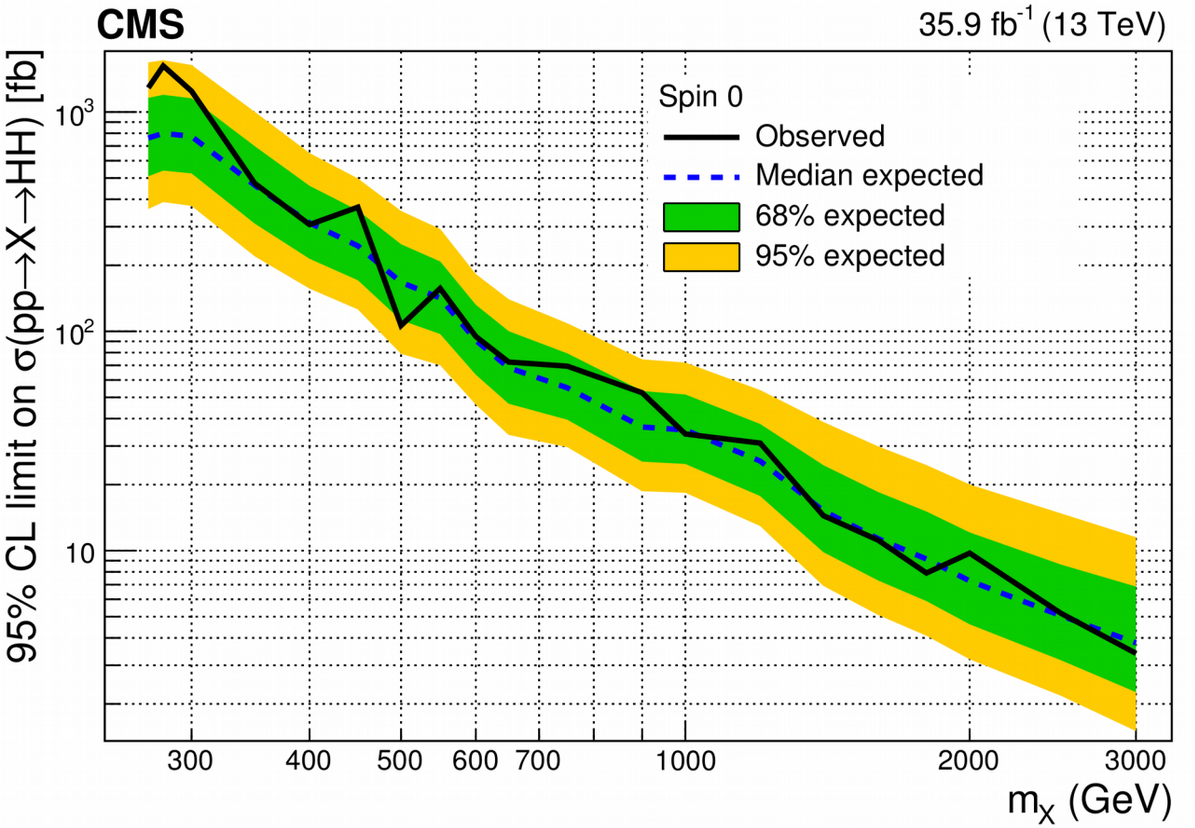


No significant excess is observed with respect to the SM prediction

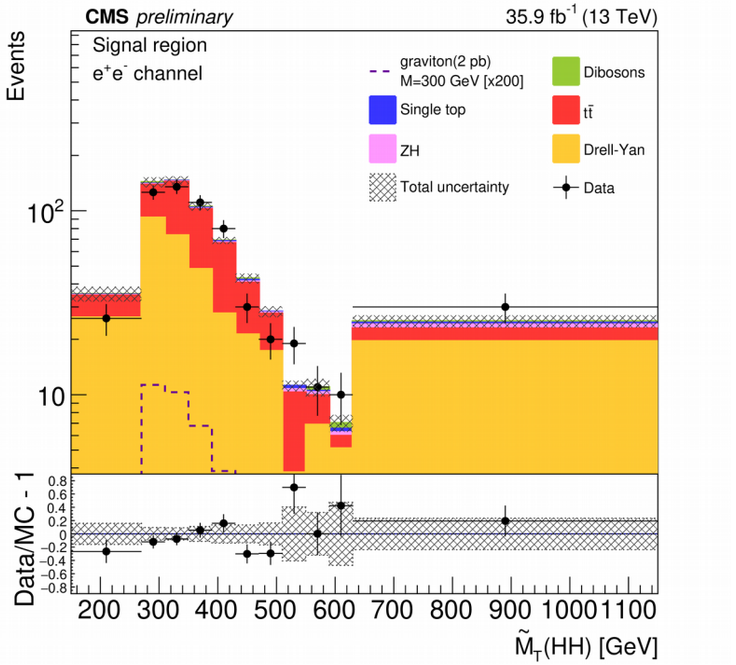

More channels, not just ggF mode,
and more data to exploit

Newest resonant HH results

$X(HH) \rightarrow b\bar{b}ZZ^{(*)}$

CMS PAS HIG-18-013

- Narrow-width spin-0 and spin-2
  - Mass range: 260 GeV - 1 TeV
  - W.E.D. interpretations
- Combination: bbℓℓjj & bbℓℓνν (ℓℓ=ee,μμ)
- Discriminant: BDT & Transverse mass



See also: $X(HH) \rightarrow b\bar{b}WW^{(*)}$ **(boosted)**

ArXiv:1904.04193

Newest resonant HH results

$X(HH) \to b\bar{b}ZZ^{(*)}$ *CMS PAS HIG-18-013*

- Narrow-width spin-0 and spin-2
  - Mass range: 260 GeV - 1 TeV
  - W.E.D. interpretations
- Combination: bblljj & bbllνν (ll=ee,μμ)
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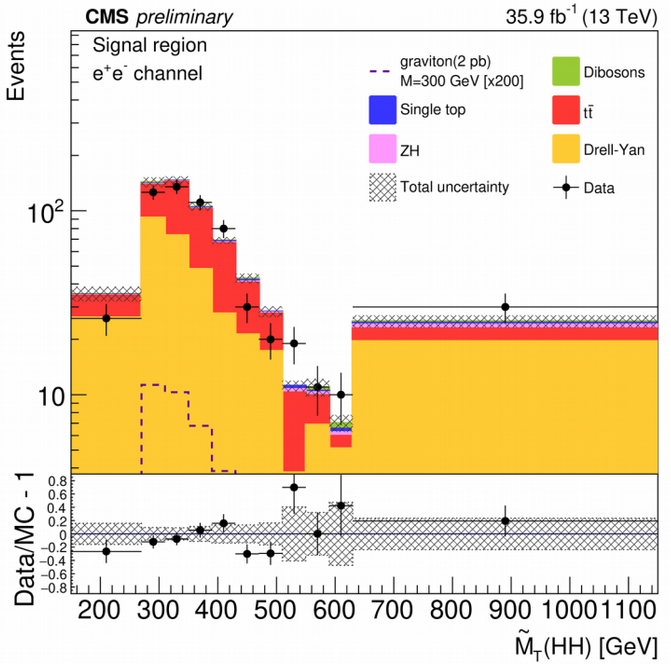
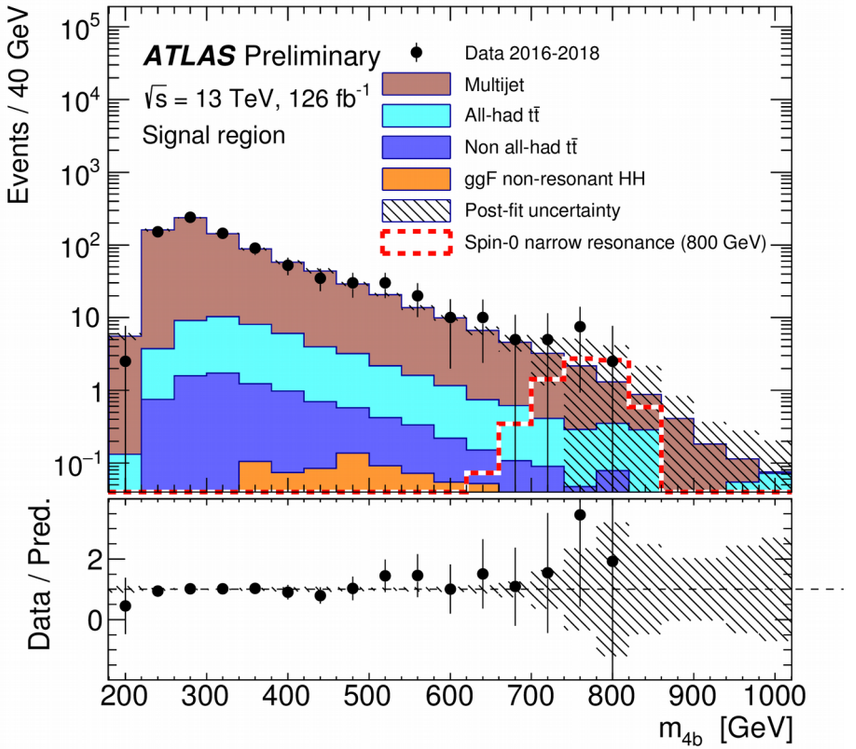


See also: $X(HH) \to b\bar{b}WW^{(*)}$ **(boosted)**

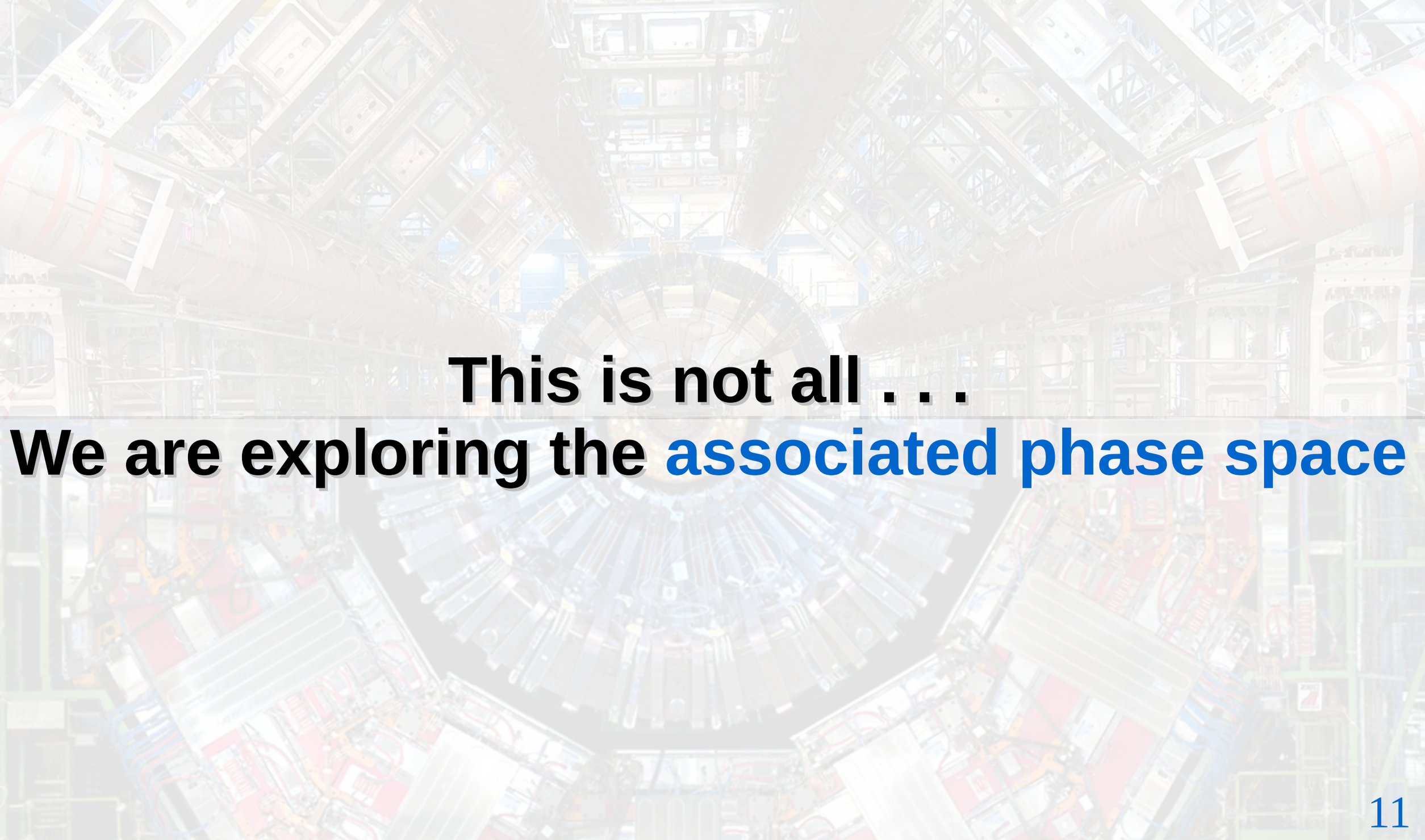
ArXiv:1904.04193

VBF $X(HH) \to b\bar{b}b\bar{b}$ *ATLAS-CONF-2019-030*

- Narrow and broad-width spin-0
  - Produced via VBF mode
  - Mass range: 260 GeV - 1 TeV
- Discriminant: Invariant mass of four b-jets



First full Run2 dataset result



This is not all . . .

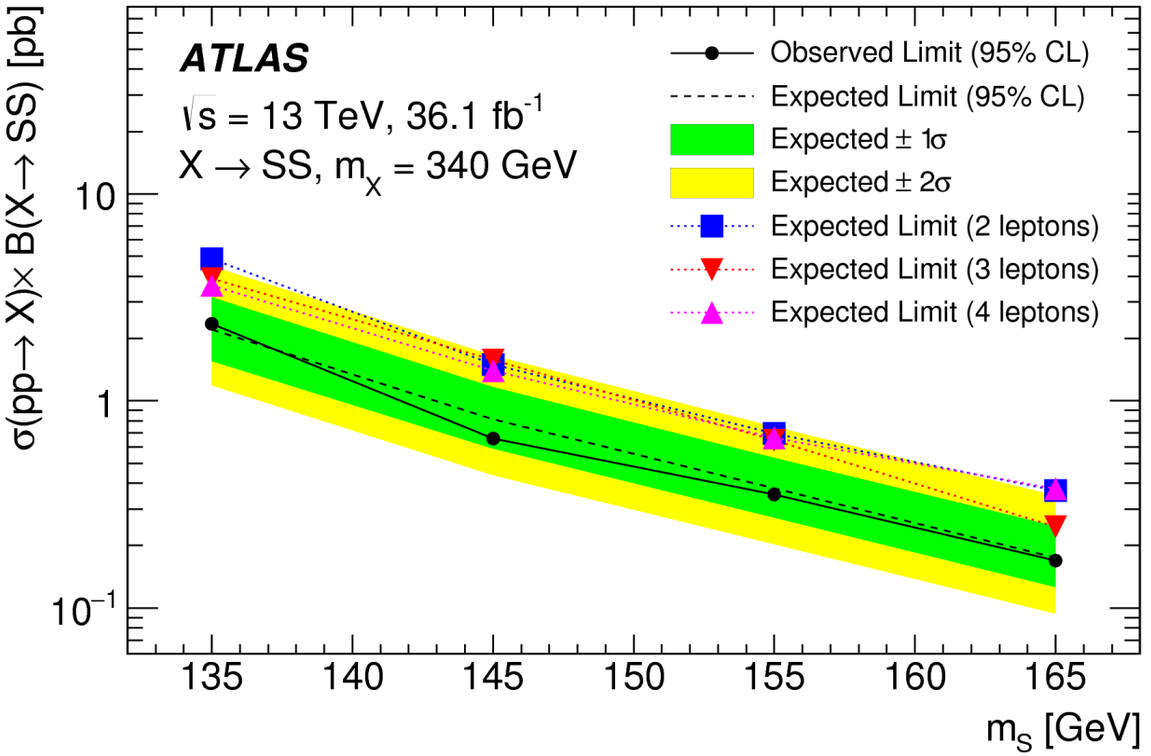
We are exploring the associated phase space

Associate search ideas

JHEP05(2019)124

Resonant production of a heavy scalar pair S
$X \rightarrow SS \rightarrow WW^{(*)}\ WW^{(*)}$

- Narrow-width X and S resonances
- Combination of event categories:
  - 2, 3, and 4 leptons (+ MET + jets)



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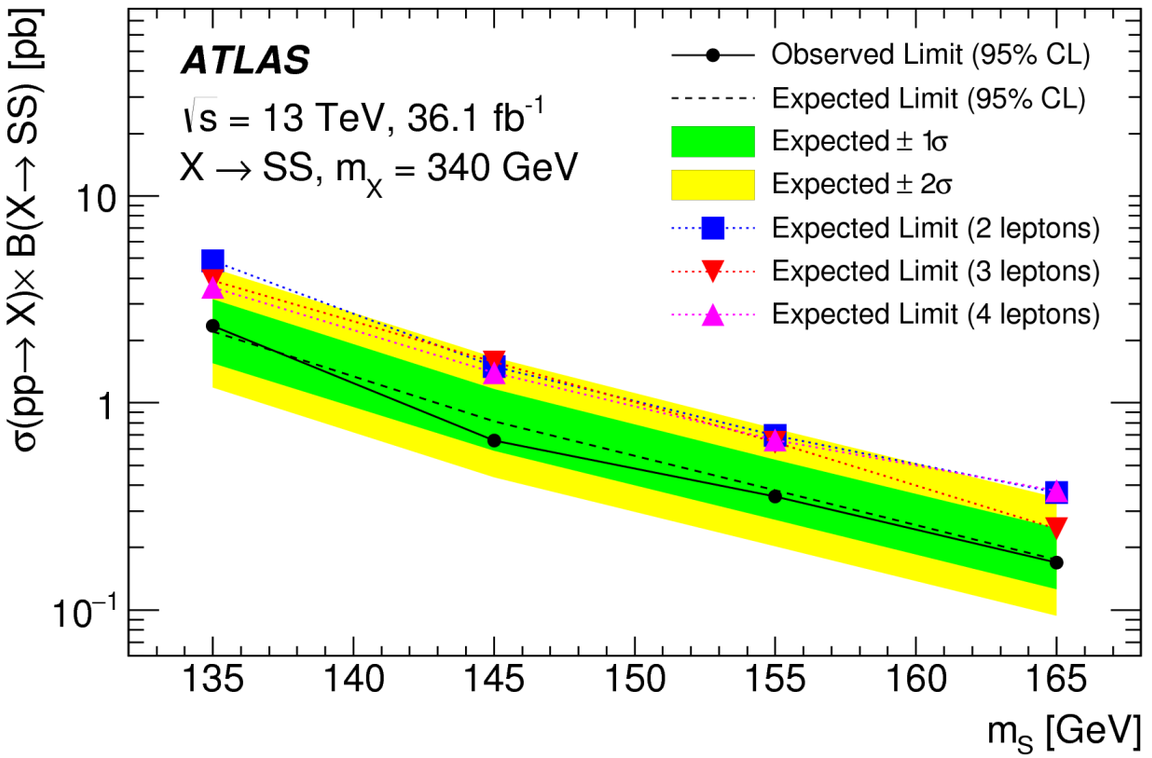
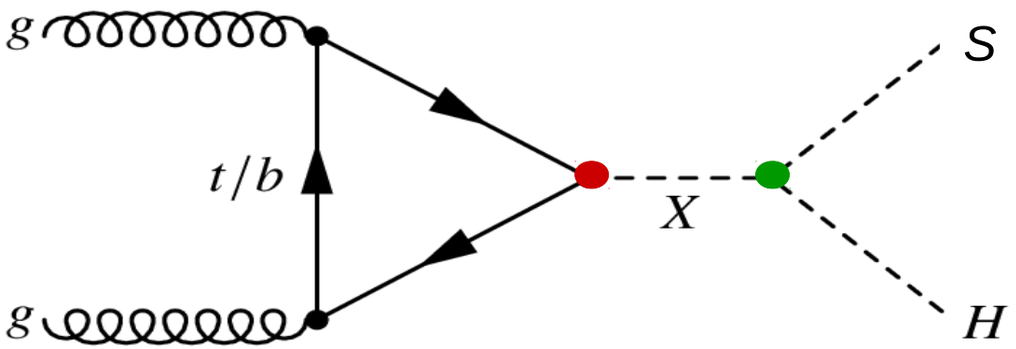


Near future

Resonant HH production searches extension to search for resonant Higgs + Scalar production



- Predicted in NMSSM (*arXiv:1707.08522*)
  - $B(\tilde{H}/A \rightarrow \tilde{H}_S/A_S + H)$ up to ~50%
    More details in NMSSM Subgroup's talk
- Model-independent search
  - X and S narrow-width resonances

Summary

Very rich program of HH resonance searches at the LHC

Multiple channels already investigated with the 2015-2016 dataset

- Spin-2 & Spin-0 hypotheses tested
- Search sensitivity is maximized by channels combination
  - No evidence of new phenomena so far
  - Constraints to BSM models: hMSSM, EWK-singlet and W.E.D.

Full-Run 2 dataset searches on the way

- On-going improvements to boost each channel sensitivity
- New corners of the phase space to be uncovered
  - VBF X→ HH, X→SS and X→ SH

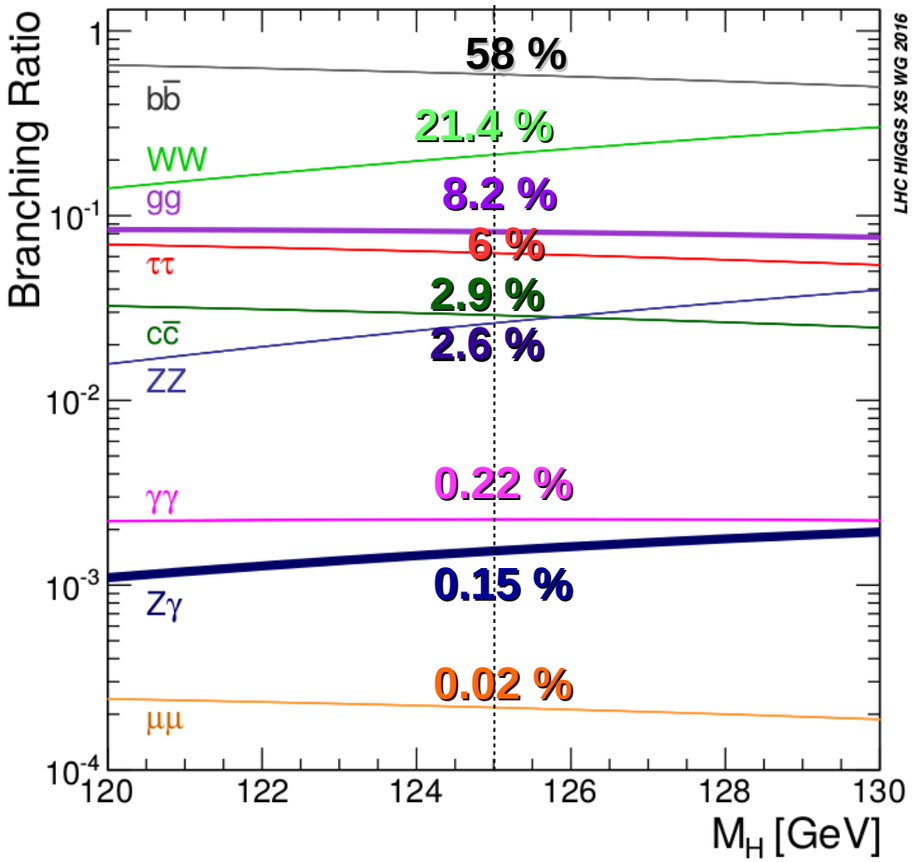
Stay tuned!


TIAN YOU

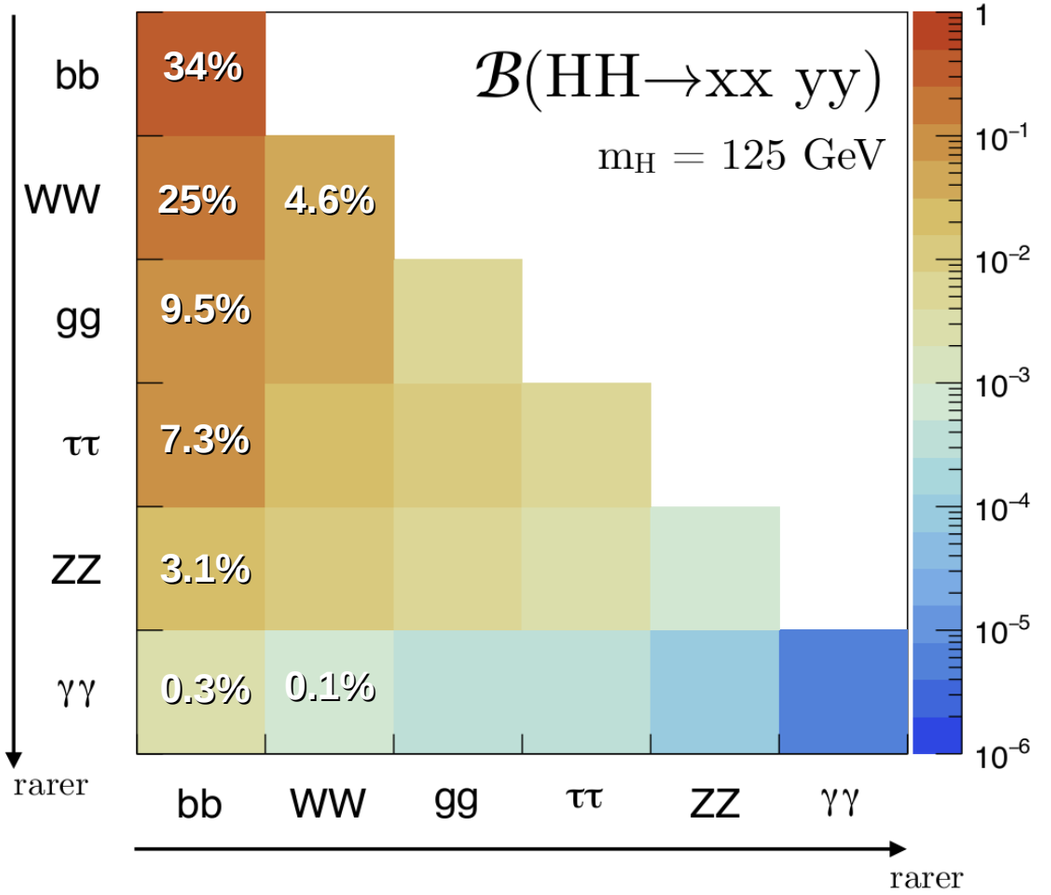
Bonus Material

Branching Ratios

SM Higgs boson



SM Higgs boson pairs

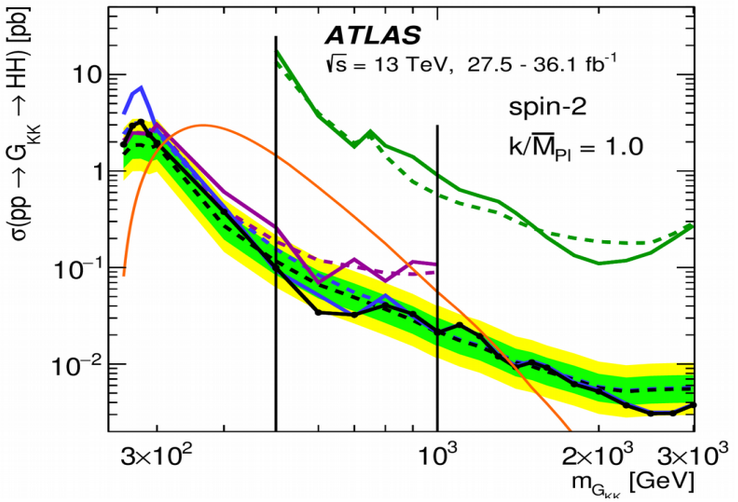


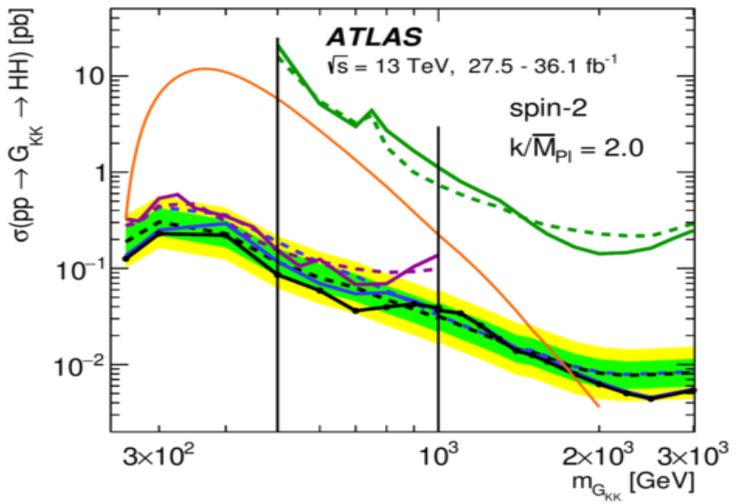
Spin-2 HH Combination

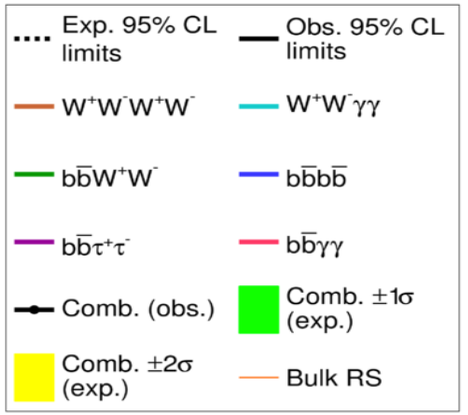
arXiv:1906.02025

PRL 122, 121803 (2019)

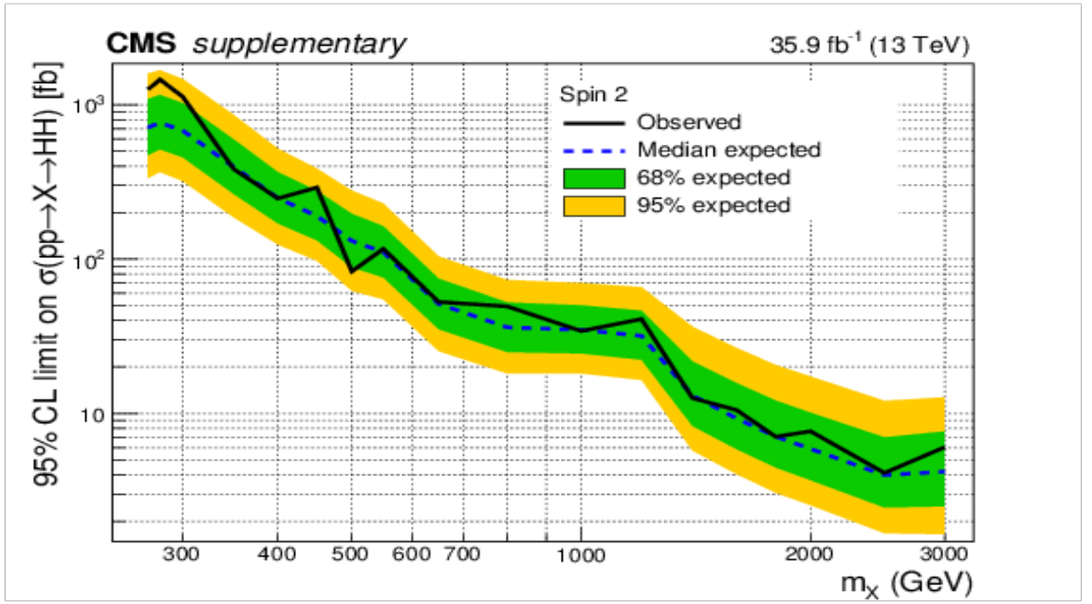
ATLAS







CMS



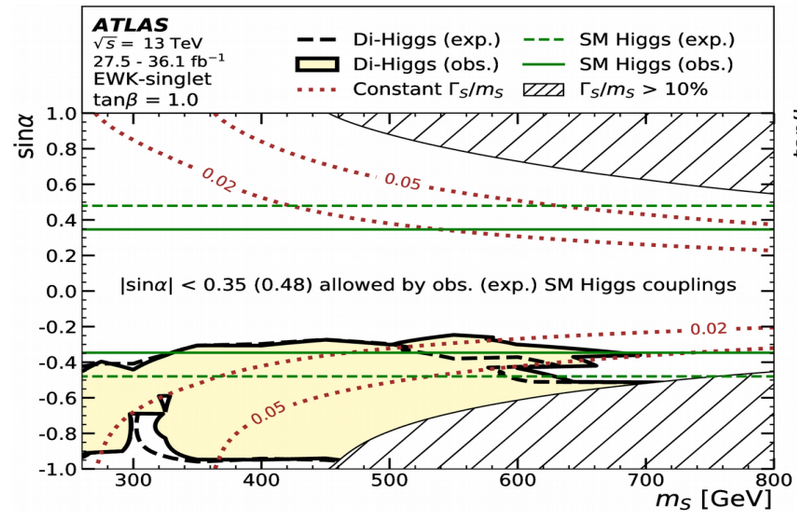
ATLAS Spin-0 Search Interpretation

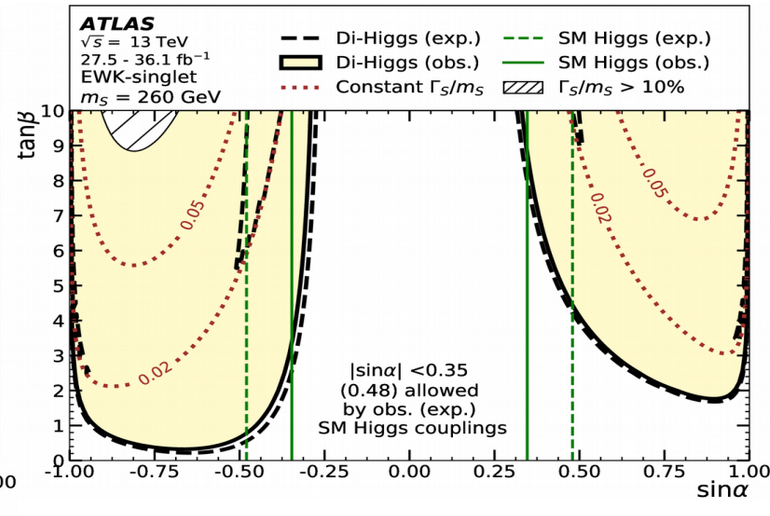
EWK-singlet model

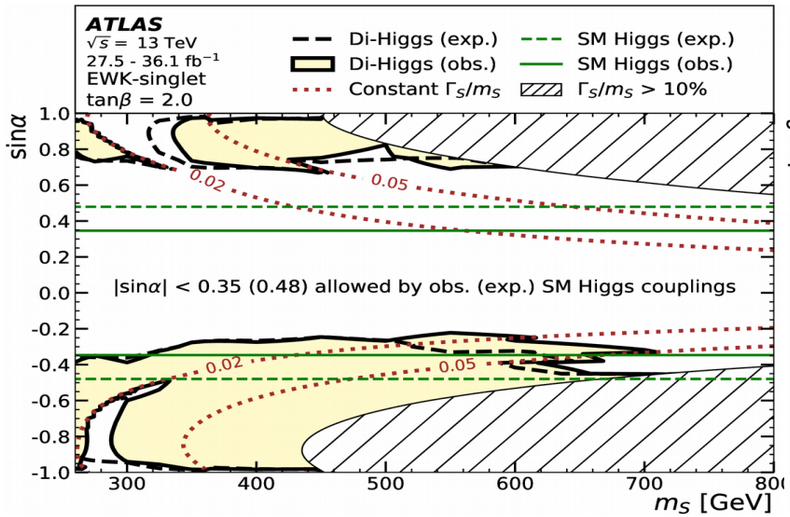
- Constraints in the mS–sinα plane
  - Two cases: tan β = 1, 2
  - Resonance width (Γ_s):
    - $\Gamma_s/m_s \leq$ experimental resolution (10%)

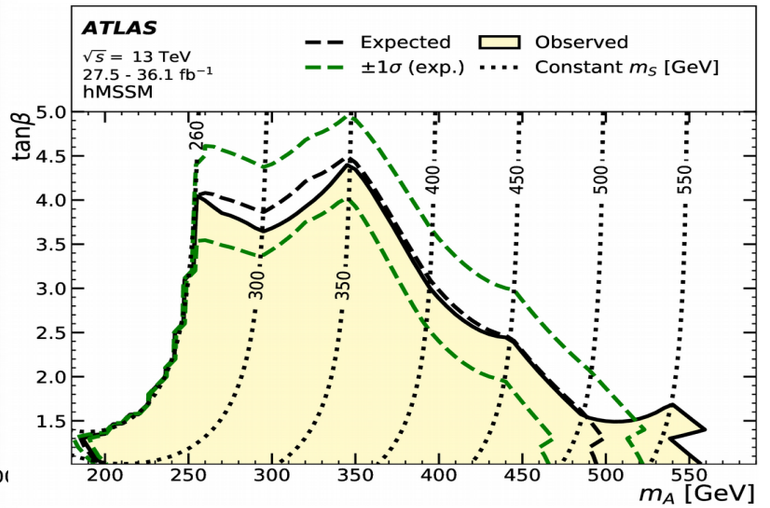
hMSSM model

- Constraints in the mA–tan β plane
- Exclusion:
  - tanβ coverage doubles w.r.t <u>result at 8 TeV</u>
  - mA from 190 to 560 GeV depending on tanβ



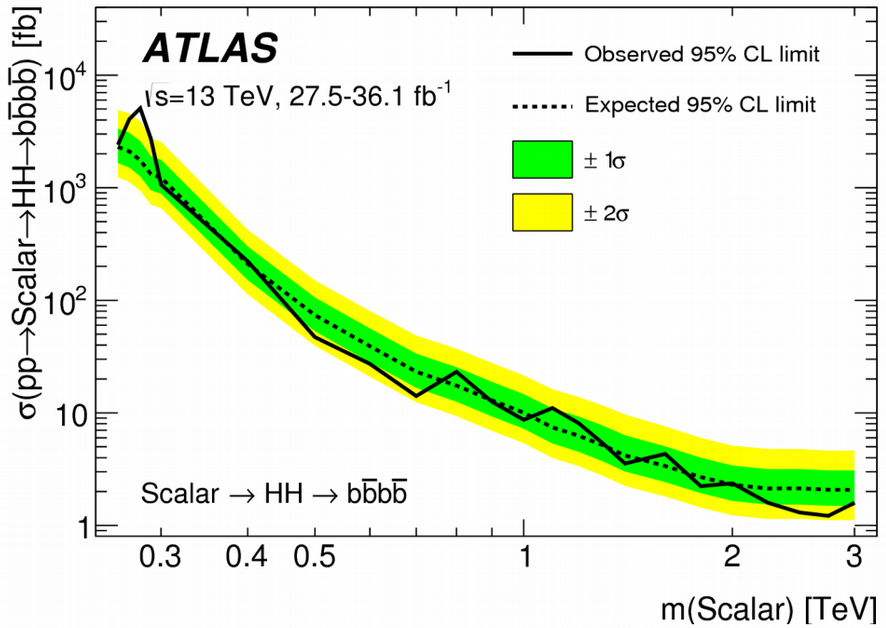


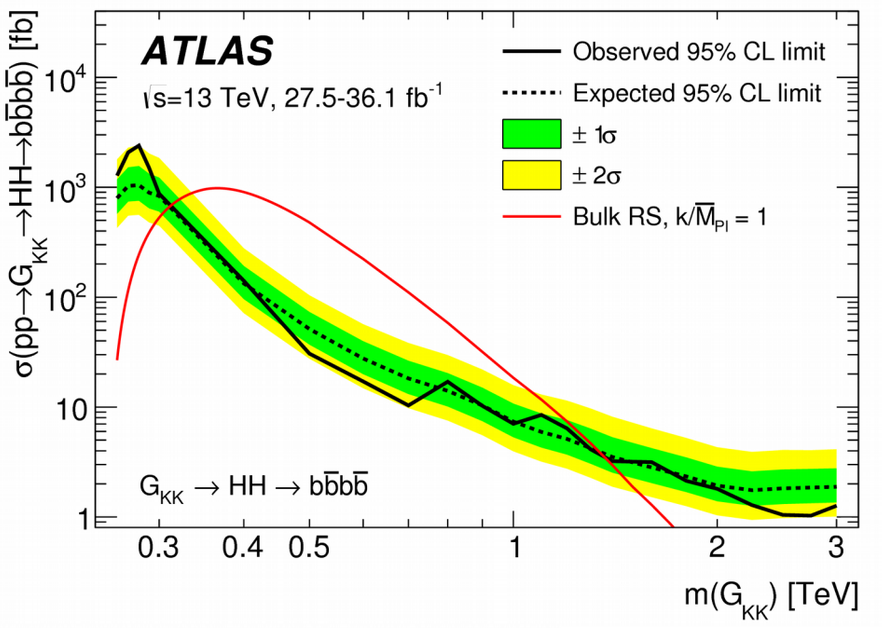


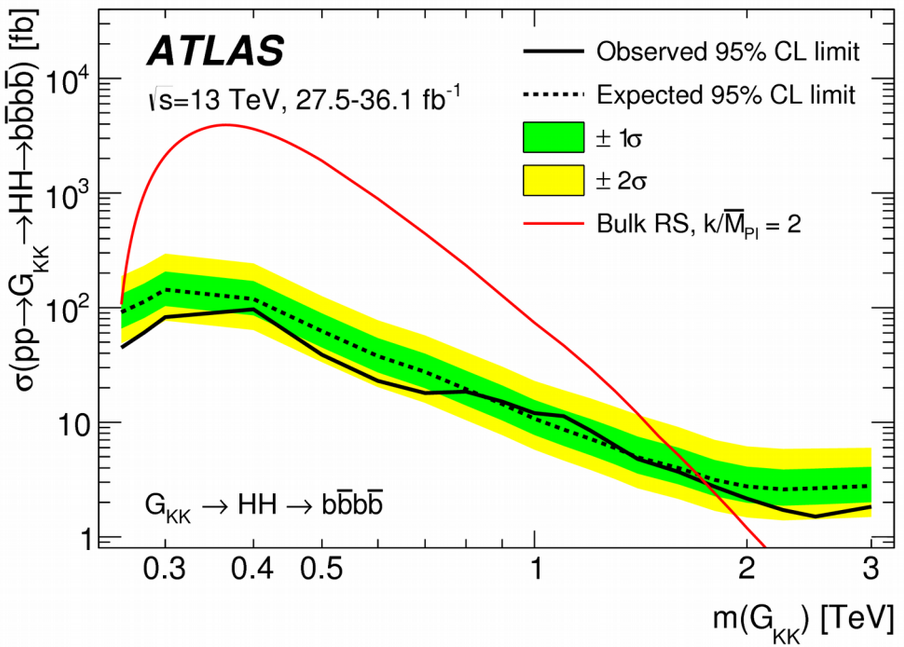


ATLAS Search X(HH)→bbbb

JHEP01(2019)040

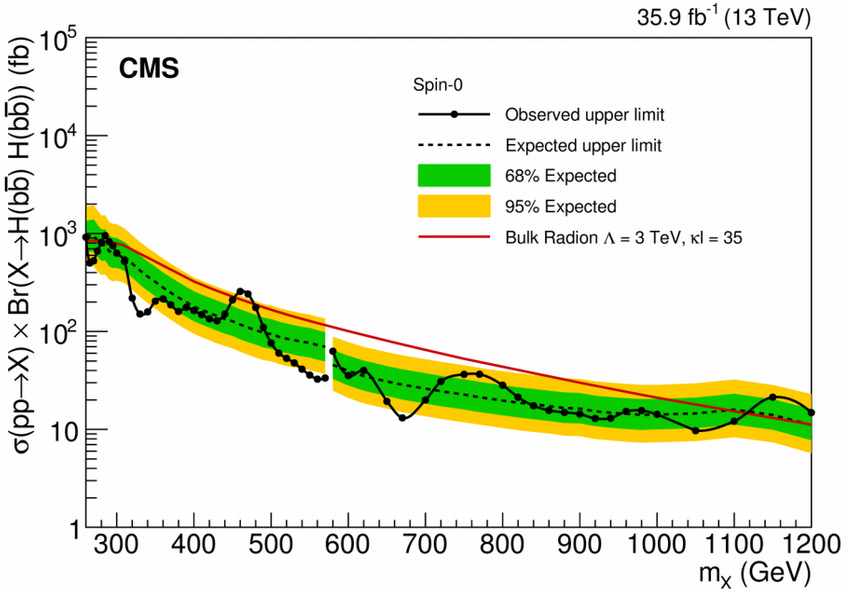


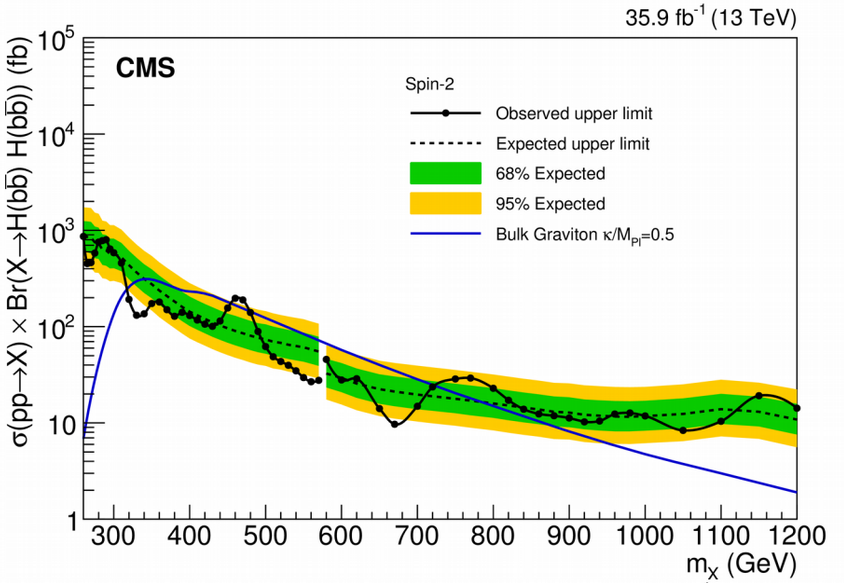


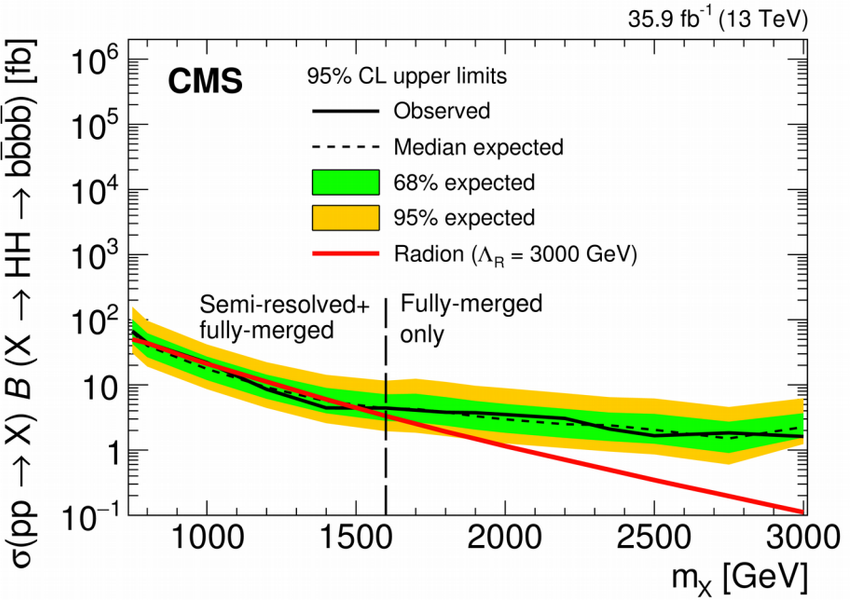


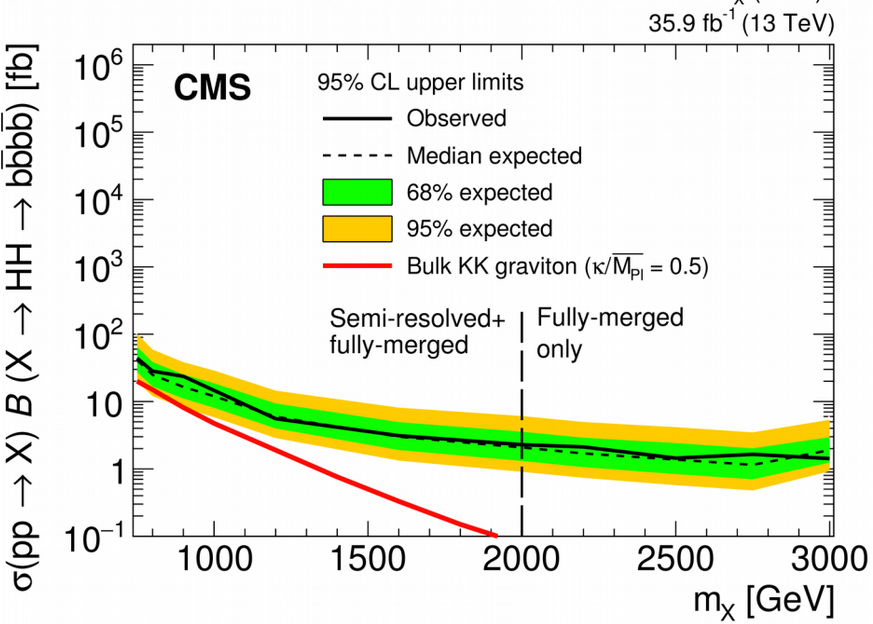
CMS Search X(HH) → bbbb

Phys. Lett. B 781 (2018) 244
JHEP01(2019)030
JHEP08(2018)152



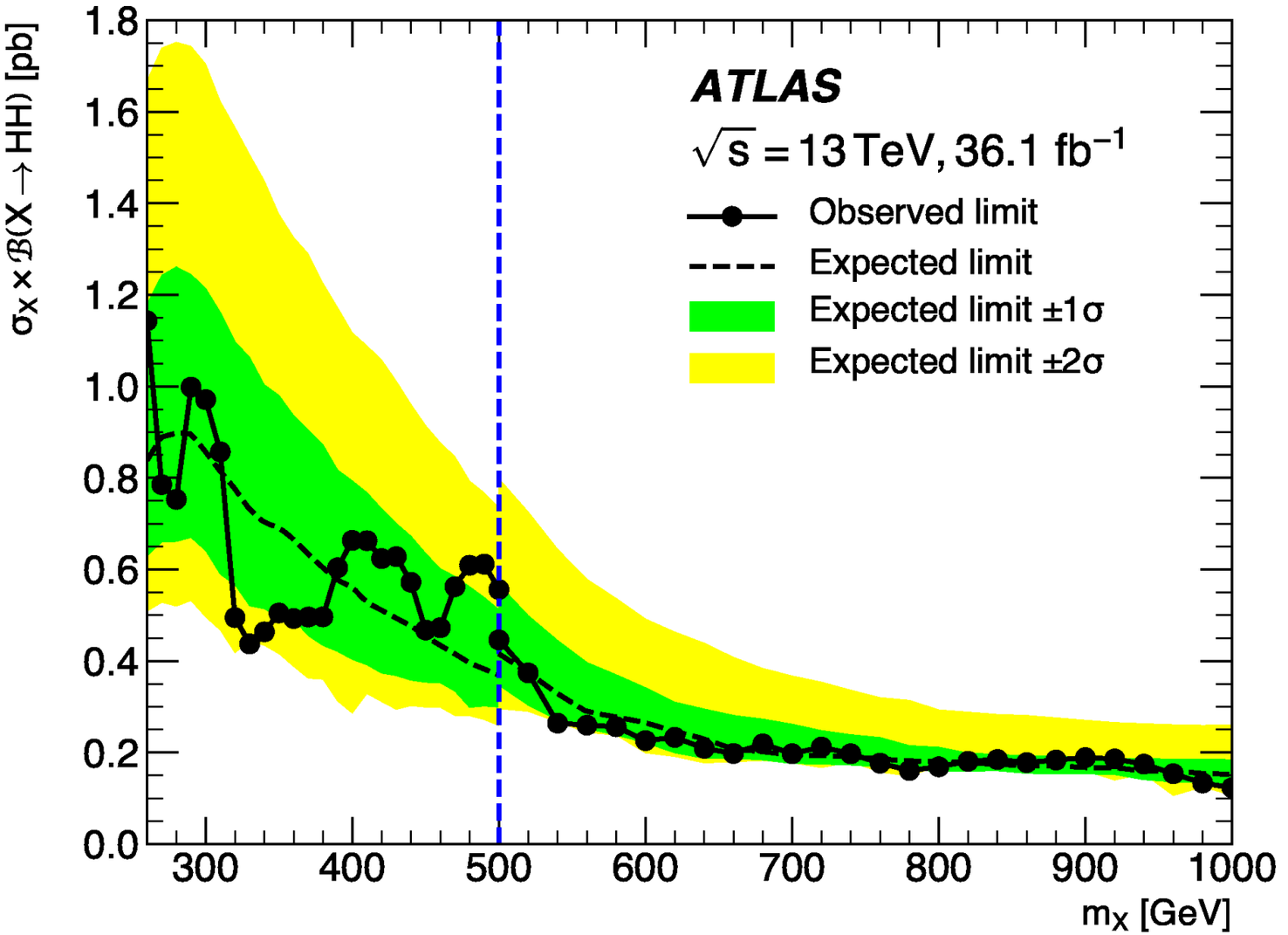






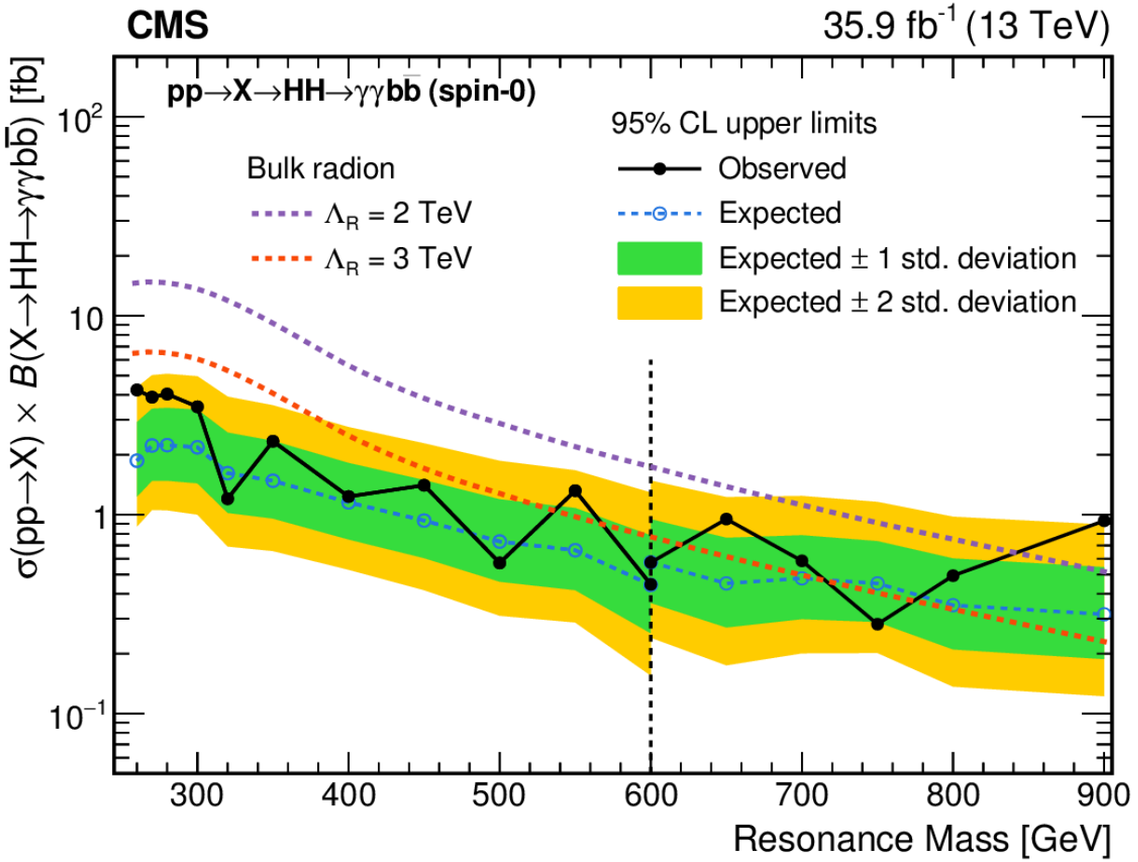
ATLAS Search X(HH) → bbγγ

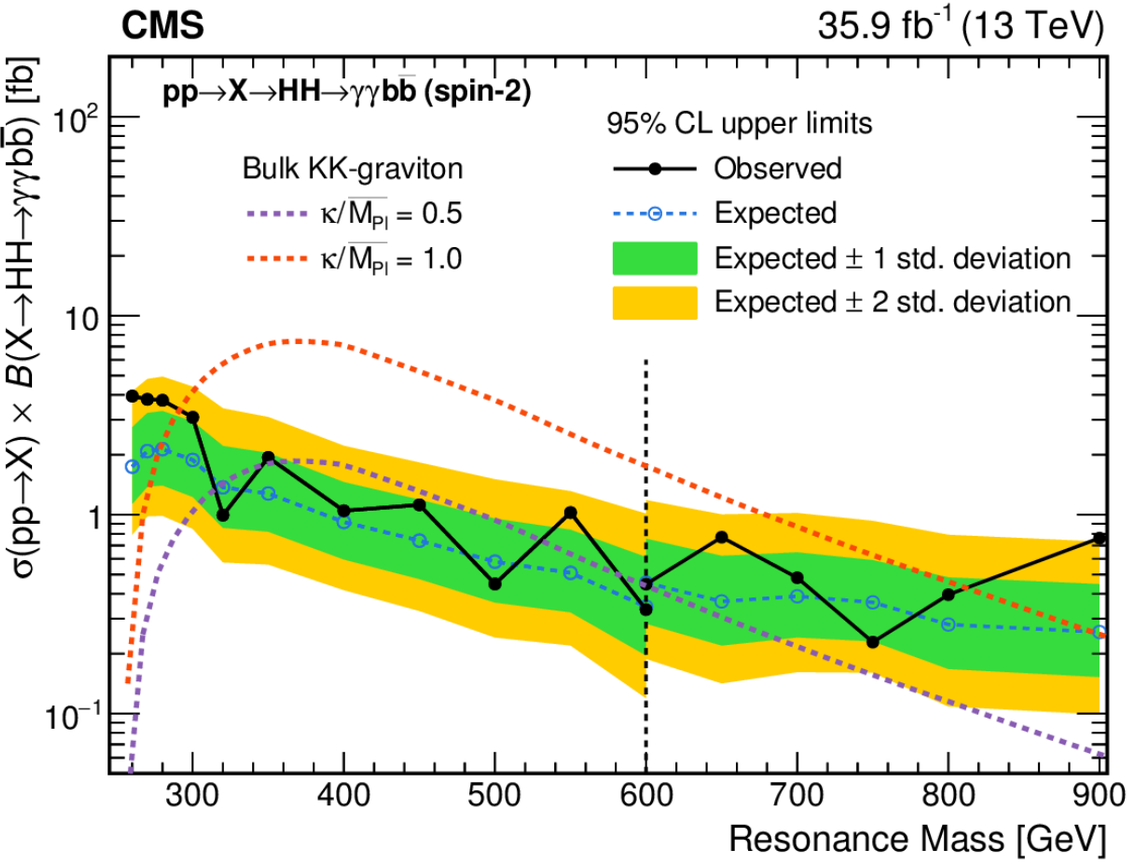
JHEP 11 (2018) 040



CMS Search X(HH) → bbγγ

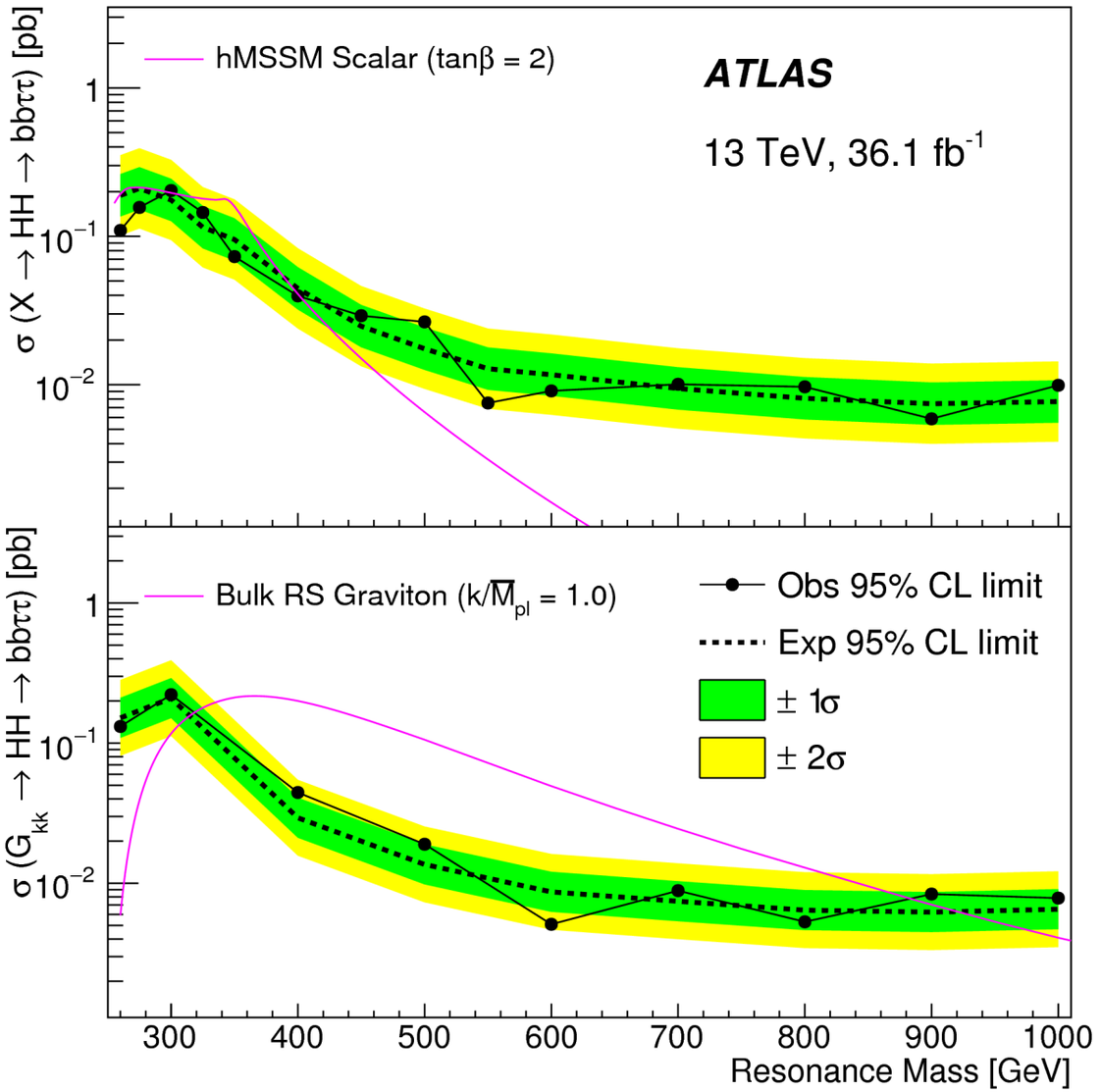
Phys. Lett. B 788 (2018) 7





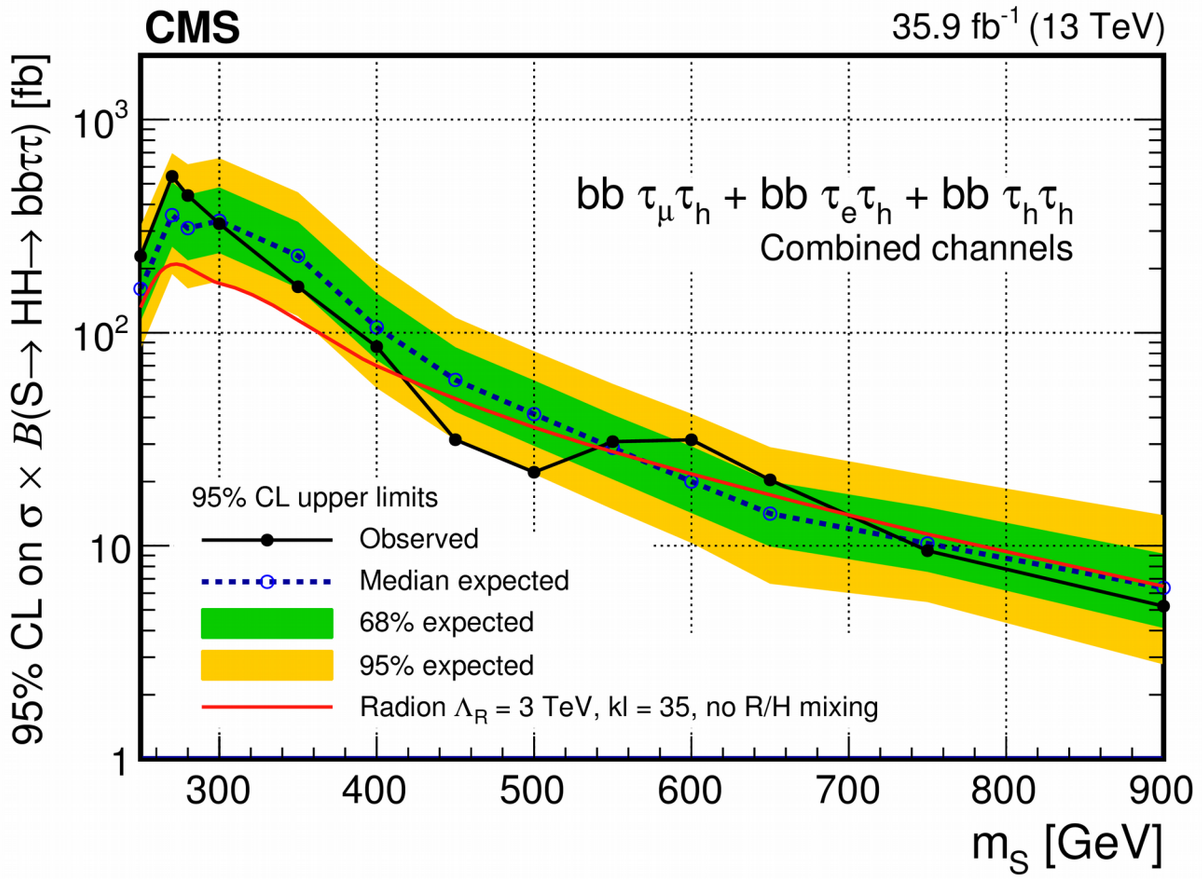
ATLAS Search X(HH) → bbττ

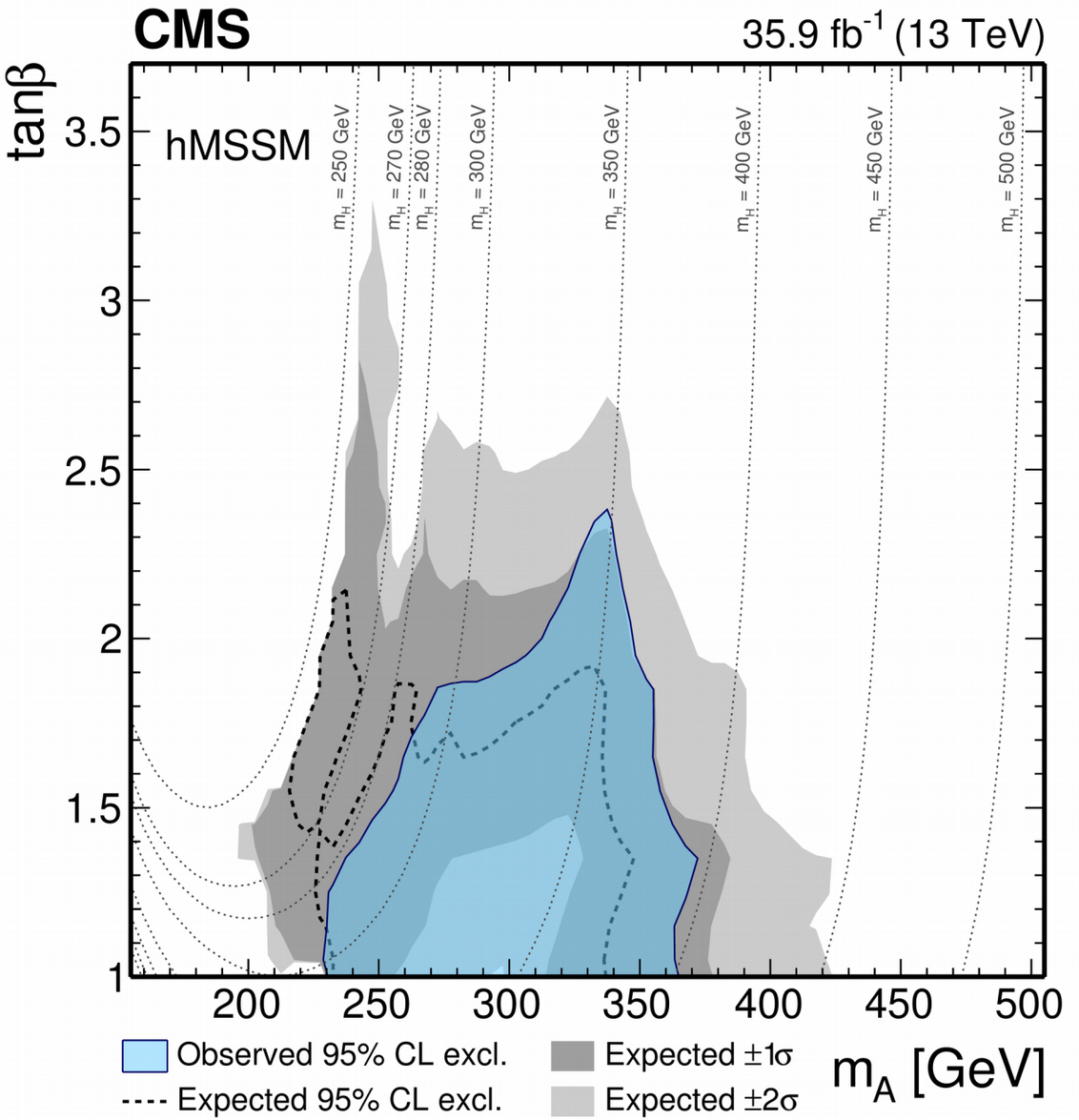
Phys. Rev. Lett. 121 (2018) 191801



CMS Search X(HH) → bbττ

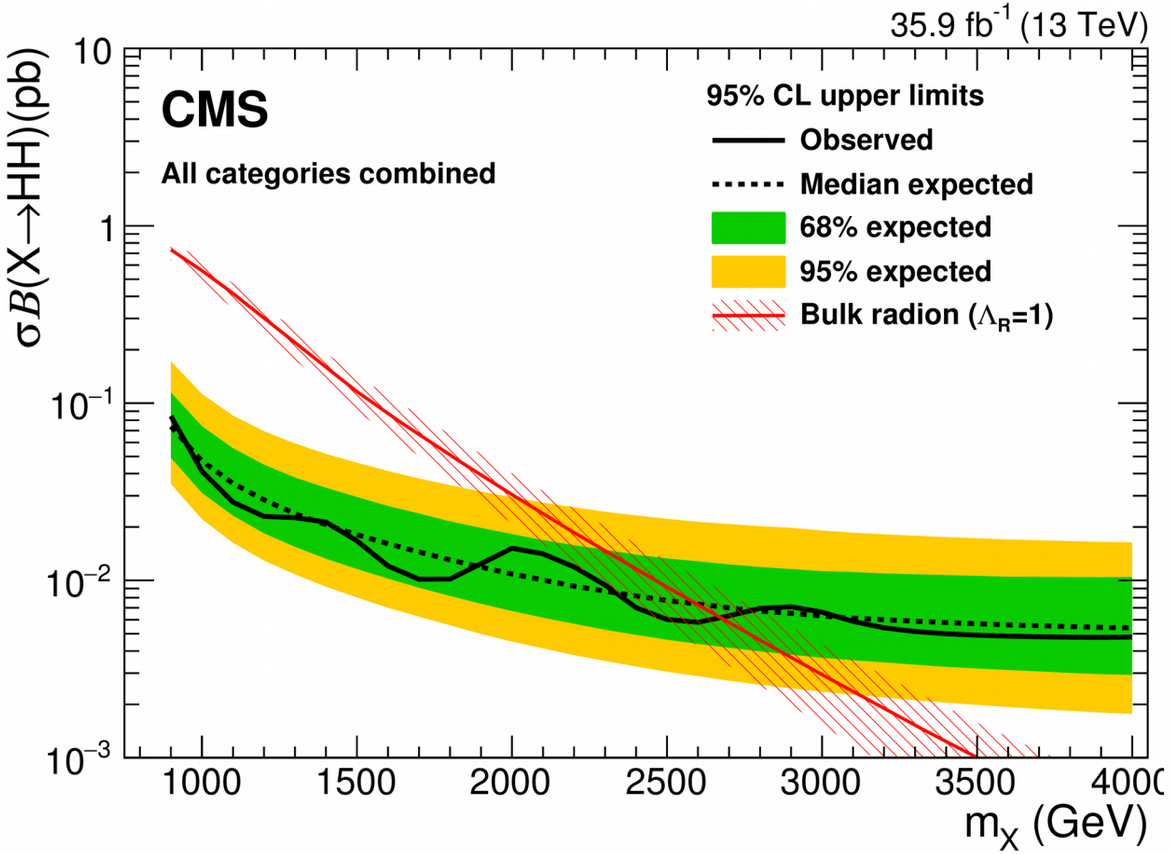
Phys. Lett. B 778 (2018) 101

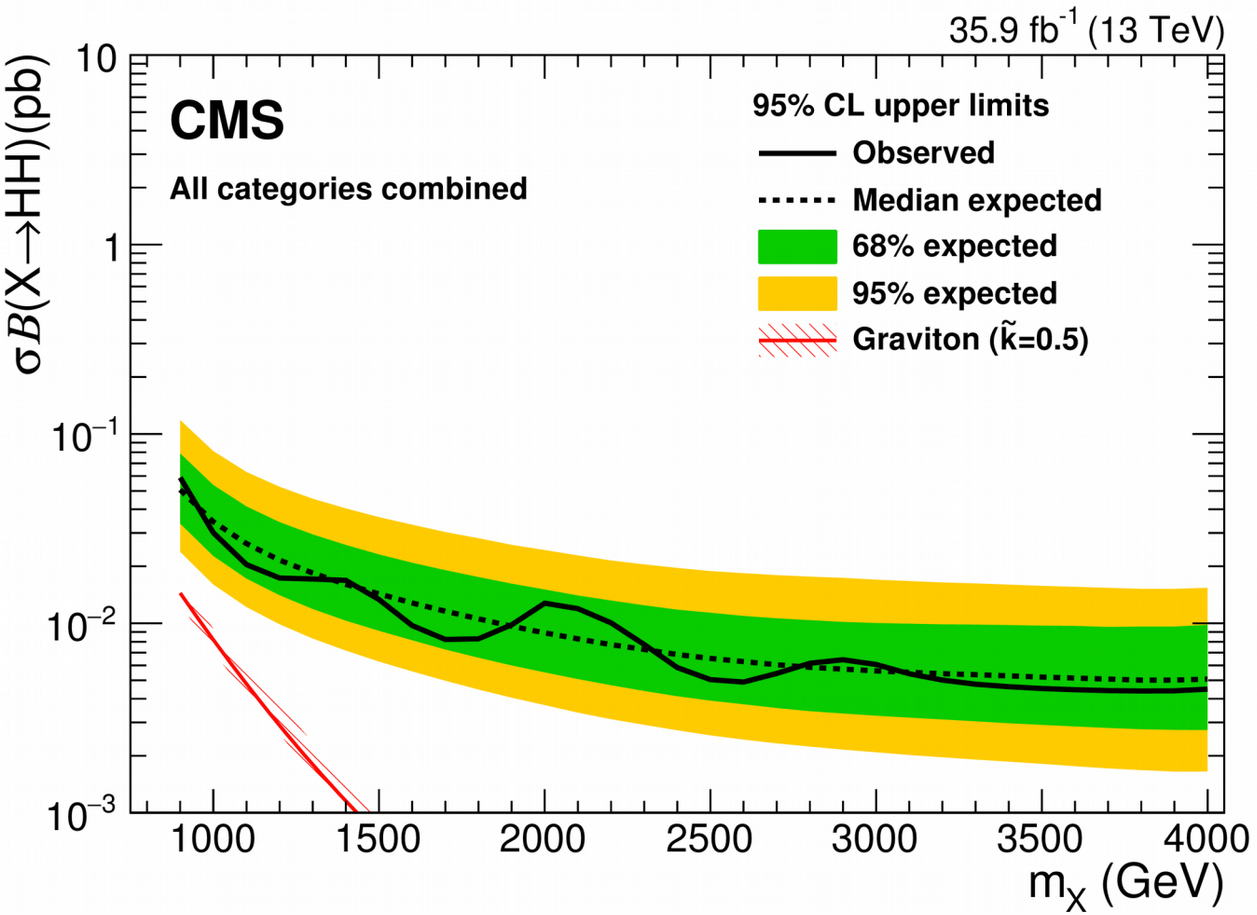




CMS Search X(HH) → bbττ (boosted)

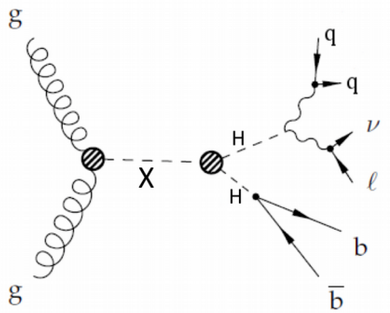
JHEP01(2019)051

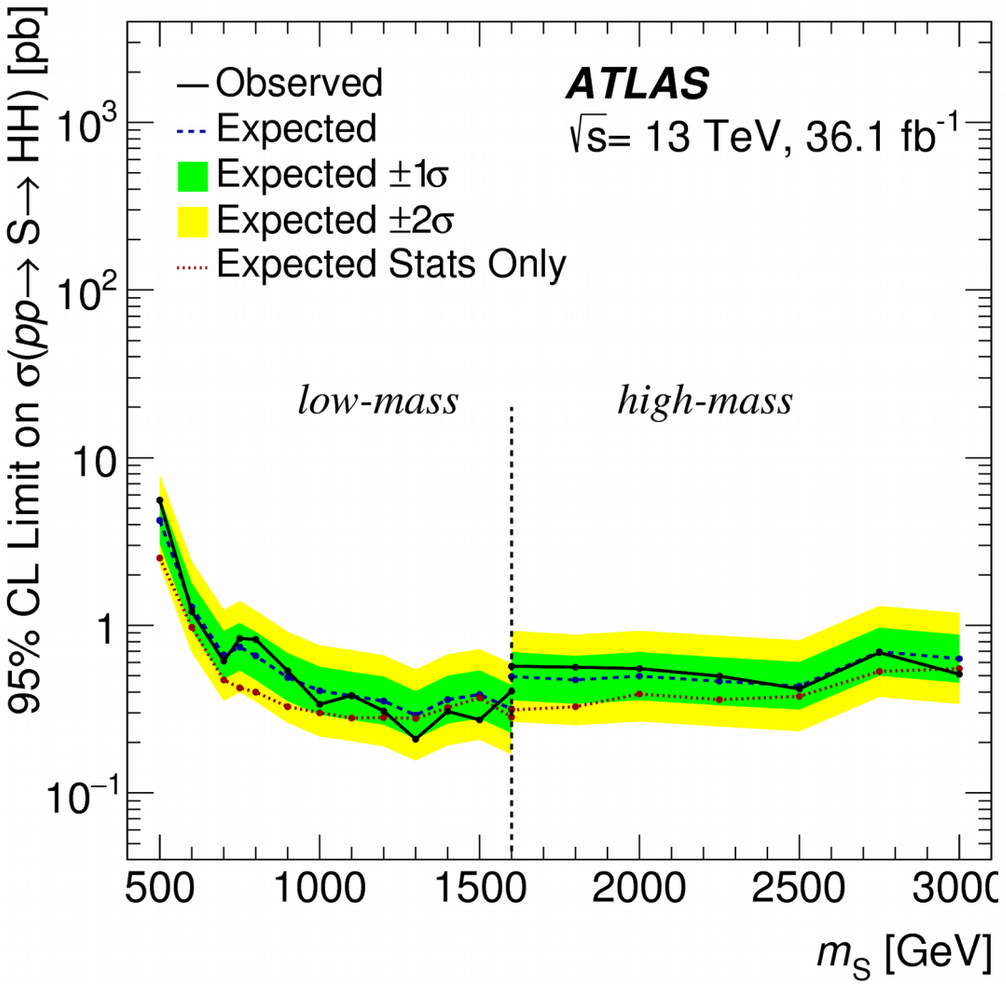


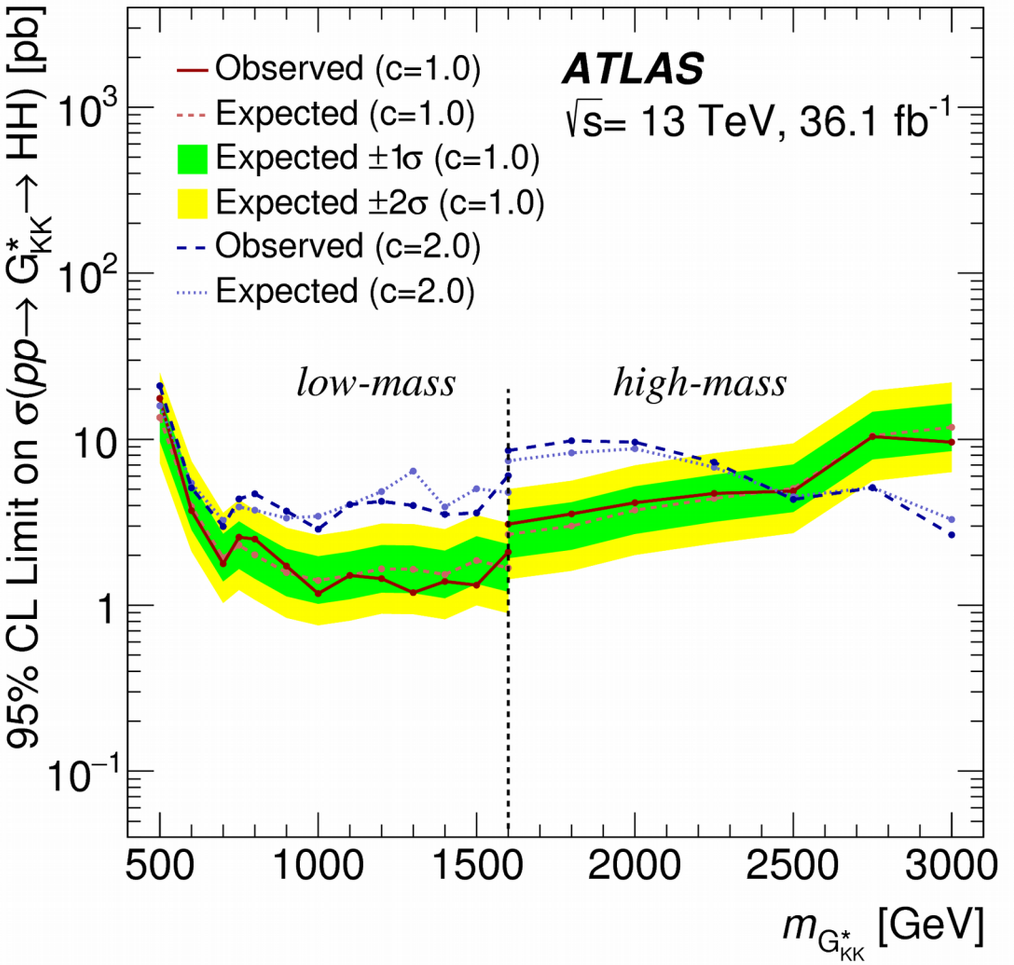


ATLAS Search X(HH) → bbWW → bblvqq

JHEP 04 (2019) 092

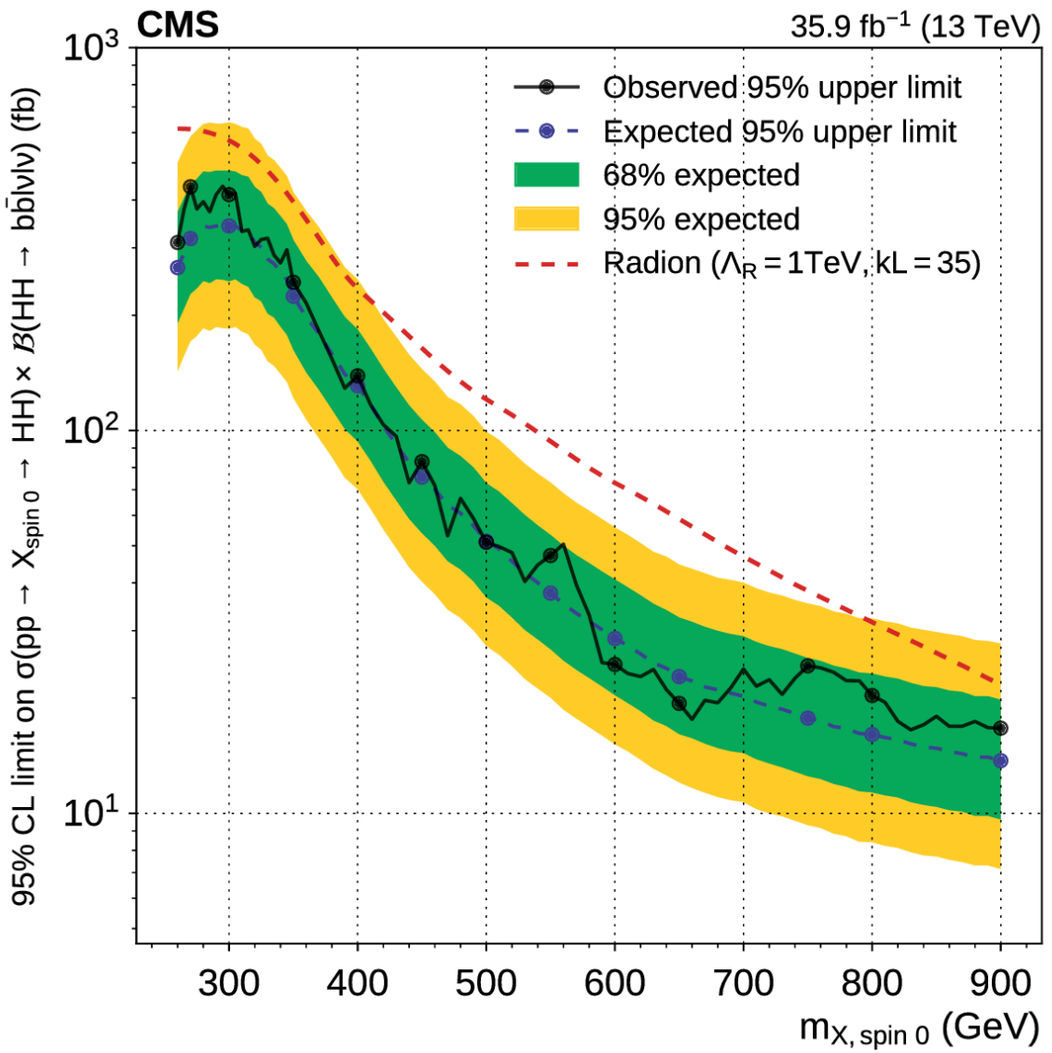


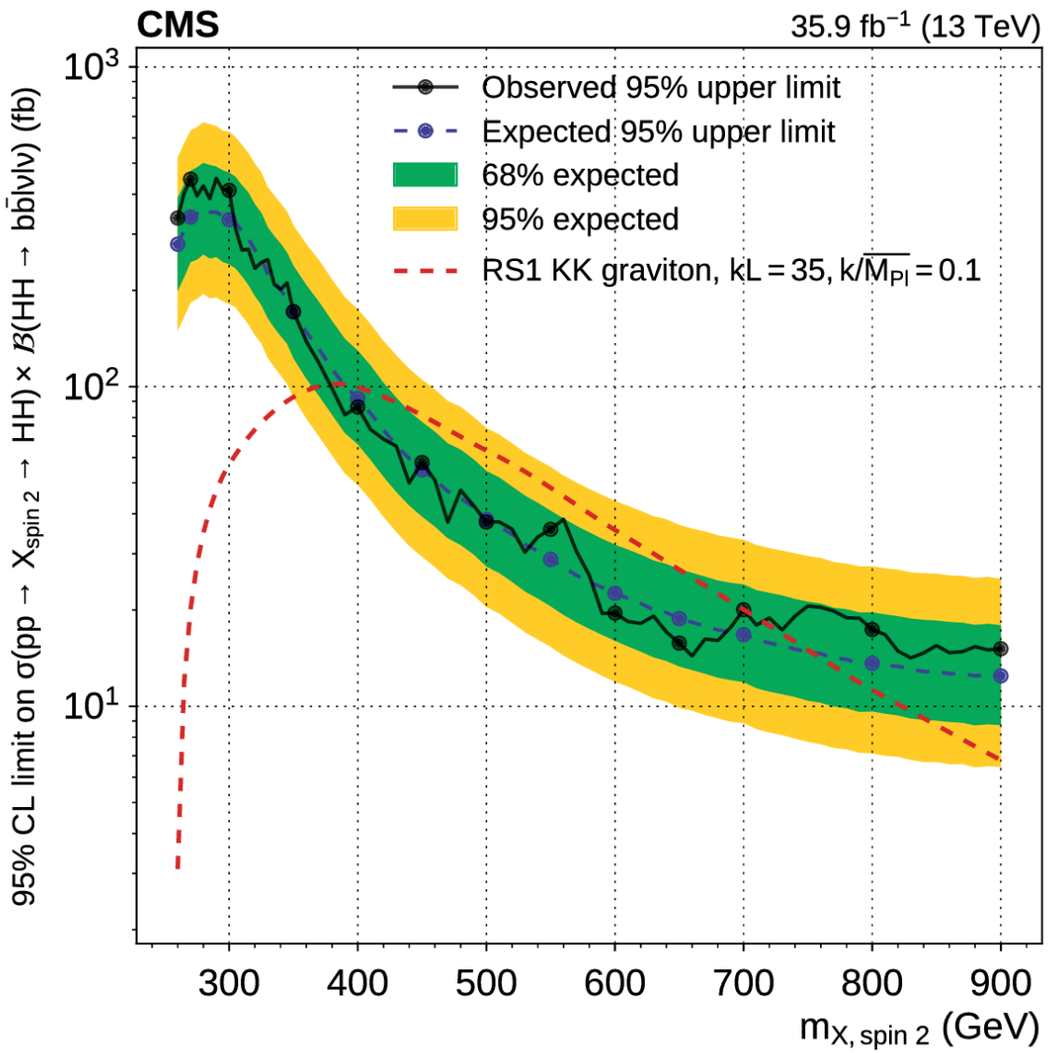




CMS Search X(HH) → bbVV(resolved) → bblvlv

JHEP 01 (2018) 054

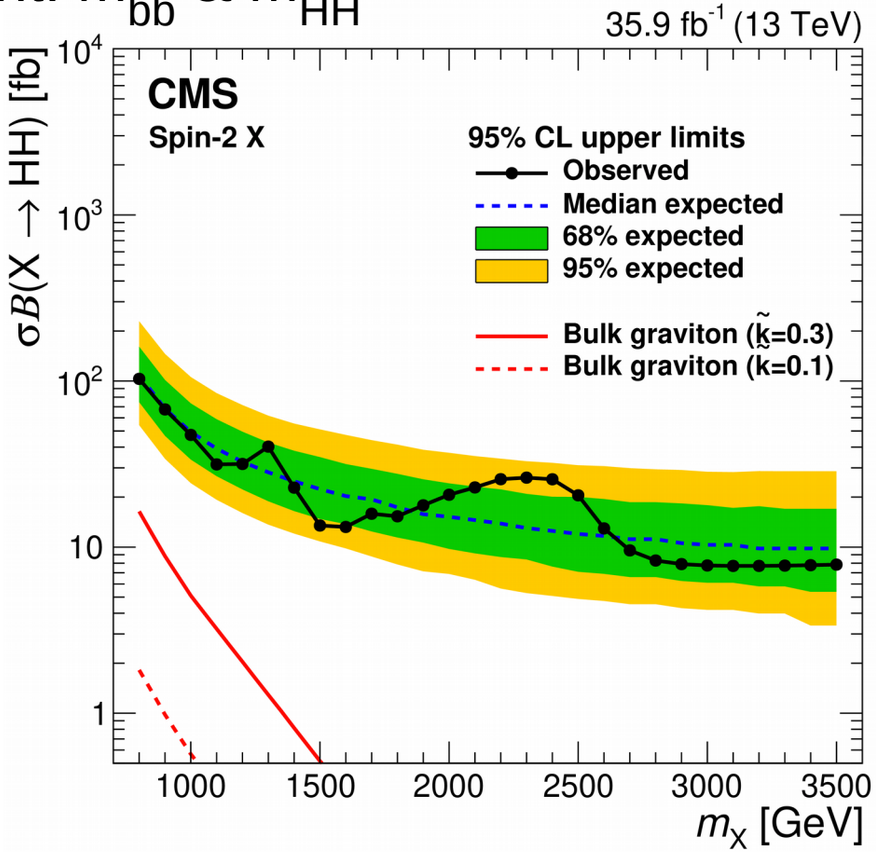


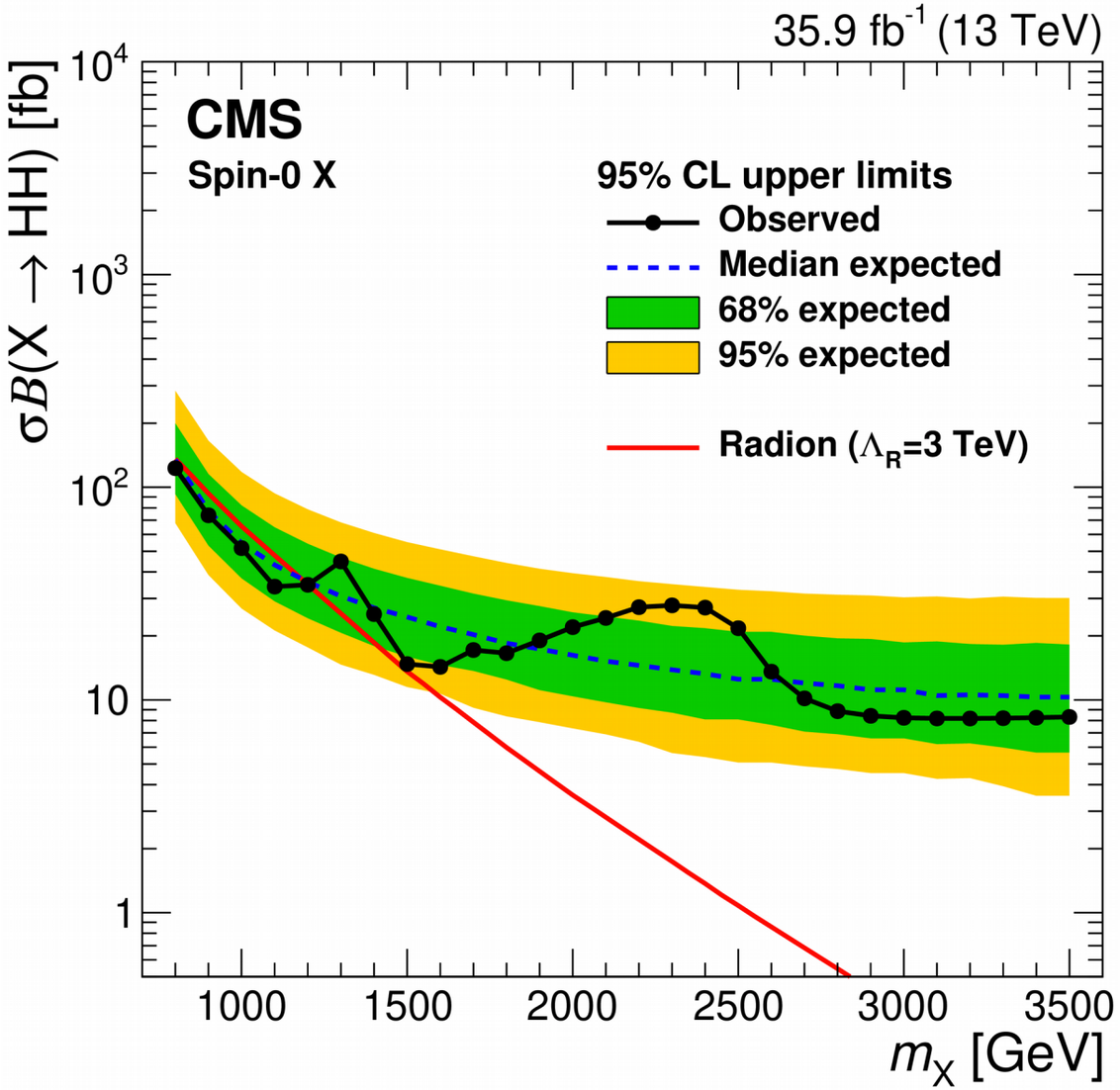


CMS Search X(HH) → bbWW (boosted) → bblνqq

- Narrow-width scalar and spin-2
  - Mass range: 0.8 – 1.5 TeV
  - W.E.D. interpretations
- Combination: bblνqq (l=e,μ)
- Simultaneous fit to 12 categories
- Discriminant: m_{bb} & m_{HH}

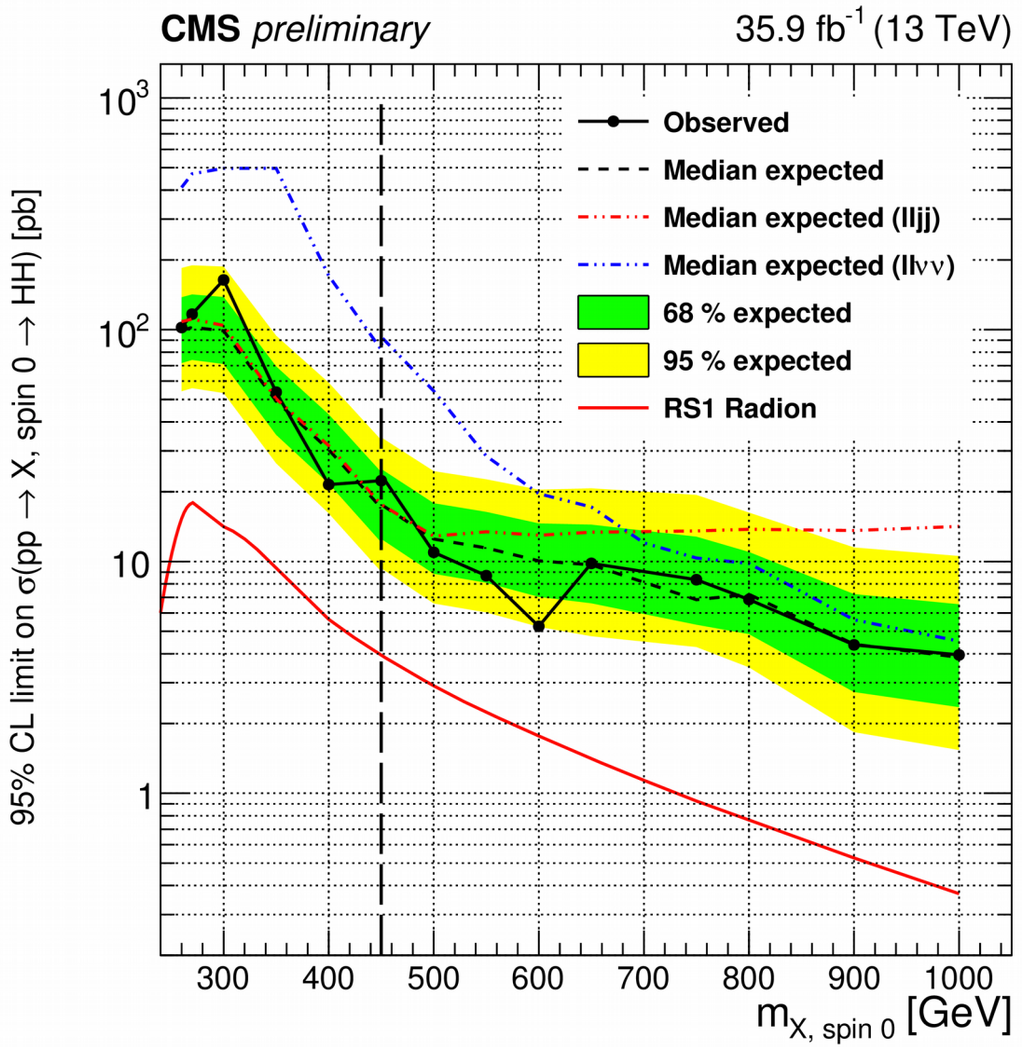
Accepted for publication in JHEP

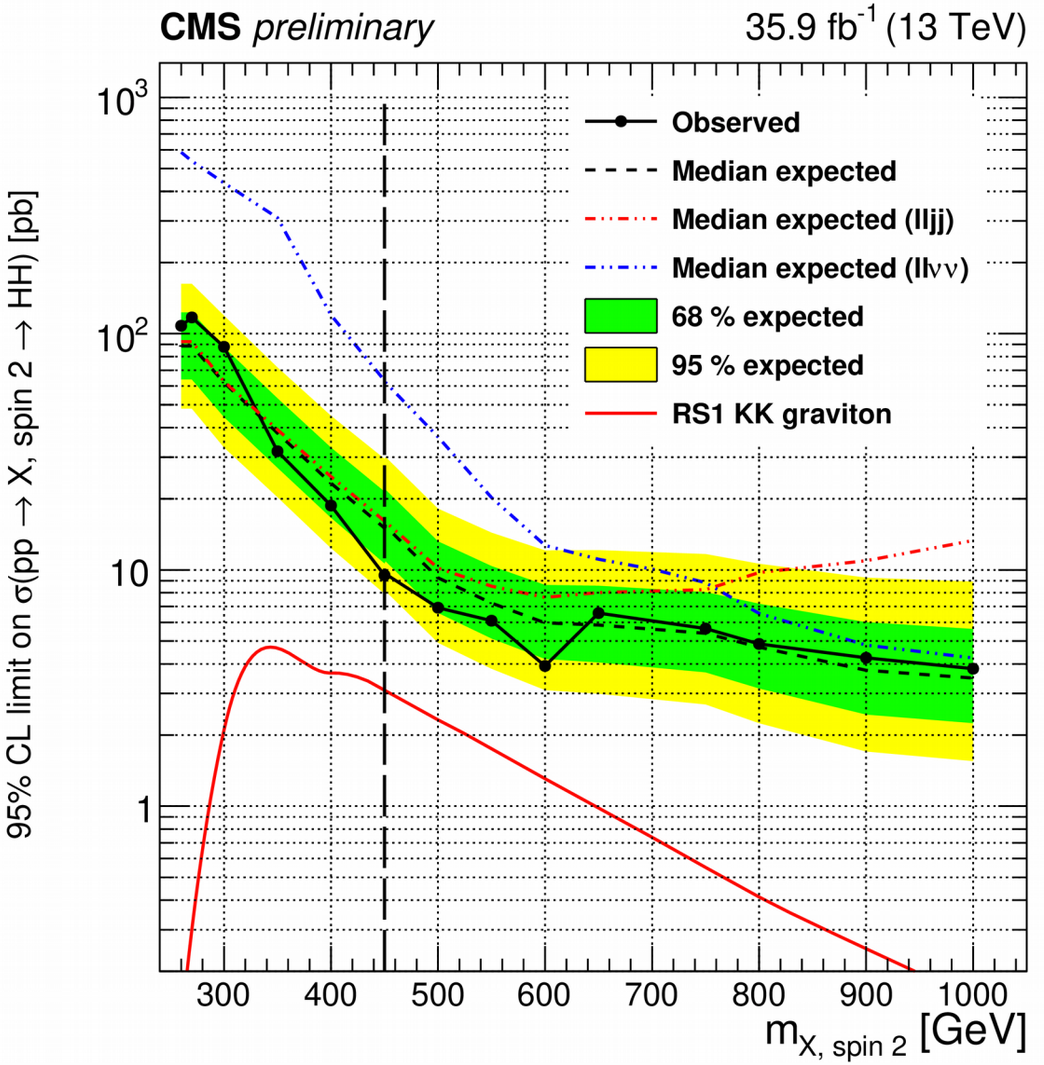




CMS Search X(HH) → bbZZ → bblvqq + bbllqq

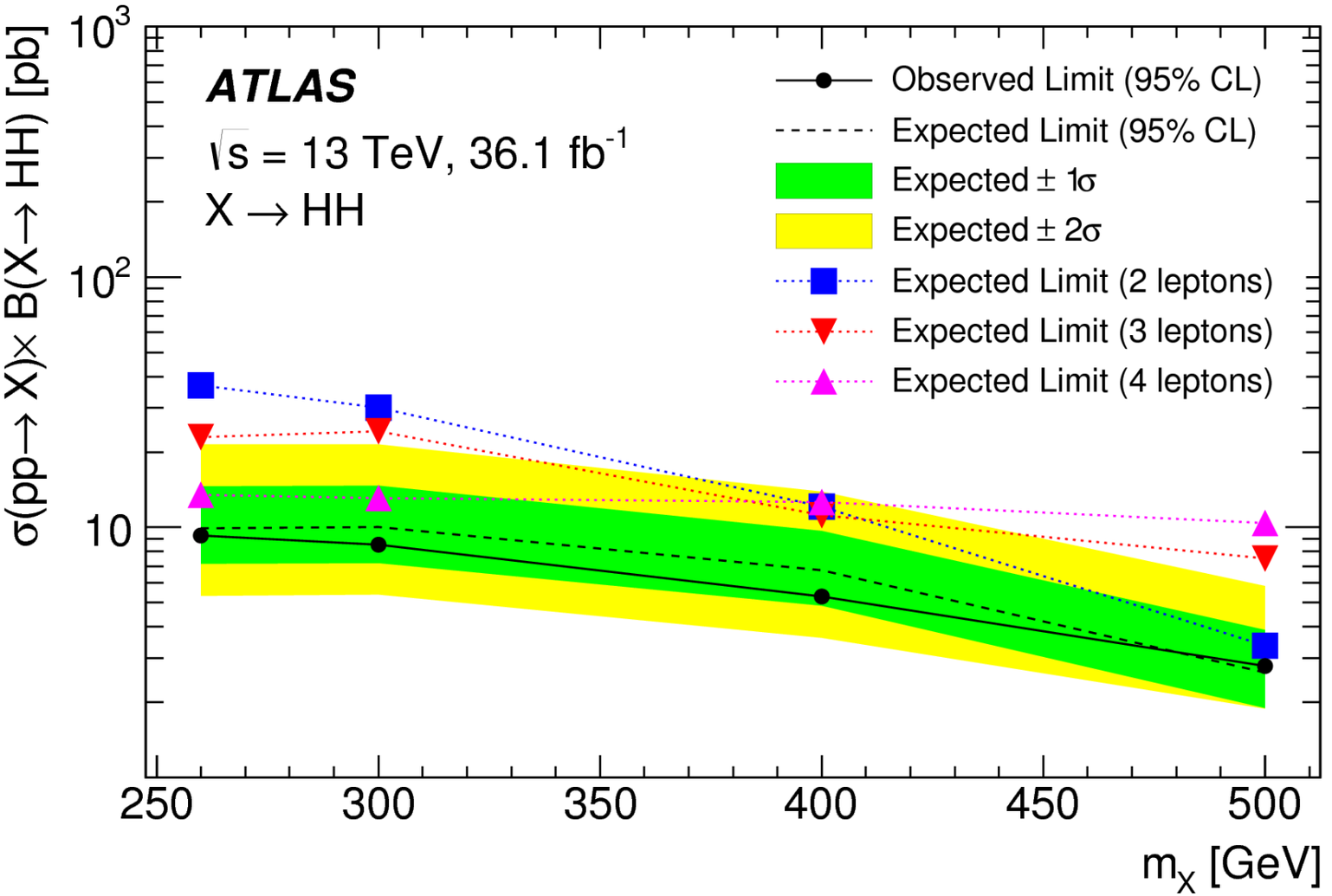
CMS PAS HIG-18-013





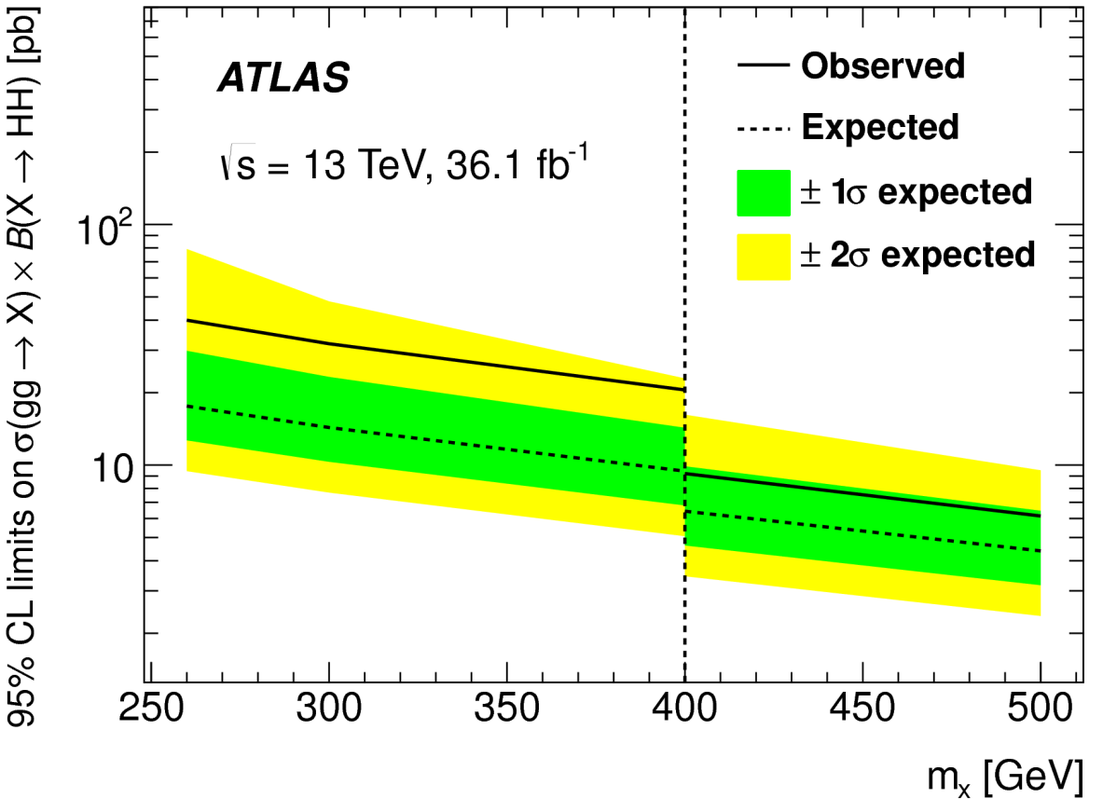
ATLAS Search X(HH) → WW(*)WW(*)

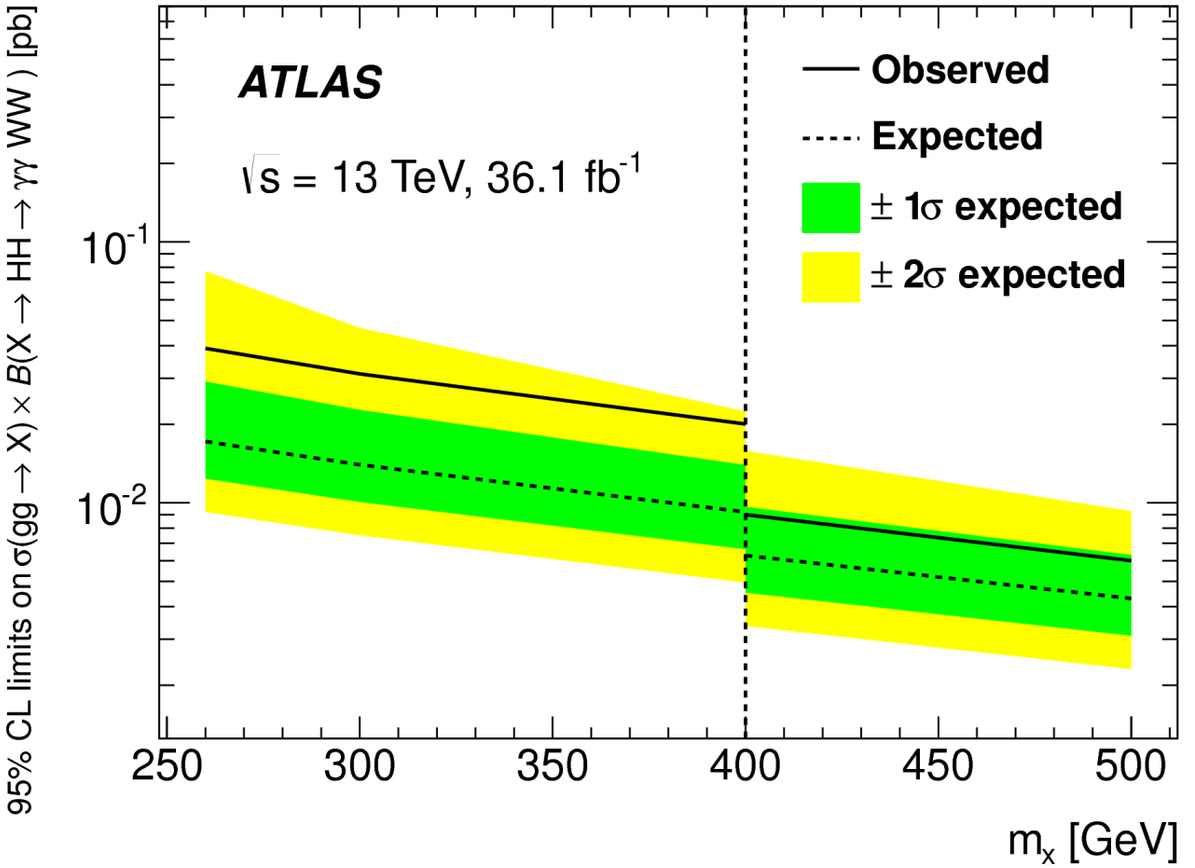
JHEP05(2019)124



ATLAS Search X(HH) → WW$^{(*)}$γγ

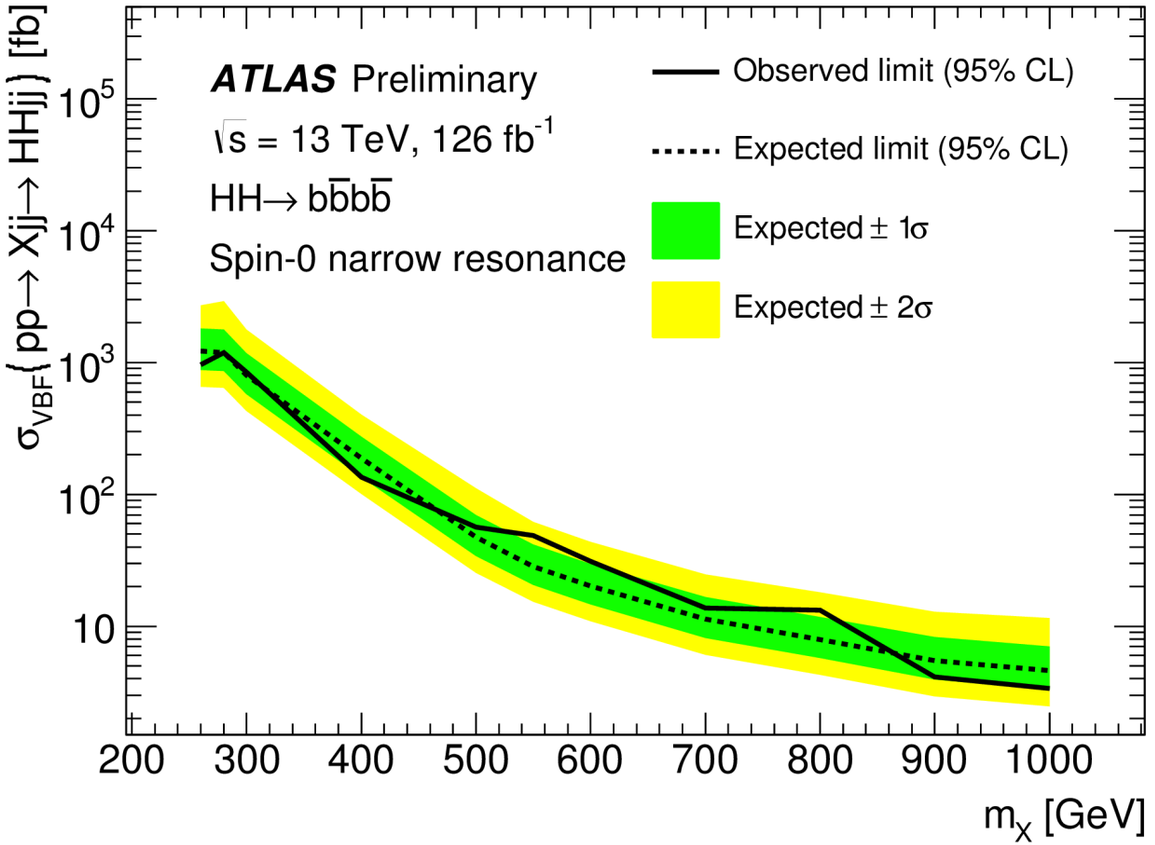
Eur. Phys. J. C 78 (2018) 1007

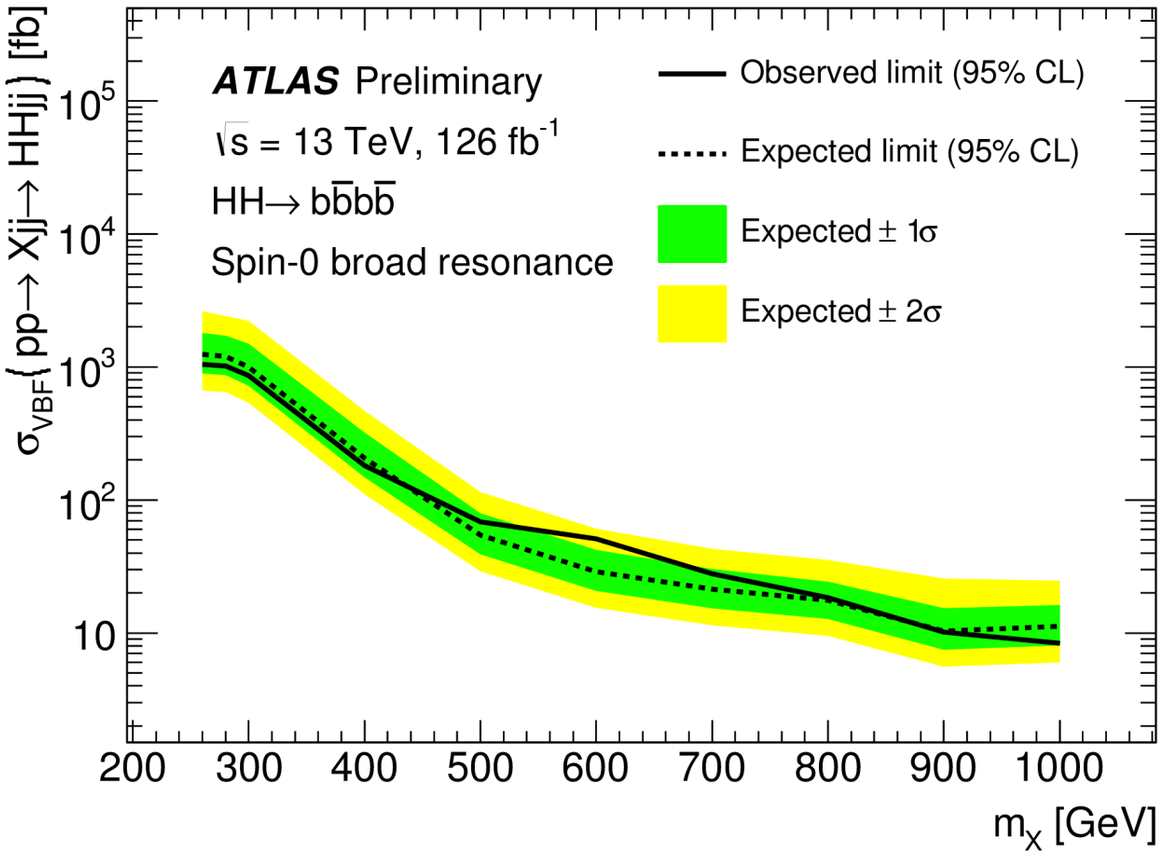




ATLAS Search for VBF X(HH) → bbbb

ATLAS-CONF-2019-030





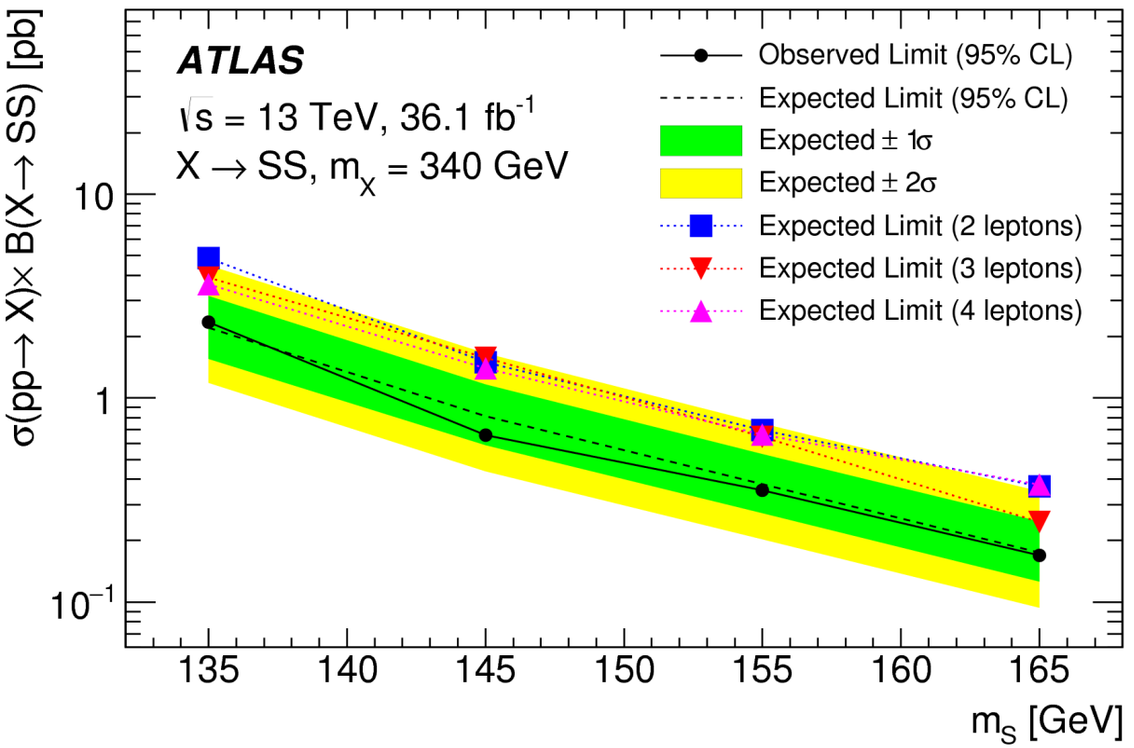
Search for X → SS → $W^+W^-W^+W^-$

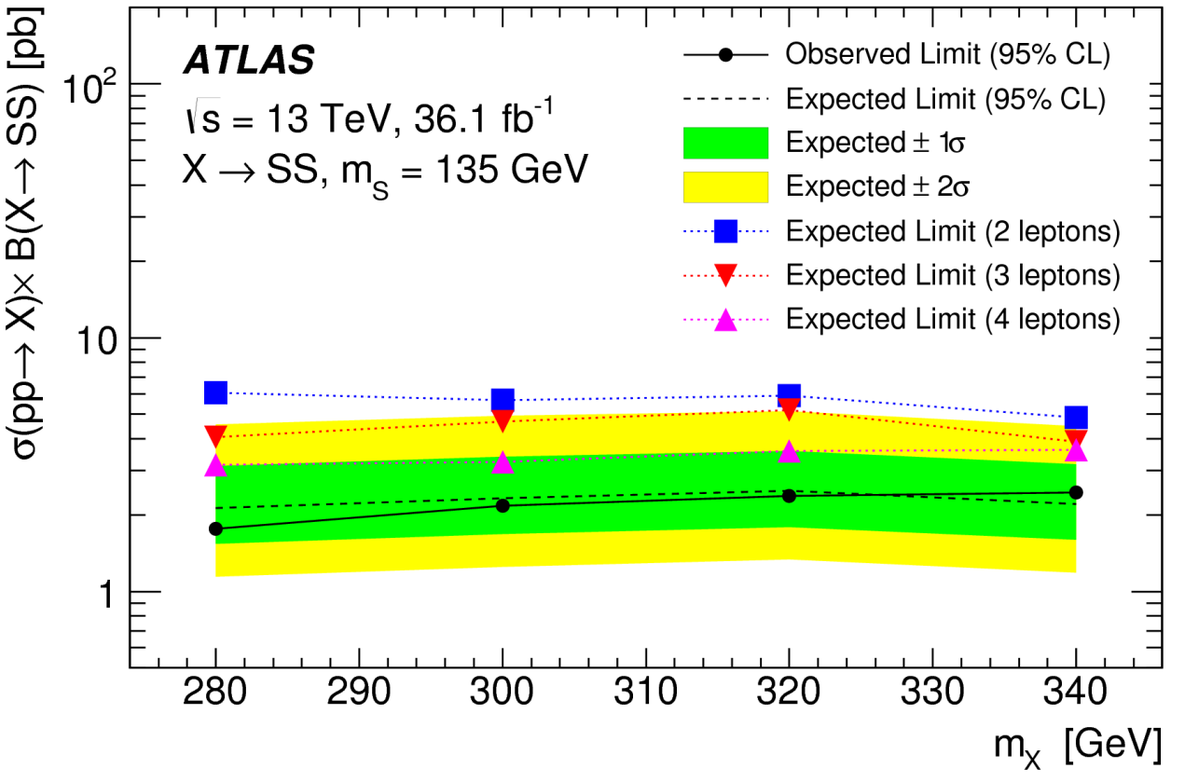
Resonant production of a pair of heavy scalars (S)

JHEP05(2019)124

- Narrow-width X and S resonances
- Both S scalars produced on-shell (mS < mX/2)
- B(X → SS)=1 & B(S → WW(*)) with SM Higgs mass dependence

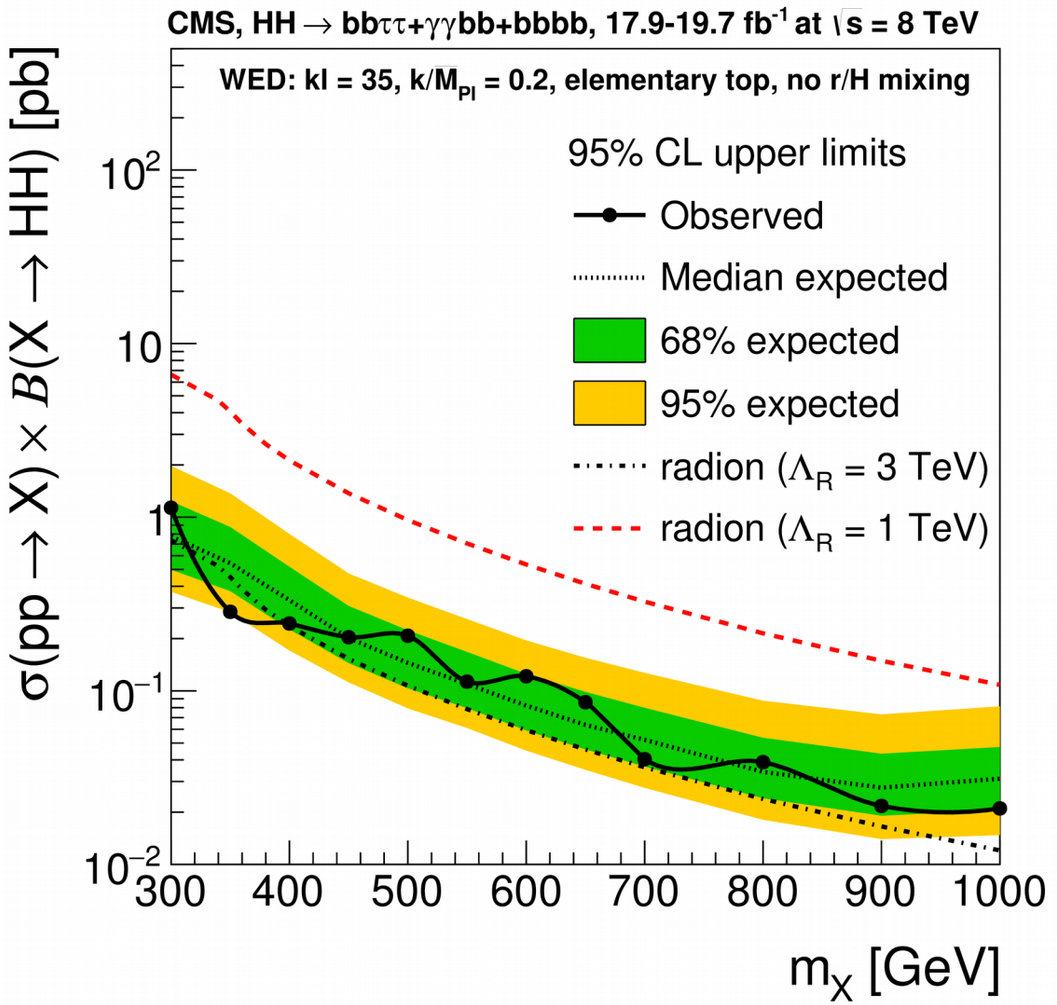
- Combination: 2, 3, and 4 leptons (+ MET + jets) channels
- Discriminant: reconstructed leptons invariant mass distribution

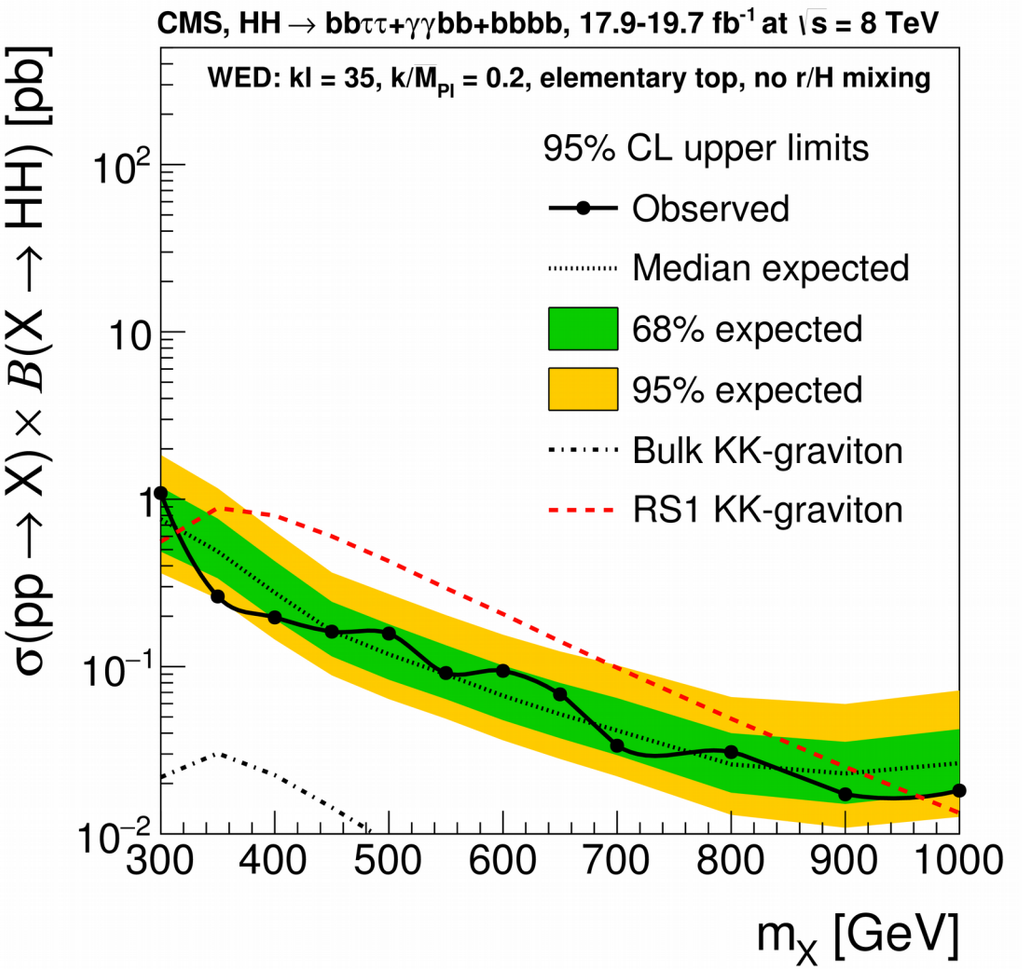




CMS Run-I HH Combination

Phys. Rev. D 96 (2017) 072004





ATLAS Run-I HH Combination

Phys. Rev. D 92, 092004 (2015)