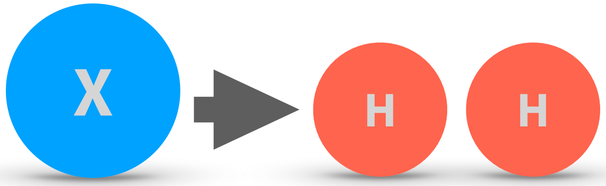
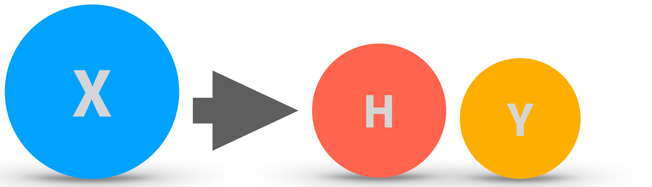
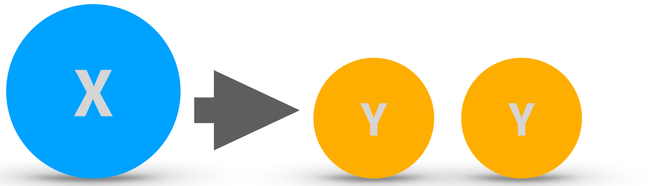
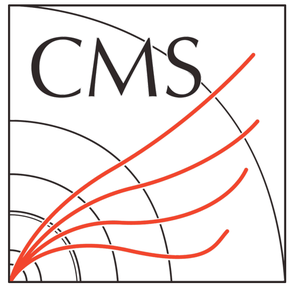








Resonant Di-Higgs Searches

Jan Steggemann for the ATLAS and CMS collaborations

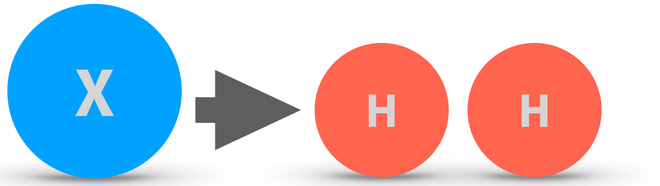
Higgs 2023, Beijing

28 November 2023

Motivation

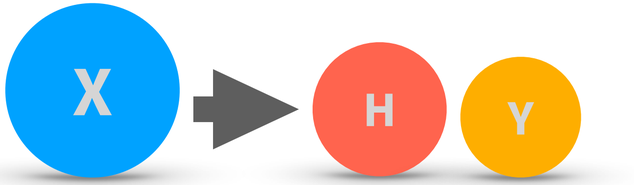
1) X→HH (H = H_{125})

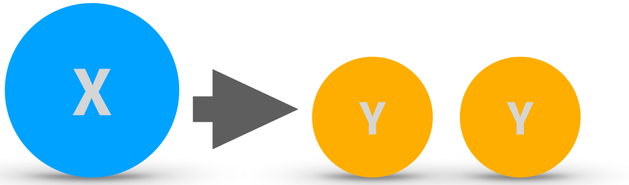
- Appears in **all extended Higgs sectors** if m_X > 250 GeV: 2HDM (including MSSM), real singlet
  - ➡ *suppressed in alignment limit*
- Also generic resonances, e.g. in warped-extra-dimension models



2) X→YH and **3) X→YY** *(often called H->hh, where H!=H_{125}!=h)*

- **Larger extended Higgs sectors**: E.g. two additional singlets (TRSM), 2-Higgs-doublet + singlet (2HDM+S including NMSSM)
  - ➡***not suppressed in alignment limit***, hence often **discovery channel if kinematically allowed**





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- Appears in **all extended Higgs sectors** if m_H > 250 GeV: 2HDM (including MSSM), real singlet
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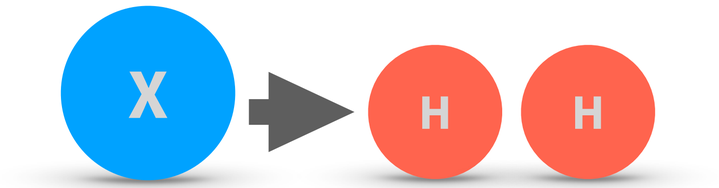
- Also generic resonances, e.g. in warped-extra-dimension models

NEW!

2) X→YH and **3) X→YY** *(often called H->hh, where H!=H_{125}!=h)*
- **Larger extended Higgs sectors**: E.g. two additional singlets (TRSM), 2-Higgs-doublet + singlet (2HDM+S including NMSSM)
  ➡***not suppressed in alignment limit***, hence often **discovery channel if kinematically allowed**

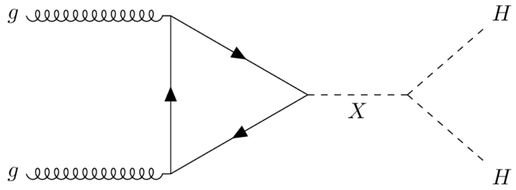
NEW!

4) Z*→HA (H != H_{125})
- In lepton-specific 2HDM at large tan **β** - which could explain g-2 - non-lepton couplings and hence **direct A/H production strongly suppressed**
- HA pair production (via Z*) with decays to 4 tau leptons can probe this scenario!



1) X→HH searches

X→HH summary: ATLAS

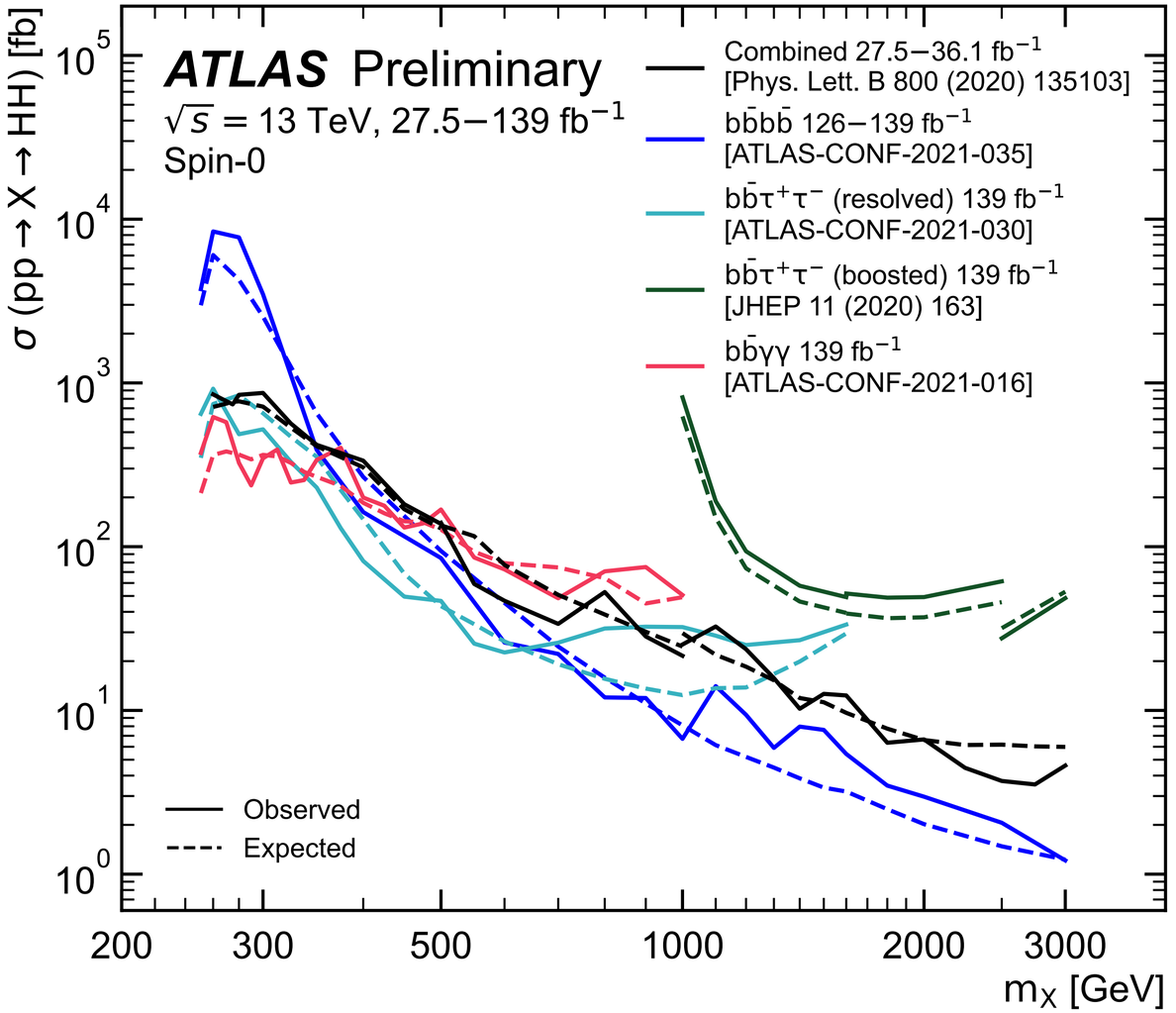


Three major final states:
bbγγ, bbττ, bbbb (from low to high mass)

ATLAS published results in all channels, all submitted more than year ago:

- bbγγ Phys. Rev. D 106 (2022) 052001
- bbττ JHEP 07 (2023) 040
- bbbb Phys. Rev. D 105 (2022) 092002
  - resolved (R = 0.4) and merged-jet (R = 1.0) topologies
- *also bbbb in VX or A→ZX Eur. Phys. J. C 83 (2023) 519*

Similar to non-resonant searches, except that mass resolution matters more!



ATL-PHYS-PUB-2021-031 (July 2021)

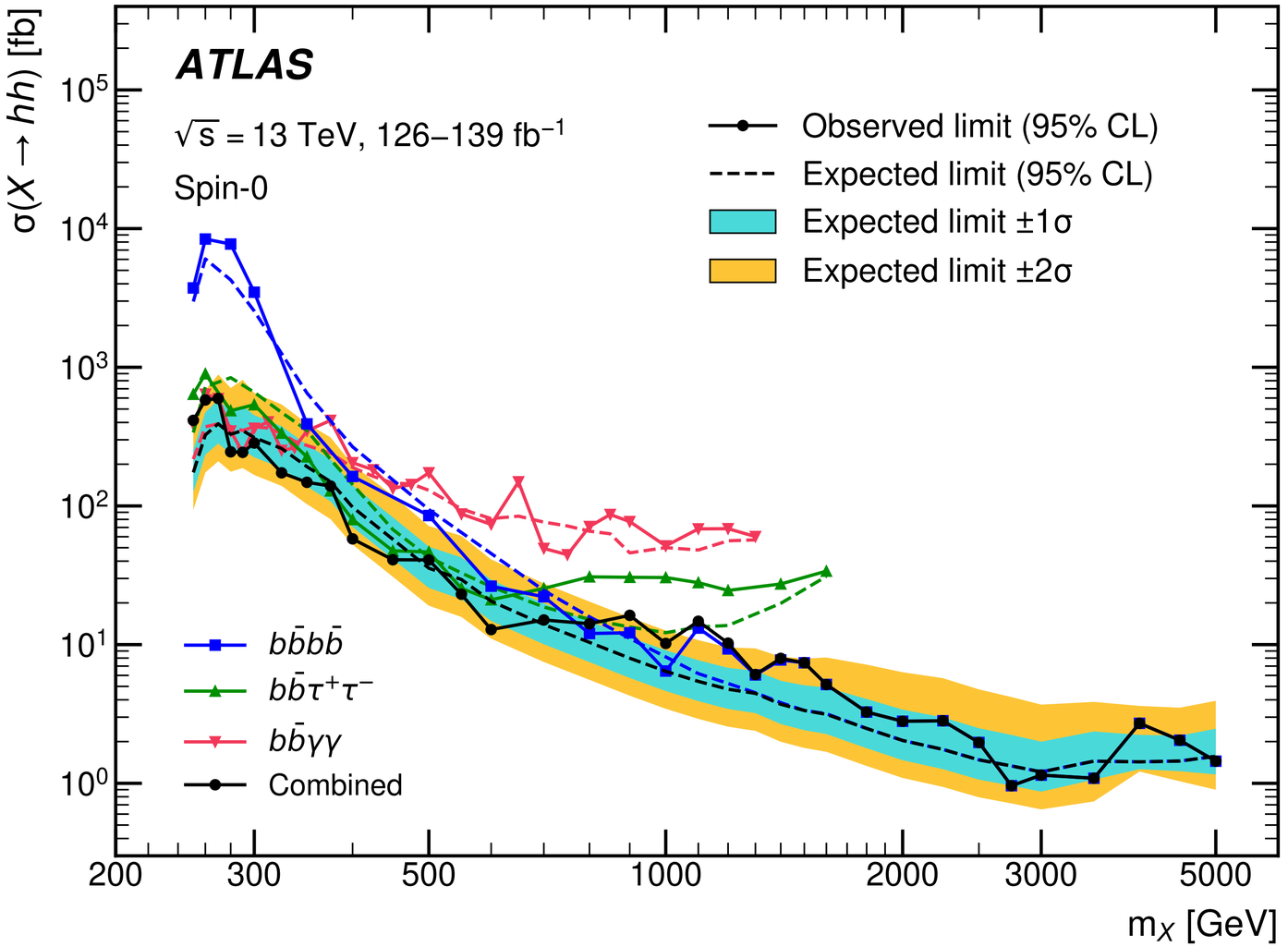
ATLAS X→HH combination

NEW!

Combined bbγγ, bbττ, bbbb analyses
- bbγγ: Mass range extended to 1.3 TeV

Largest local (global) significance:
3.3 (2.1) σ at 1.1 TeV

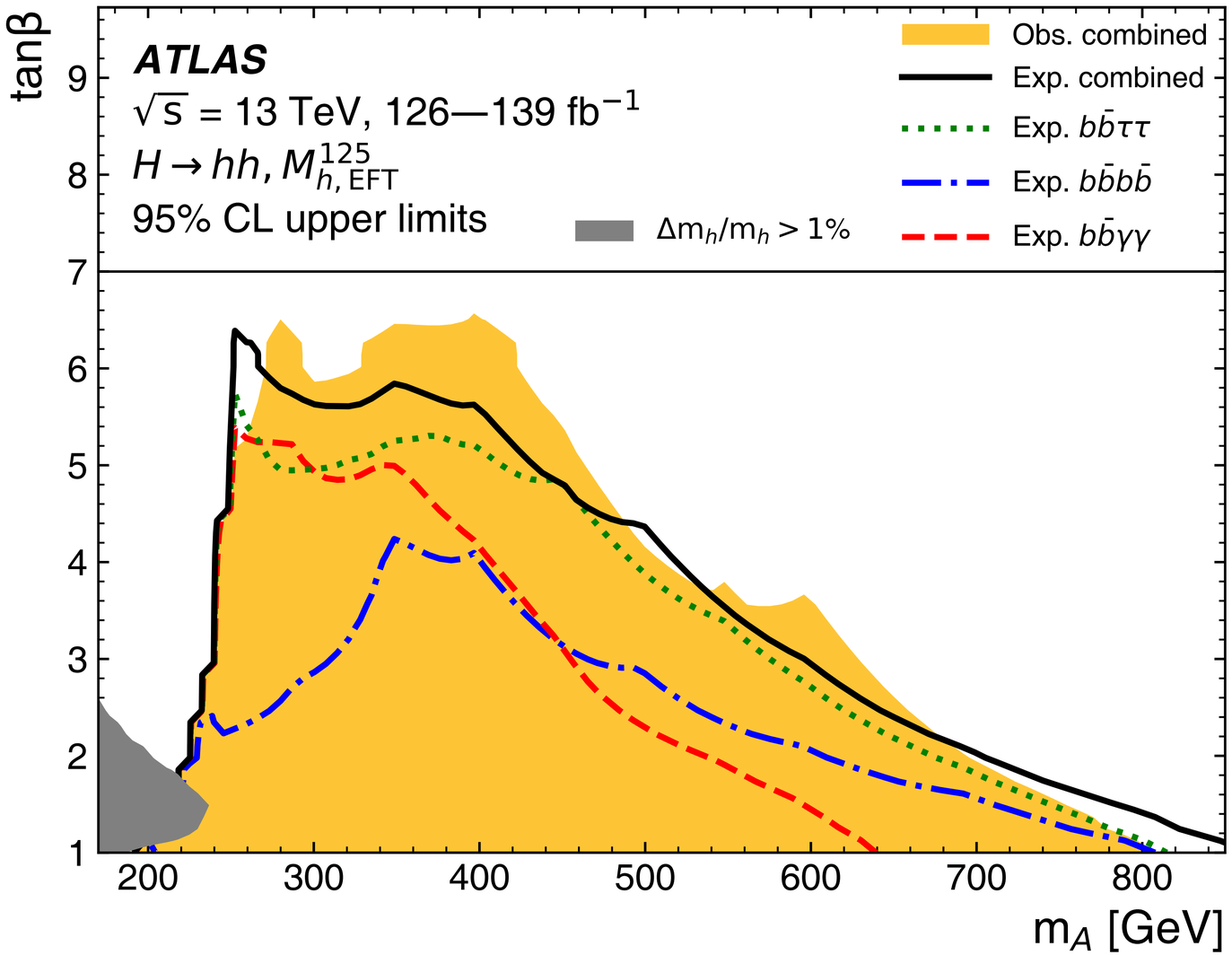
Improvement by a factor of 2-5 compared to previous ATLAS combination!



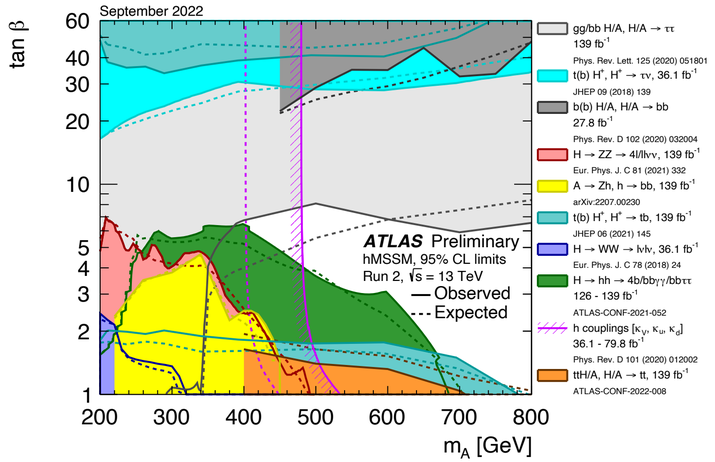
HDBS-2023-17

MSSM constraints

NEW!



ATL-PHYS-PUB-2022-043

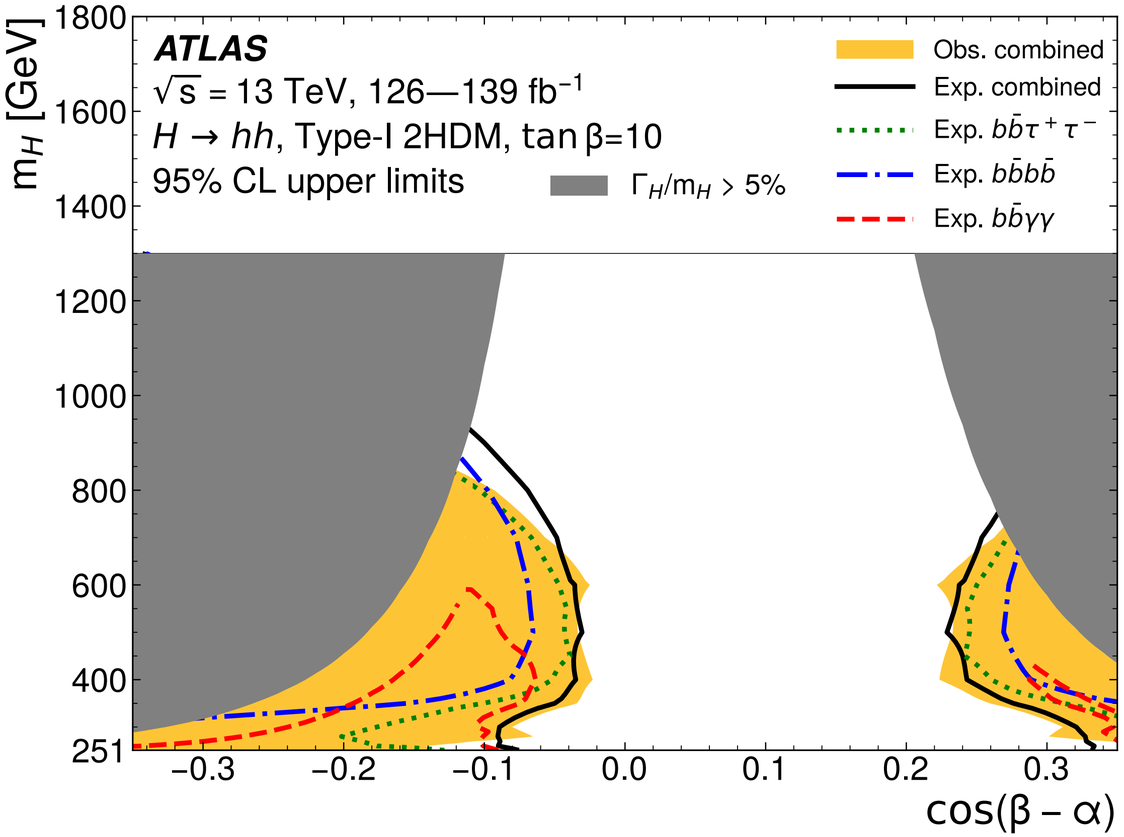


Most sensitive analysis for **intermediate tan β**

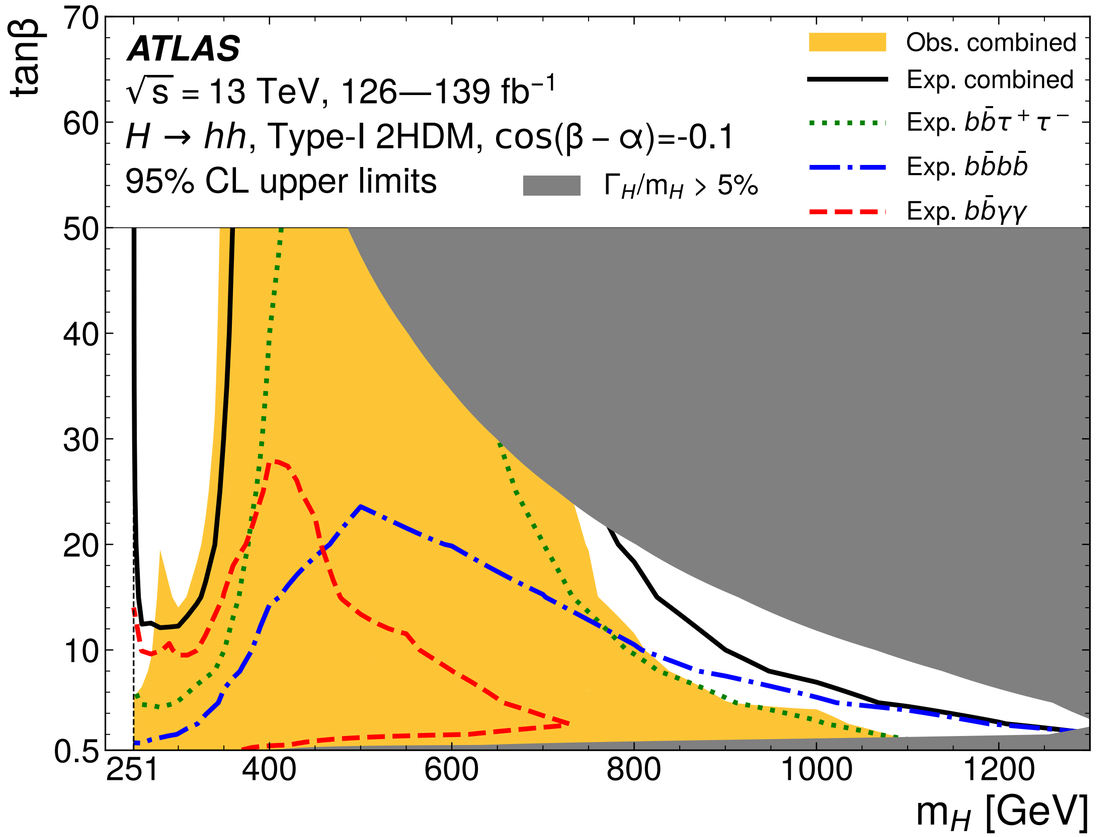
HDBS-2023-17

2HDM type I constraints

NEW!



Type I: Difficult to probe at high $\tan\beta$ since all SM couplings suppressed:
Significant reach for $\tan\beta = 10$



2HDM: Drives sensitivity in type I model for $\cos(\beta-\alpha) = -0.1$

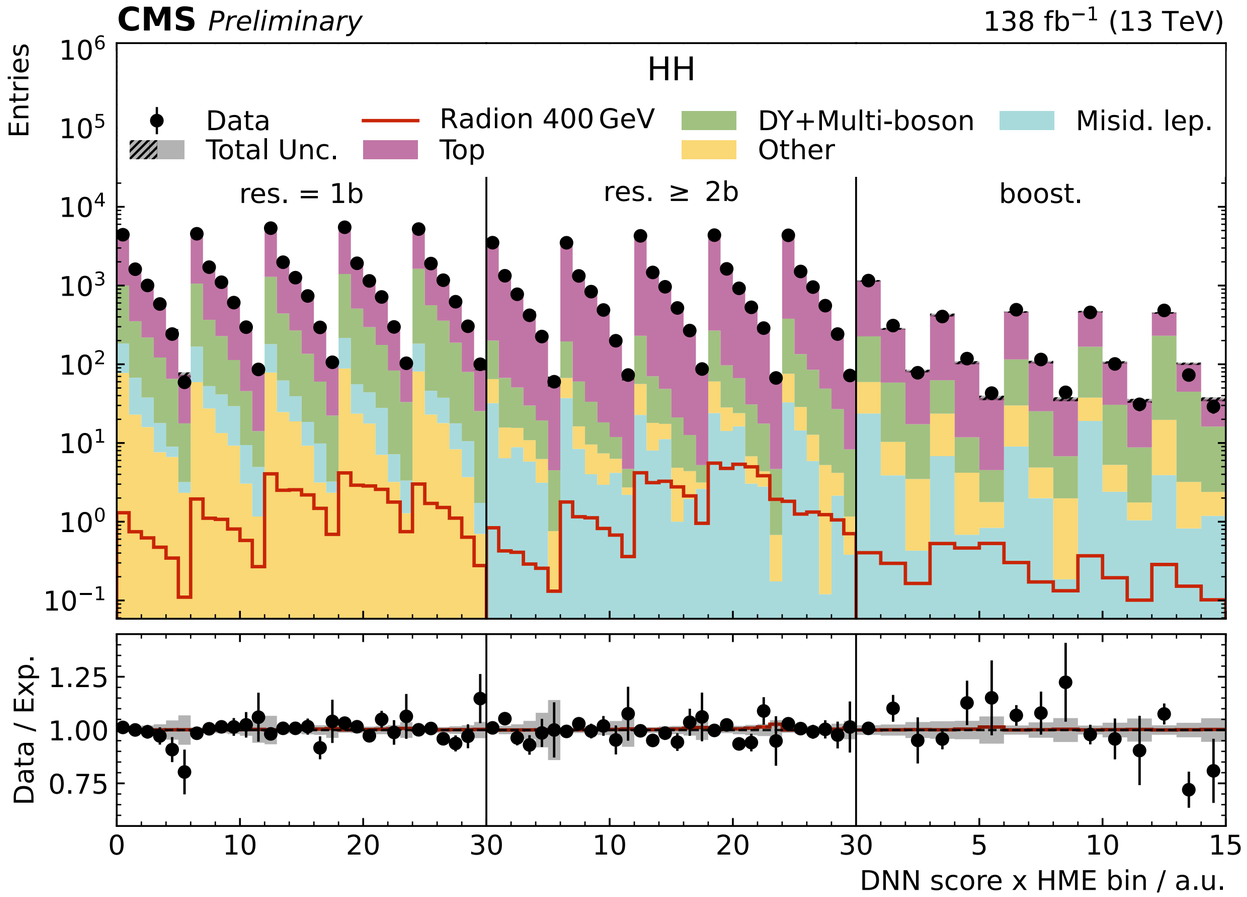
HDBS-2023-17

X→HH→bbWW resolved (CMS)

In addition to the three most important final states bbγγ, bbττ, bbbb, also released results in **bbWW** and **multilepton** final states

bbWW resolved:

- Dilepton and single-lepton channels
- Fit DNN scores (times X mass estimator in dilepton channel) in three signal regions (1b, 2b, boosted) and two control regions
- tt is main background

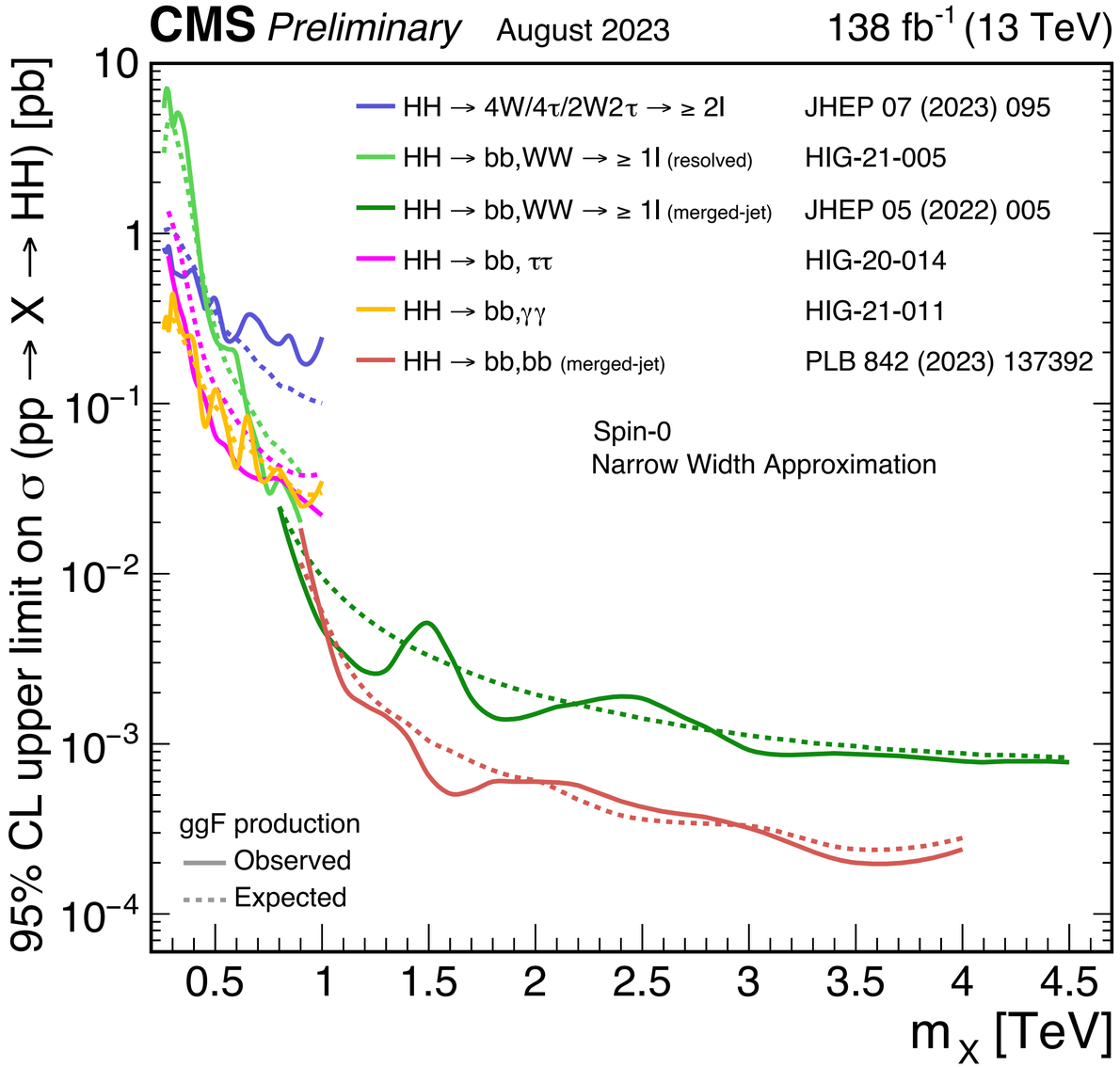


HIG-21-005 (March 2023)

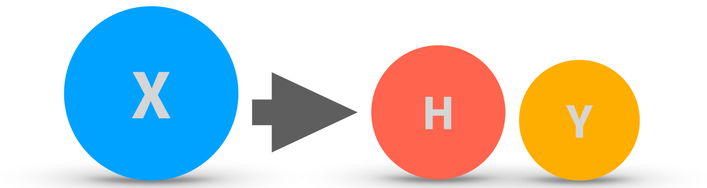
X→HH summary: CMS

- Similar to ATLAS, **bbγγ** is strongest at low mass, and **bbbb** at the highest masses
  ➡**Increased reach in bbbb merged-jet analysis from using ParticleNet tagger** - ATLAS excess at 1.1 TeV not confirmed
- **bbWW helps in intermediate mass range** - both resolved and merged-jet
- **Resolved 4b and more updates to watch out for!**

- bbγγ 2310.01643 (subm. to JHEP)
- bbττ JHEP 11 (2021) 057
- bbbb (merged-jet) Phys. Lett. B 842 (2023) 137392
- 4W/4τ/2W2τ JHEP 07 (2023) 095
- bbWW (merged-jet) JHEP 05 (2022) 005
- bbWW HIG-21-005 (March 2023)

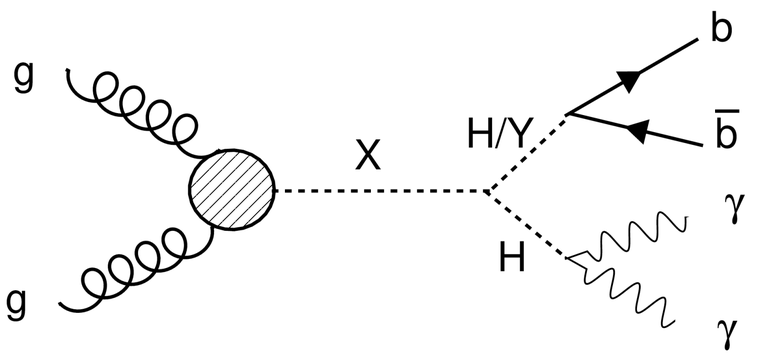


CMS B2G Summary Plots



2) X→YH searches

X→YH overview



Compared to X→HH:

- bbɣɣ, bbττ, bbbb generally still most important
- However, Y branching fractions can be very non-SM-H-like, so other final states can be most sensitive depending on Y mass and the model!
- Asymmetry: often only one H decay probed (e.g. H→ɣɣ for public bbɣɣ result)
- Two masses to scan: Large phase space to probe, larger look-elsewhere effect

Public searches

No dedicated searches with early run 2 data!

First search: CMS **bbττ** JHEP 11 (2021) 057 (PAS early 2021)

CMS **bbbb merged-jet**: Phys. Lett. B 842 (2023) 137392 (PAS late 2021)

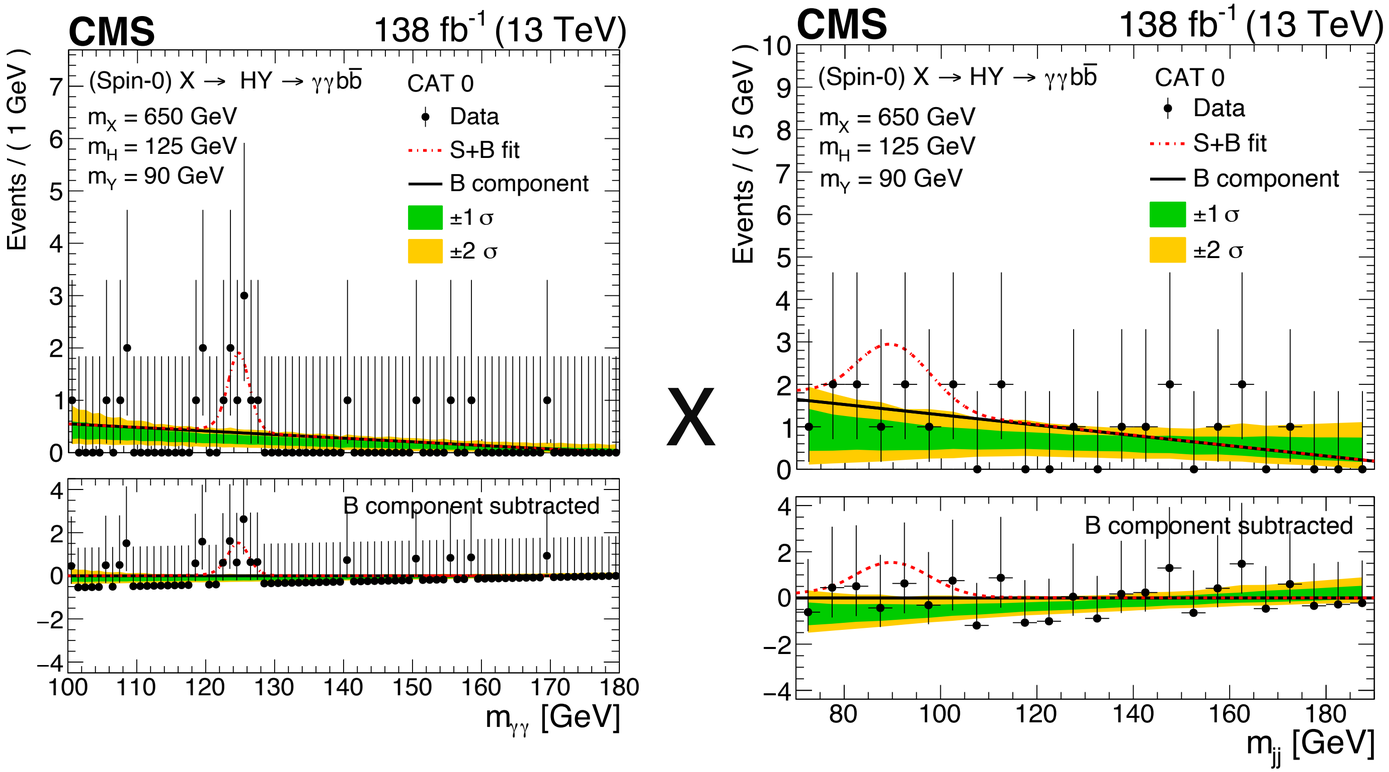
CMS **bbɣɣ** 2310.01643 (subm. to JHEP) (PAS summer 2022)

ATLAS **bb + generic hadronic** Phys. Rev. D 108 (2023) 052009 (June 2023)

ATLAS **ττ + WW/ZZ** JHEP 10 (2023) 009 (July 2023)

2310.01643 (subm. to JHEP)

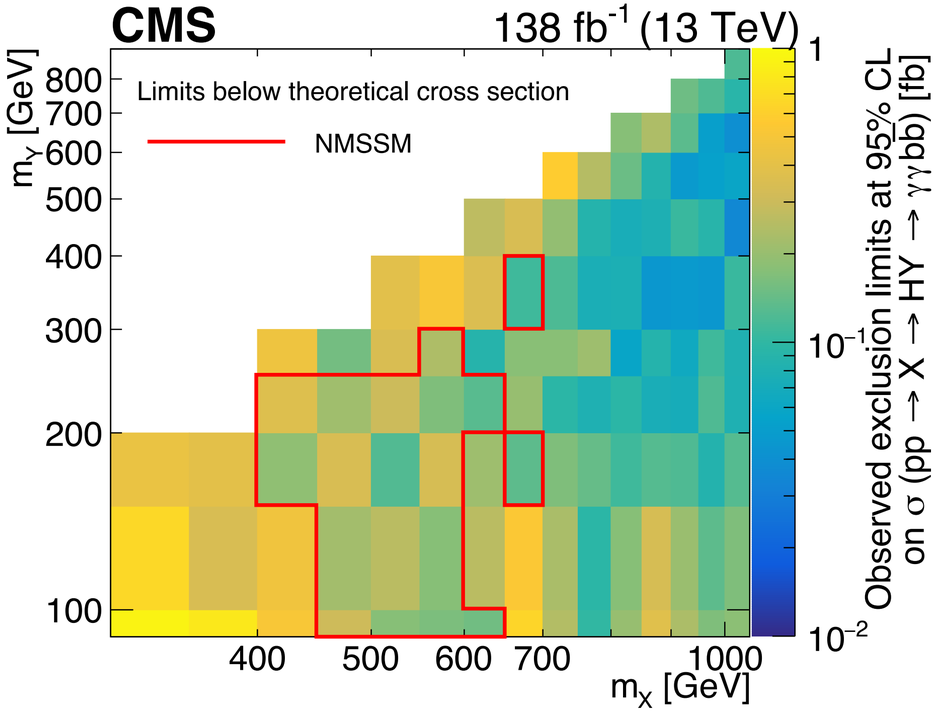
X→YH→bbγγ



X

Strategy:

- BDT against non-resonant background
- DNN against ttH for $m_X < 550$ GeV
- Parametric fit in $m_{\gamma\gamma}$-m_{bb} plane

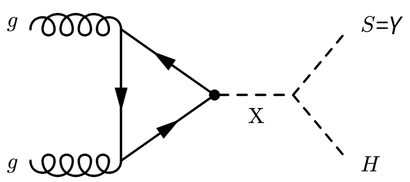


Largest excess at **m_X = 650 GeV, m_Y = 90 GeV**
with 3.8 σ local/2.8 σ global significance

Sensitive to NMSSM predictions
(max. allowed cross sections from NMSSMTools 5.5.0)

JHEP 10 (2023) 009

X→YH→WW/ZZ + ττ

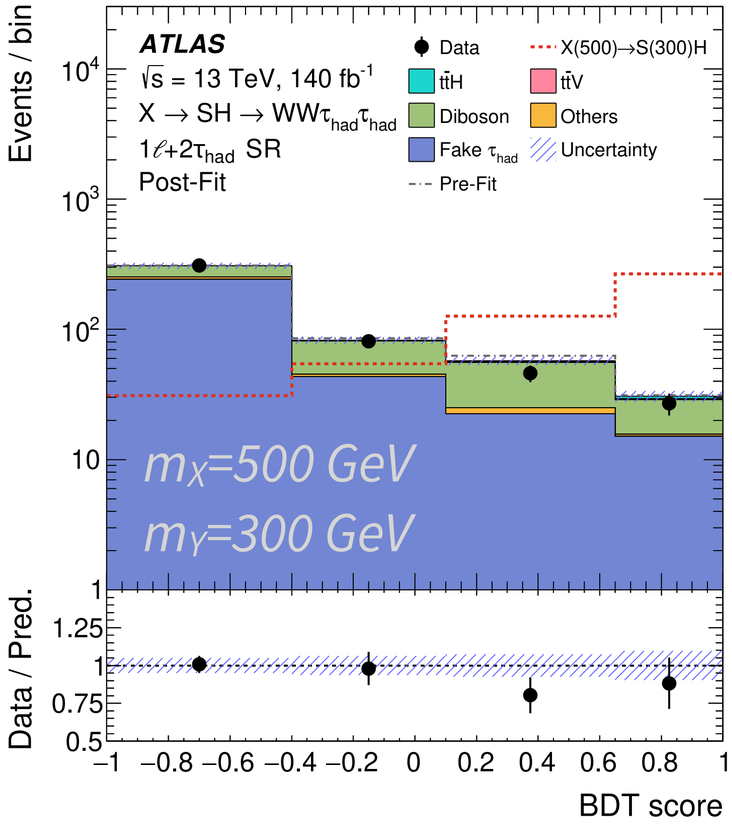


Y→WW/ZZ: one or two light leptons

Dominant decay mode in tested range 200 < m_Y < 500 GeV

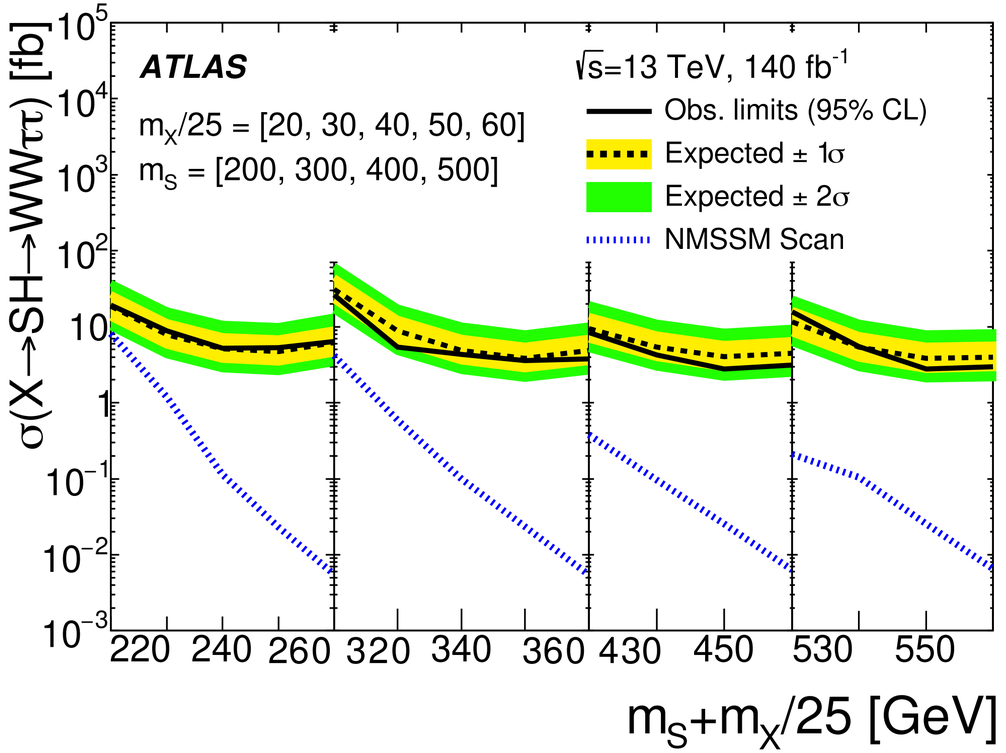
H→ττ: $\tau_h\tau_h$ final state

S=Y



12 X-mass-parametrised BDTs are trained

Results are extracted from BDT score distribution for each considered m_X-m_Y pair



Approaching NMSSM cross sections at the lowest masses

(max. allowed cross sections from NMSSMTools 6.0.0)

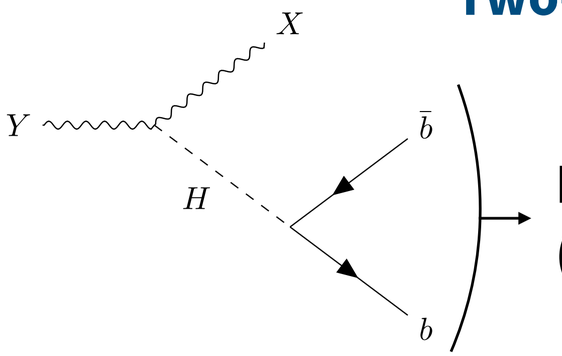
Y→HX→bb+hadronic

Targets high Y masses → two large-R jet taggers

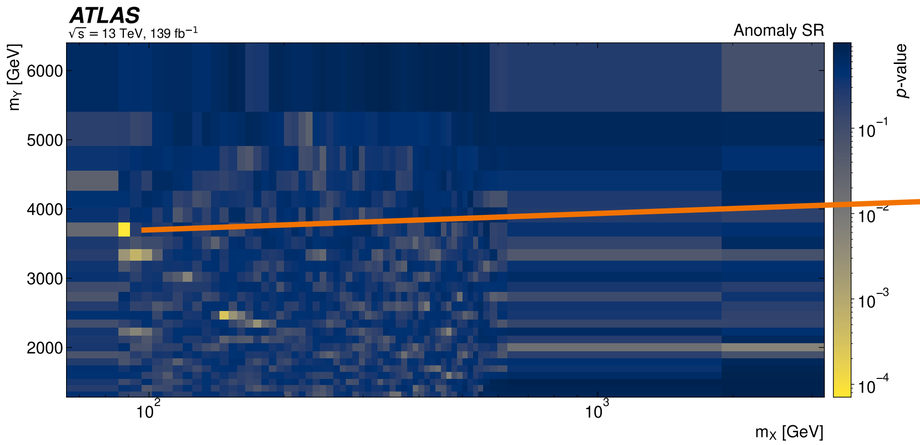
Anomaly signal region:
Targets generic signals - non-compatibility with learned background model

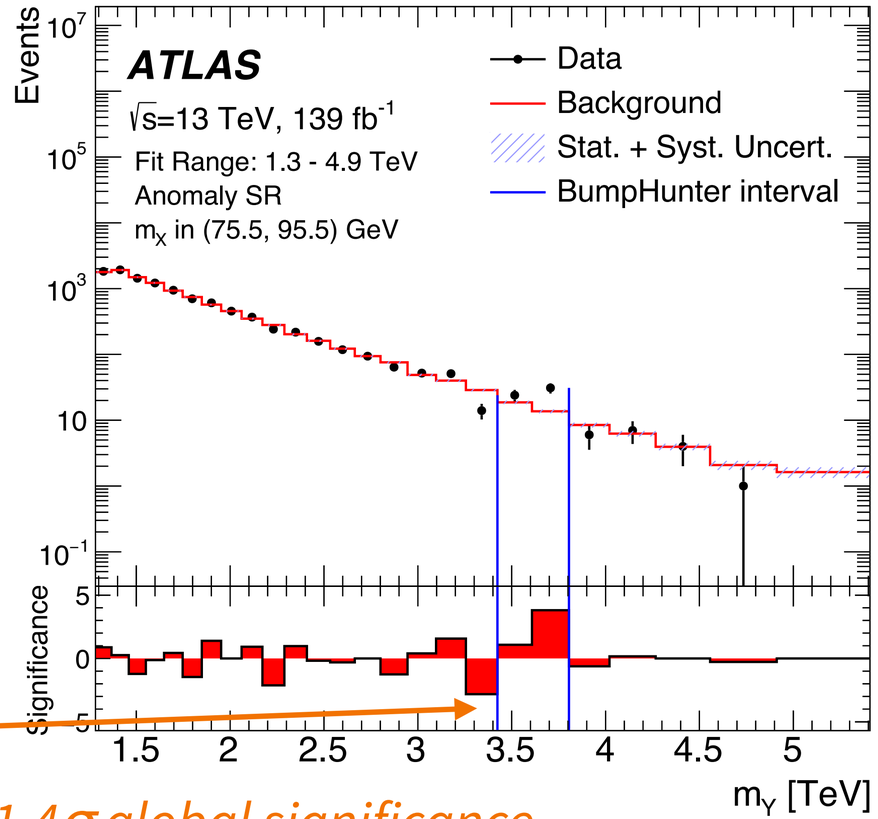
Anomaly

X tagger: **Two-prong (merged)** / **Two-prong (resolved)** → *benchmark X→qq decay*



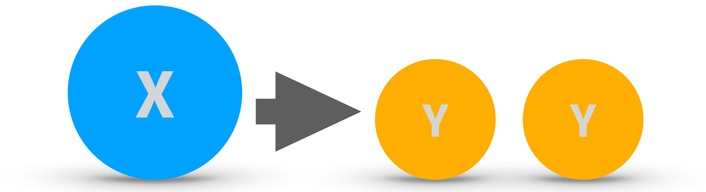
DNN H→bb tagger
(sidebands for BG estimation)





1.4σ global significance

Phys. Rev. D 108 (2023) 052009



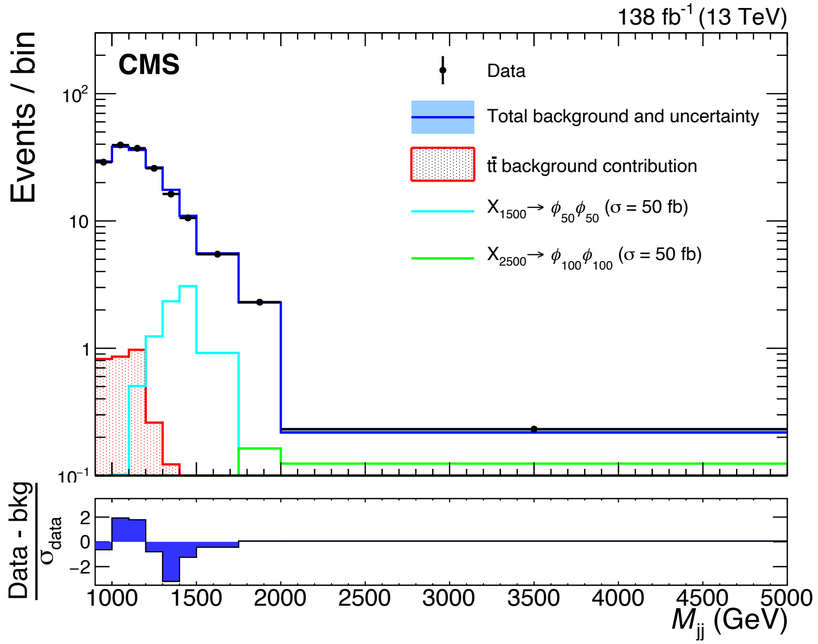
3) X→YY searches

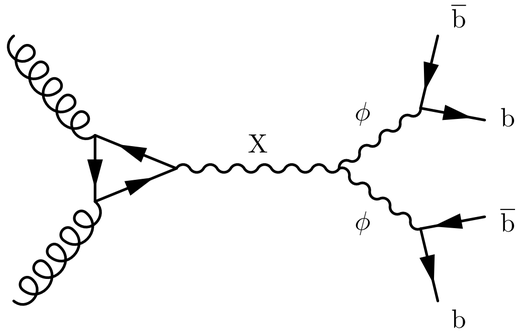
X→YY overview

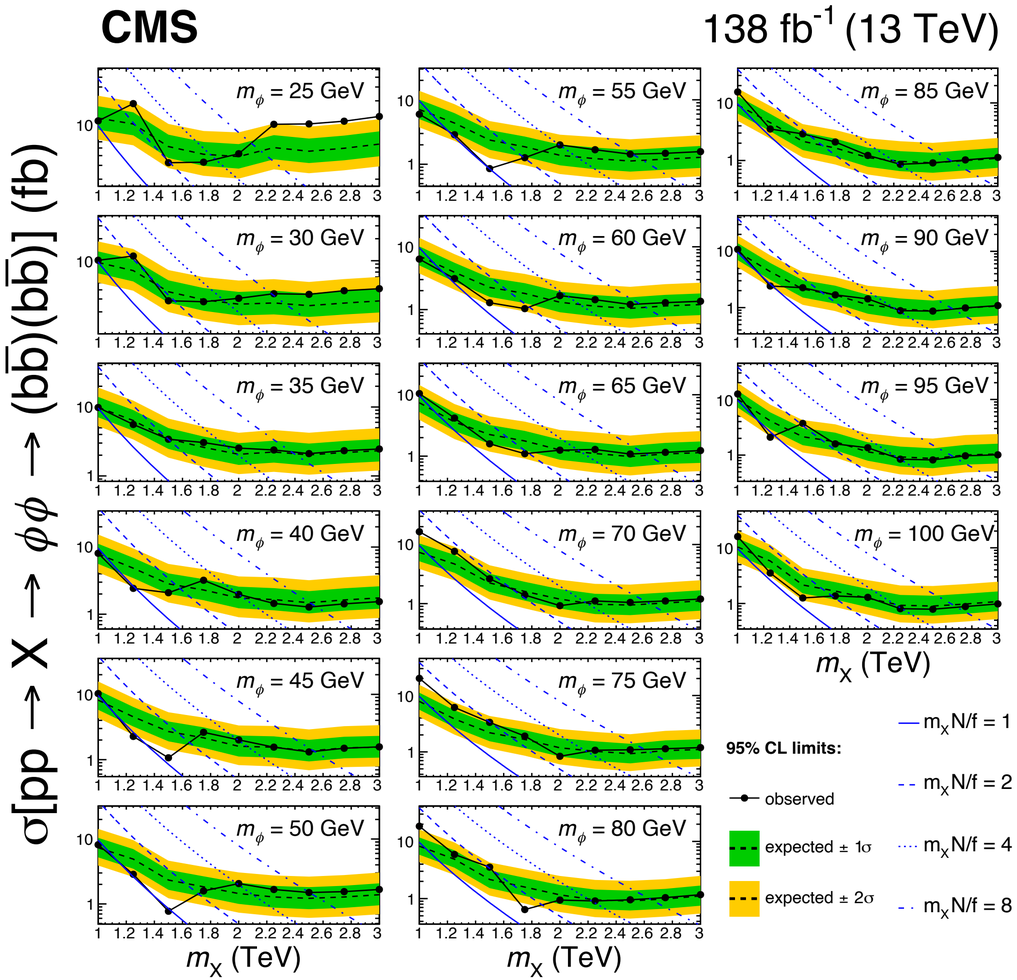
CMS **bbbb merged-jet**: Phys. Lett. B 835 (2022) 137566

M_X: 1-3 TeV

M_Y: 25-100 GeV (highly boosted!)

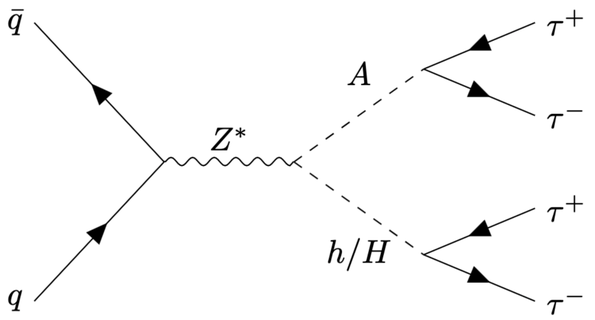




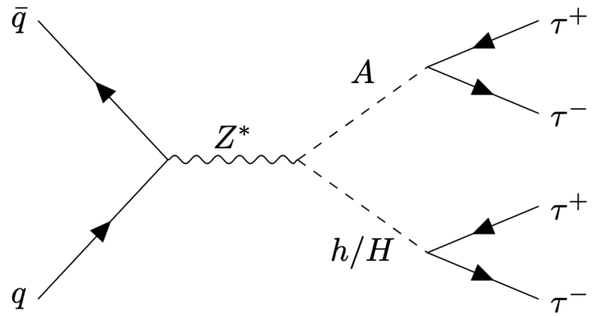


Only public search!

4) Z*→HA



Z*→HA→4τ



CMS-PAS-SUS-23-007

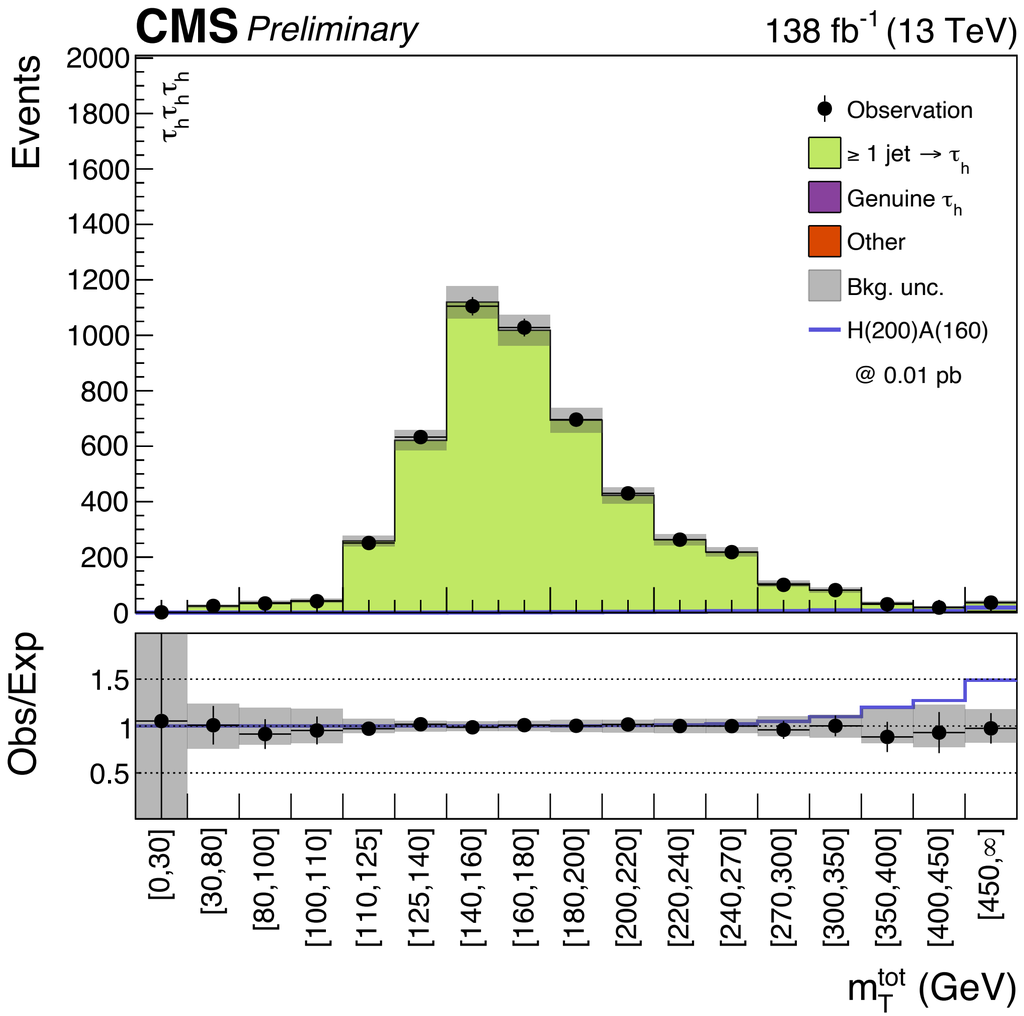
NEW!

- In lepton-specific (or type X) 2HDM at large tan **β** - which could explain g-2 - non-lepton couplings and hence **direct A/H production strongly suppressed**
- HA pair production (via Z*) with decays to 4 tau leptons can probe this scenario!

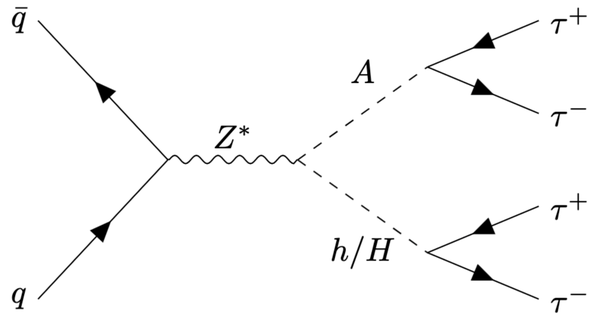
- Target the 6 final states with 4/3/2 τ_h (87% of total)
- In ee/μμ/eμ + $\tau_h\tau_h$ final states, further subdivide by light lepton charge (opposite- or same-sign)
- Dominant background: **jet→τ_h fakes**, estimated using BDT-based fake factor method

➡Fit m_T^{tot} distribution

$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{\sum_{i,j=1;i<j}^{N} m_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\,i}, \vec{p}_{\mathrm{T}}^{\,j})^2} + 4\tau_h + p_T^{miss}$$



Z*→HA→4τ



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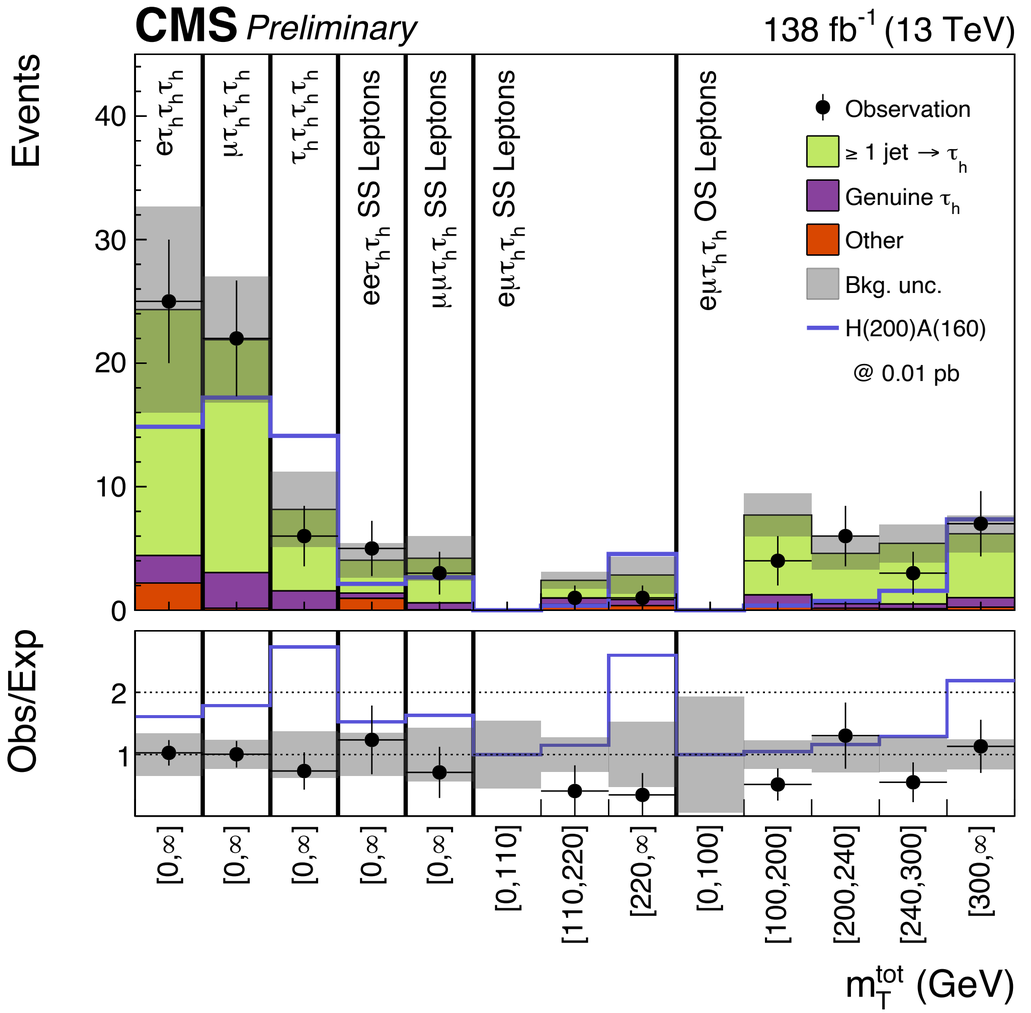
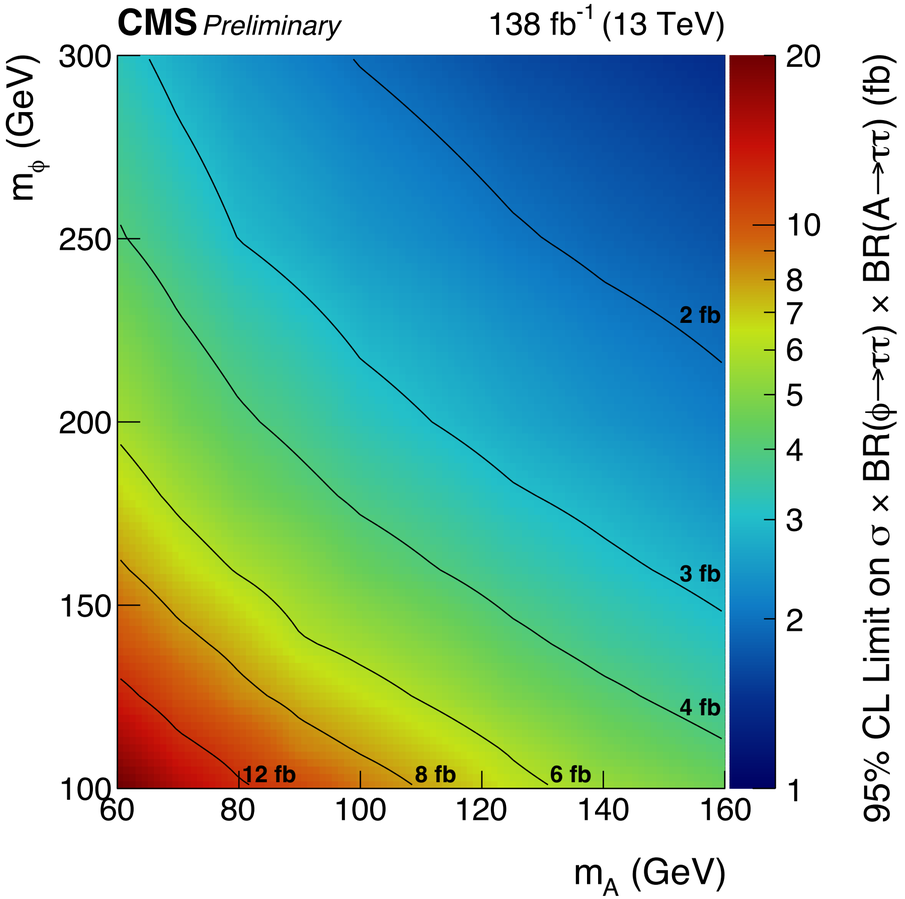
➡Fit m_T^{tot} distribution

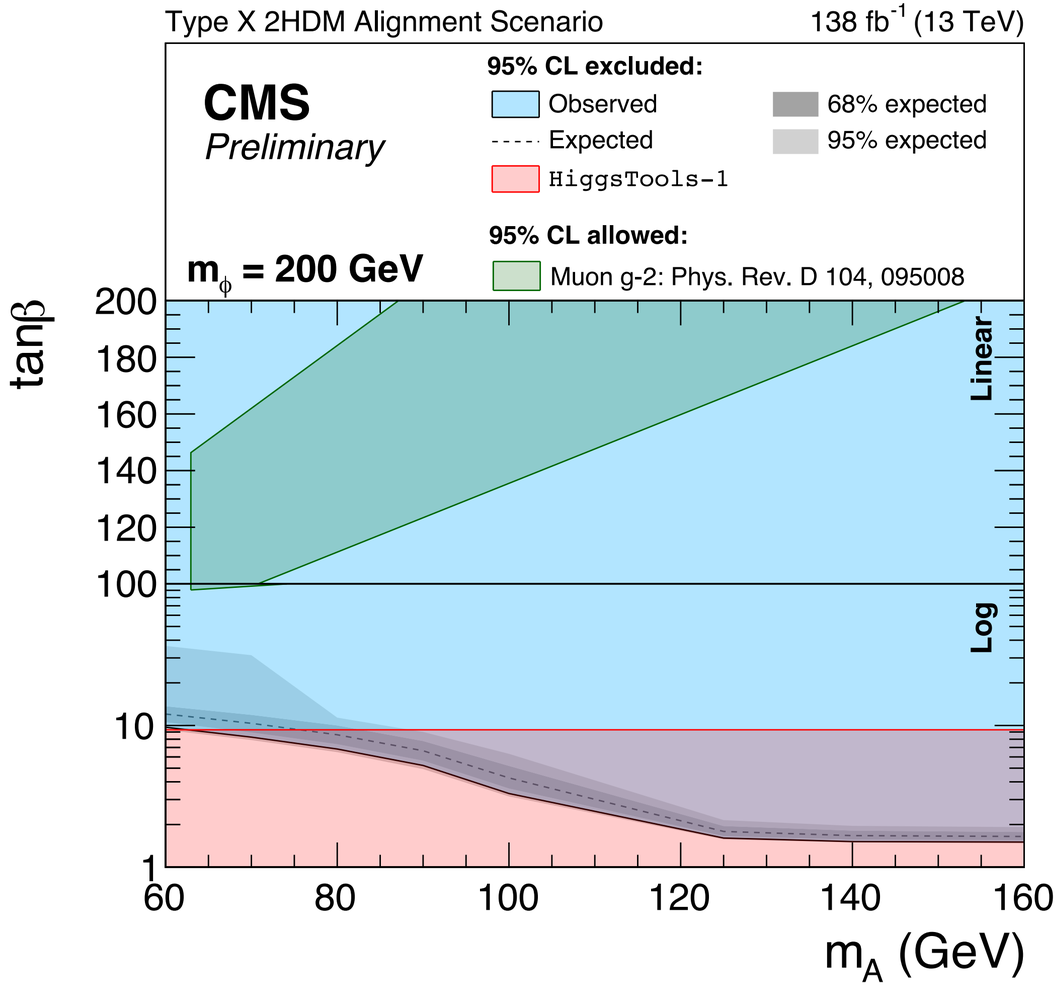


Z*→HA→4τ - results

NEW!

CMS-PAS-SUS-23-007





Cross-section limits ranging from 1.4 to 20 fb, well below all predicted 2HDM type X cross sections

- **Excludes type X 2HDM as muon g-2 explanation**
- Excludes type X 2HDM in probed mass range

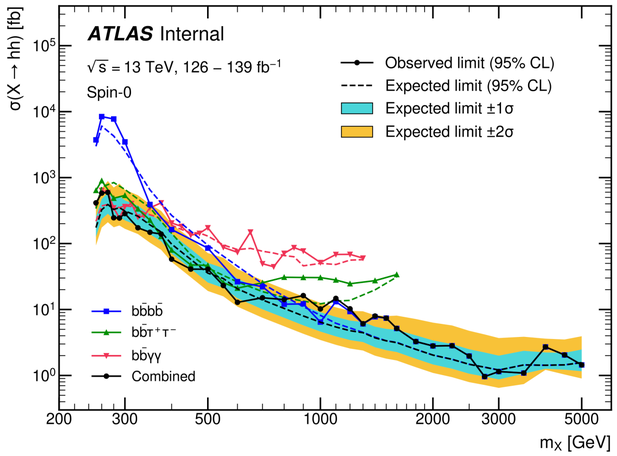
Summary

Brand new X→HH combination (ATLAS):
Significantly enhanced reach and various model interpretations

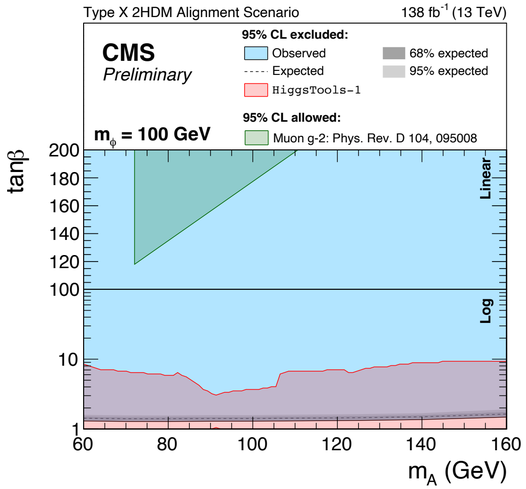
Brand new search for Z*→HA (CMS):
Excludes large parts of lepton-specific 2HDM that were previously unprobed

Many other searches for X→HH, X→YH, and X→YY:
All are potential discovery channels

Looking forward to seeing more run 2 and first run 3 results!



NEW!



NEW!

See also:
Tue 12:10: Khawla Jaffel (CMS heavy Higgs)
Wed 16:30: Tobias Kramer (CMS HH/YH)
Wed 17:10: Olof Lundberg (ATLAS X->HH/VV)
Thu 14:00: Yanwen Liu (ATLAS + CMS additional Higgs)
Fri 11:00: Zhengliang Guo (CMS HH/YH prospects)

Additional information

CMS X→YH summary plots

Higgs summary plots