DiHiggs searches (HH, XH) at ATLAS and CMS

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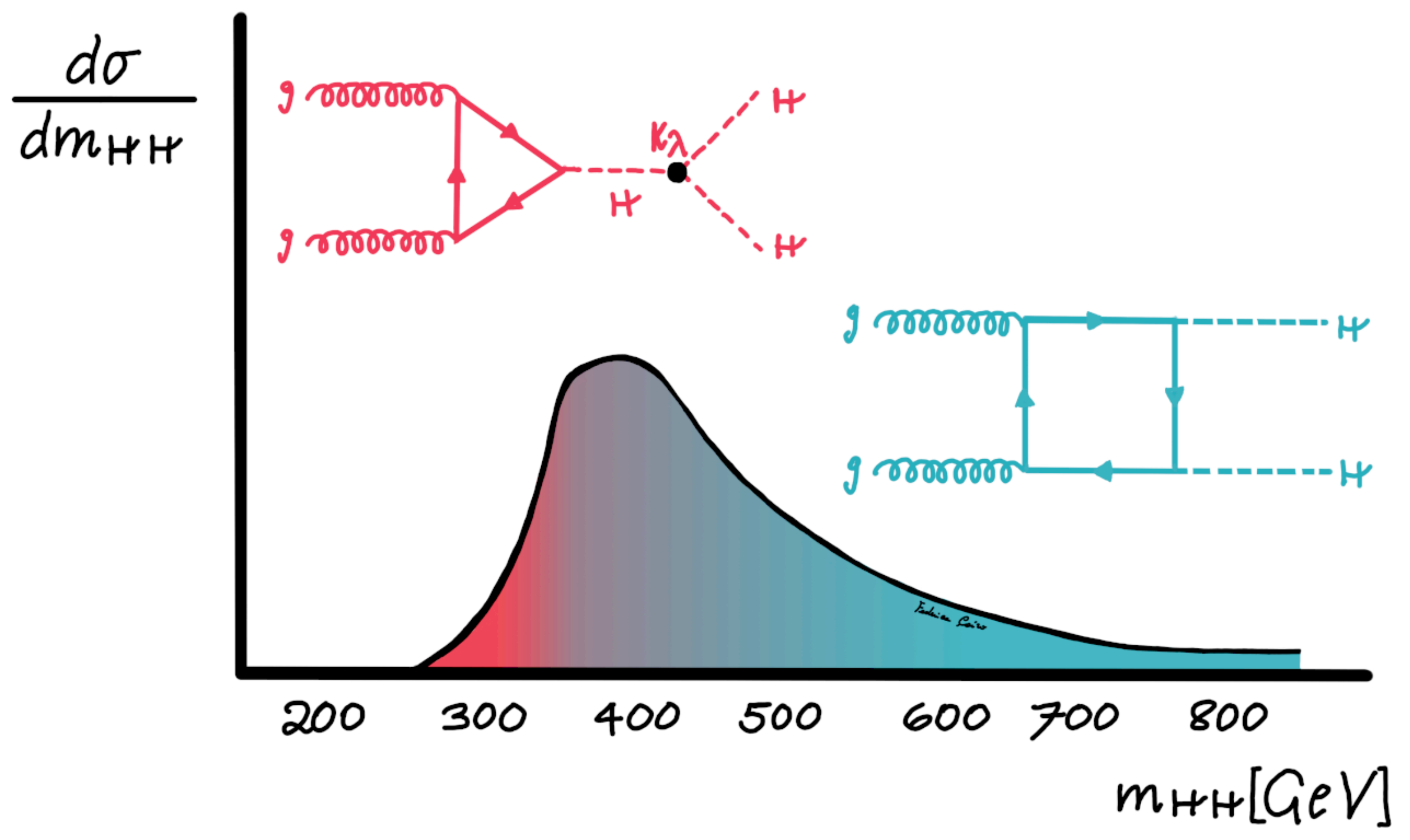
o.b.o the ATLAS and CMS collaborations

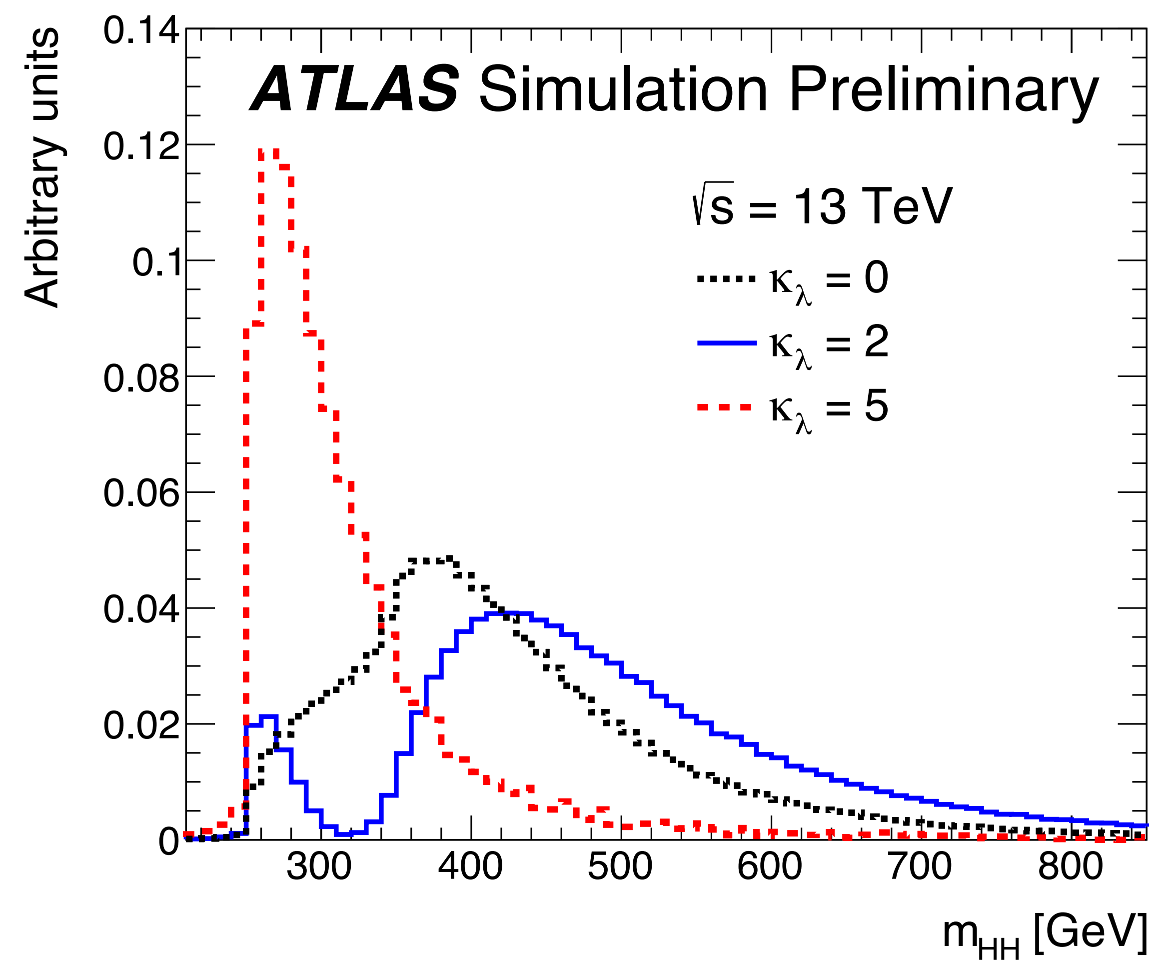
Moriond EW - 24/03/2024

How are Higgs pairs produced?

Searching for a pair of Higgs boson is directly connected to probing the Higgs potential, more particularly to the trilinear coupling λ, one of the two free parameters of the SM theory:

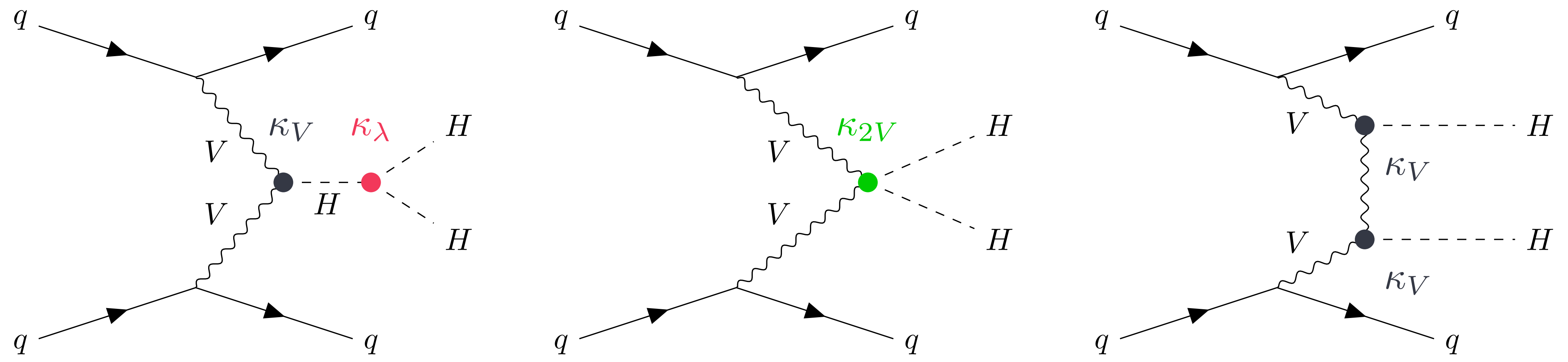


- **gluon-gluon Fusion (ggF):** $\sigma_{HH}^{ggF} = 31.02$ fb*
  - Destructive interference between triangle and box diagrams makes the cross-section tiny (1000x smaller than single Higgs);
  - Coupling strength denoted as $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$
  - m_{HH} shape very dependent on the κ_λ.

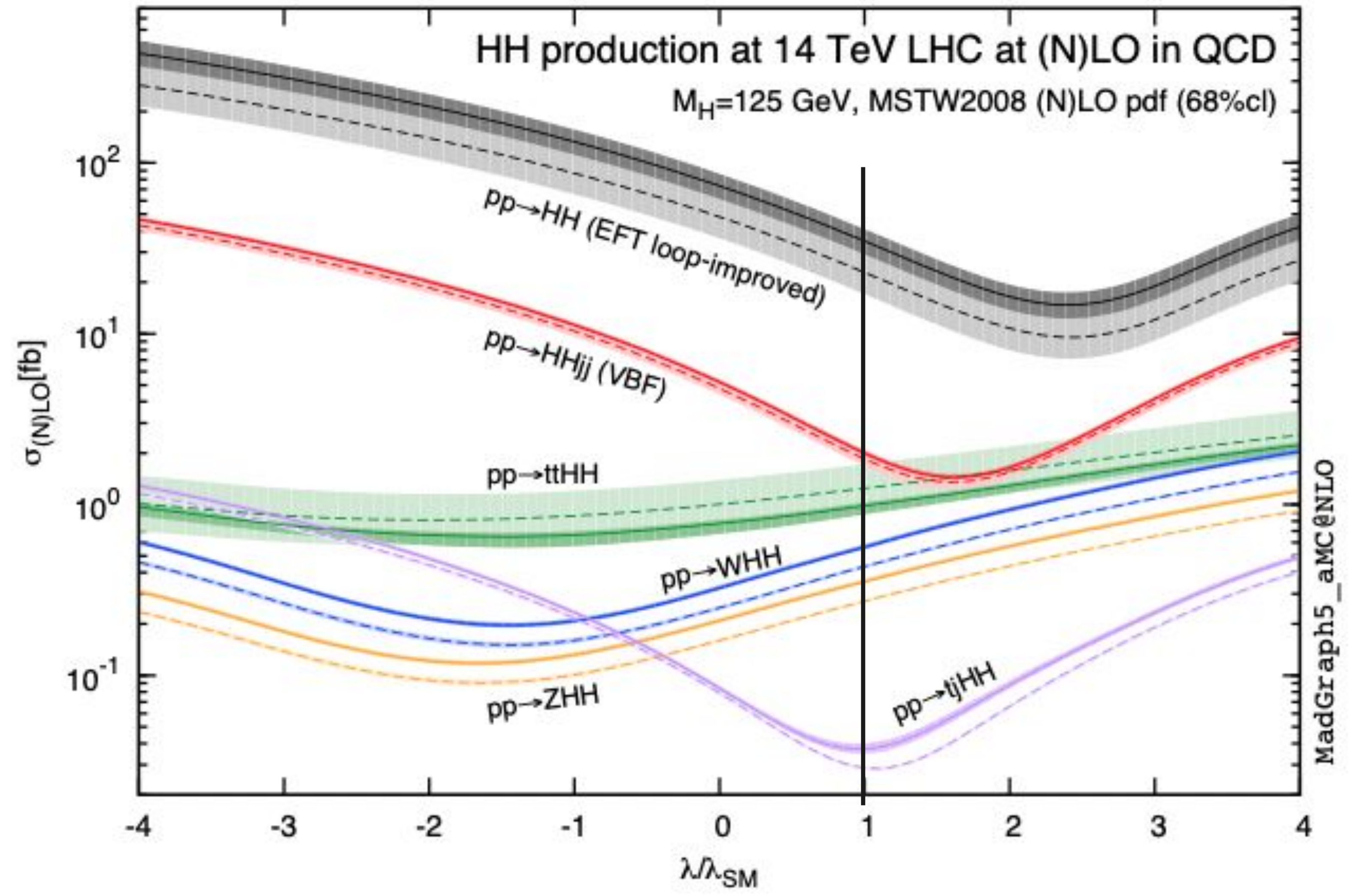


- **Vector Boson Fusion (VBF):** $\sigma_{HH}^{VBF} = 1.72$ fb*

Second order contribution to total production, but direct handle to vector boson coupling modifiers κ_{2V} and κ_V:



And many more production modes to probe ...

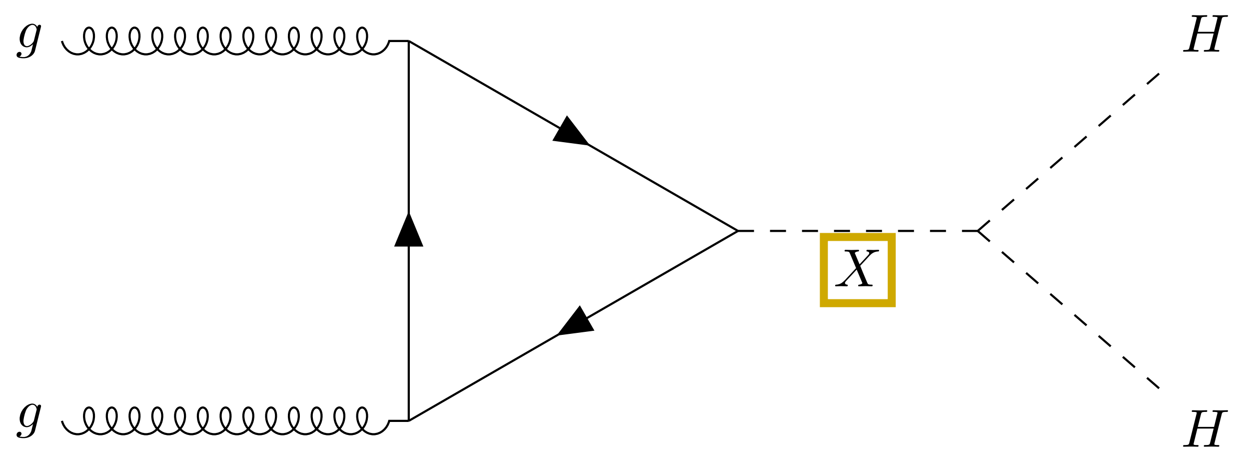


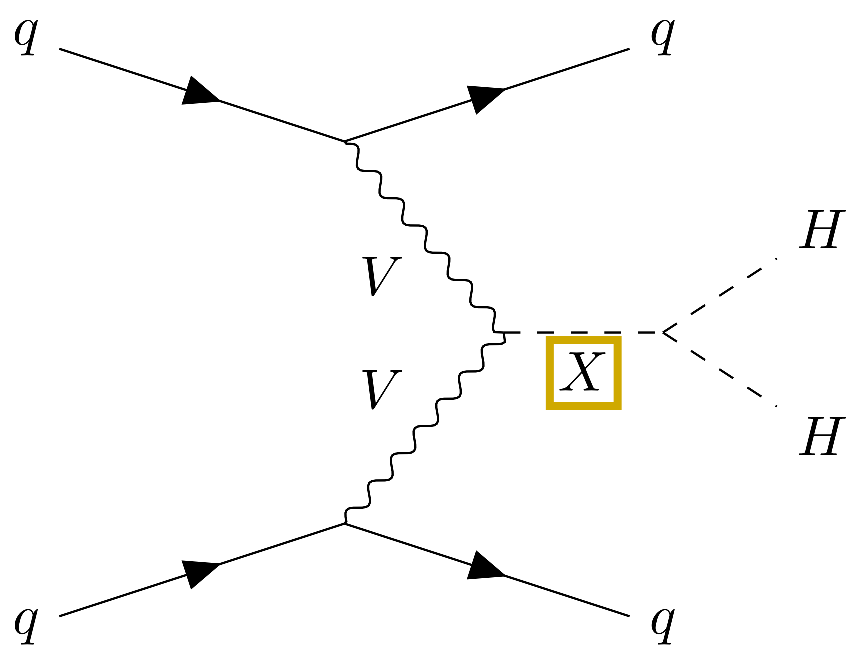
* at $\sqrt{s}$ 13 TeV

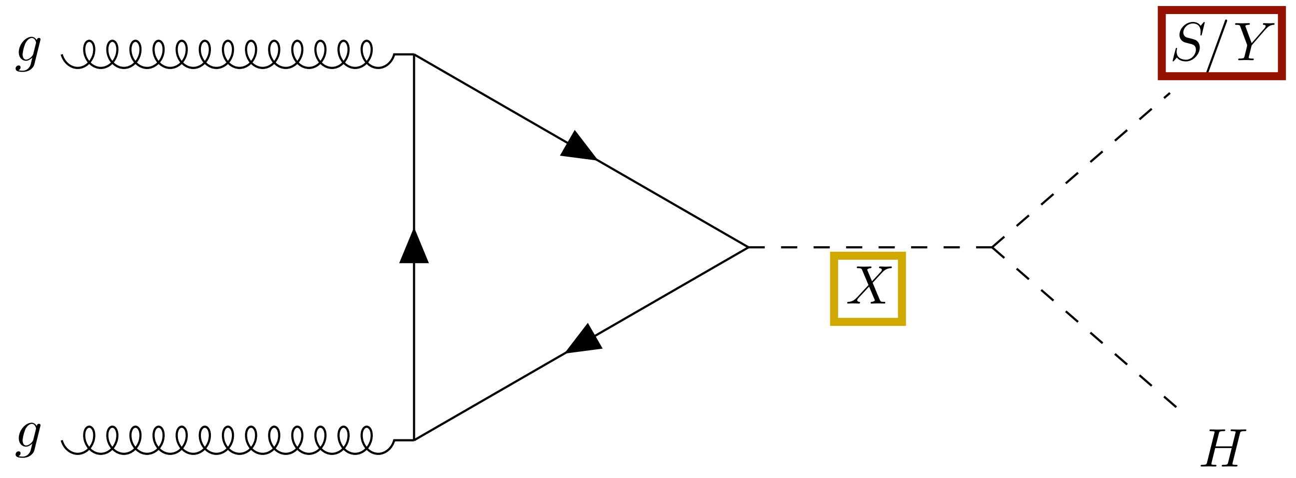
How are Higgs pairs produced?

The nature of the couplings of the Higgs to particles beyond the standard model makes it a natural probe, but the HH final state allows also to explore new topologies:

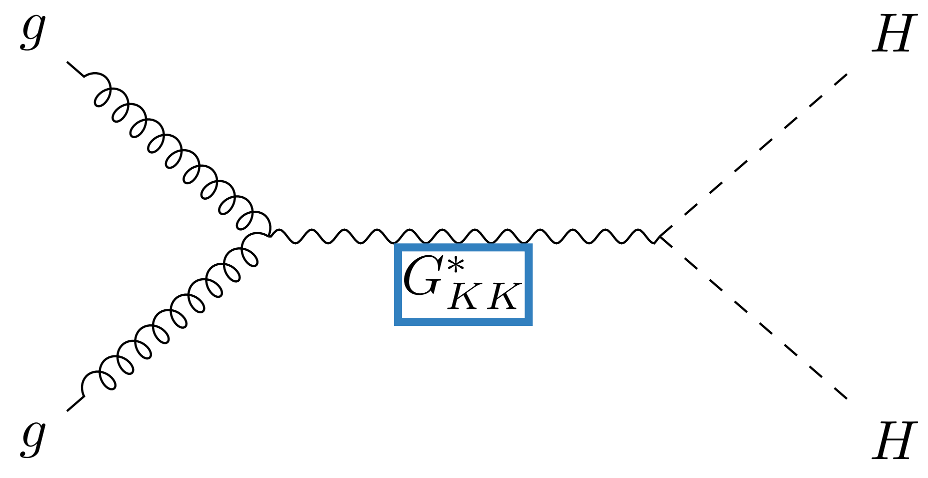
- **Spin-0**: for exemple predicted by Two-Higgs-Doublet-Models completed by an Electroweak Singlet:
  - *Beware that ATLAS and CMS have different convention to denote the extra scalar (S vs Y);*







- **Spin-2**: for example predicted by a Kaluza–Klein graviton in the context of the bulk Randall-Sundrum (RS) model of warped extra dimensions.



🚨🚨 Most of the time, only the narrow width approximation is used, neglecting the interference with the SM production.

How to look for Higgs pairs?

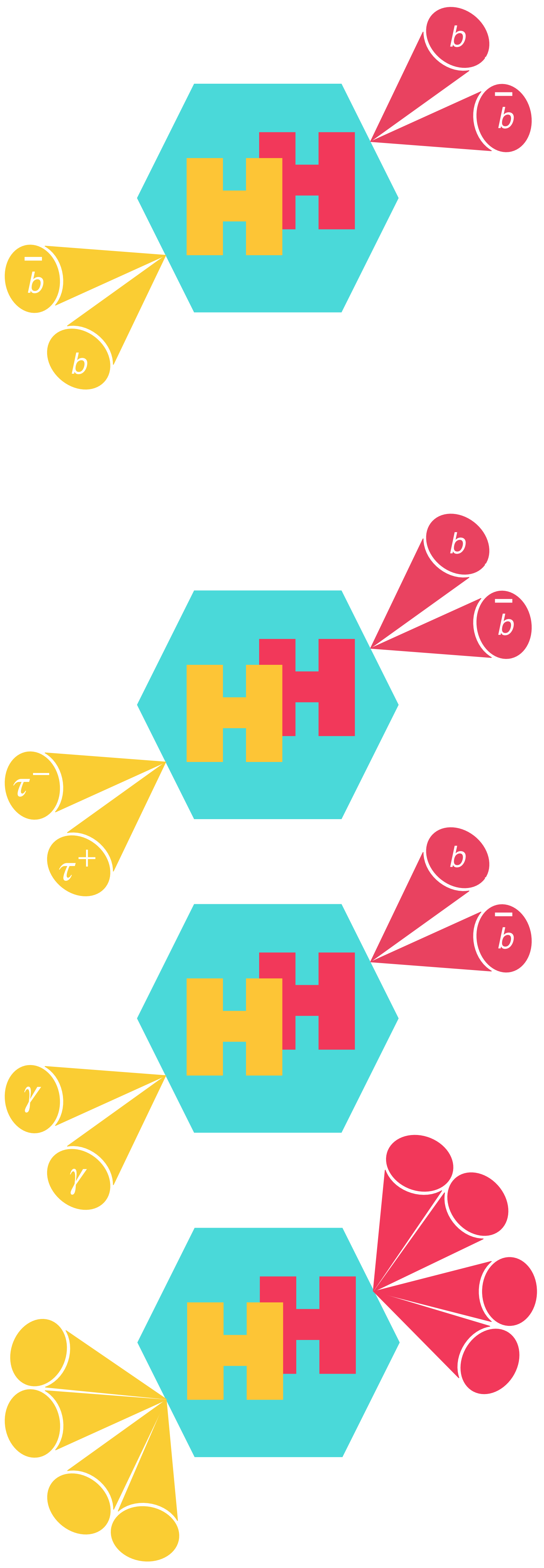
There is no clear **Golden channel for the non-resonant search**, but several promising signatures:

$BR(HH \to XXYY)$ (gluons, c, muon not shown)

	bb	WW	ττ	ZZ	γγ
bb	34 %				
WW	25 %	4.6 %			
ττ	7.3 %	2.7 %	0.39 %		
ZZ	3.1 %	1.1 % A	0.33 % A	0.069 %	
γγ	0.26 %	0.10 %	0.028 %	0.012 % A	0.0005 %

Full Run-2 analyses: A for ATLAS only

Combining the results is necessary **for observation**.



$HH \to b\bar{b}b\bar{b}$
- $H \to b\bar{b}$: High BR
- Large hadronic background

ATLAS: Phys. Rev. D 108 (2023)
+ ATLAS-CONF-2024-003 (VBF, boosted) ← NEW
+ Eur. Phys. J. C 83 (2023) 519 (VHH)

CMS: Nature 607 (2022)
+ CMS-PAS-B2G-21-001 (VBF, boosted)
+ CMS-PAS-HIG-22-006 (VHH)

$HH \to b\bar{b}\tau^+\tau^-$
- $H \to b\bar{b}$: High BR
- $H \to \tau^+\tau^-$: Low background

ATLAS: ATLAS-CONF-2023-071

CMS: Phys. Lett. B 842 (2023)

$HH \to b\bar{b}\gamma\gamma$
- $H \to b\bar{b}$: High BR
- $H \to \gamma\gamma$: Good mass resolution

ATLAS: JHEP 01 (2024) 066

CMS: JHEP 03 (2021) 257

$HH \to b\bar{b}VV$ and friends (with leptons)
- Decent BR from $H \to VV$
- High number of leptonic and hadronic channels

ATLAS: JHEP 02 (2024) 037 ($b\bar{b}(ZZ/WW/\tau\tau)$, 2l+MET)
+ ATL-CONF-2024-005 ($b\bar{b}ZZ/4V/2V2\tau/4\tau/2\gamma2V/2\gamma2\tau$) ← NEW

CMS: JHEP 07 (2023) 095 ($4W/WW\tau\tau/4\tau$, ≥2l)
+ JHEP 06 (2023) 130 ($b\bar{b}ZZ$, 4l)
+ CMS-PAS-HIG-21-005 ($b\bar{b}WW$, ≥1l)
+ CMS-PAS-B2G-21-001 ($\gamma\gamma WW$)
+ HIGG-22-012 ($\gamma\gamma\tau\tau$) ← NEW

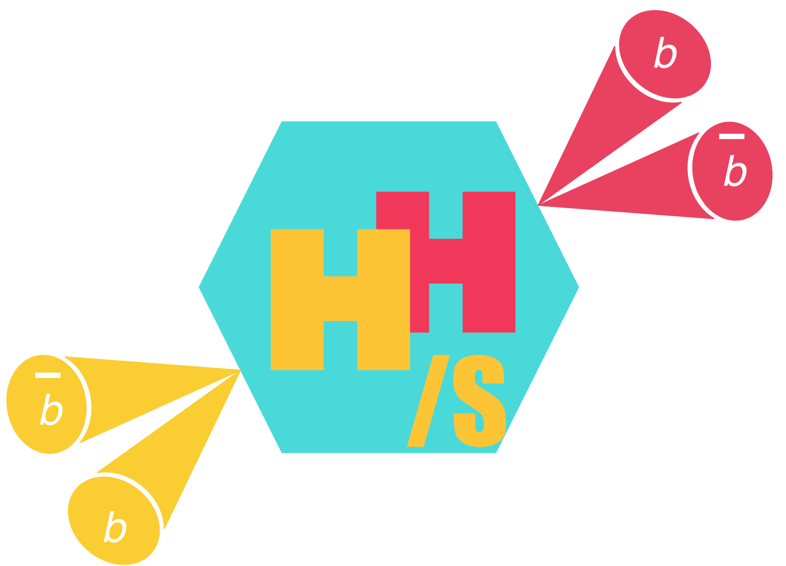
How to look for Higgs pairs?

BSM Searches with Higgs pairs and friends are also covering a wide range of signatures:

$BR((S/H)H \rightarrow XXYY)$ (gluons, c, muon not shown)

	bb	WW	ττ	ZZ	γγ
bb	34 %				
WW	25 % C	4.6 % C			
ττ	7.3 %	2.7 % C	0.39 % C		
ZZ	3.1 %	1.1 %	0.33 %	0.069 %	
γγ	0.26 %	0.10 % C	0.028 %	0.012 %	0.0005 %

Full Run-2 analyses: C for CMS only

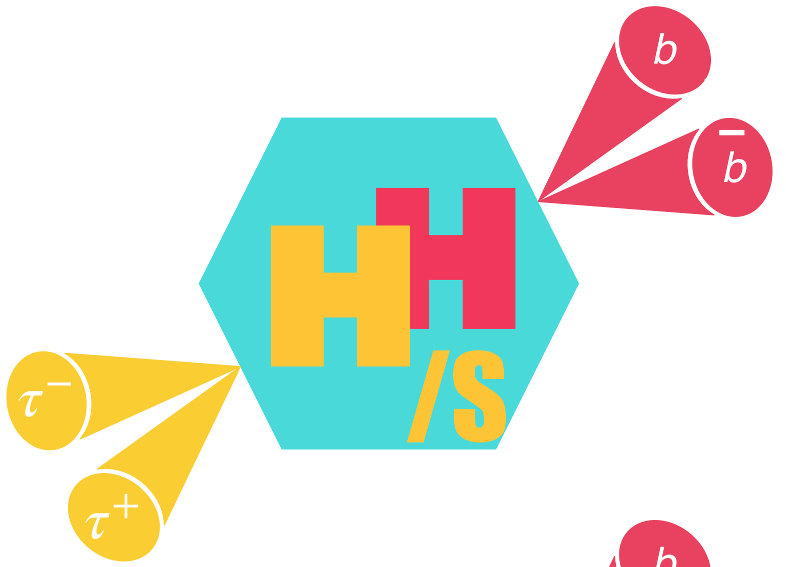


$HH \rightarrow b\bar{b}b\bar{b}$

- $S/H \rightarrow b\bar{b}$: High BR
- Large hadronic background

ATLAS: Phys. Rev. D 105 (2022) (X->HH)
+ JHEP 07 (2020) 108 (VBF X->HH)

CMS: CMS-PAS-B2G-20-004 (X->HH, boosted)
+ Phys. Lett. B 842 (2023) (X->SH)

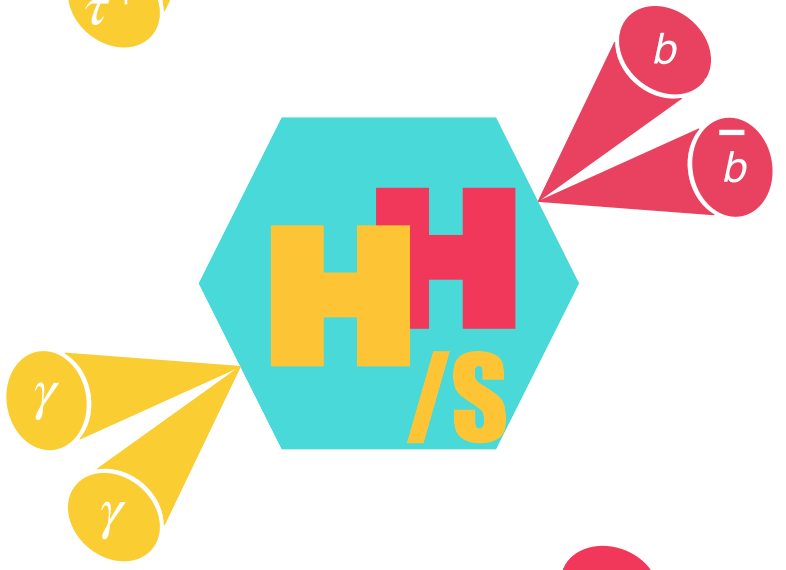


$HH \rightarrow b\bar{b}\tau^+\tau^-$

- $S/H \rightarrow b\bar{b}$: High BR
- $H \rightarrow \tau^+\tau^-$: Low background

ATLAS: JHEP 07 (2023) 040 (X->HH)

CMS: JHEP 11 (2021) 057 (X->SH)

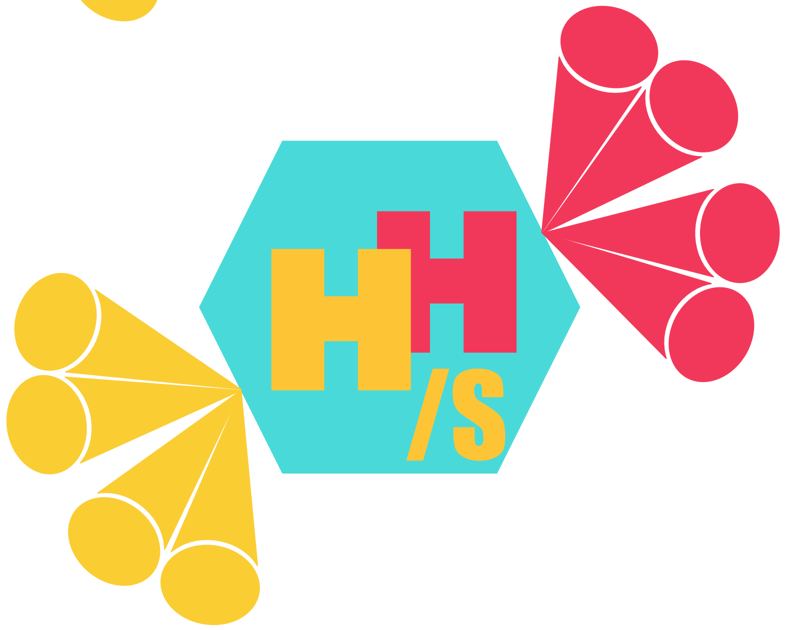


$HH \rightarrow b\bar{b}\gamma\gamma$

- $S/H \rightarrow b\bar{b}$: High BR
- $H \rightarrow \gamma\gamma$: Good mass resolution

ATLAS: Phys. Rev. D 106 (2022) (X->HH)
+ ATL-CONF-XXX (X->SH) ← **NEW** *Presented in ATLAS wildcard talk*

CMS: Sub. to JHEP (X->SH and X->HH)



$HH \rightarrow b\bar{b}VV$ and friends (with leptons)

- Decent BR from $H \rightarrow VV$
- High number of leptonic and hadronic channels

ATLAS: X

CMS: JHEP 07 (2023) 095 (X->HH->ML, ≥2l)
+ JHEP 05 (2022) 005 (X->HH->$b\bar{b}(WW/\tau\tau)$)
+ HIGG-22-012 (X->HH and X->HH) ← **NEW**

Limits on HH production

One of the key figure of merit is the limit on either the HH **cross-section** to its SM prediction, or the **signal strength μ**. The later incorporates the theoretical uncertainties on the SM prediction.

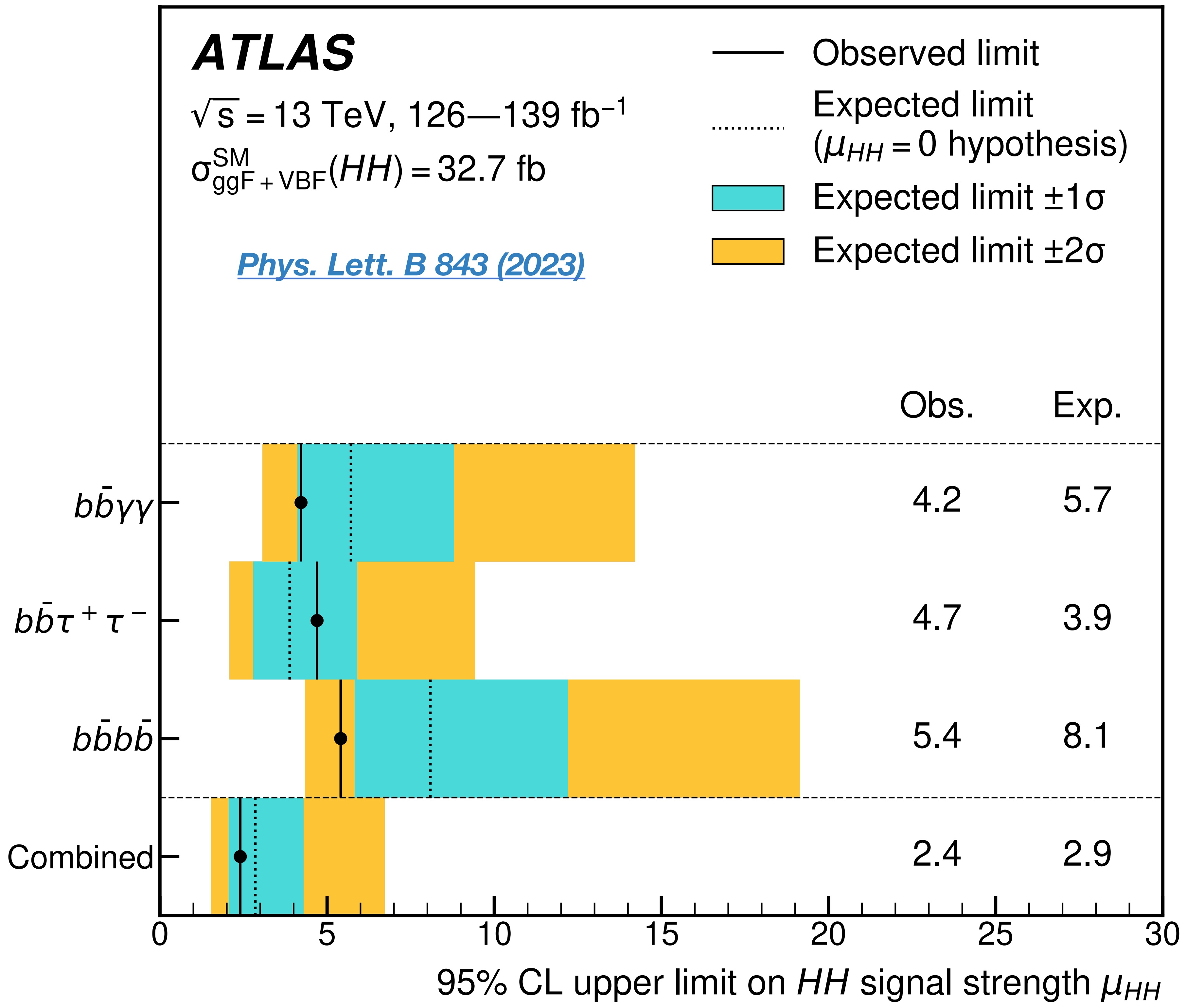
The leading 3 channels ($b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$) are very close by with expected limits around ~ 5 x SM prediction. The global combination leads then to a limit **~ 2.5-3 x SM**.

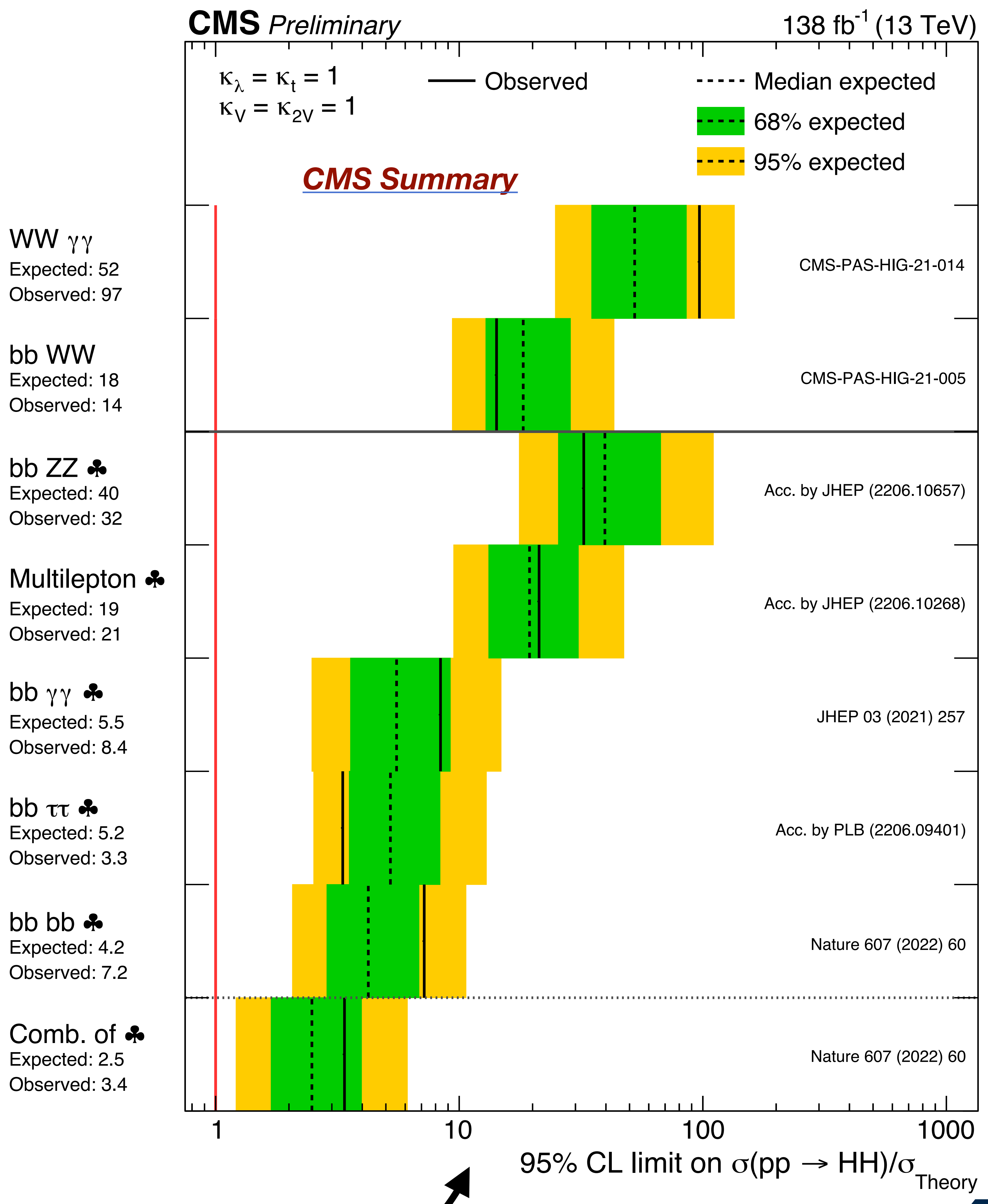
- ATLAS hasn't published a combination with their latest $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ results;
- CMS is showing a combination between their resolved and boosted analyses for the $b\bar{b}b\bar{b}$ results.

This limit is dominated by the ggF, but some analysis have also shared specific VBF limits:

Obs.	4b	bbγγ	bbττ
ATLAS	130	96	94
CMS	226*	225	124

** Only the resolved analysis is considered*



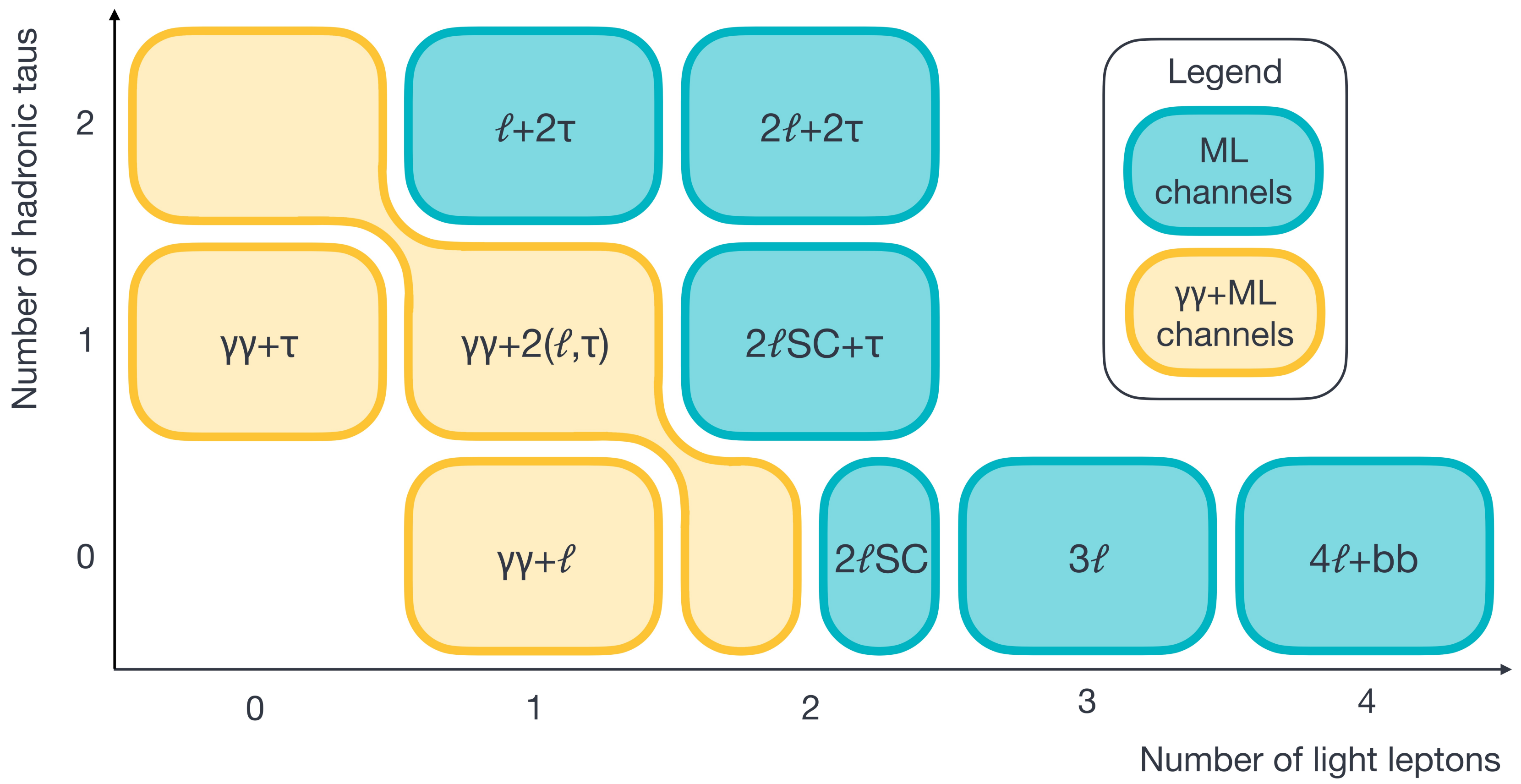


log scale

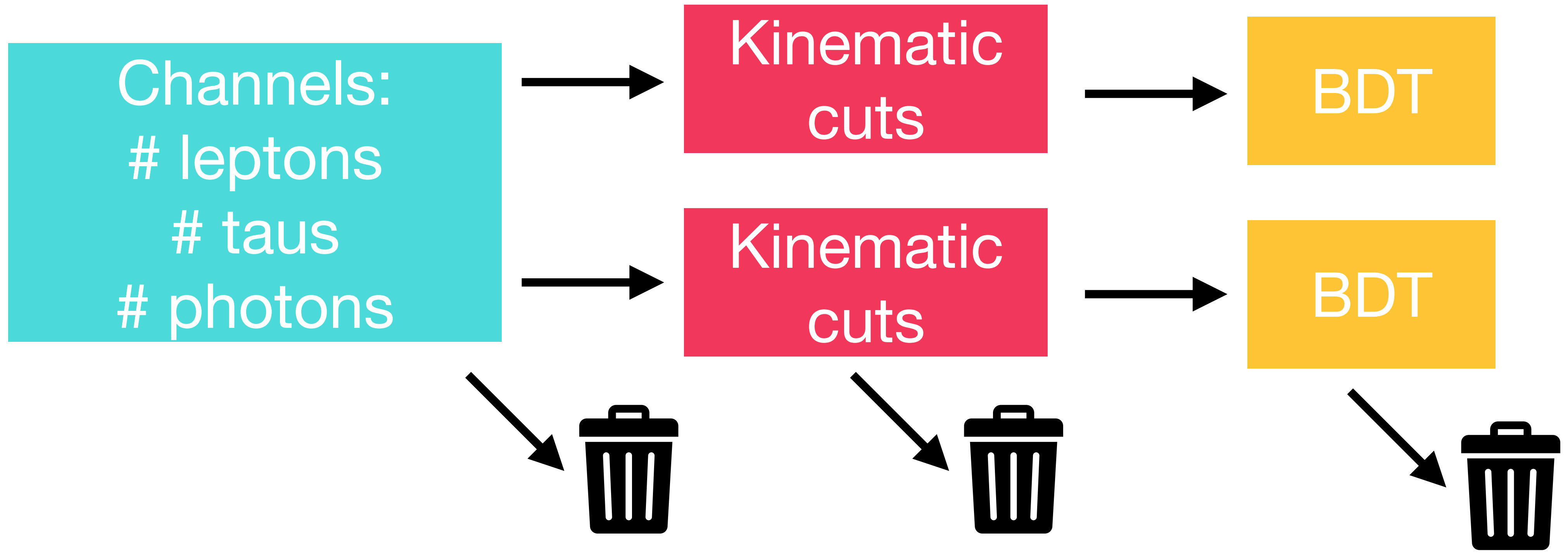
NEW ATLAS results: HH ML

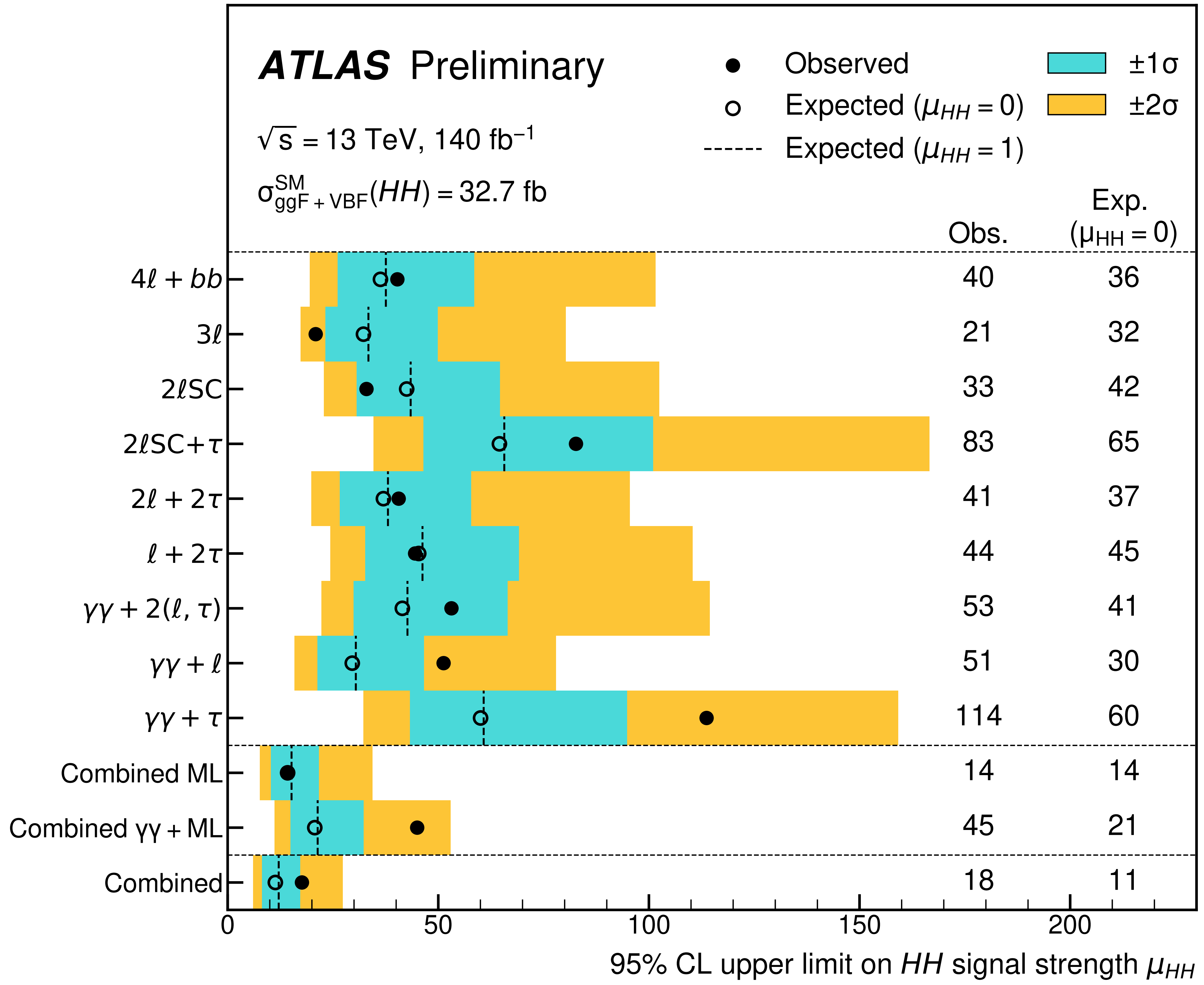
For the first time, ATLAS is analysing data in with a **holistic way** considering all the $H \to WW, ZZ, \tau\tau$ lepton decay modes, in addition with $H \to \gamma\gamma$. No b-jets are expected, except for the $HH \to b\bar{b}ZZ$ channel.

ATLAS-CONF-2024-005



A set of kinematic and BDT cuts are set in each channel, except in the $\gamma\gamma + 2(l, \tau)$ one where the number of preselected events is too low.





From CMS (no $\gamma\gamma$ channel)

Combined

$\mu < 21.3$ (19.4 exp)

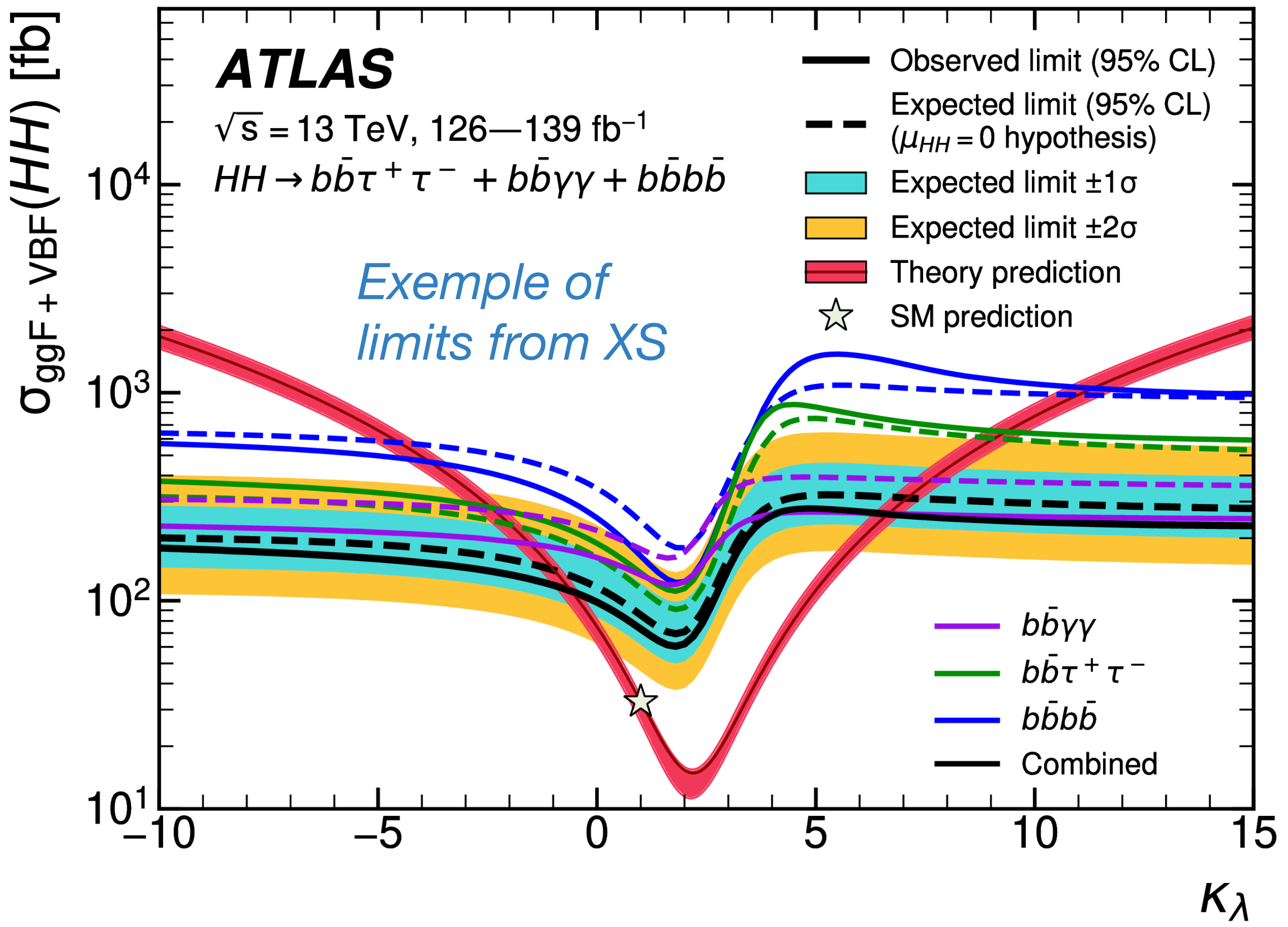
JHEP 07 (2023) 095

The result is interpreted in terms of limit on the signal strength. No single channel is dominating, and the combination yields an **observed (expected) limit of 18 (11)**.

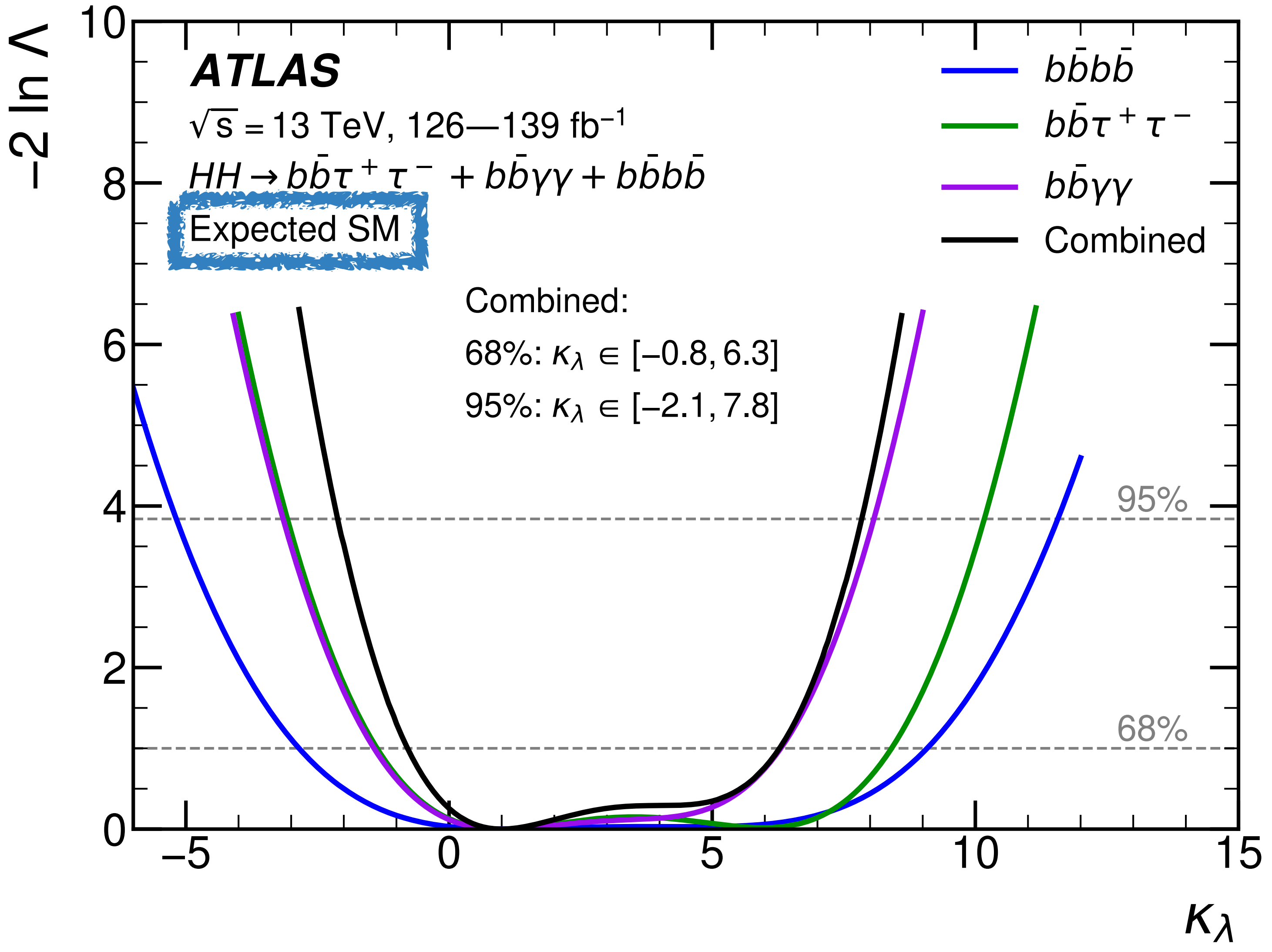
Interpretation in κ framework: κ_λ

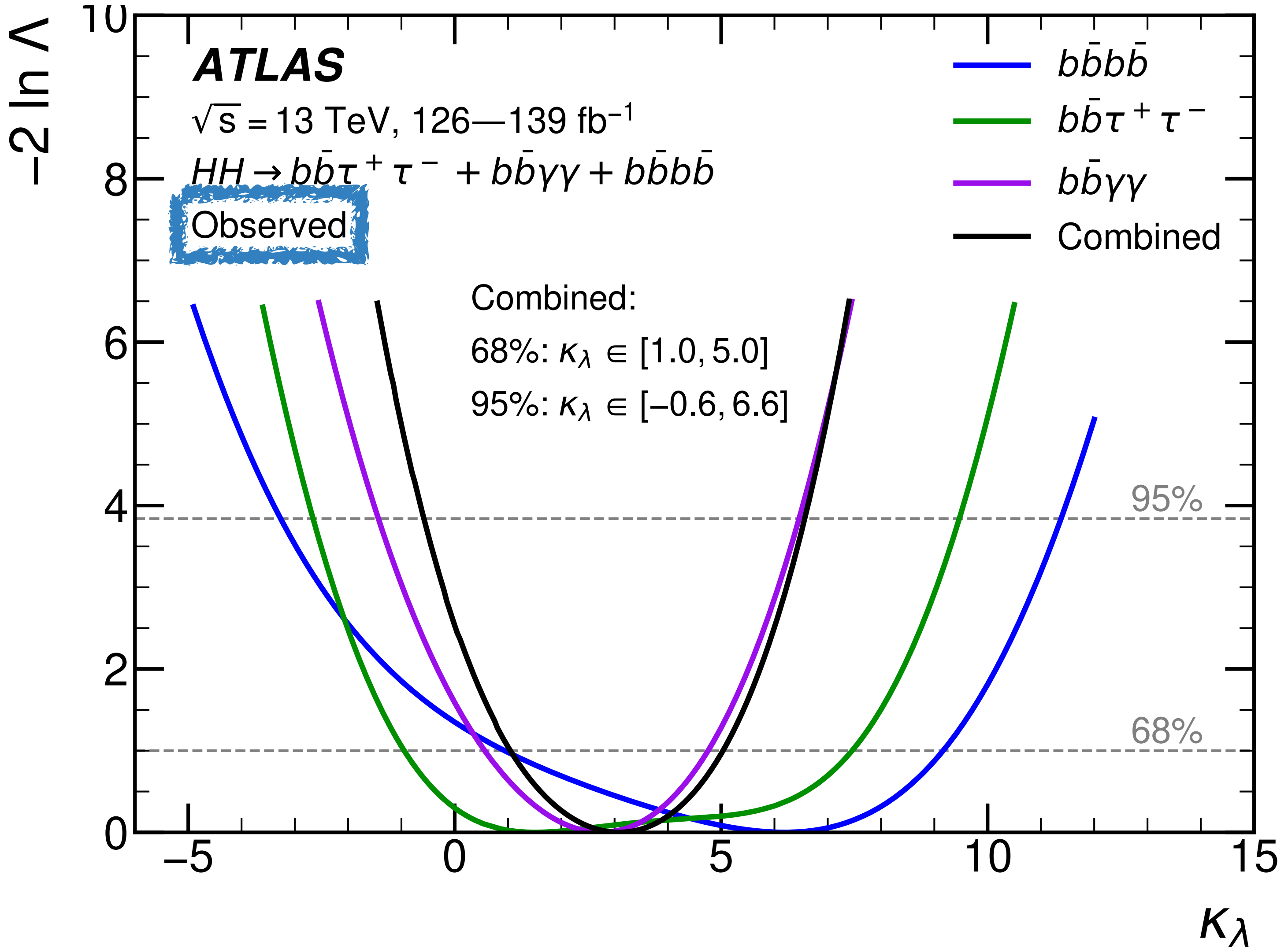
Both collaborations are gradually moving from deriving limits from the cross-section, to providing the likelihood limits.

- **ATLAS** hasn't published a combination with their latest $HH \to b\bar{b}\gamma\gamma$ and $HH \to b\bar{b}\tau\tau$ results;
- **CMS** is showing on the same plot the 95% CL from cross section limit, and the best fit value from likelihood with 1σ error.

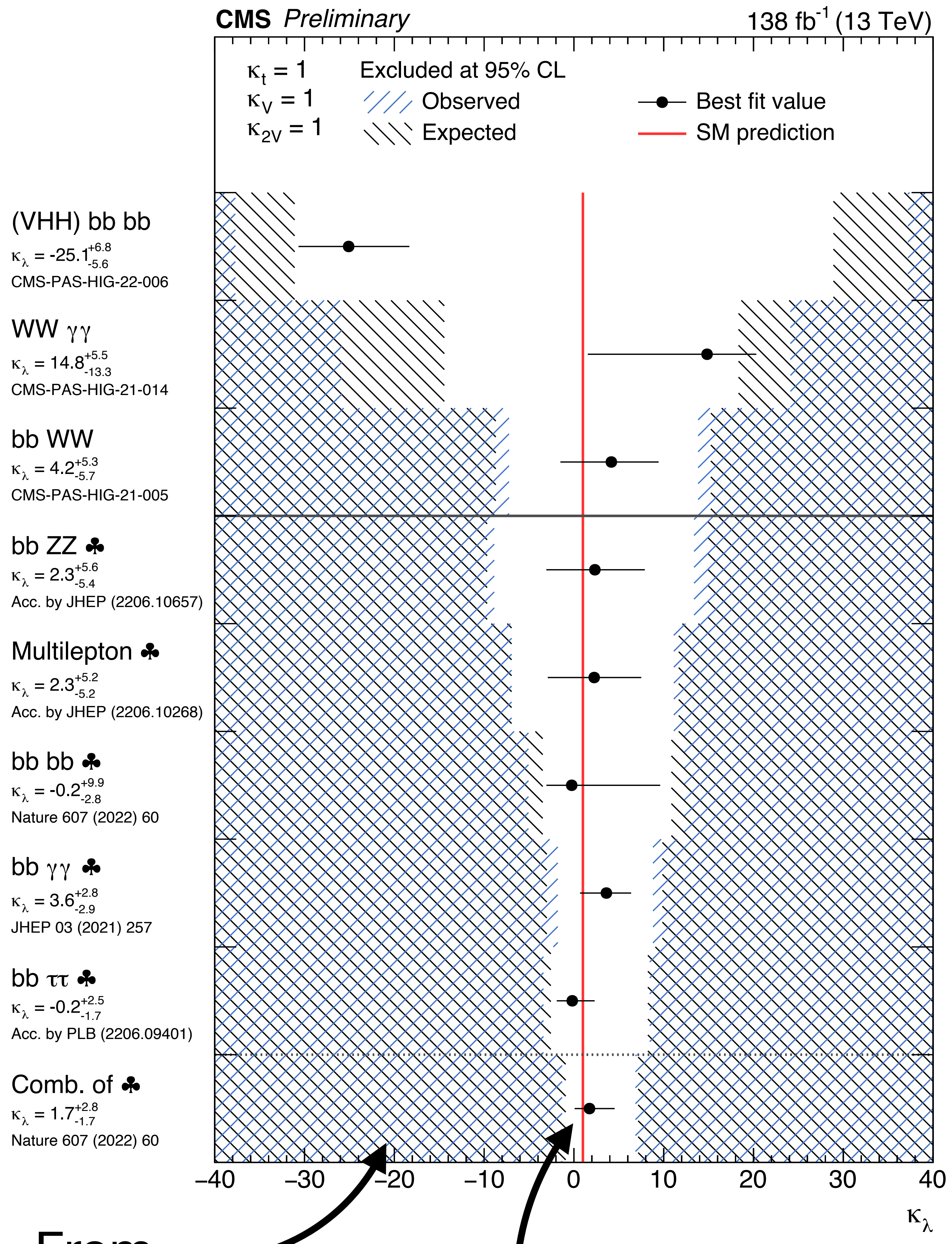


Phys. Lett. B 843 (2023)





CMS Summary



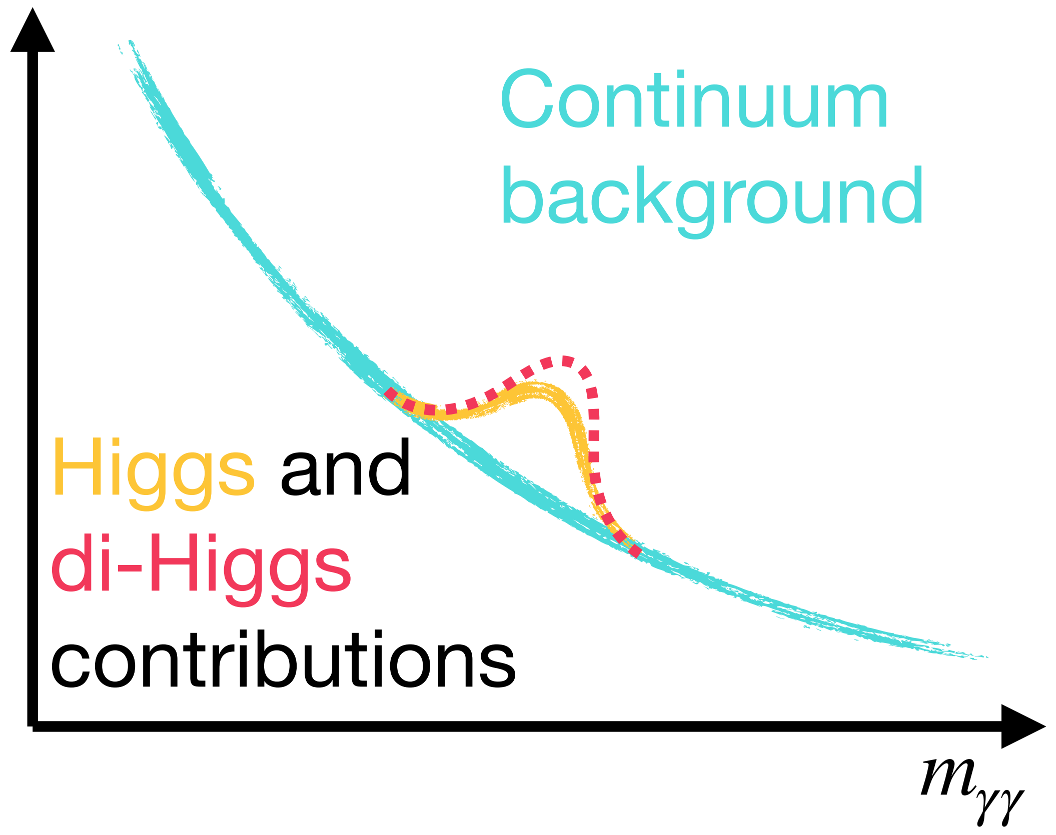
From XS limit

From likelihood result with 1σ error

NEW CMS results: HH→$\gamma\gamma\tau\tau$

Despite the very low branching ratio, this channel benefit from the very good di-photon mass resolution and the clean lepton decay from taus.

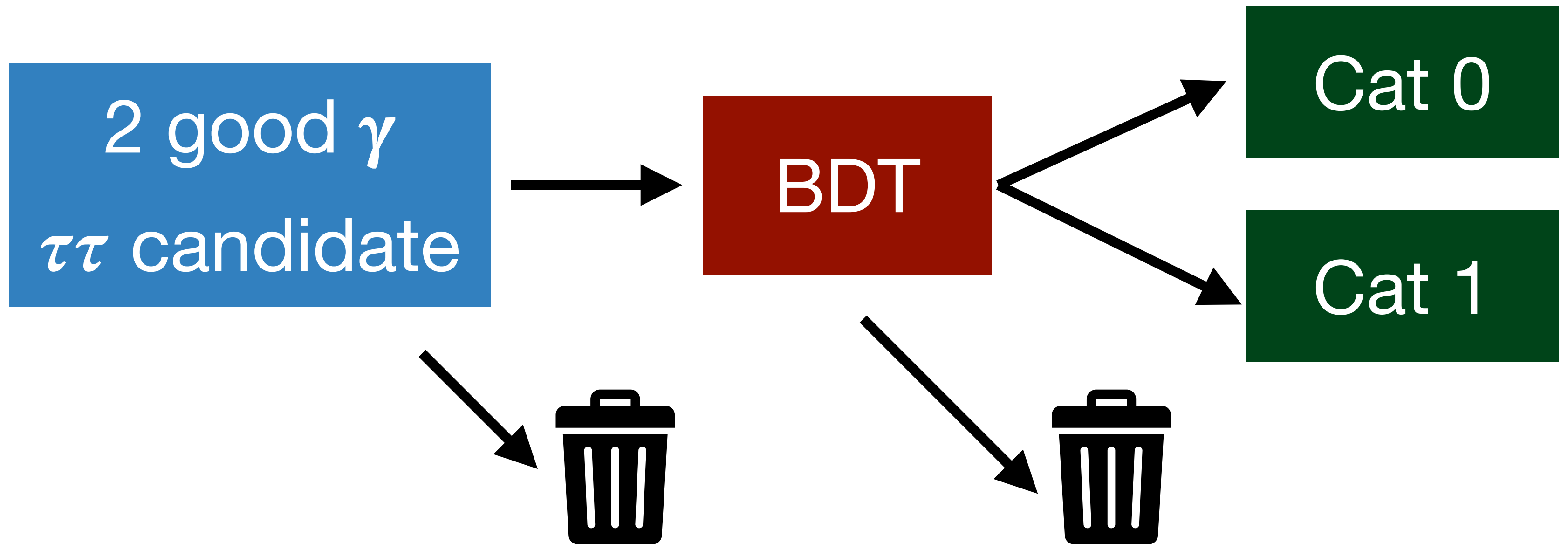
CMS-HIGG-22-012



Thus these type of search are exploiting the $\gamma\gamma$ mass as a discriminant variable. All the processes are parametrised with functional forms.

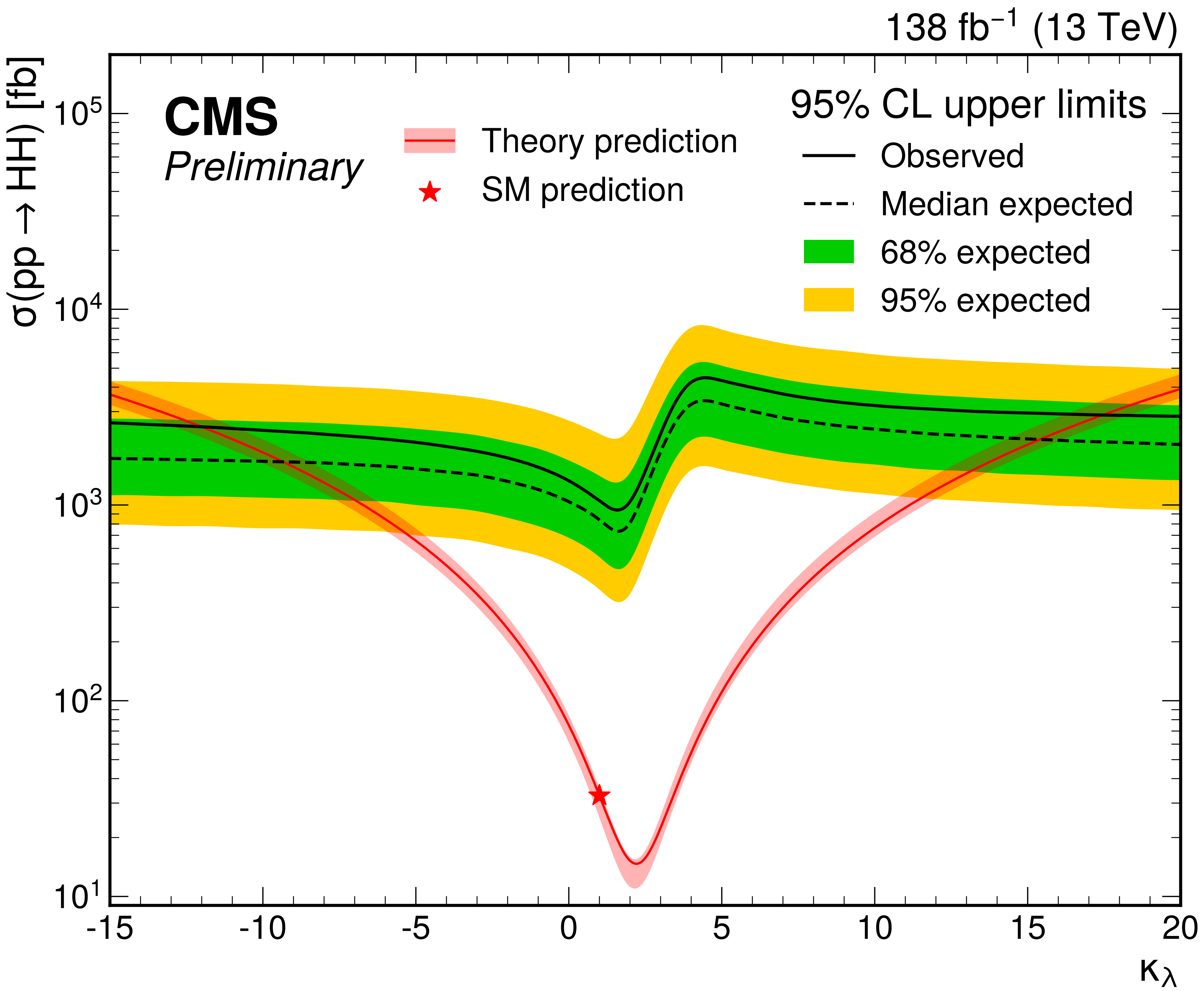
The selection is performed in 2 phases:

- Finding 2 good photons and a di-tau candidate (from leptons and hadronic taus);
- A **BDT** is used to further reject backgrounds: 2 categories are defined to maximise the XS expected limit.



The result is interpreted in terms of limit on the Cross section, with an **observed (expected) limit of 33 (26)** times the SM.

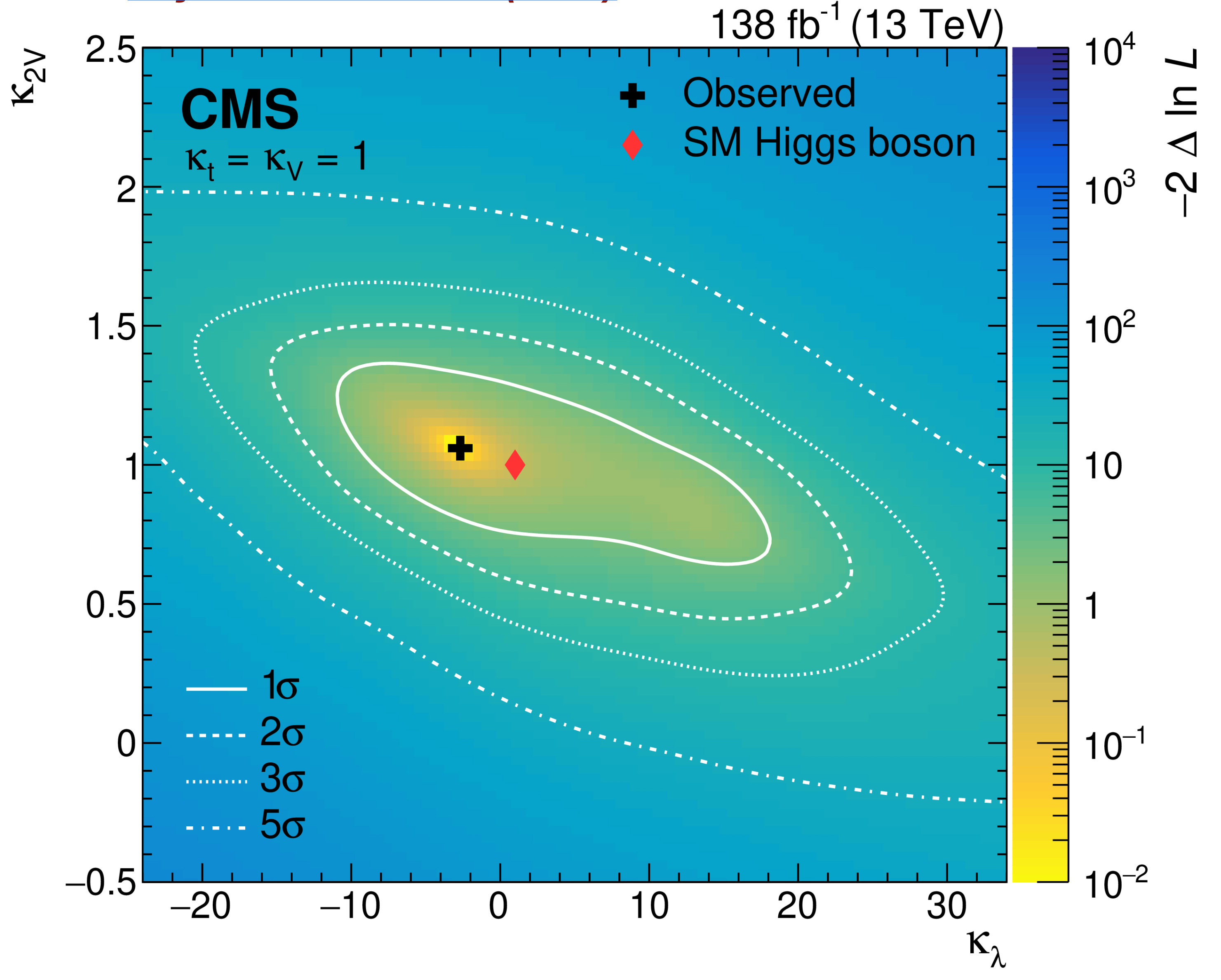
The observed (expected) constraint on κ_λ rejects values outside of the interval **[–12, 17] ([–9.4, 15])**.



Interpretation in κ framework: κ_{2V}

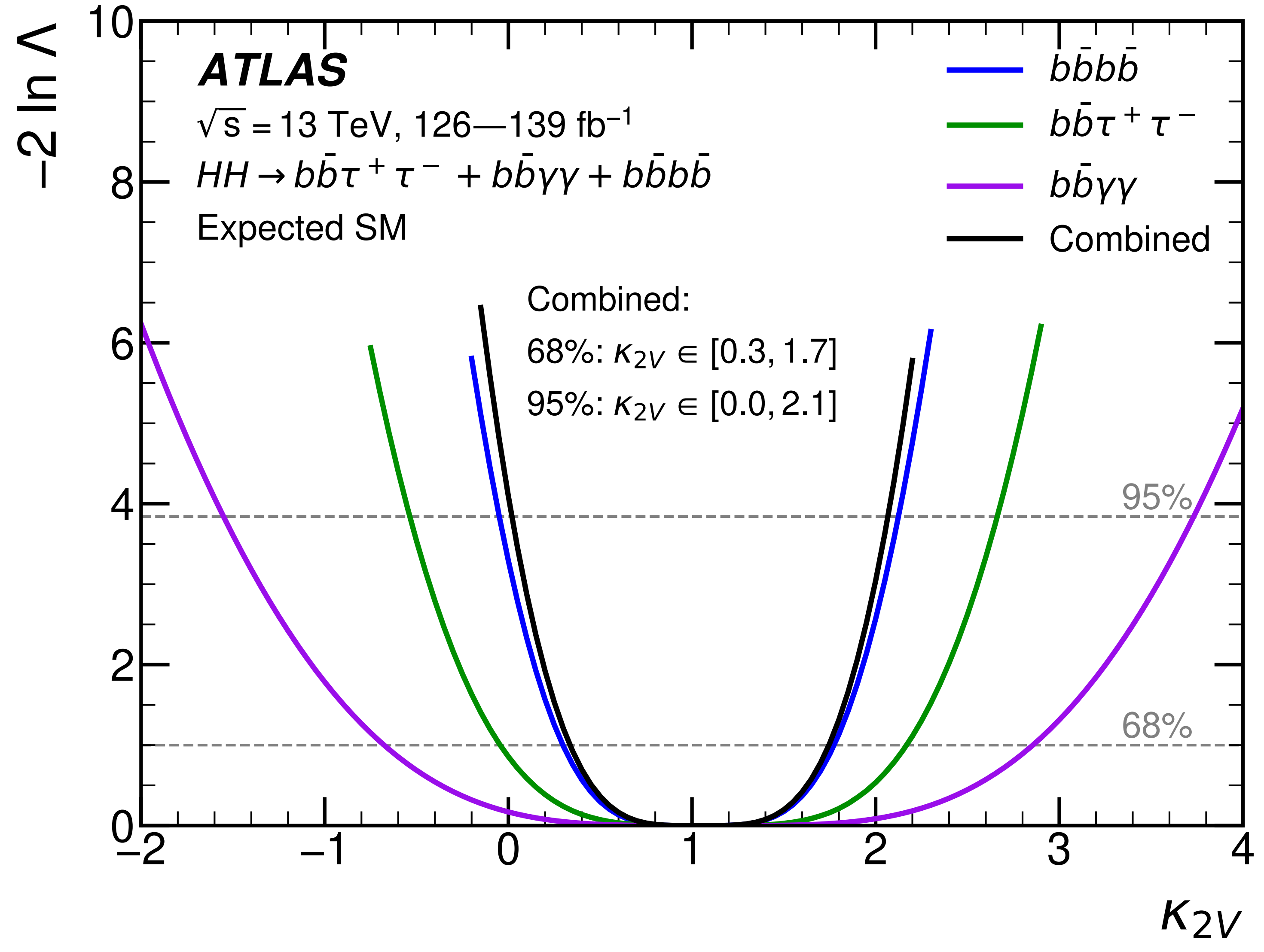
The κ_{2V} parameter is well constrained by the $HH \to b\bar{b}b\bar{b}$ boosted analysis from **CMS**, excluding $\kappa_{2V} = 0$, with a significance of **6.3 standard deviations**.

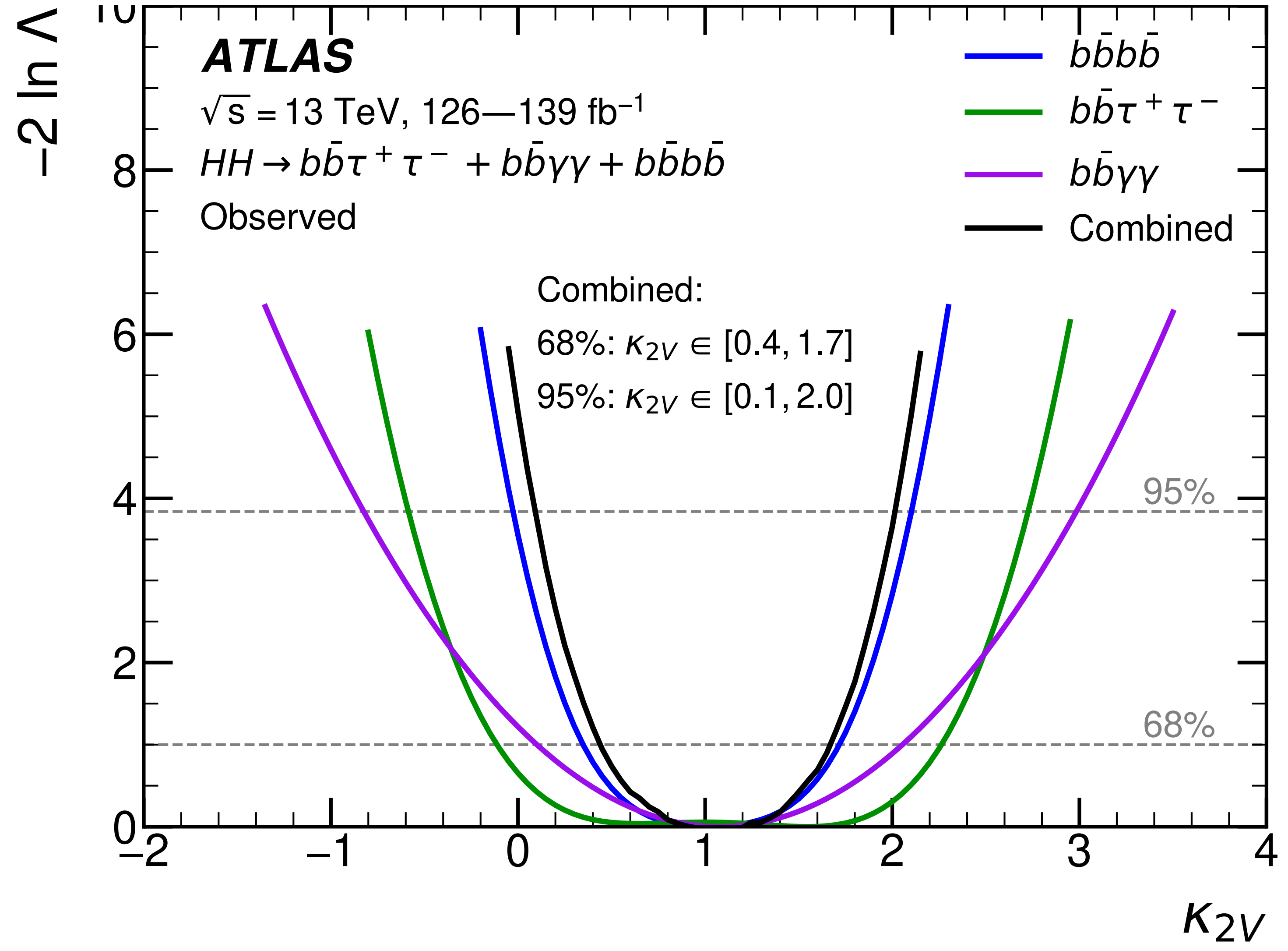
Phys. Rev. Lett. 131 (2023)



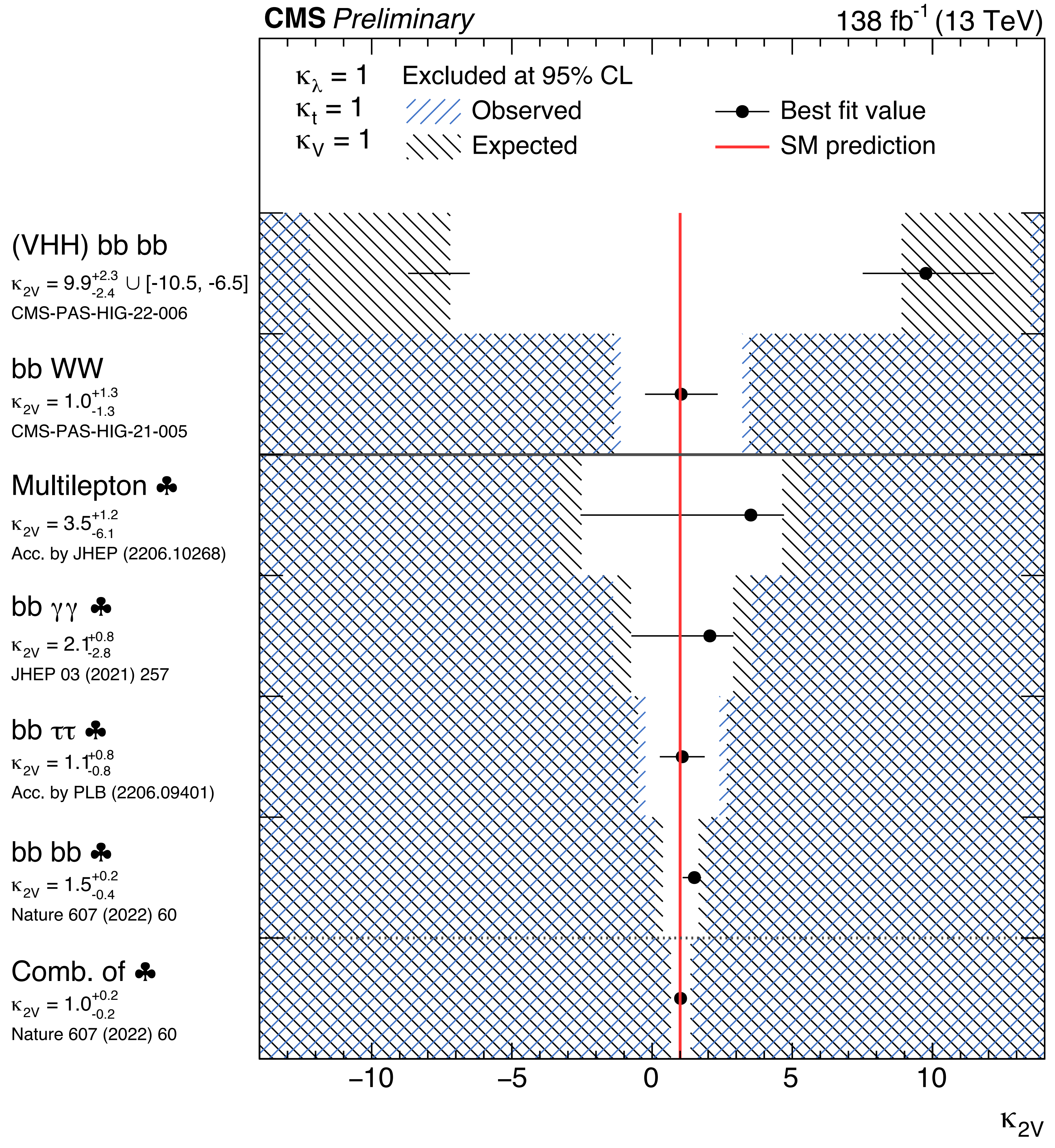
Both collaborations have also published other 2-D plots, including the limit with κ_t .

Phys. Lett. B 843 (2023)

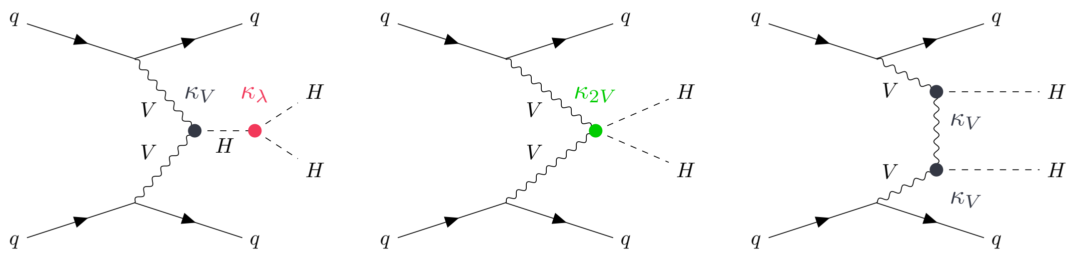




CMS Summary



NEW ATLAS results: VBF 4b

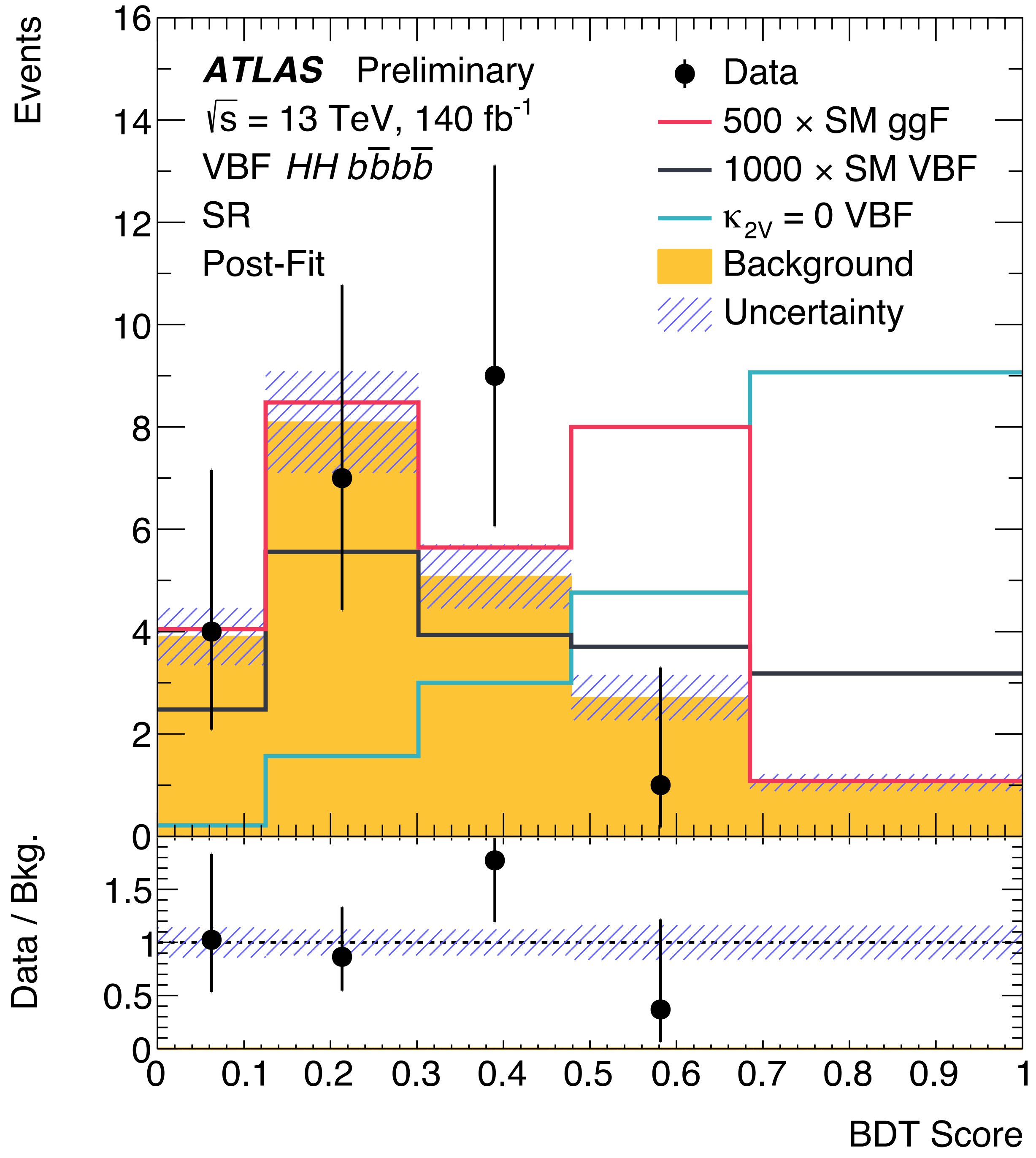


ATLAS-CONF-2024-003

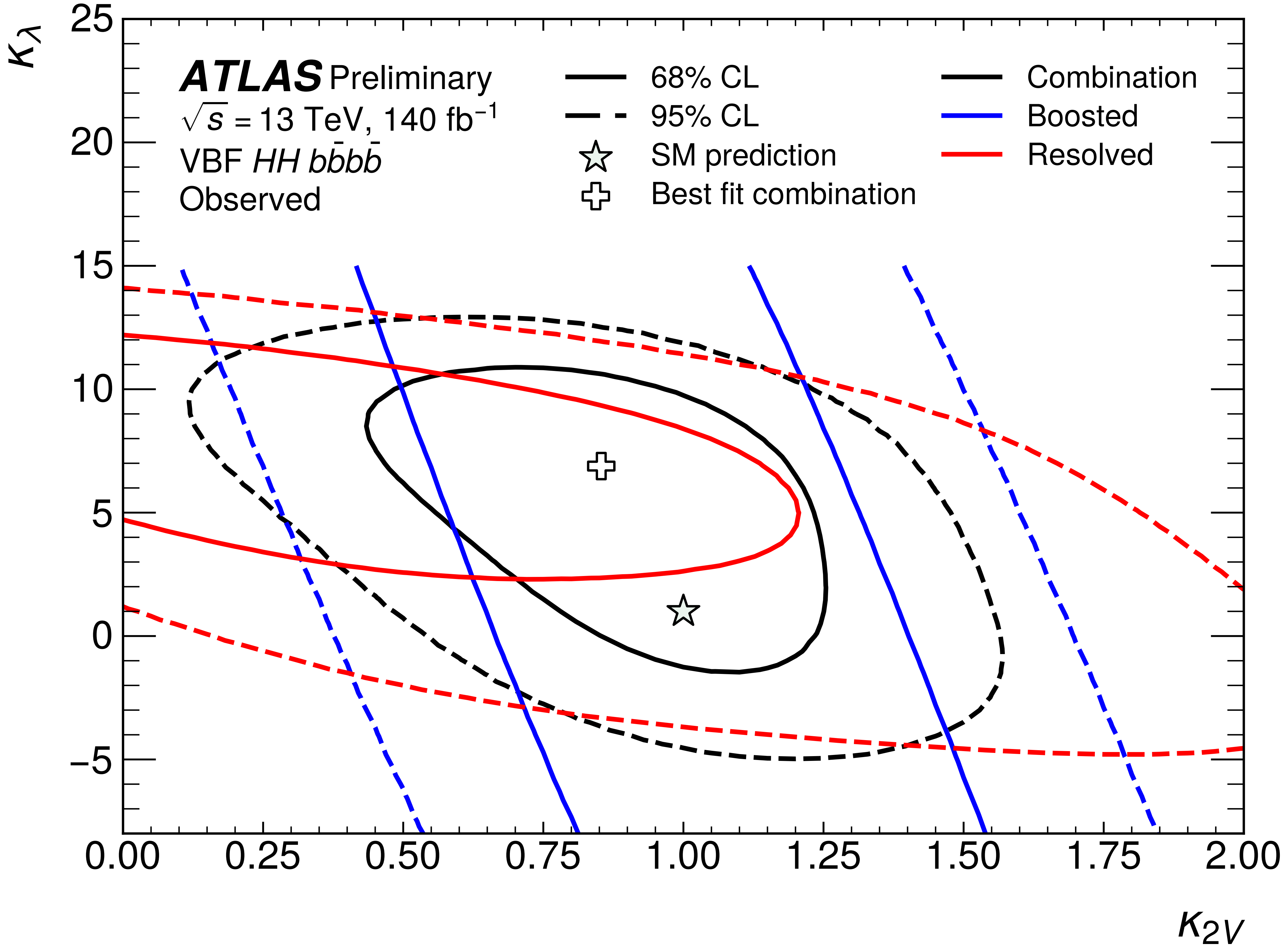
This new analysis is focussing on VBF production of $HH \to b\bar{b}b\bar{b}$ in the boosted regime where the Higgs decay products are reconstructed in single large radius jets, using dedicated $X \to b\bar{b}$ tagger.

The analysis is also combined with the previous non-resonant analysis, using resolved topology (Phys. Rev. D 108 (2023)).

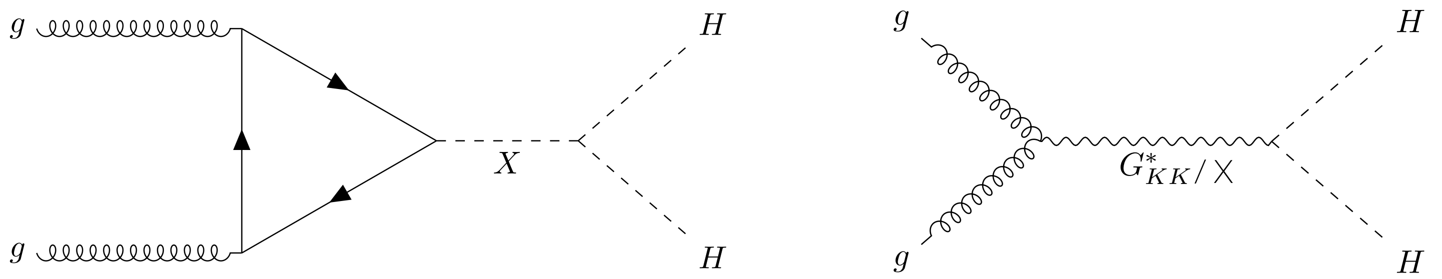
It uses a combination of kinematic cuts on the reconstructed Higgses masses and a BDT trained to select events with $\kappa_{2V} = 0$.



- The constraints on κ_{2V} are greatly improved, with an exclusion of $\kappa_{2V} = 0$ with a observed (expected) significance of **3.4**σ (2.9σ).
- No significant gain is observed on the XS limit or κ_{λ}.



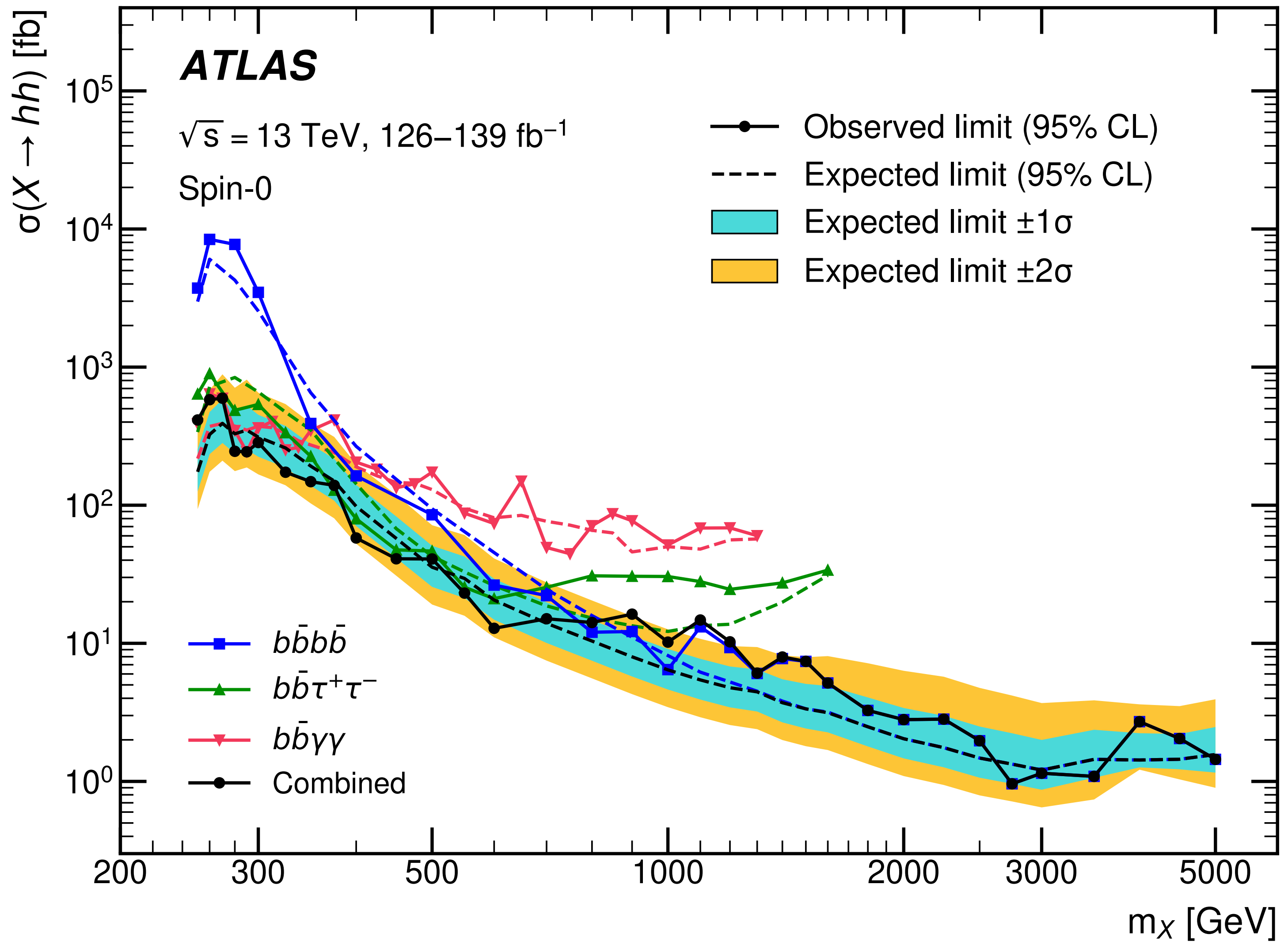
Limits on BSM X→HH

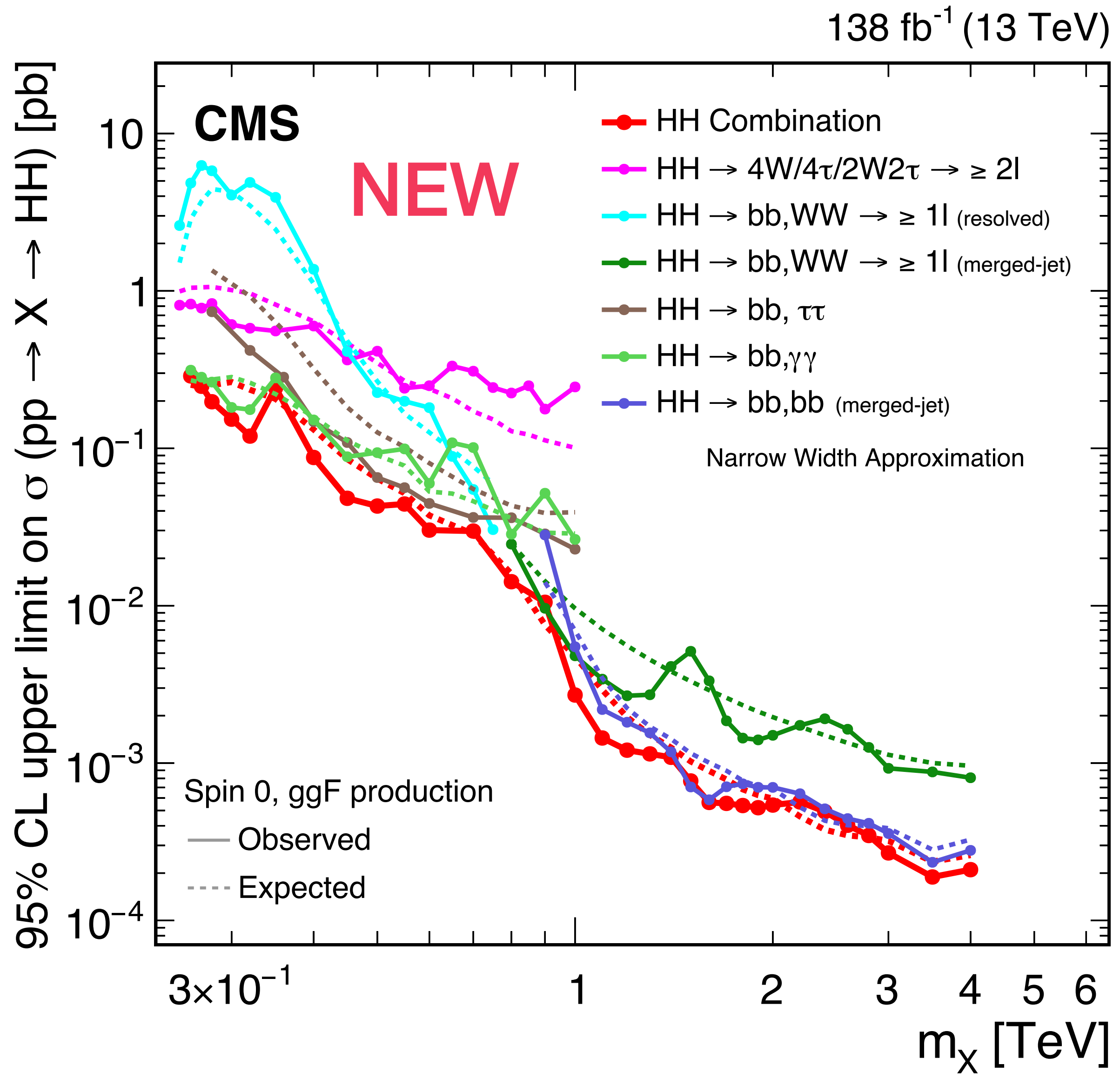


The different searches are often complementary for different mass ranges. They are presented in a model agnostic way and often reinterpreted in the 2HDM and MSSM models.

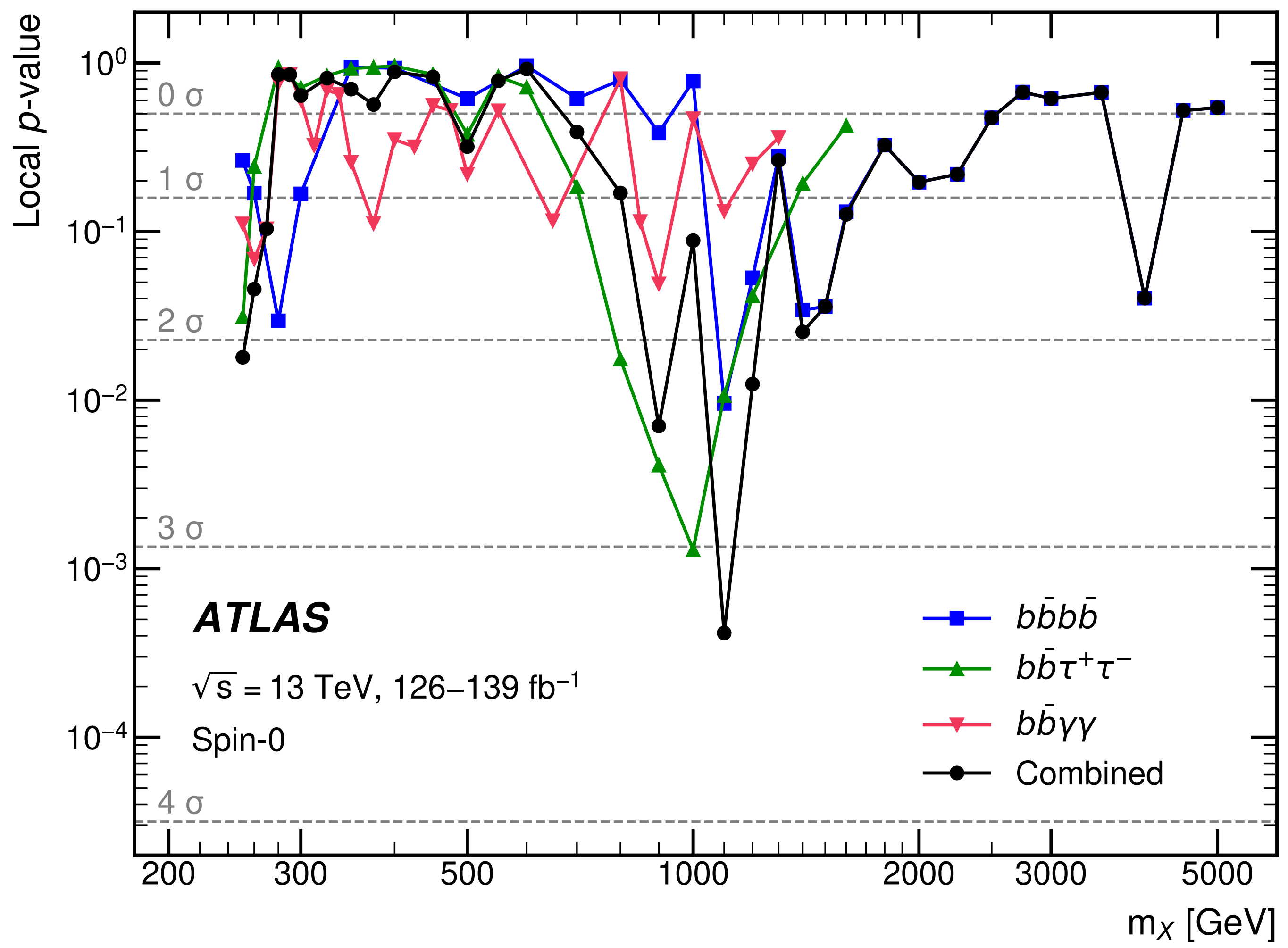
- ATLAS also found a small excess with combined local (global) significance of 3.2 σ (2.1 σ) at 1.1 TeV.
- CMS released **new** combinaison, setting stringer limits bellow 320 GeV and above 1 TeV.

arXiv:2311.15956 (Sub. to: Phys. Rev. Lett.)

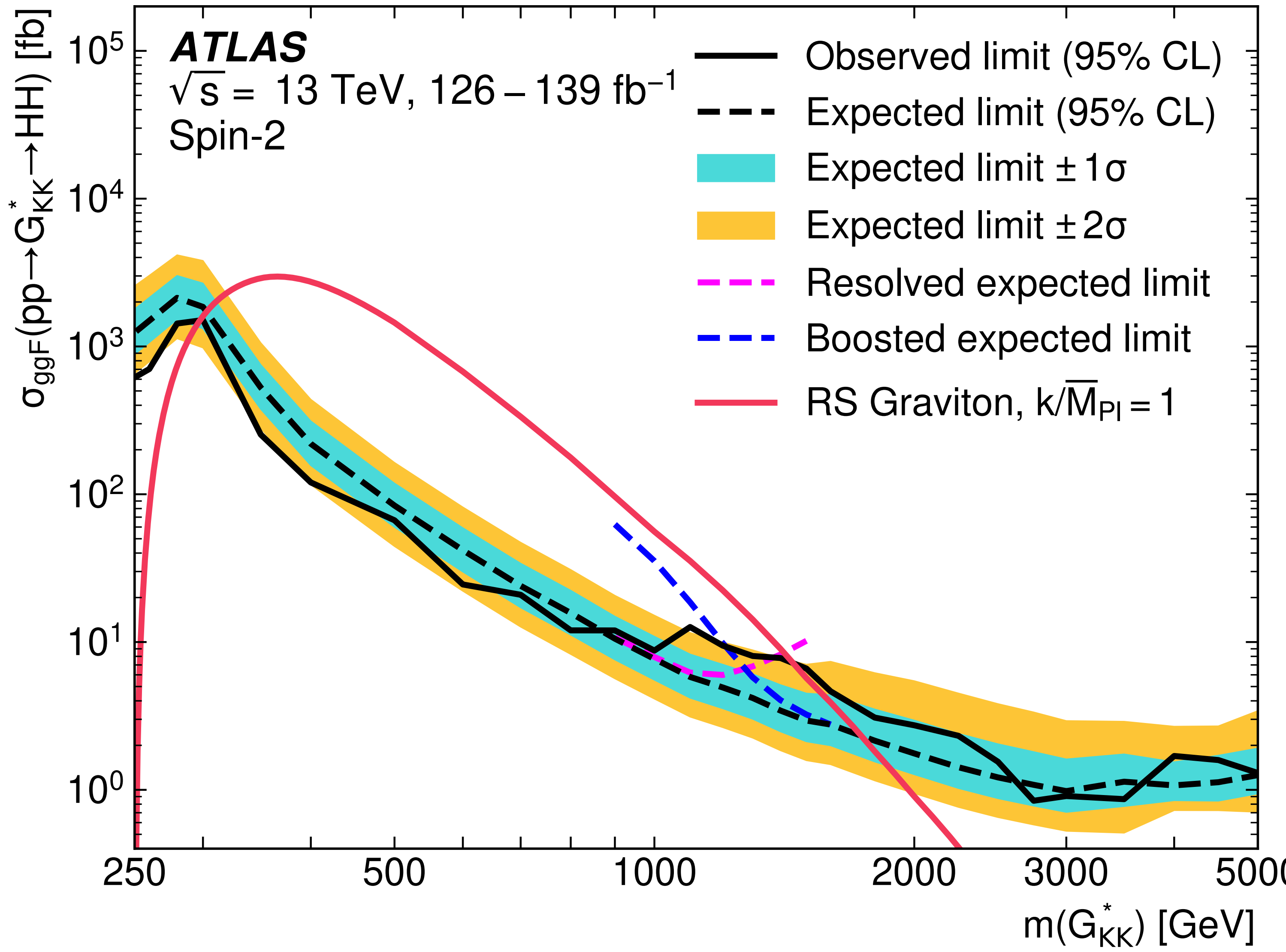


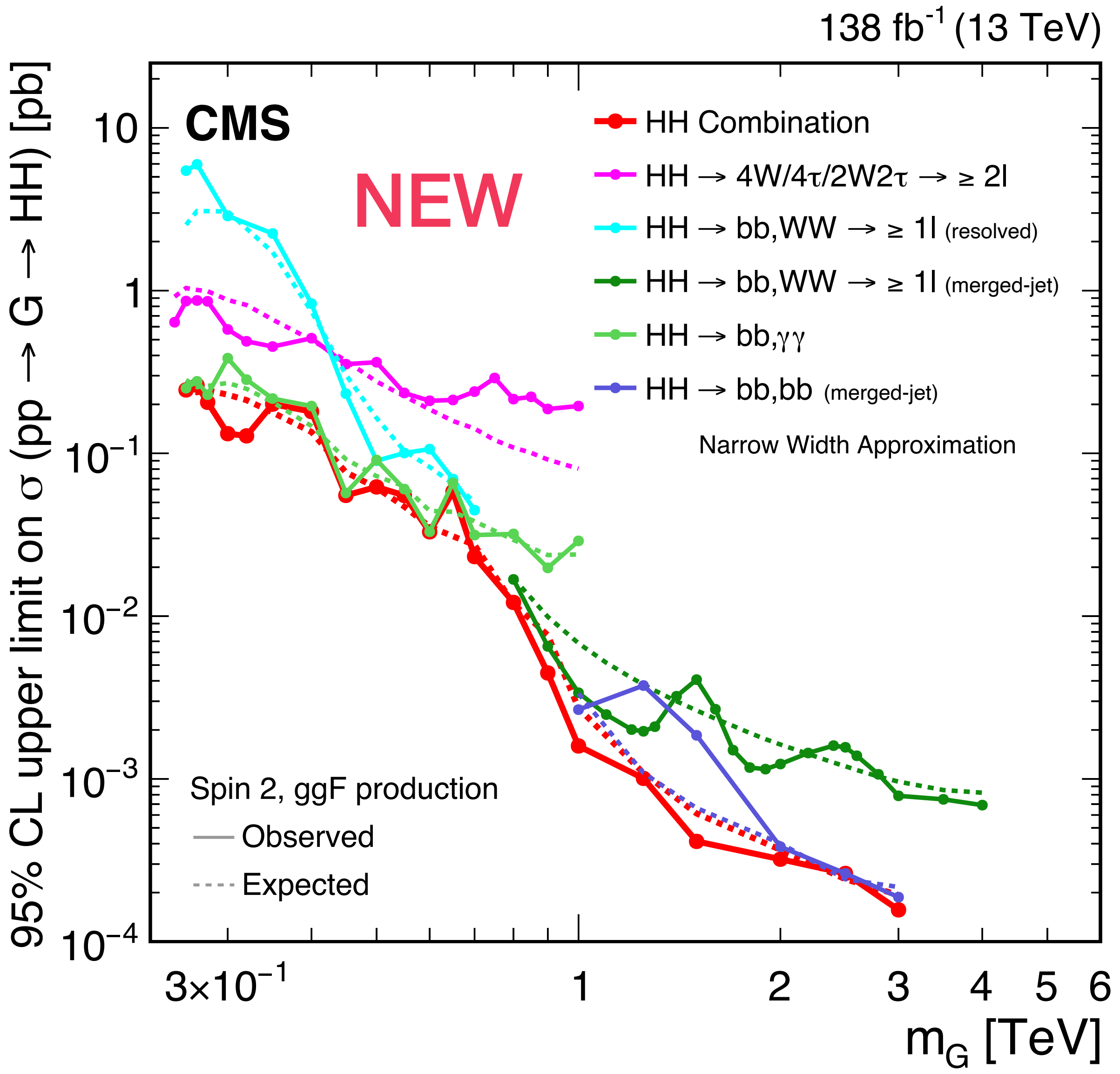


arXiv:2311.15956 (Sub. to: Phys. Rev. Lett.)

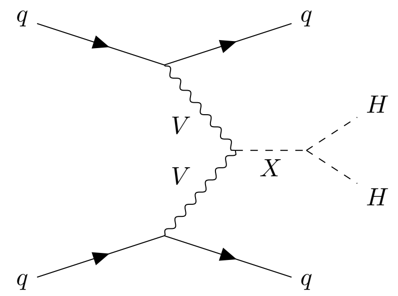


Phys. Rev. D 105 (2022)





NEW ATLAS results: VBF 4b

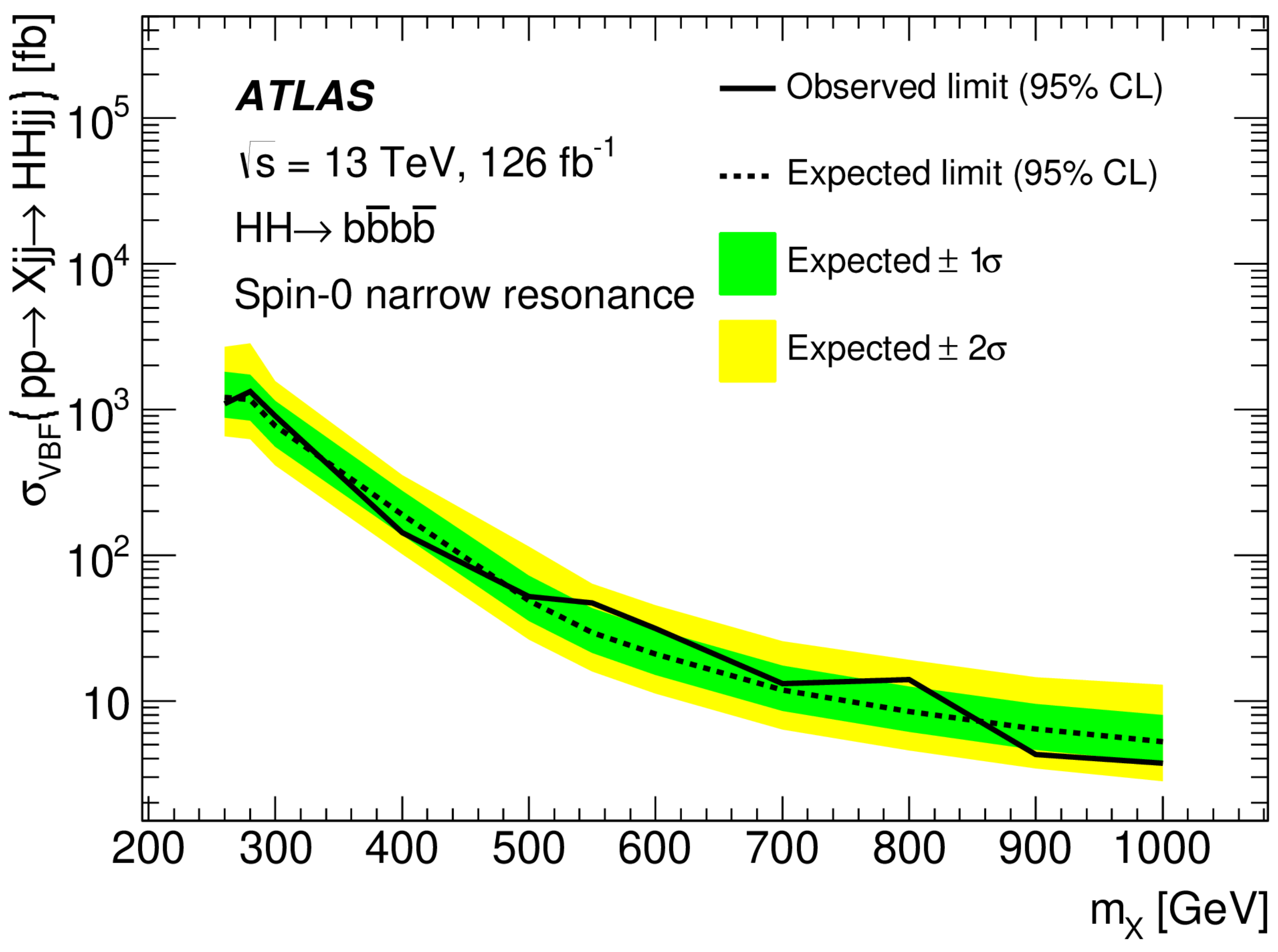


ATLAS-CONF-2024-003

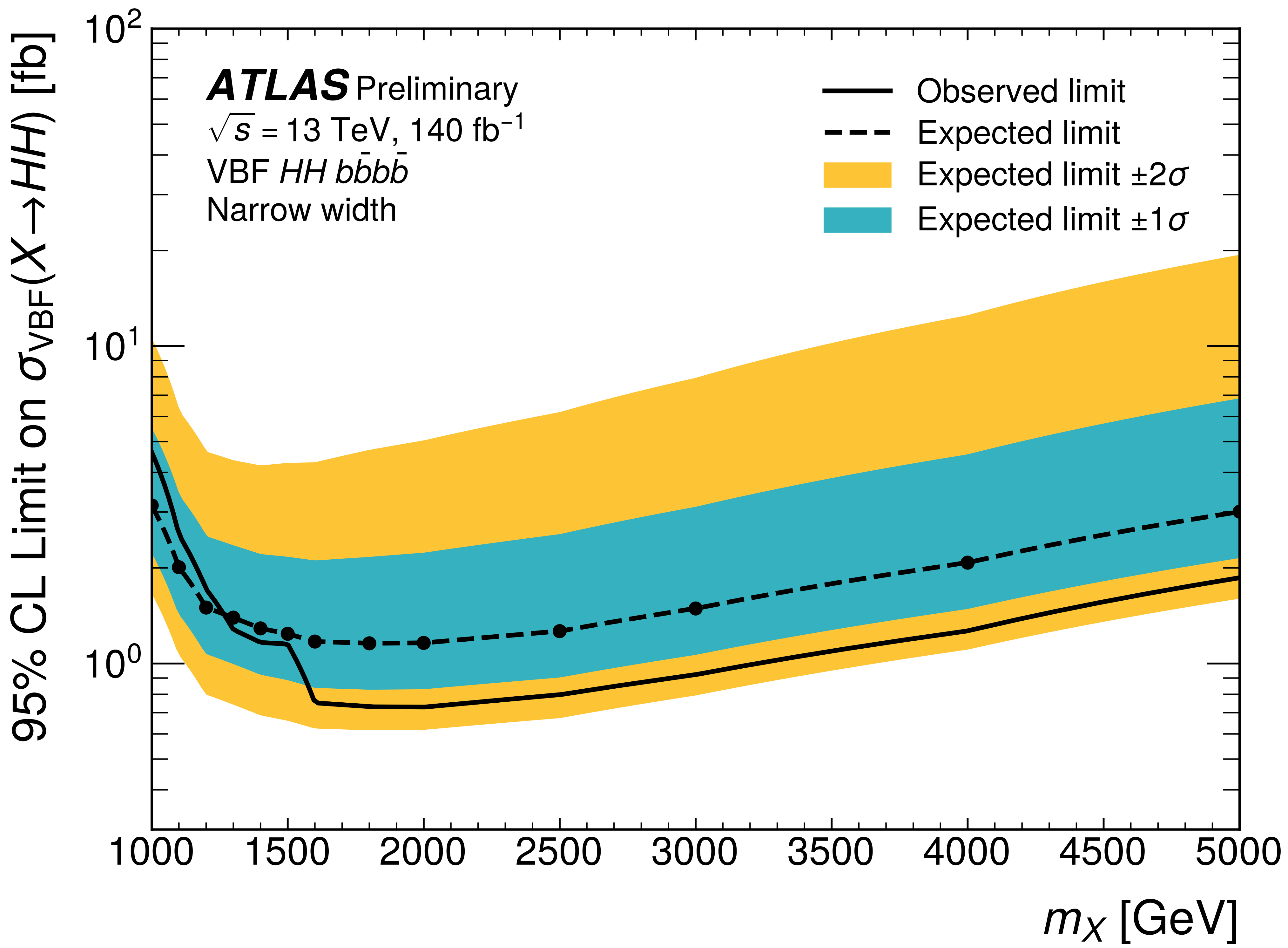
The same **VBF analysis** of $HH \to b\bar{b}b\bar{b}$ in the **boosted regime** presented before is also providing limits to resonant VBF models considering masses > 1 TeV.

On top of the same combination of **kinematic cuts** on the reconstructed Higgses masses as for the κ_{2V} result, a **parametrised BDT** is trained on 13 different resonant mass hypothesis.

This supplement the previous resonant analysis, using resolved topology (JHEP 07 (2020) 108).



- This analysis set limits on a mass range never explored before;
- No significant excess observed, the tighter observed limits after 1.6 TeV are due to lack of data.
- Interpretations are provided in the narrow and broad ($\Gamma_X = 0.2 m_X$) width approximation.



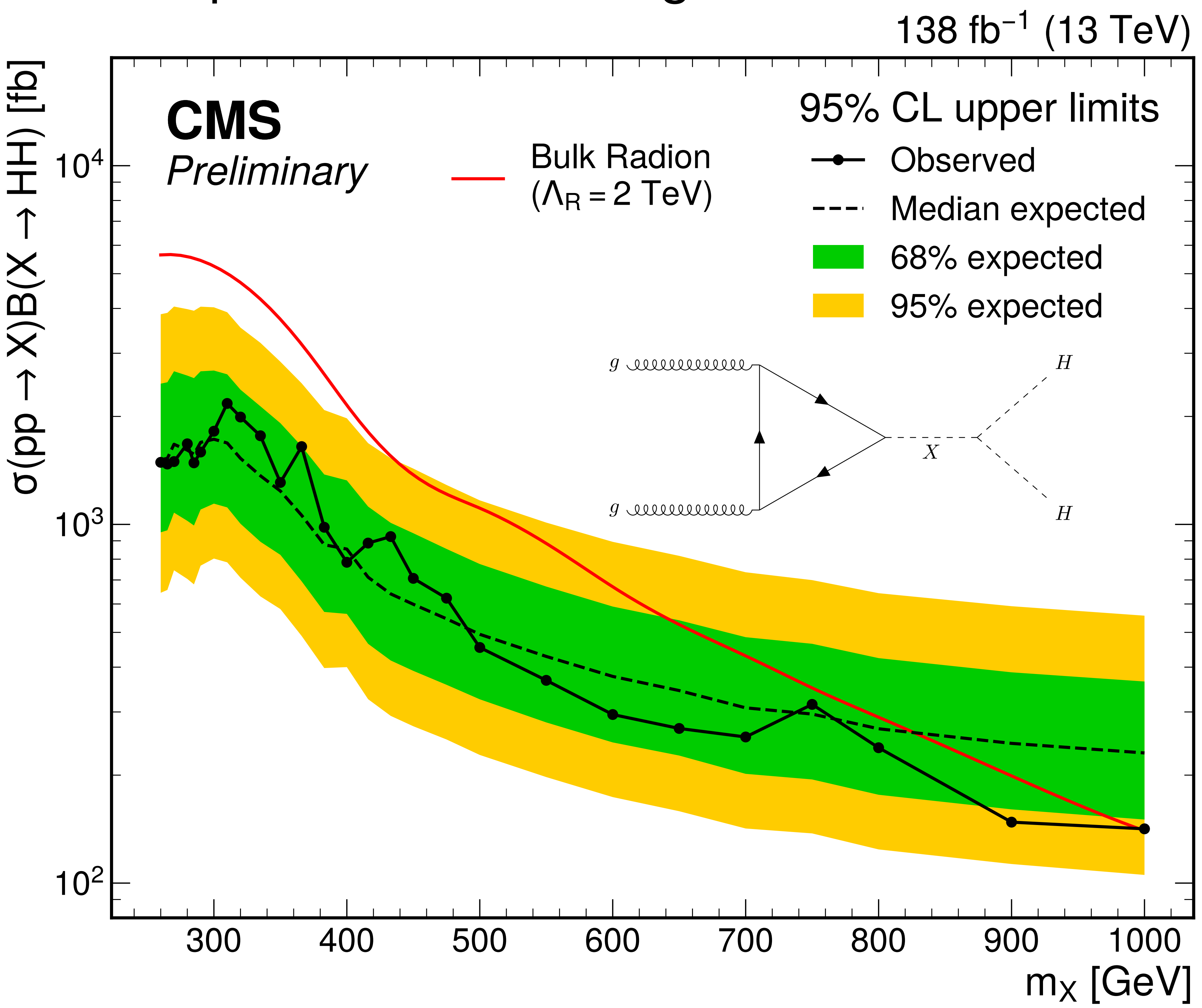
NEW CMS results: X→HH→$\gamma\gamma\tau\tau$

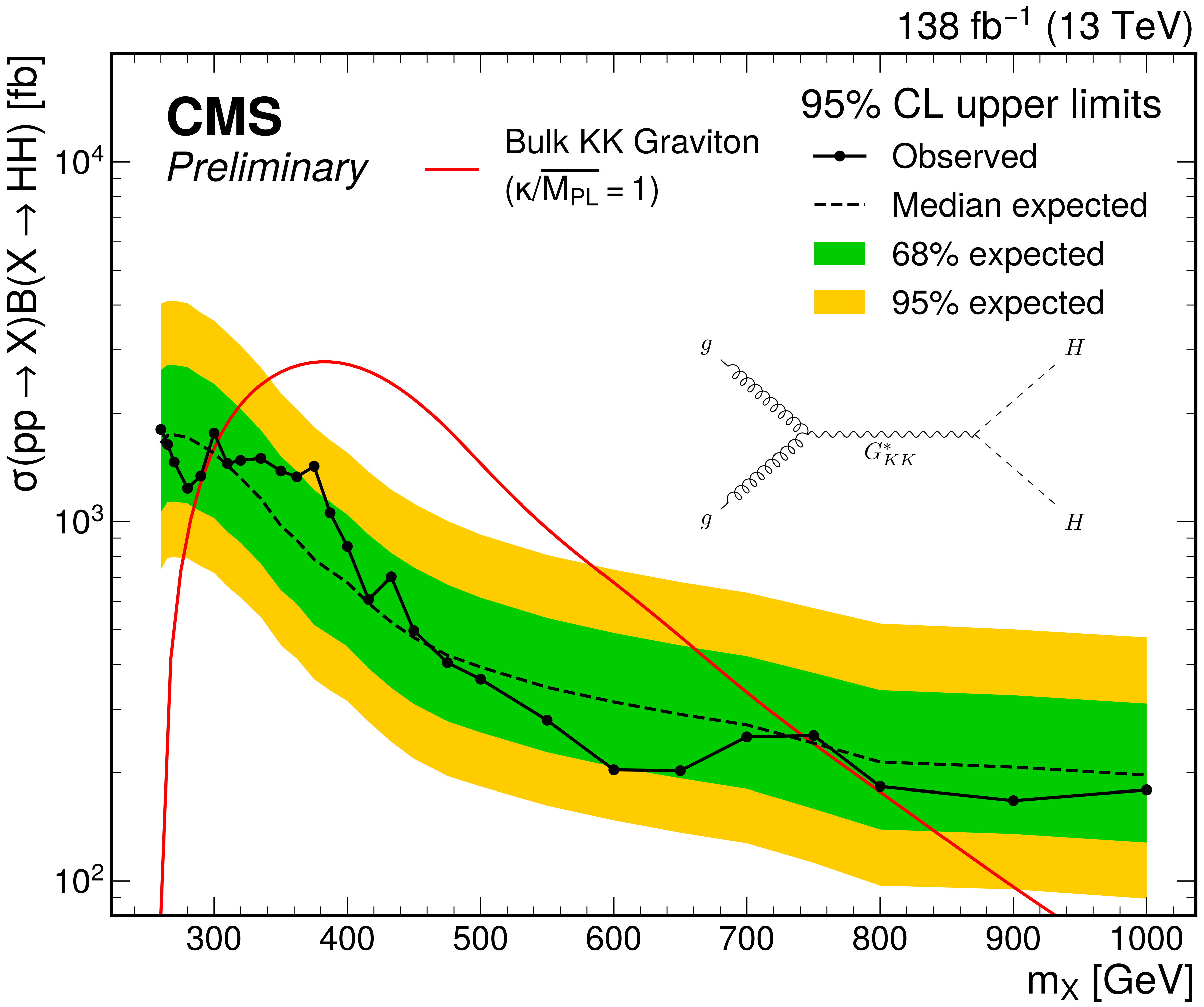
CMS-HIGG-22-012

A similar strategy as for the non resonant is chosen for these search:

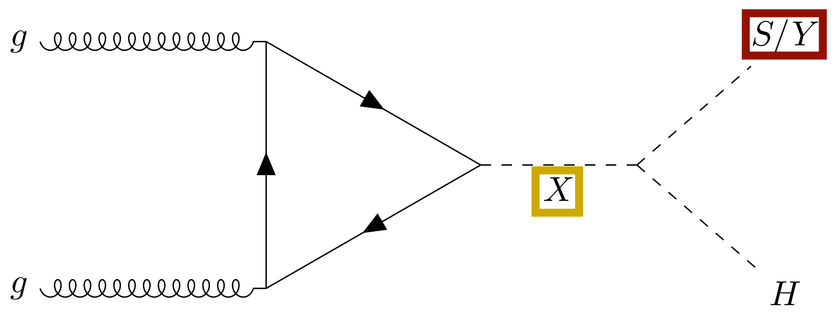
- Instead of a BDT, a **Parametrised Neural Network** is using the information on the mass of the new scalar(s):
  - The output is transformed to get a flat background distribution;
  - The categorisation is based on the expected number of background events, with a lower limit set at 10 events.
- The **signal and background modelling** are adapted to get a continuous description in between interpolation points.

No significant excesses beyond 1.7 σ are found in data and limits are set in the context of the Randall-Sundrum model for both spin-0 radion and spin-2 Kaluza-Klein graviton.





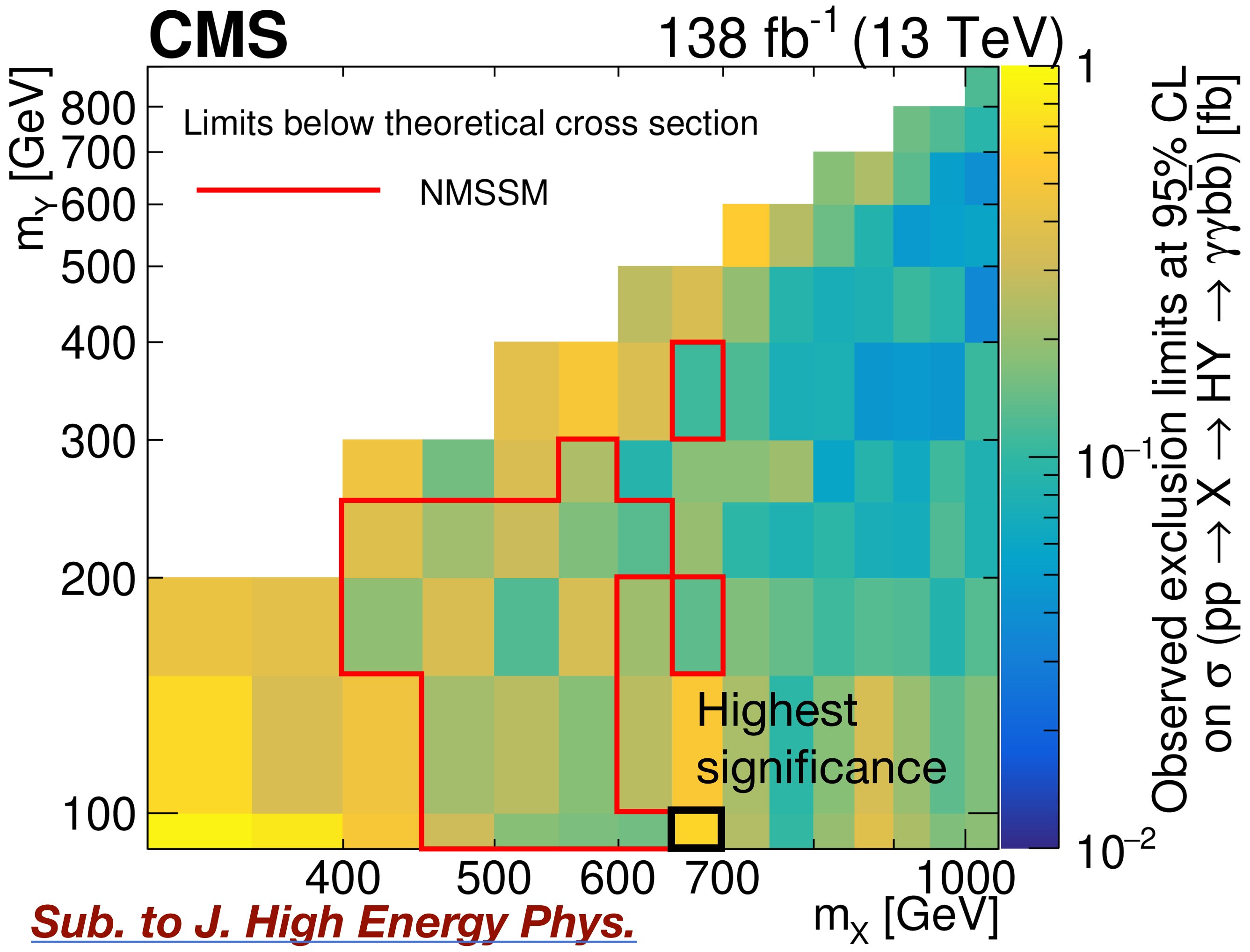
Summary of BSM (S/Y)H



CMS has been conducting X→HY searches for the main 3 channels, with no significant excess. The highest excess local (global) significance for $(m_X, m_{(S/Y)})$:

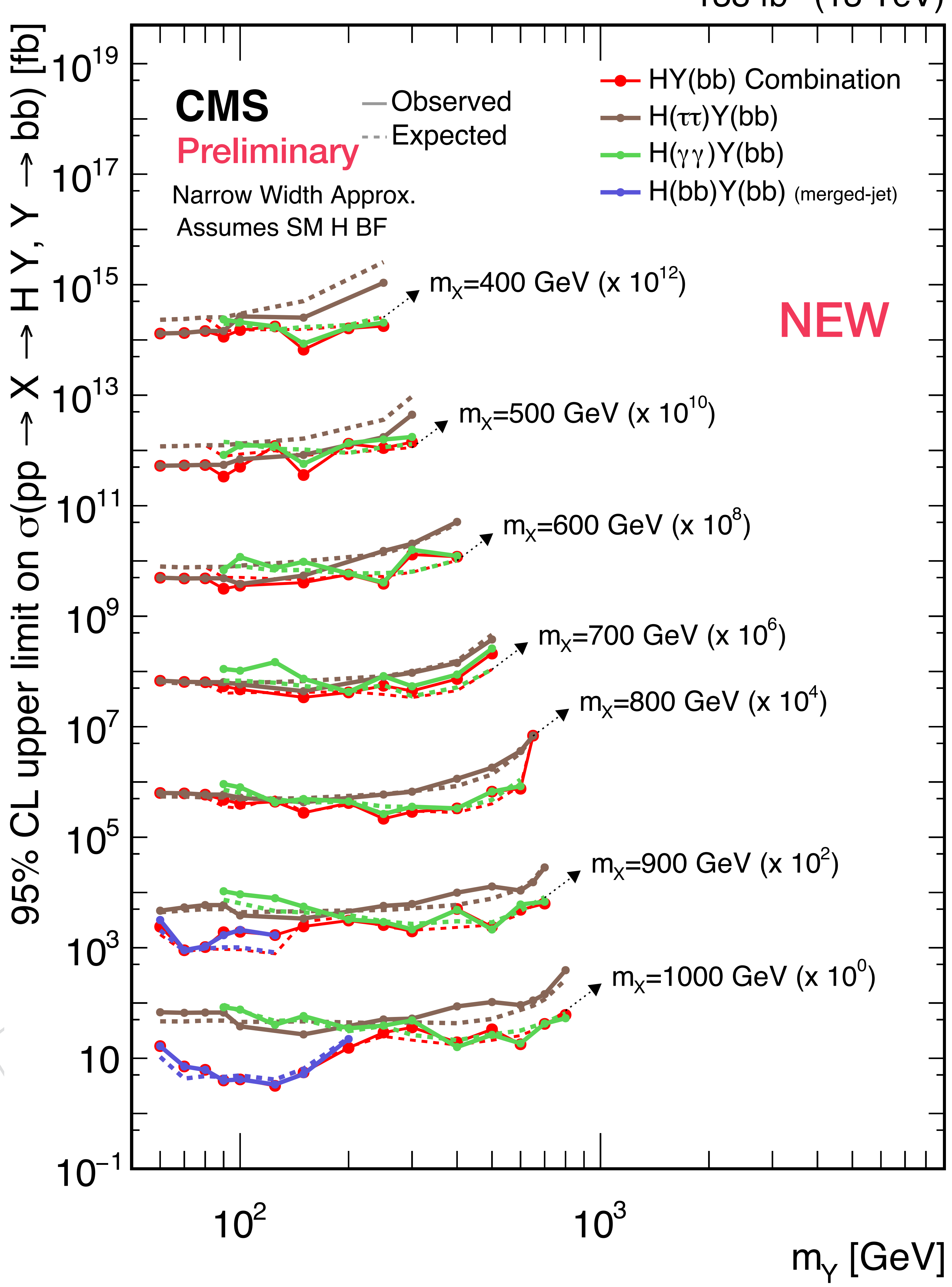
- $b\bar{b}b\bar{b}$: 3.1 σ (0.7 σ) at (1.6 TeV, 90 GeV);
- $b\bar{b}\gamma\gamma$: 3.8 σ (2.8 σ) at (650 GeV, 90 GeV).

The limits are then reinterpreted in terms of NMSSM.

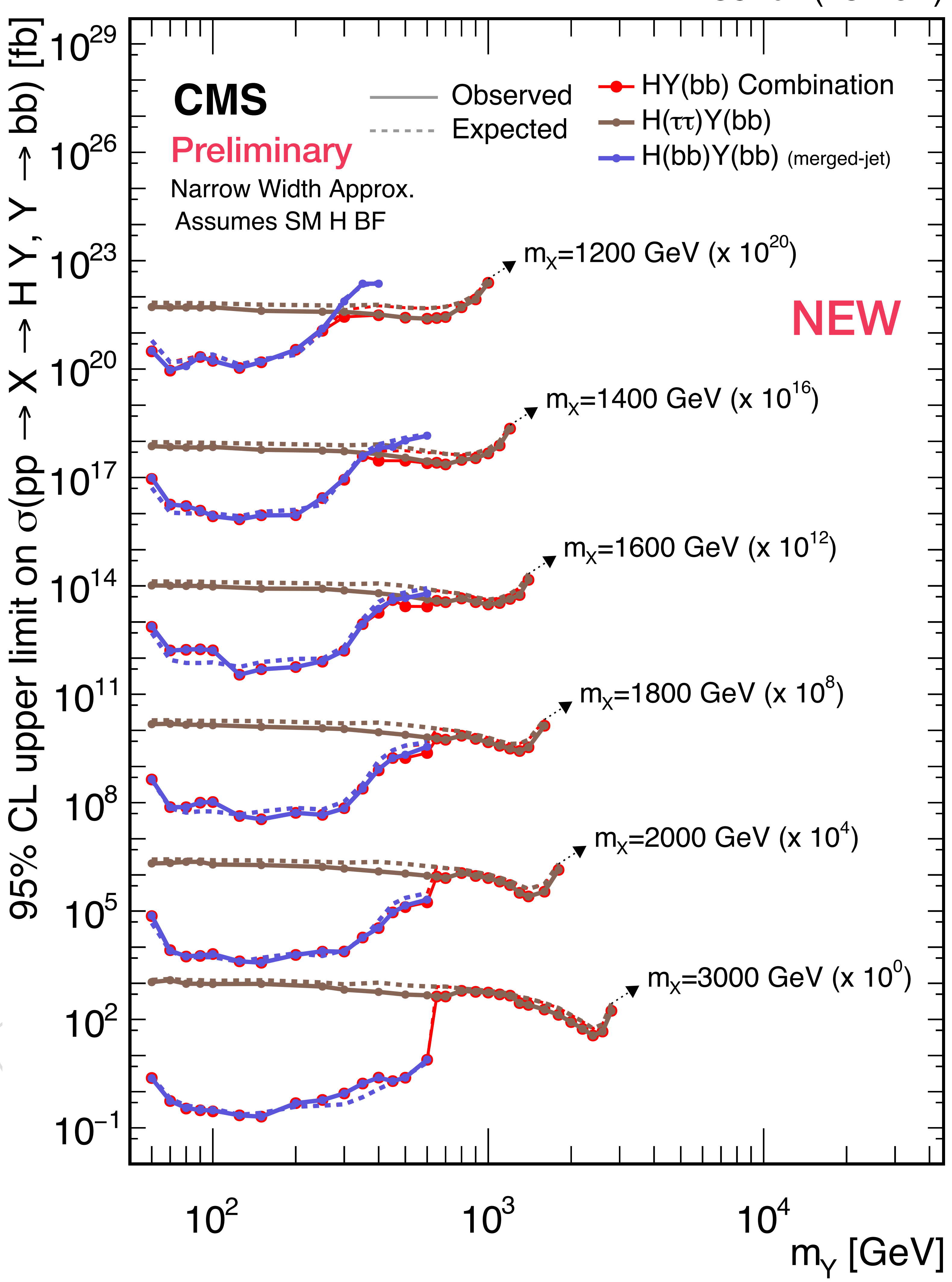


Sub. to J. High Energy Phys.

B2G-23-002



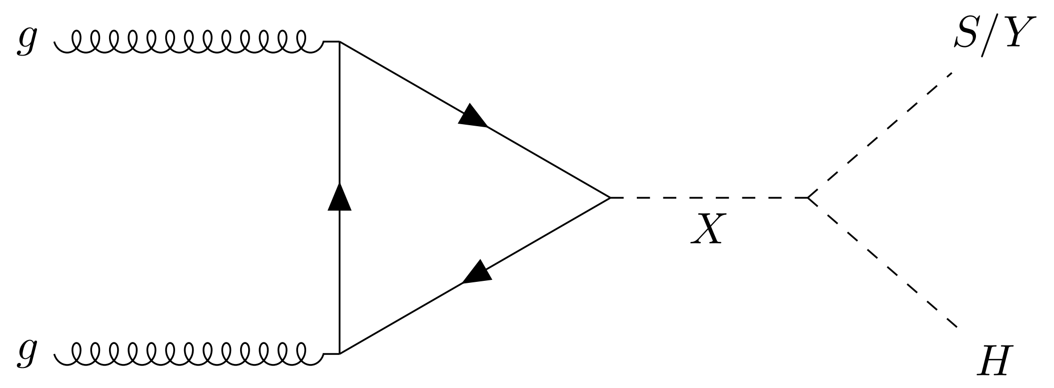
B2G-23-002



CMS produced new extrapolation for HL-LHC, shown in back-up.

NEW CMS results: X→YH→$\gamma\gamma\tau\tau$

CMS-HIGG-22-012

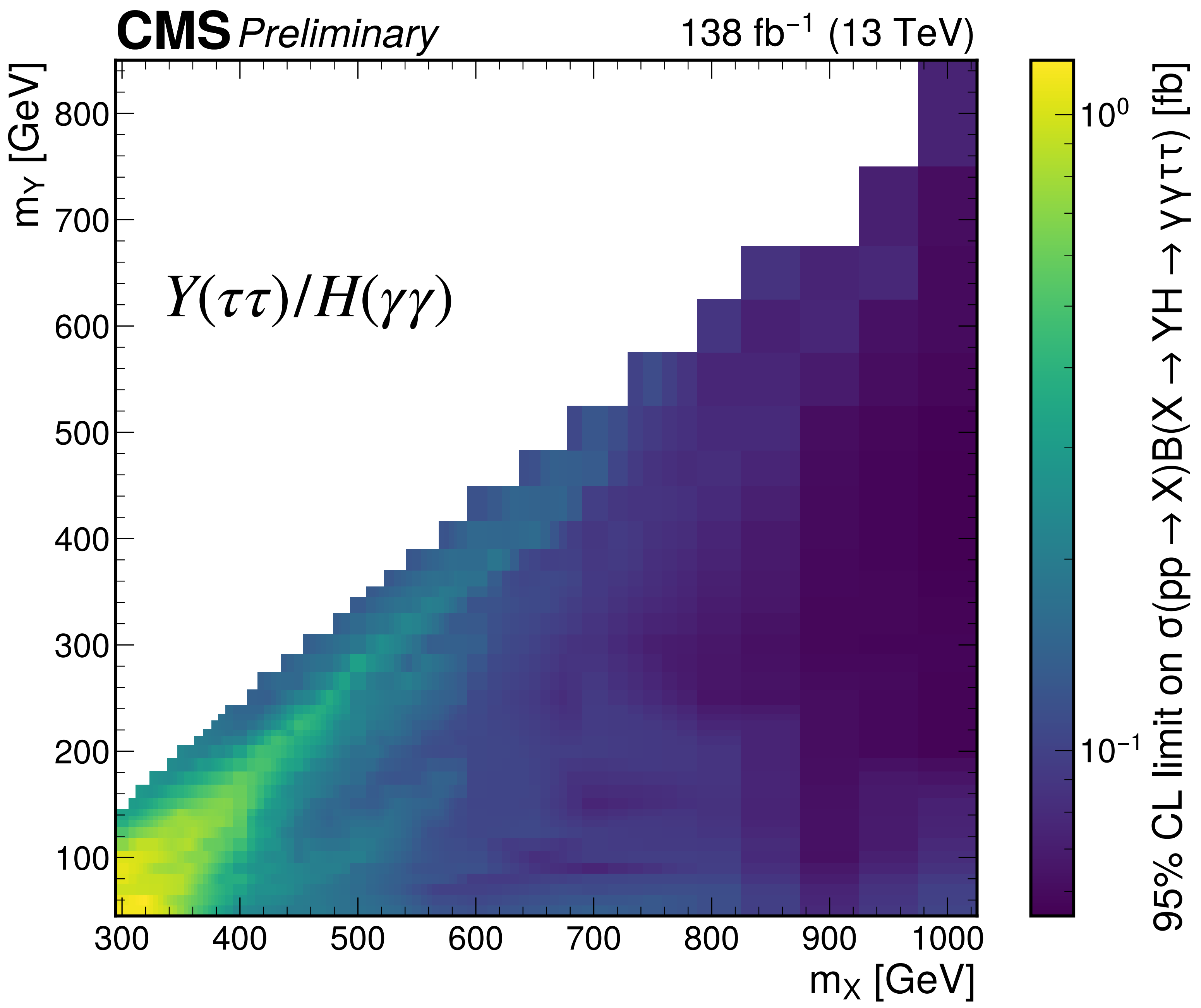


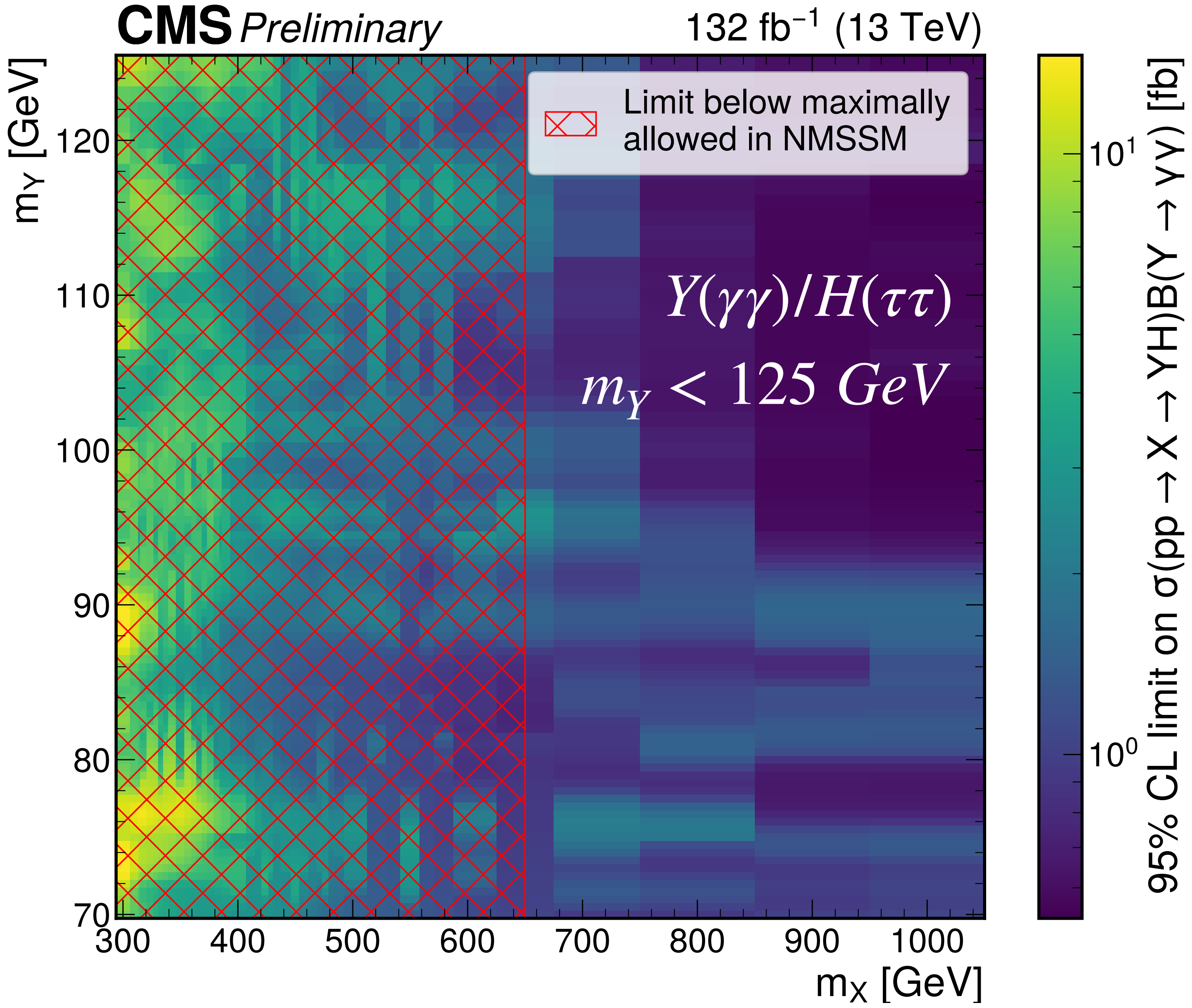
Similarly limits are set for X→YH processes, where both Y and H are allowed to decay to $\gamma\gamma$ and $\tau\tau$:

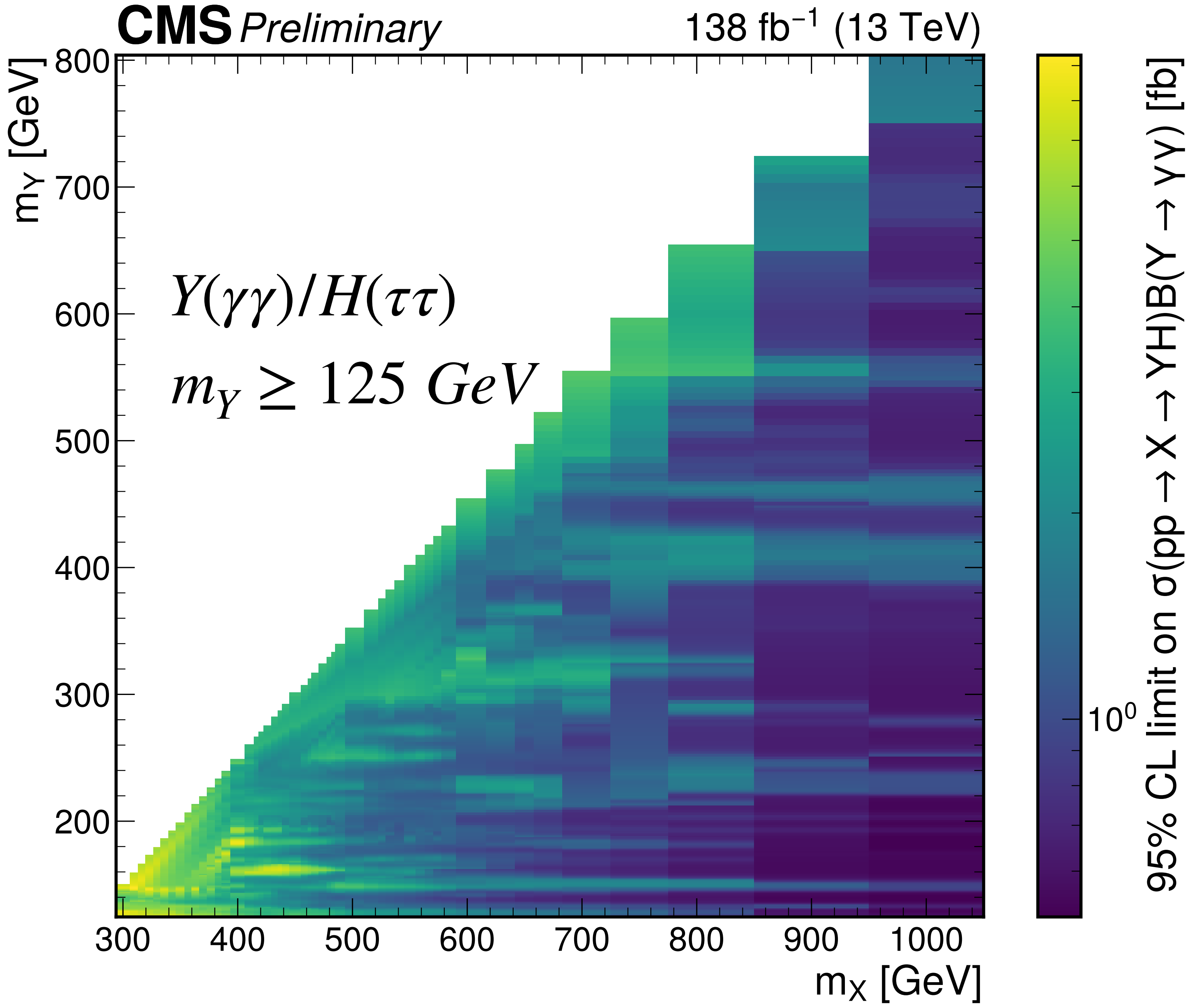
- Given the different trigger strategies, the search for Y→$\gamma\gamma$ is split into two, with m_Y = 125 GeV.
- In the low mass region, the Drell-Yann background is taken into account via an ABCD method.

No significant excess is observed. The highest excess local (global) significance for $(m_X, m_{(S/Y)})$:

- $Y(\tau\tau)/H(\gamma\gamma)$: 2.6 σ (2.2 σ) at (320 GeV, 60 GeV);
- $Y(\gamma\gamma)/H(\tau\tau)$, low mass: 3.4 σ (0.1 σ) at (525 GeV, 115 GeV);
- $Y(\gamma\gamma)/H(\tau\tau)$, high mass: 3.2 σ (0.3 σ) at (462 GeV, 161 GeV).

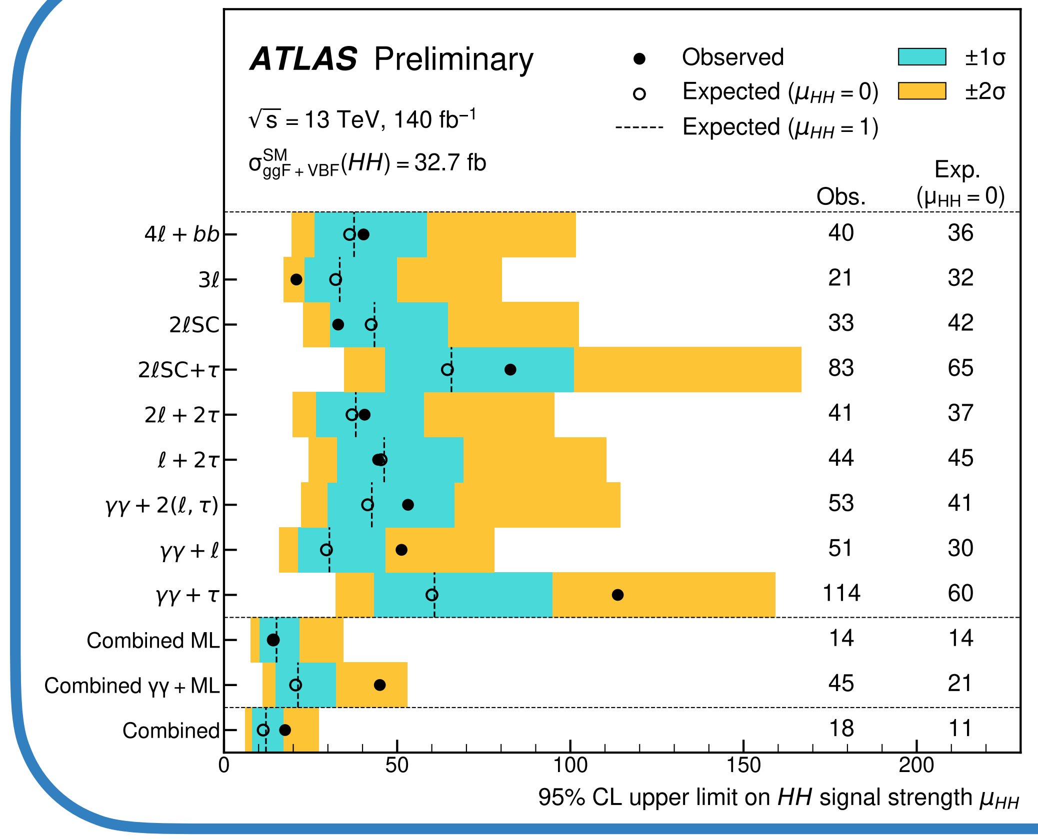






Summary: New results

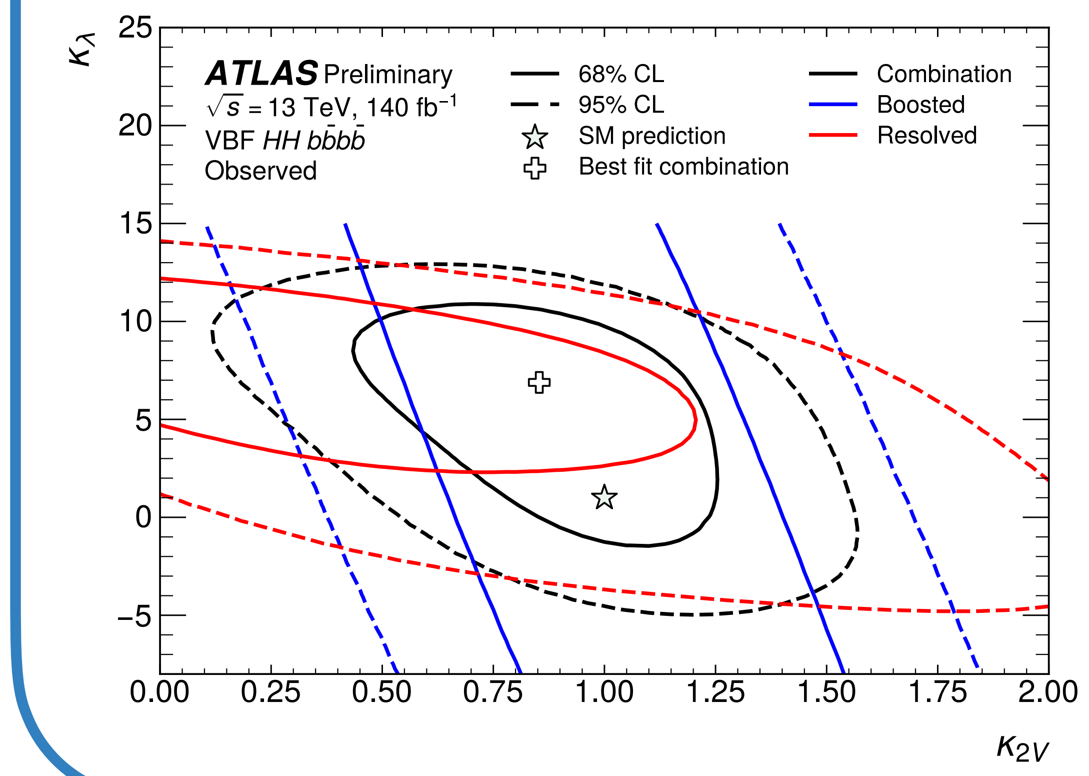
ATLAS-CONF-2024-005

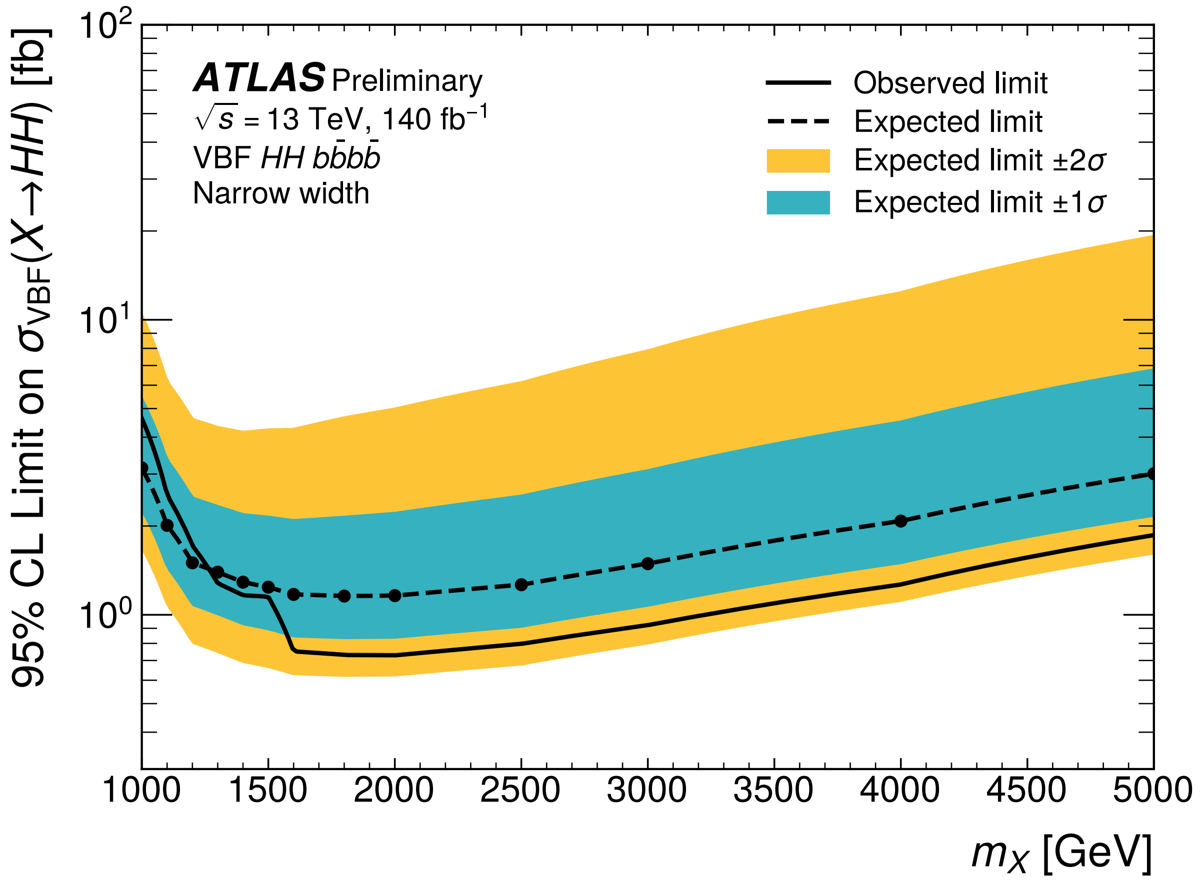


First global search in the multi-lepton channels with combined observed (expected) limit of 18 (11).

ATLAS-CONF-2024-003

Exclusion of $\kappa_{2V} = 0$ with a observed (expected) significance of 3.4σ (2.9σ).



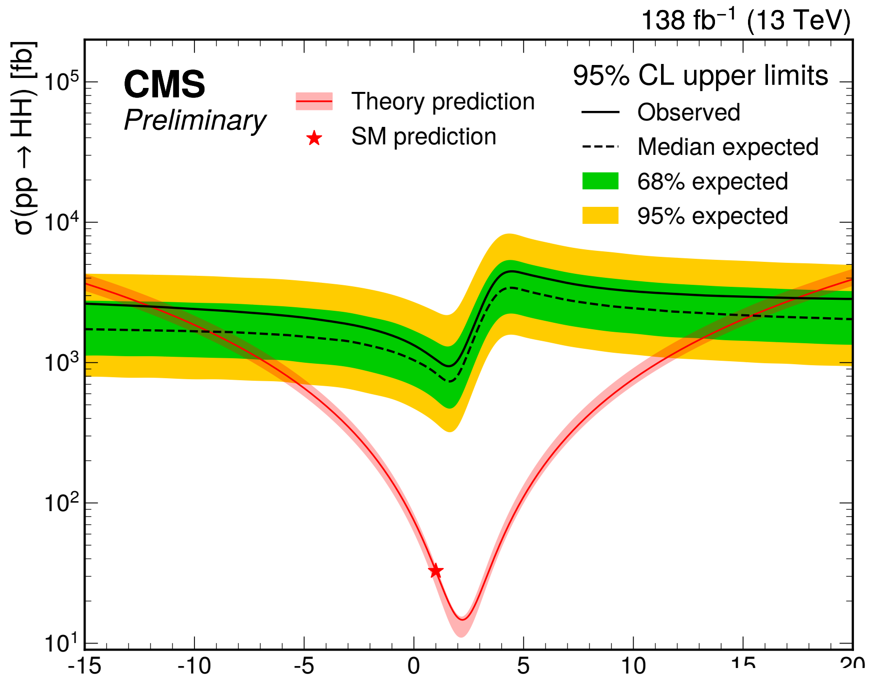


No significant excess in resonant VBF search.

+ New combination of resonant results

CMS-HIGG-22-012

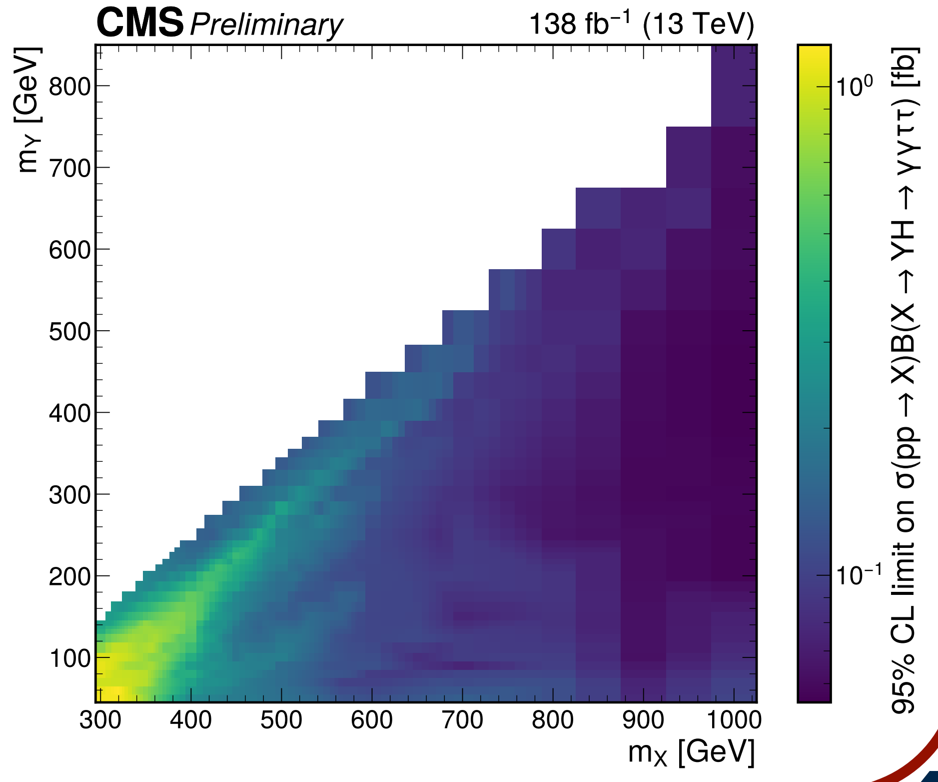
First dedicated $\gamma\gamma\tau\tau$ search with an observed (expected) limit of 33 (26) times the SM.



The observed (expected) constraint on κ_λ rejects values outside of the interval [–12, 17] ([–9.4, 15]).

No significant excess found in:

- X→HH→$\gamma\gamma\tau\tau$;
- X→(S/Y)H→$\gamma\gamma\tau\tau$;
- X→H(S/Y)→$\gamma\gamma\tau\tau$;



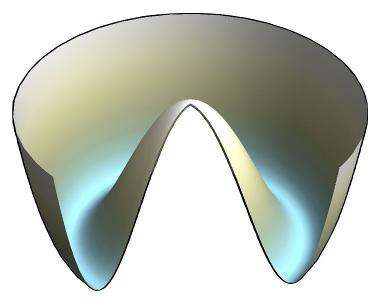
Stay tuned for the wildcard talks

BACK-UP

Why searching for di-Higgs ?

The full expression of the Higgs potential is encoded with parameters μ and λ as:

$$V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

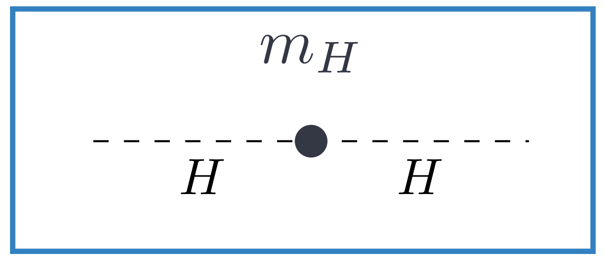


When linearising the Higgs field after the EWSB around the vacuum expected value ν one gets:

$$V(H) \supset \boxed{\underbrace{\mu^2}_{\frac{1}{2}m_H^2}\ H^2} + \boxed{\lambda\nu\ H^3}$$

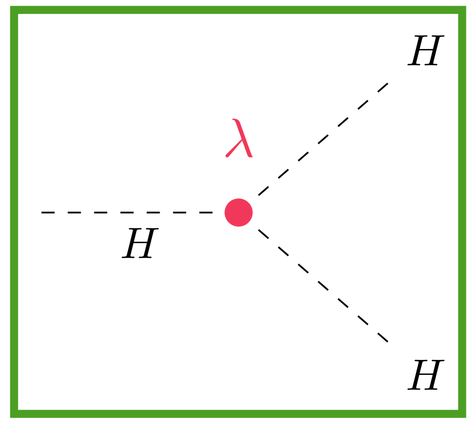
Where the potential parameters are linked by :

$$\lambda = \frac{\mu^2}{\nu^2} = \mu^2\sqrt{2}\ G_F$$

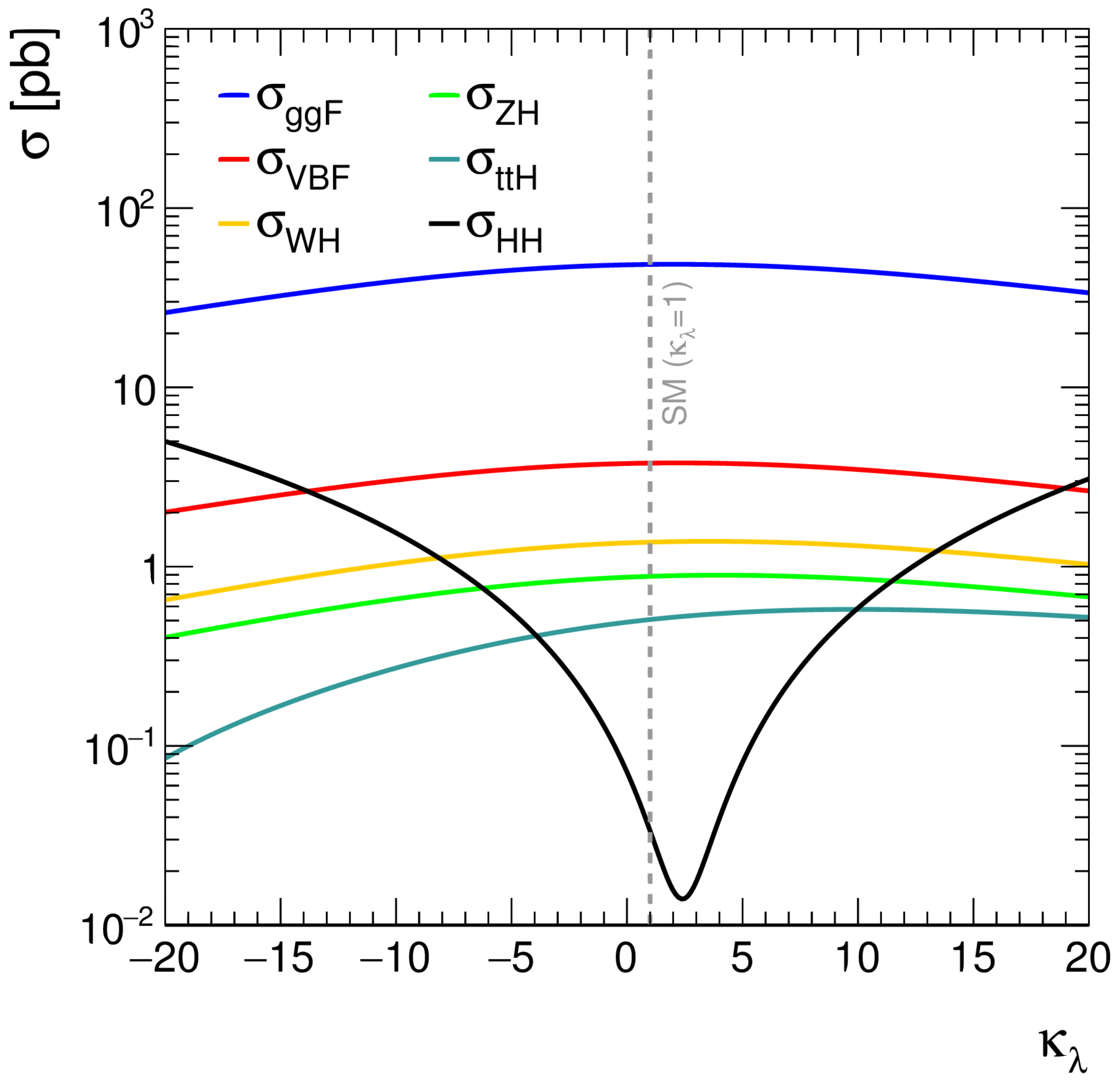


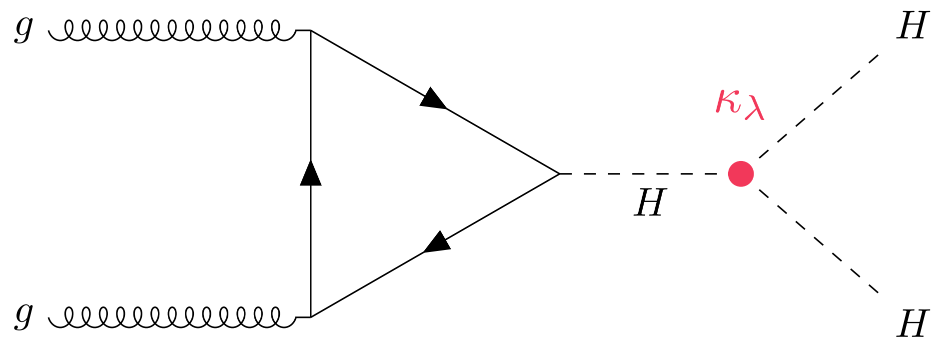
- The first piece of information came from the Higgs boson discovery:
  - Existence of a new particle with couplings according to prediction from EWSB;
  - First measurement of Higgs mass:

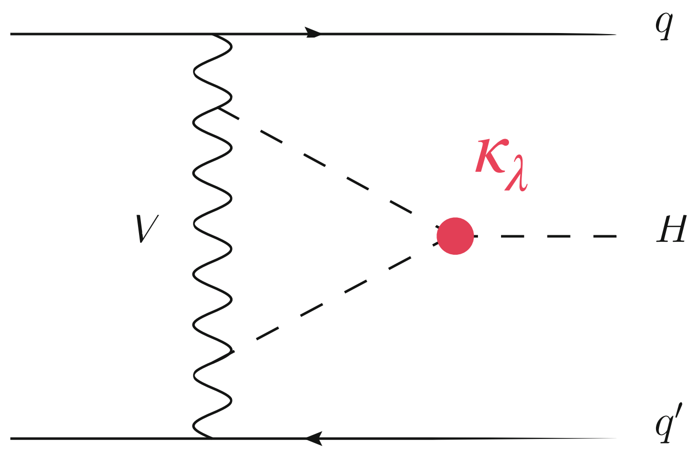
$$m_H = 125.09 \text{ GeV} \leftrightarrow \mu = 88.45 \text{ GeV} \leftrightarrow \lambda = 0.13$$



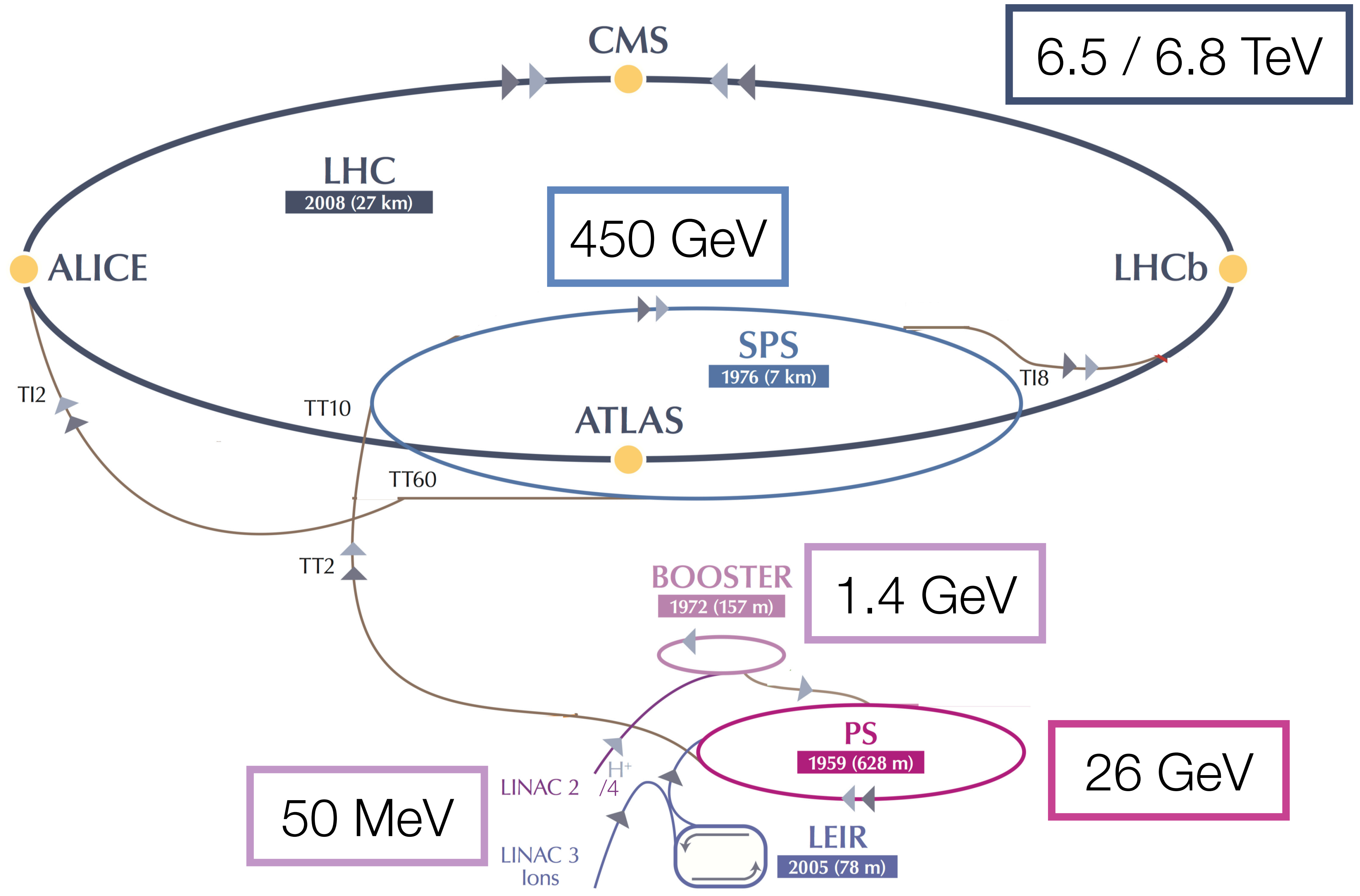
- Direct access to λ through Higgs pair creation:
  - Coupling strength denoted as $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$
  - At tree level: production of pair of Higgs bosons →strong effect on XS.
  - At loop level: effect on the single Higgs cross-section and deviations in kinematics.







The LHC: a (double) Higgs factory ?

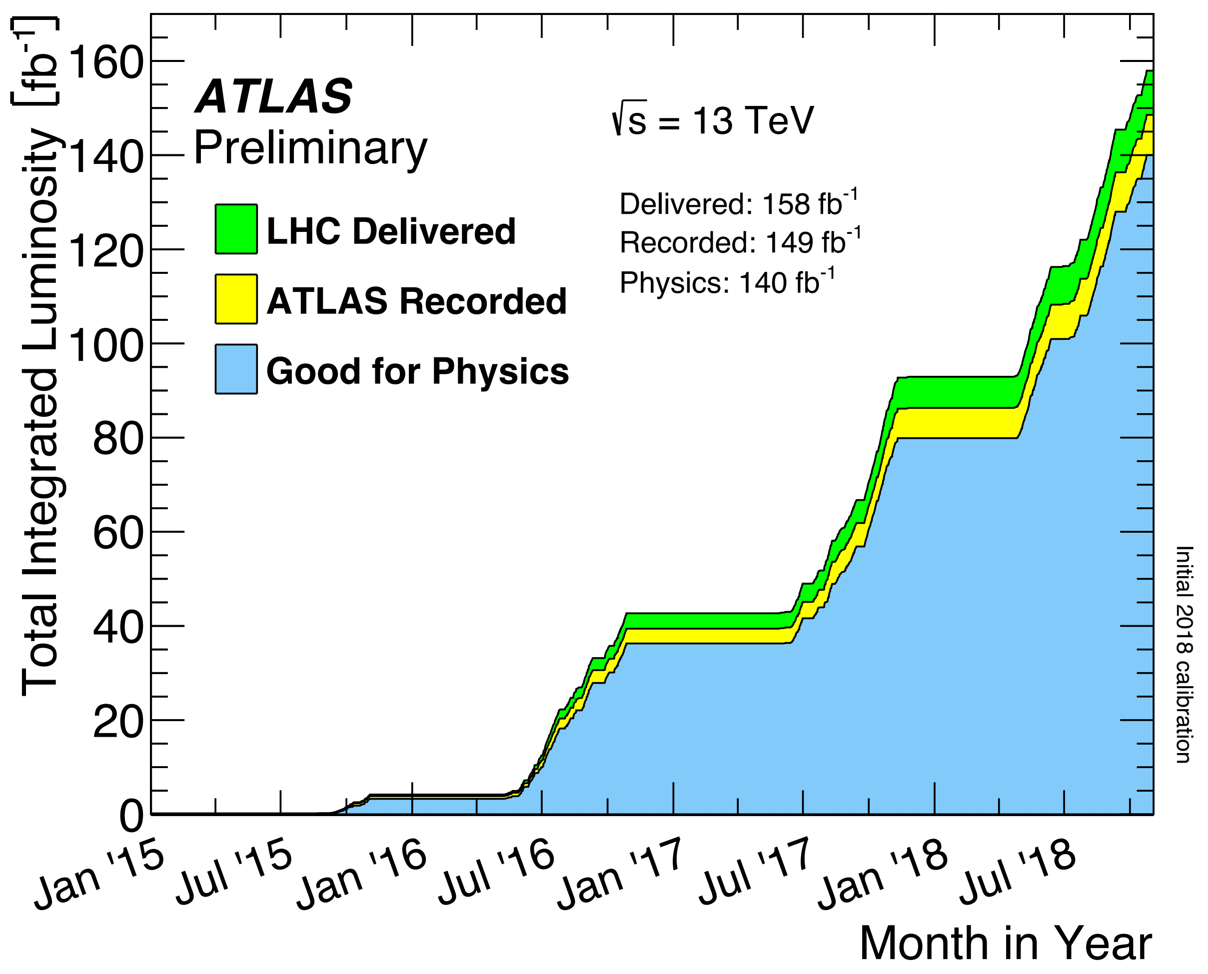


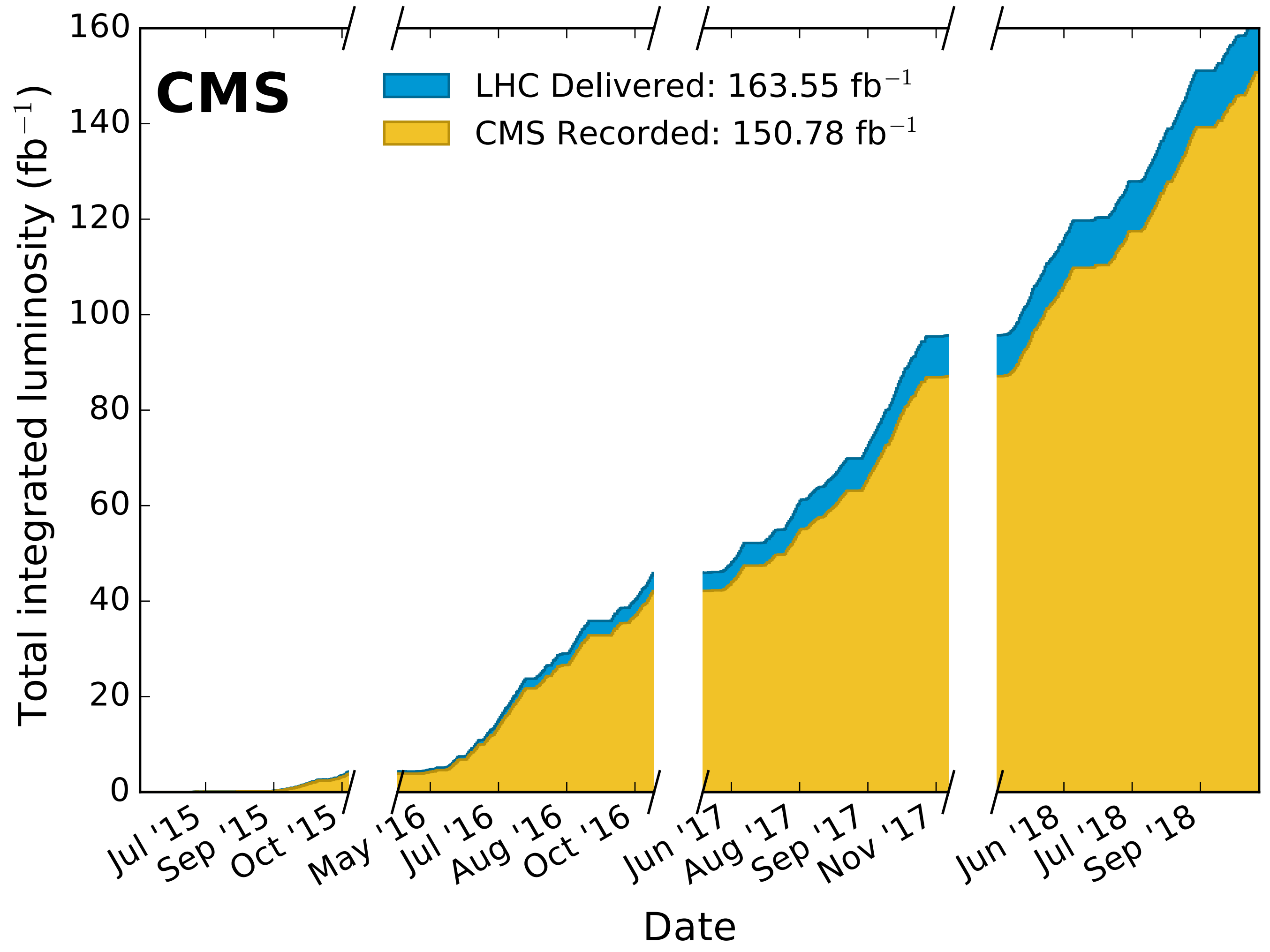
	N_H	N_{HH}
Run-1	512,000	200
Run-2	6,800,000	4,300
Run-3*	7,700,000	5,000
HL-LHC*	165,000,000	110,000

**estimated*

Located under the French-Swiss border, the **Large Hadron Collider** is the final piece of a staged acceleration chain allowing high luminosity **proton-proton** collisions.

With a 13 TeV center-of-mass energy, it has allowed the ATLAS and CMS collaboration to record $\mathscr{L} \simeq 150\ (140)\ fb^{-1}$ of (physics) data during the **Run-2** phase of the LHC.

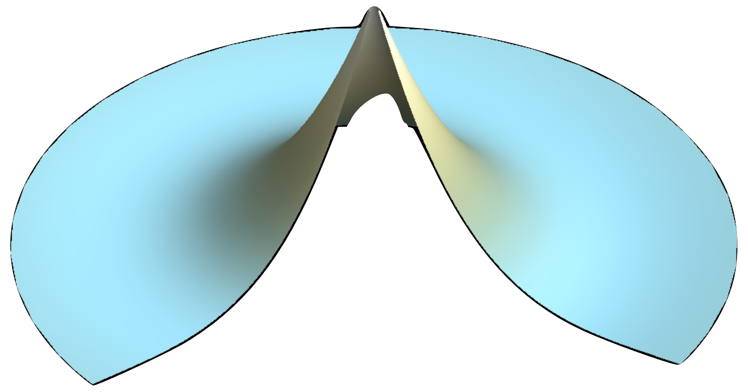




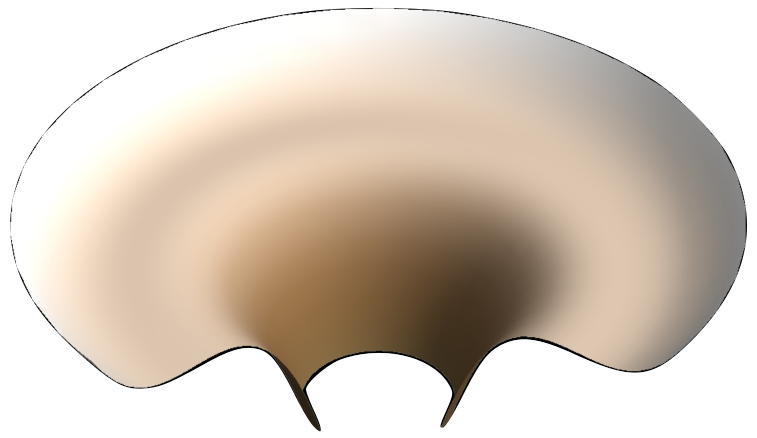
The **Run-3** phase is now ongoing at an unprecedented energy of 13.6 TeV, allowing to record $\mathscr{L} \simeq 66\ fb^{-1}$ of data so far.

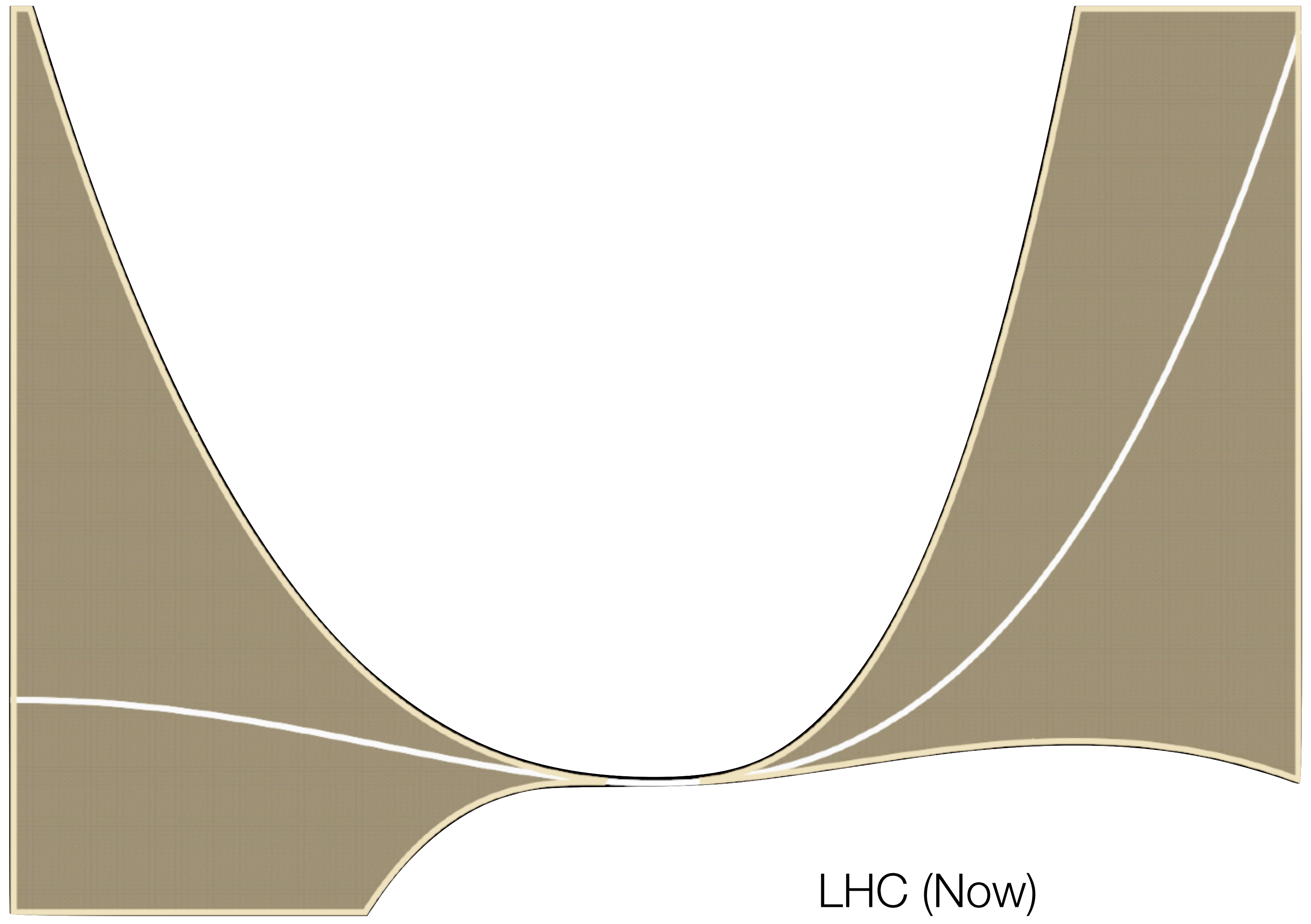
Exploring alternative scenarios

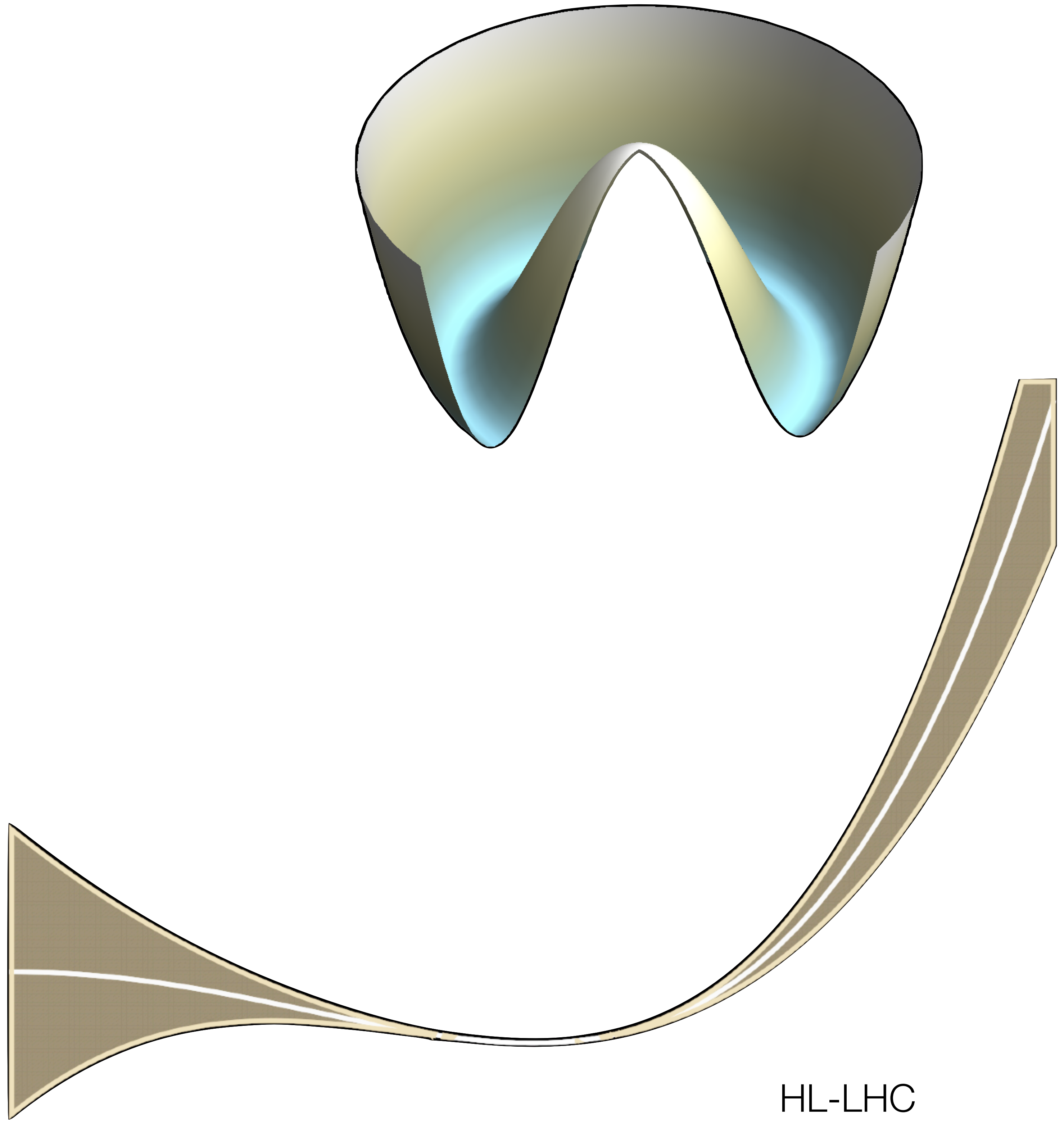
The measurement of the Higgs potential is a key element to answer the nature of its mechanism.
The exact value of λ can lead to very different shapes and could help us to understand better the type of transition that occurred from the high temperatures to the current situation.



Equiprobable shapes of the potential given our current knowledge.







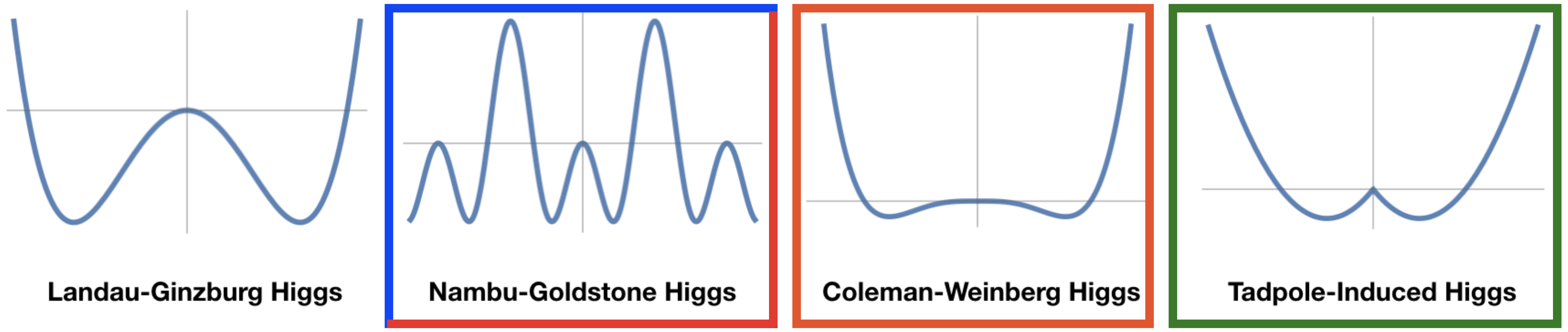
Taken from Nathaniel Craig's talk

Exploring alternative scenarios

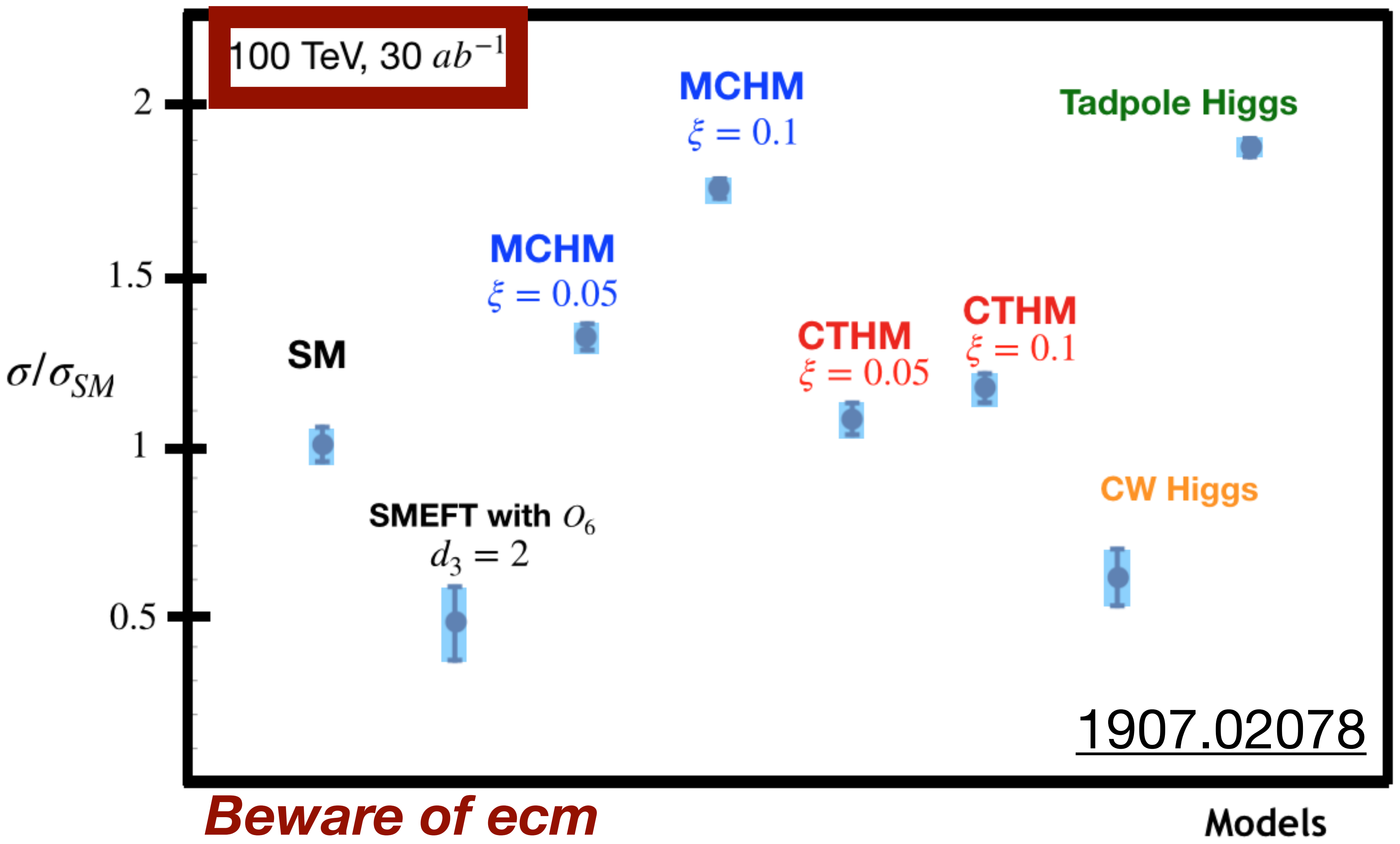
The measurement of the Higgs potential is answering the fundamental question of its nature.
Several other models can show a non zero vacuum expected value with a different second order contribution:

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2}(H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

- Nambu-Goldstone Higgs: pseudo Nambu-Goldstone boson emerging from strong dynamics at a high scale
- Coleman-Weinberg Higgs: EWSB is triggered by renormalization group (RG) running effects
- Tadpole-induced Higgs: EWSB is triggered by the Higgs tadpole



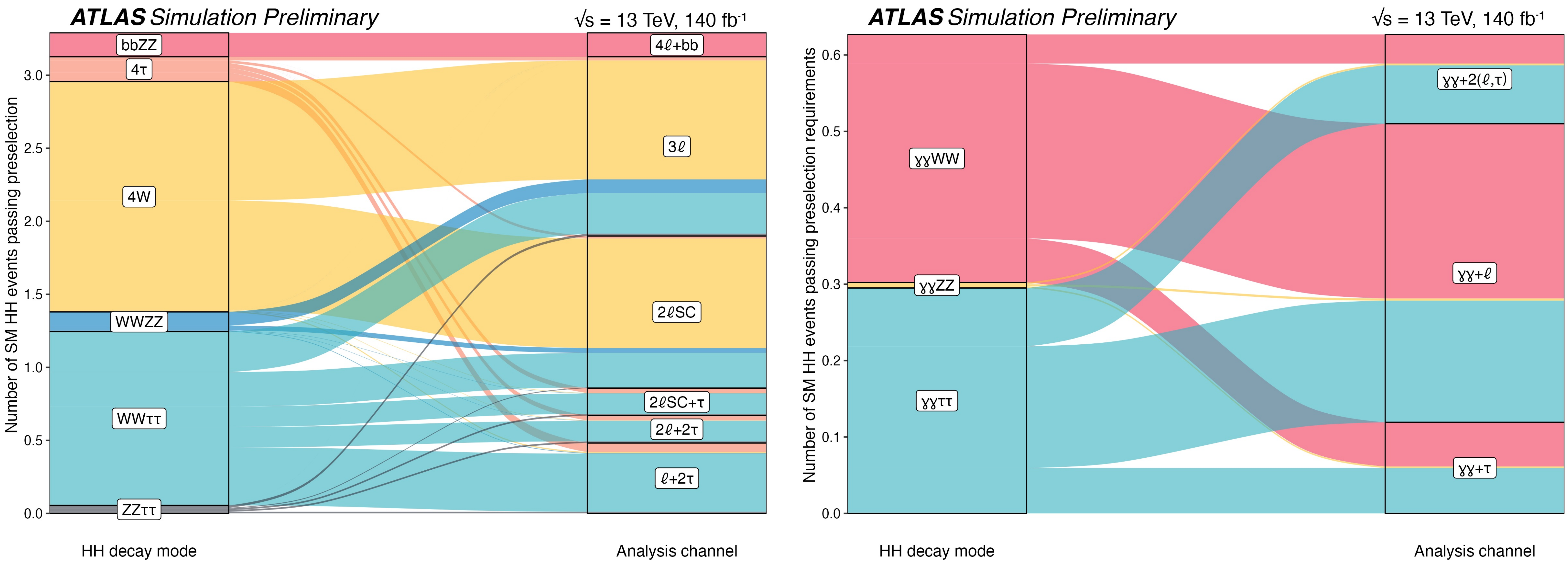
minimal composite Higgs model/
composite twin Higgs model :
different coupling to top quark



Beware of ecm

NEW ATLAS results: HH ML

ATLAS-CONF-2024-XXX

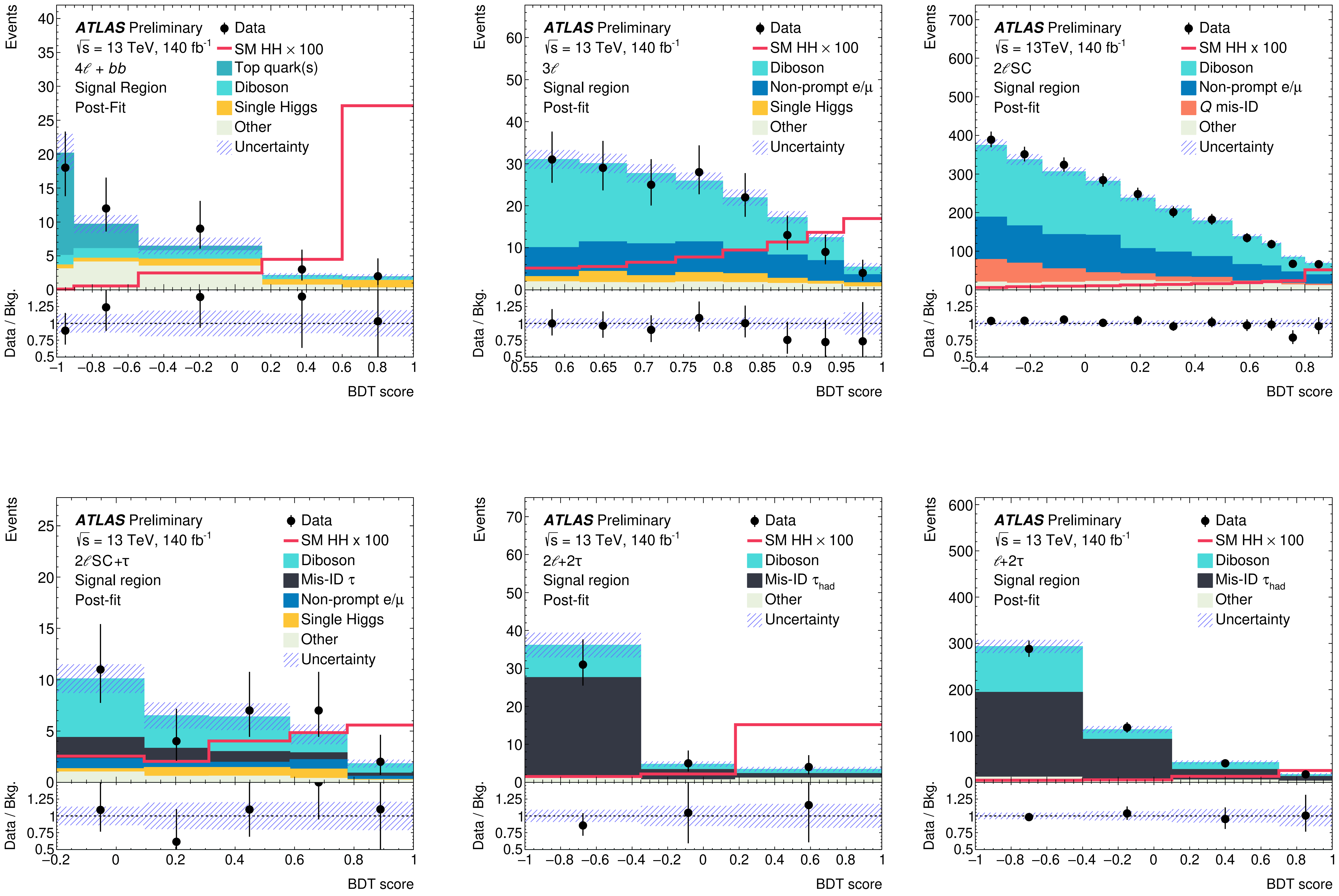


These plots show the signal HH event migration from the different final states to the analysis categories.

NEW ATLAS results: HH ML

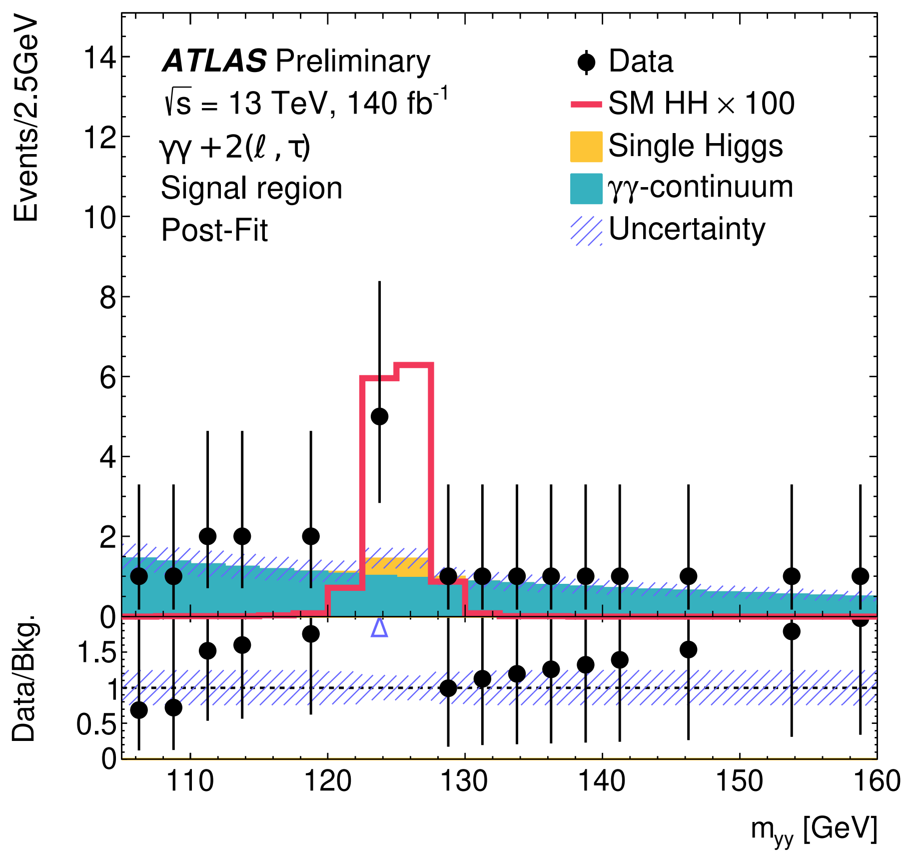
ATLAS-CONF-2024-005

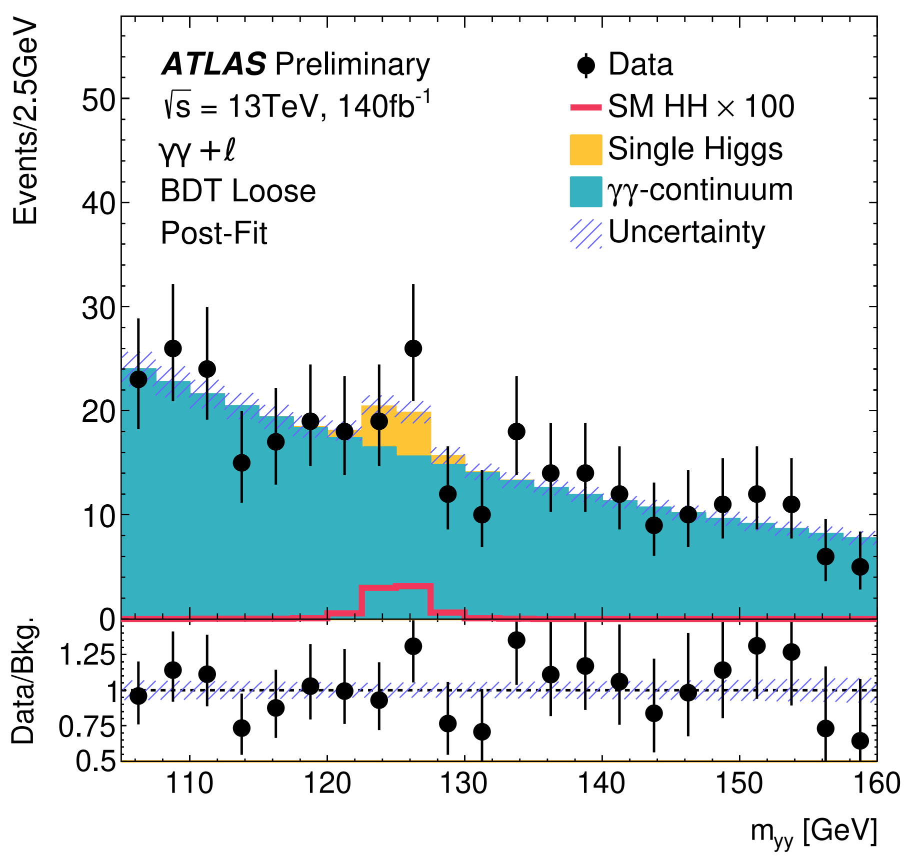
Channel	ℓ	$\tau_{\text{had-vis}}$	Jets	b-jets
4ℓ+bb	4ℓ(B) $p_T(\ell_1) > 20$ GeV $p_T(\ell_2) > 15$ GeV $p_T(\ell_3) > 10$ GeV ℓ_3 or ℓ_4 pass loose PLV 2 SFOC pairs $50 < m^{\text{SFOC}}_{\text{on-shell-}\ell\ell} < 106$ GeV $5 < m^{\text{SFOC}}_{\text{off-shell-}\ell\ell} < 115$ GeV All 4 pairs $\Delta R(\ell_i, \ell_j) > 0.02$ $115 \text{ GeV} < m_{4\ell} < 135$ GeV	$N_\tau = 0$	$N_{\text{jet}} \geq 2$	$1 \leq N_{b\text{-jet}} \leq 3$
3ℓ	3ℓ, sum of charges = ±1 ℓ_{OC}(L) ℓ_{SC1}(T), $p_T > 15$ GeV ℓ_{SC2}(T), $p_T > 15$ GeV All $m^{\text{SFOC}}_{\ell\ell} > 12$ GeV Z-veto $\lvert m_{3\ell} - m_Z \rvert > 10$ GeV	$N_\tau = 0$	$N_{\text{jet}} \geq 1$	$N_{b\text{-jet}} = 0$
2ℓSC	2ℓ(T), $p_T > 20$ GeV, SC $m_{\ell\ell} > 12$ GeV	$N_\tau = 0$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$
2ℓSC+τ	2ℓ(T), $p_T > 20$ GeV, SC $m_{\ell\ell} > 12$ GeV	$N_\tau = 1$ $p_T > 25$ GeV OC to ℓ	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$
2ℓ+2τ	2ℓ(L), OC $m_{\ell\ell} > 12$ GeV Z-veto	$N_\tau = 2$, OC $\Delta R(\tau_1, \tau_2) < 2$	-	$N_{b\text{-jet}} = 0$
ℓ+2τ	1ℓ(L)	$N_\tau = 2$, OC $\Delta R(\tau_1, \tau_2) < 2$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$

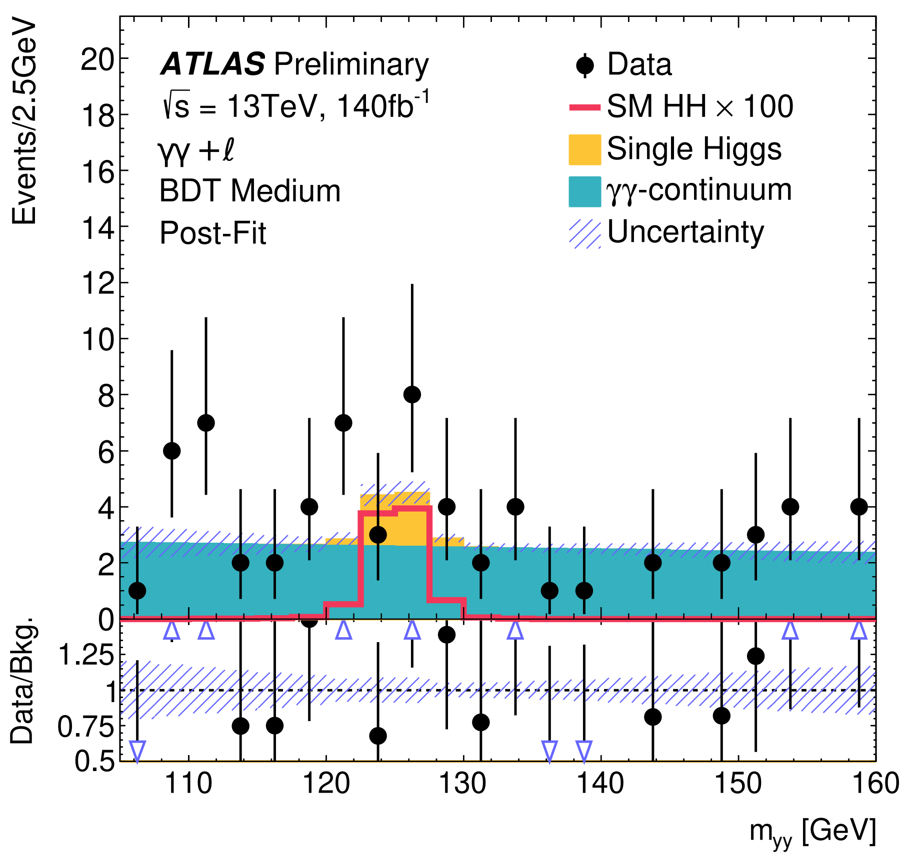


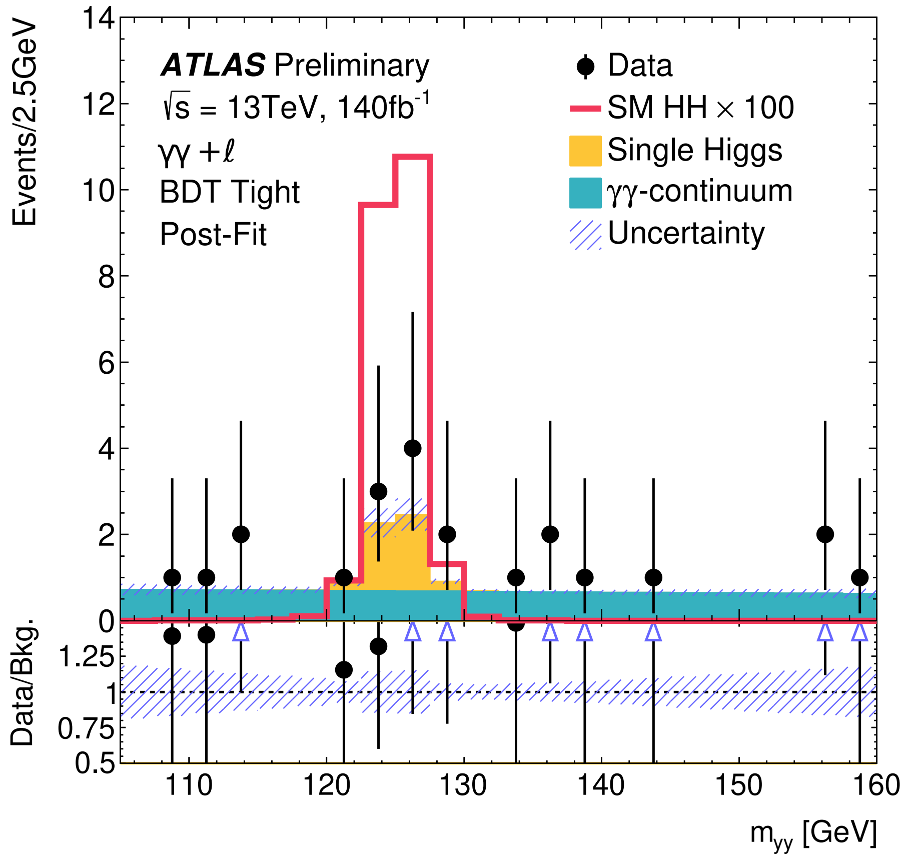
NEW ATLAS results: HH ML

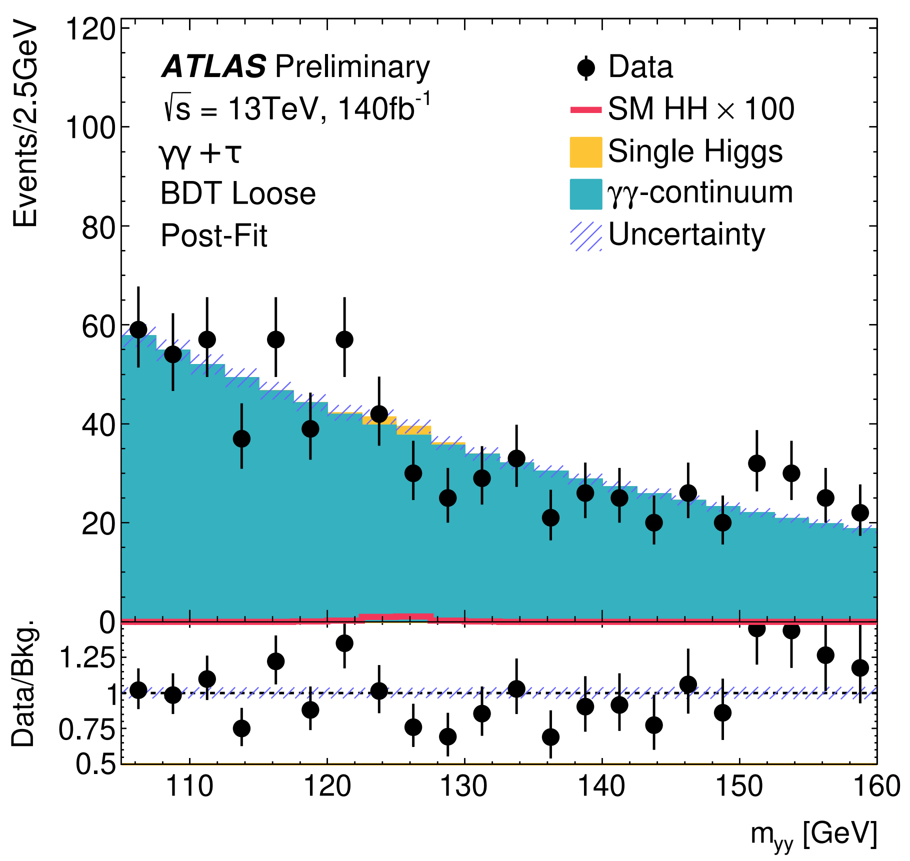
ATLAS-CONF-2024-005

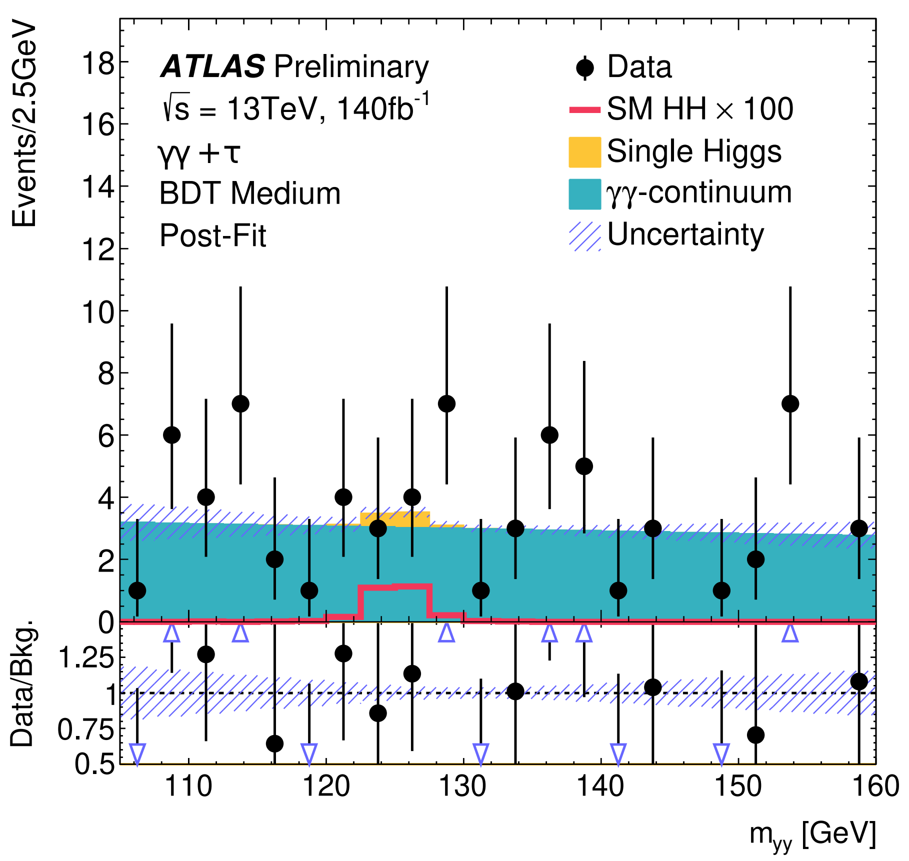


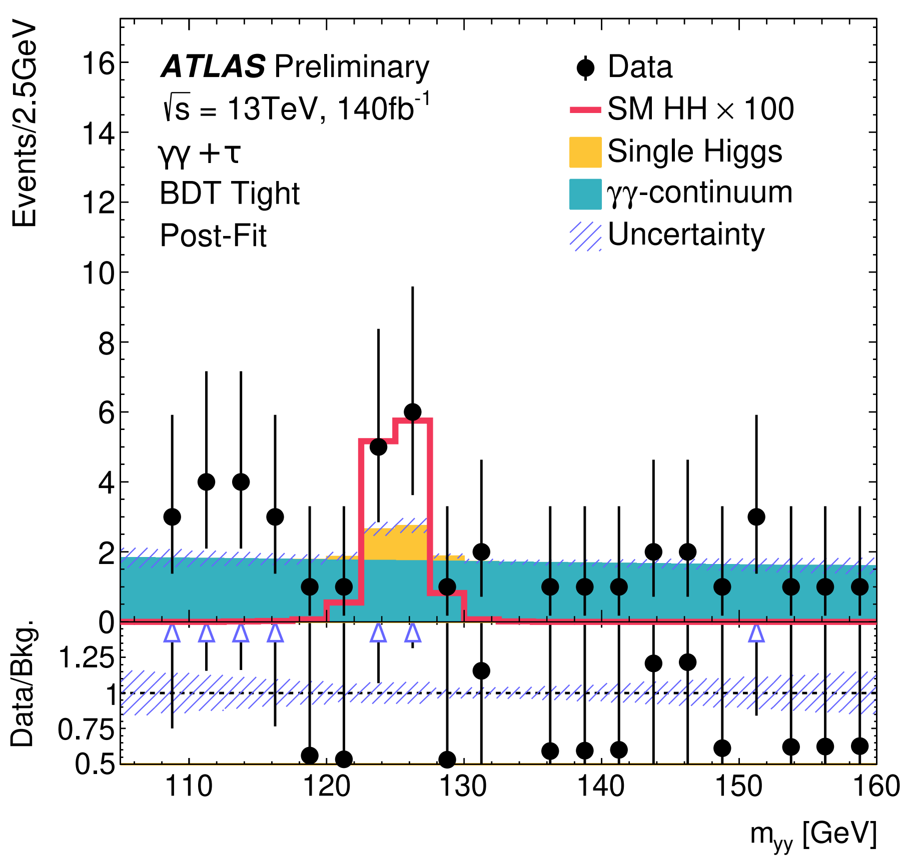










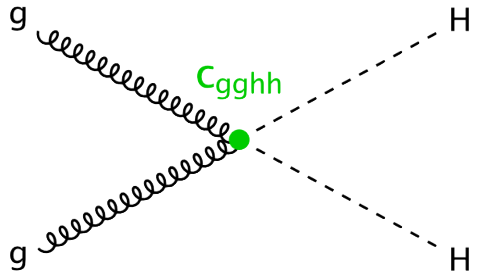


An overview of EFT

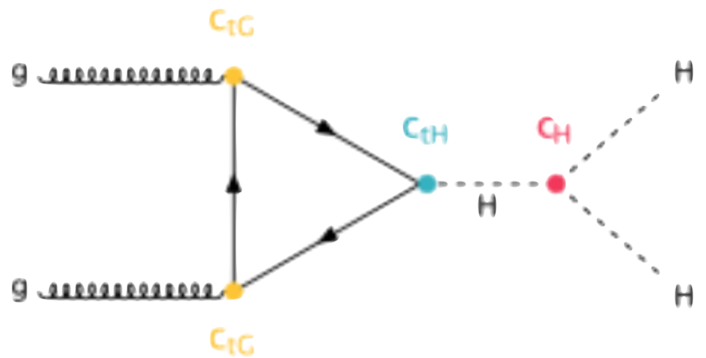
The results can be further interpreted using Effective Field Theories:

- In the Standard Model EFT (SMEFT): the SM Lagrangian is supplemented with a set of extra operators, respecting gauge symmetries of the SM.
- In the Higgs EFT (HEFT): is following the same strategy, but recasting the operators to have a one-to-one correspondance between operators and effective interactions.

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_k c_k^{(6)} O_k^{(6)}$$



The constraints are often set in terms of coefficients but several sets of benchmark models are also available (be careful though since the definitions might have changed between papers).



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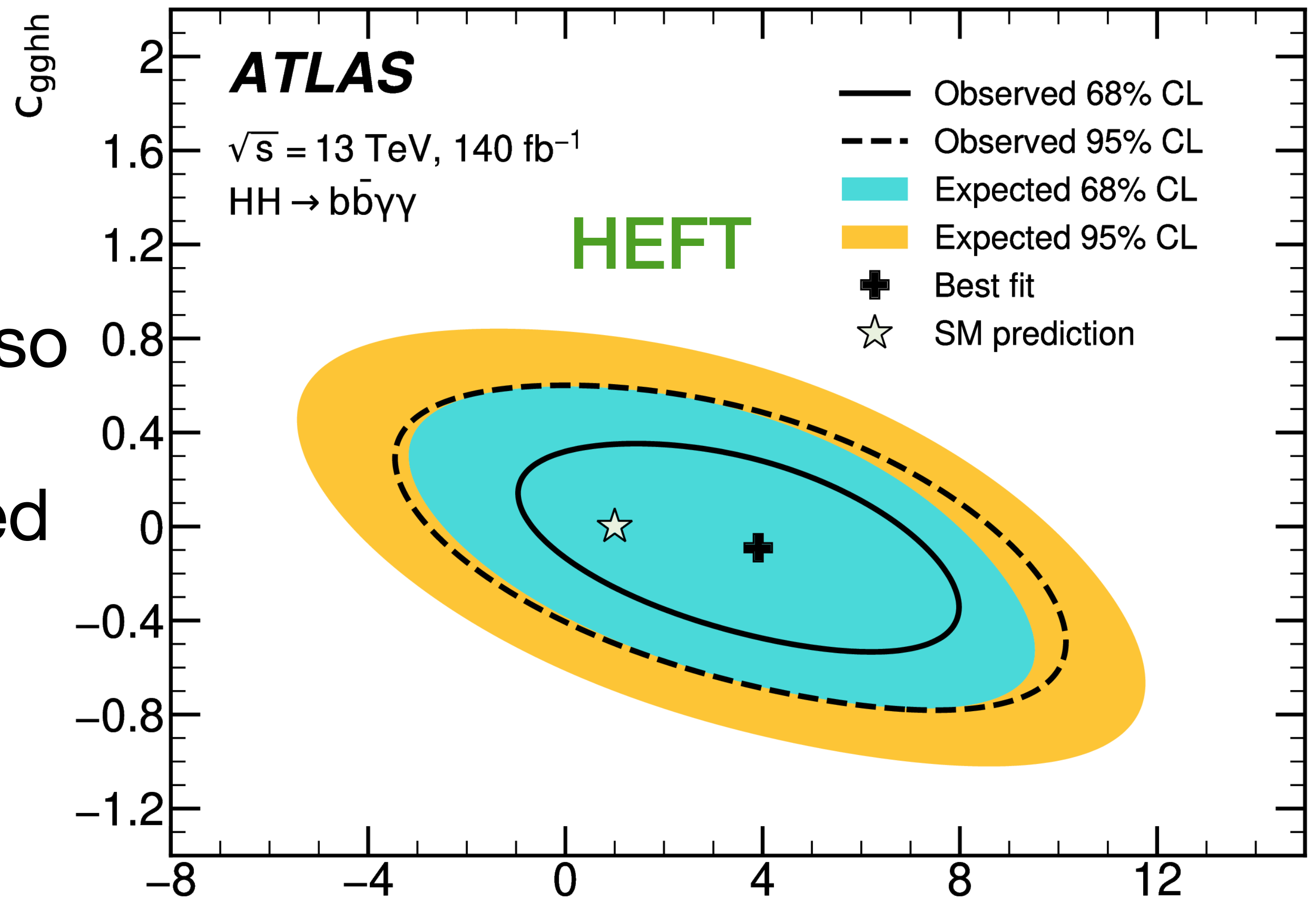

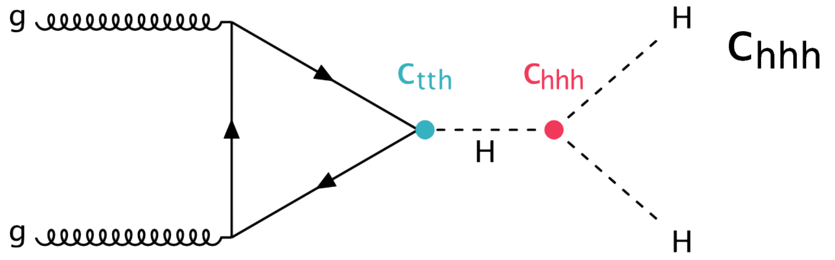

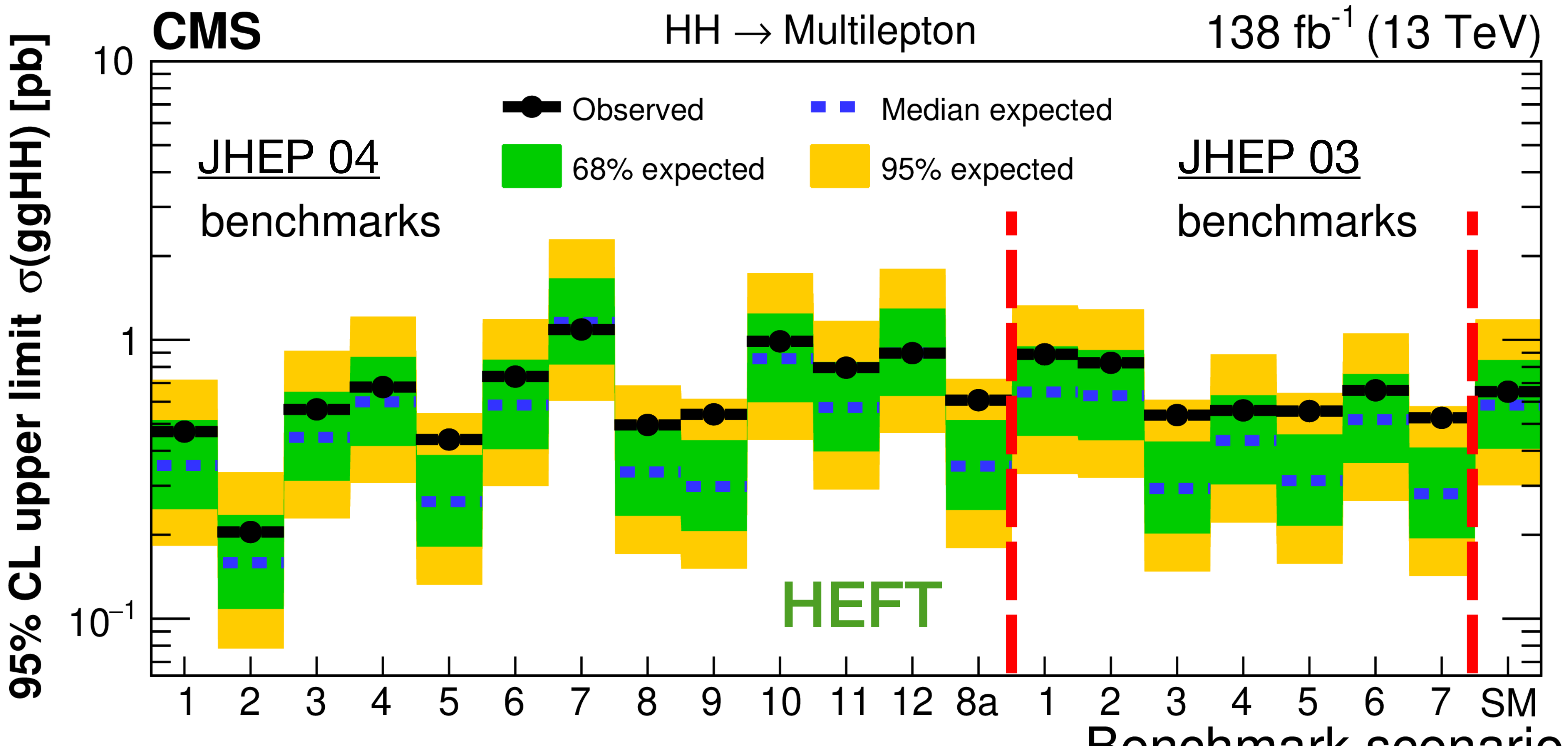

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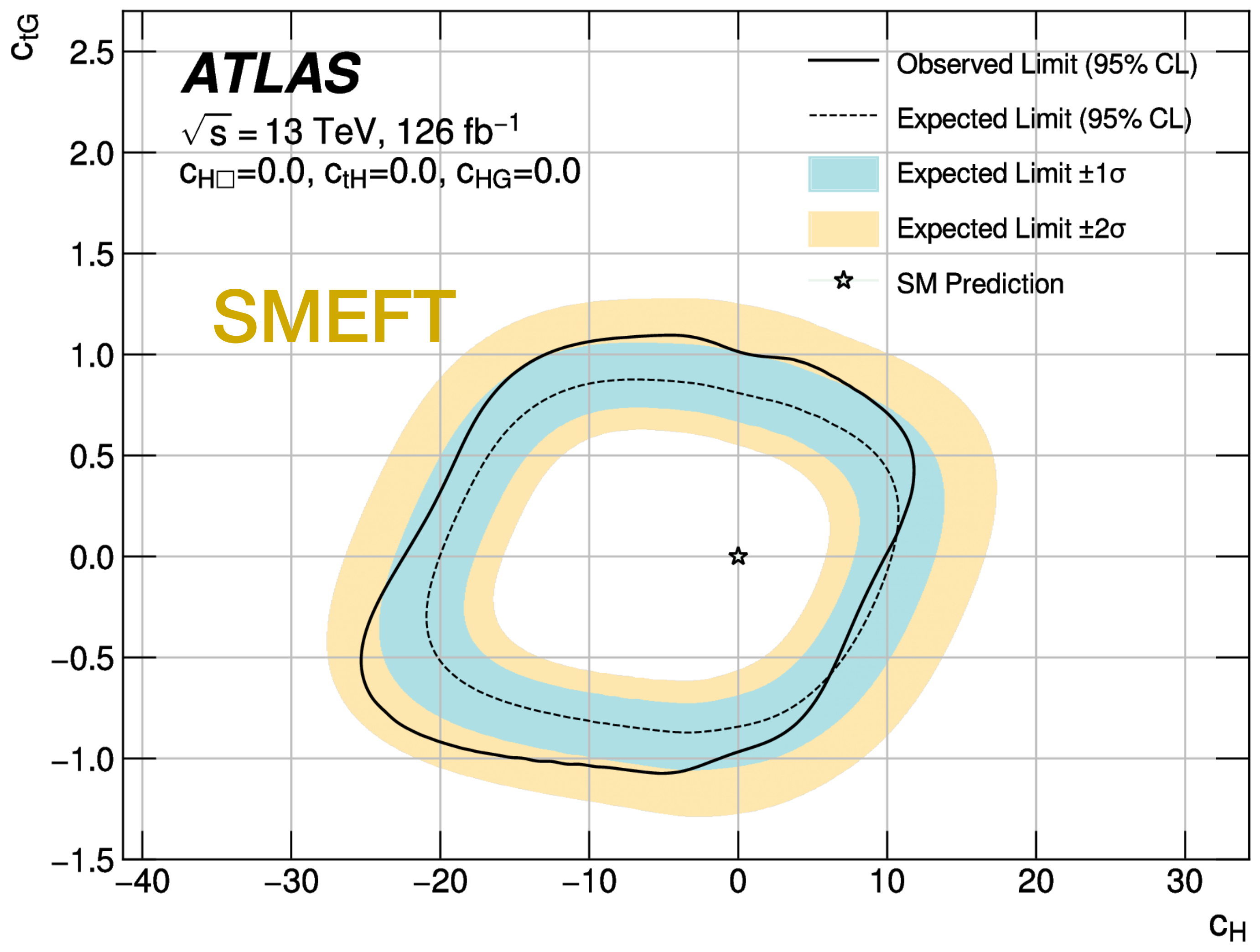
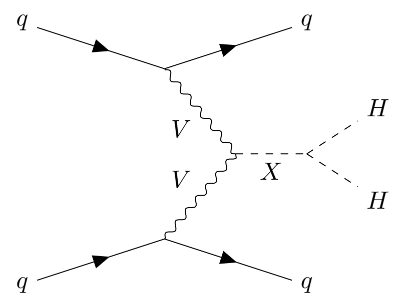
Phys. Rev. D 108 (2023)



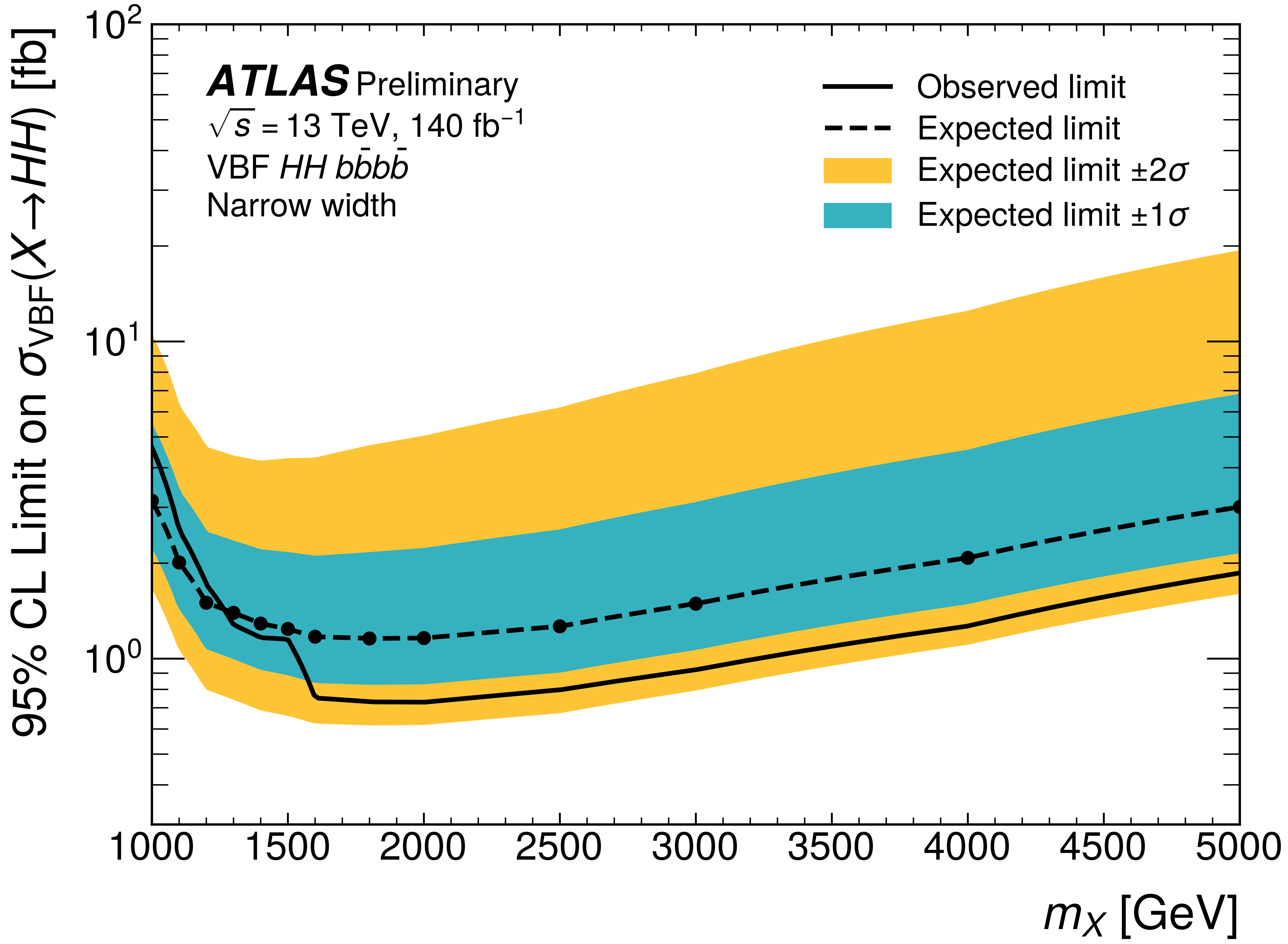
The pure extra EFT operator effect can be studied in the so-called quadratic case (~ $1/\Lambda^4$), while the interaction with the SM is taken into account in the linear one (~ $1/\Lambda^2$). In all the results released, the linear+quadratic terms are considered.

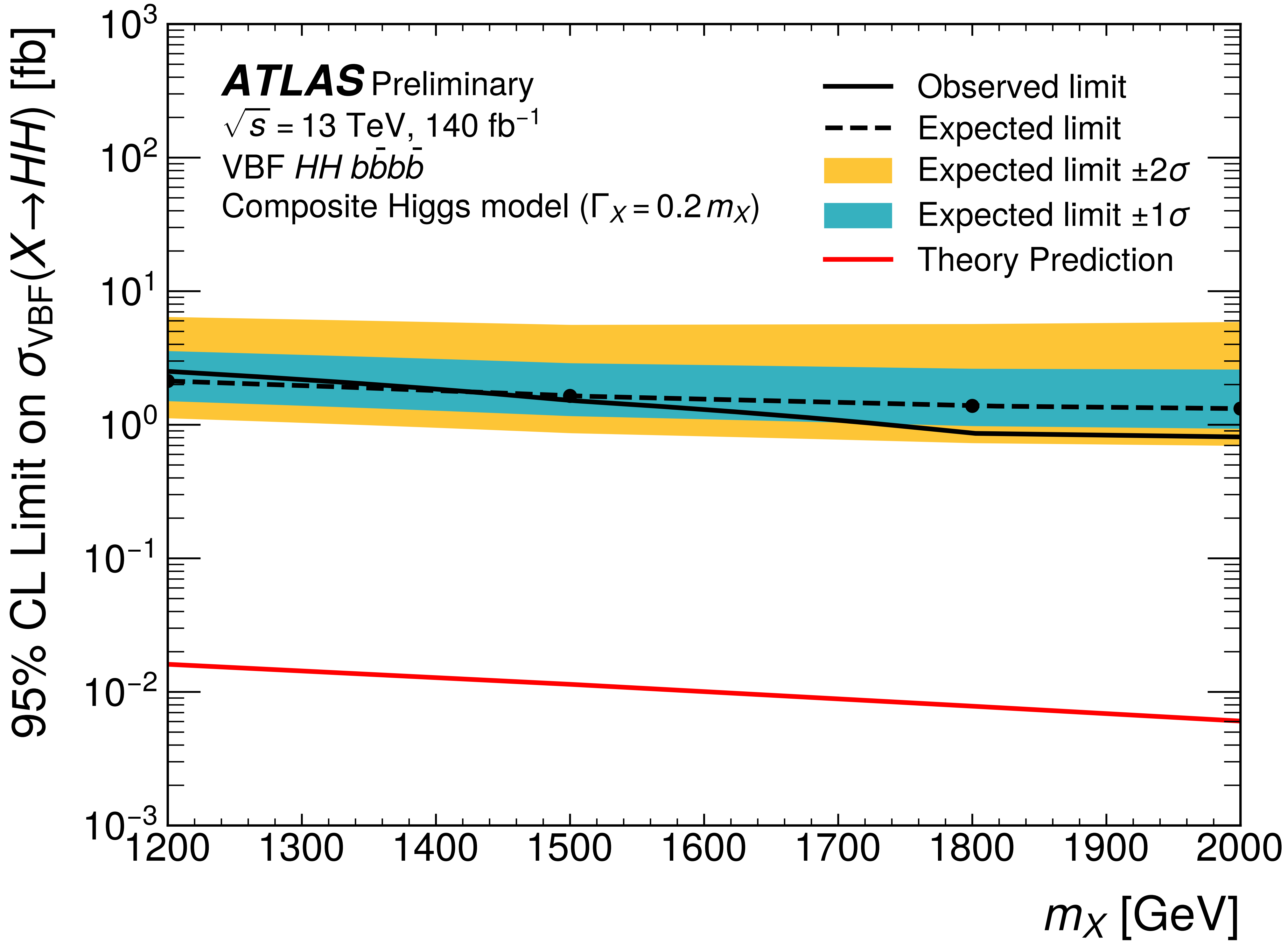
NEW ATLAS results: VBF 4b



ATLAS-CONF-2024-003

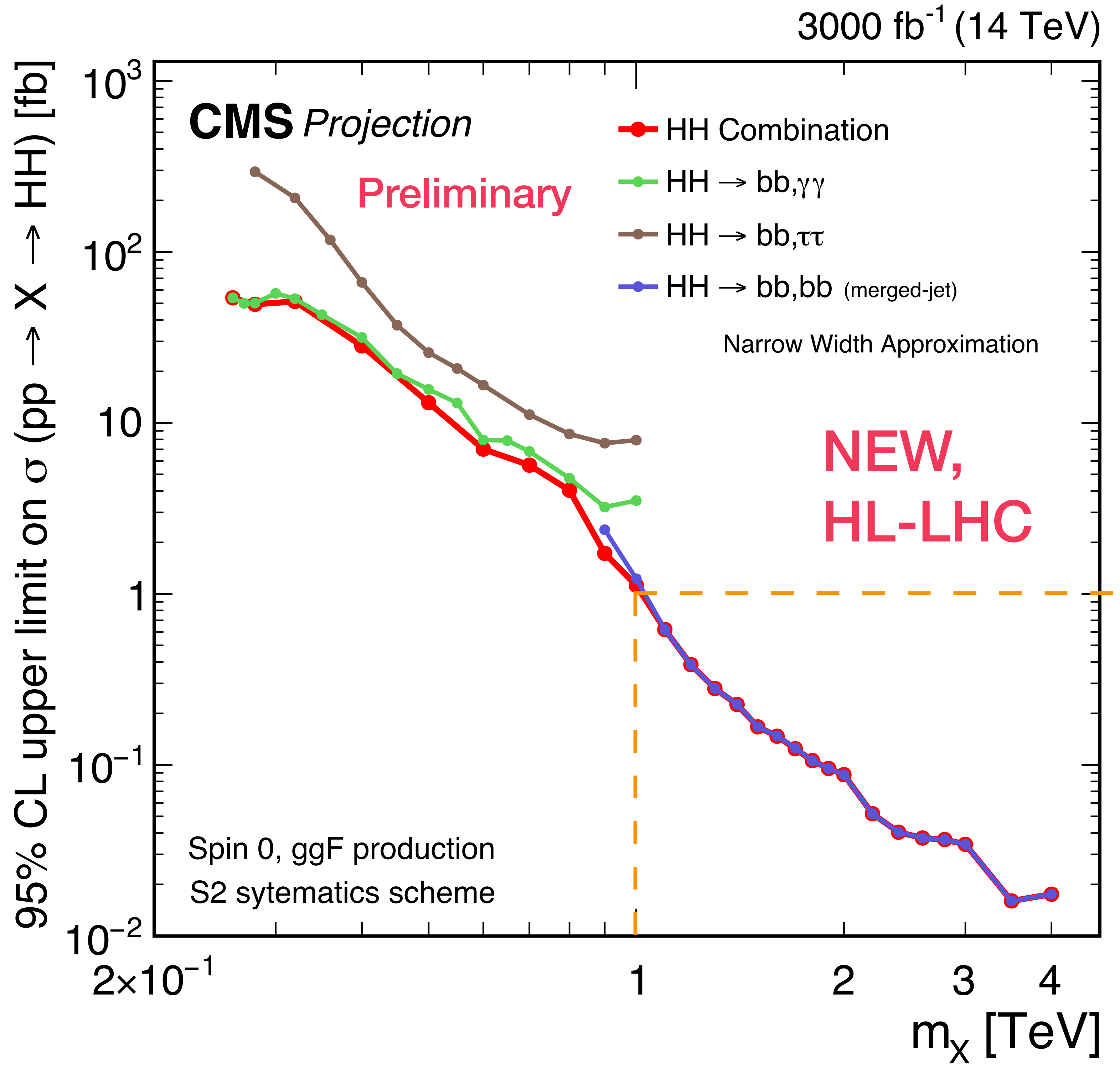
- No significant excess observed, the tighter observed limits after 1.6 TeV are due to lack of data.
- Interpretations are provided in the narrow and broad ($\Gamma_X = 0.2 m_X$) width approximation.

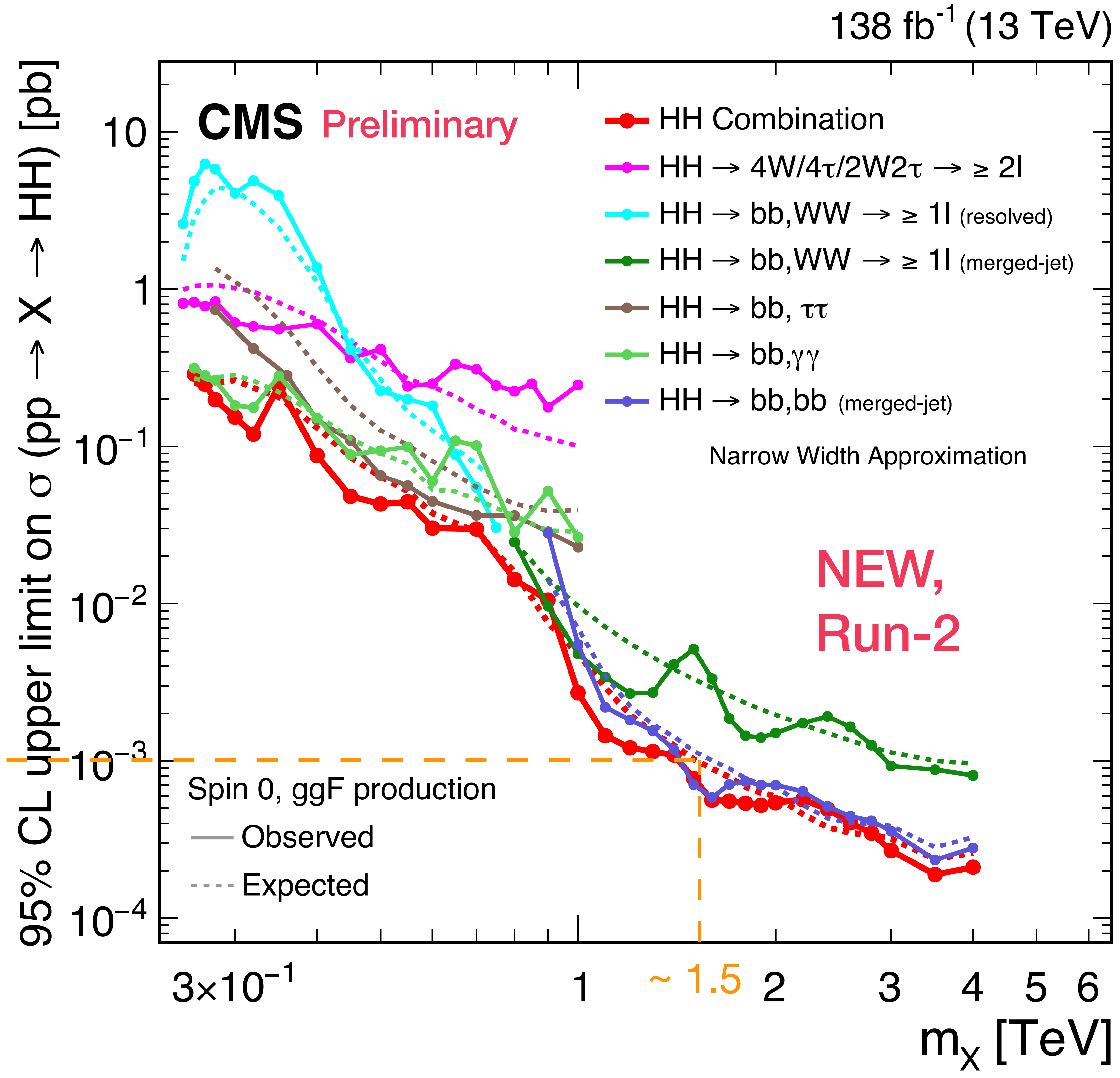




Extrapolation to HL-LHC: BSM

B2G-23-002



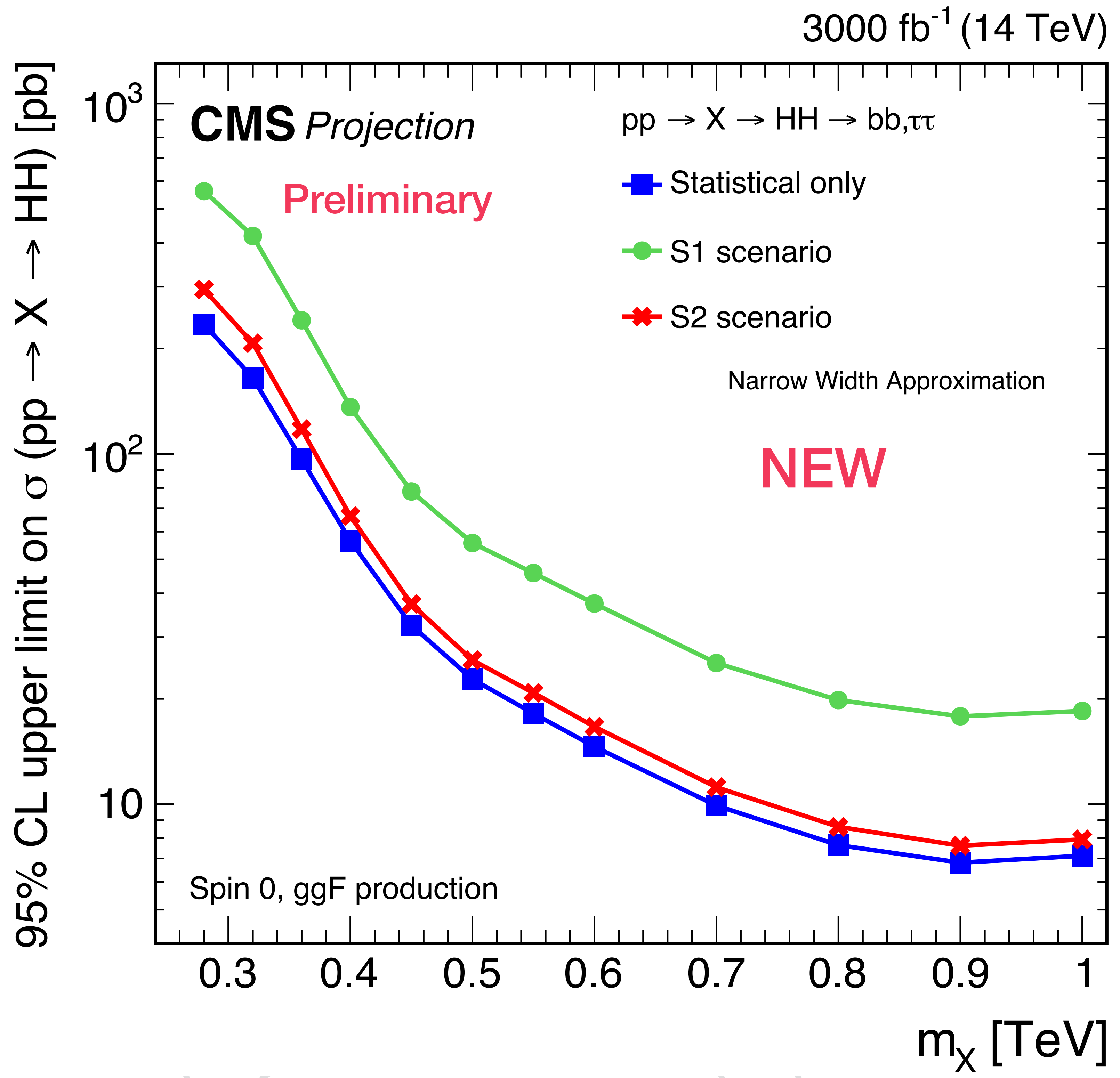


Beware that the axis have different units, the plots are aligned to allow comparisons (10^{-3} pb = 1 fb).

For instance the limit expected at 1 TeV is the one expected at ~1.5 TeV currently

Extrapolation to HL-LHC: BSM

B2G-23-002

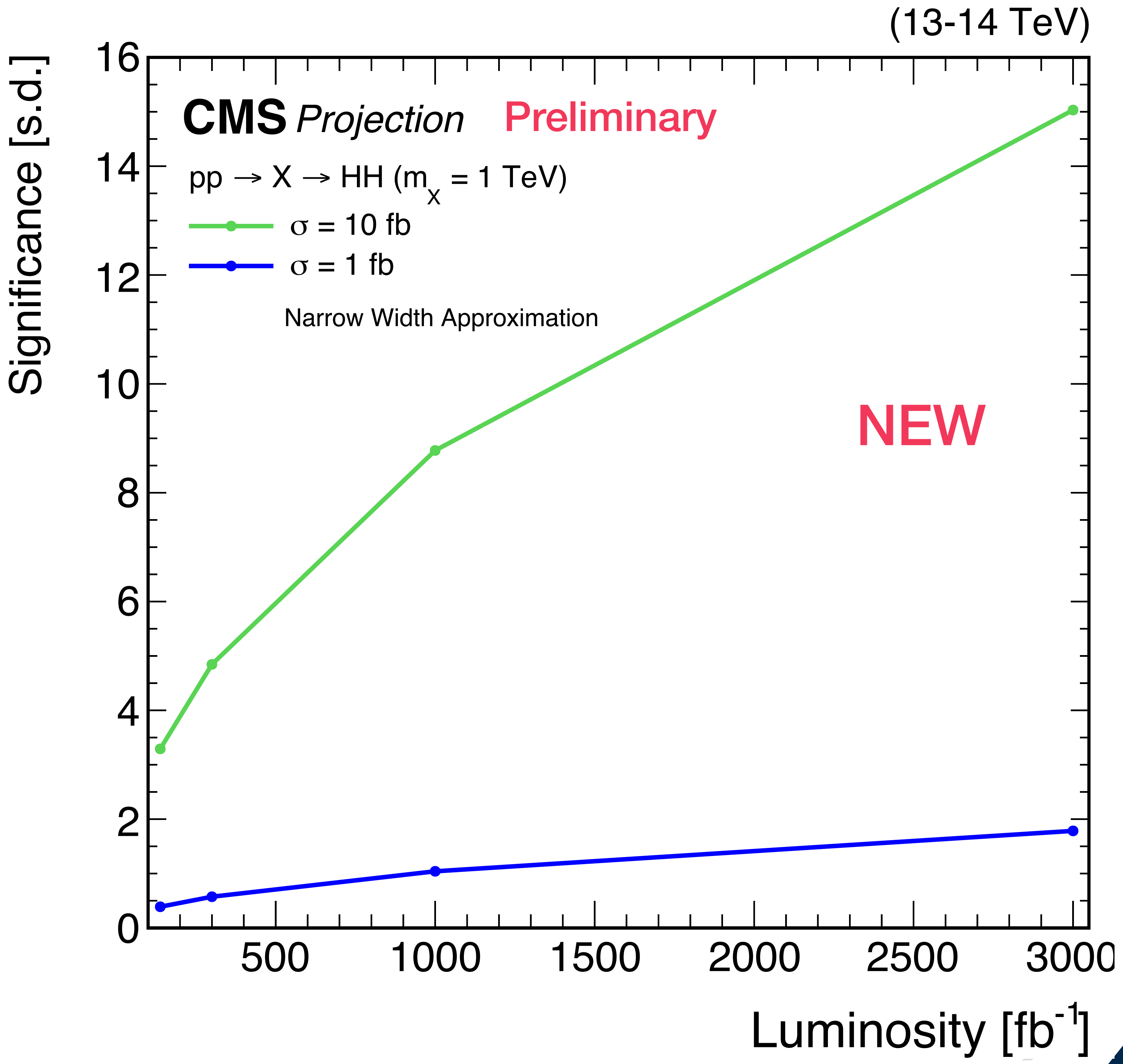


Two scenarios are considered:

- S1 (conservative): All the systematic uncertainties are assumed to remain the same as in Run 2. Furthermore, progress in the theory calculations is expected to reduce the uncertainties in the predictions.
- S2: The theory uncertainties are halved, while the experimental uncertainties are set according to the recommendations.

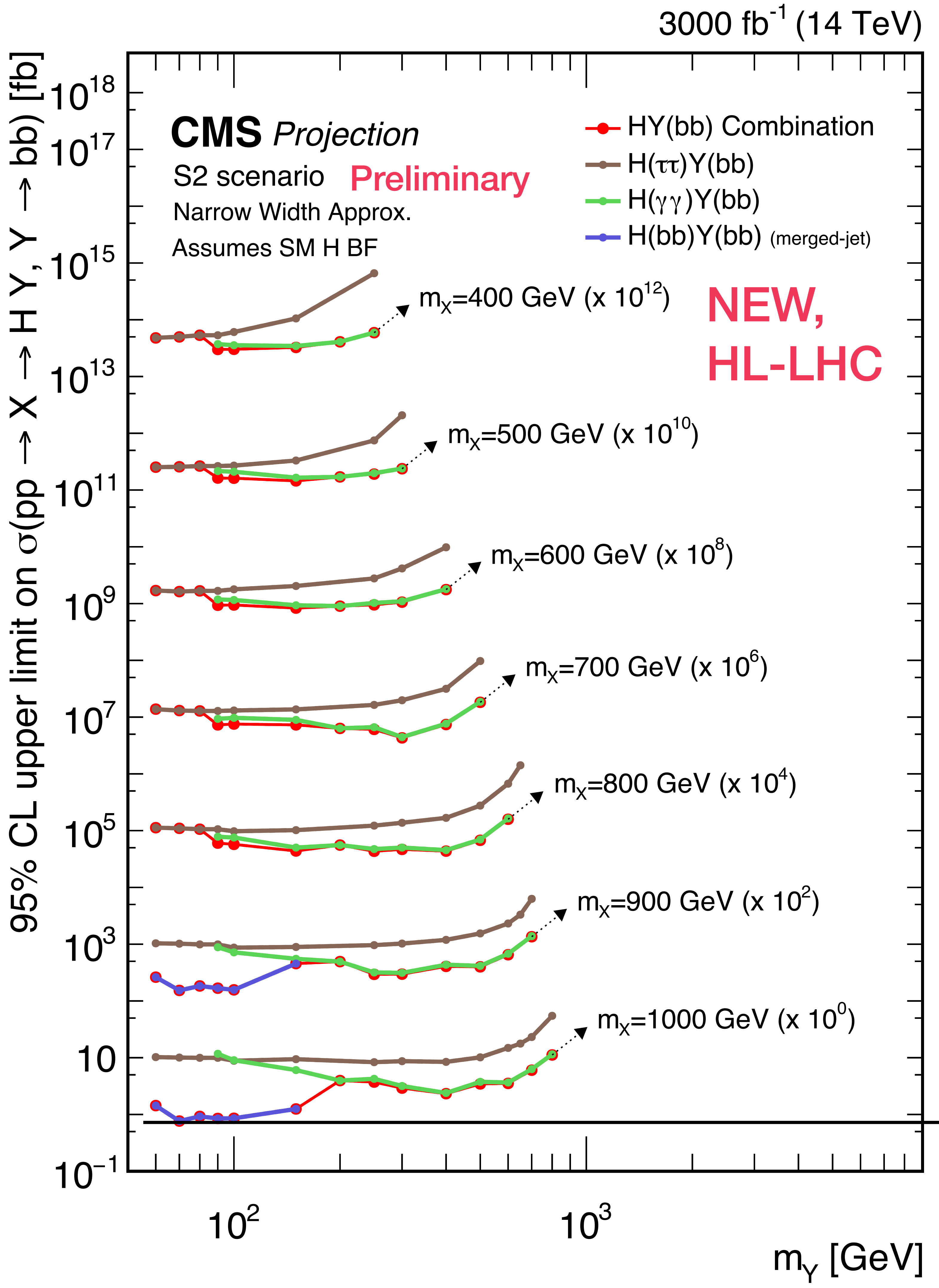
The only channel that is senstive to the different scenarios is the $bb\tau\tau$ channel, the other ones being statistically dominated.

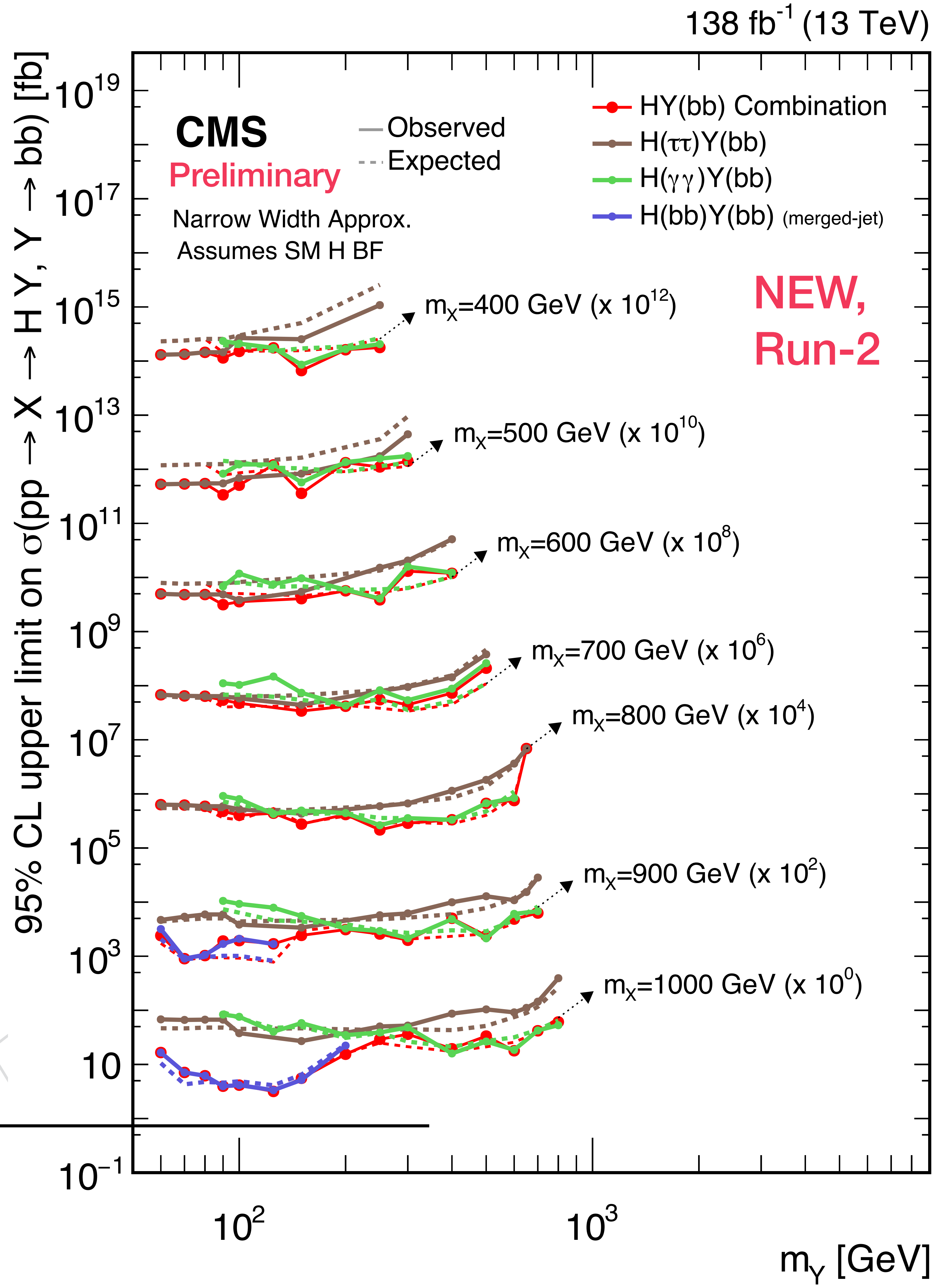
The discovery potential can be assessed for a 1 TeV resonance when combining all the channels, for two possible cross sections.



Extrapolation to HL-LHC: BSM

B2G-23-002



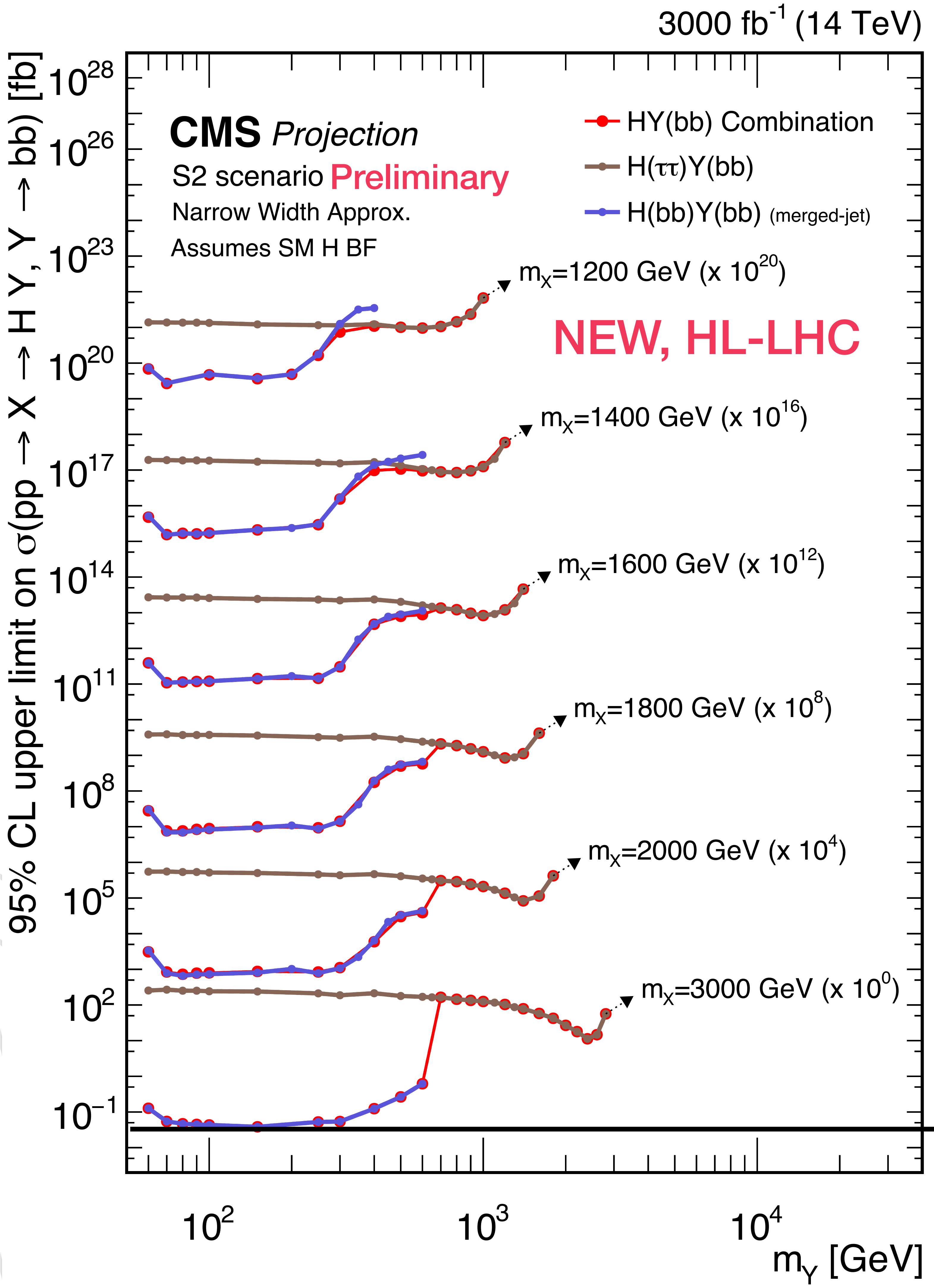


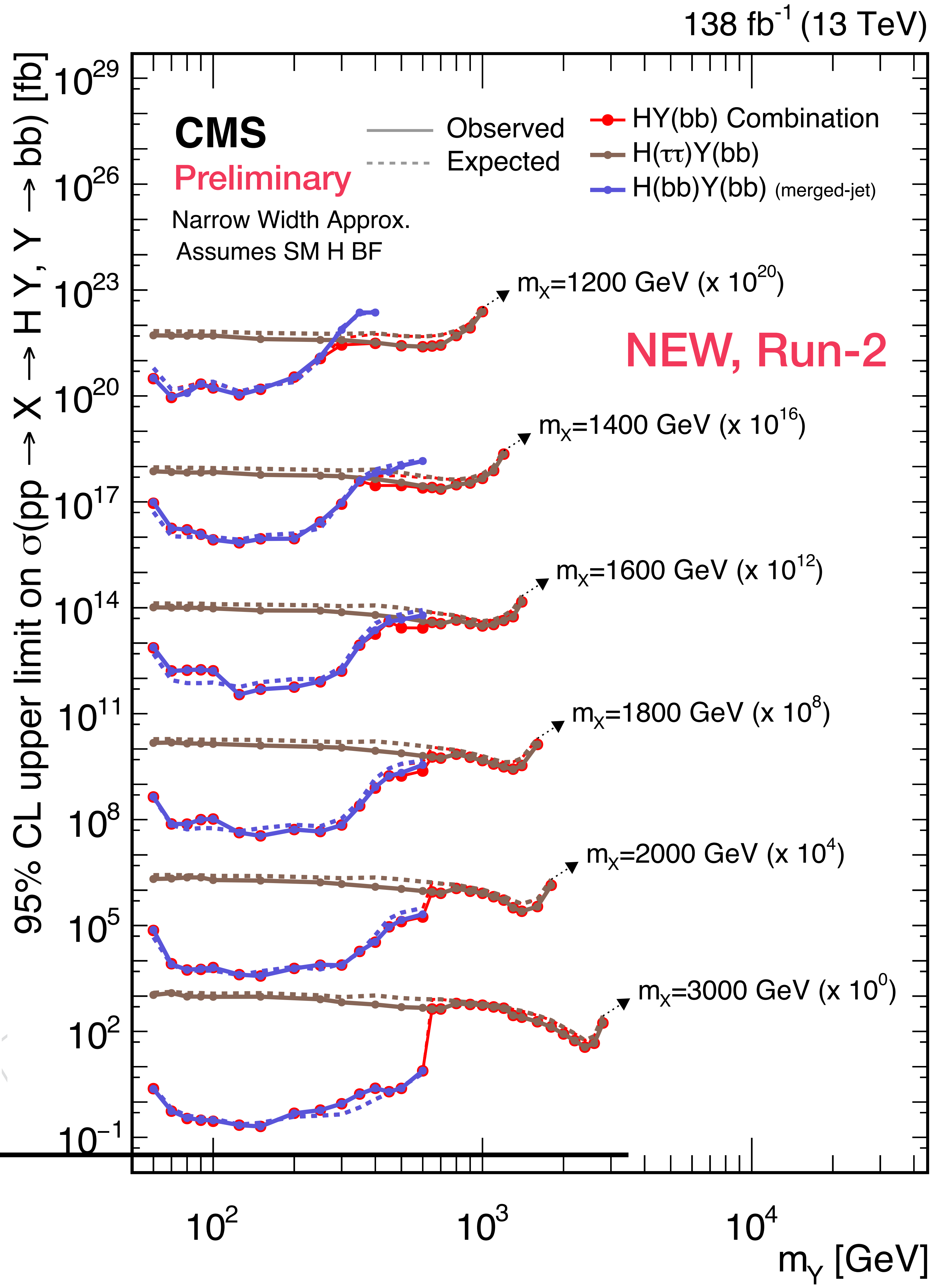
Same axis and scale factors for the same mass points between Run-2 and prospects at HL-LHC.

Only the expected limits are to be compared.

Extrapolation to HL-LHC: BSM

B2G-23-002





Same axis and scale factors for the same mass points between Run-2 and prospects at HL-LHC.

Only the expected limits are to be compared.

List of results CMS (full Run-2):

- Summary: https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG
- Combinaison: https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-22-001/index.html

HH:

- HH->4b (PRL 22) https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-20-005/index.html
    - VBF Boosted search (PRL 23): https://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-22-003/index.html
    - Superseeded by the combination result;
    - VHH->4b (PAS) https://cds.cern.ch/record/2853338
- HH->bbtautau (PLB 23) https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-20-010/index.html
- HH->bbyy (JHEP 21) https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-19-018/index.html
- HH->ML (4W,2W2taus, 4taus) (JHEP 23) https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-21-002/index.html
- HH->WWyy (PAS) https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-21-014/index.html
- HH->bbWW(l+) (PAS) https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-21-005/index.html
- HH->bbZZ(4l) (JHEP 23) https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-20-004/index.html
- HH->yytt (CONF) https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-22-012/index.html

X->HH

- X->HH->bbyy (submitted to JHEP) https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-21-011/
- X->HH->4b (PLB 22) https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G-20-004/index.html
- X->HH->bbWW/bbtt (JHEP 2022) https://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-20-007/index.html
- X->HH->ML (JHEP 23) https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-21-002/index.html

X->SH

- X->SH->4b (boosted) (PLB 23) https://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-21-003/index.html
- X->SH->bbtt (JHEP 21) https://link.springer.com/article/10.1007/JHEP11(2021)057
- X->SH->bbyy (submitted to JHEP) https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-21-011/

List of results ATLAS (full Run-2):

Combination:

- Non resonant: (PLB 23) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2022-03/
- Resonant: (Sub. PRL) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2023-17/
- EFT bbyy+bbtautau (Pub Note) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-019/

HH:

- HH->4b: (PRD 23) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-29/
    - Boosted VBF (CONF) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2024-003/
    - VHH->4b (EPJC 23) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-31
- HH->bbtautau (Conf) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-071/
- HH->bbyy (JHEP 24) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2021-10
- HH->bbll (WW,ZZ,tautau) (JHEP 24) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-02/
- HH->ML (CONF) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2024-005/

To be noted there are some partial Run-2 analysis not available with full Run-2

X->HH

- X->HH->bbyy (PRD 22) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-34/
- X->HH->4b (PRD 22) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-41/
    - Resonant VBF (JHEP 20) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-18/
    - Boosted Resonant VBF (CONF) XXX
- X->HH->bbtautau (JHEP 23) https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-40/

X->SH

- X->SH->bbyy (CONF) XXX