

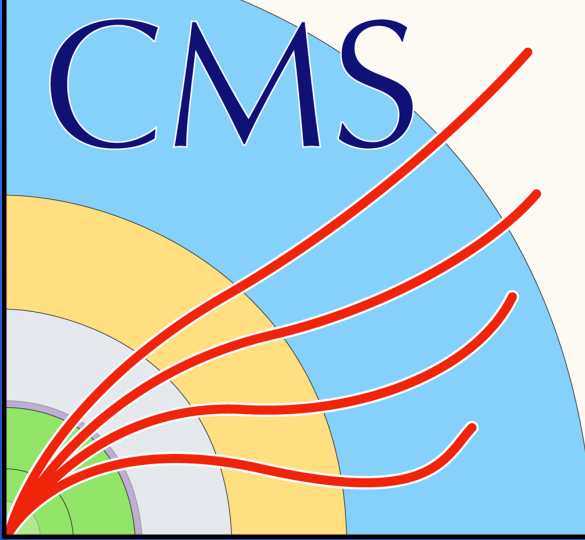


# HH and H BSM

Teng Jian Khoo

obo the ATLAS and CMS collaborations

*Standard Model at the LHC Workshop 2022*



# Making more of the Higgs

- 10 years later, 125 GeV scalar looks pretty much like SM Higgs boson
  - Major branching fractions observed [[Scanlon, Tues](#)]
  - CP properties do not show obvious anomalies [[Liang, later today](#)]
- Main single-Higgs production channels do not give full picture
  - Di-Higgs production predicted, unique sensitivity to anomalous couplings
- Exotic decays and extended Higgs sector could reveal new physics
  - Portal to dark/hidden sectors
  - Effective Field Theories as generic interpretation across many analyses
- **Highlight recent results indicating directions of experimental exploration**

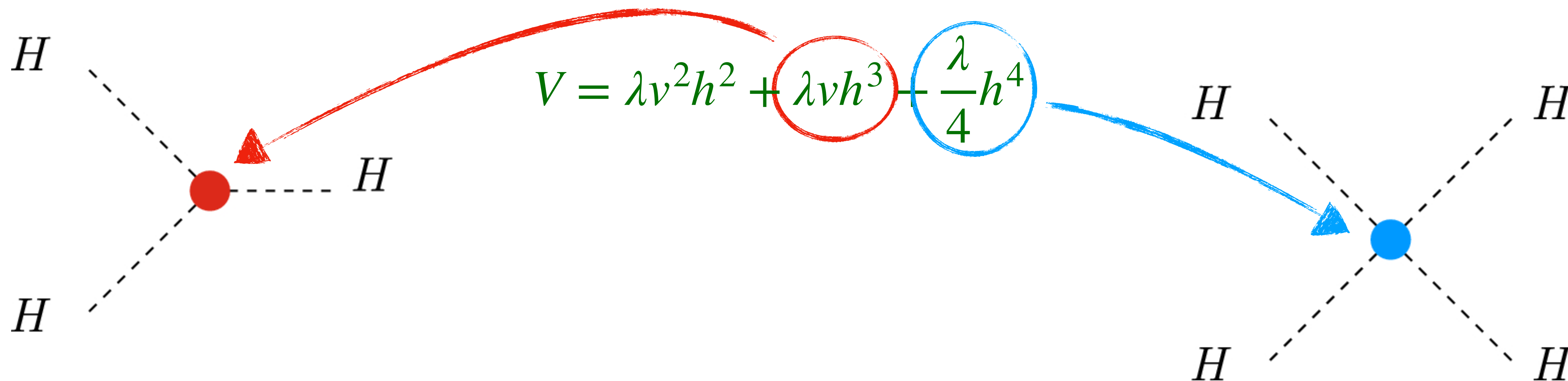
# Two Higgses are better than one





# SM Higgs mechanism

demands a Higgs self-coupling!



Self-interactions implied by Higgs potential



# SM Higgs mechanism

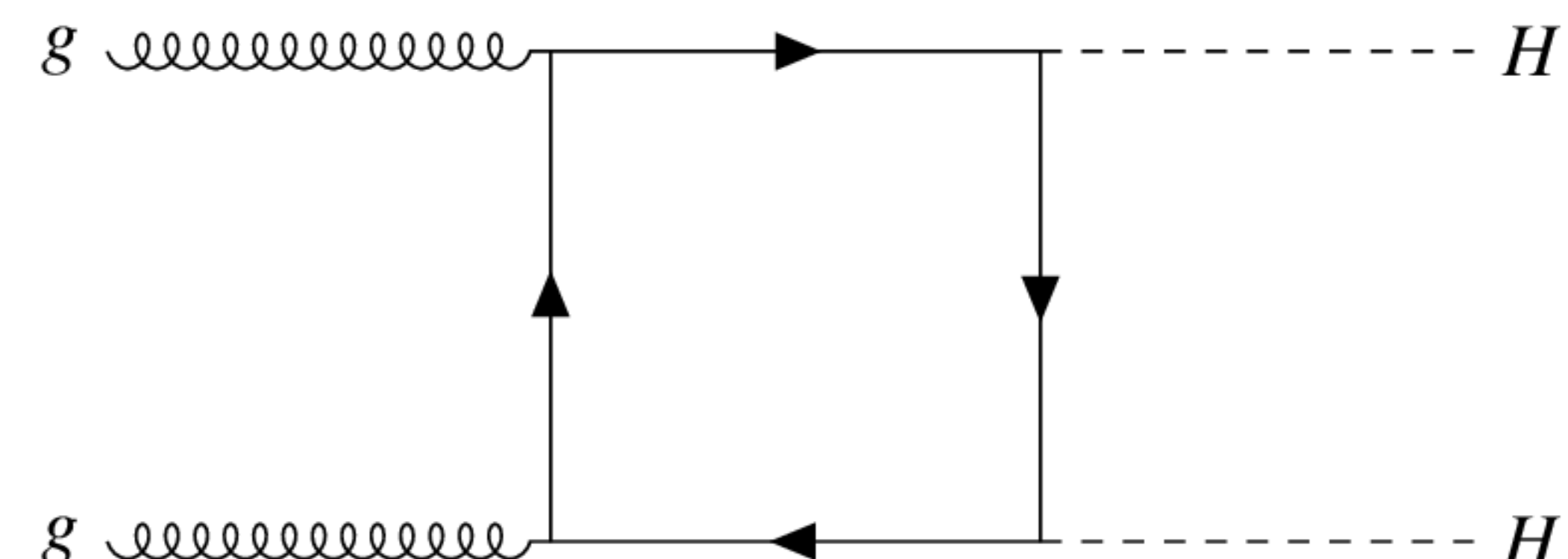
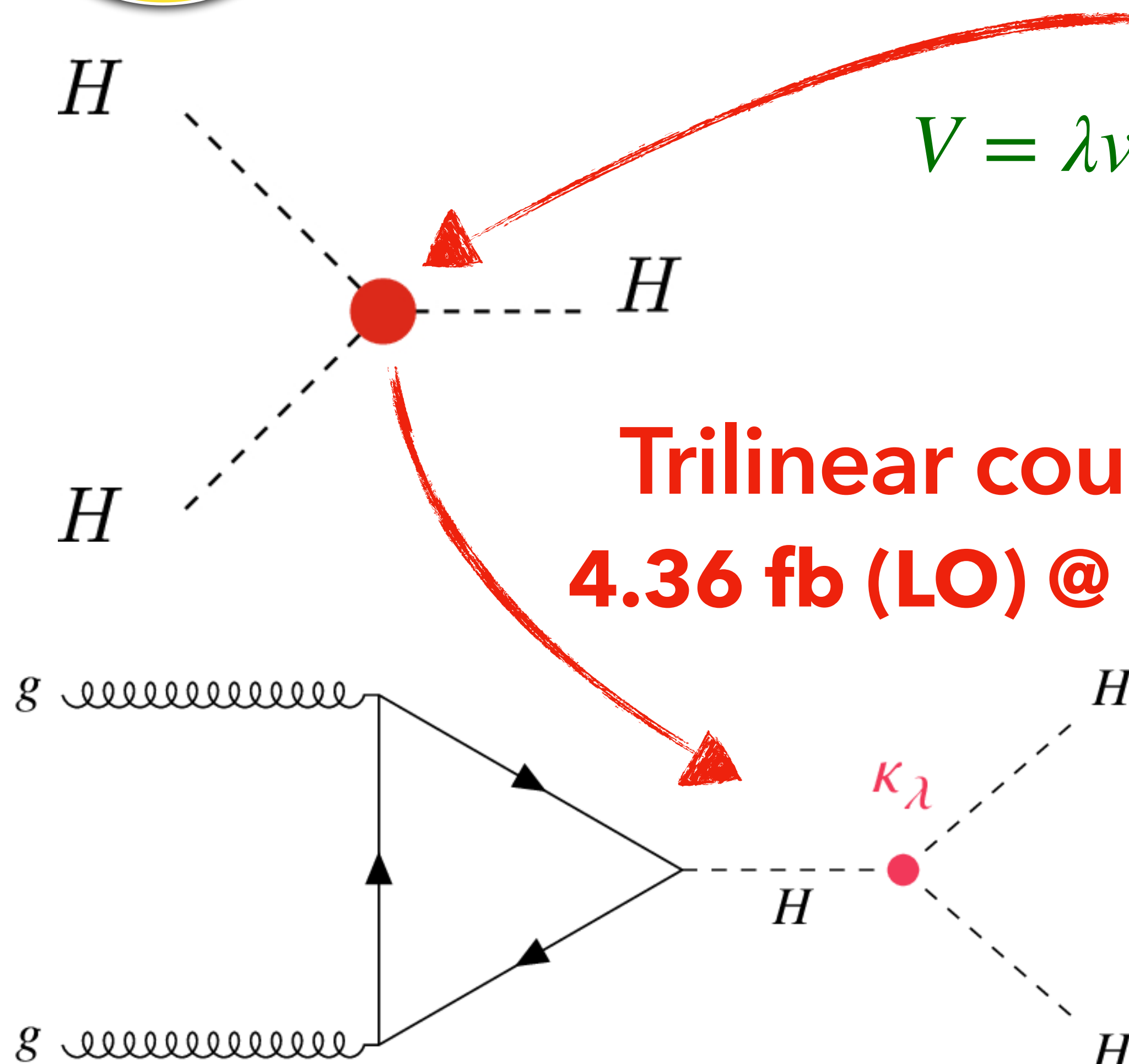
demands a Higgs self-coupling!

$$V = \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

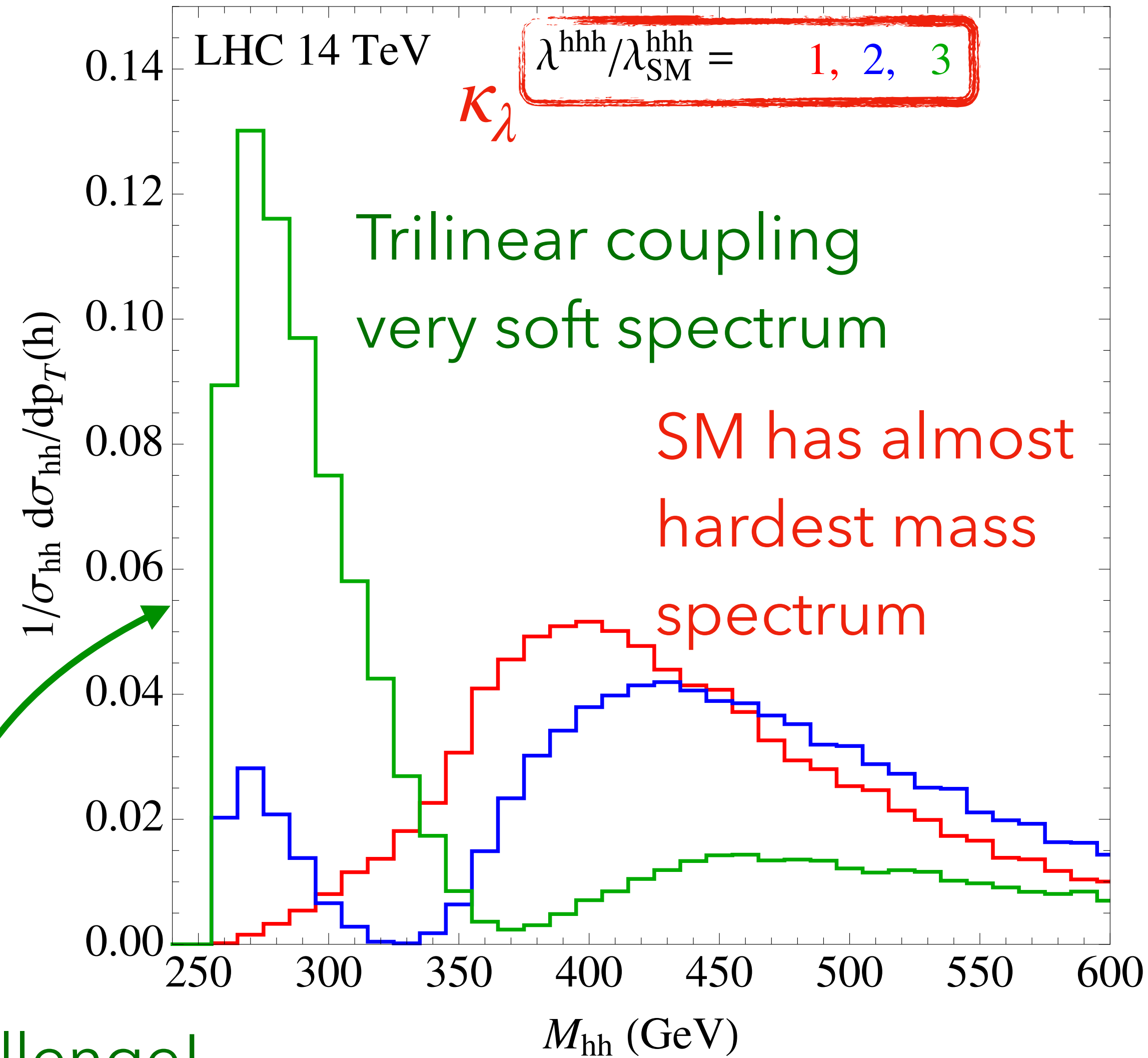
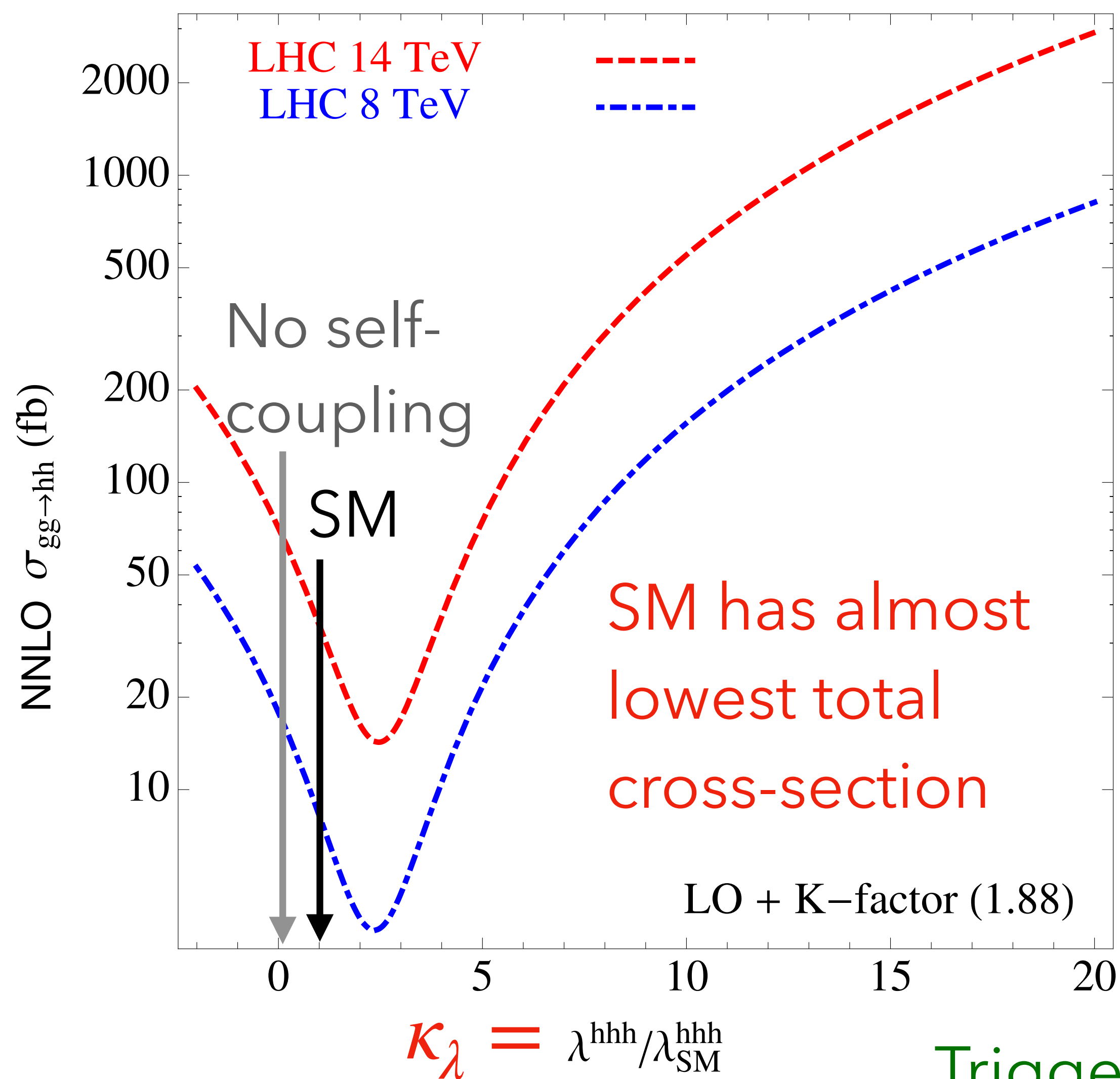
**Trilinear coupling**  
**4.36 fb (LO) @ 13 TeV**

Interference!

**Box diagram**  
**31.6 fb (LO) @ 13 TeV**



# DiHiggs @ LHC

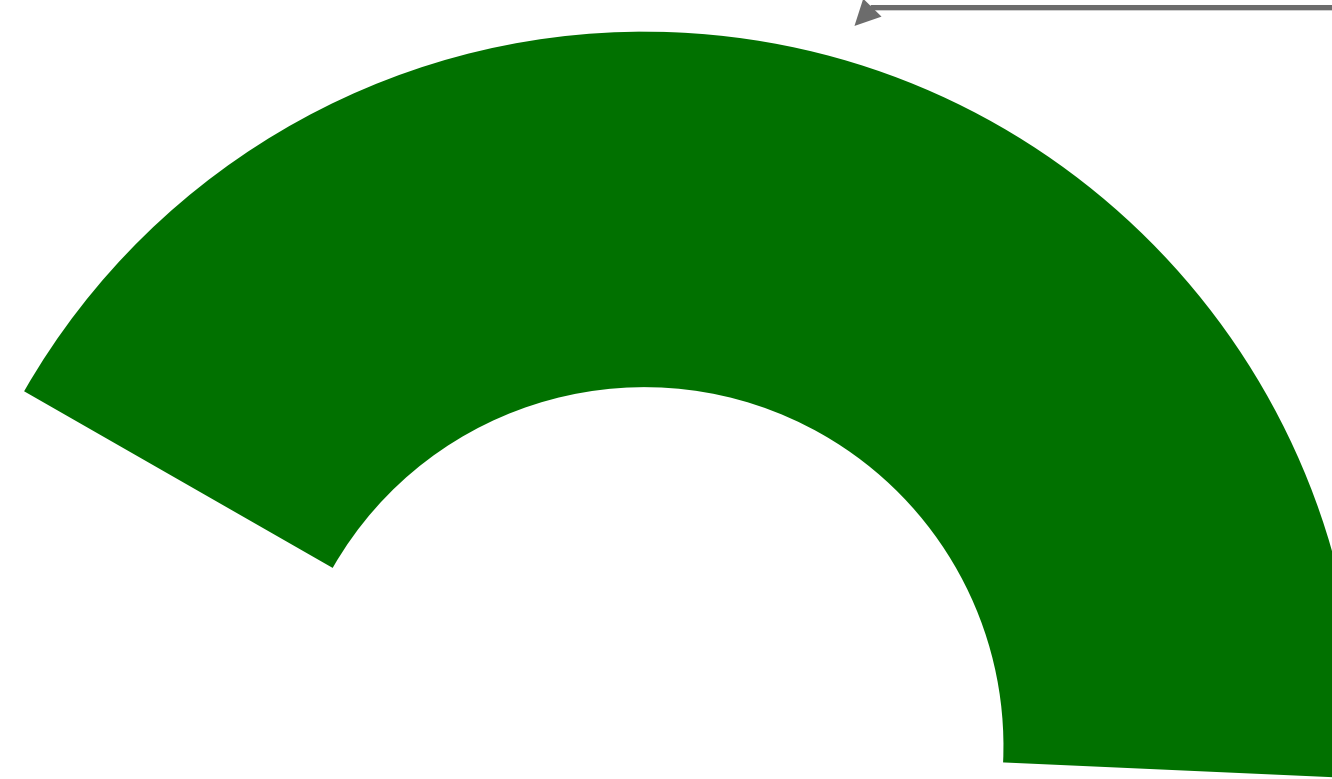
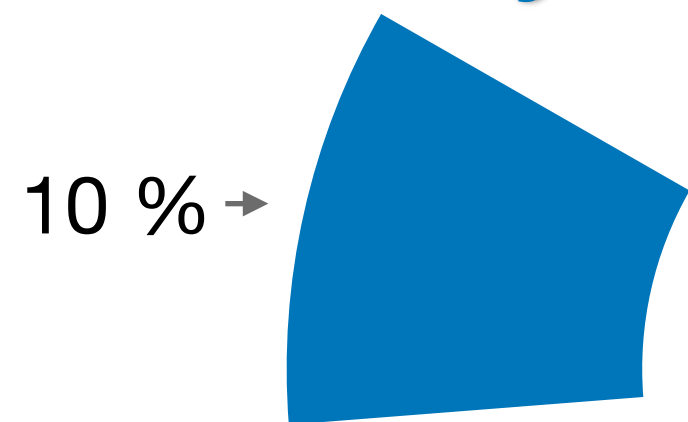


Trigger challenge!

# Primary experimental signatures

$bb\tau\tau$

- Mixed leptonic/hadronic decays

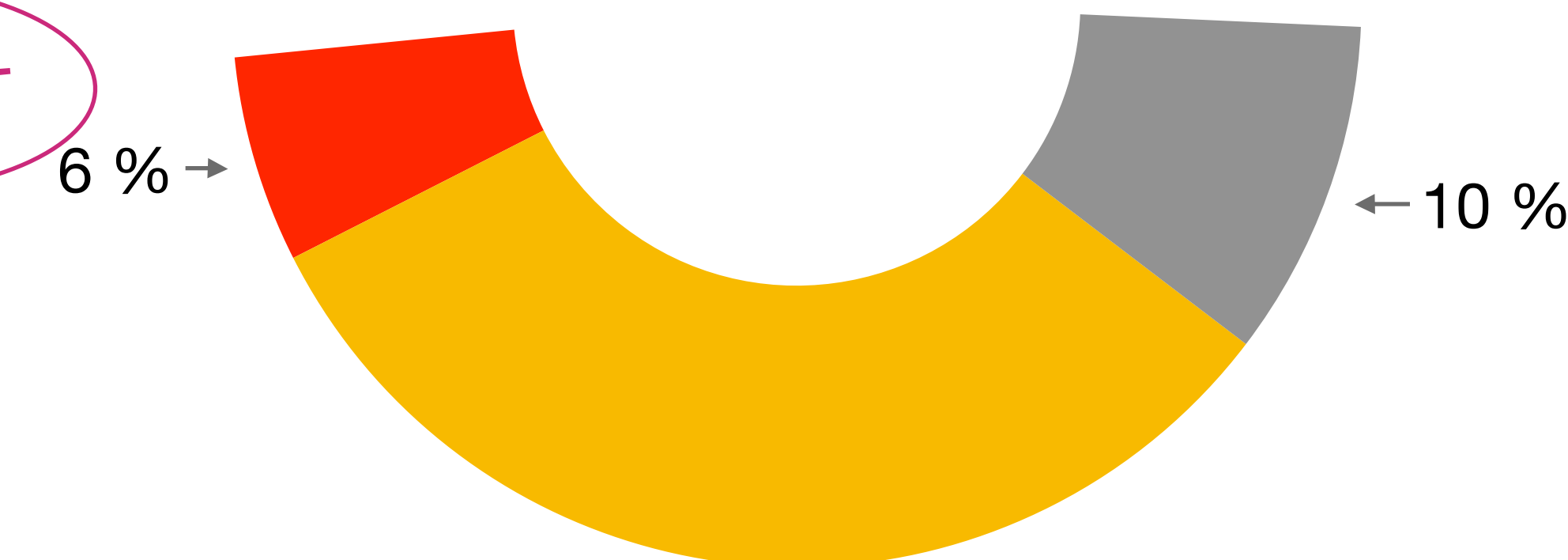


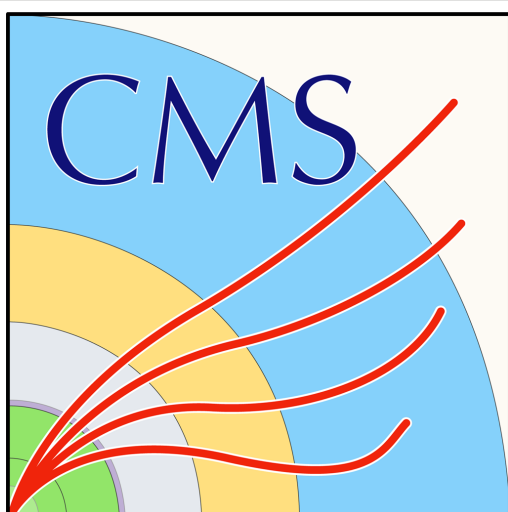
$bbbb$

- Largest statistics
- Challenging background

$bb\gamma\gamma$

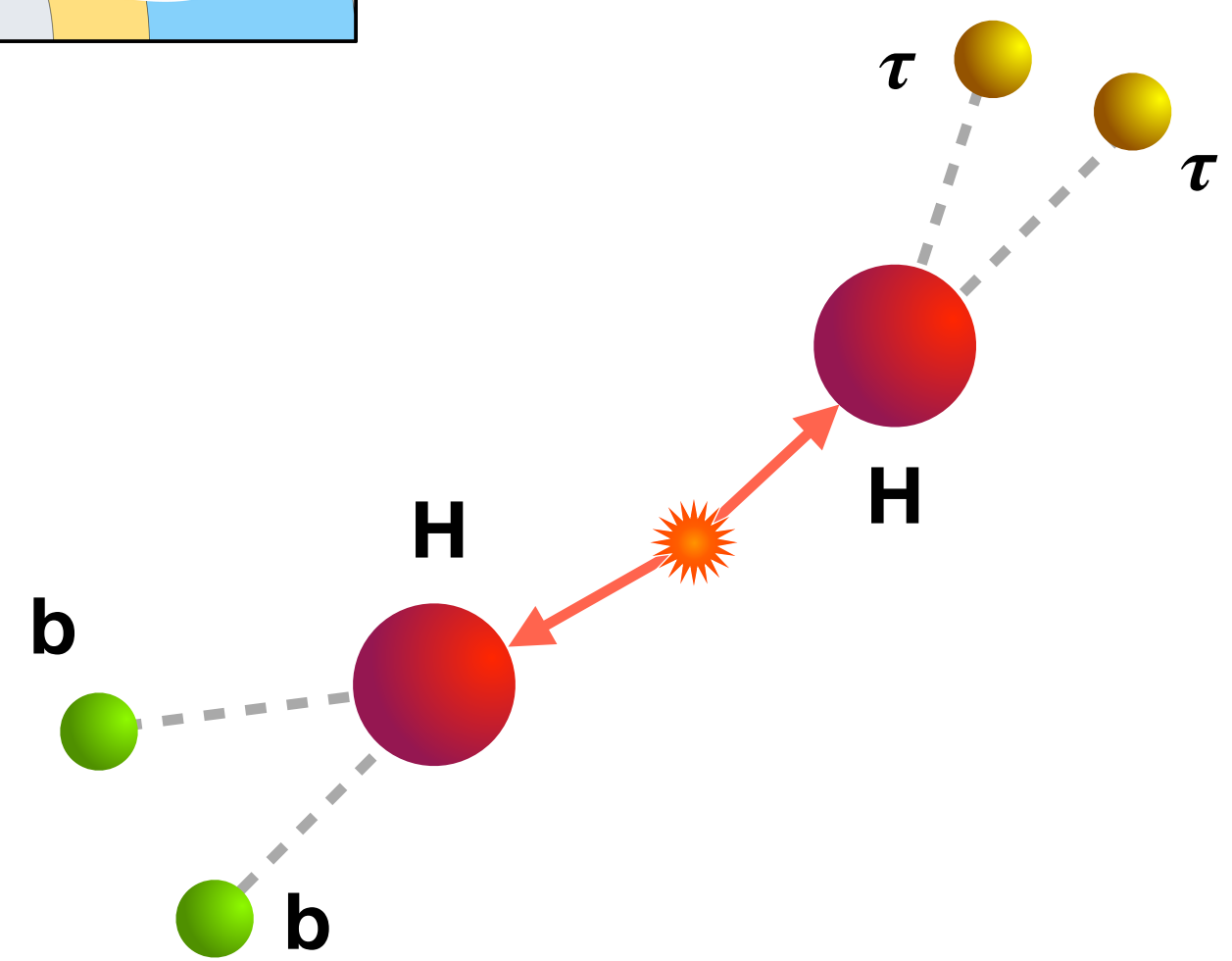
- Cleanest peak
- Small branching fraction (0.26%)



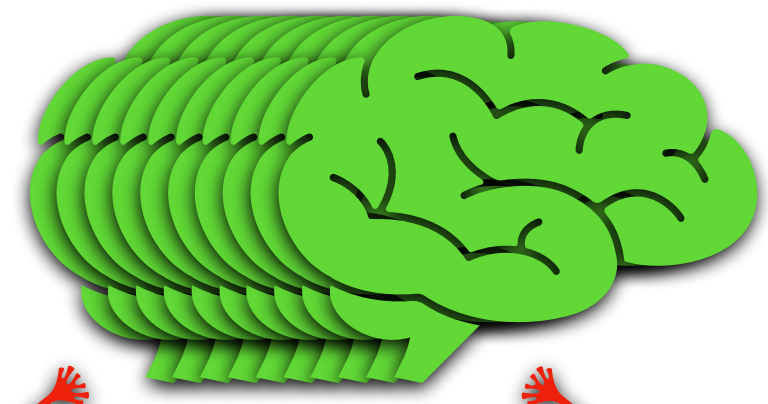


# CMS $bb\tau\tau$ (Mar 2022)

As seen on Tues  
*Holgado YSF talk*

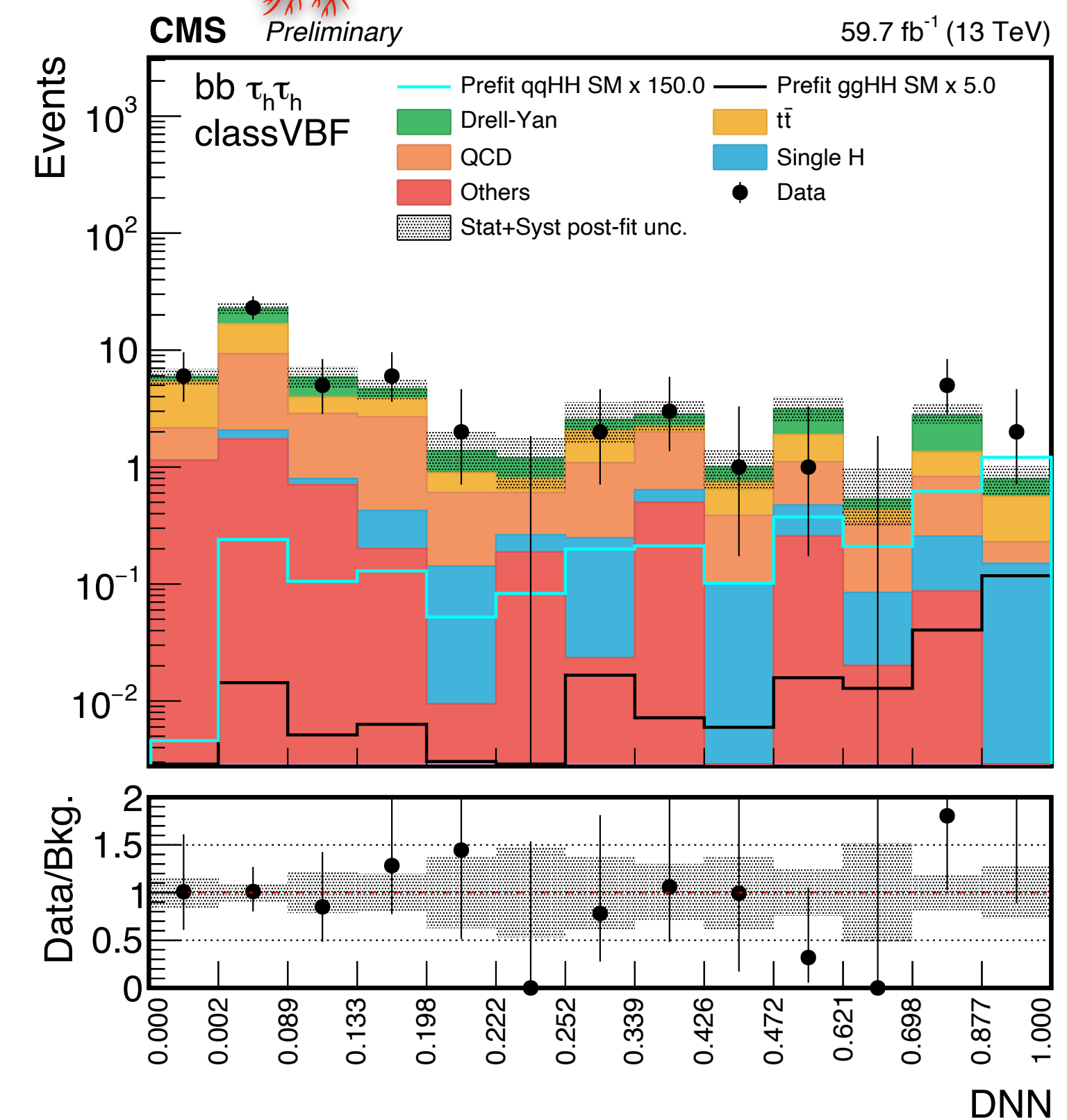
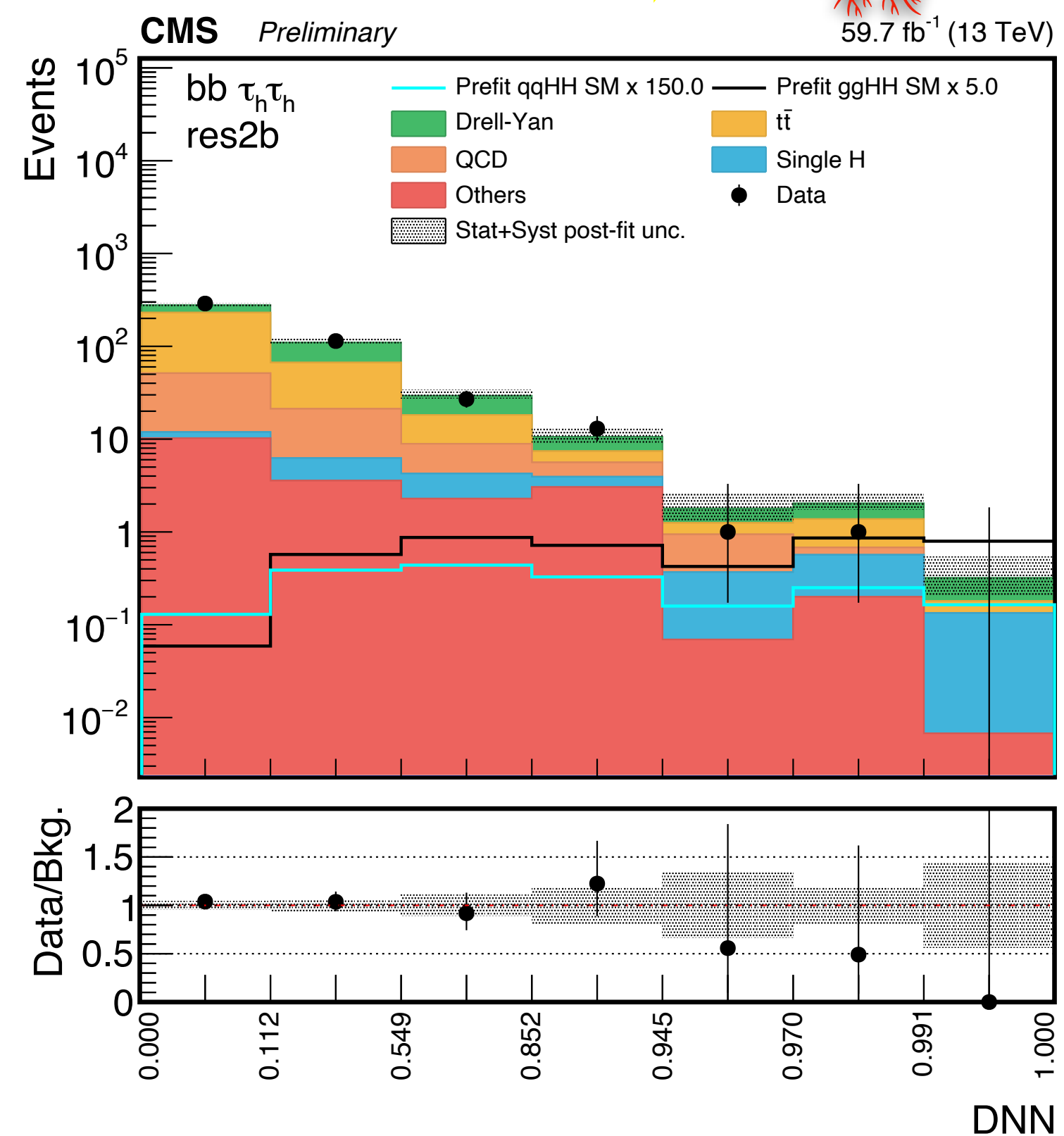


8-way event classification:  
Resolved 1b, 2b  
Boosted  
VBF vs (ggF / ttH / tt / DY)

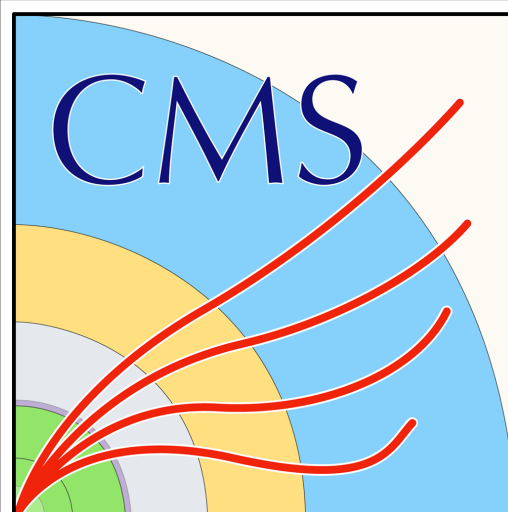


Ensemble of Deep  
Neural Networks for  
signal/background  
discrimination  
[arXiv:2002.01427](https://arxiv.org/abs/2002.01427)

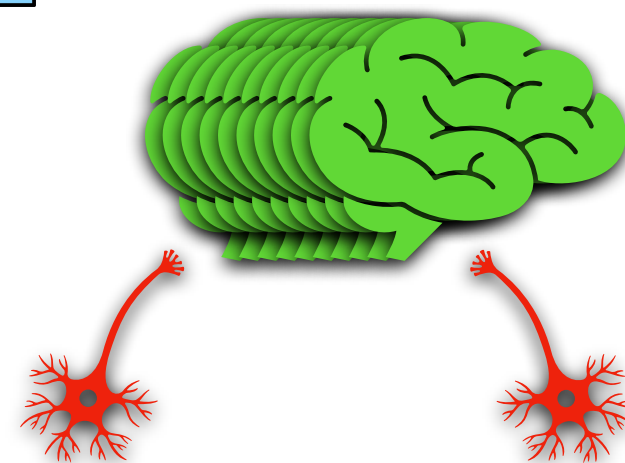
138 fb<sup>-1</sup> (2016-2018) pp @ 13 TeV  
DeepTau classification vs e/mu/jet  
Decay channels:  $\tau_h\tau_h, \tau_e\tau_h, \tau_\mu\tau_h$   
with corresponding triggers (incl VBF)  
DeepJet b-tagger  
HH-BTag NN for b-tag pairing



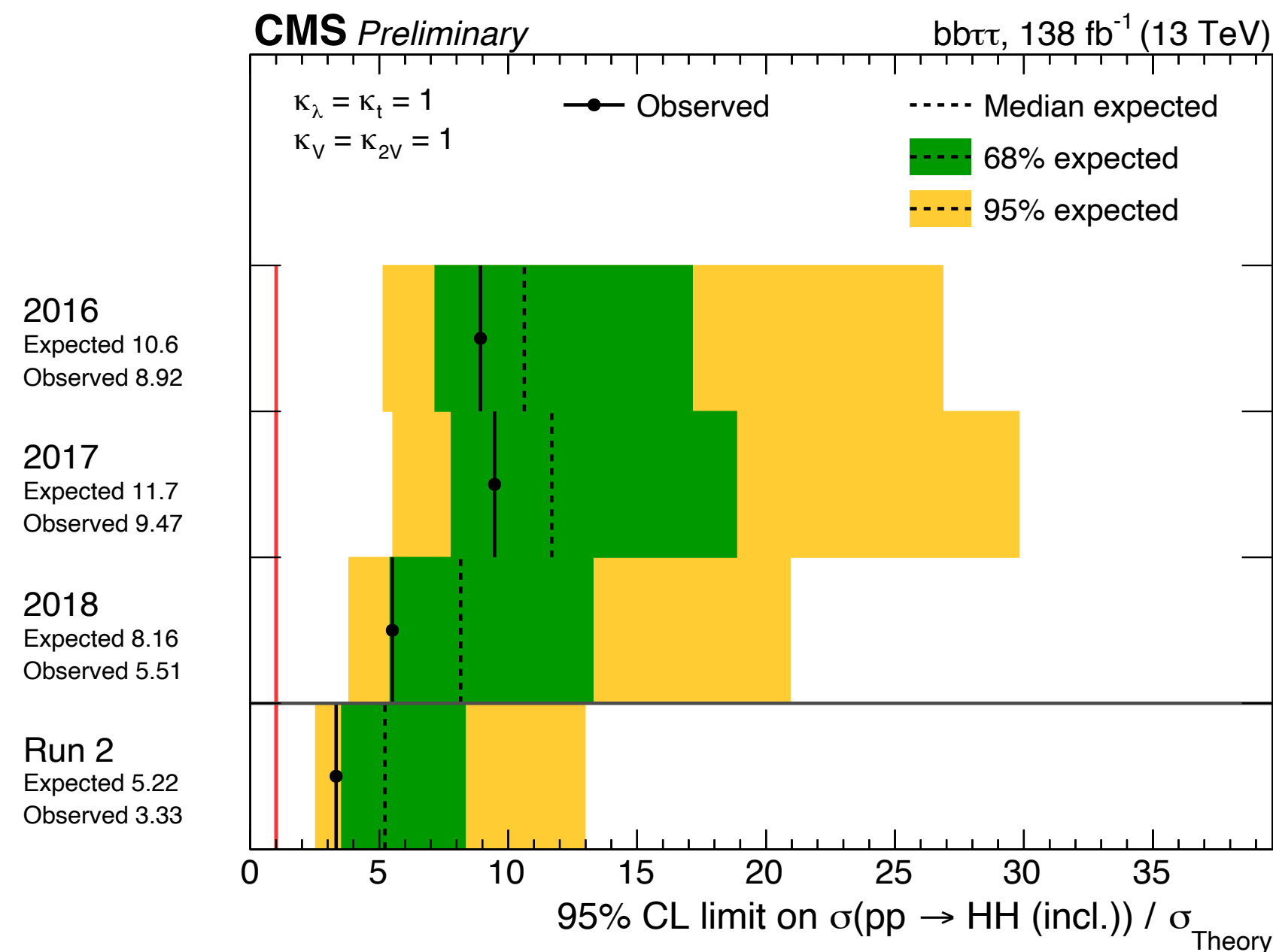
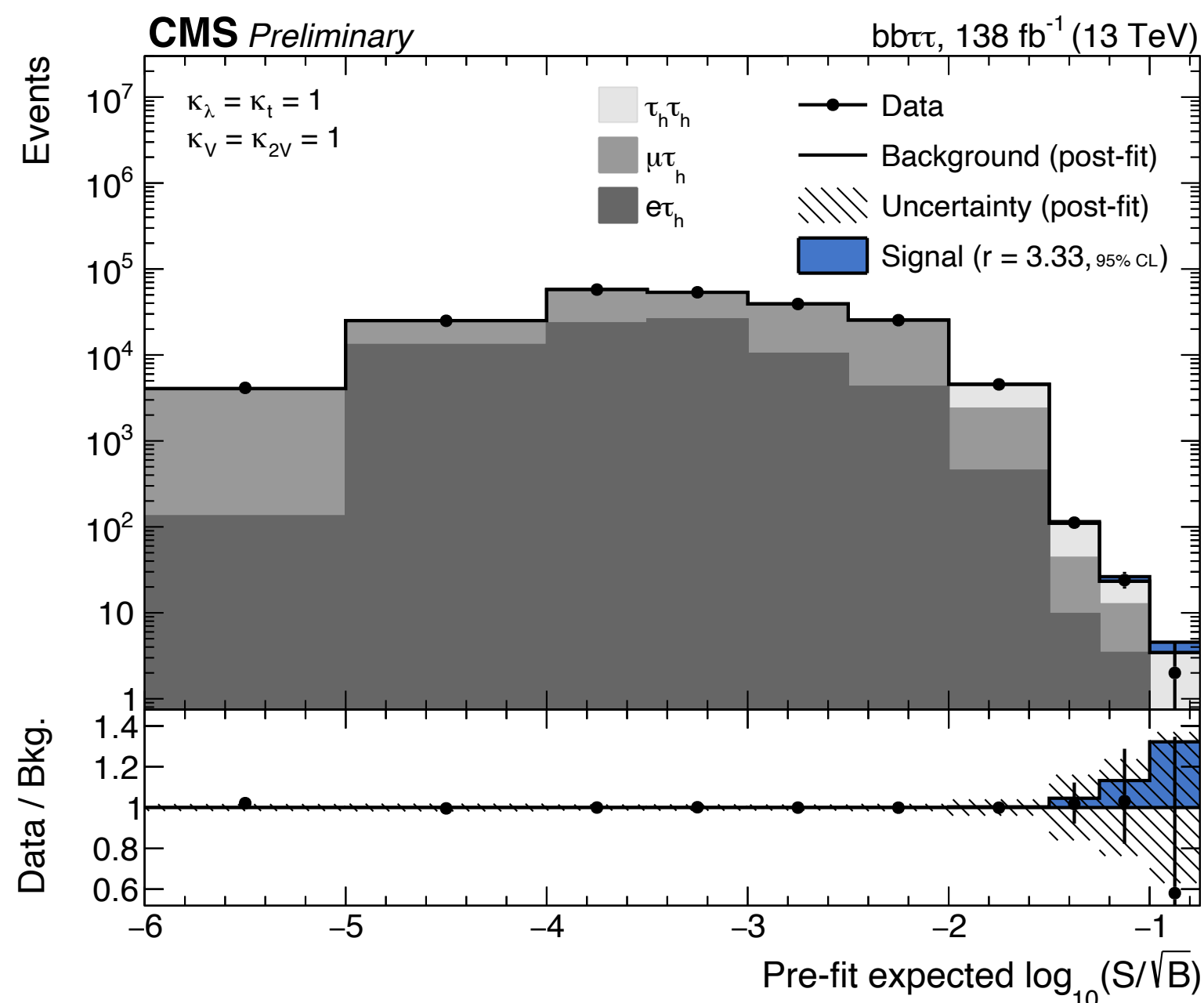




# CMS $bb\tau\tau$ (Mar 2022)

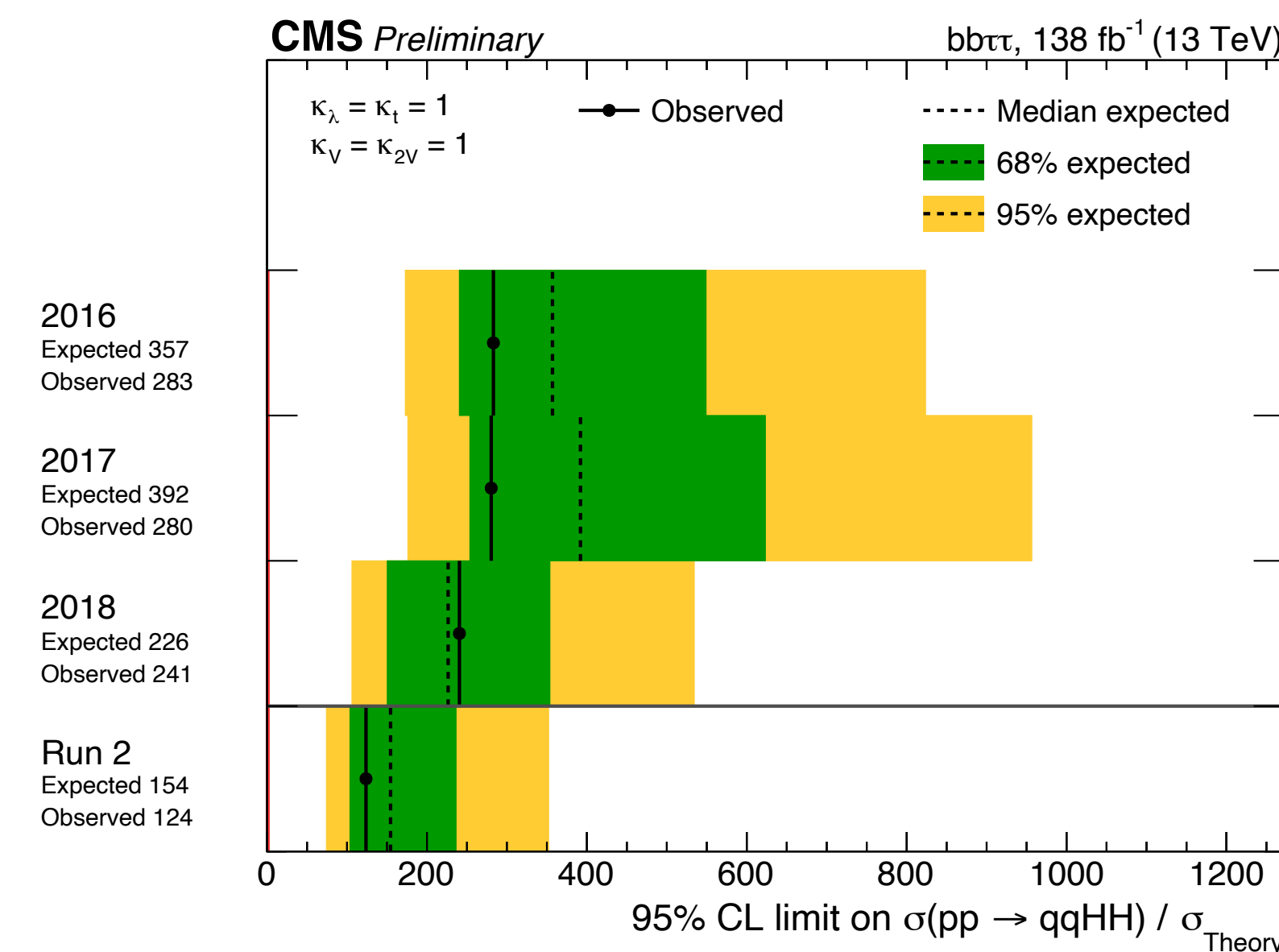


**Binned maximum likelihood fit over DNN output values**  
*Displayed by tau decay channel*



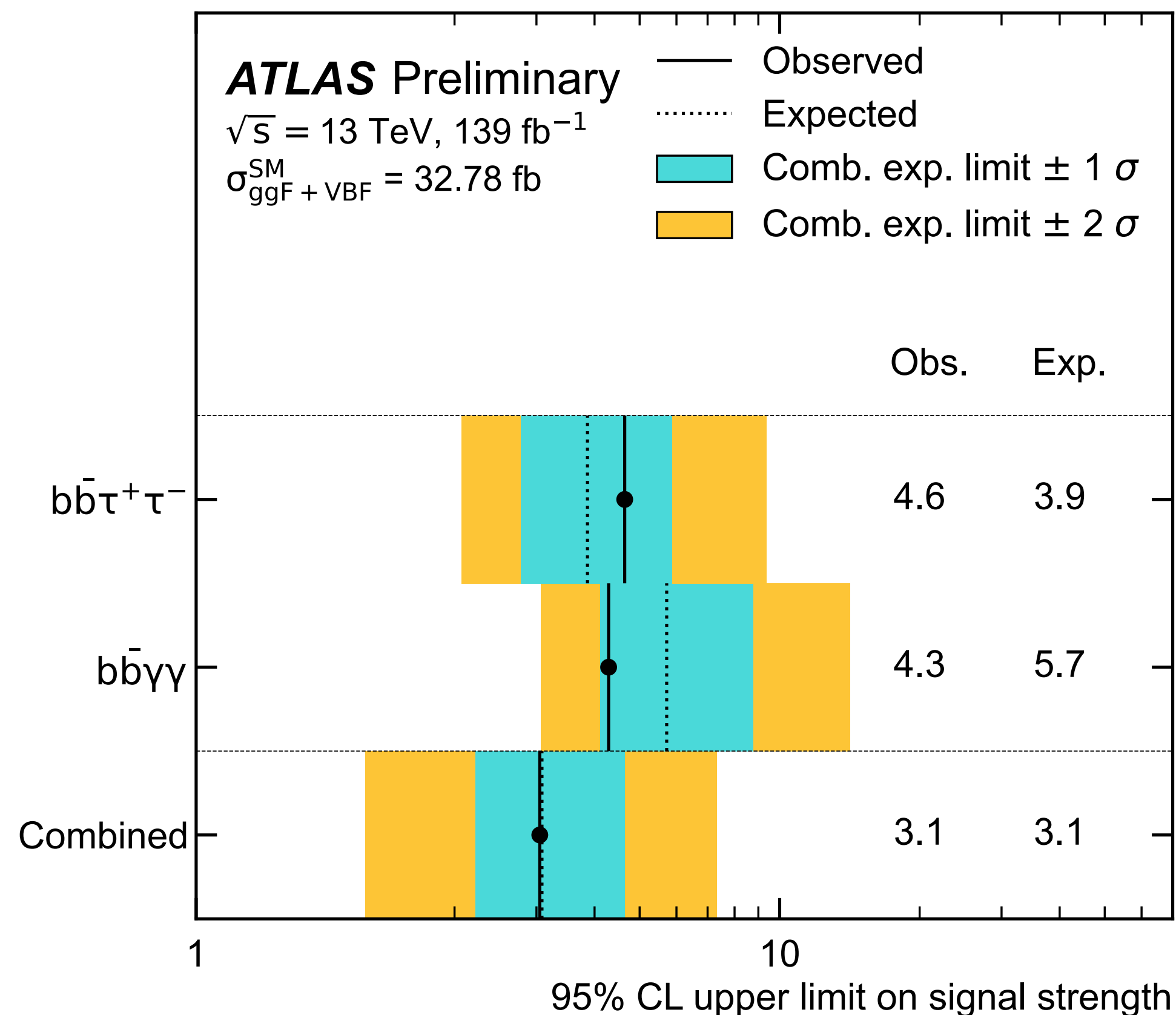
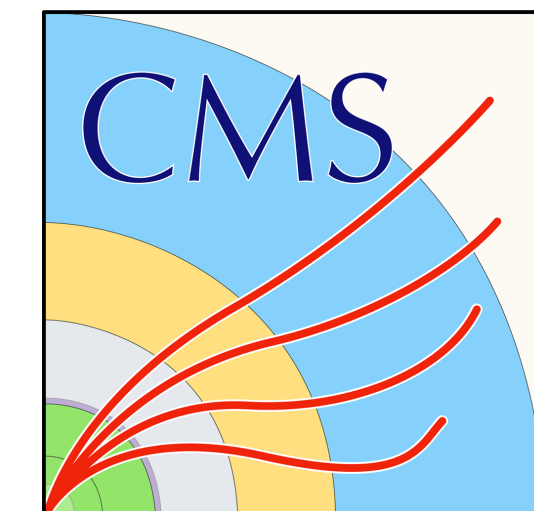
**Limit on VBF alone:**  
**124 x  $\sigma_{SM}$**   
 (expected 154)

**Limit on ggF+VBF:**  
**3.33 x  $\sigma_{SM}$**   
 (expected 5.22)





# SM $\sigma_{HH}$ limits



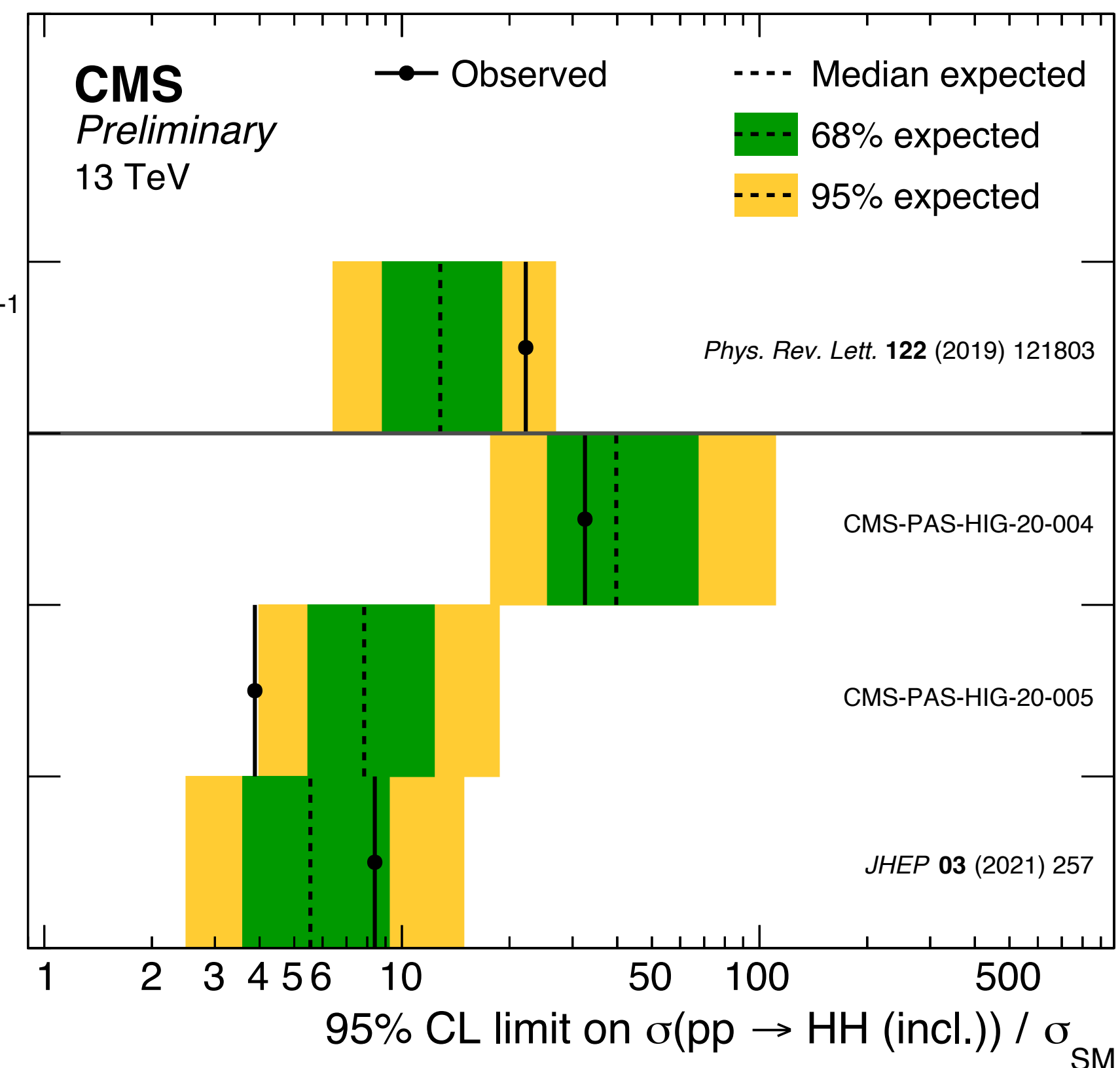
ATLAS combination  
[ATLAS-CONF-2021-052](#)

Run II 2016, 35.9  $\text{fb}^{-1}$   
 Expected 12.8  
 Observed 22.2

$b\bar{b}ZZ, 138 \text{ fb}^{-1}$   
 Expected 39.8  
 Observed 32.5

$b\bar{b}bb, 138 \text{ fb}^{-1}$   
 Expected 7.84  
 Observed 3.88

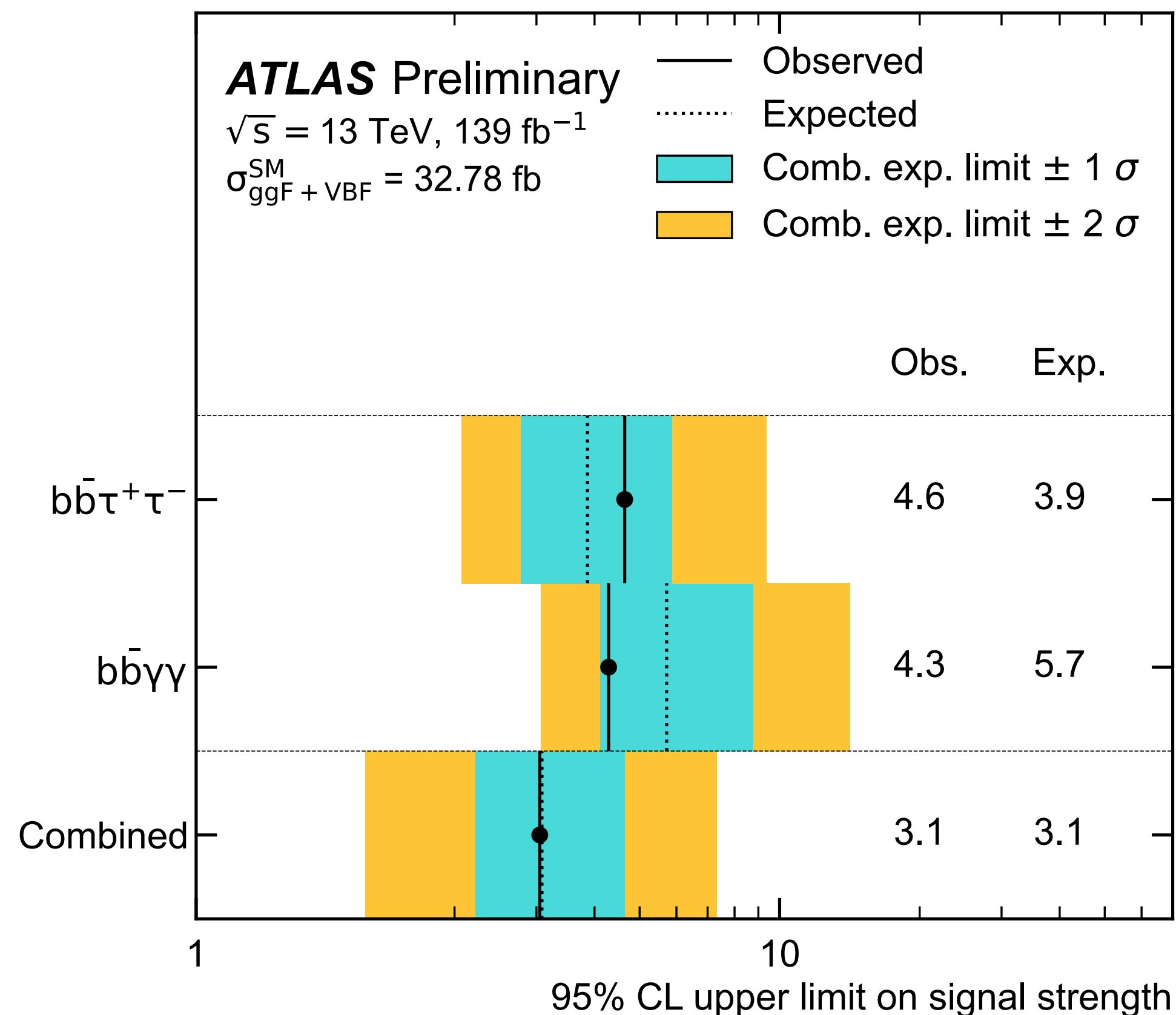
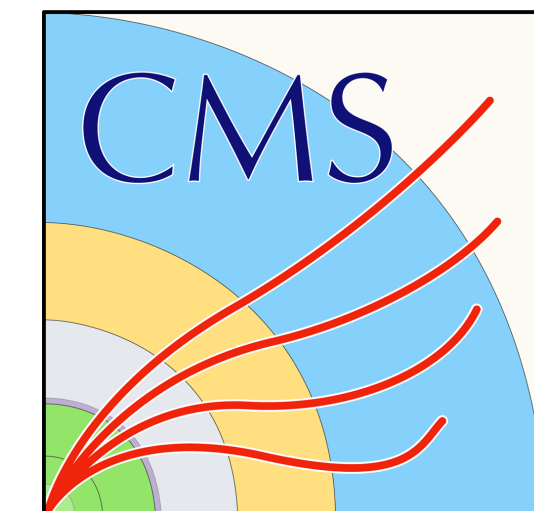
$b\bar{b}\gamma\gamma, 138 \text{ fb}^{-1}$   
 Expected 5.55  
 Observed 8.40



CMS summary plot  
[SummaryResultsHIG](#)



# SM $\sigma_{HH}$ limits



ATLAS combination  
[ATLAS-CONF-2021-052](#)

**2022  $4W/\text{WW}\tau\tau/4\tau$**   
**Obs 21.8**  
**[CMS-PAS-HIG-21-002](#)**

Run II 2016, 35.9  $\text{fb}^{-1}$   
 Expected 12.8  
 Observed 22.2

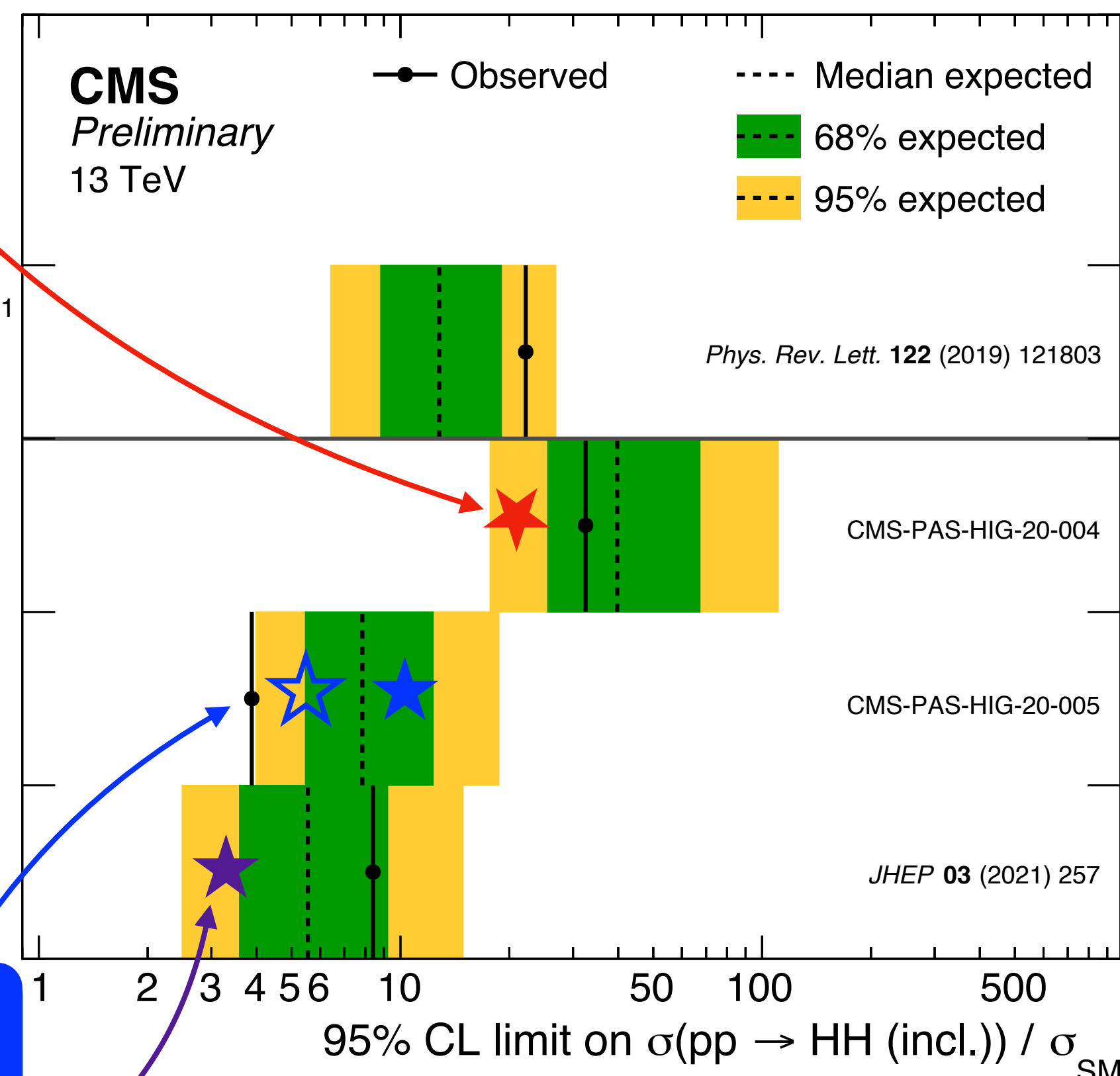
$b\bar{b}ZZ, 138 \text{ fb}^{-1}$   
 Expected 39.8  
 Observed 32.5

$b\bar{b}bb, 138 \text{ fb}^{-1}$   
 Expected 7.84  
 Observed 3.88

$b\bar{b}\gamma\gamma, 138 \text{ fb}^{-1}$   
 Expected 5.55  
 Observed 8.40

**2022  $b\bar{b}bb$  boosted**  
**[CMS-PAS-B2G-22-003](#)**

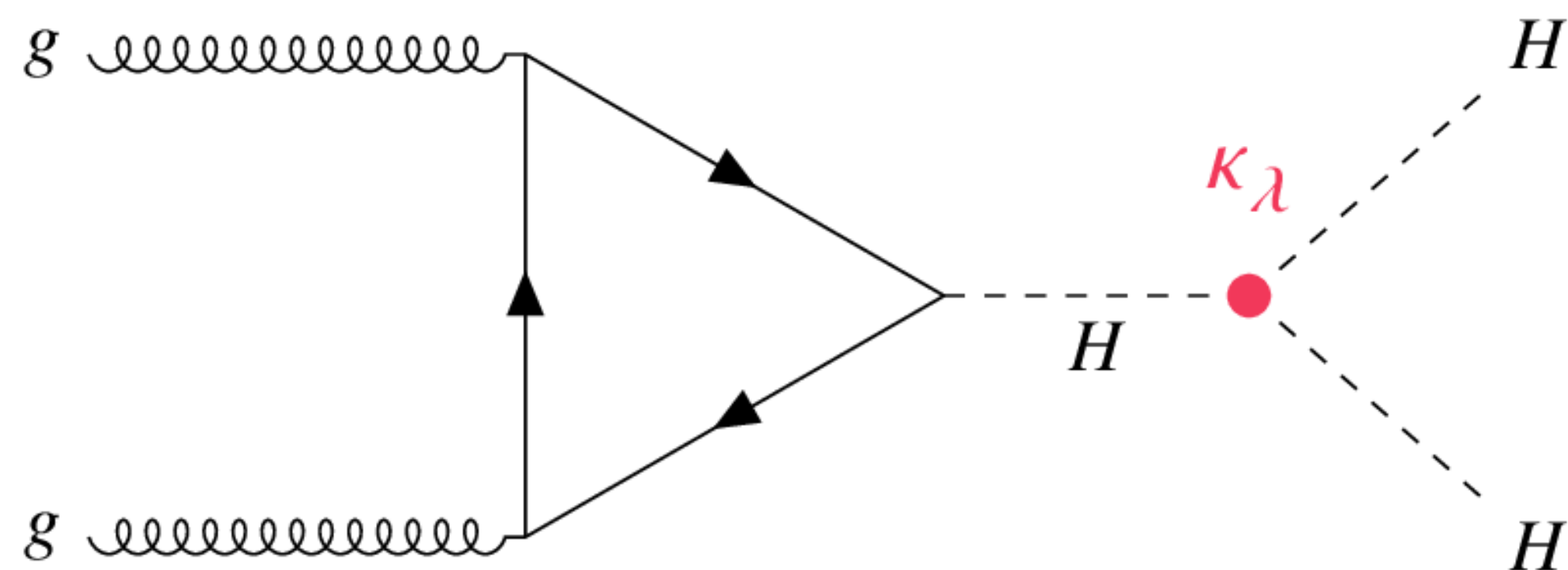
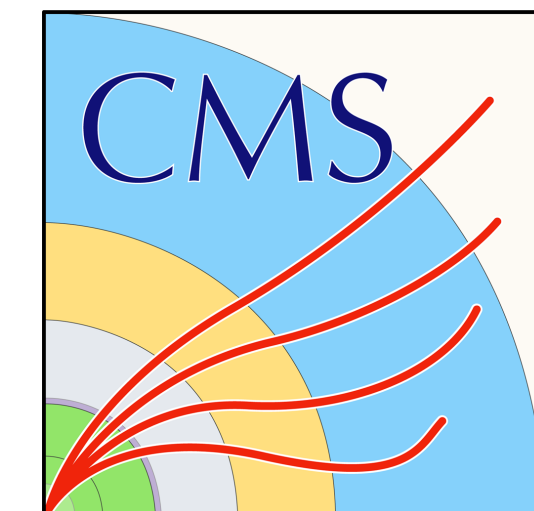
**2022  $b\bar{b}\tau\tau$  Obs 3.3**  
**[CMS-PAS-HIG-20-010](#)**



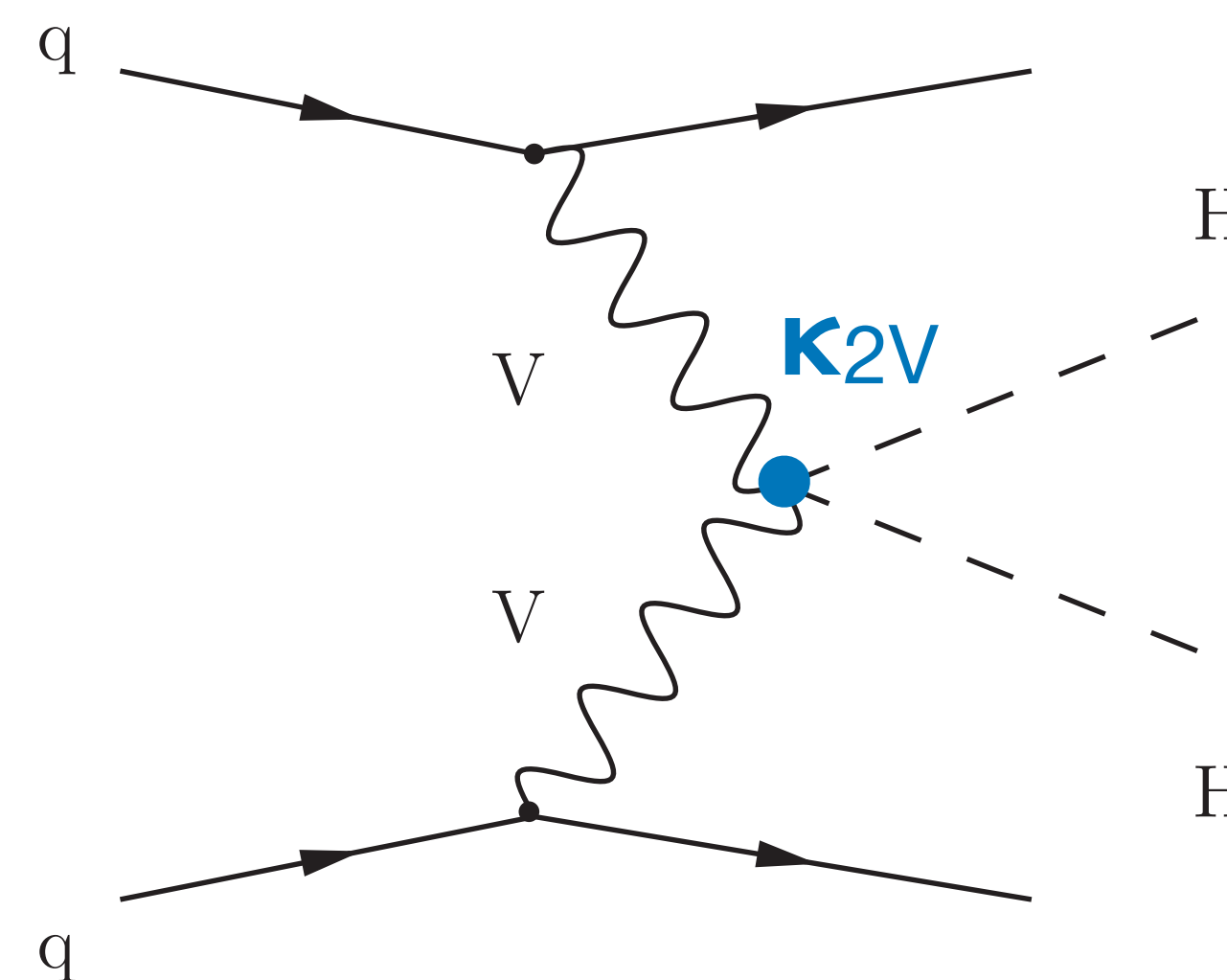
CMS summary plot  
[SummaryResultsHIG](#)



# Coupling limits

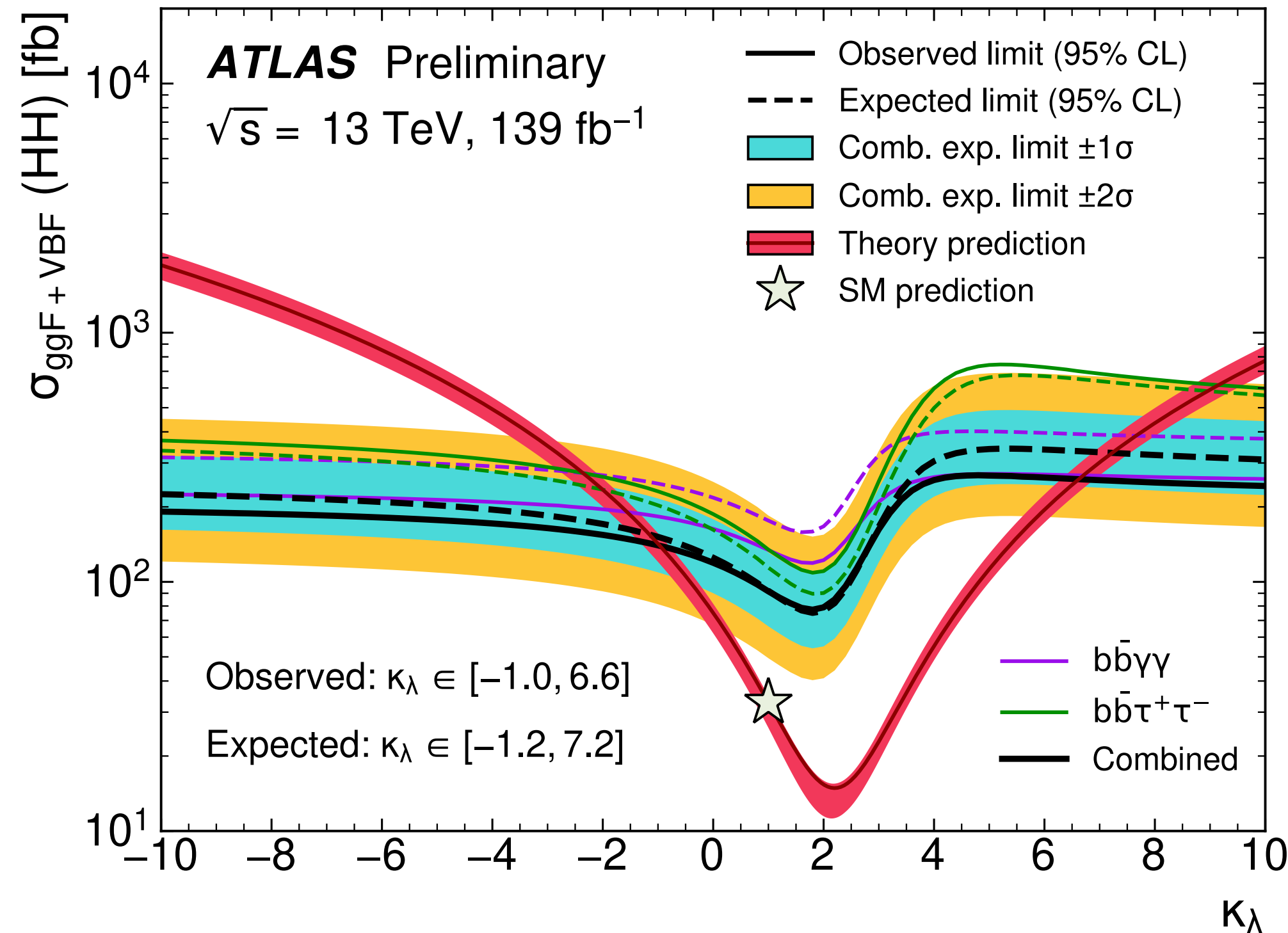
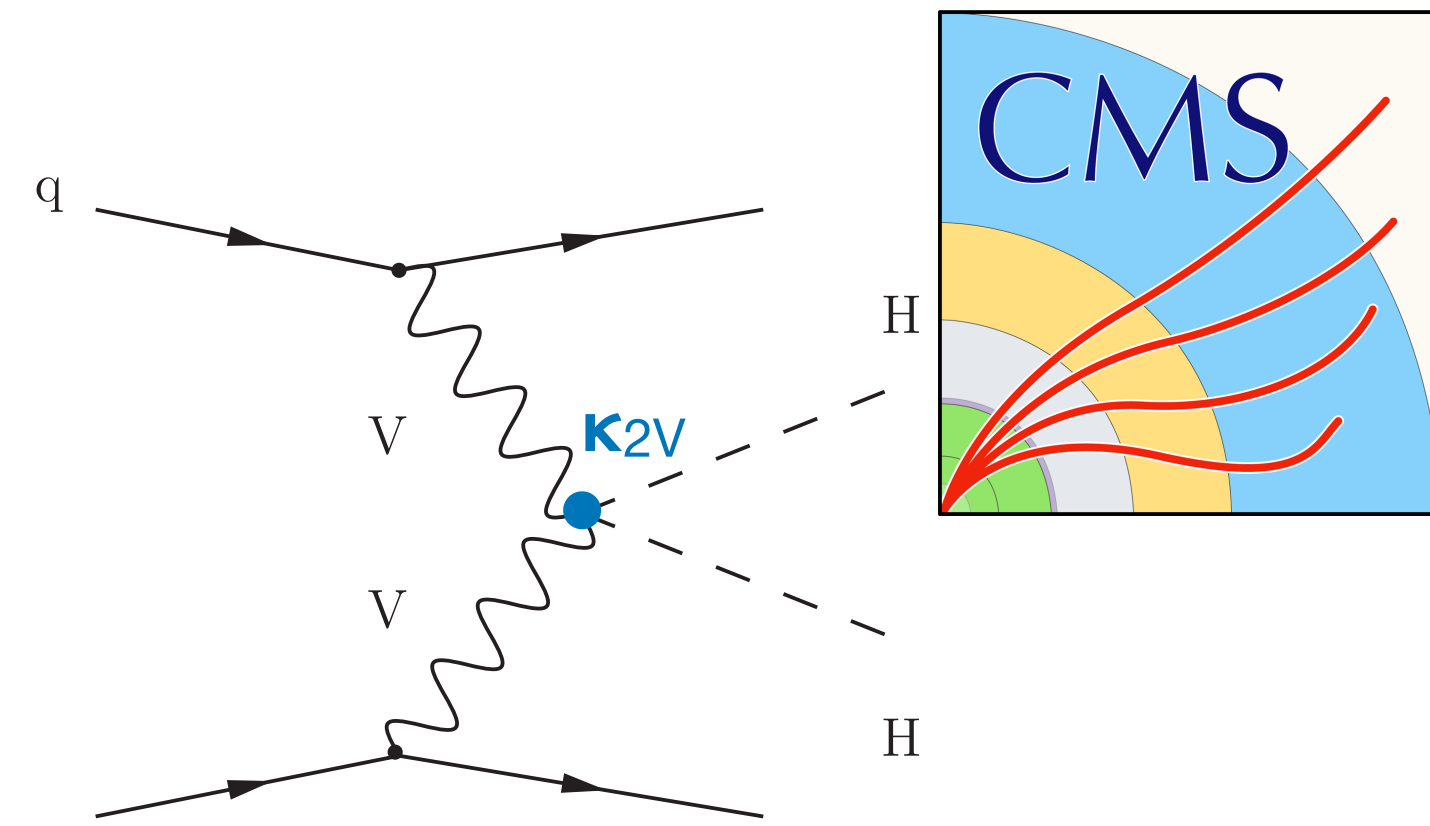
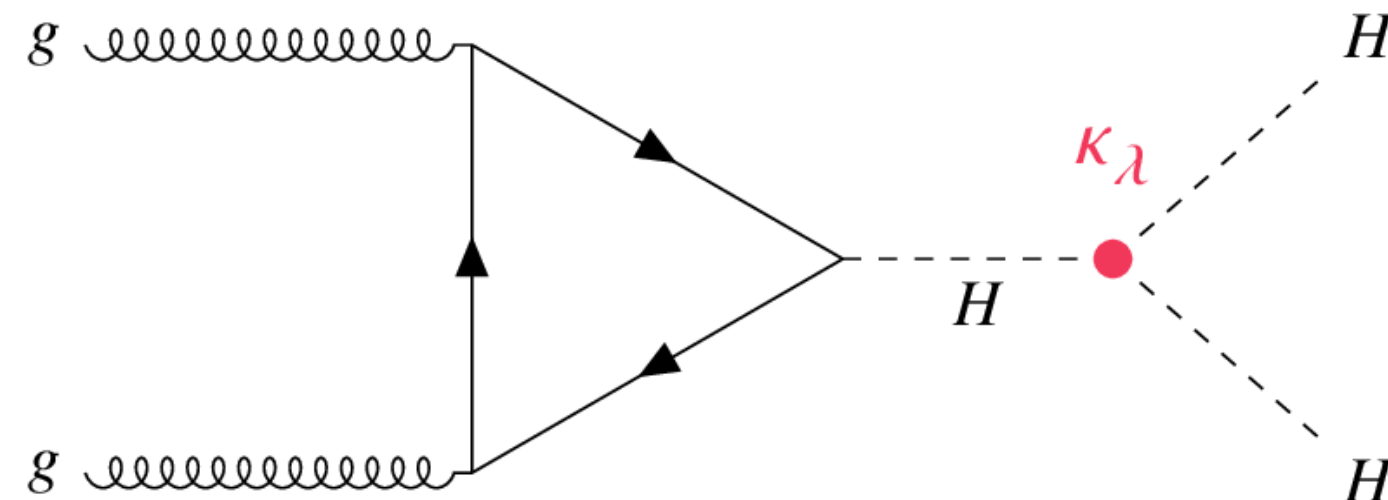


Anomalous enhancement of Higgs trilinear coupling:  $\kappa_\lambda$   
 $\Rightarrow$  unique sensitivity in HH channels

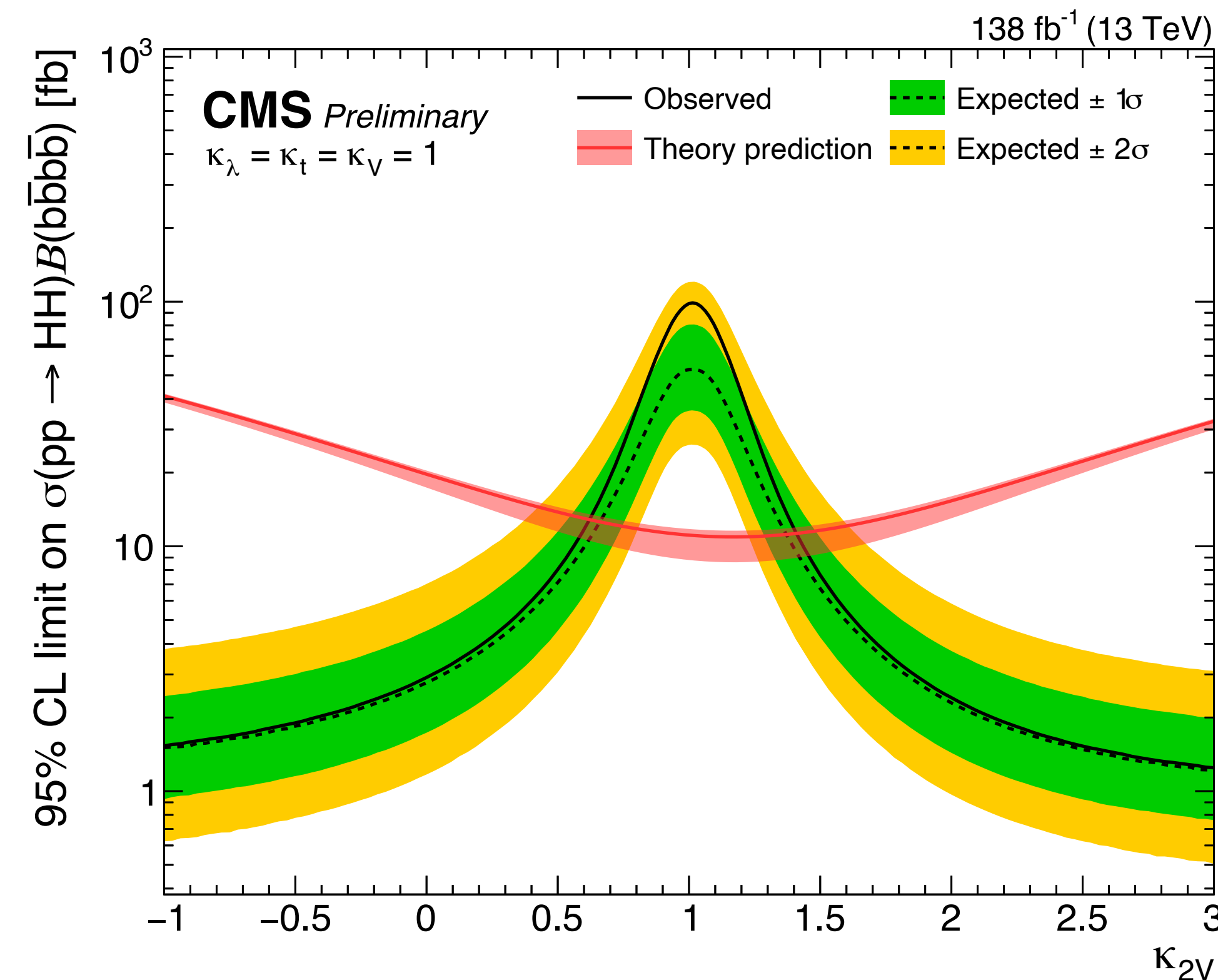


Anomalous enhancement of HH to VV coupling:  $\kappa_{2V}$   
 $\Rightarrow$  unique sensitivity in VBF HH

# Coupling limits



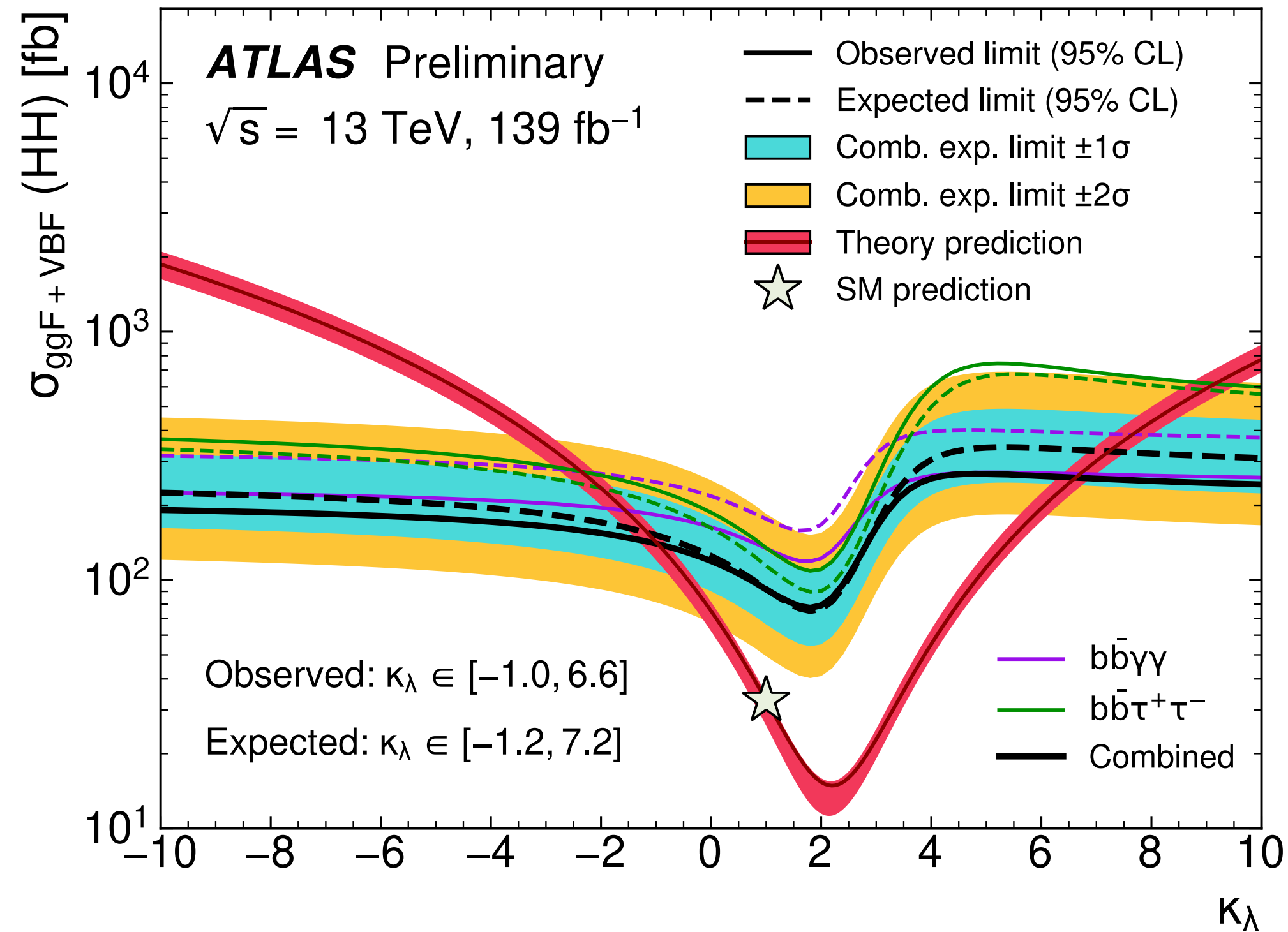
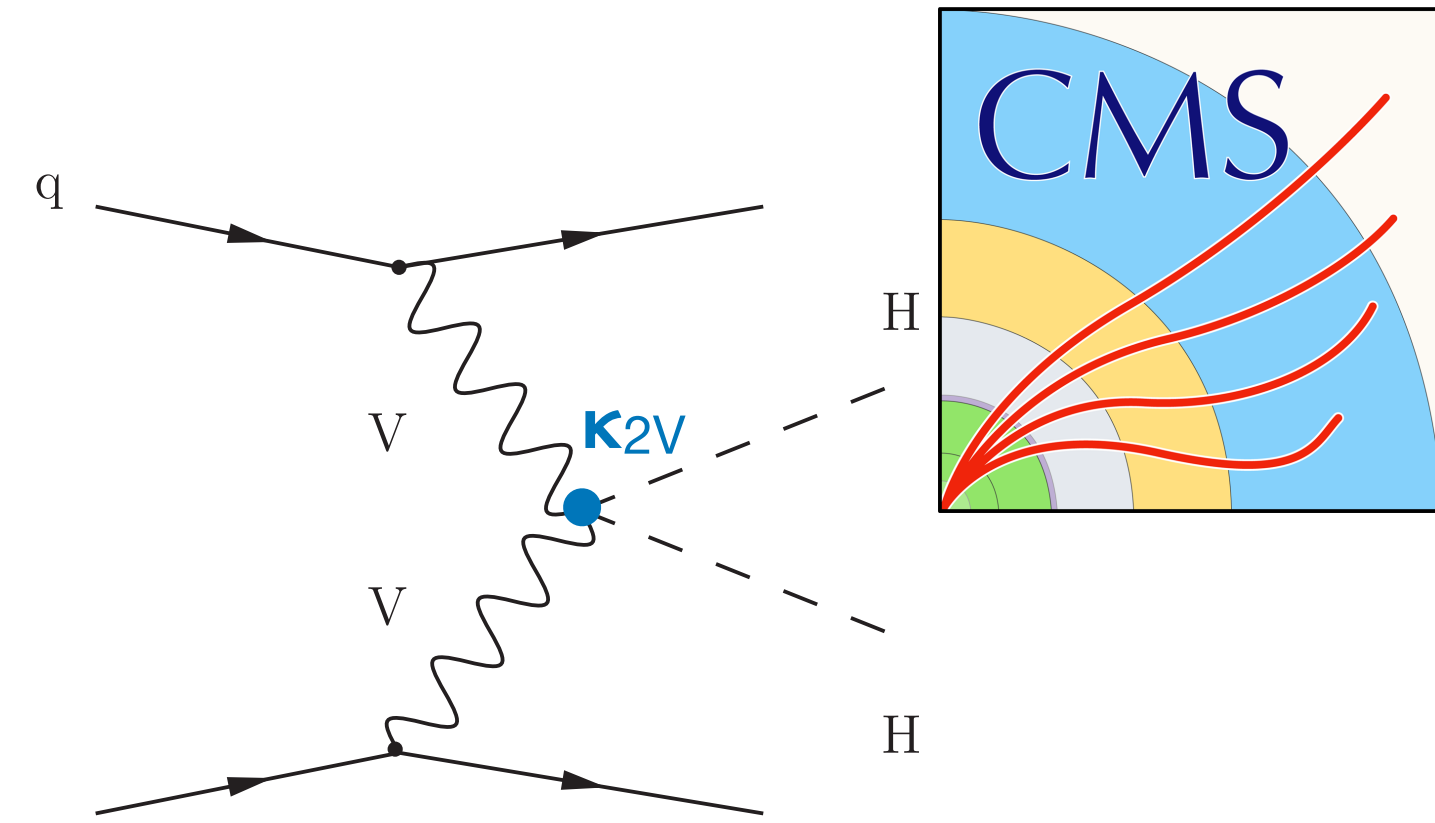
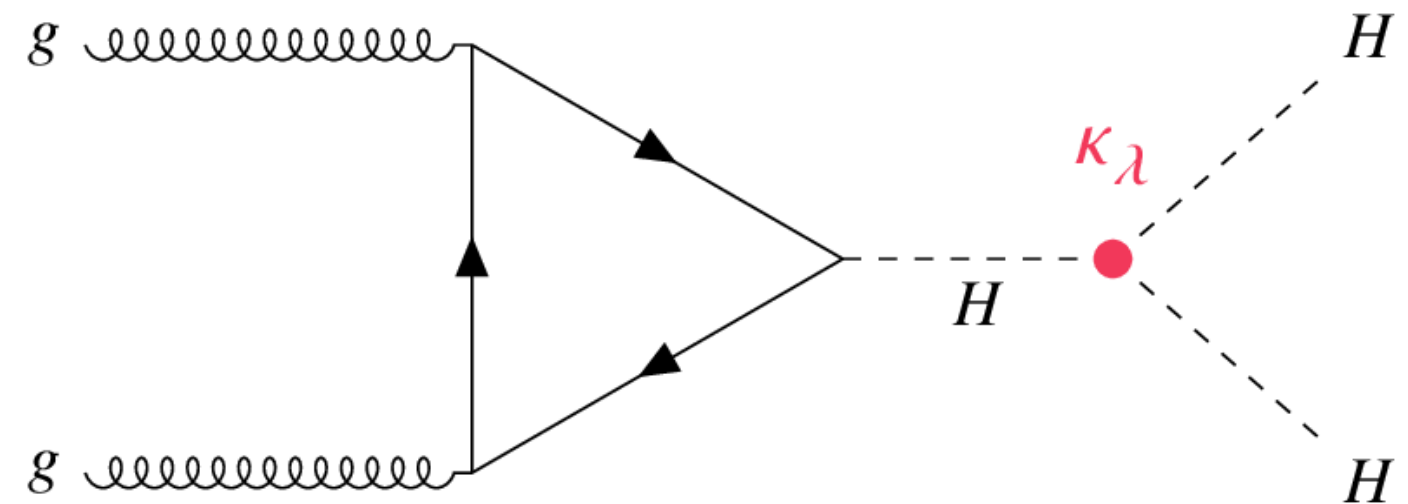
ATLAS combination  
[ATLAS-CONF-2021-052](#)



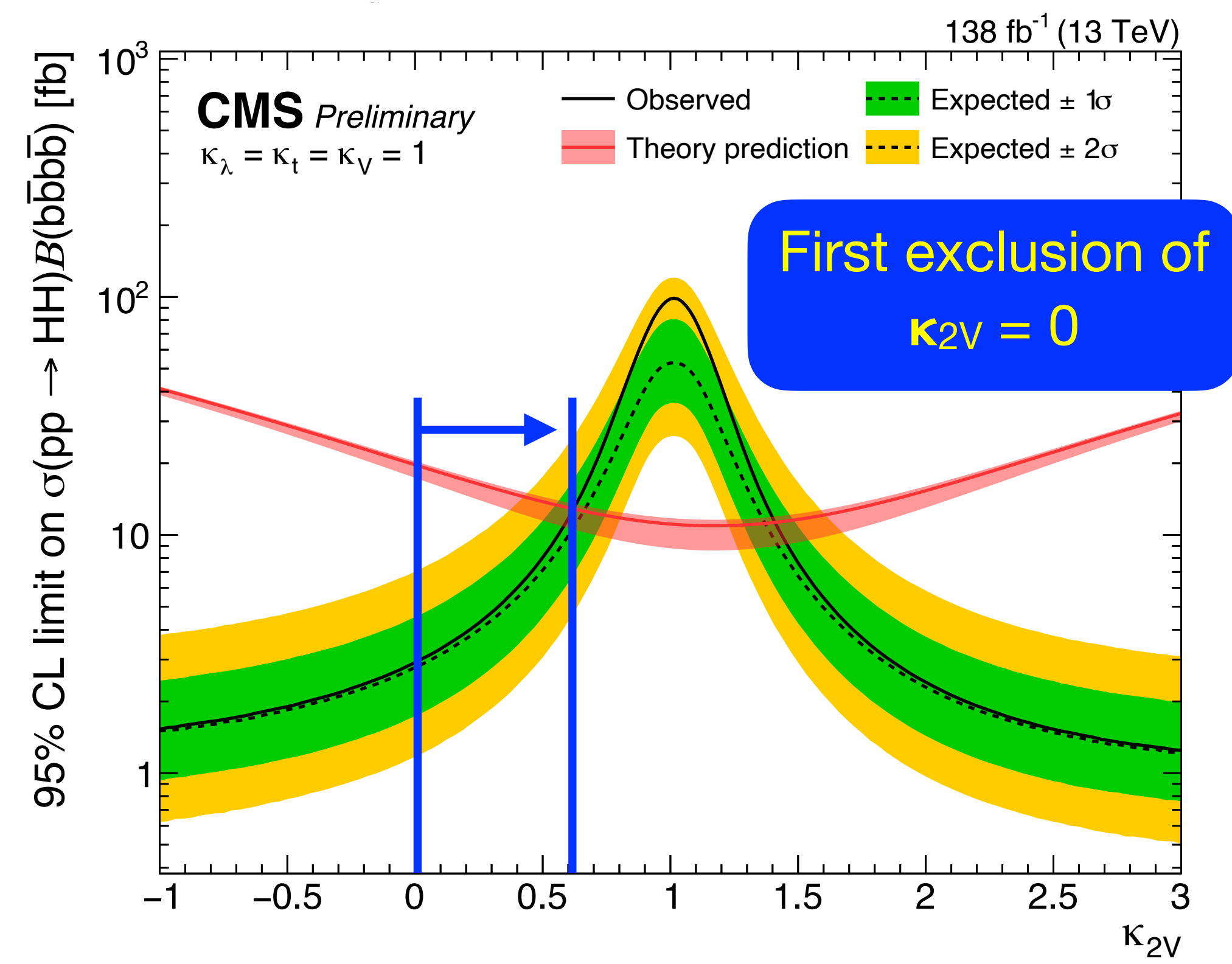
CMS bbbb boosted  
[CMS-PAS-B2G-22-003](#)



# Coupling limits

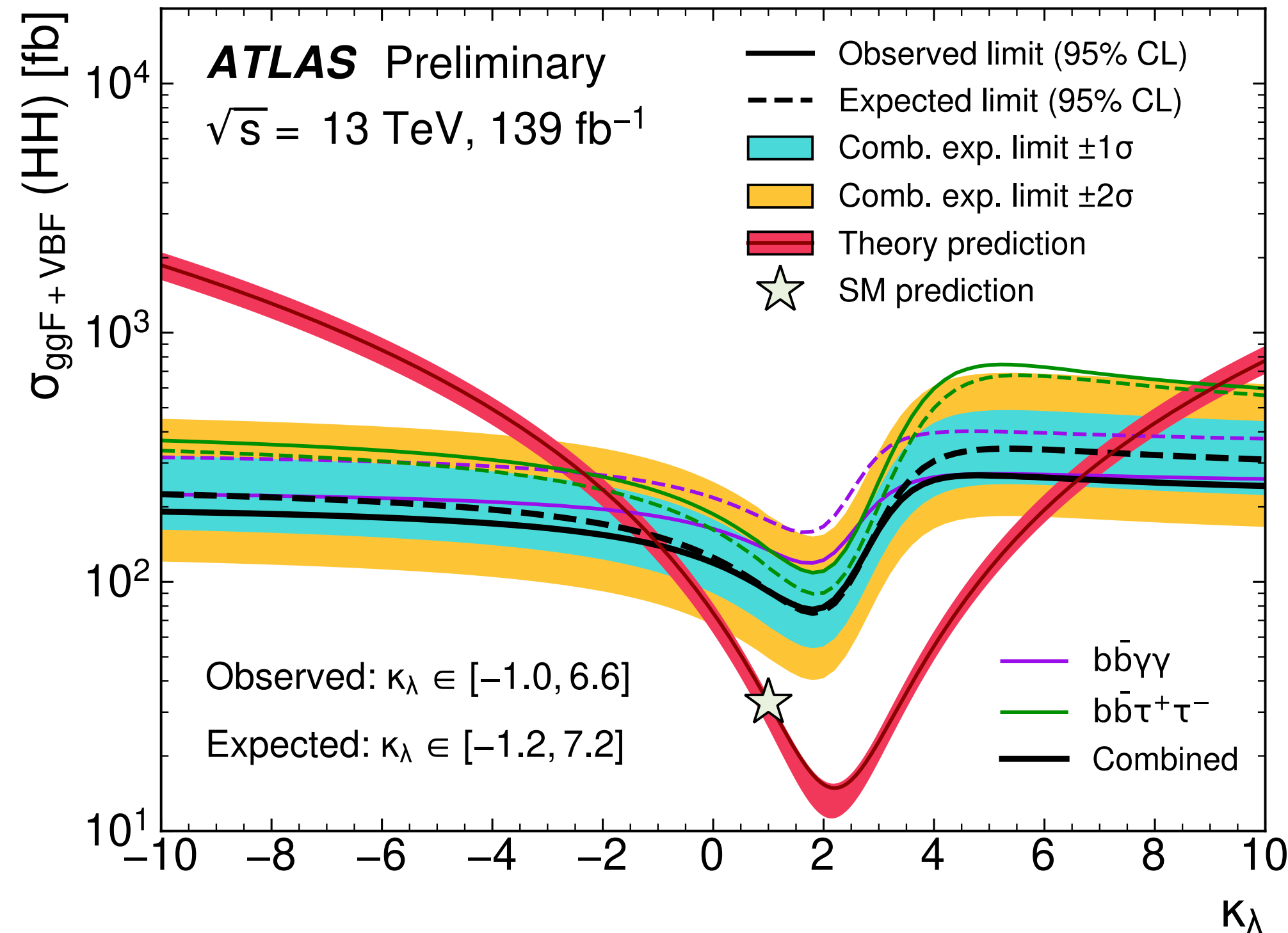
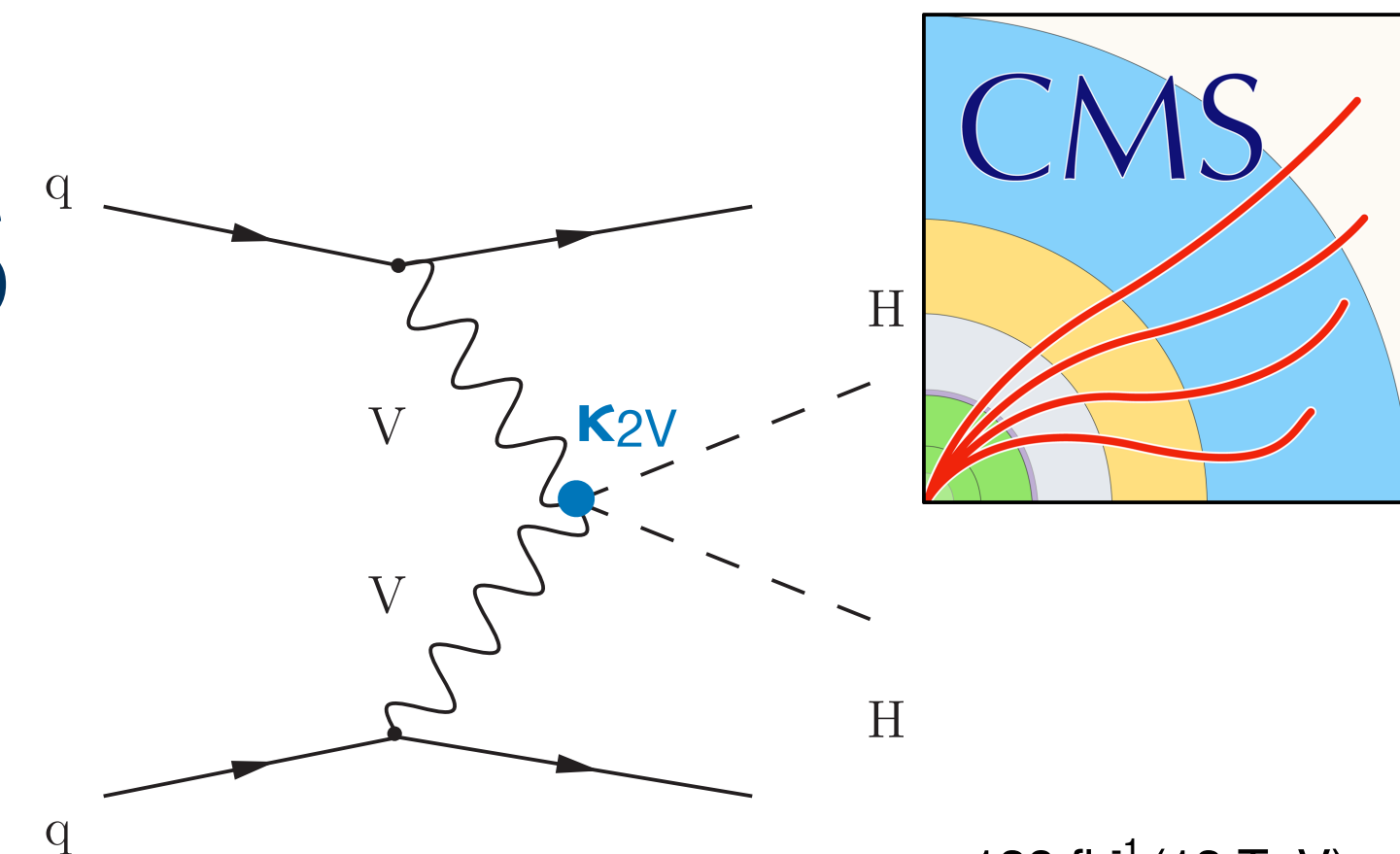
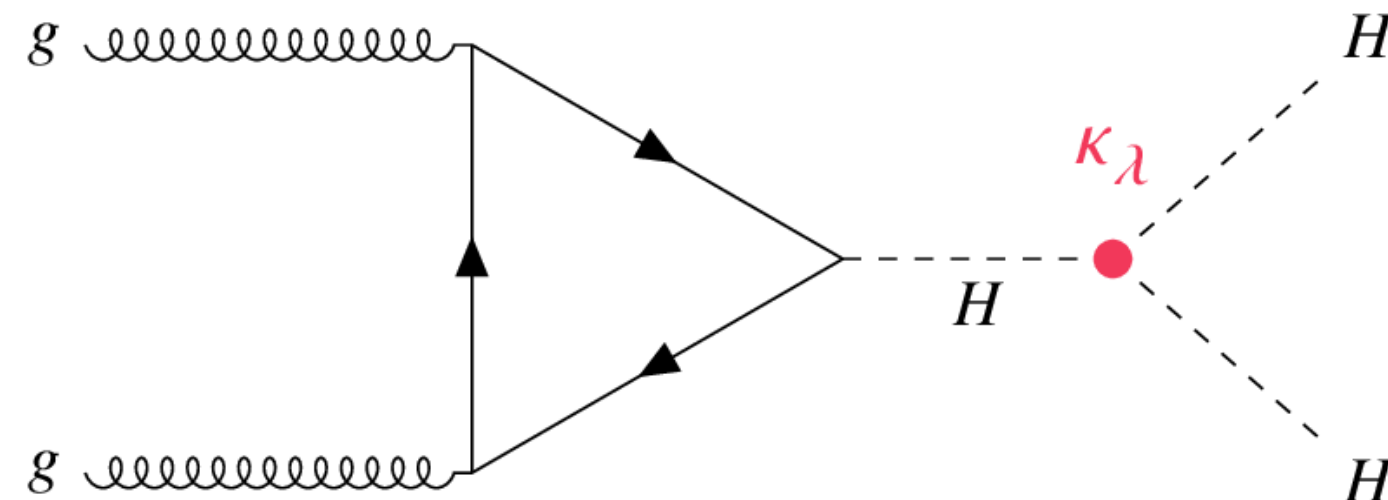


ATLAS combination  
 ATLAS-CONF-2021-052



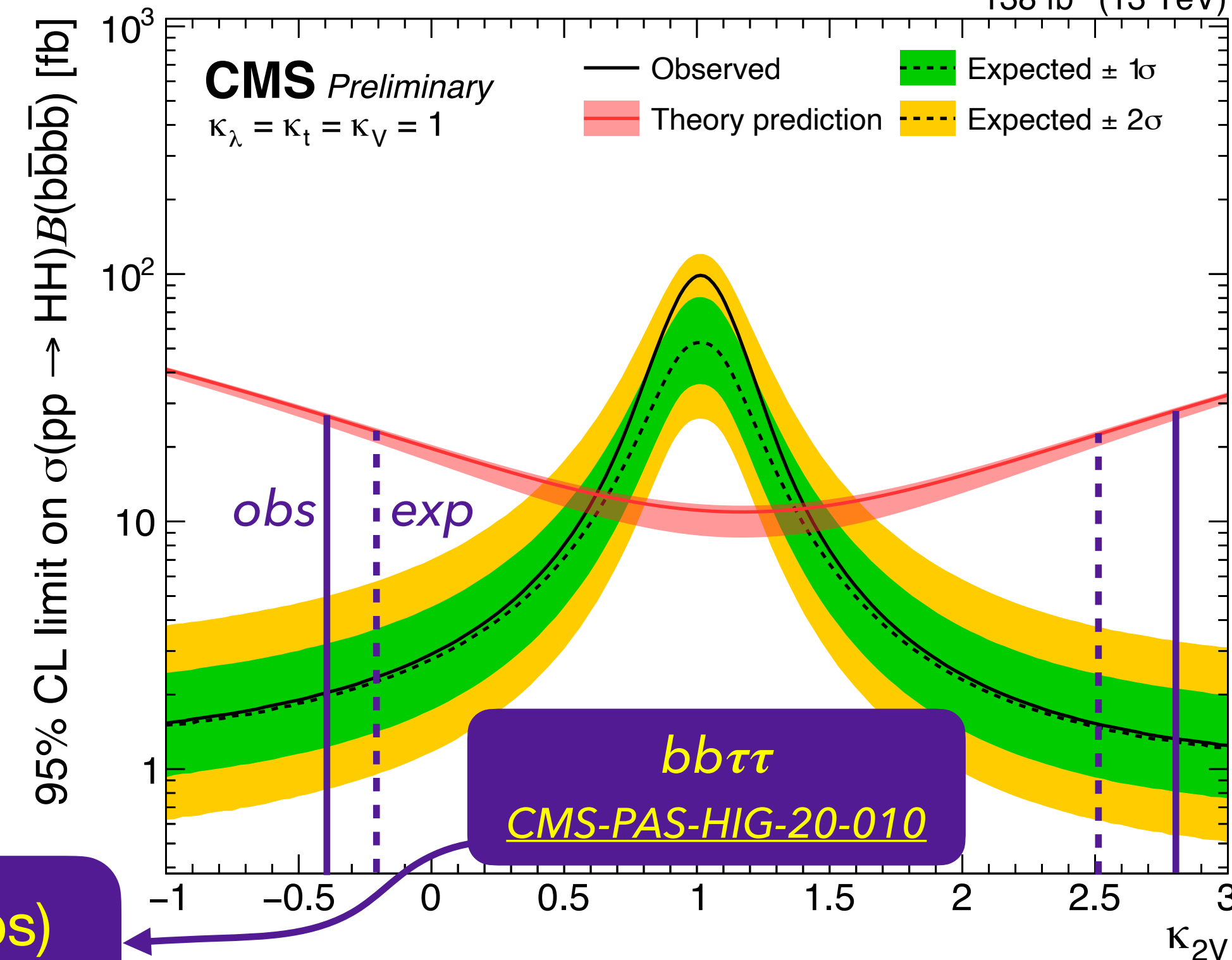
CMS bbbb boosted  
 CMS-PAS-B2G-22-003

# Coupling limits



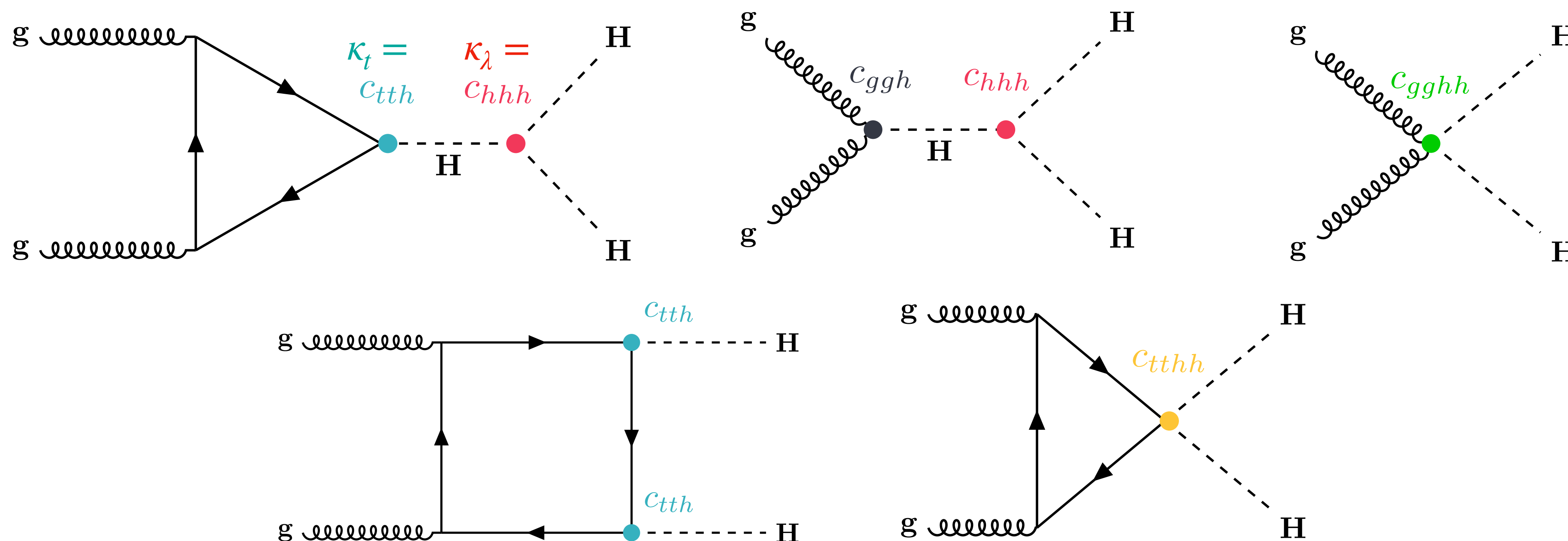
ATLAS combination  
 ATLAS-CONF-2021-052

$-1.8 < \kappa_\lambda < 8.8$  (obs)  
 $-3 < \kappa_\lambda < 9.9$  (exp)



CMS bbbb boosted  
 CMS-PAS-B2G-22-003

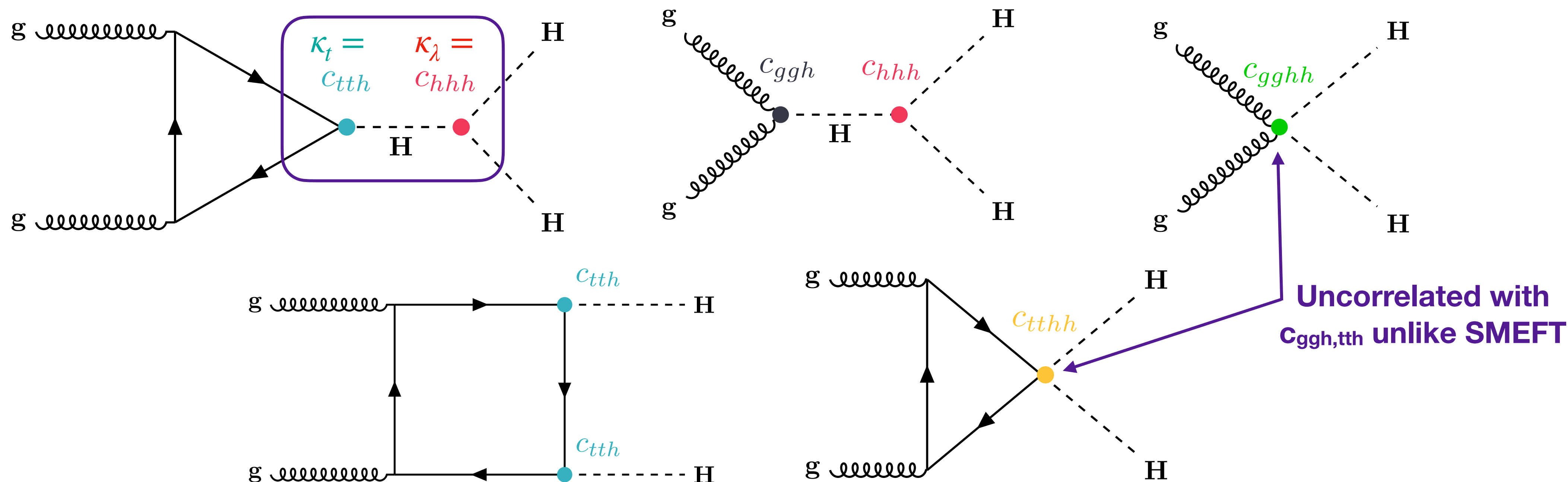
# HH $\rightarrow$ bb $\tau\tau$ /bb $\gamma\gamma$ vs HEFT



- Higgs Effective Field Theory [[arXiv:1212.3305](https://arxiv.org/abs/1212.3305), [arXiv:1312.5624](https://arxiv.org/abs/1312.5624)]
  - Less stringent gauge (SU2) constraints on operators in H sector than SMEFT [[arxiv.org:1308.2627](https://arxiv.org/abs/1308.2627)]
  - Broader UV theories where e.g. BSM particles gain mass via EWSB (non-decoupling) [[arXiv:1902.05936](https://arxiv.org/abs/1902.05936)]
- Two Wilson coefficients ( $c_{tth}$ ,  $c_{hhh}$ ) correspond to Kappa framework ( $\kappa_t$ ,  $\kappa_\lambda$ )



# HH $\rightarrow$ bb $\tau\tau$ /bb $\gamma\gamma$ vs HEFT



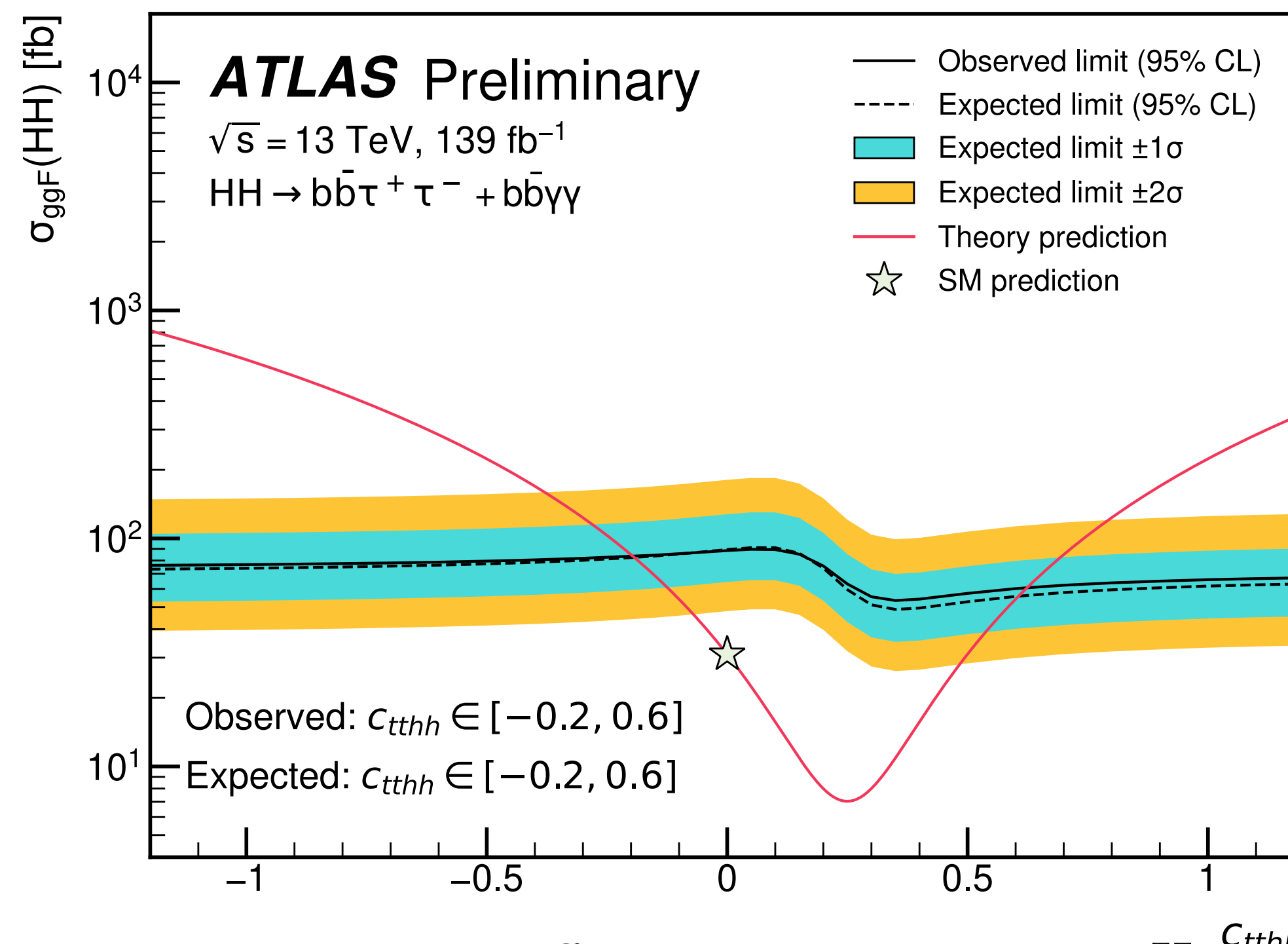
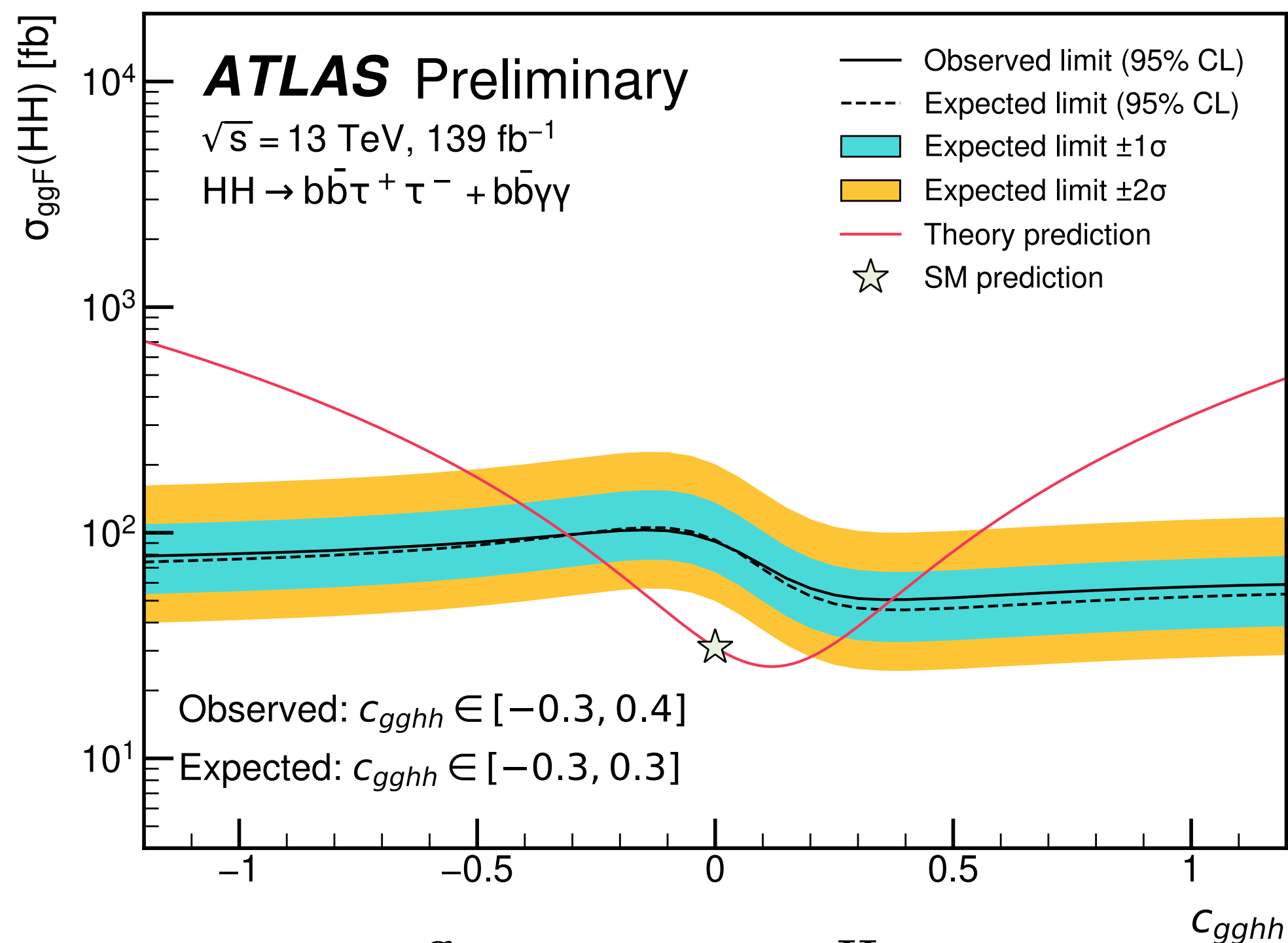
- Higgs Effective Field Theory [[arXiv:1212.3305](https://arxiv.org/abs/1212.3305), [arXiv:1312.5624](https://arxiv.org/abs/1312.5624)]
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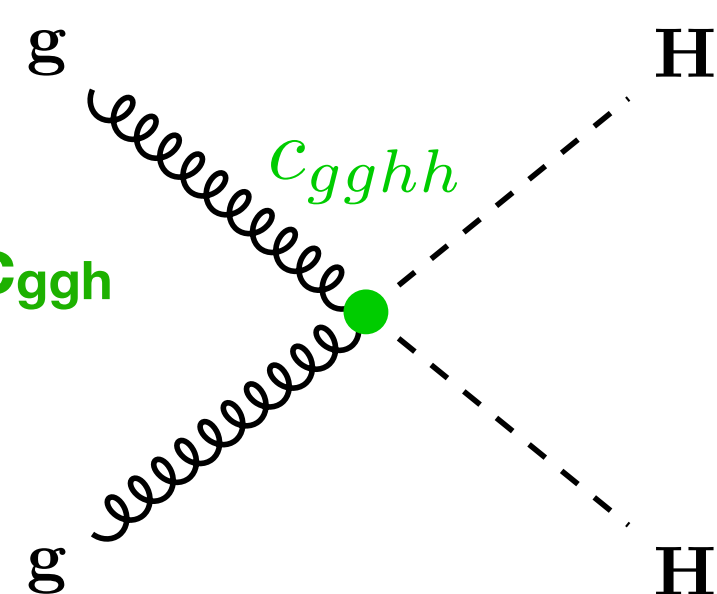
# HH → bbττ/bbγγ vs HEFT

Limits set also on  $m_{HH}$  shape benchmarks  
[arXiv: 1908.08923](https://arxiv.org/abs/1908.08923)  
 (see [backup](#))

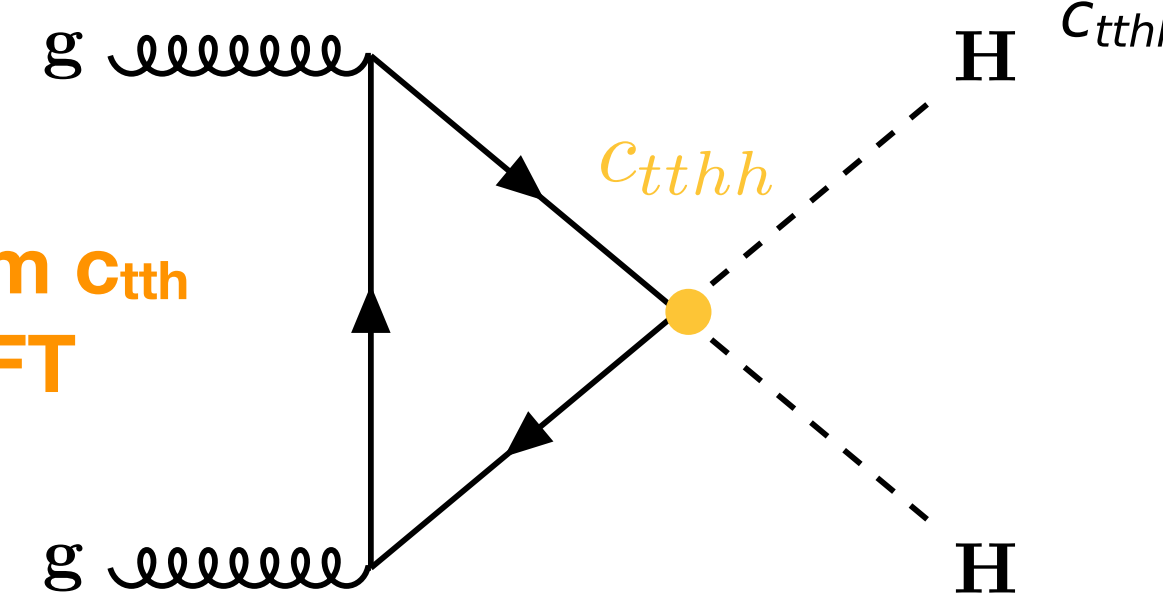
Constrain HH to gluon/top couplings via ggF cross-section



Decoupled from  $c_{ggh}$   
 unlike SMEFT



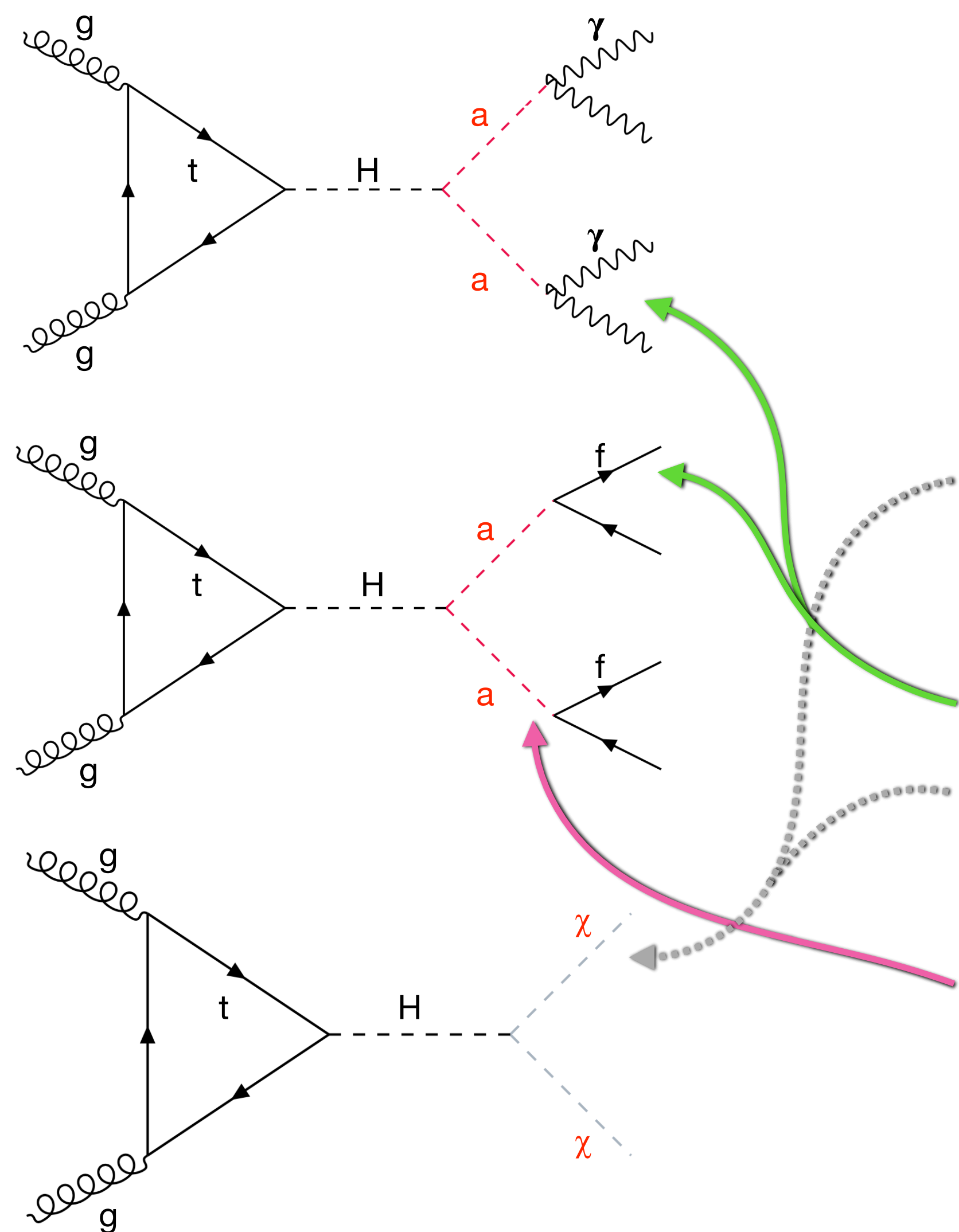
Decoupled from  $c_{tth}$   
 unlike SMEFT



# When Higgs goes Beyond (SM)



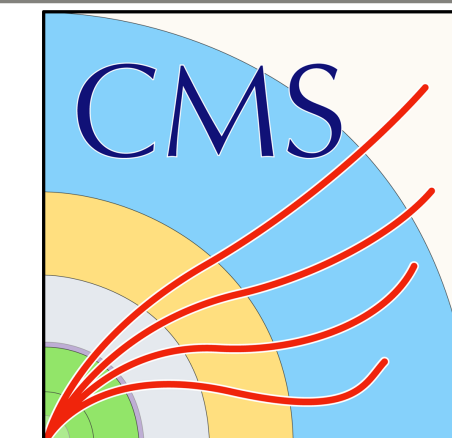
# Exotic Higgs decays



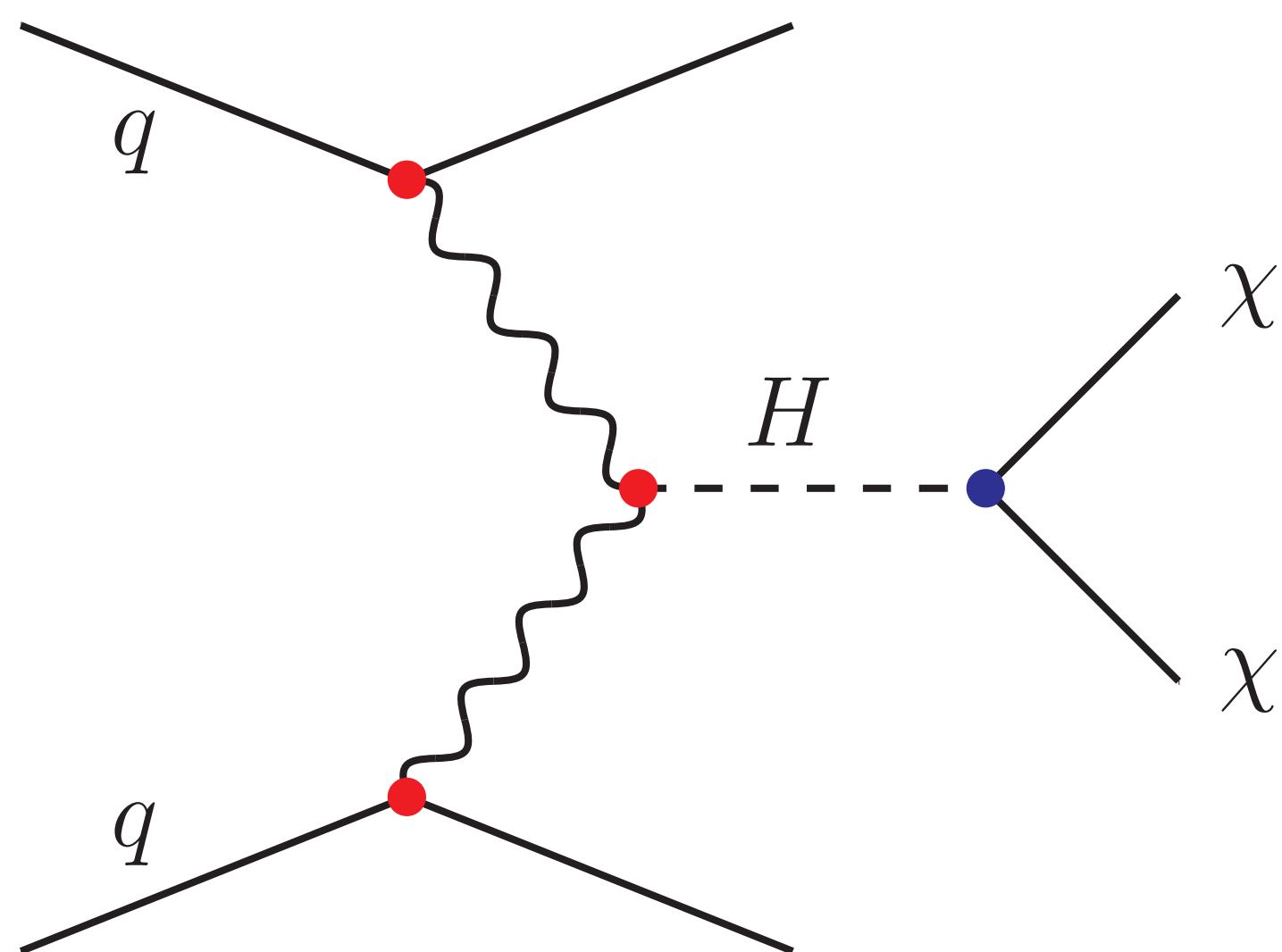
- Low-mass new physics could appear in H decay without significantly affecting production
  - Axion-like Particles (ALPs)
  - 2 Higgs Doublet Model + Scalar (2HDM+S)
  - Dark Matter
- Sensitive channels vary widely
  - Boosted/collimated decays
  - Invisible decays (MET)
  - Asymmetric decays
  - Long-lived particles (LLPs)
- Large range of analyses and models!



# VBF $H \rightarrow$ invisible



**H assumed to couple directly to dark matter (Higgs portal)**

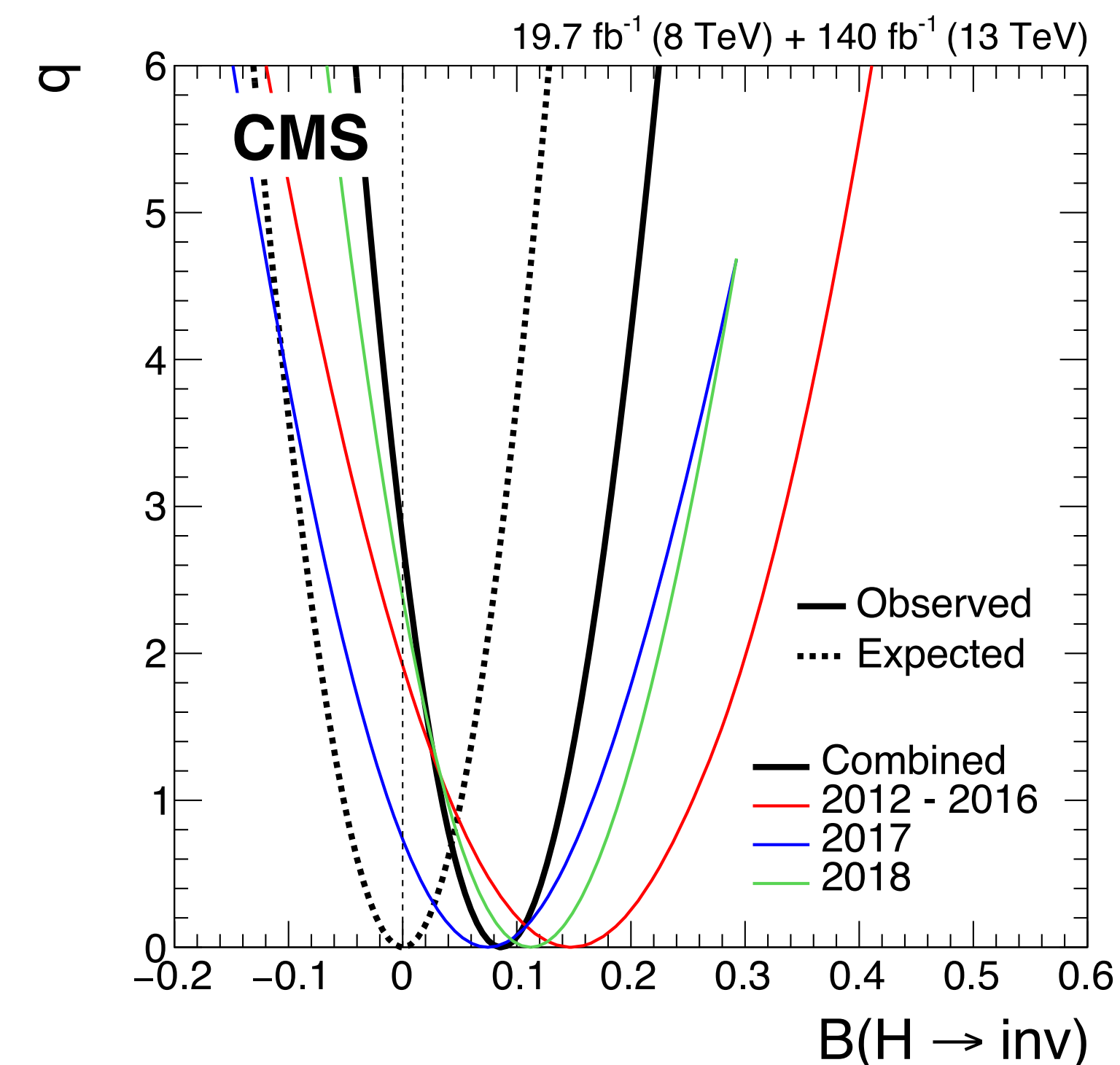


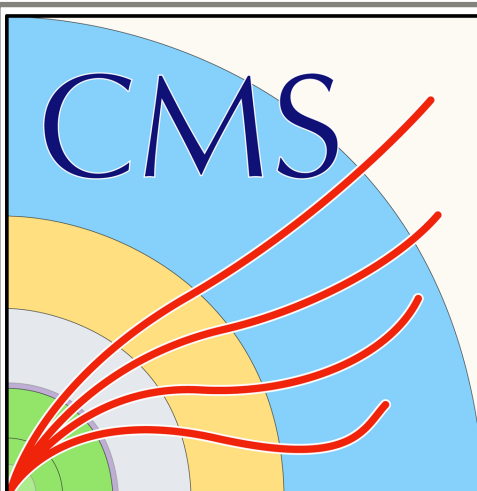
Limits provided on DM scenarios for comparison with direct DM searches  
See backups

- ATLAS analysis [arXiv:2202.07953](https://arxiv.org/abs/2202.07953)  
139 fb<sup>-1</sup> @ 13 TeV (previous 36 fb<sup>-1</sup>)  
*Sensitivity improvements quantified:*
- 36% data/MC stats, lepton ID/acceptance
  - 17% forward pileup jet tagging [fJVT]
  - 19% event selection (3-4 jets, lower MET)
  - 10% multijet background estimation
  - 6% V+jets background estimation

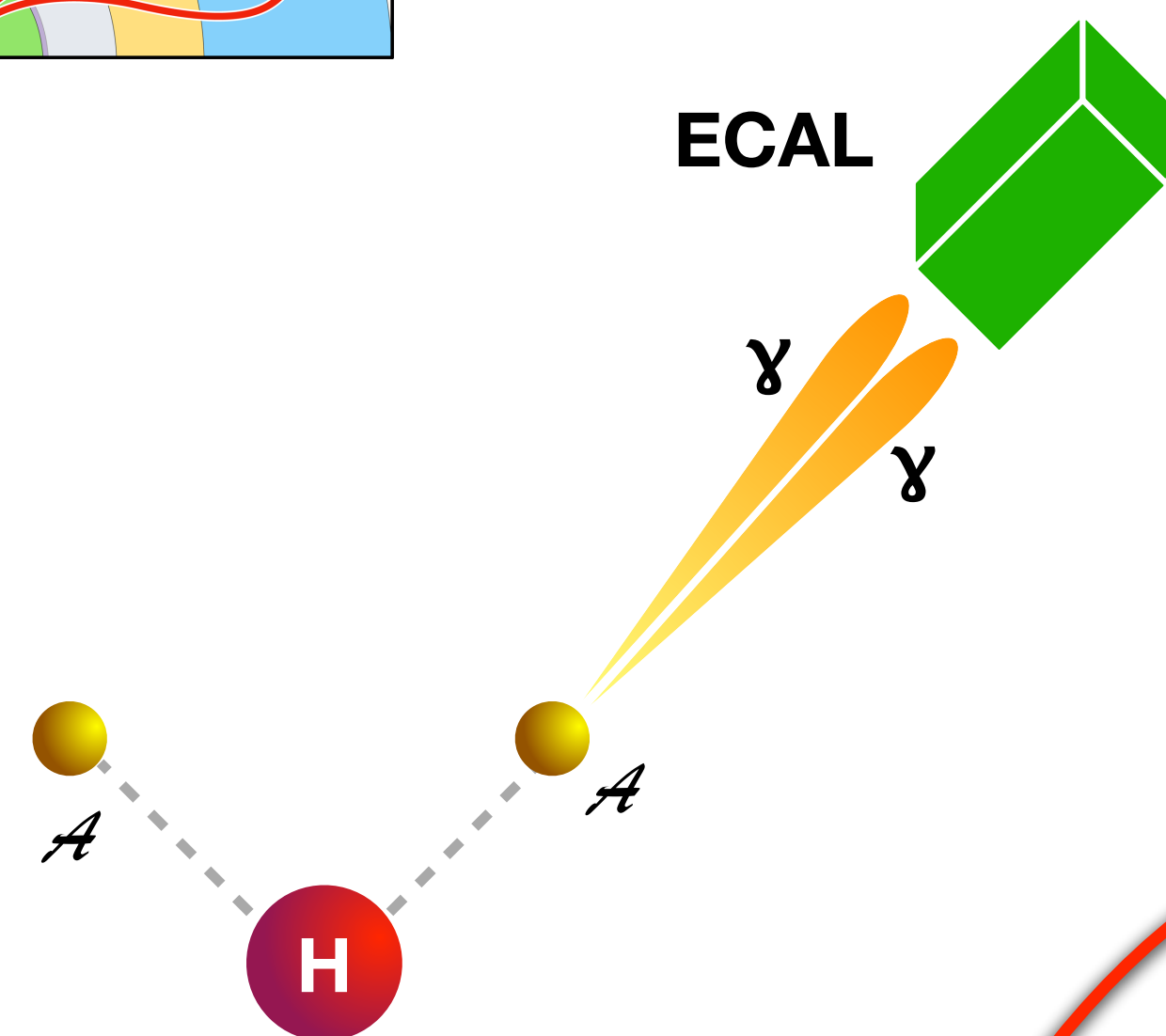
- CMS analysis [arXiv:2201.11585](https://arxiv.org/abs/2201.11585)  
140 fb<sup>-1</sup> @ 13 TeV + 19.7 fb<sup>-1</sup> @ 8 TeV  
*New event category @ low p<sub>T</sub><sup>H</sup>*  
*Photon+jets control region for Z → νν*

SM expectation  $B(H \rightarrow ZZ^* \rightarrow 4\nu) = 0.12\%$   
**New analyses improve best limits to**  
**ATLAS: 14.5% obs (10.3% exp)**  
**CMS: 18% obs (10% exp)**



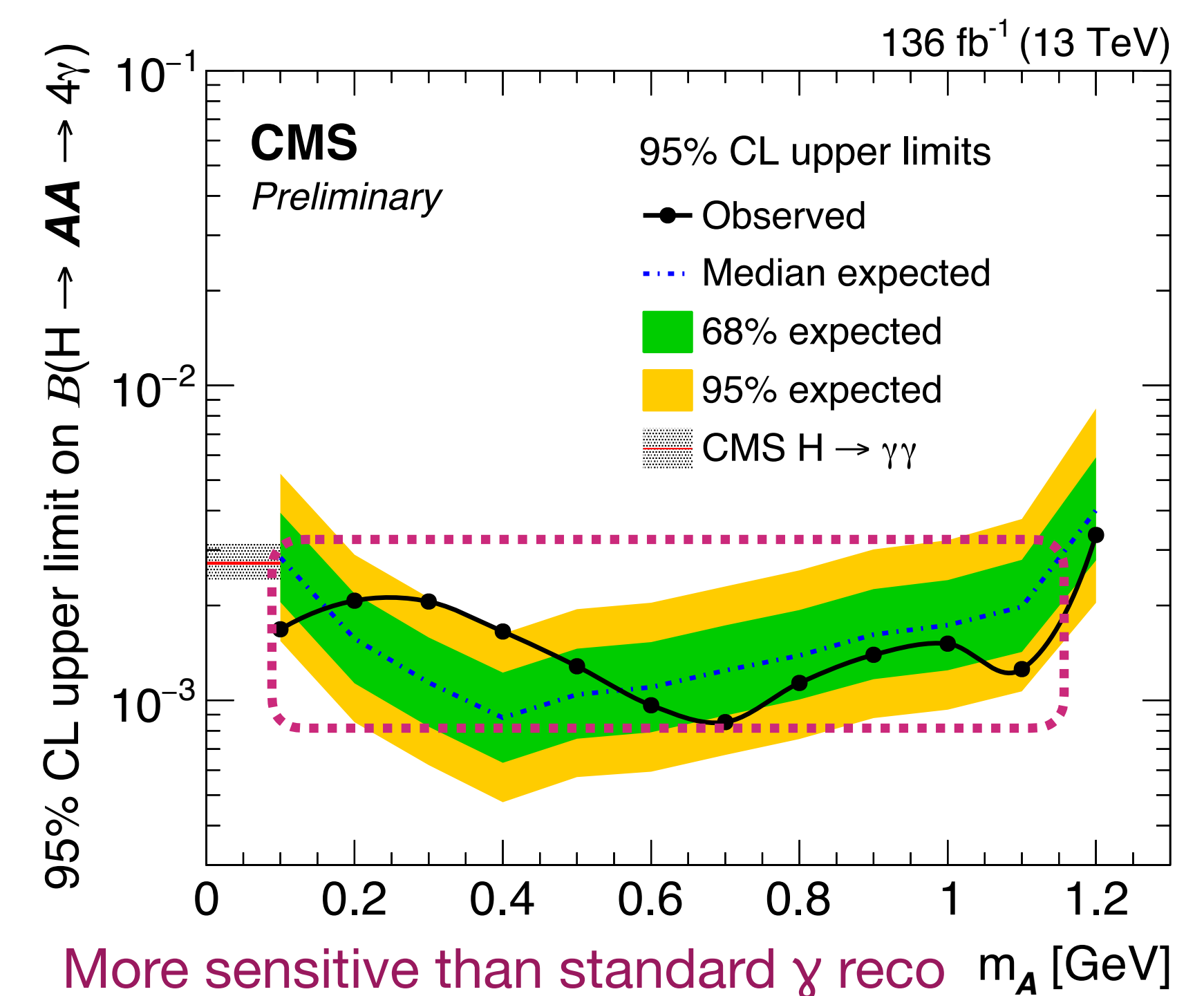
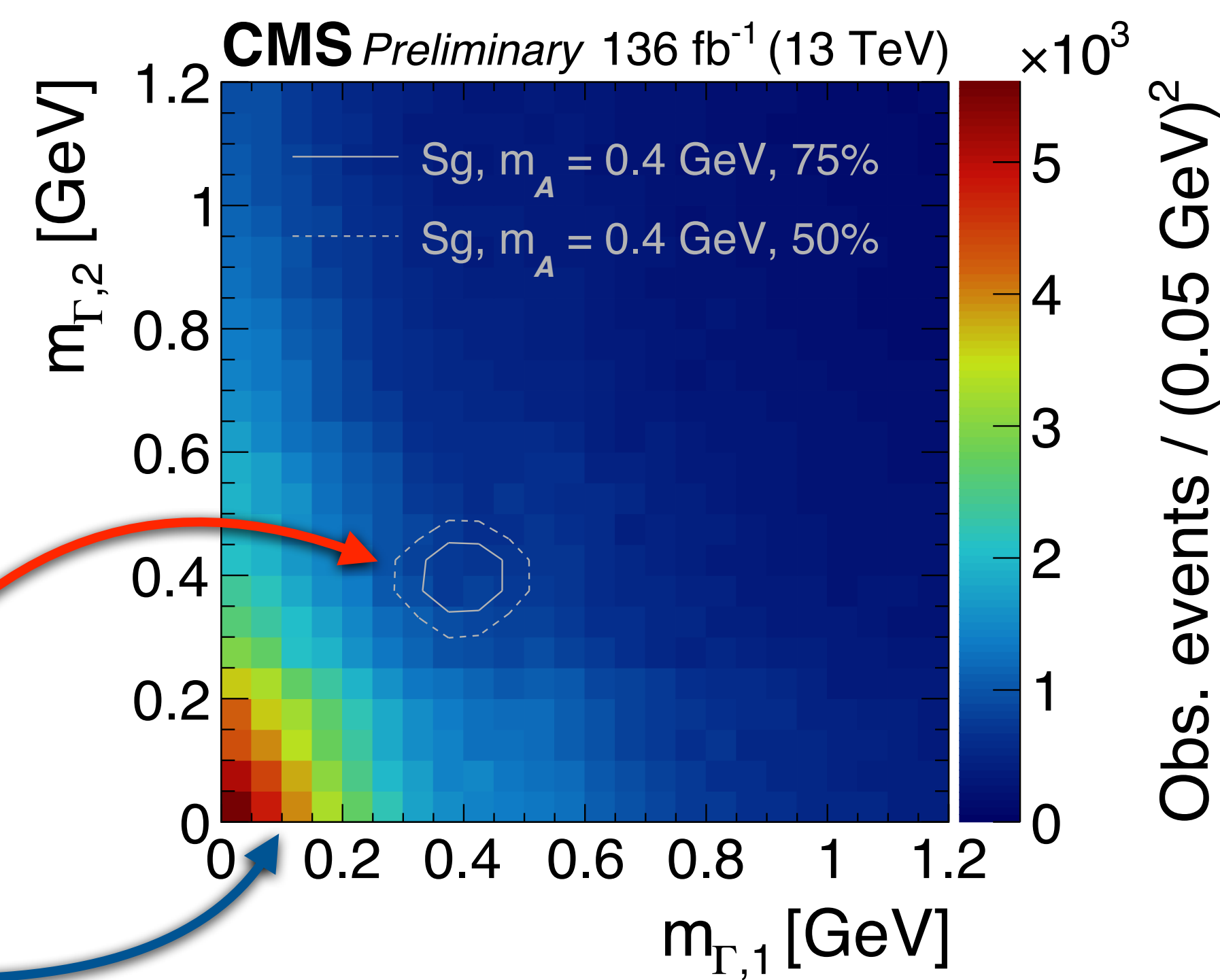


# Higgs $\rightarrow$ Axion Like Particles



Signal goes here

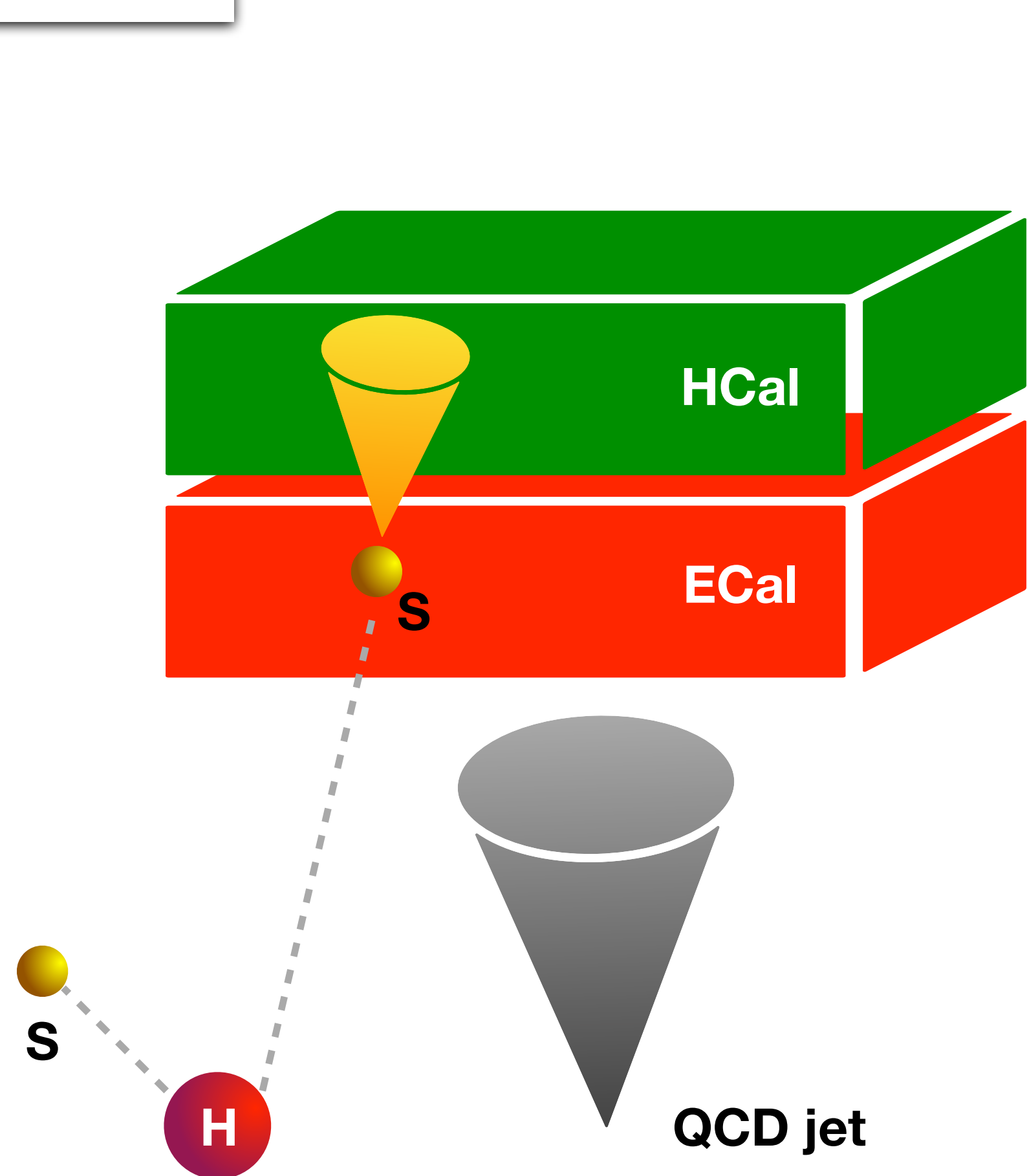
Background shape from  $m_H$  sideband



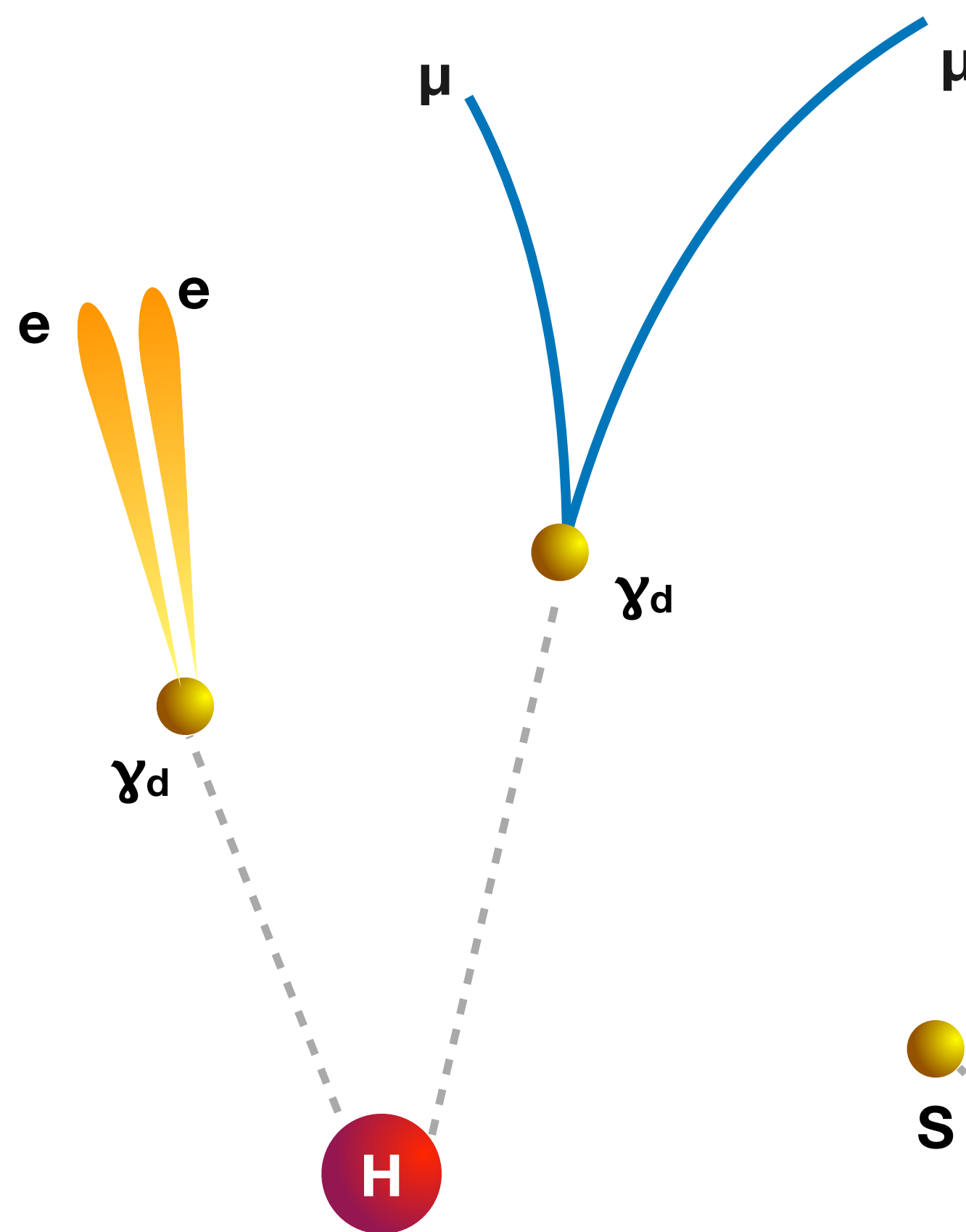
- Axion-like particle  $A$  with mass below 1 GeV decays to 2 photons
  - Low mass renders decays to fermions inaccessible
  - Special reconstruction required to identify merged photon pairs from boosted  $A$  decay



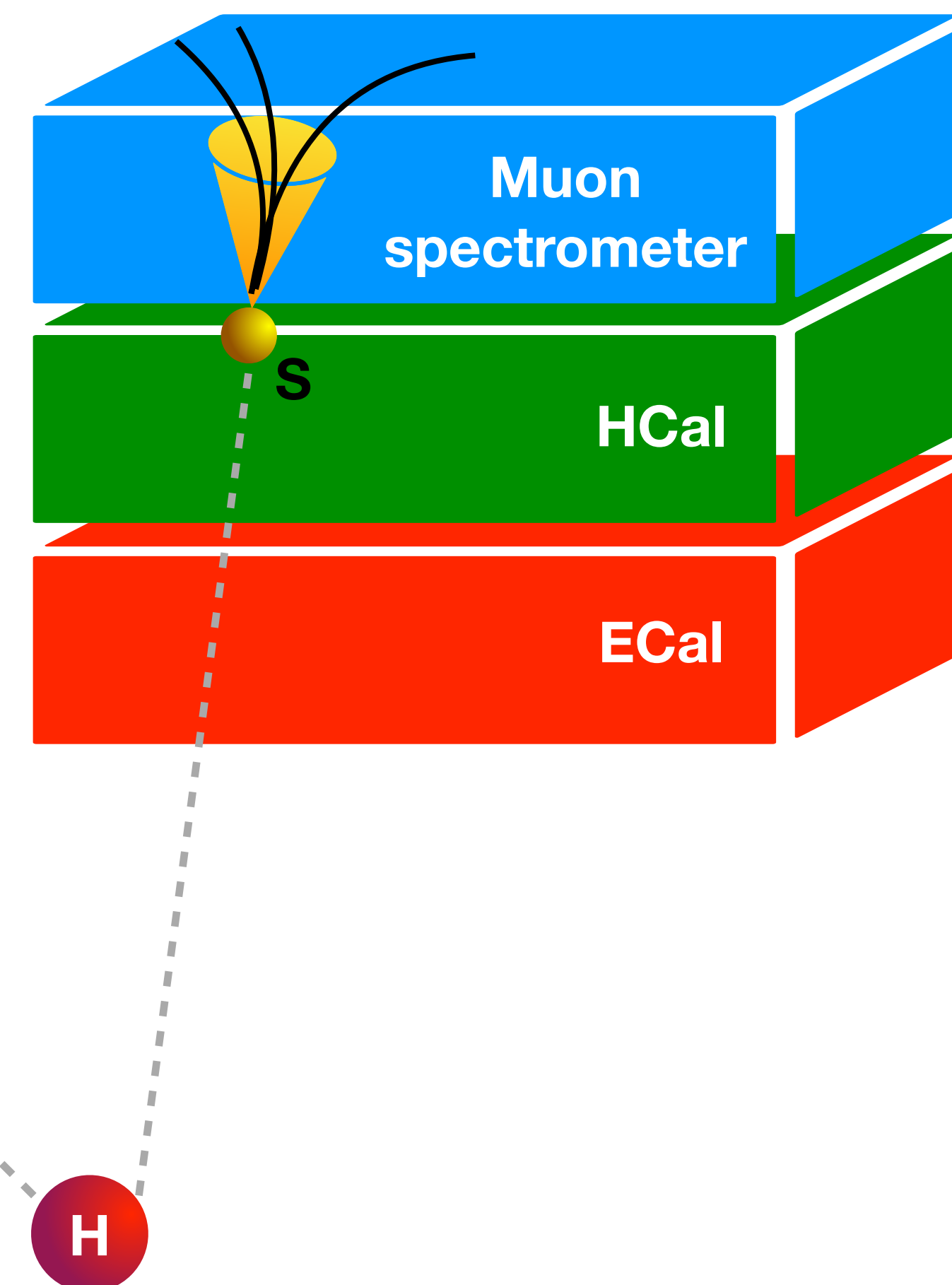
# Higgs $\rightarrow$ Long Lived Particles



*Displaced jets (calo E ratio)*  
[arXiv:2203.01009](https://arxiv.org/abs/2203.01009)



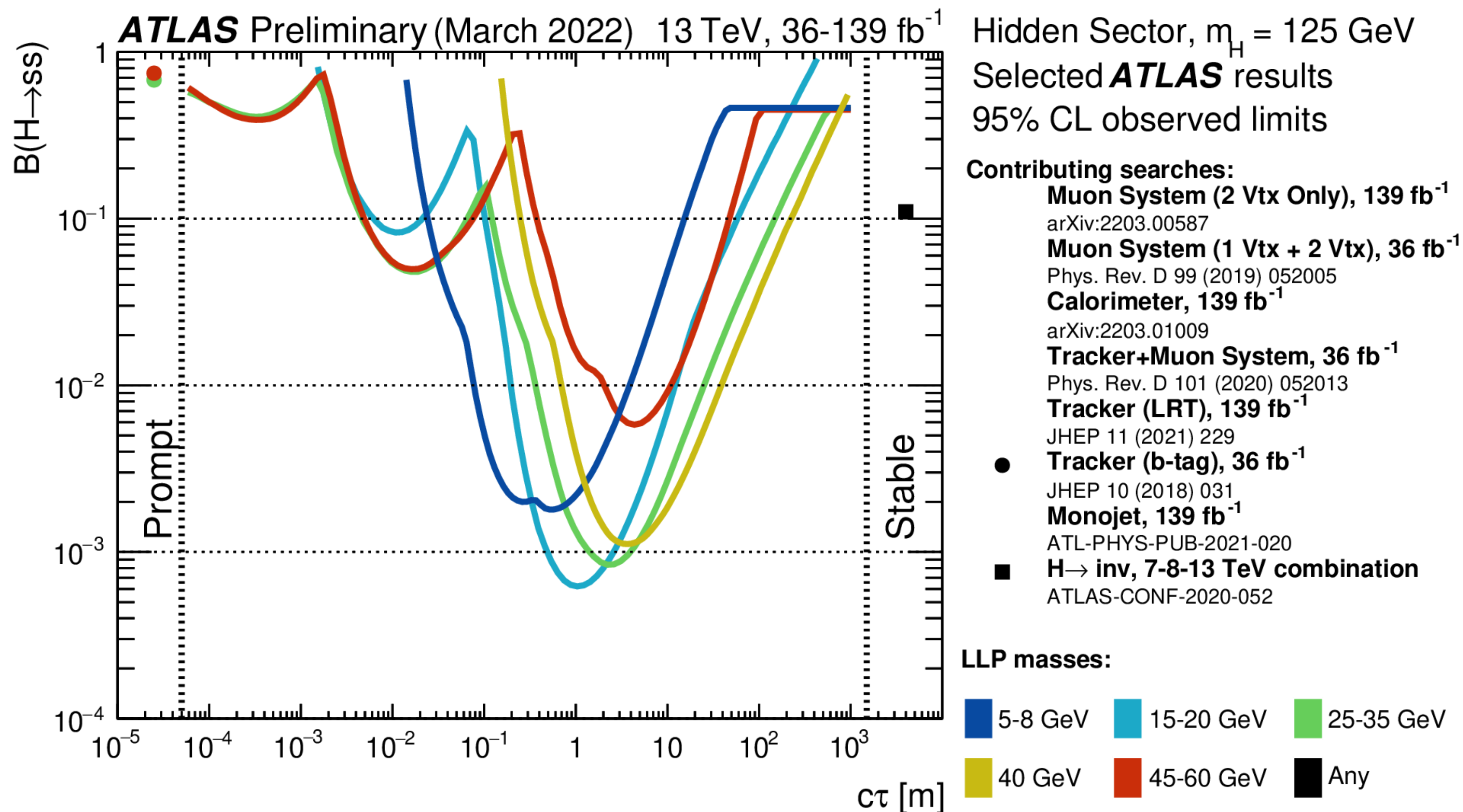
*Lepton jets*  
[ATLAS-CONF-2022-001](https://arxiv.org/abs/2203.00587)



*Displaced jets (Muon spectrometer)*  
[arXiv:2203.00587](https://arxiv.org/abs/2203.00587)



# Higgs → Long Lived Particles



See [backup](#) for individual search contributions





# Limits on 2HDM+S

from searches in wide array of decay modes

**ATLAS** Preliminary

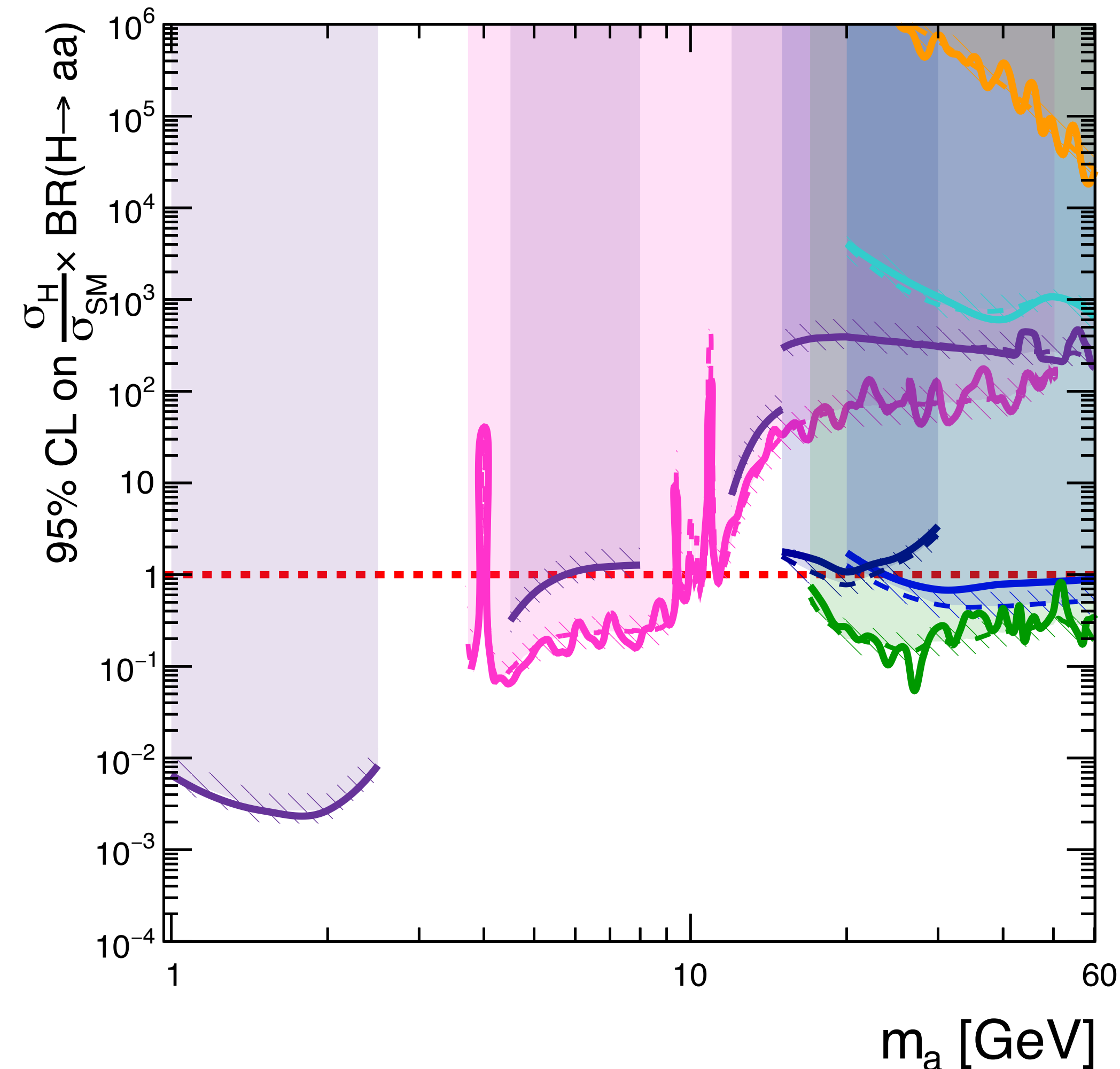
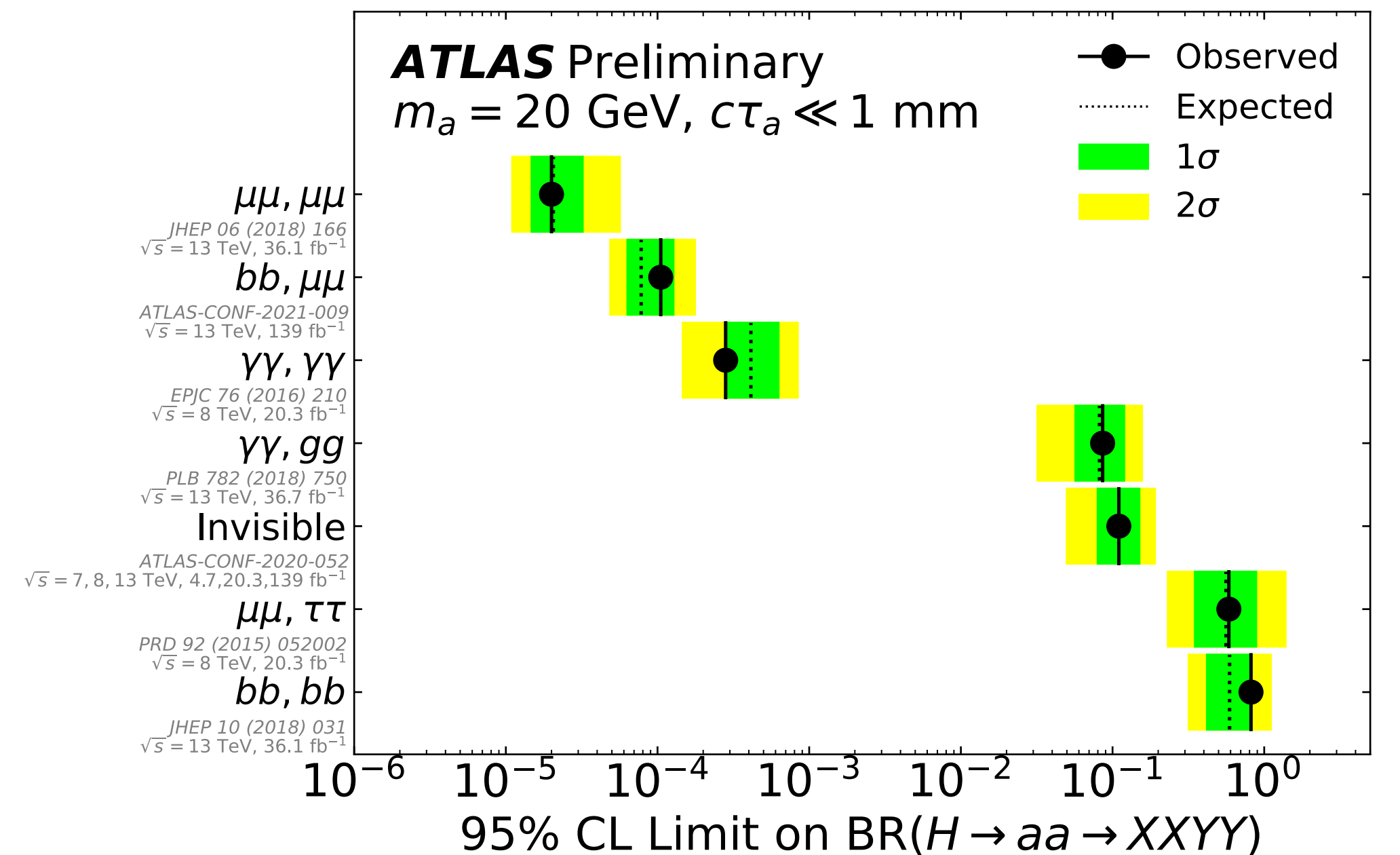
March 2021

Run 1:  $\sqrt{s} = 8$  TeV

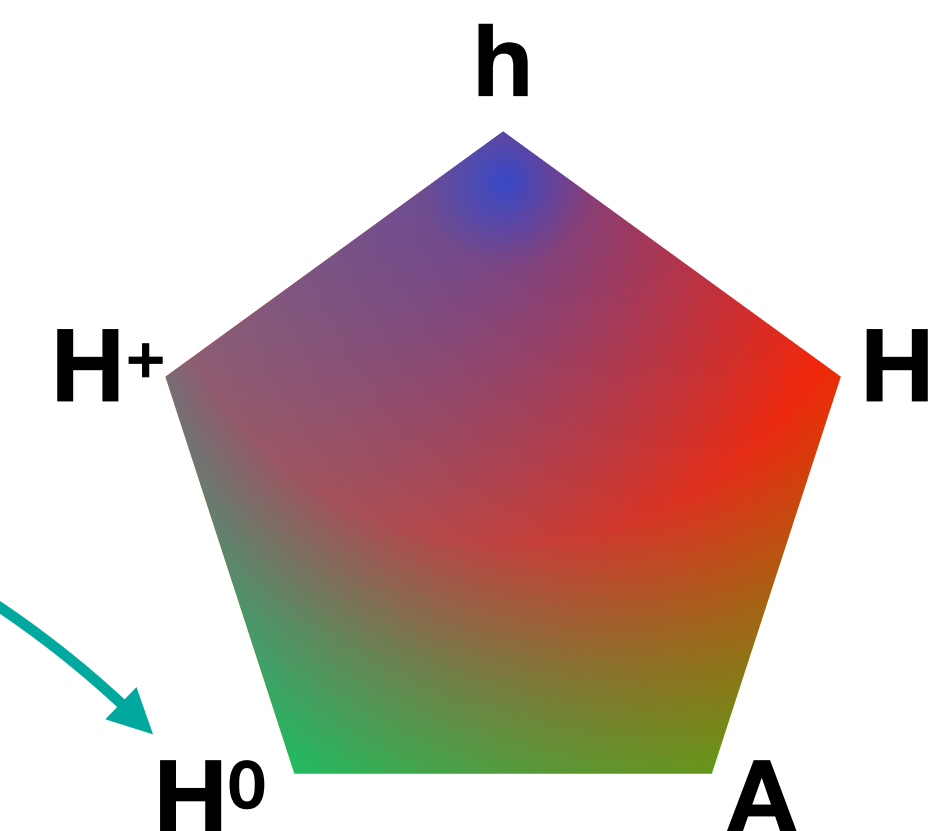
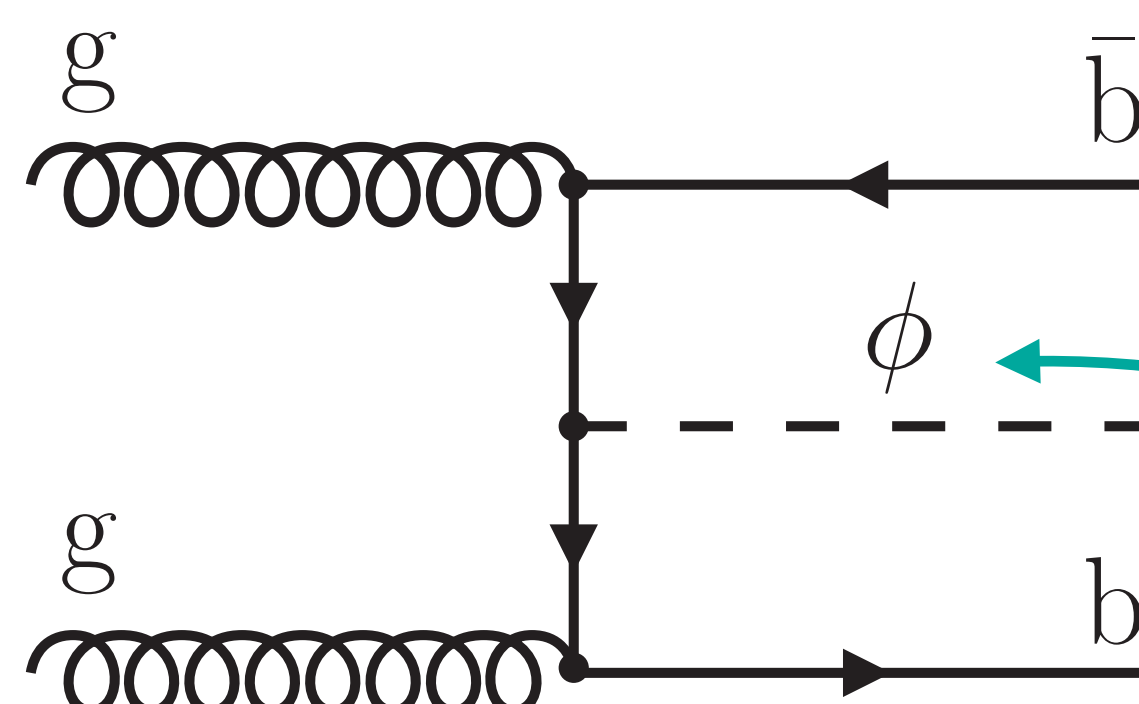
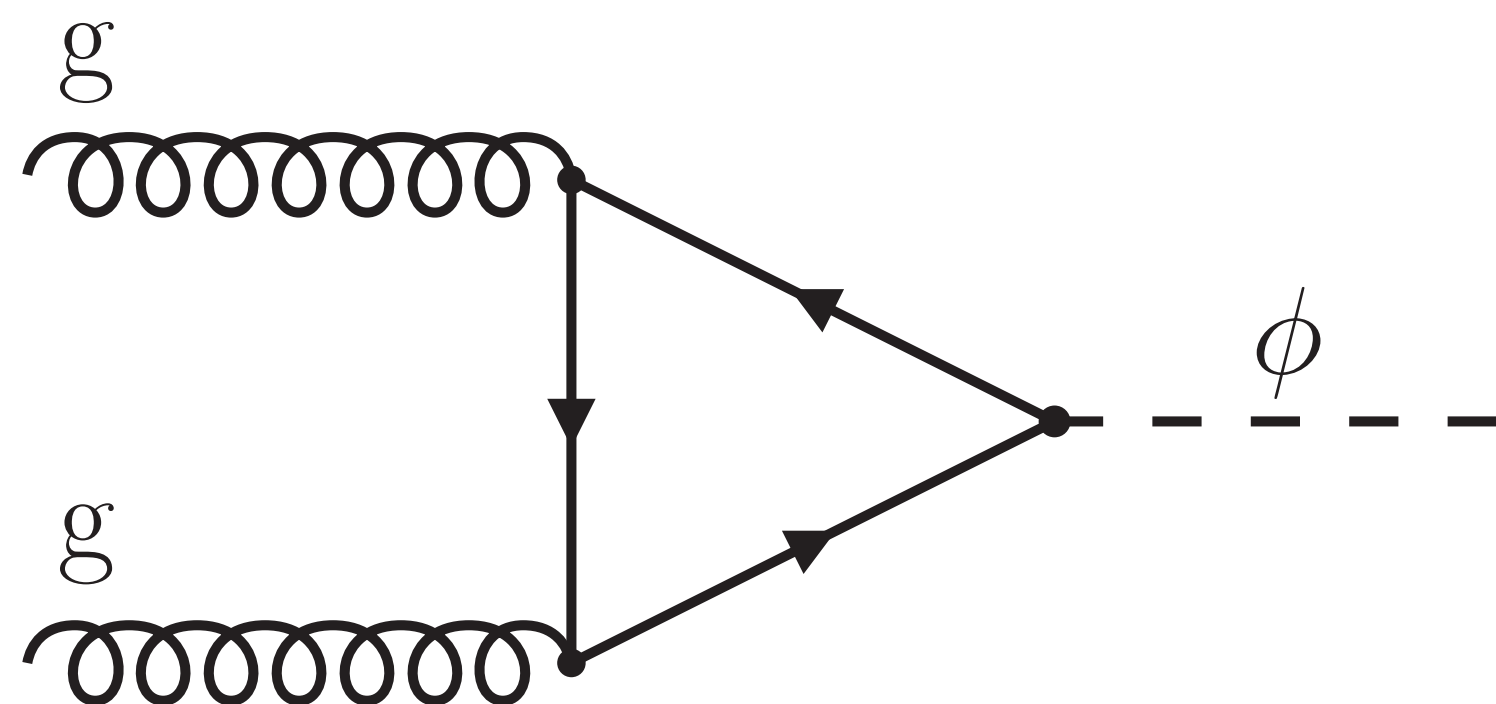
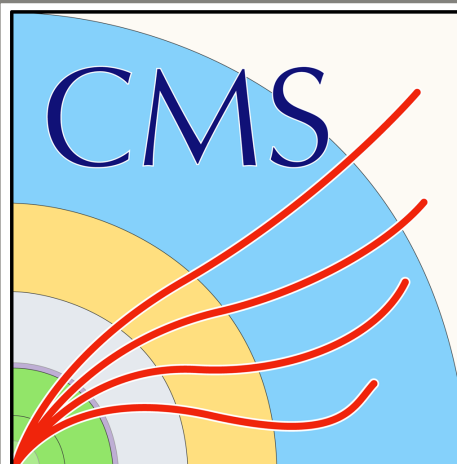
Run 2:  $\sqrt{s} = 13$  TeV

*2HDM+S Type-I*

March 2021

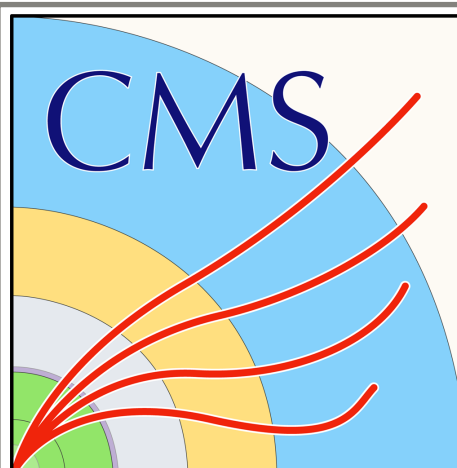


# Extended H sector in $\tau\tau$

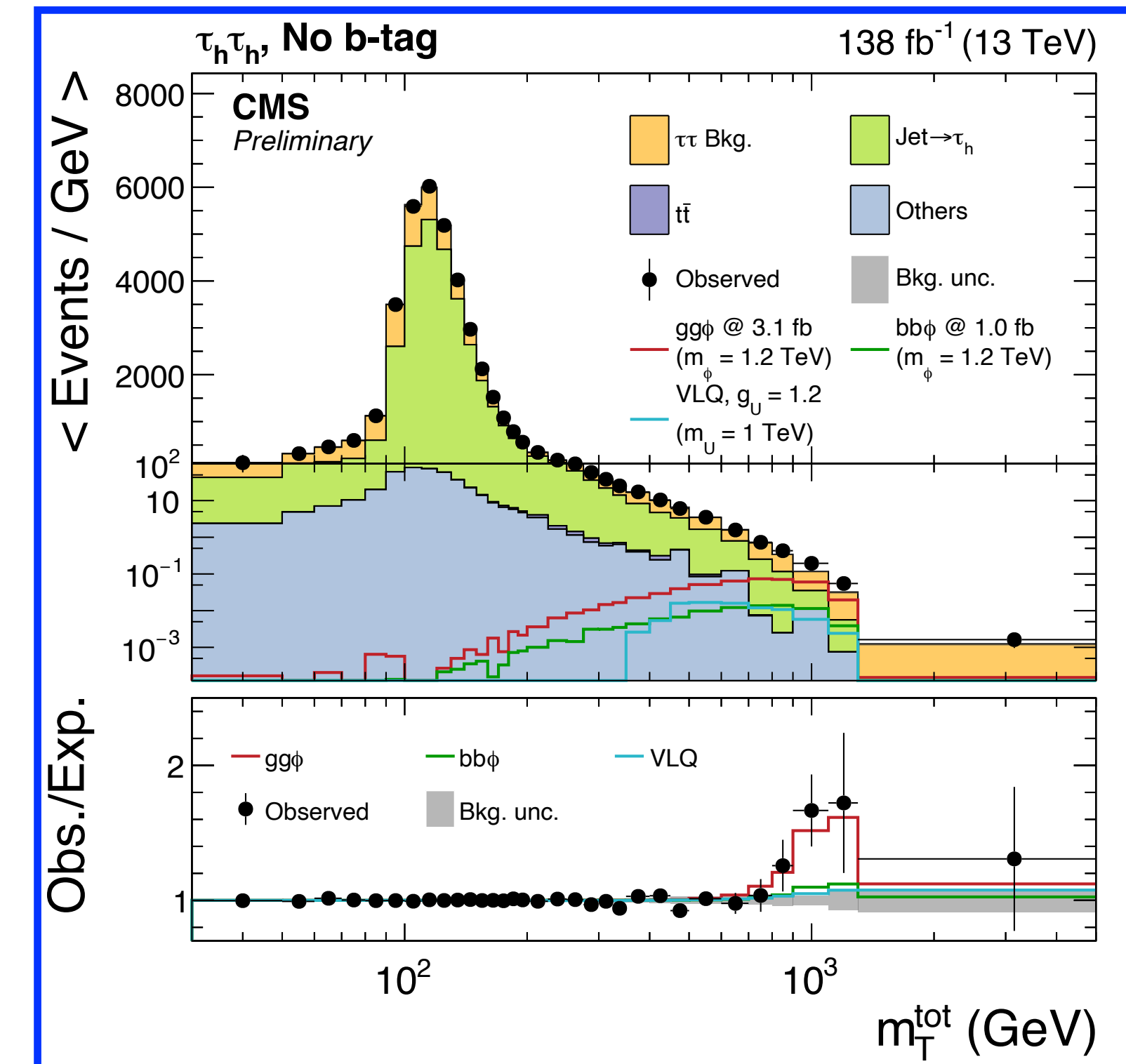
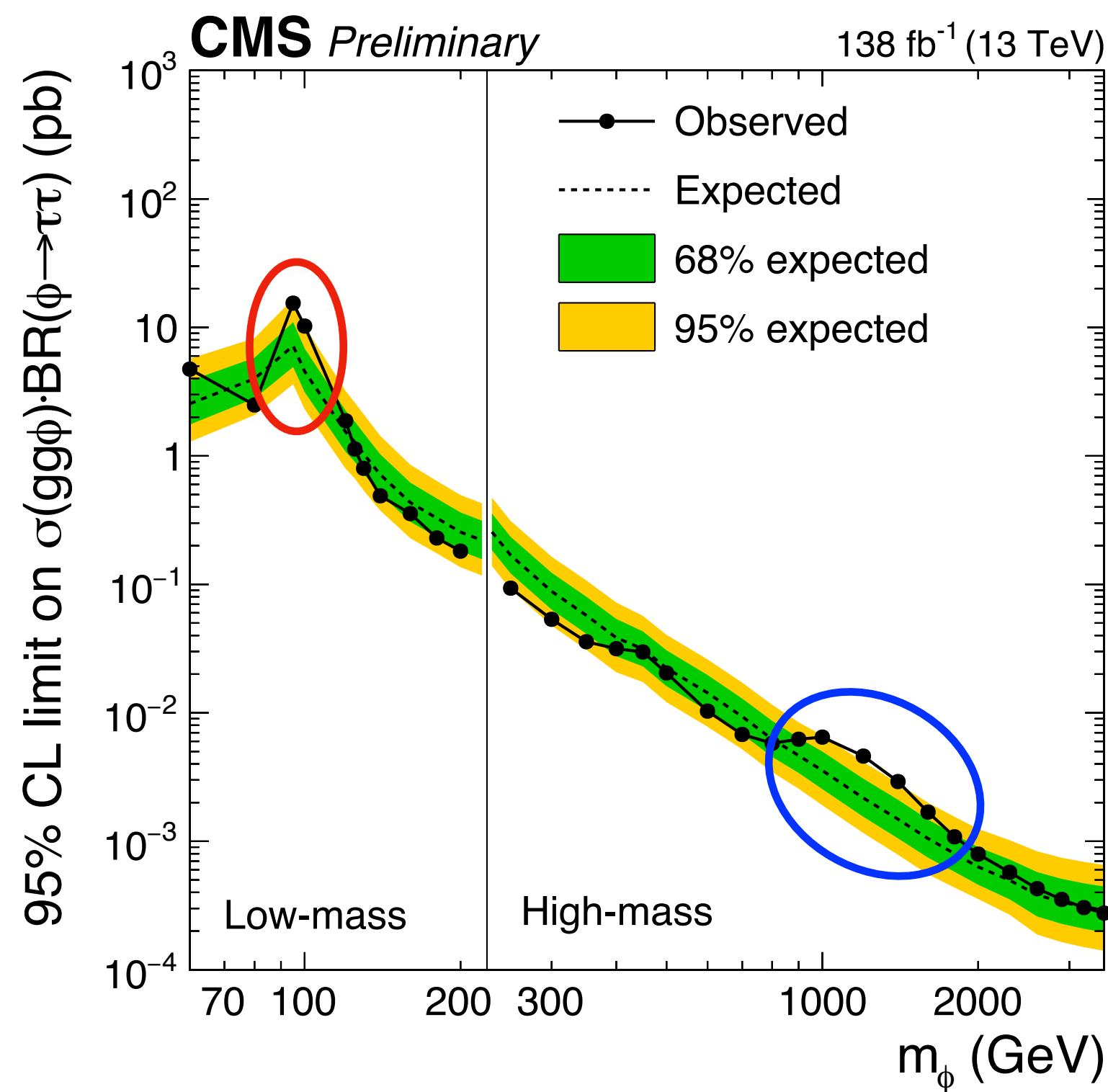
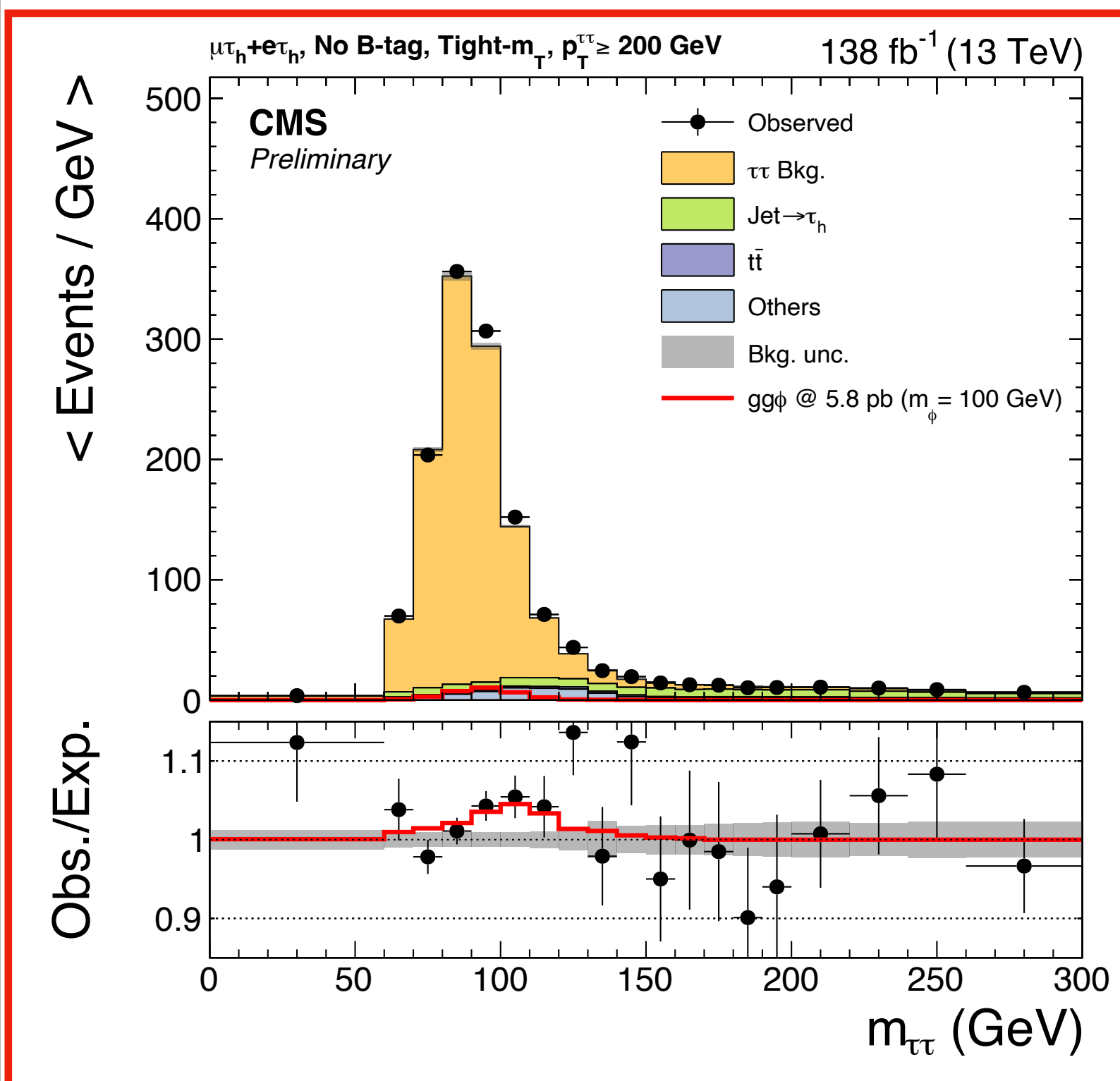


- Search for additional 2HDM-inspired scalar bosons
  - General search for single narrow-width scalar or multi-resonance from MSSM A,H
- DEEPJET/DEEPTAU object taggers
- Event selection split into high/low-mass and b-tag/no-b-tag categories
  - Neural Network analysis of  $m_{\tau\tau} < 250$  GeV based on  $H\tau\tau$  cross-section measurement

Complementary new search in  $WW \rightarrow \ell\ell$ : [CMS-PAS-HIG-20-016](#)



# Extended H sector in $\tau\tau$



Excesses observed in model-independent no-b-tag selection

2.7 $\sigma$  global at  $m_{\tau\tau} = 100$  GeV across years/decay modes

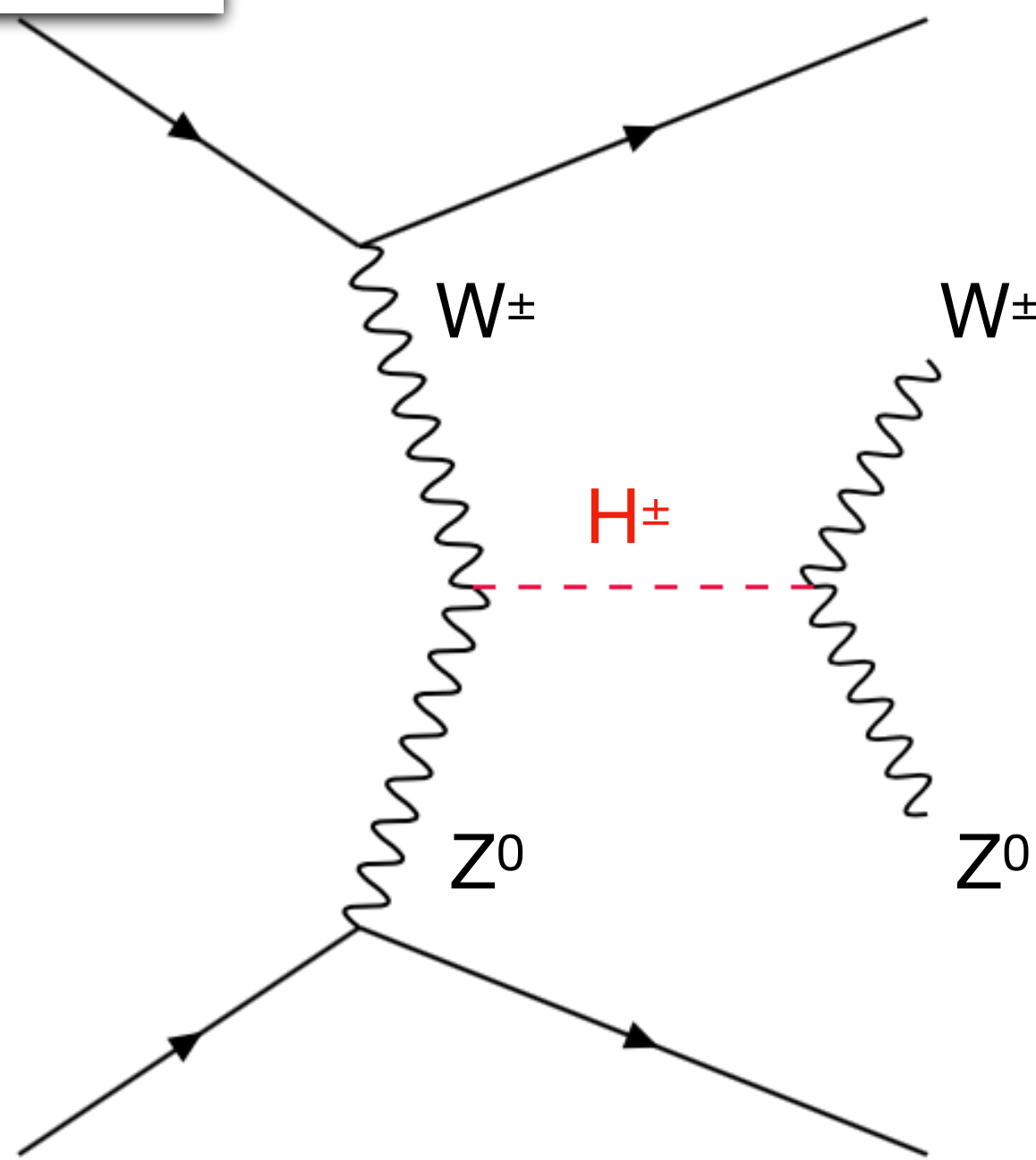
Compare [arXiv:1811.08459](https://arxiv.org/abs/1811.08459)

2.3 $\sigma$  global at  $m_{\tau\tau} = 1.2$  TeV concentrated in  $\tau_h\tau_h$



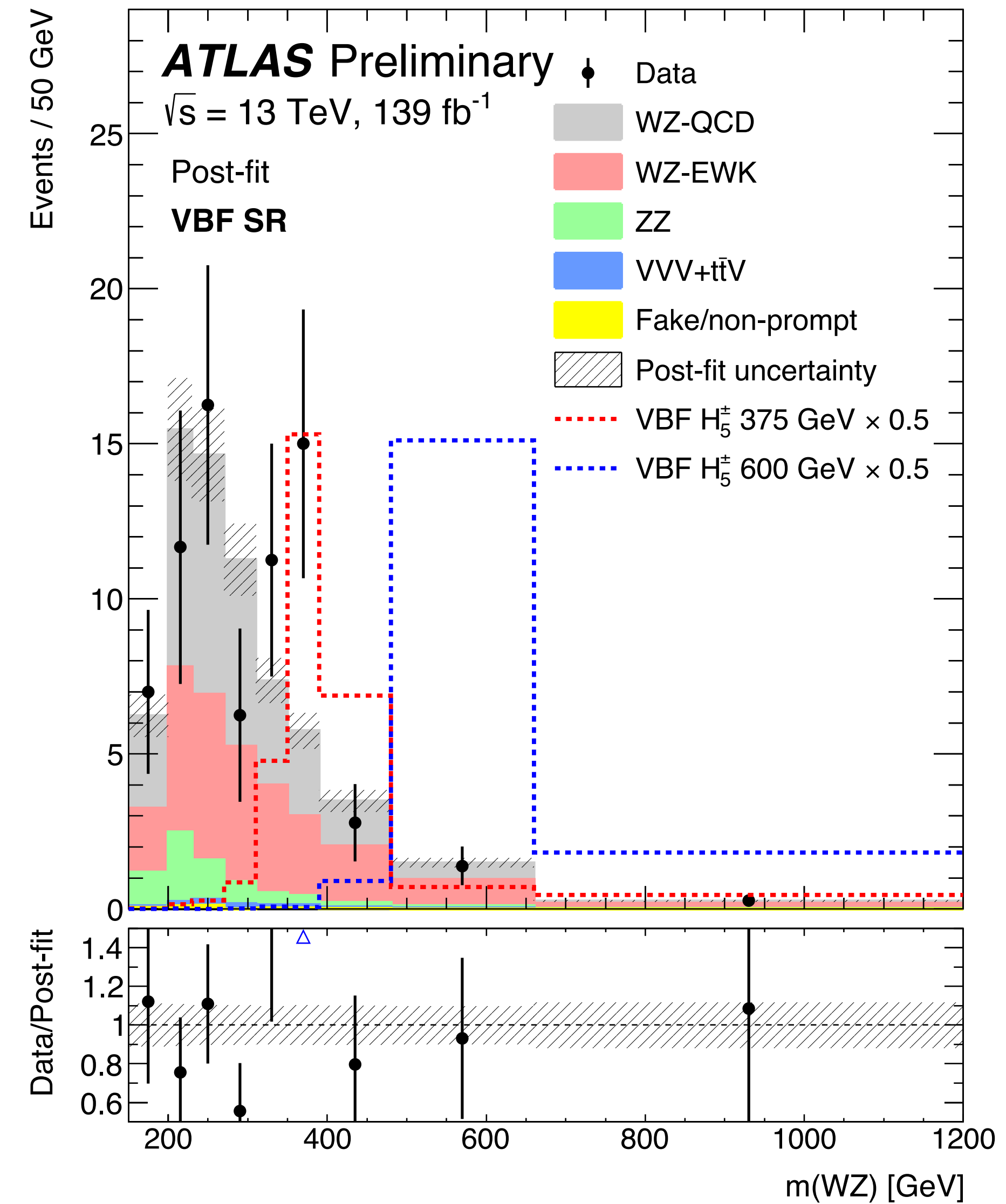
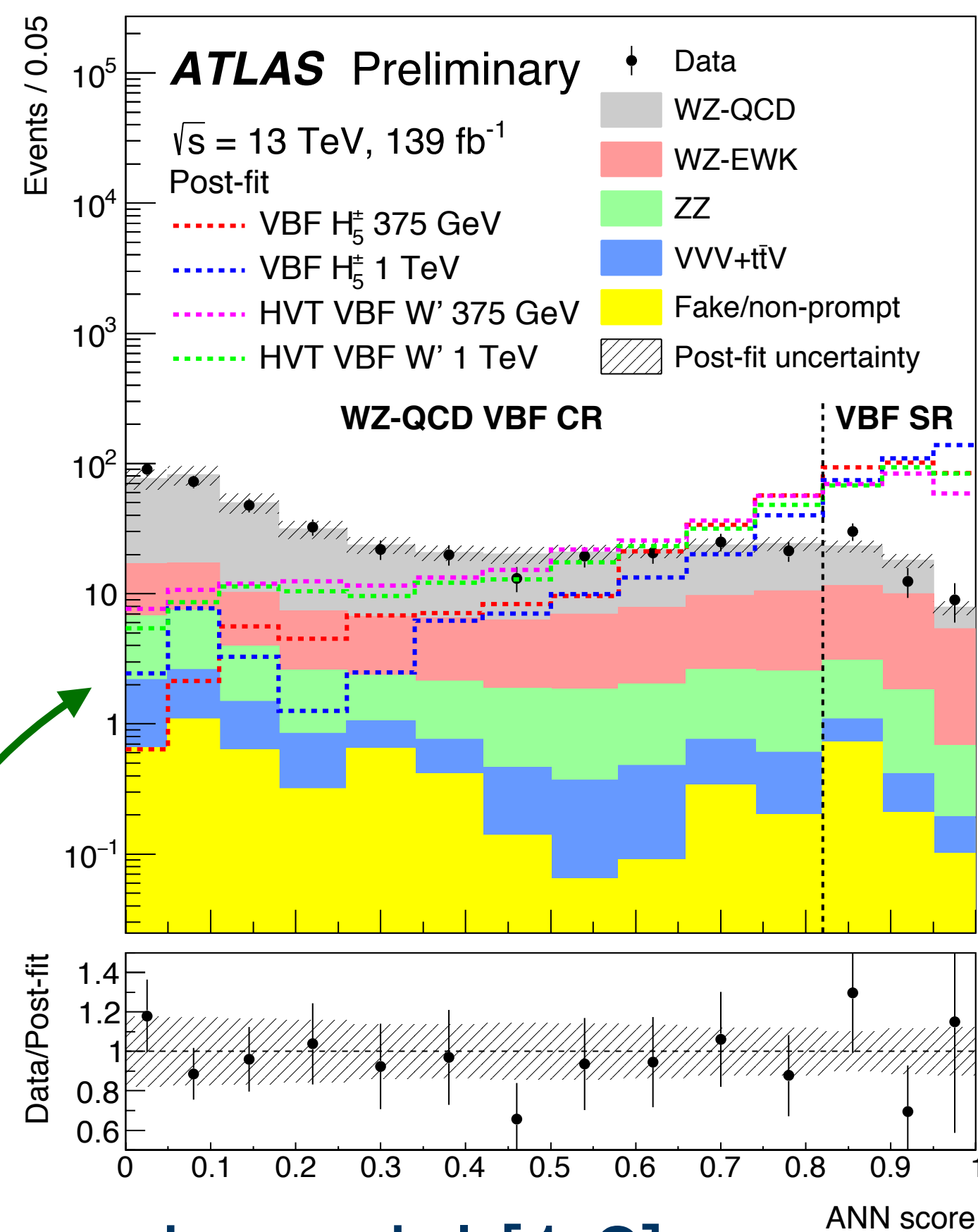
# Charged Higgs in $WZ \rightarrow \ell\nu\ell\ell$

As seen in Tues  
Magherini VBF talk



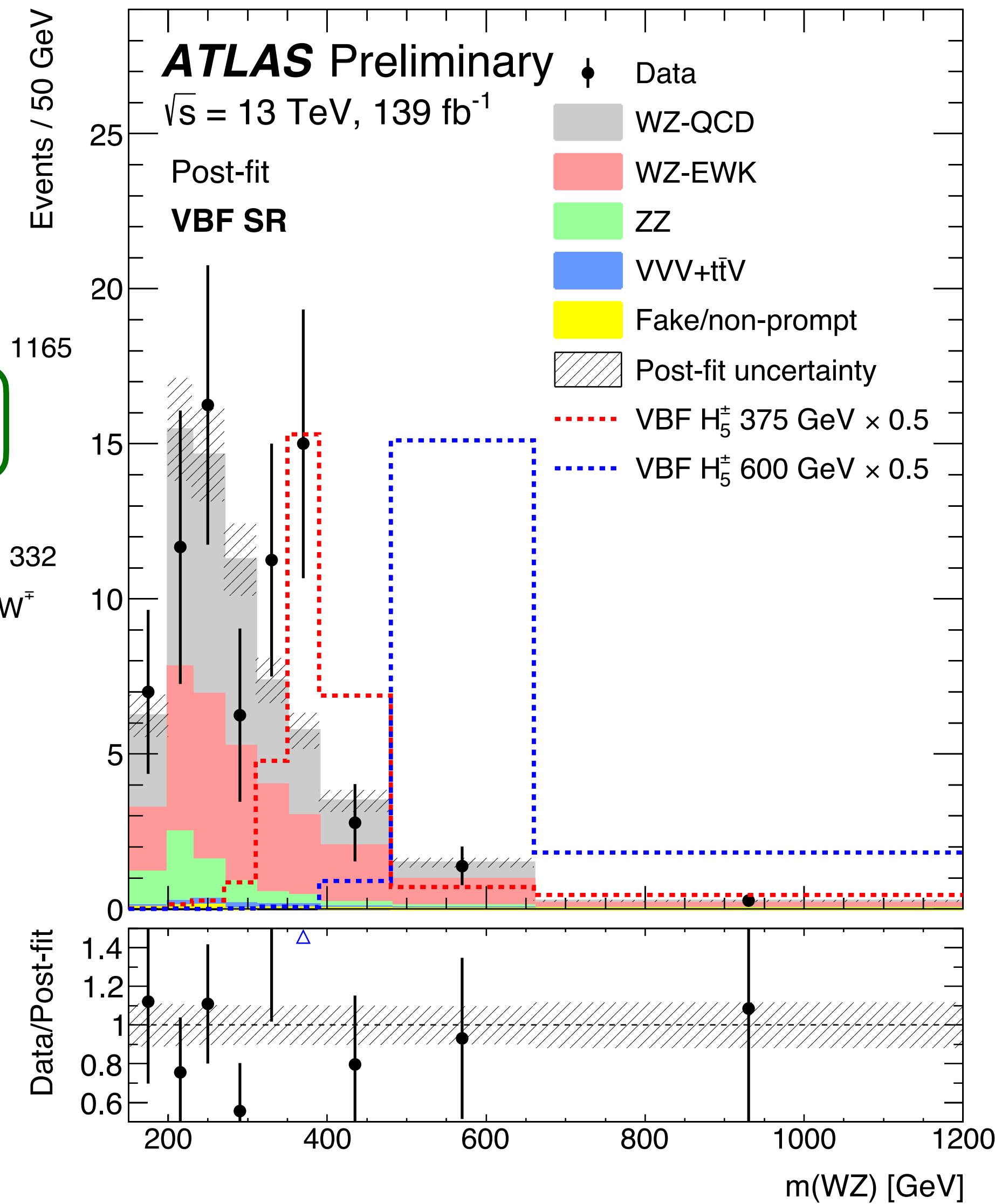
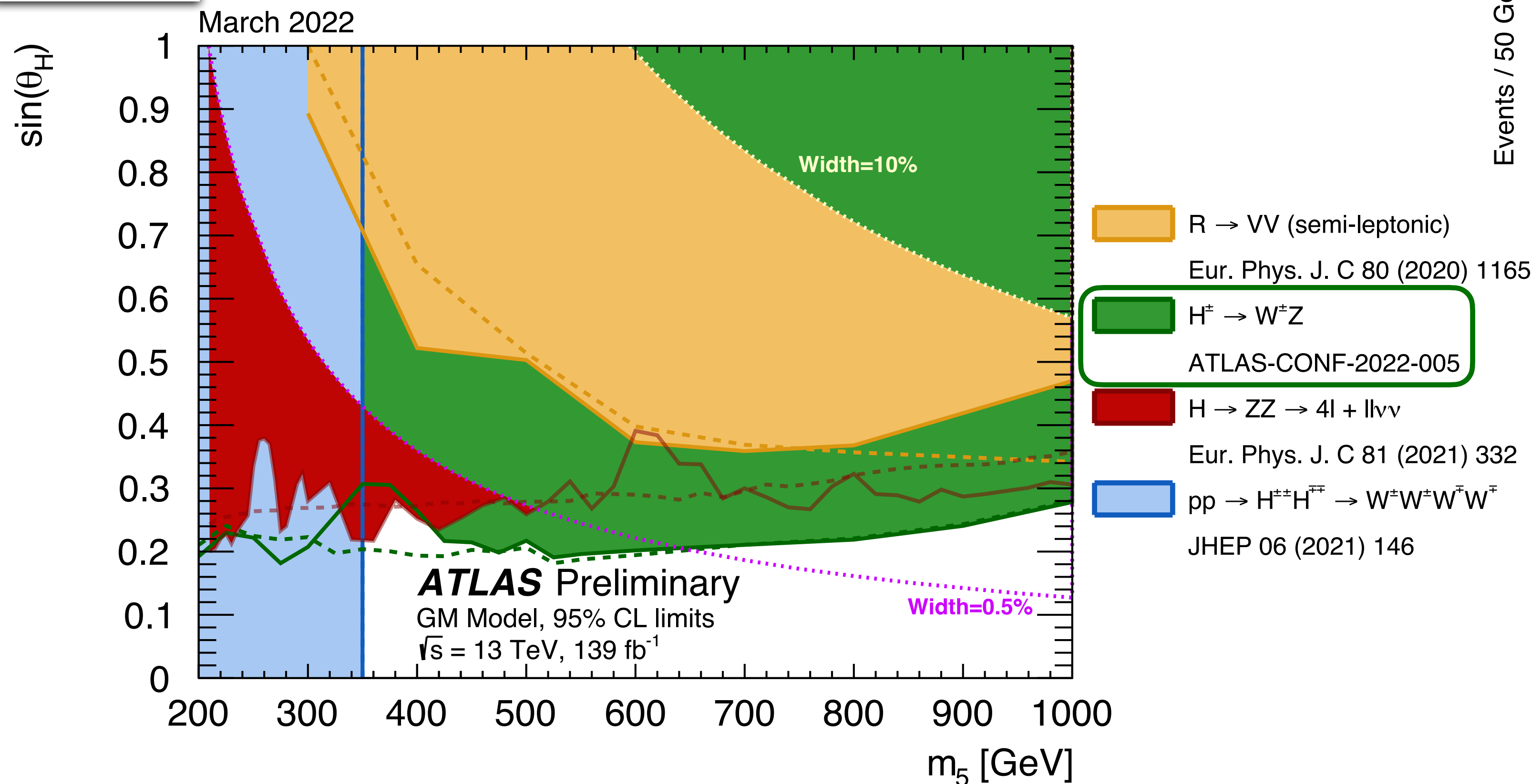
NN trained on wide  $H^\pm$  mass spectrum,  
cut optimised for  $m = 200$  GeV

- Motivated by Georgi-Machacek model [1,2]: permits tree-level couplings to W,Z
  - Fermiophobic  $H^\pm$  in five-plet produced by WZ fusion, decays back to WZ





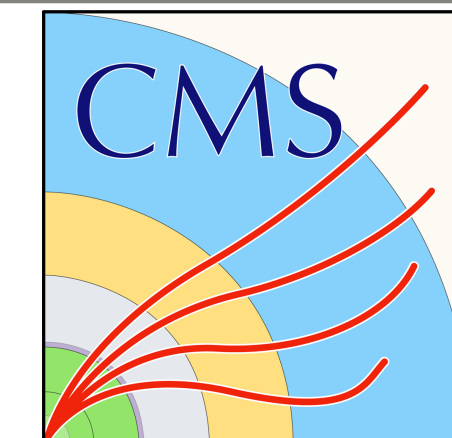
# Charged Higgs in $WZ \rightarrow \ell \nu \ell \ell$



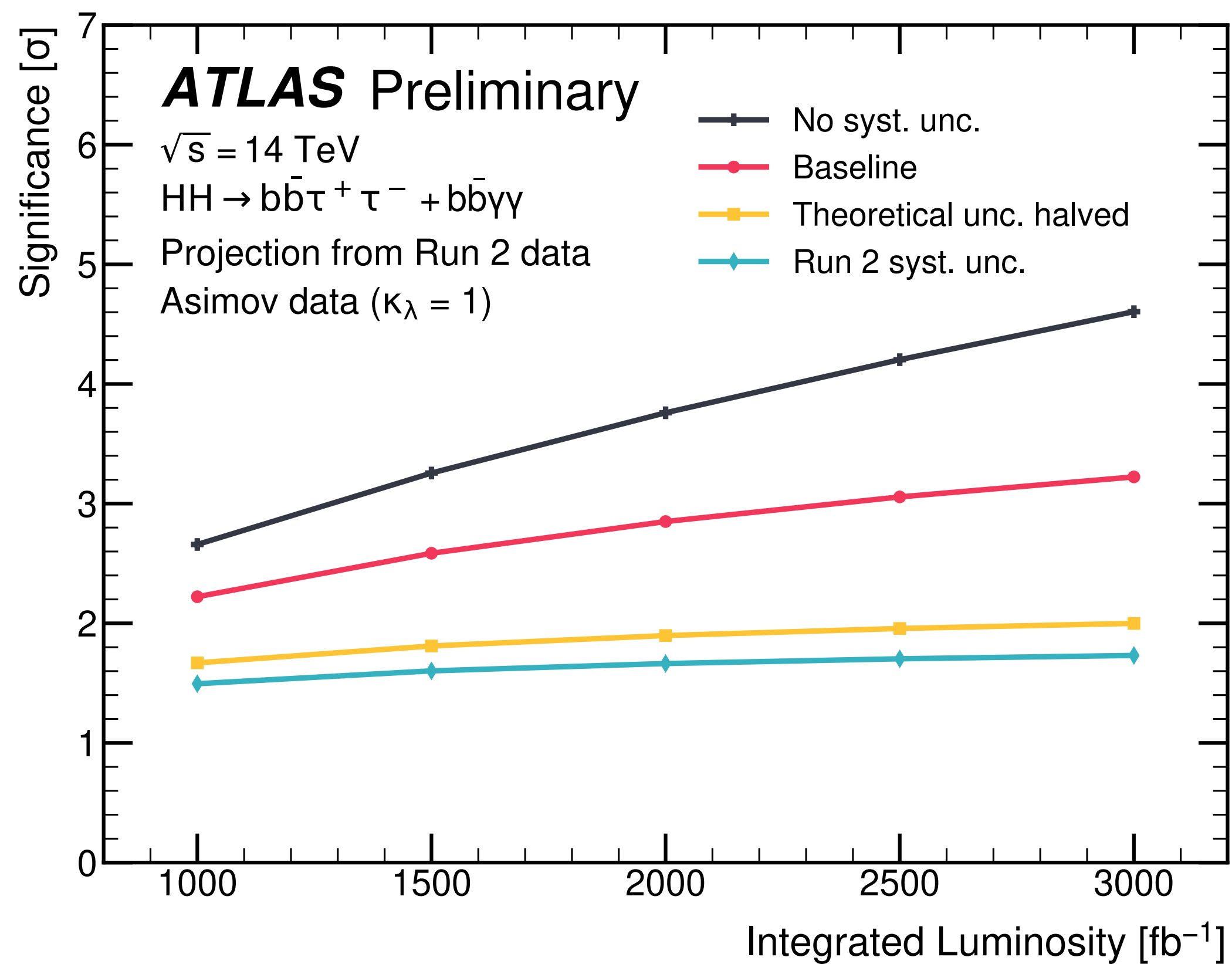
- Motivated by Georgi-Machacek model [1,2]: permits tree-level couplings to W,Z
  - Fermiophobic  $H^\pm$  in five-plet produced by WZ fusion, decays back to WZ



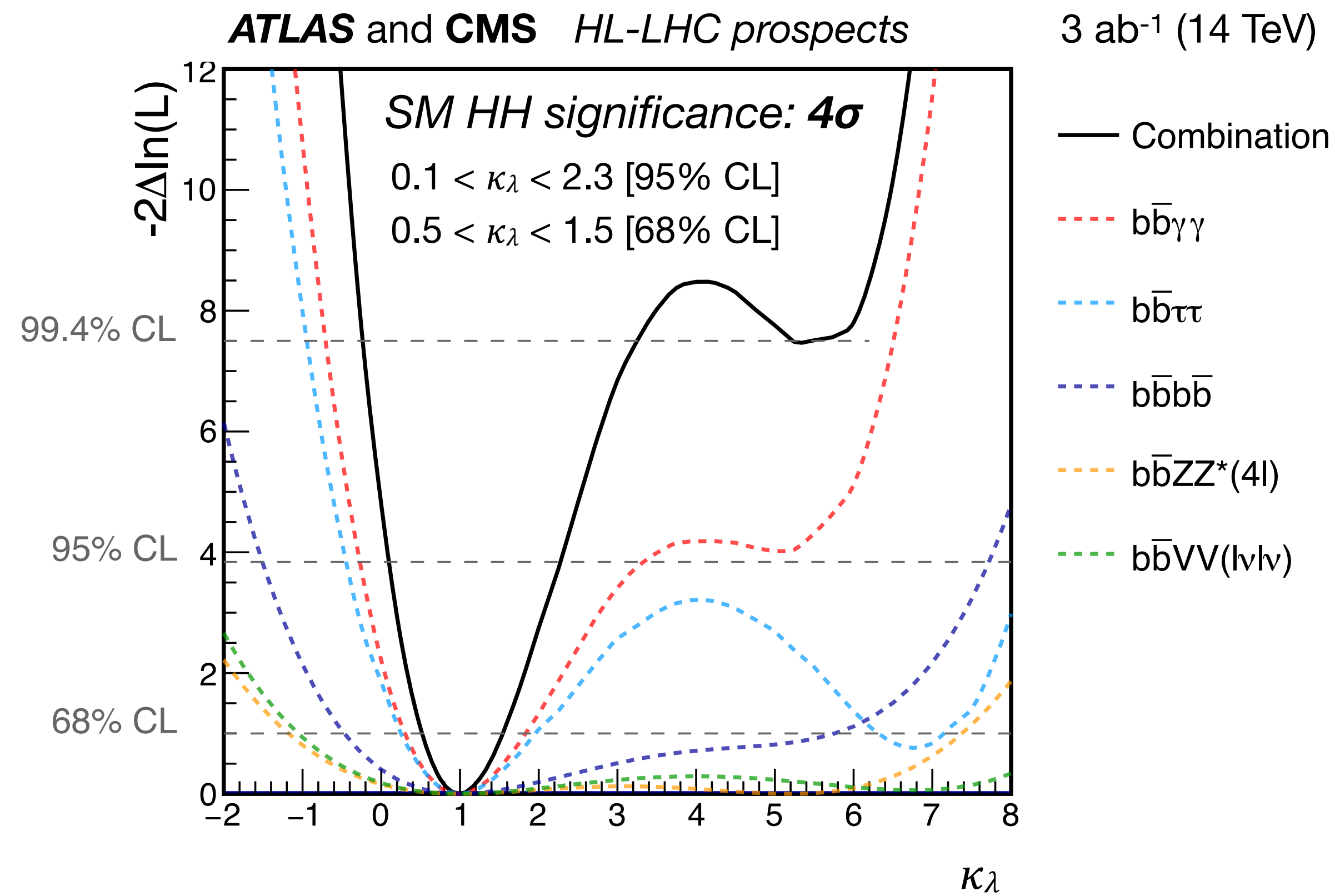
# Looking ahead to HL-LHC



Assume SM signal



[New ATLAS HL-LHC projections](#)  
 ( $b\bar{b}\tau\tau$ ,  $b\bar{b}\gamma\gamma$ )



[Snowmass White Paper: Physics with ATLAS/CMS Phase-II](#)  
 ATL-PHYS-PUB-2022-018/CMS-PAS-FTR-22-001

# Honourable mentions

Feb 2022

Feb 2022

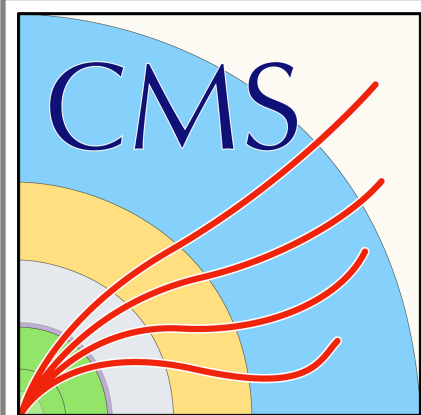
- HH 4b: ATLAS resonant [arXiv:2202.07288](https://arxiv.org/abs/2202.07288), CMS non-resonant [arXiv:2202.09617](https://arxiv.org/abs/2202.09617)
  - ATLAS resonant combination [ATLAS-CONF-2021-052](https://atlas.cern/ATLAS-CONF-2021-052)
- CMS H decay via dark Z to 4l [arXiv:2111.01299](https://arxiv.org/abs/2111.01299)
- ATLAS combination of searches for 2HDM+a [ATLAS-CONF-2021-036](https://atlas.cern/ATLAS-CONF-2021-036)
- ATLAS constraints on 2HDM via SM Higgs combination [ATLAS-CONF-2021-053](https://atlas.cern/ATLAS-CONF-2021-053)
- Charged Higgs searches:
  - ATLAS  $H^\pm$  in top decays [ATLAS-CONF-2021-052](https://atlas.cern/ATLAS-CONF-2021-052)
  - CMS  $H^\pm$  via  $WH(\tau\tau)$  [CMS-PAS-HIG-21-010](https://cms.cern/CMS-PAS-HIG-21-010) **March 2022**
  - ATLAS  $H^{\pm\pm}$  in multilepton final states [ATLAS-CONF-2022-010](https://atlas.cern/ATLAS-CONF-2022-010) **March 2022**
- ATLAS ttH/A search in tttt final state [ATLAS-CONF-2022-008](https://atlas.cern/ATLAS-CONF-2022-008) **March 2022**

# Wrapping up

- Have shown selected highlights of ATLAS/CMS HH and BSM-H searches
- Pursuing SM HH in many decay channels, increasing power in VBF HH
  - Run 3 is opportunity to augment dataset beyond  $\sqrt{N}$  with new triggers
- Exotic Higgs decays motivating advanced reconstruction techniques
  - Boosted reconstruction beyond jets
  - Non-prompt decays of special interest
- Machine learning widespread in reconstruction, classification, background modelling — take care not to impact interpretation

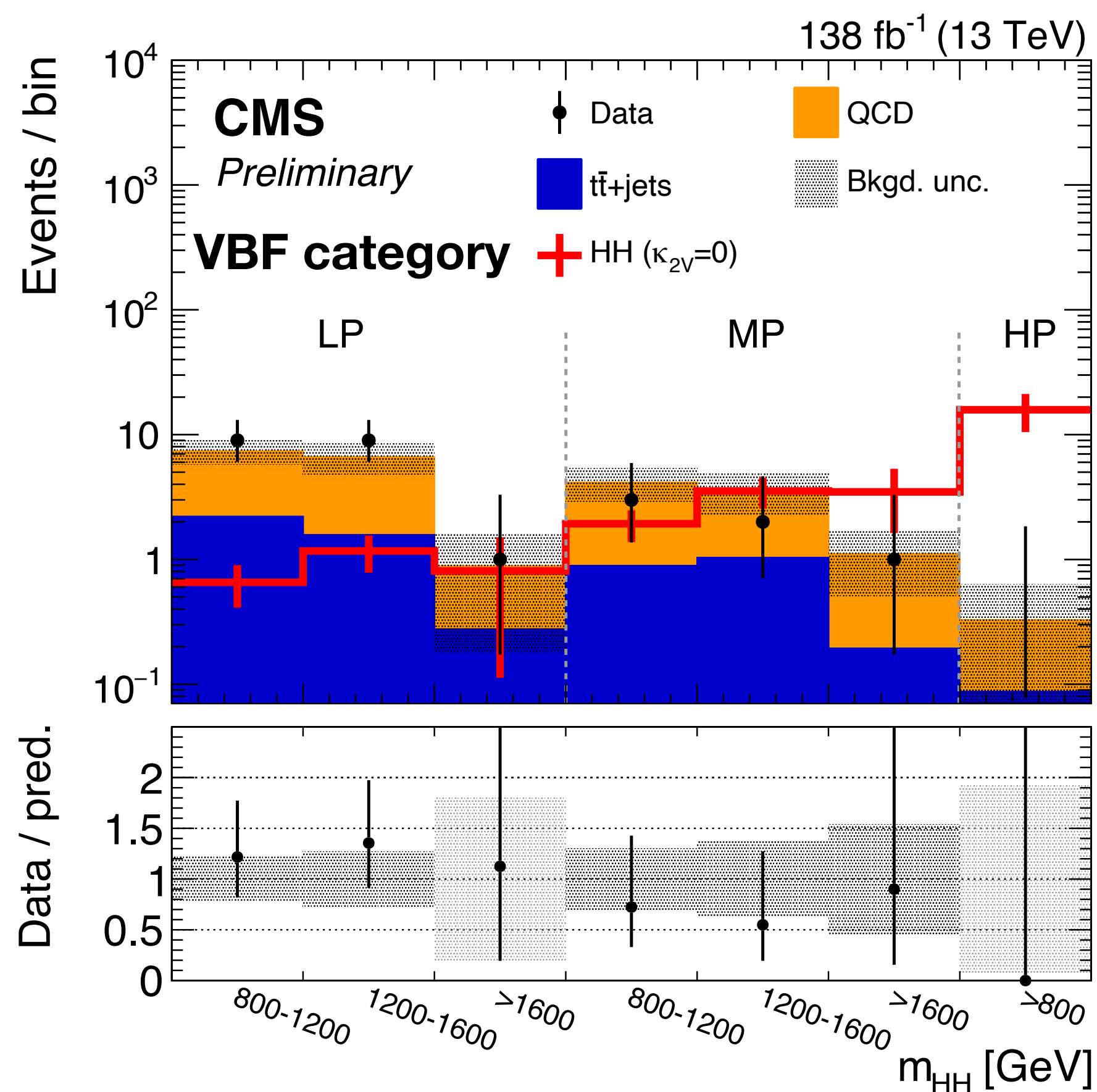


# Backups

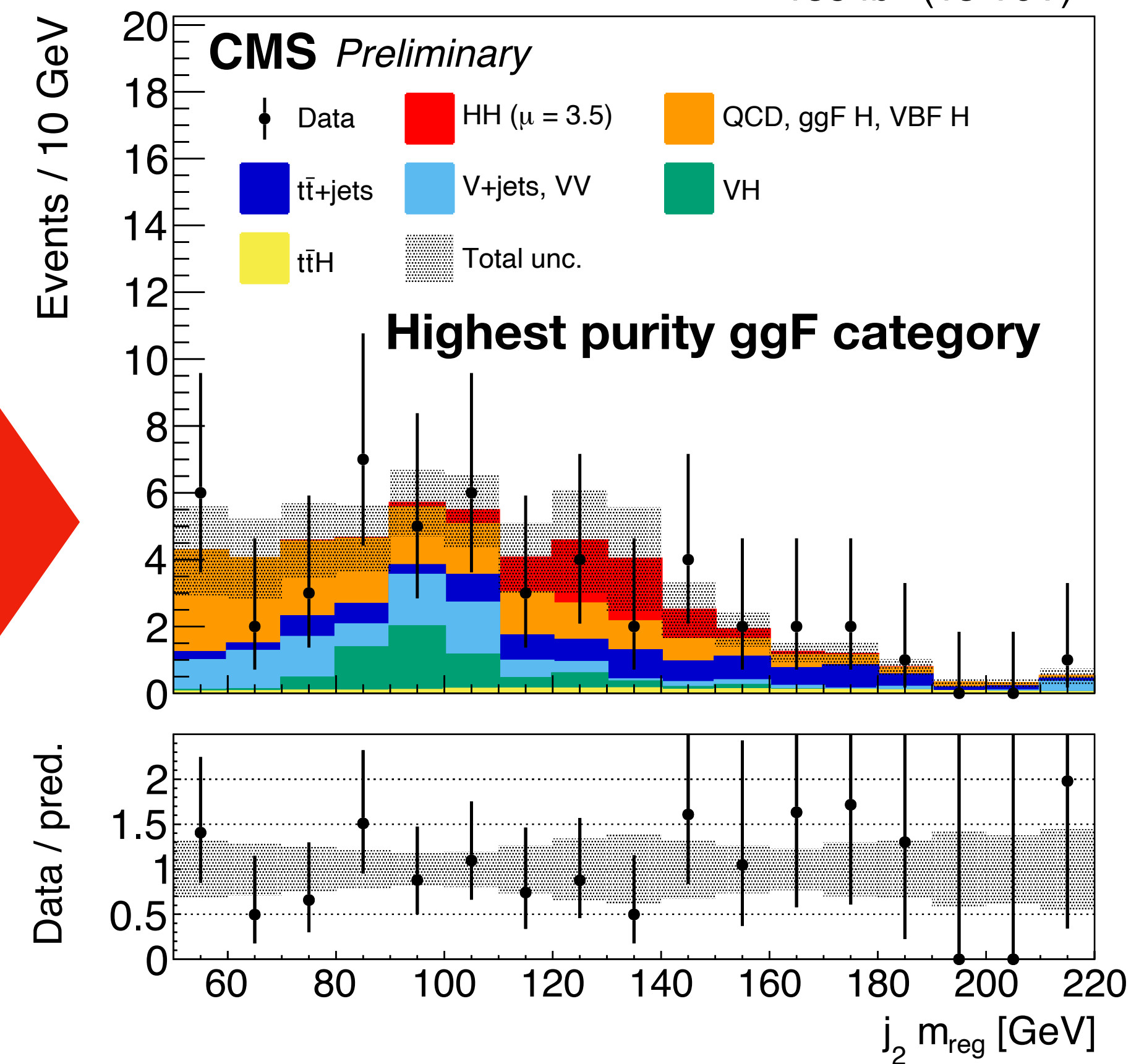


# CMS boosted HH → bbbb

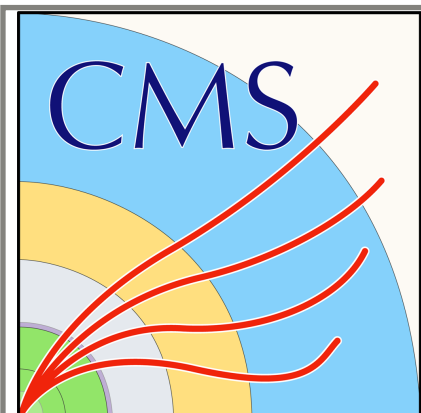
138 fb<sup>-1</sup> (13 TeV)



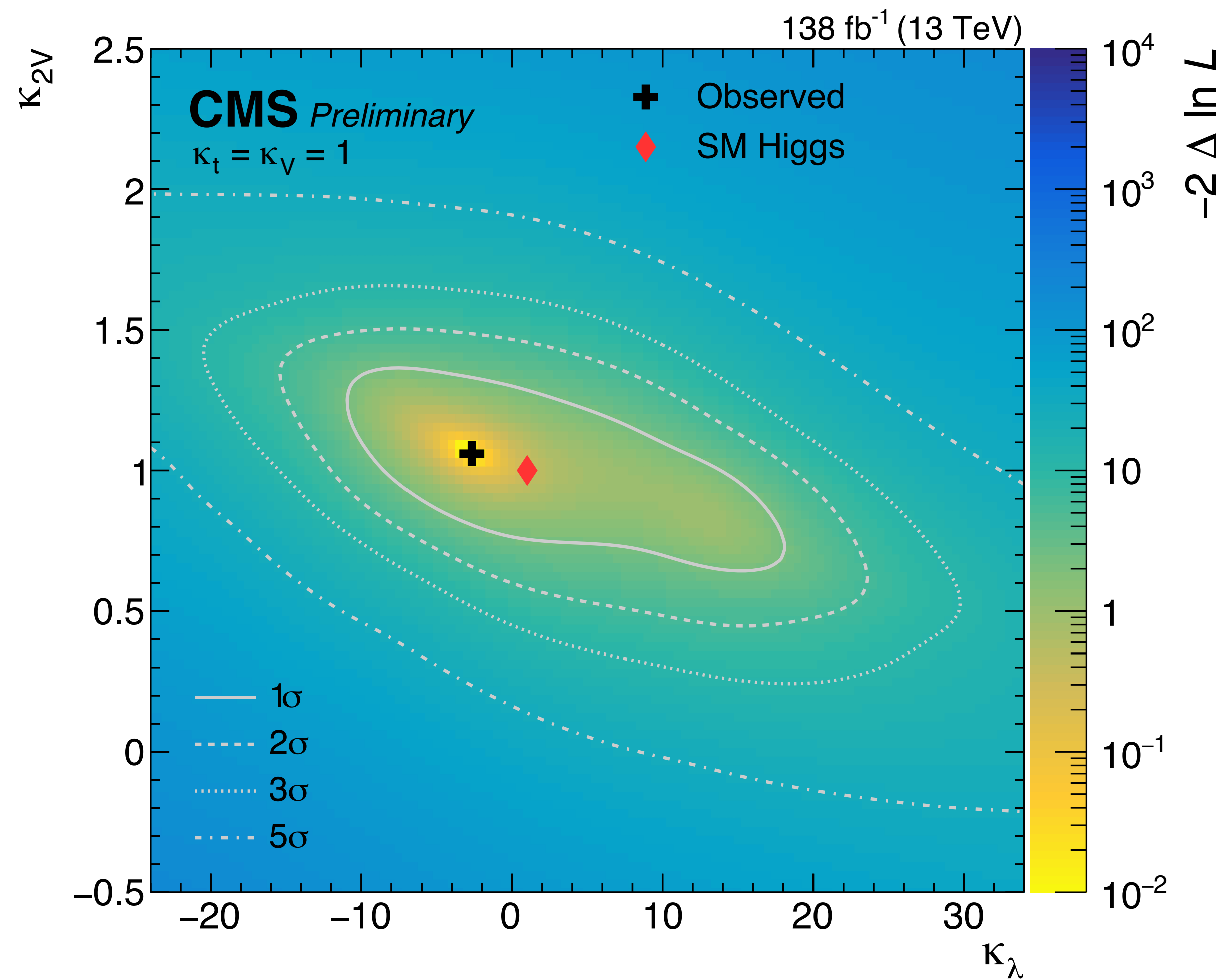
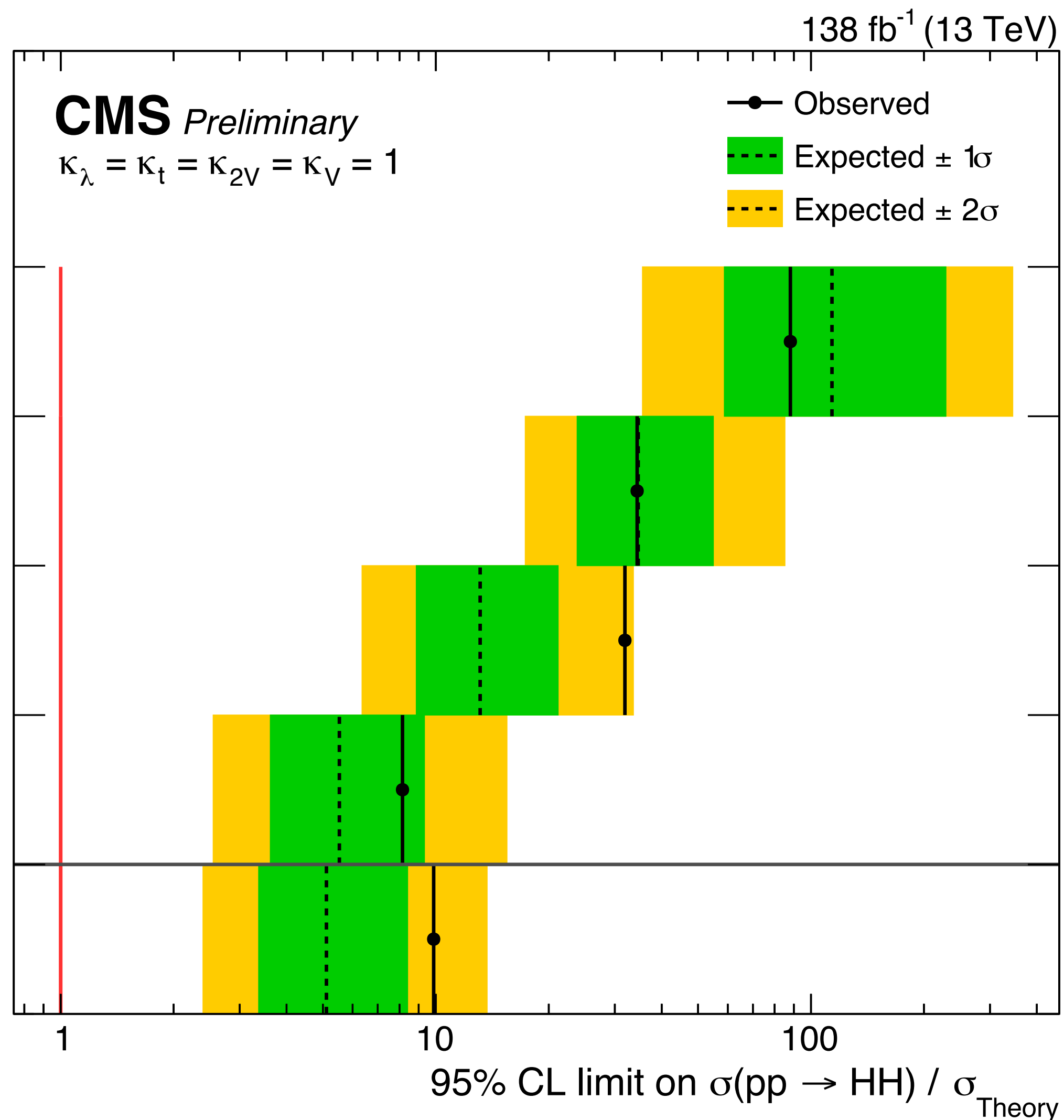
ggF BDT WP	HH eff	BG misID
Loose	33 %	12 %
Medium	27 %	2 %
Tight	23 %	1 %



- Boosted H jets reconstructed with Soft Drop particle flow jets
- Identification and jet mass regression with ParticleNet Graph Neural Network



# CMS boosted HH → bbbb



# RosEFTa stone (HH operators)

## HEFT

$C_{hhh}$	$C_{tth}$	$C_{ggh}$	$C_{tthh}$	$C_{gggh}$
$C_{hhh}$	$C_t$	$C_{ggh}$	$C_{tt}$	$C_{gggh}$
$\kappa_\lambda$	$\kappa_t$	$C_g$	$C_2$	$C_{2g}$

## SMEFT → HEFT translation

*L. Alasfar, LHC-HH*

HEFT	SMEFT	
	SILH	Warsaw
$C_{hhh}$	$1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H$	$1 - 2\frac{v^4}{m_h^2}C_H + 3C_{H,kin}$
$C_t$	$1 - \frac{\bar{c}_H}{2} - \bar{c}_u$	$1 + C_{H,kin} - C_{uH}\frac{v^3}{\sqrt{2}m_t}$
$C_{tt}$	$-\left(\frac{3}{2}\bar{c}_u + \frac{\bar{c}_H}{2}\right)$	$-C_{uH}\frac{3v^3}{2\sqrt{2}m_t} + C_{H,kin}$
$C_{ggh}$	$\frac{128\pi^2}{g_2^2}\bar{c}_g$	$\frac{8\pi}{\alpha_s}v^2C_{HG}$
$C_{gggh}$	$\frac{64\pi^2}{g_2^2}\bar{c}_g$	$\frac{4\pi}{\alpha_s}v^2C_{HG}$

## SMEFT

Relevant ggF HH operators

Warsaw operators	<u>ATLAS STXS</u> $c_i/\Lambda^2$	<u>Alasfar &amp; Gruber '19</u> $c_i$	<u>SMEFIT '21</u> $c_i/\Lambda^2$	<u>SMEFT@NLO</u> $c_i/\Lambda^2$
$Q_\phi$	$C_H$	$c_H/\Lambda^2$	$C_6$	cp
$Q_{\phi G}$	$C_{HG}$	$c_{HG}/\Lambda^2$	$C_{\Phi G}$	cpG
$Q_{u\phi}$	$C_{tH}$	$c_{uH}/\Lambda^2$	$C_{t\Phi}$	ctp
$Q_{uG}$	$C_{tG}$	-	$C_{tG}$	ctG
$Q_{\phi\Box}$	$C_{H,\Box}$	$c_{H,kin}$	$C_H$	cdp
$Q_{\phi D}$	$C_{HD}$	$c_{HD}/\Lambda^2$	-	cpDC

Where  $C_{H,kin} = (C_{H,\Box} - \frac{1}{4}C_{HD})$

[arXiv:1008.4884](https://arxiv.org/abs/1008.4884) [arXiv:1008.4884](https://arxiv.org/abs/1008.4884)



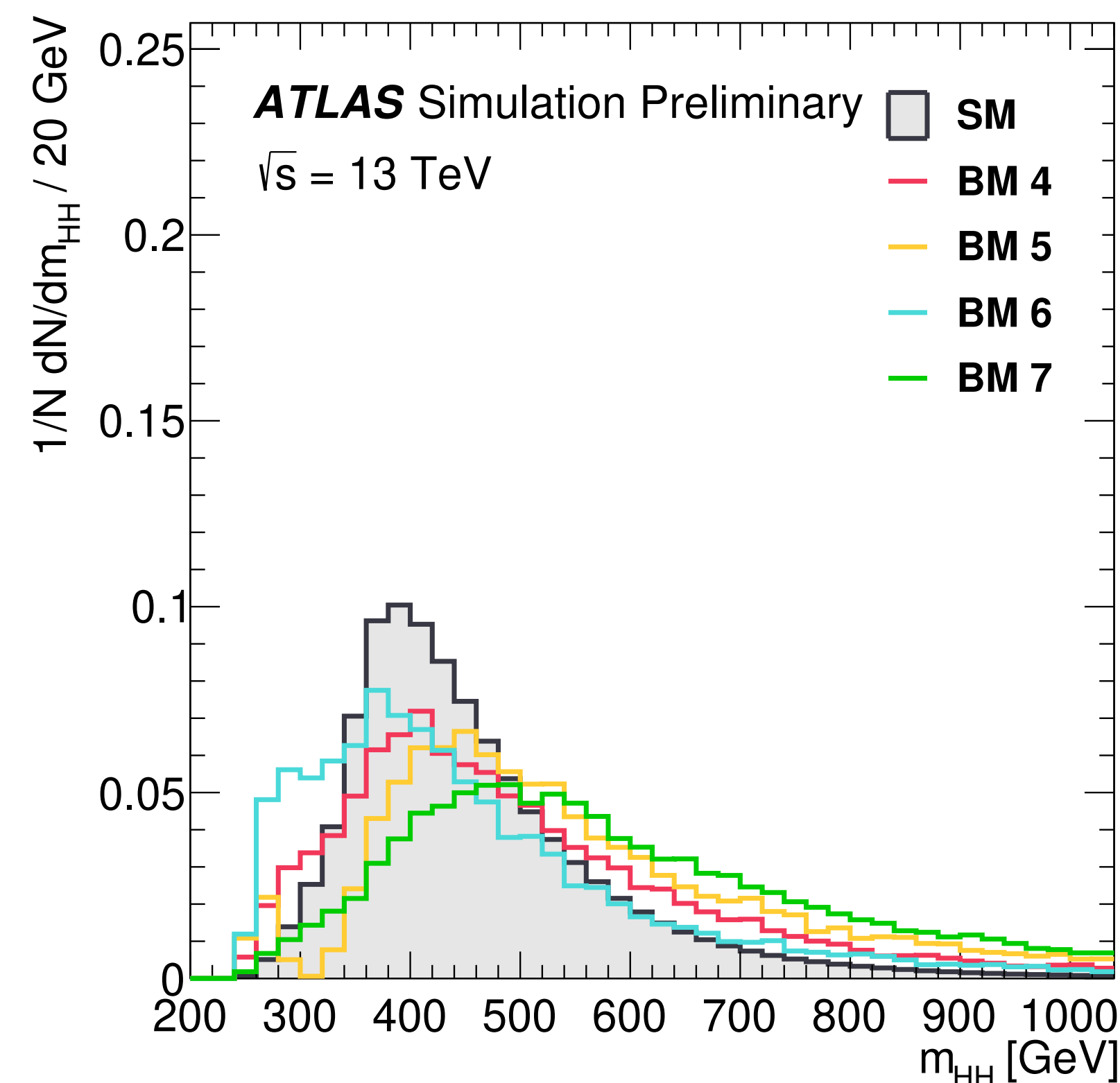
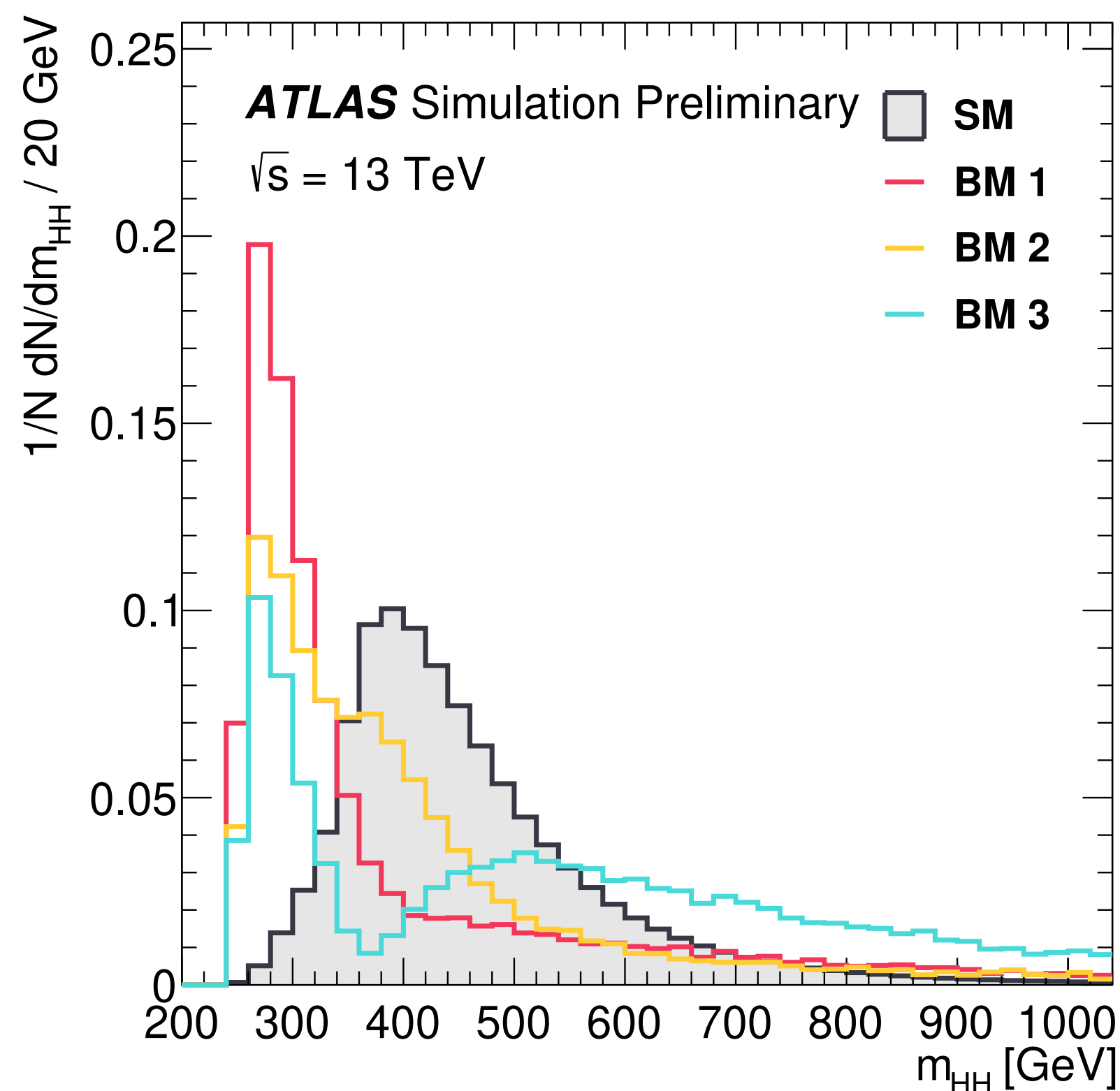
# ATLAS $bb\tau\tau/bb\gamma\gamma$ vs HEFT

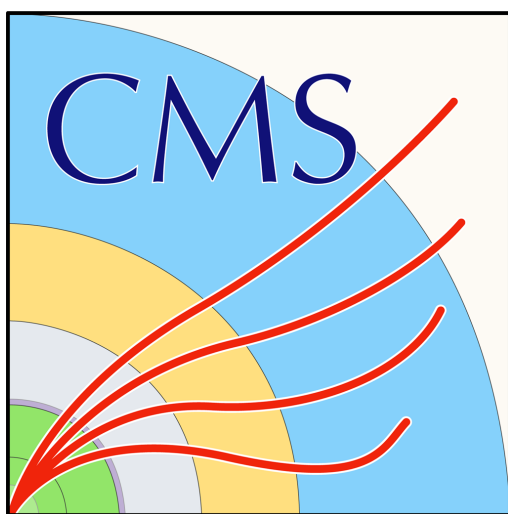
Benchmark model	$c_{hhh}$	$c_{tth}$	$c_{ggh}$	$c_{gggh}$	$c_{tthh}$
SM	1	1	0	0	0
BM 1	3.94	0.94	1/2	1/3	-1/3
BM 2	6.84	0.61	0.0	-1/3	1/3
BM 3	2.21	1.05	1/2	1/2	-1/3
BM 4	2.79	0.61	-1/2	1/6	1/3
BM 5	3.95	1.17	1/6	-1/2	-1/3
BM 6	5.68	0.83	-1/2	1/3	1/3
BM 7	-0.10	0.94	1/6	-1/6	1

HEFT benchmarks via [arXiv: 1908.08923](https://arxiv.org/abs/1908.08923)

$m_{HH}$  shapes representative of Wilson coeff variations

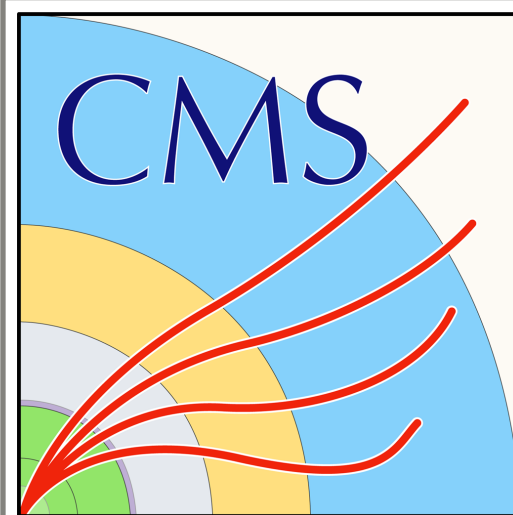
See e.g. [CMS JHEP 03 \(2021\) 257](https://arxiv.org/abs/2103.12571)  
for SMEFT benchmarks



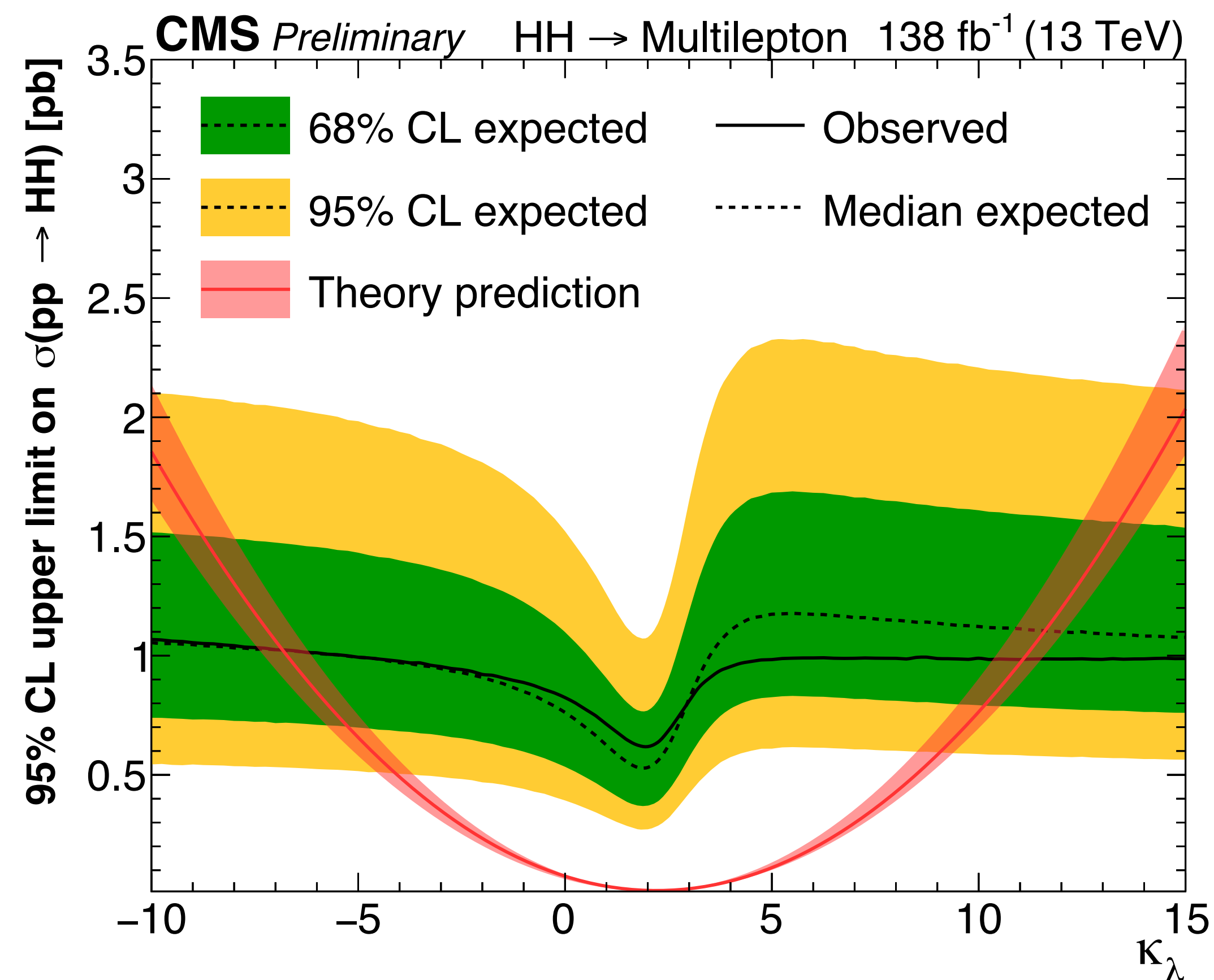
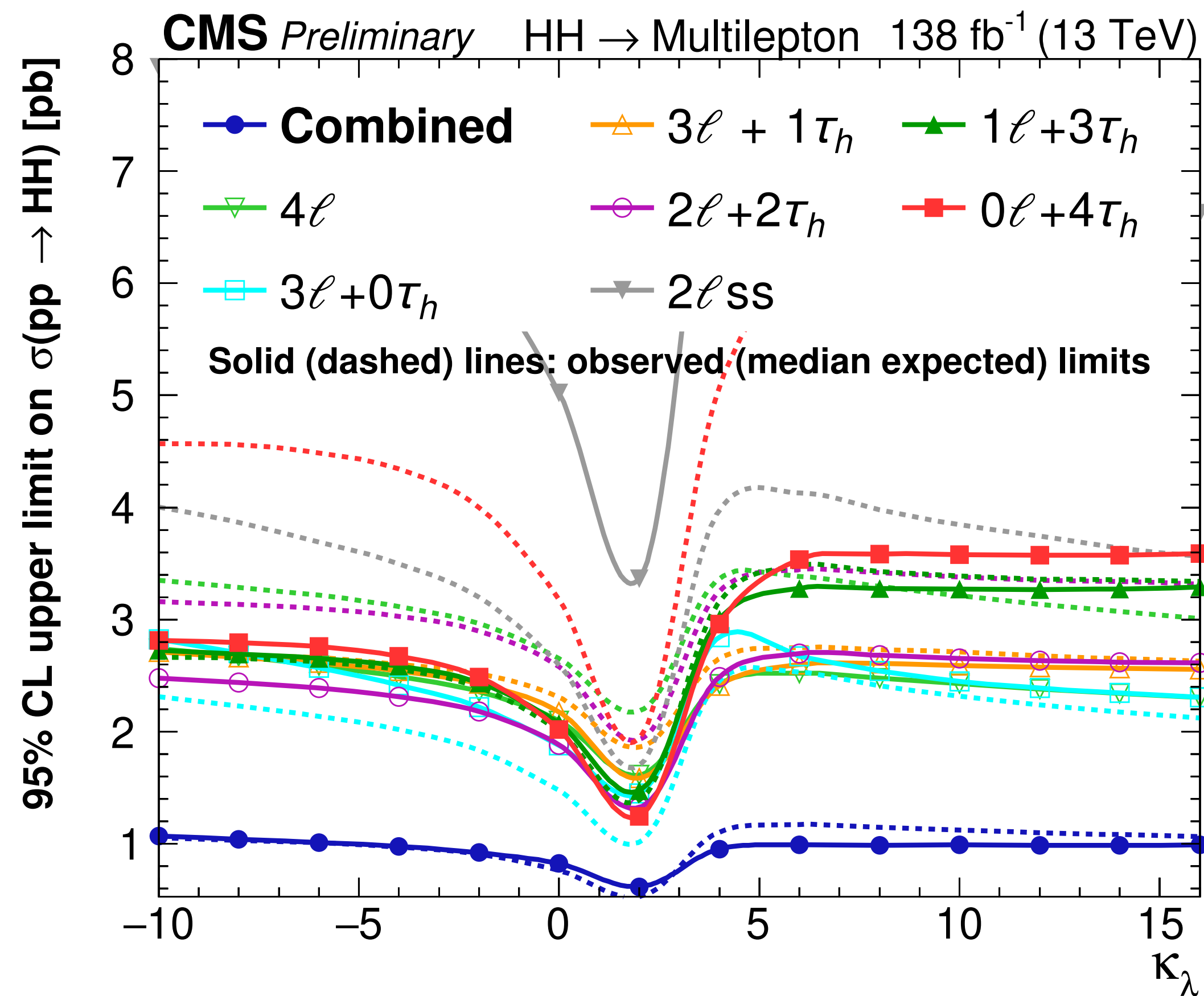


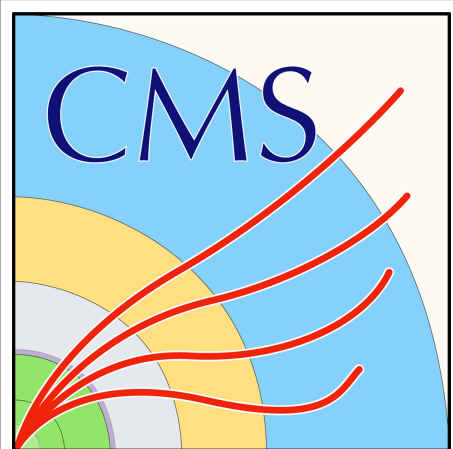
# CMS multilepton

- Decays to  $WWWW$  (4.5%),  $WW\tau\tau$  (2.7%),  $\tau\tau\tau\tau$  (0.4%)
- Select events in 7 categories: 2 same-charge  $e/\mu$  or 3-4  $e/\mu/\tau_h$ 
  - Orthogonal to  $bbZZ$ : remove events with opposite-sign  $\ell\ell+l'\ell'$  and total mass  $< 140$  GeV
- Reject major backgrounds:
  - Top: events with b-tagged jets
  - Z+jets: events with an opposite-sign  $e/\mu$  pair with mass in 81-101 GeV
- Boosted Decision Tree classifiers (XGBOOST) trained in each category
  - Binned maximum-likelihood fit on BDT outputs

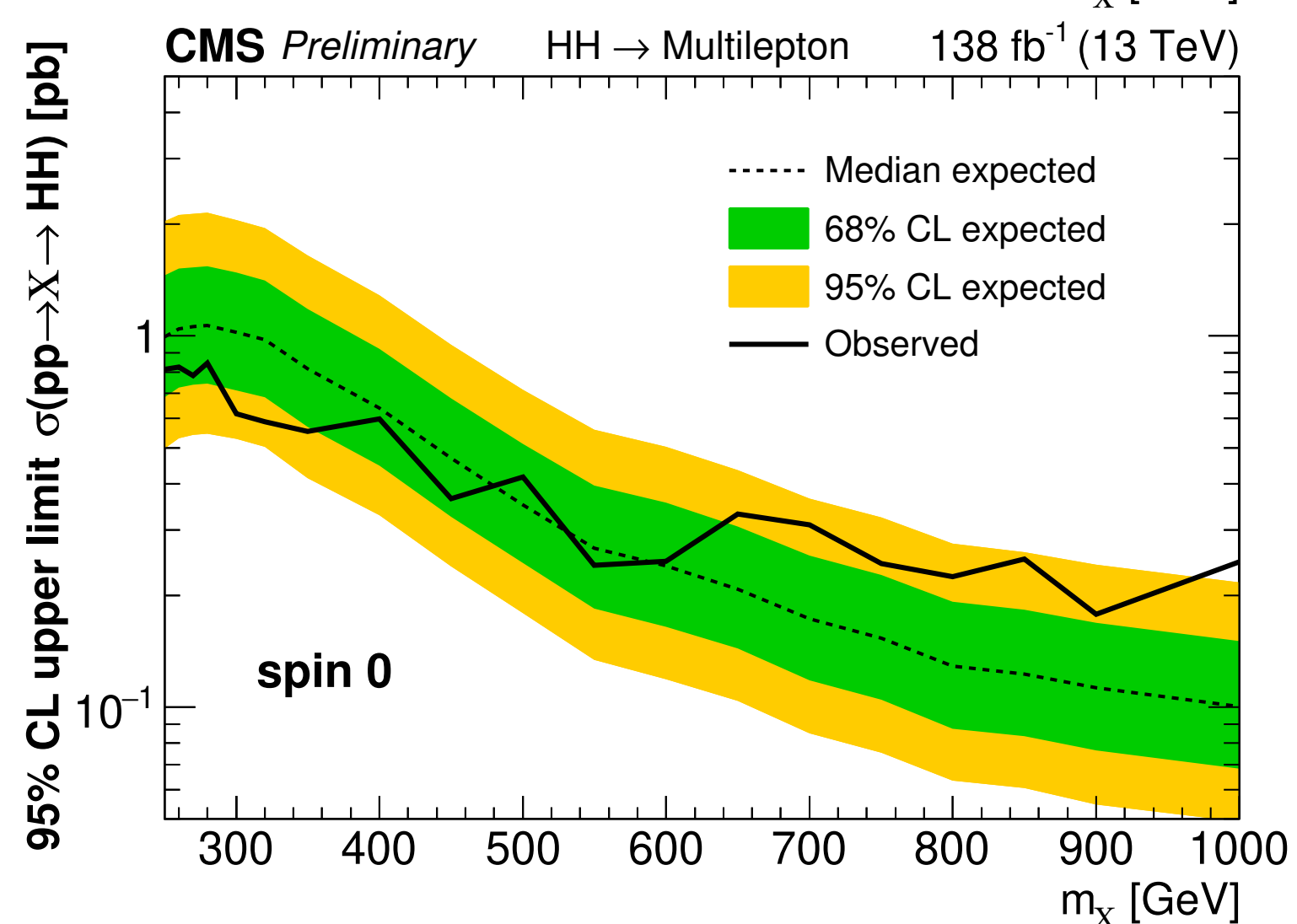
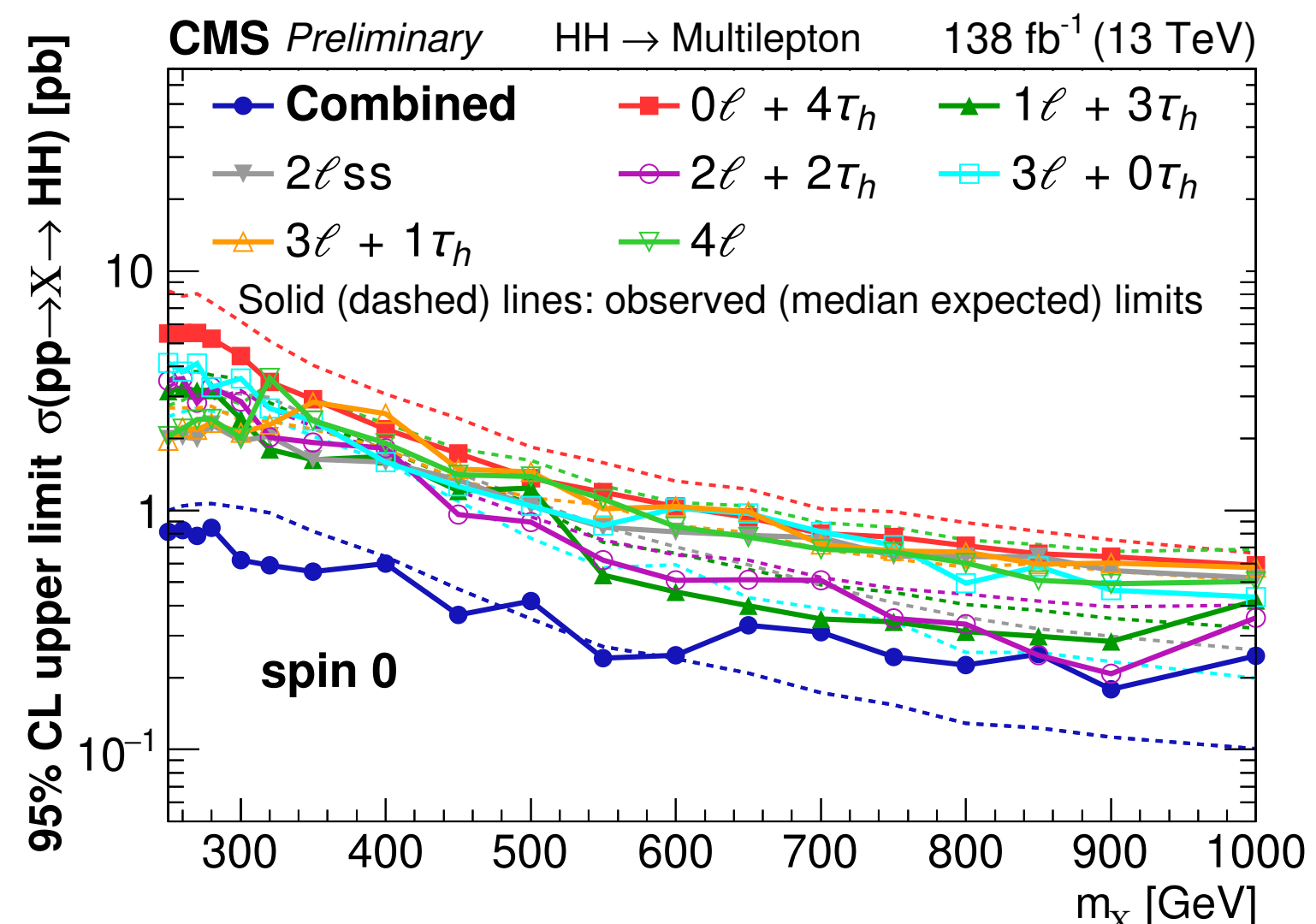


# CMS multilepton HH limits

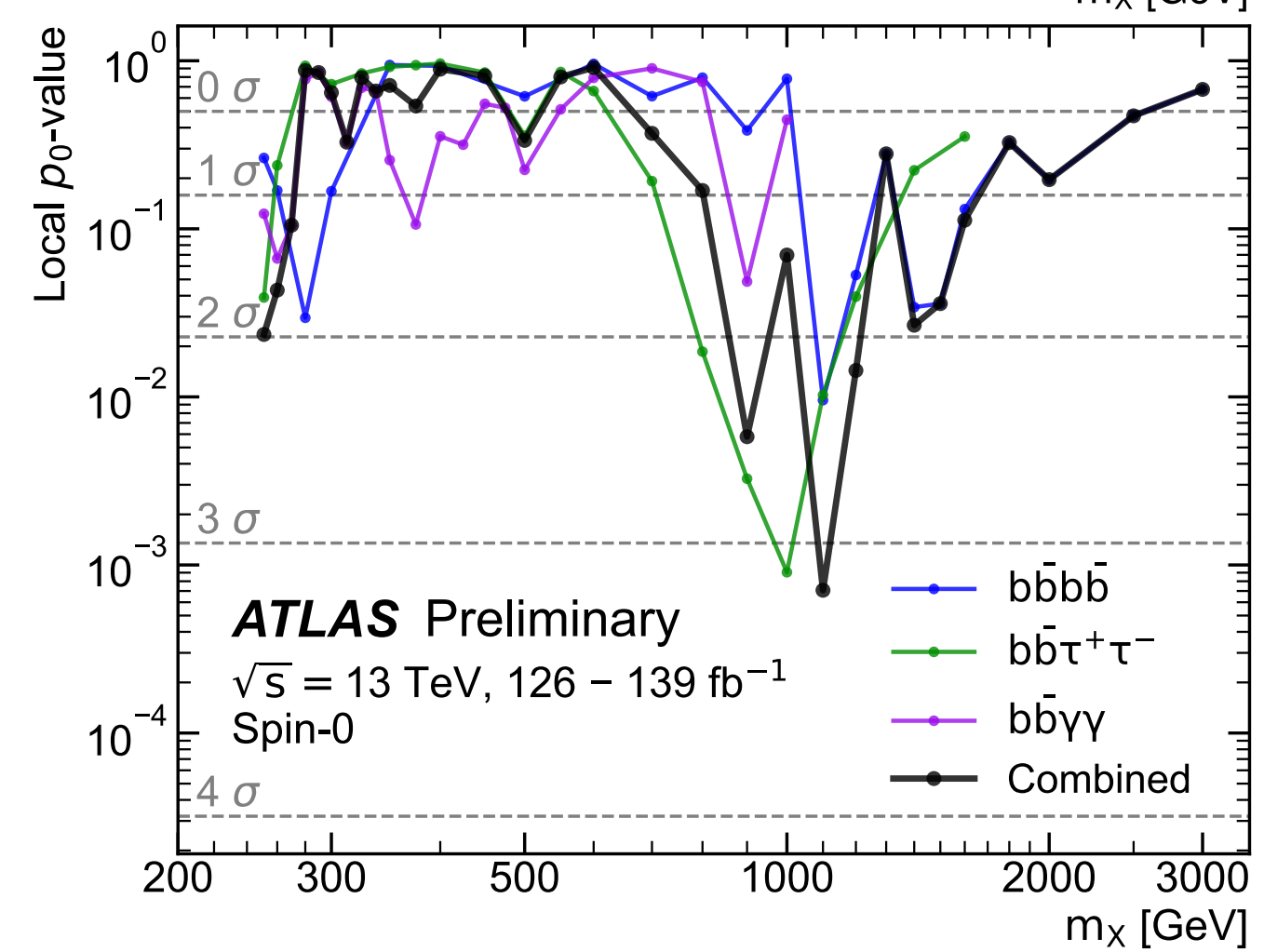
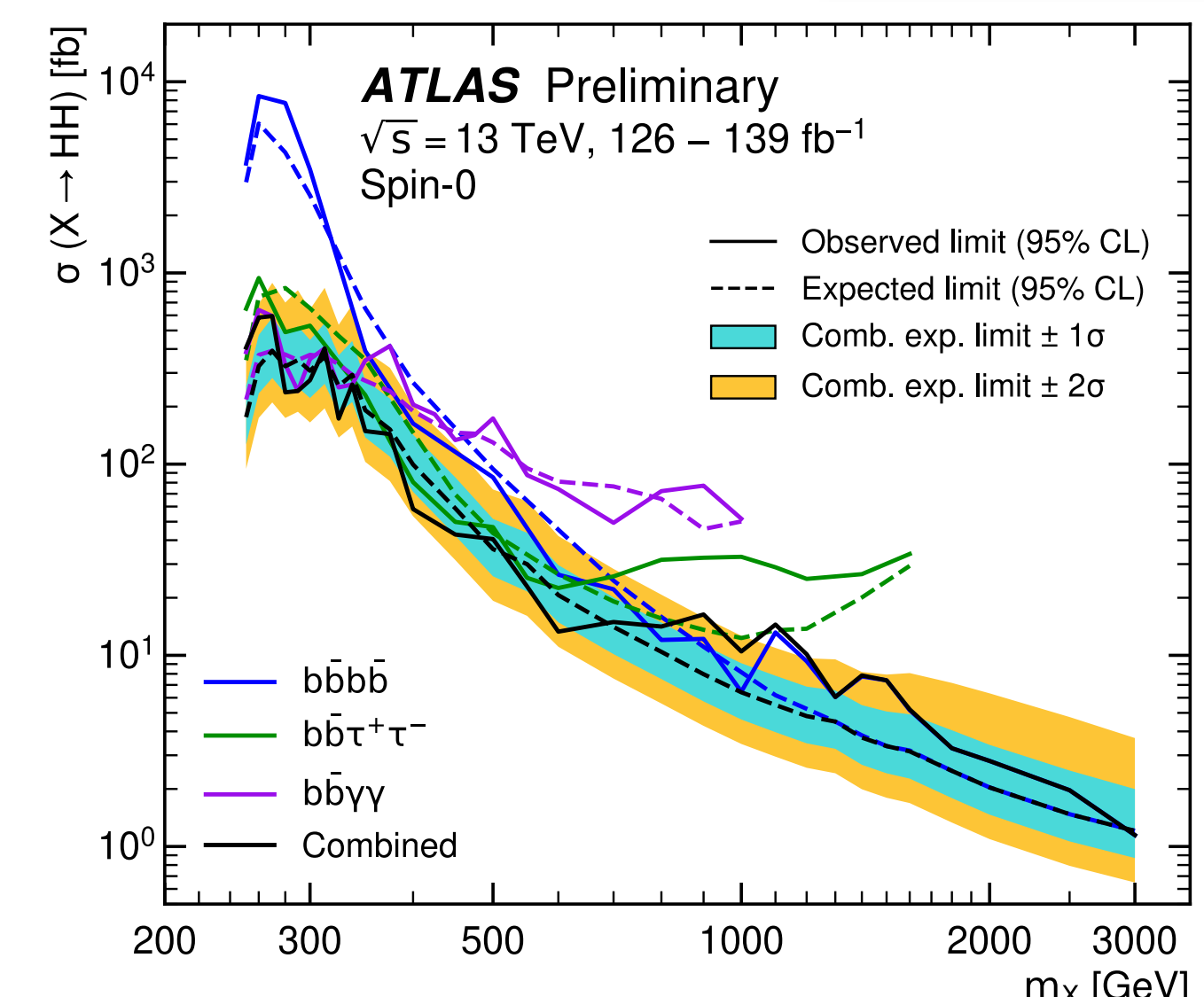




# Resonant HH limits

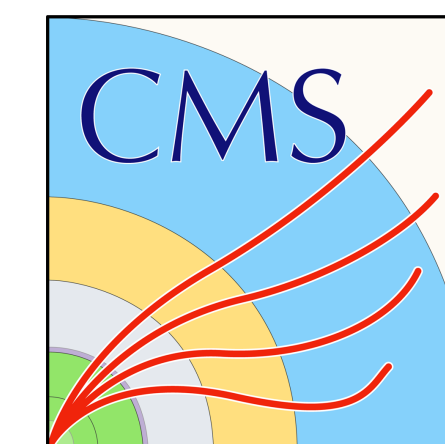


- Limits set in multiple channels on heavy 'X' decays to HH
- Spin 0 and spin 2 hypotheses
- Boosted reconstruction e.g. in 4b channel significant contributor at high mass

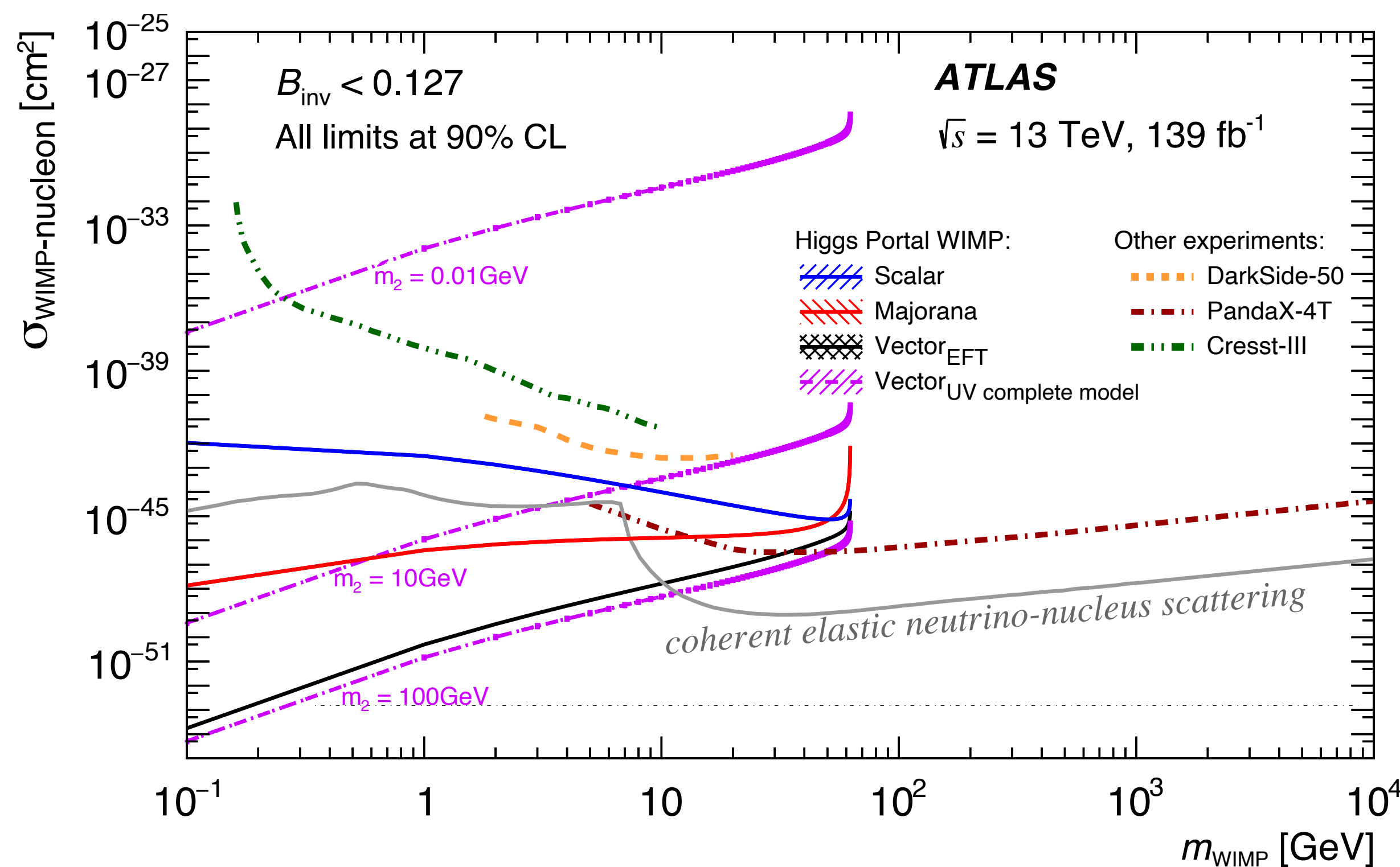




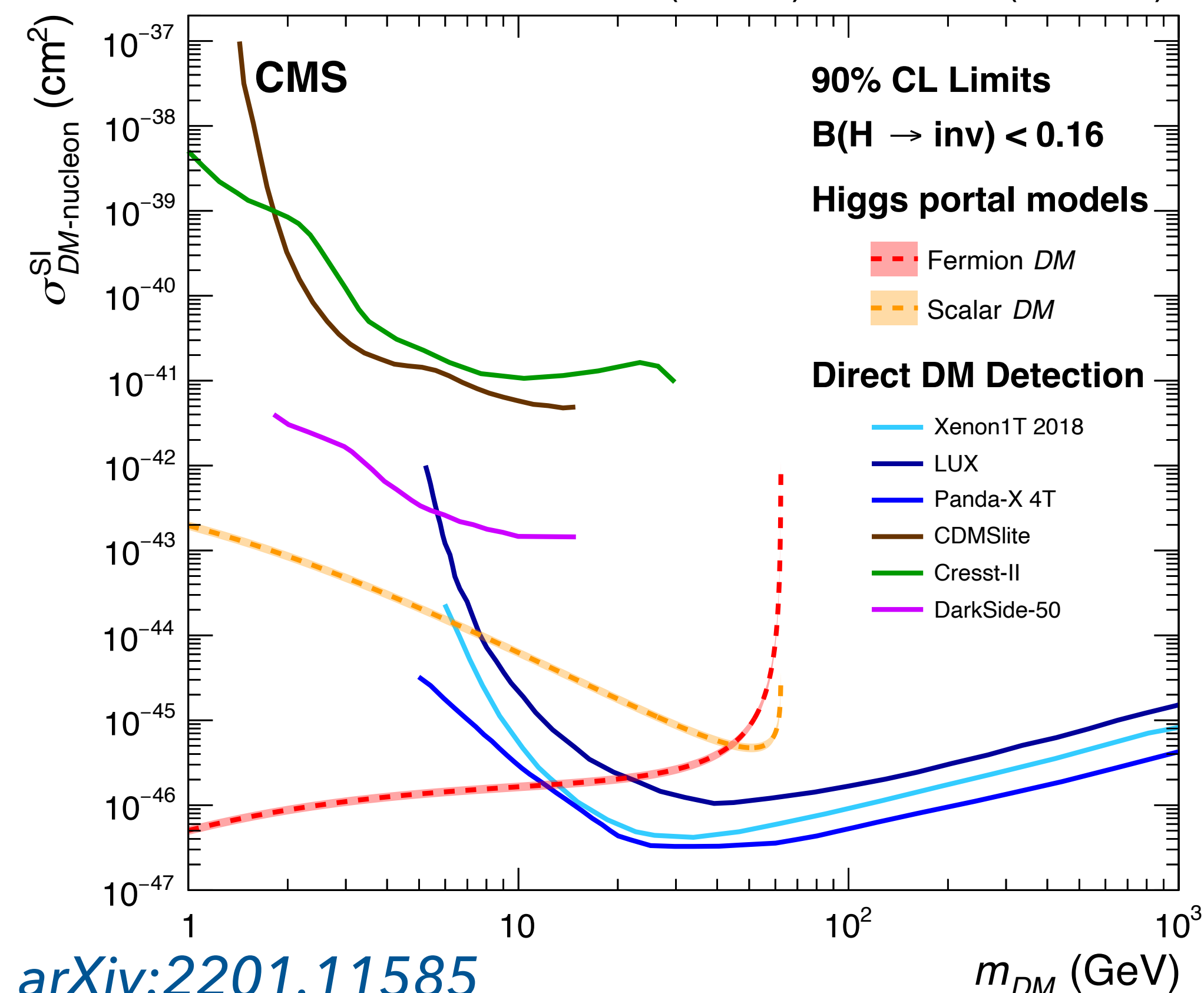
# Dark Matter limits from VBF $H_{inv}$



19.7 fb<sup>-1</sup> (8 TeV) + 140 fb<sup>-1</sup> (13 TeV)



[arXiv:2202.07953](https://arxiv.org/abs/2202.07953)

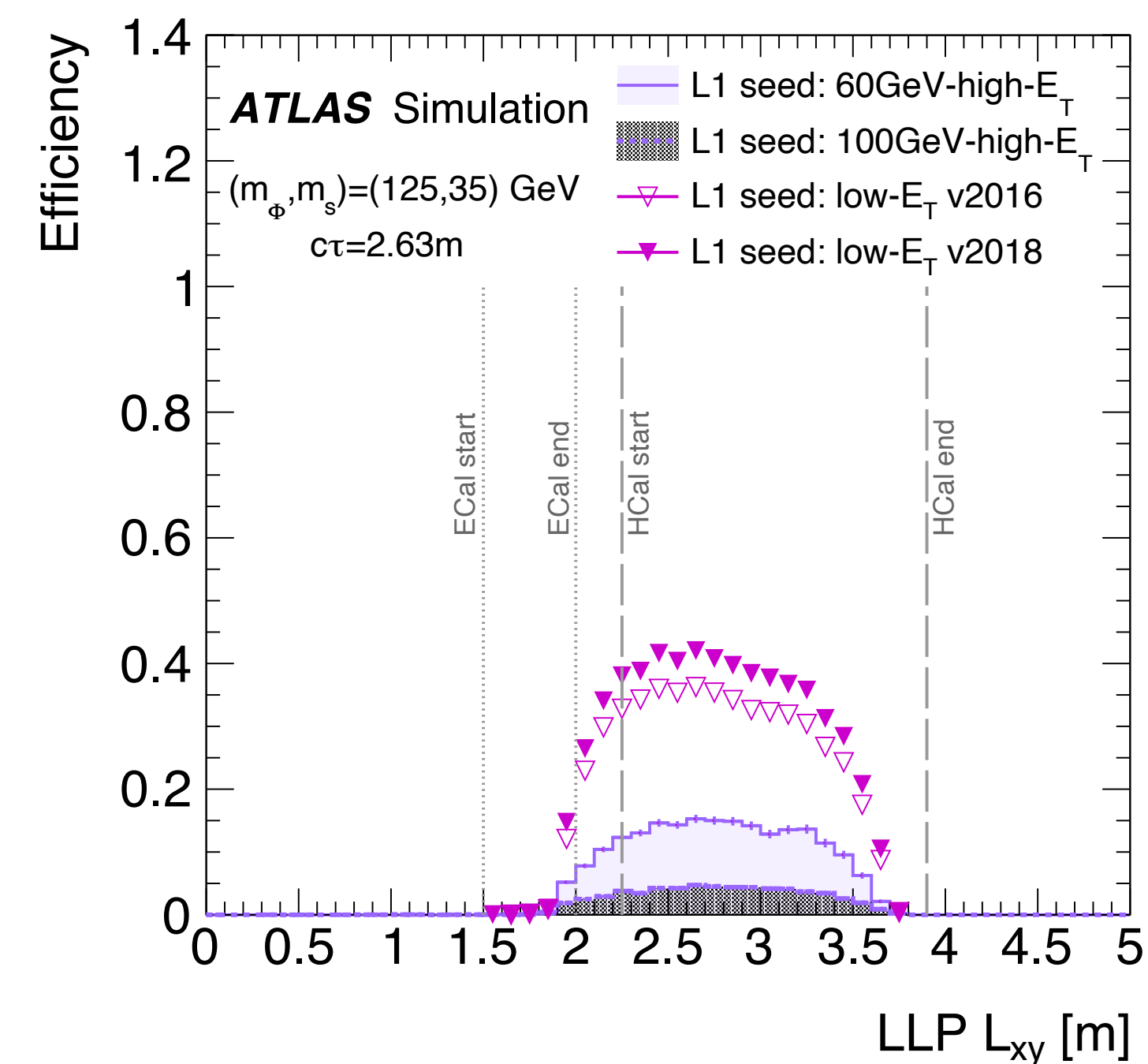
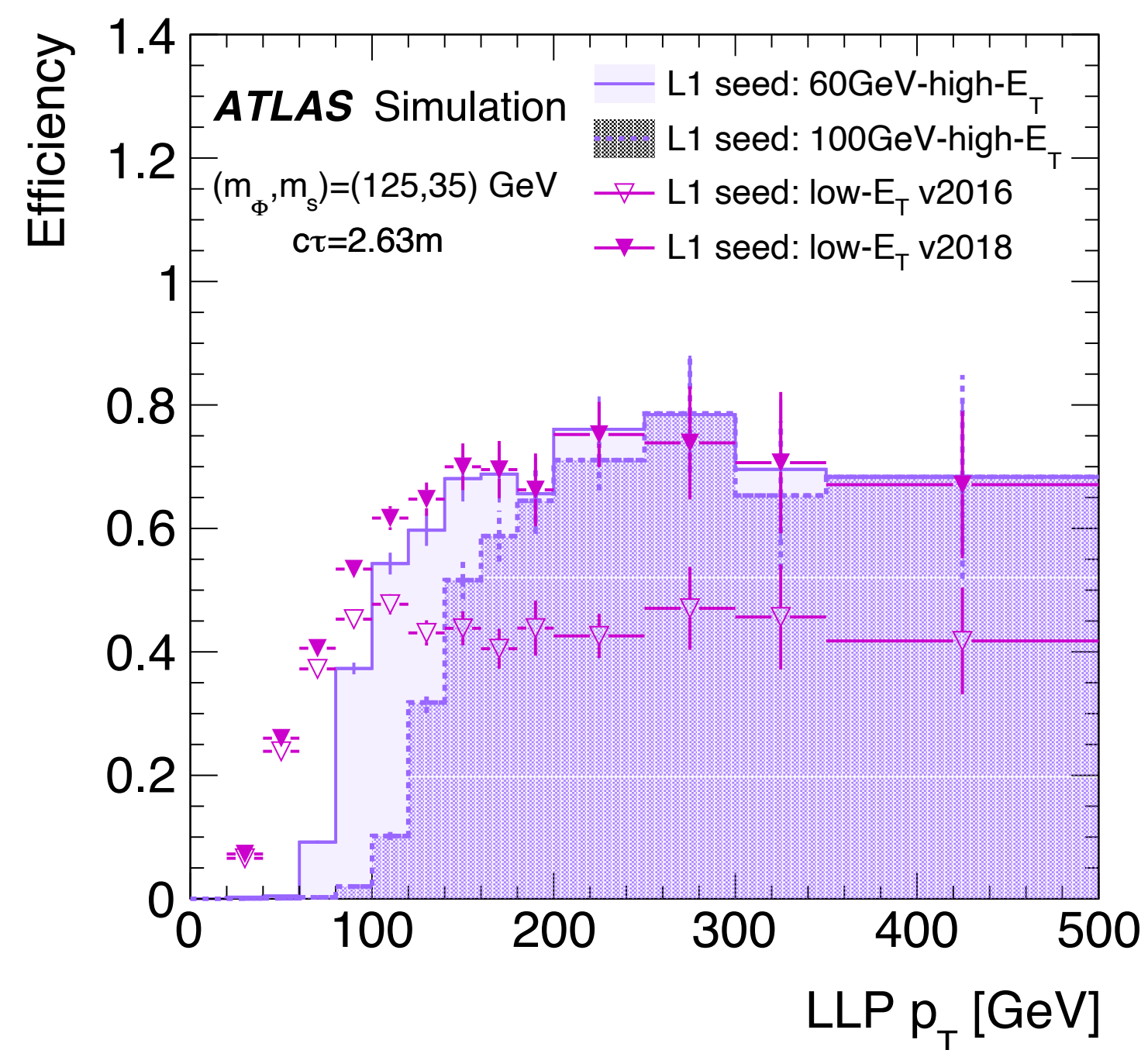
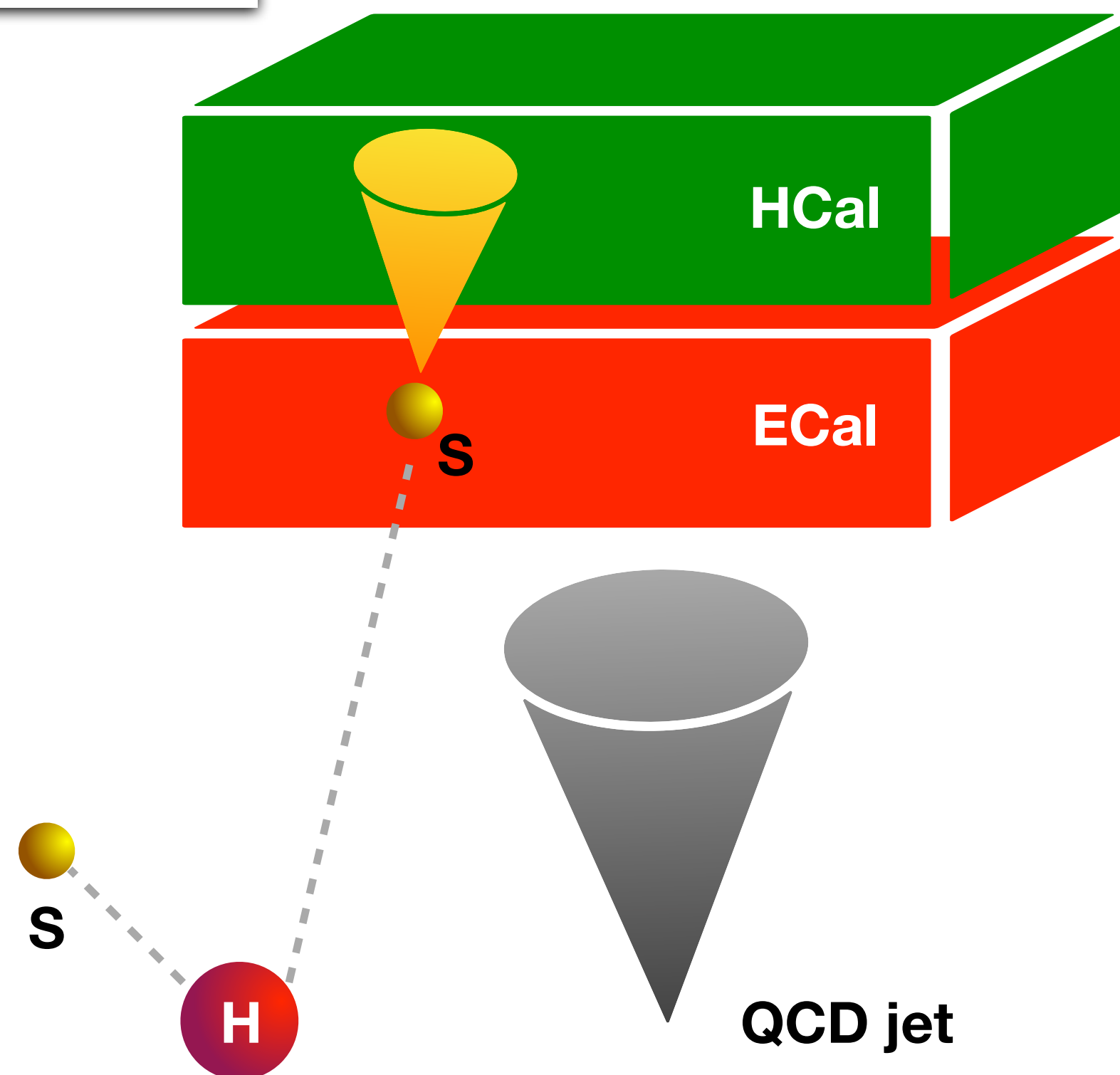


[arXiv:2201.11585](https://arxiv.org/abs/2201.11585)



# ATLAS displaced jets

Dedicated triggers based on HCAL energy ratio  
Need to reject beam-induced backgrounds (narrow in phi)



- Higgs as mediator between SM and Hidden Sector

- Hidden sector scalar decays close to/in electromagnetic calorimeter into  $b, c, t, \tau$  pairs
- Late showering signal  $\Rightarrow$  anomalously large fraction of energy in hadronic calorimeter

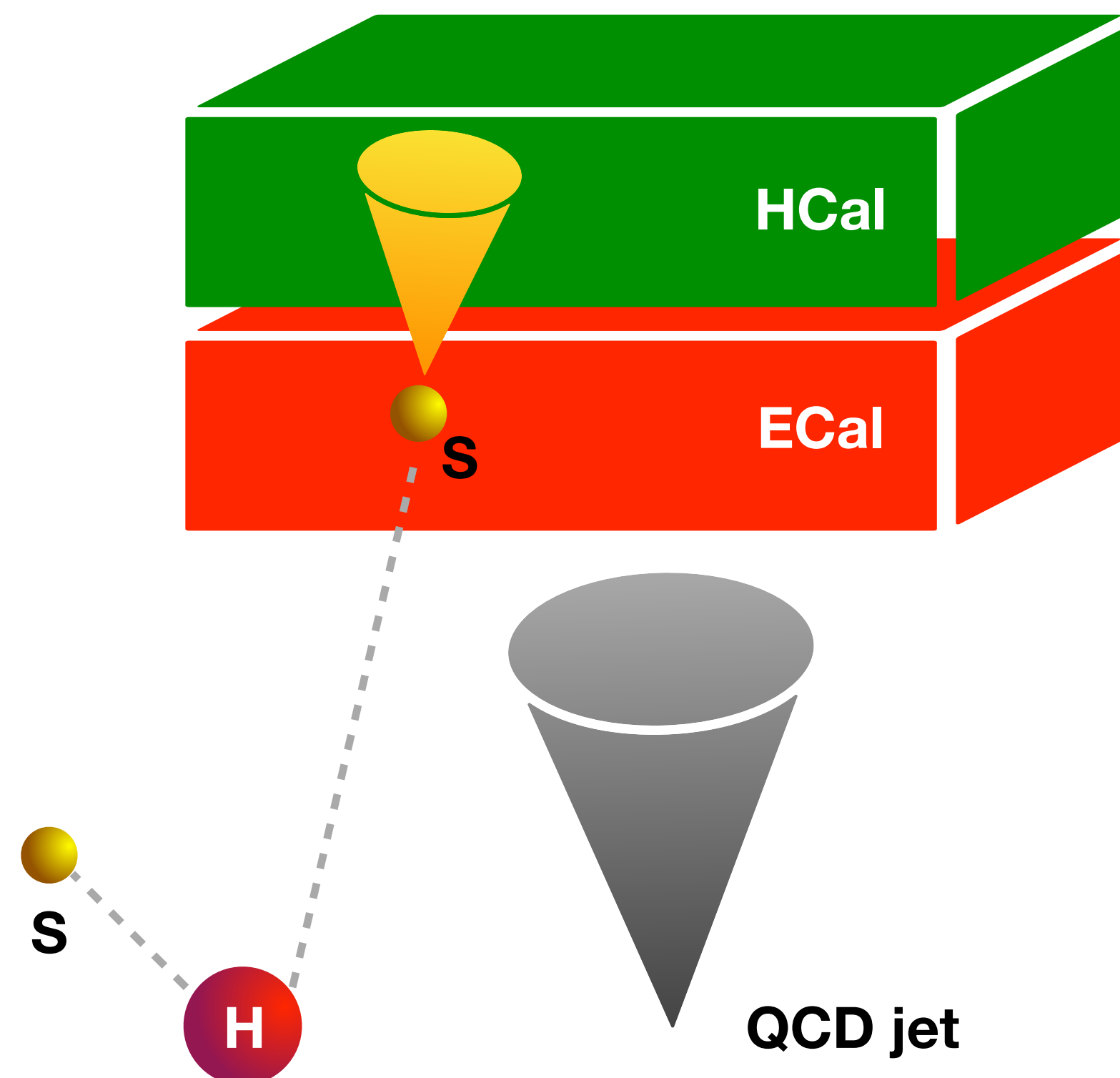


# Higgs decays to LLPs

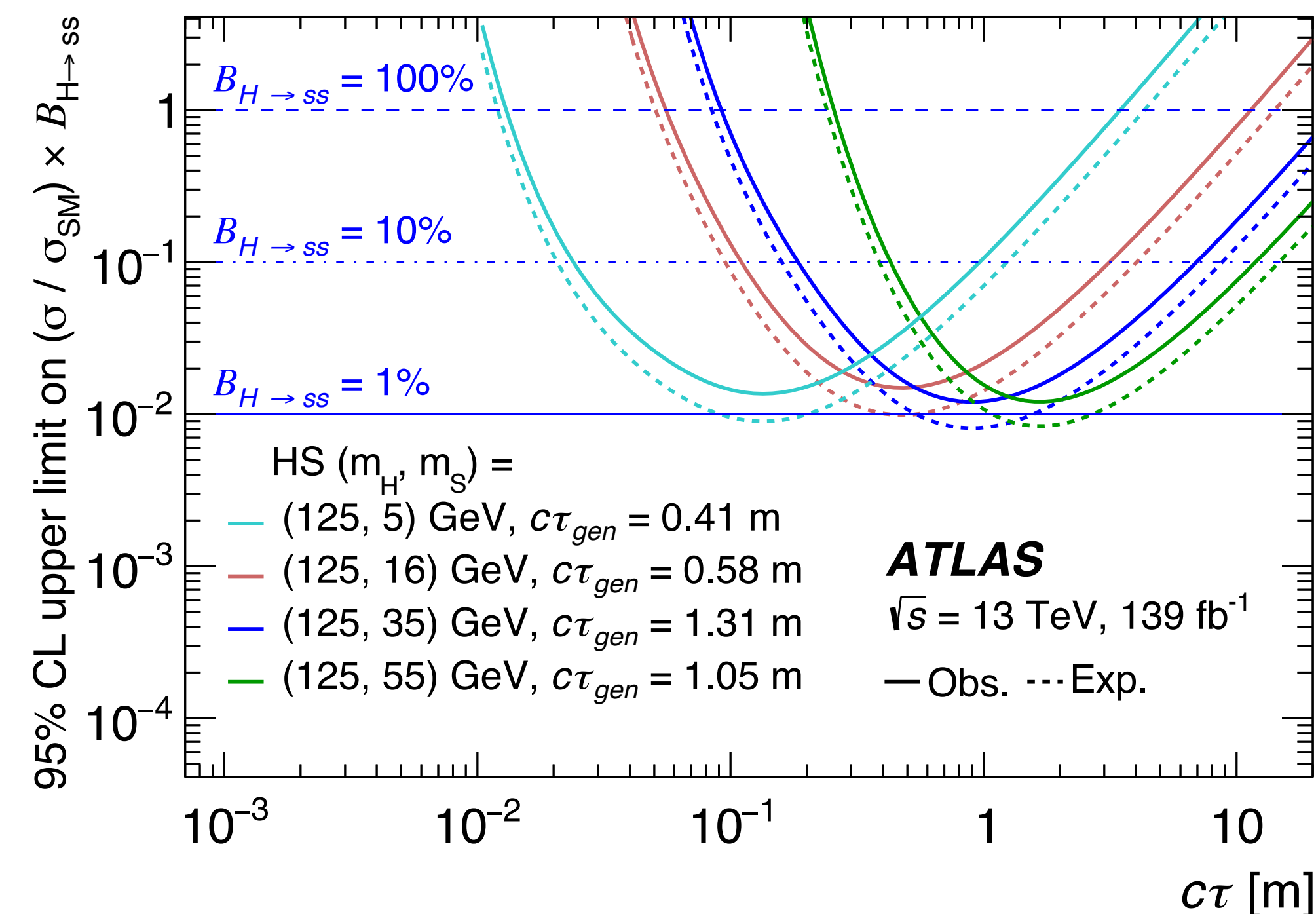
Late showering signal  
→ narrow jets with large  
HCal energy fraction

Hidden sector scalar  
decays in ECal into  
 $b, c, t, \tau$  pairs

Higgs as mediator  
between SM and  
Hidden Sector



Limits extend to scalar mediators in wider mass range

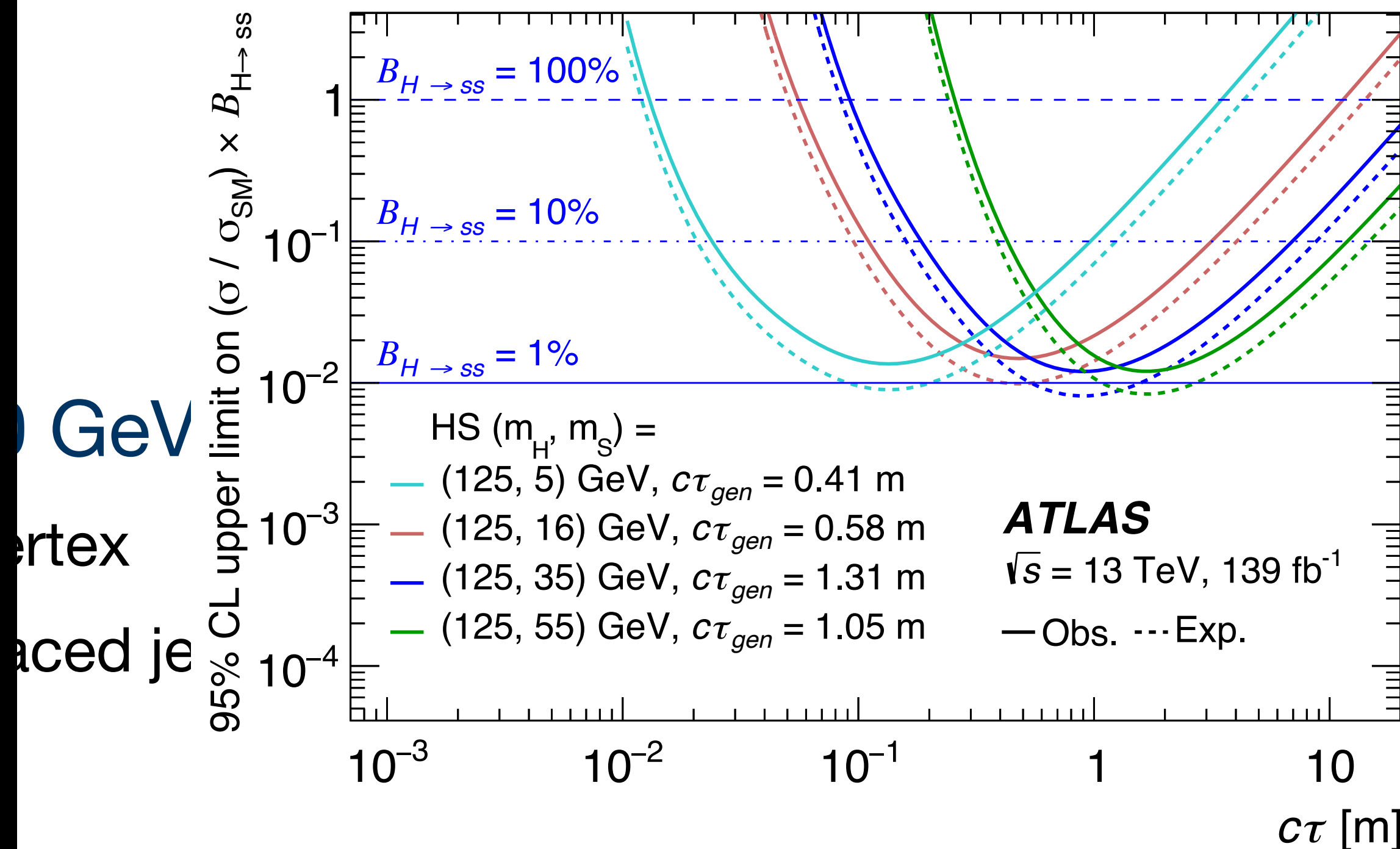
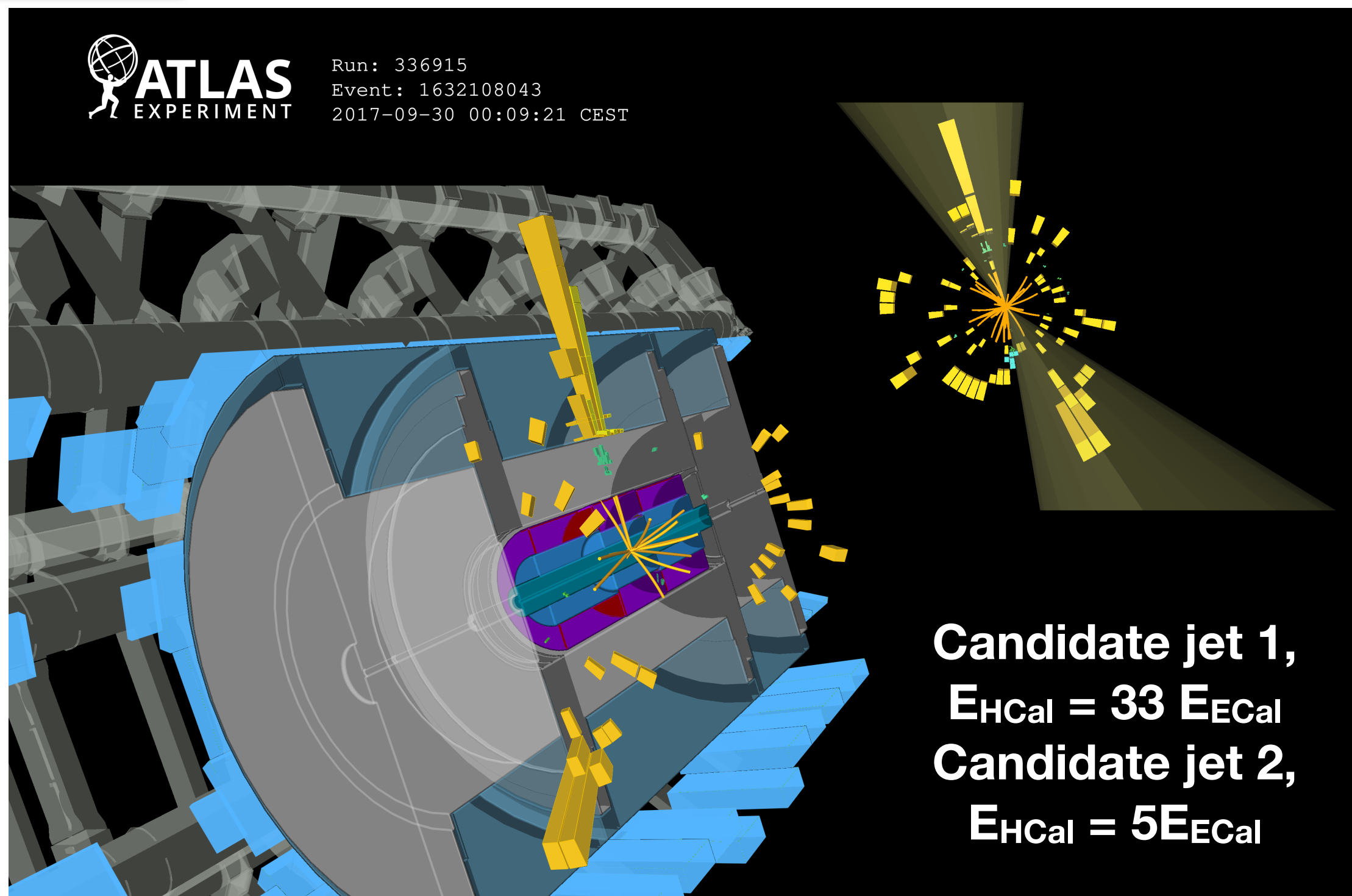


- Offline & trigger selections remove Beam-Induced Background
- (LSTM+Convolution) Neural Network tags displaced jet candidates
- Further event-level BIB rejection with Boosted Decision Trees



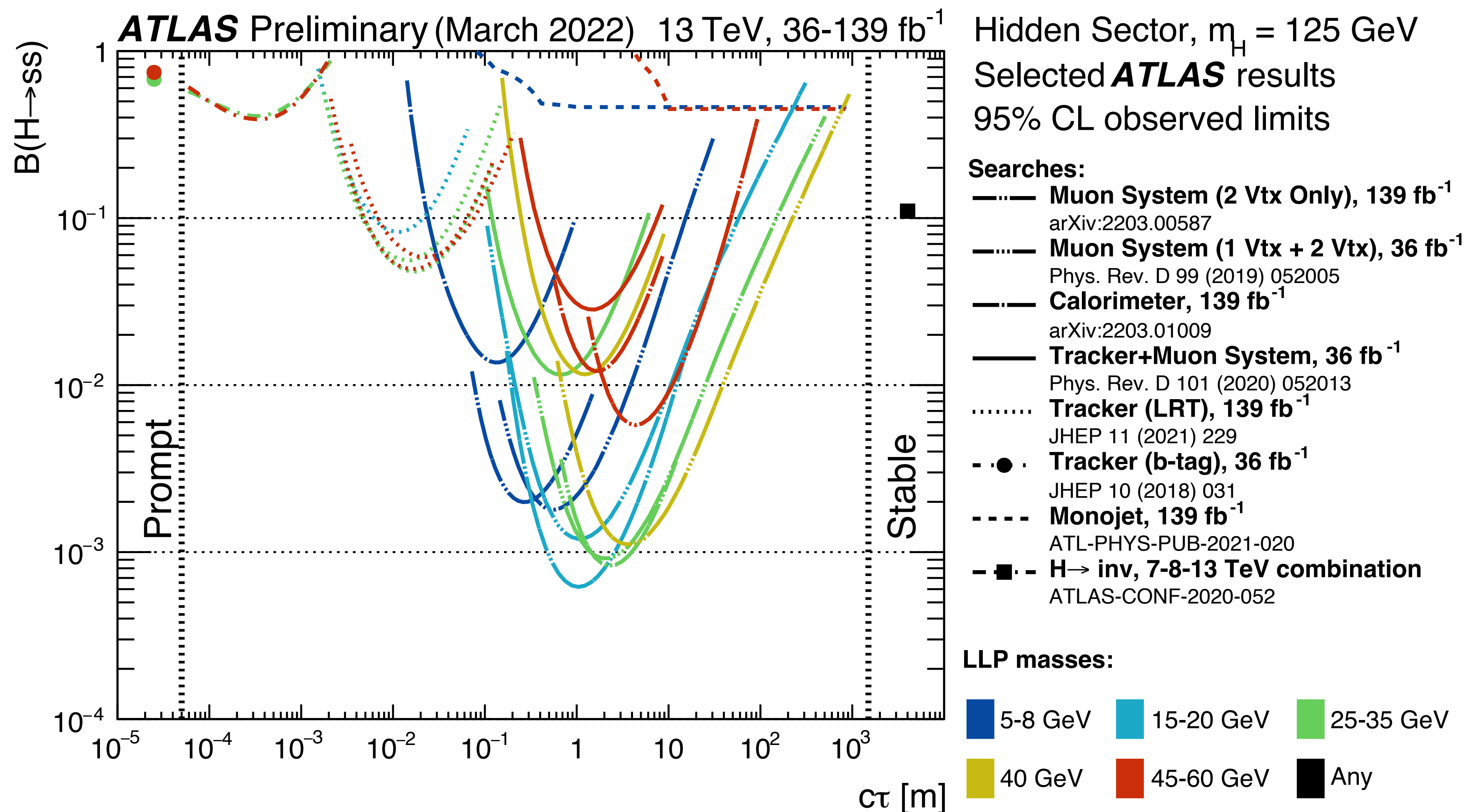
# ATLAS displaced jets

Limits extend to scalar mediators in wider mass range





# Long-lived decays



# Extended H sector in $\tau\tau$

