Searching for scalar boson pairs at the LHC

The Mitchell Conference on Collider, Dark Matter, and Neutrino Physics
College Station, Texas: May 23rd - 26th, 2024

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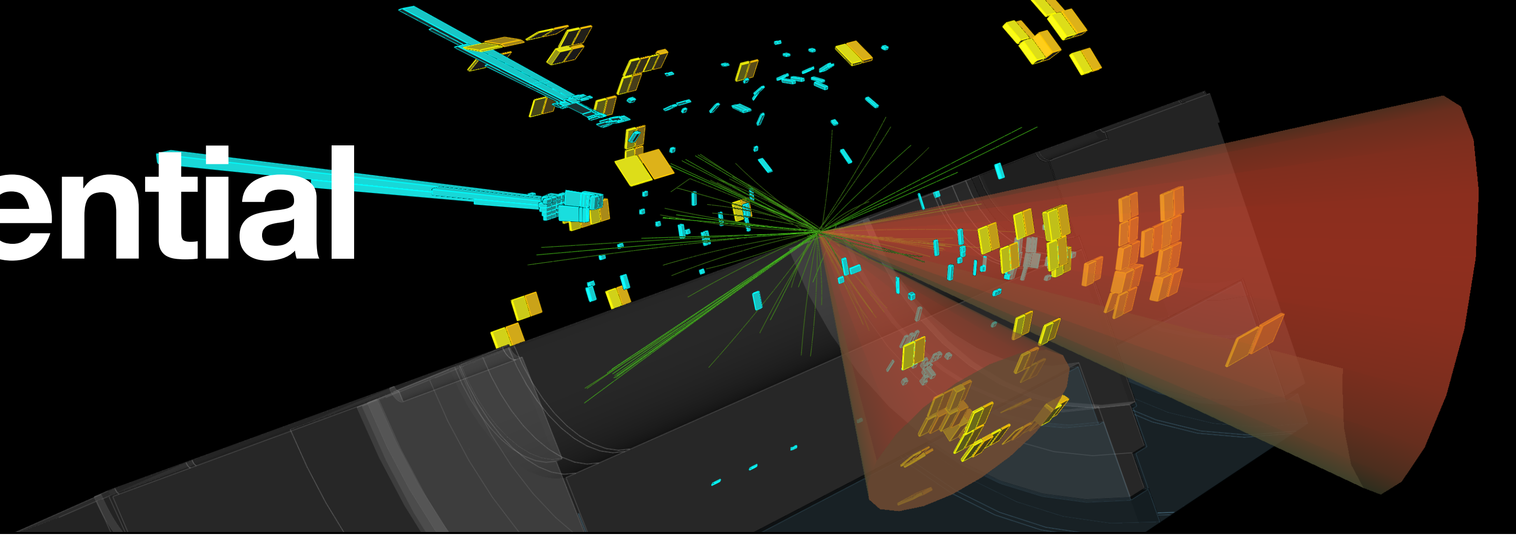
California State University Stanislaus

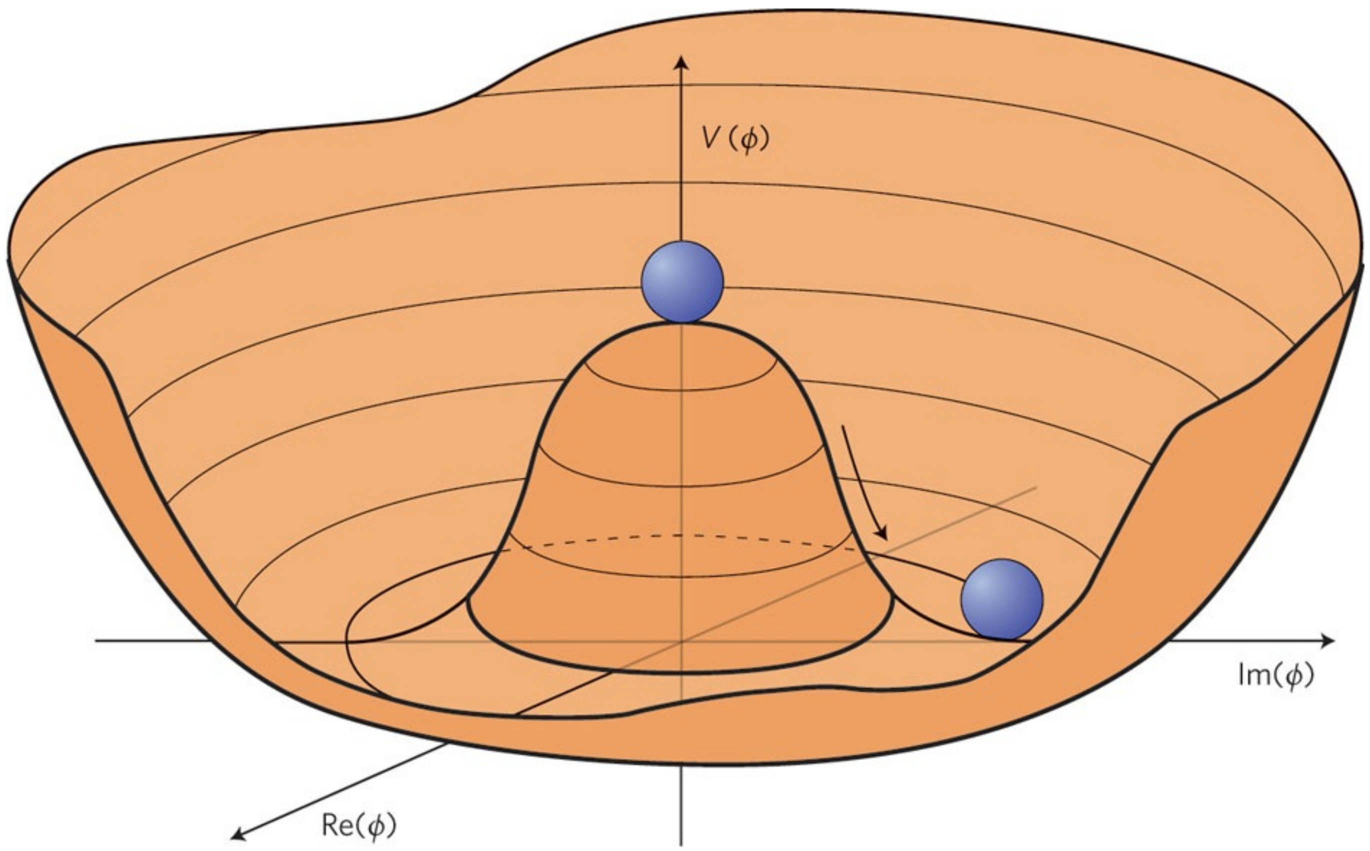
Talk Outline

- Overview of theoretical motivations
- How to search for scalar pair production
- Survey of experimental channels
- Experimental results and interpretations

The Standard Model

The Higgs Potential





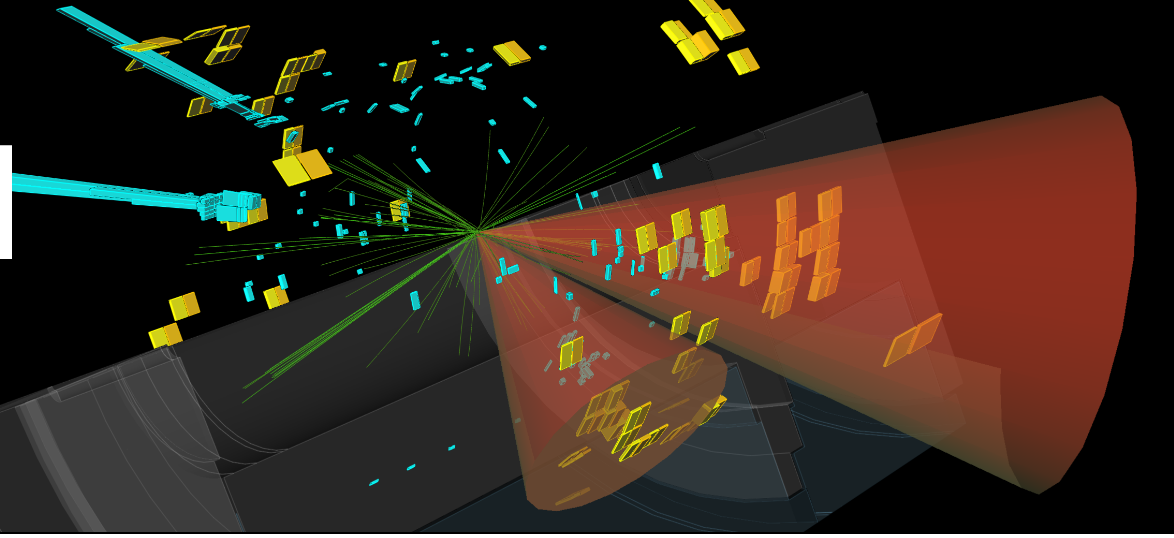
$$V(\Phi) = \mu^2 \Phi^* \Phi + \lambda |\Phi^* \Phi|^2$$

μ^2 is related to m_H, so we have measured it directly

λ has not been measured **directly**, but the SM predicts it to be $\lambda^{SM} \sim 0.13$

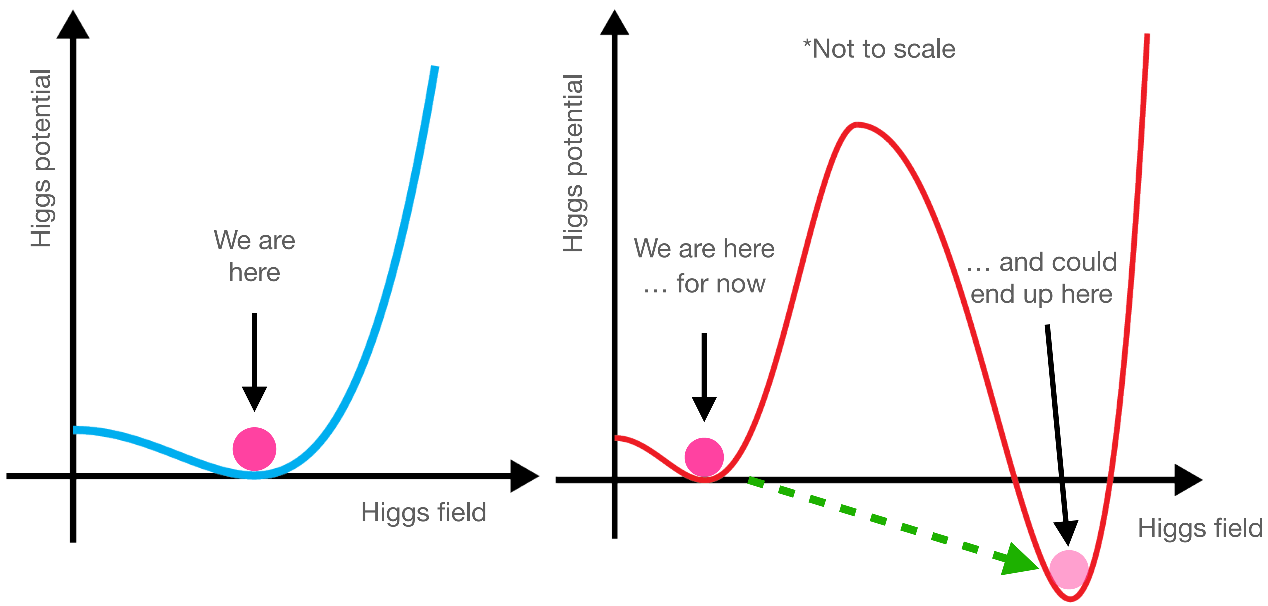
The Higgs Potential

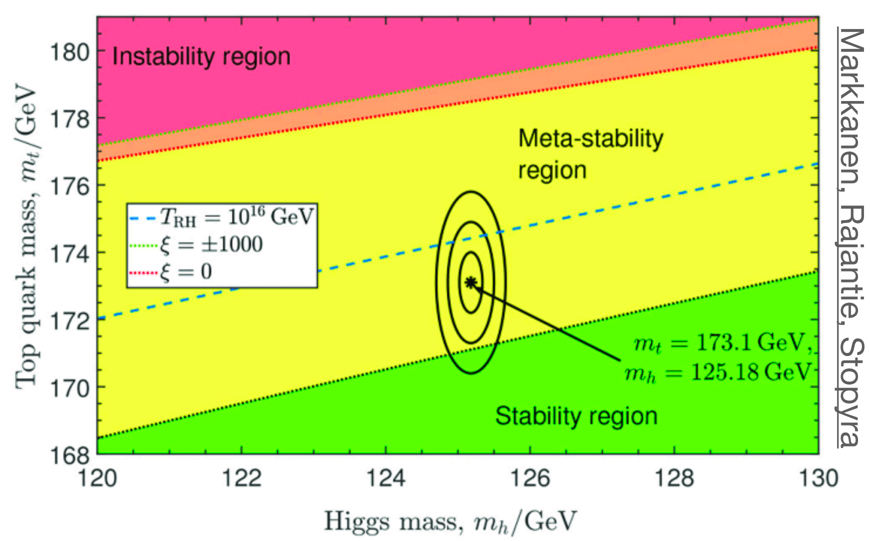
Open Questions



Vacuum Stability

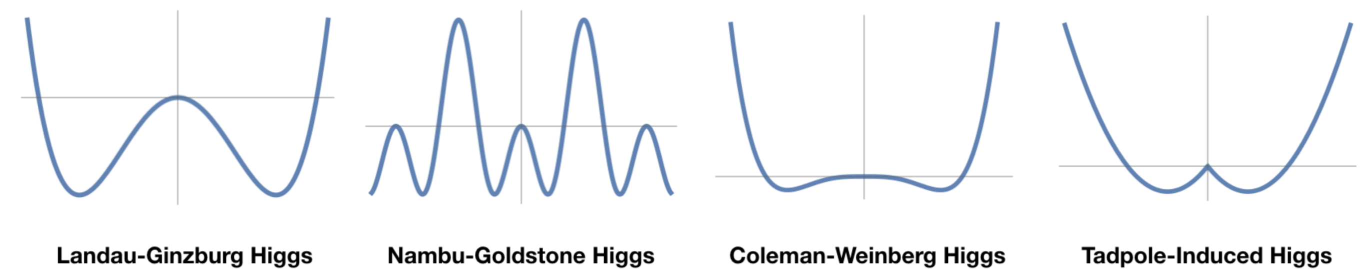
Are we in a local or a global minimum?





Markkanen, Rajantie, Stopyra

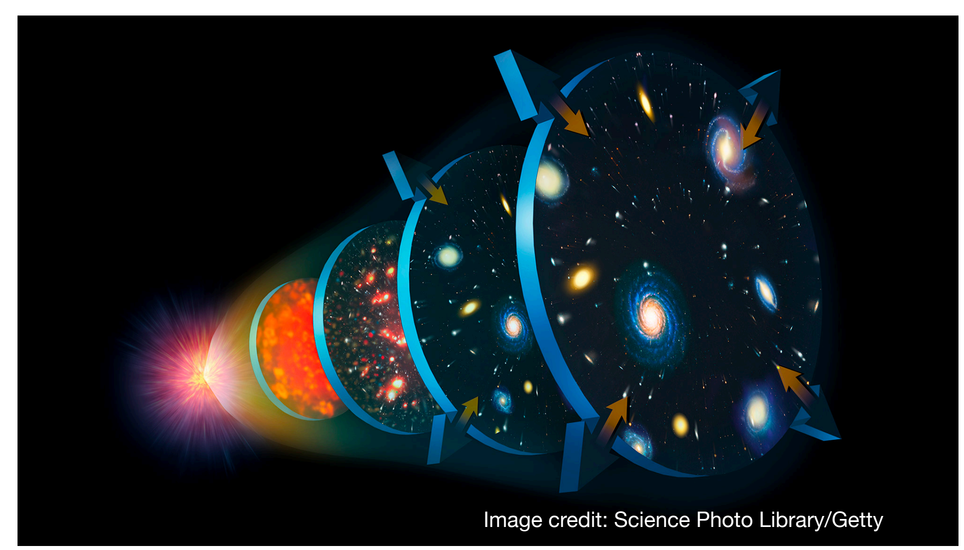
Shape of the Higgs Potential



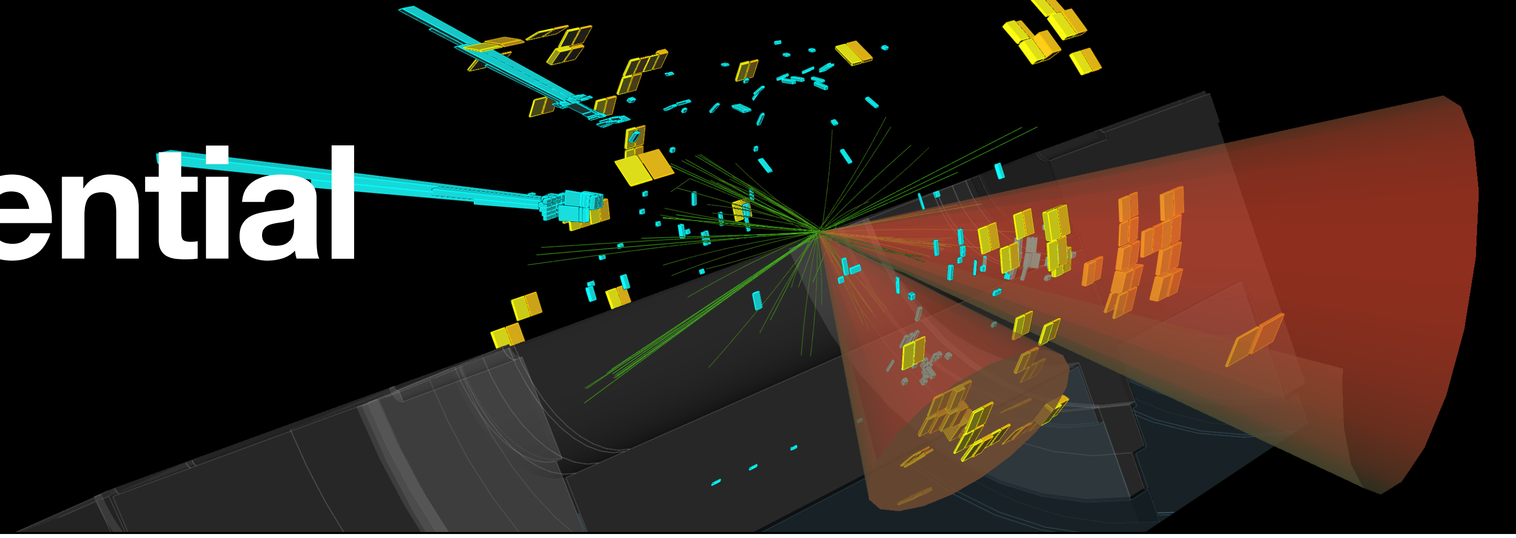
Phys. Rev. D 101, 075023 (2020)

The Early Universe

- Electroweak baryogenesis can lead to $\mathcal{O}(1)$ Higgs self-coupling modifications
- Some inflation models modify the shape of the Higgs potential (Higgs couplings to gravity)



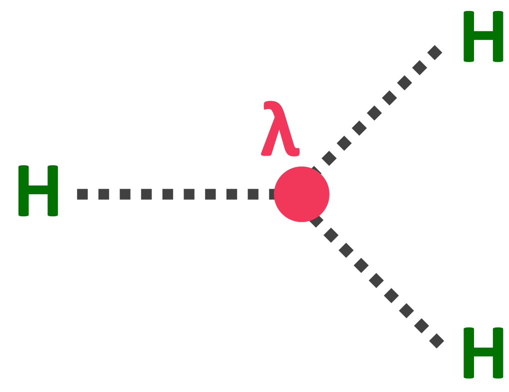
The Higgs Potential



The Higgs potential:

$$V(h) \simeq \frac{1}{2}m_H^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + ...$$

This is the same λ and it shows up in the Higgs boson self coupling

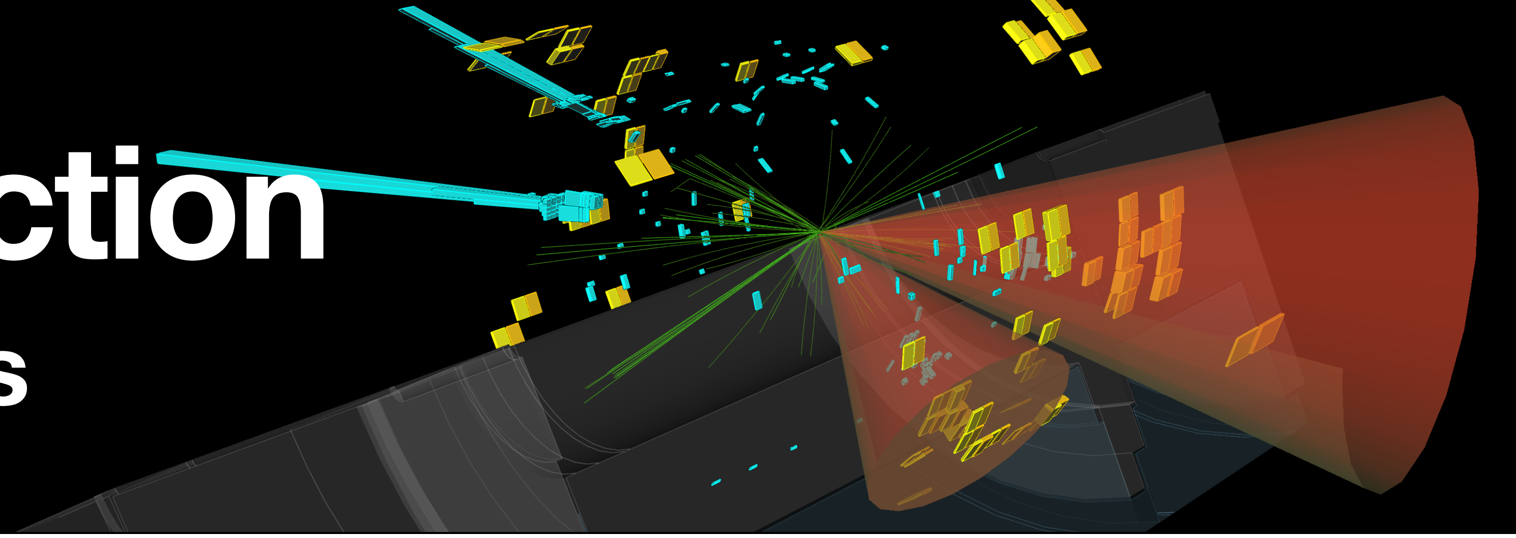


If we can measure the self coupling, we will know the term λ that defines the shape of the Higgs potential

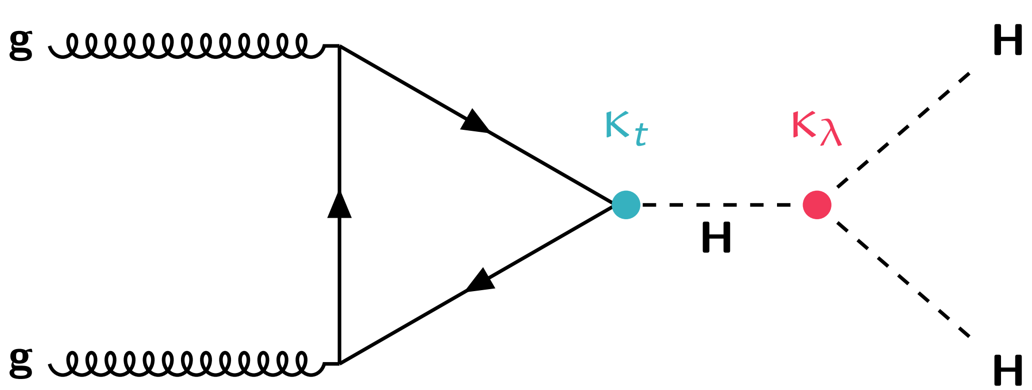
If λ ≠ the SM prediction (λ^{SM}), it might indicate new physics

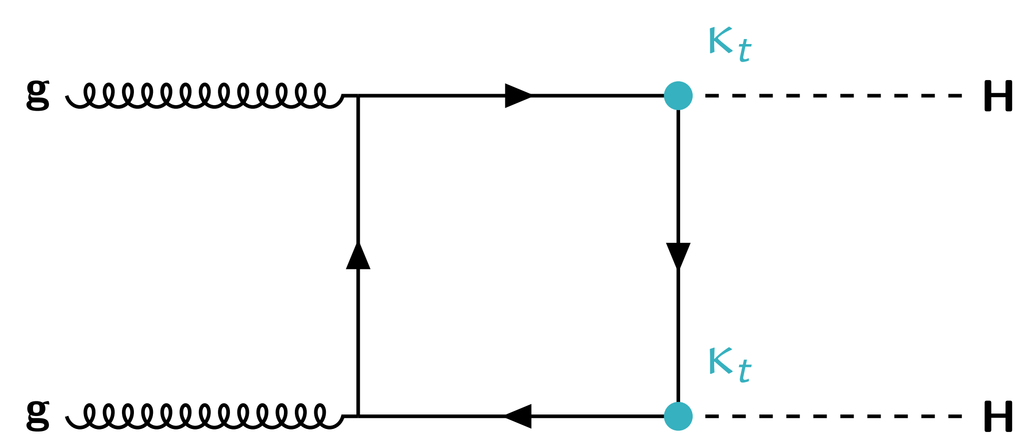
ggF HH Production

A tale of two diagrams



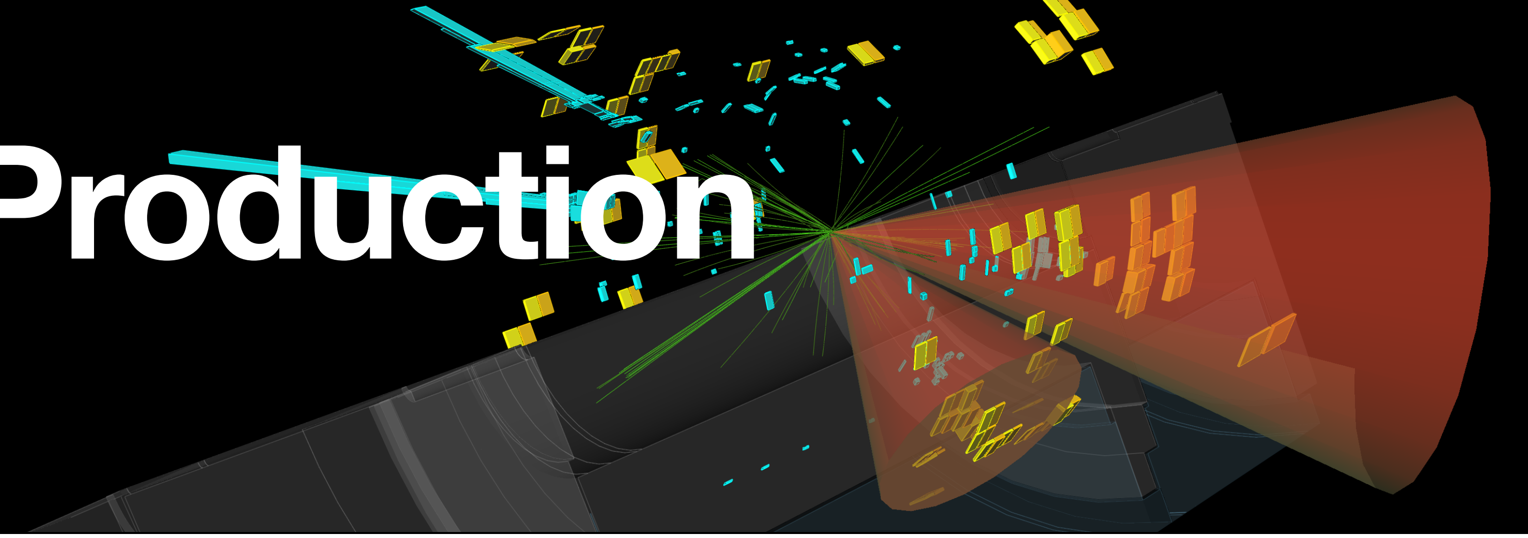
- The SM predicts the production of two Higgs bosons (HH)
- Gluon-gluon fusion (ggF) is the leading production mode at the LHC (~90% of σ_{tot})
- Vector boson fusion (VBF) is the second leading production mode
- The “triangle” diagram involves Higgs boson self-coupling
- The “box” diagram interferes, resulting in a small cross-section (~31 fb @ 13 TeV)
  - Compared to ~52 pb (@ 13 TeV) for single Higgs production



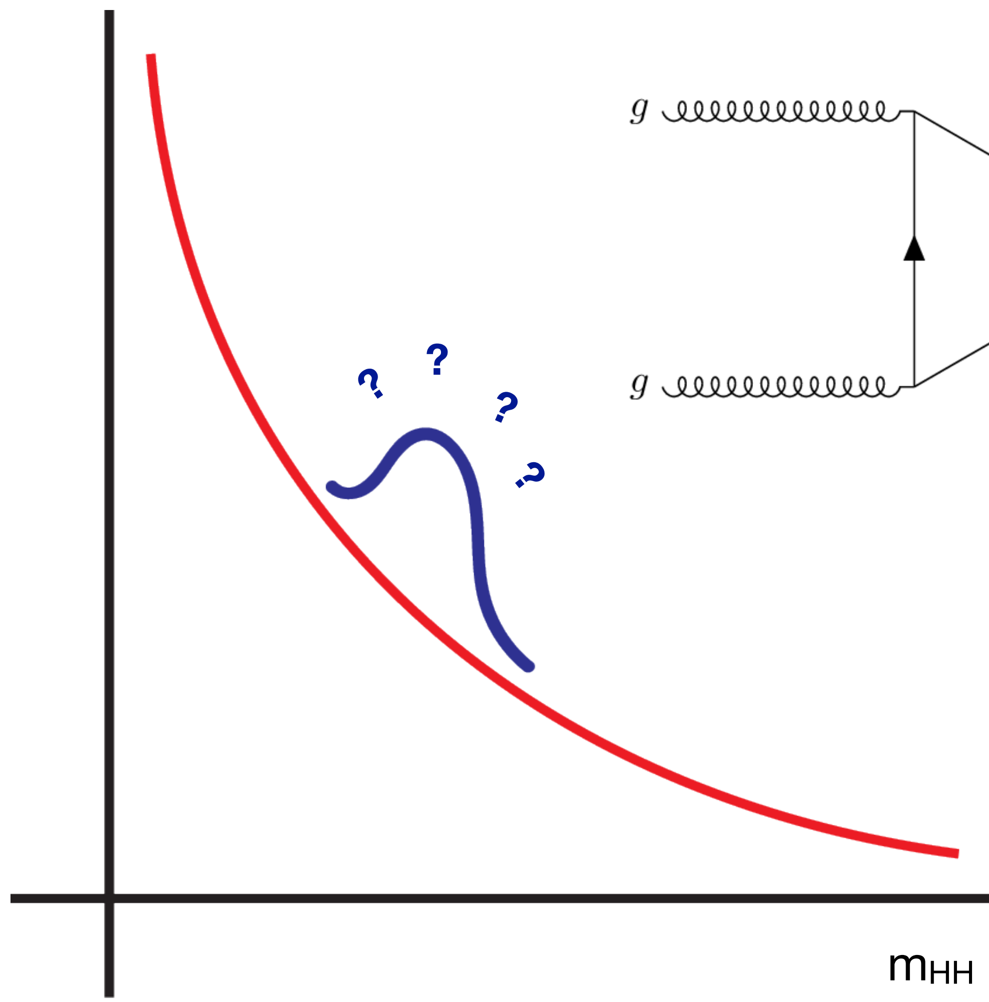


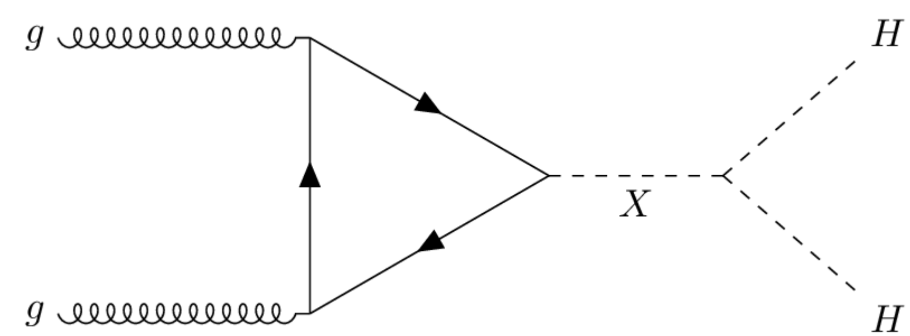
Beyond the Standard Model

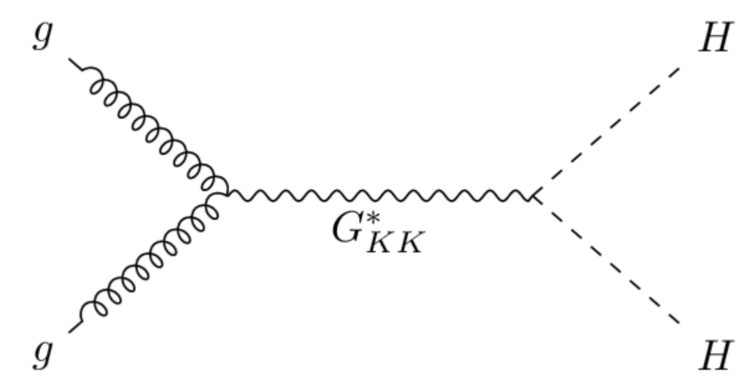
Resonant HH Production



- Many BSM models predict new heavy particles that decay into HH
  - 2HDM, MSSM, Kaluza-Klein models, extra dimensions, etc.
- Narrow spin-0 scalar and spin-2 gravitons used as benchmark models

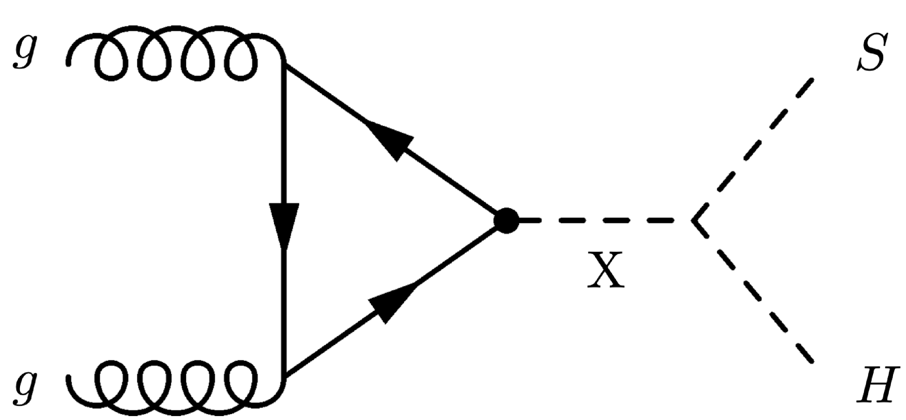


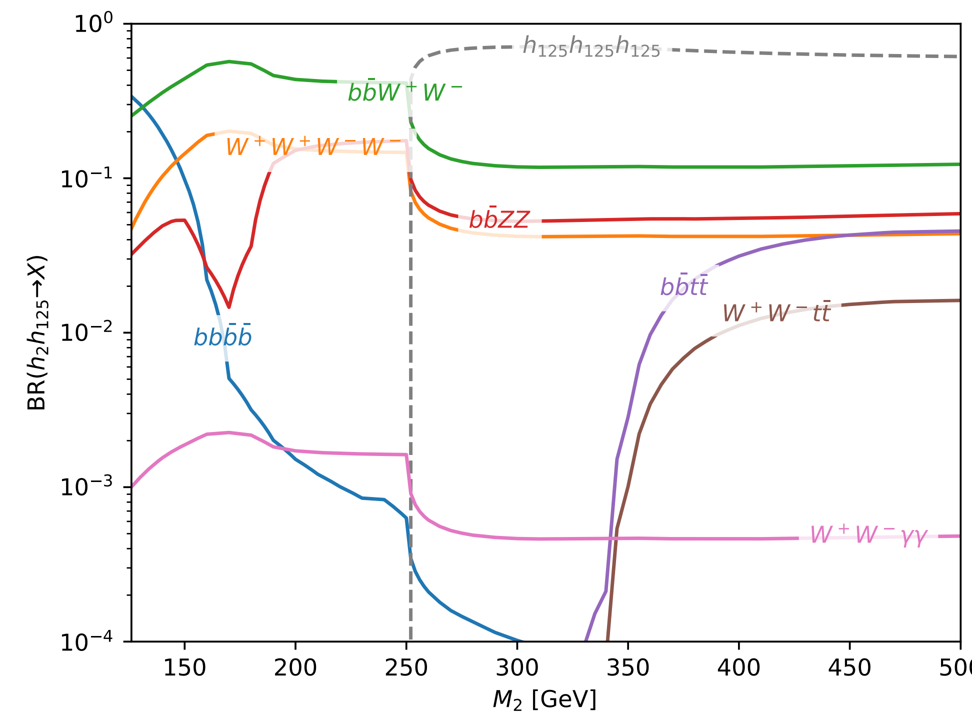




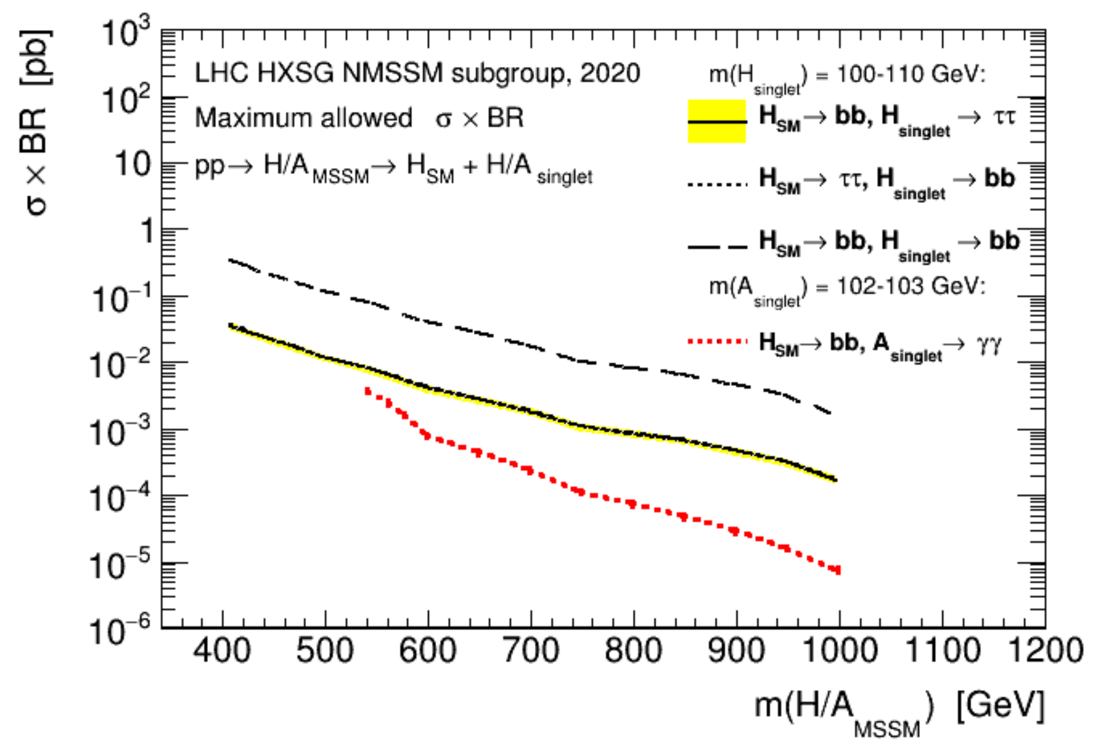
Resonant SH Production

- Numerous other models predict extended Higgs sectors with more scalar bosons
  - NMSSM, TRSM, N2HDM, CxSM, etc.
- X is a heavy scalar and S is a scalar with Higgs-like couplings
- Resonant X→SH production can be found using HH search techniques
- Wide range of S decay modes means many channels could be sensitive





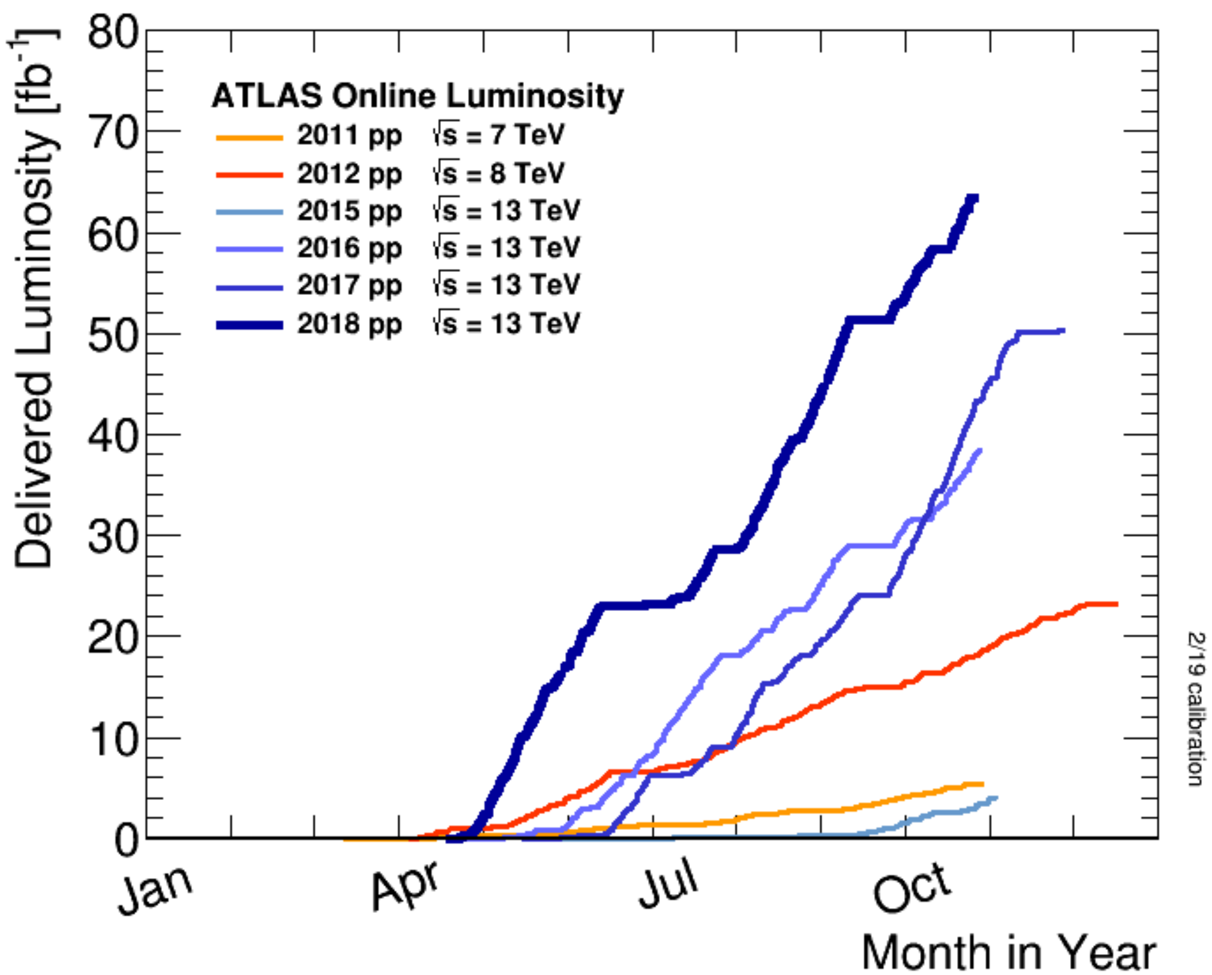
Eur. Phys. J. C 80, 151 (2020)

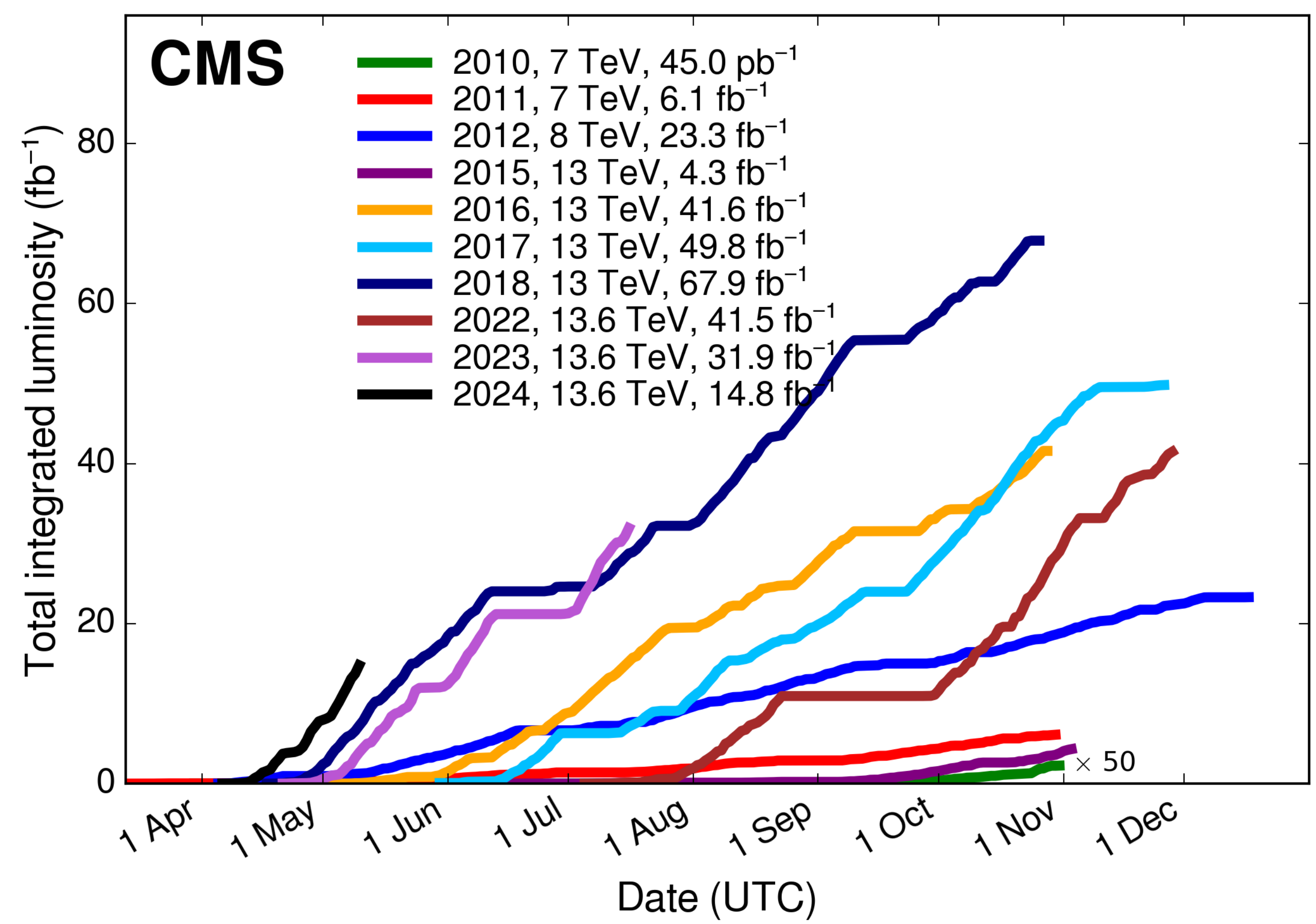


Searches

Run II Dataset

- Run II delivered 140-150 fb^{-1} of pp collision data at 13 TeV
- Increase of ~7x in integrated luminosity and ~1.6x energy from Run I





HH/SH Decay Modes

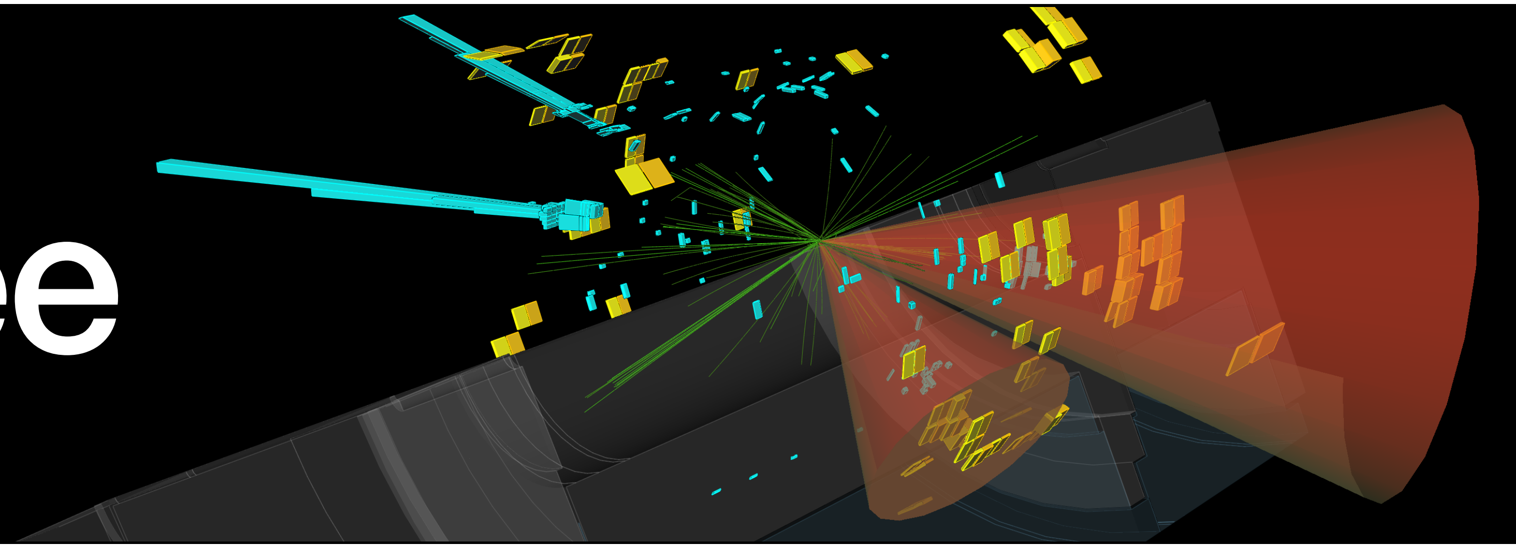
- The small HH cross-section means multiple final states must be used
- Most of the channels shown here are now used

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

Available Run II Results

	4b	bbττ	bbγγ	bbWW/bbll	Multilepton
ATLAS EXPERIMENT	Phys. Rev. D 108 (2023) 052003 Phys. Rev. D 105 (2022) 092002 JHEP 07 (2020) 108	JHEP 07 (2023) 040 JHEP 11 (2020) 163	JHEP 01 (2024) 066 Phys. Rev. D 106 (2022) 052001 Sumitted to JHEP	Phys. Lett. B 801 (2020) 135145	ATLAS-CONF-2024-005 JHEP 10 (2023) 009
CMS	Phys. Rev. Lett. 129 (2022) 081802 Phys. Lett. B 842 (2023) 137392	Phys. Lett. B 842 (2023) 137531 JHEP 11 (2021) 057	JHEP 03 (2021) 257	Submitted to JHEP	JHEP 07 (2023) 095 JHEP 06 (2023) 130 CMS-PAS-HIG-21-014

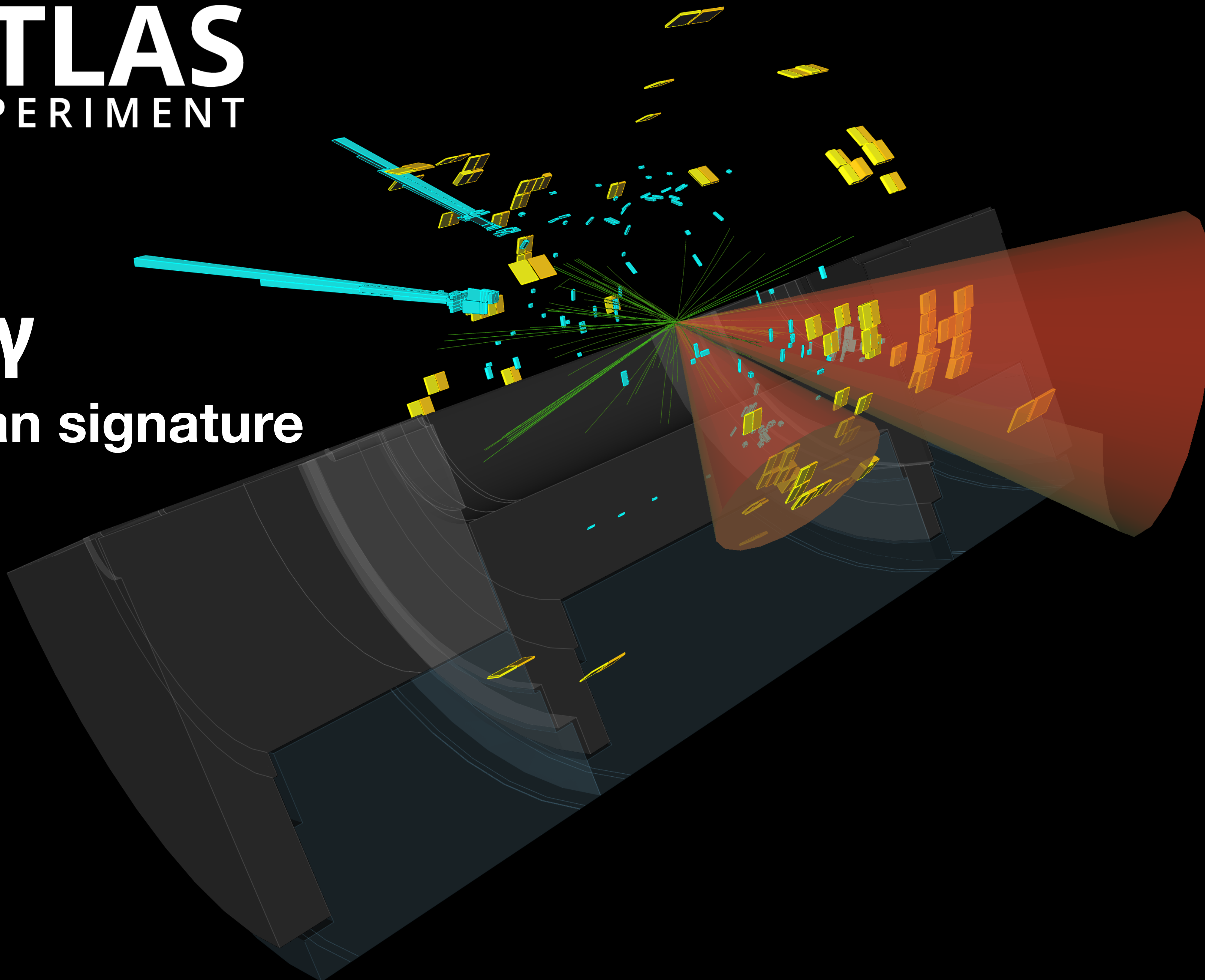
The Big Three



ATLAS EXPERIMENT

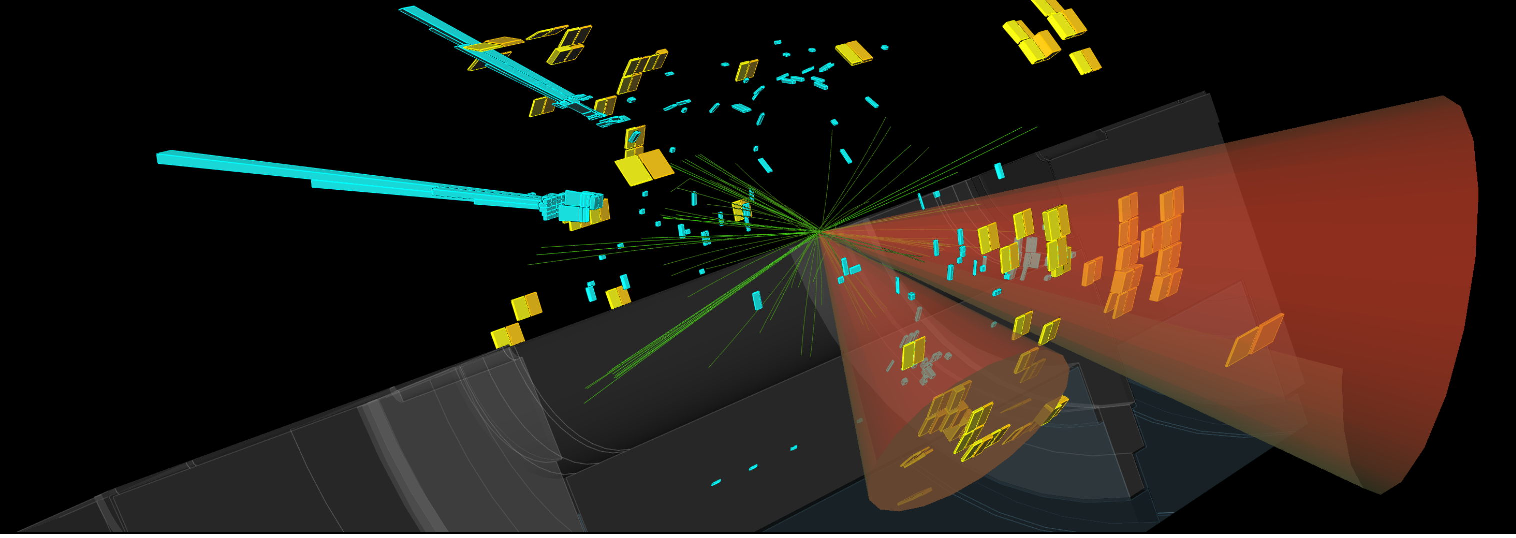
bbγγ

A clean signature

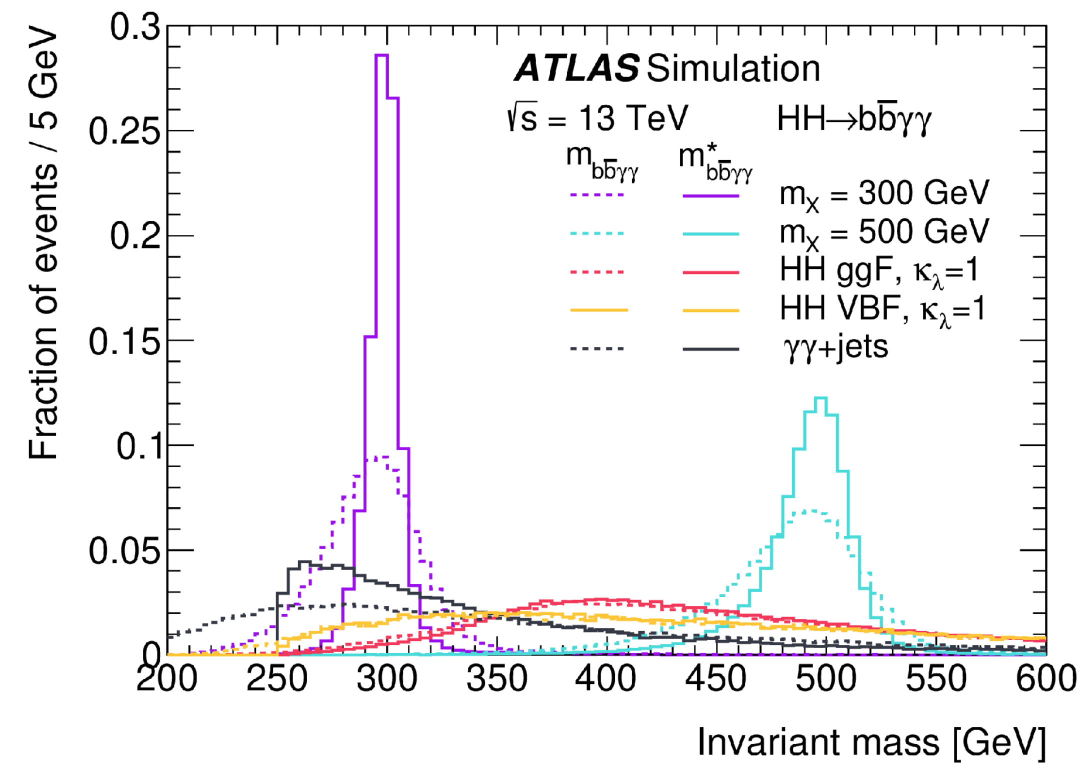


Phys. Rev. D 106 (2022) 052001

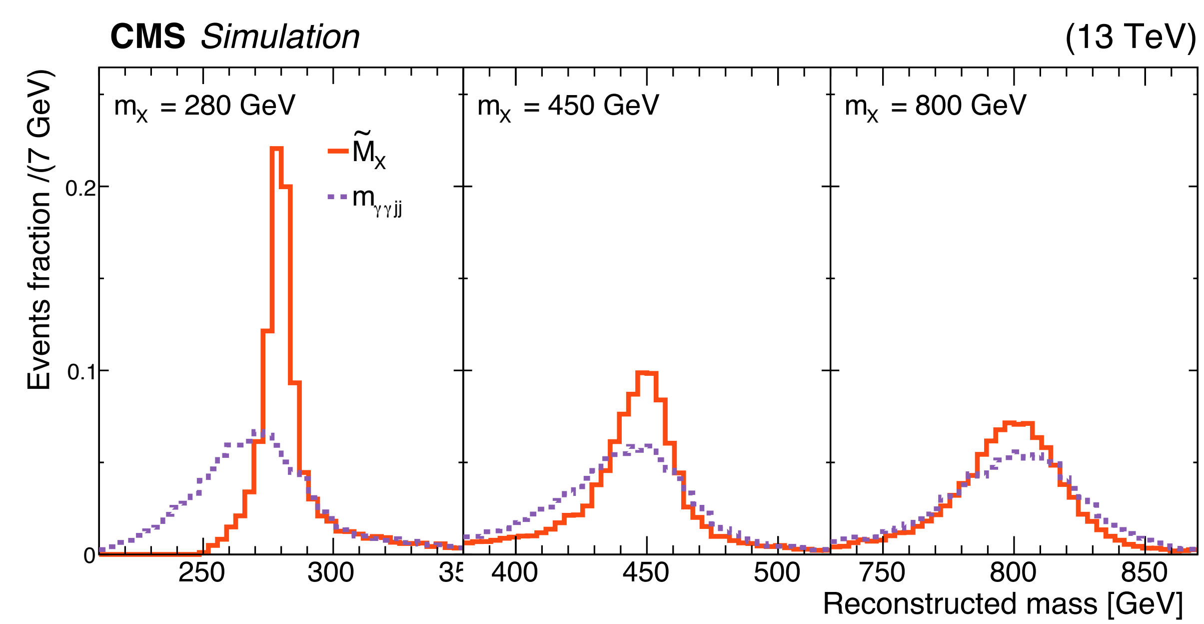
bbγγ
Signature



- A clean channel with low background
  - H→γγ decay gives a unique signature and excellent mass resolution
- Low BR of 0.26% - statistically limited
- Event selection:
  - 2 photons with $m_{\gamma\gamma}$ near m_H
  - 1 or 2 b-tagged jets



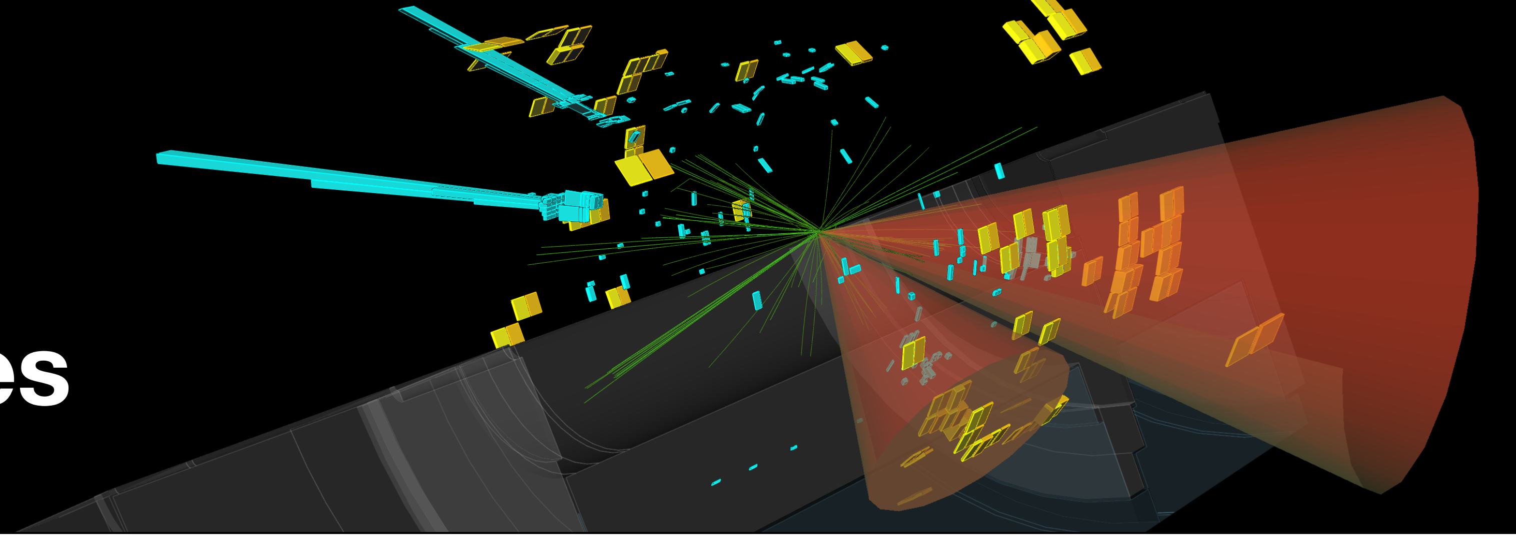
Phys. Rev. D 106 (2022) 052001



Phys. Lett. B 788 (2019) 736

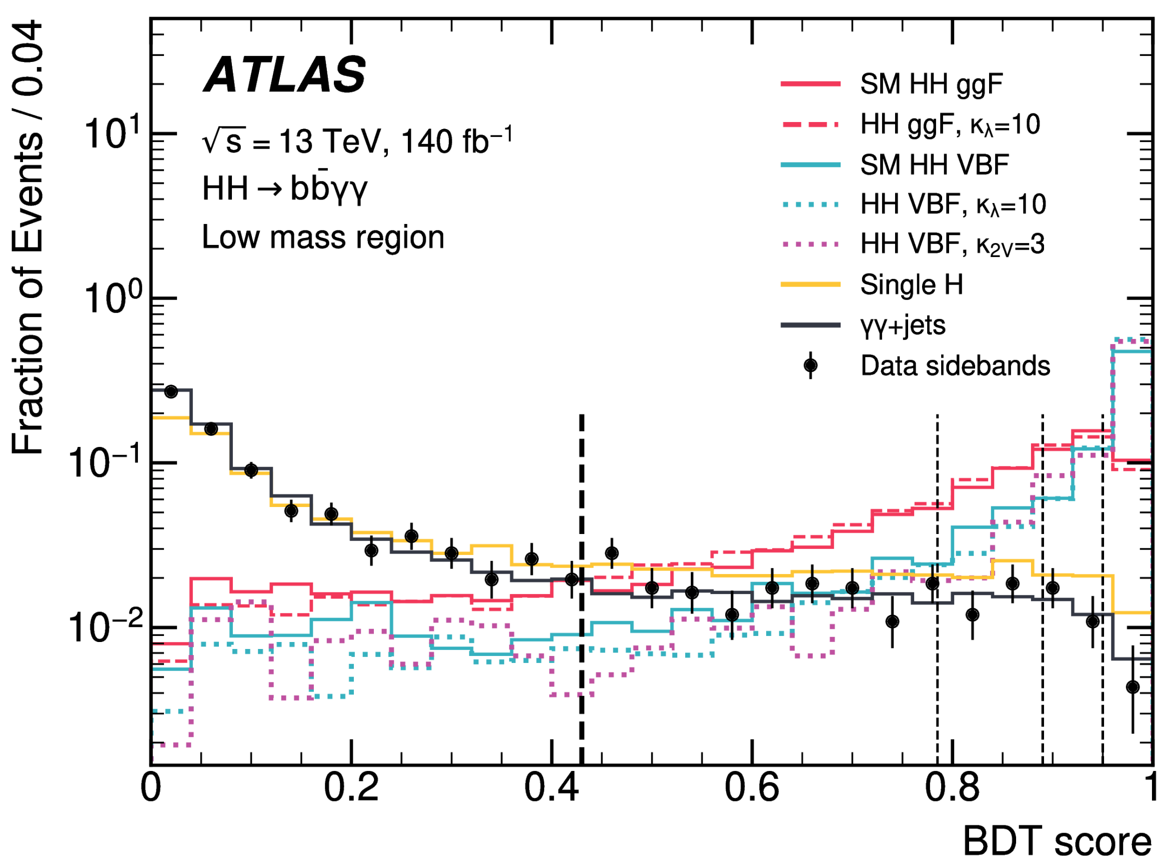
bbγγ

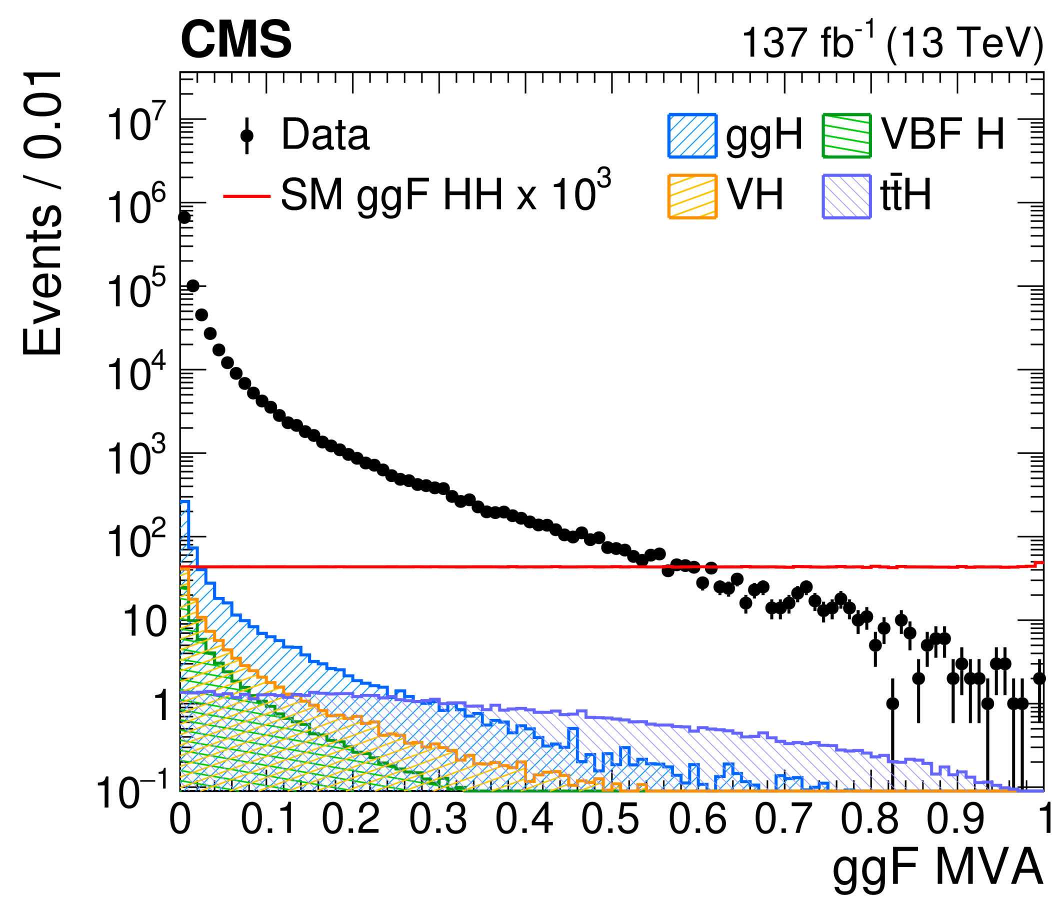
Multivariate techniques



- Use Boosted Decision Trees (BDTs) to distinguish signal from background
  - Combination of BDTs trained against continuum and single Higgs bkgs
  - BDTs trained separately for each analysis category

JHEP 01 (2024) 066

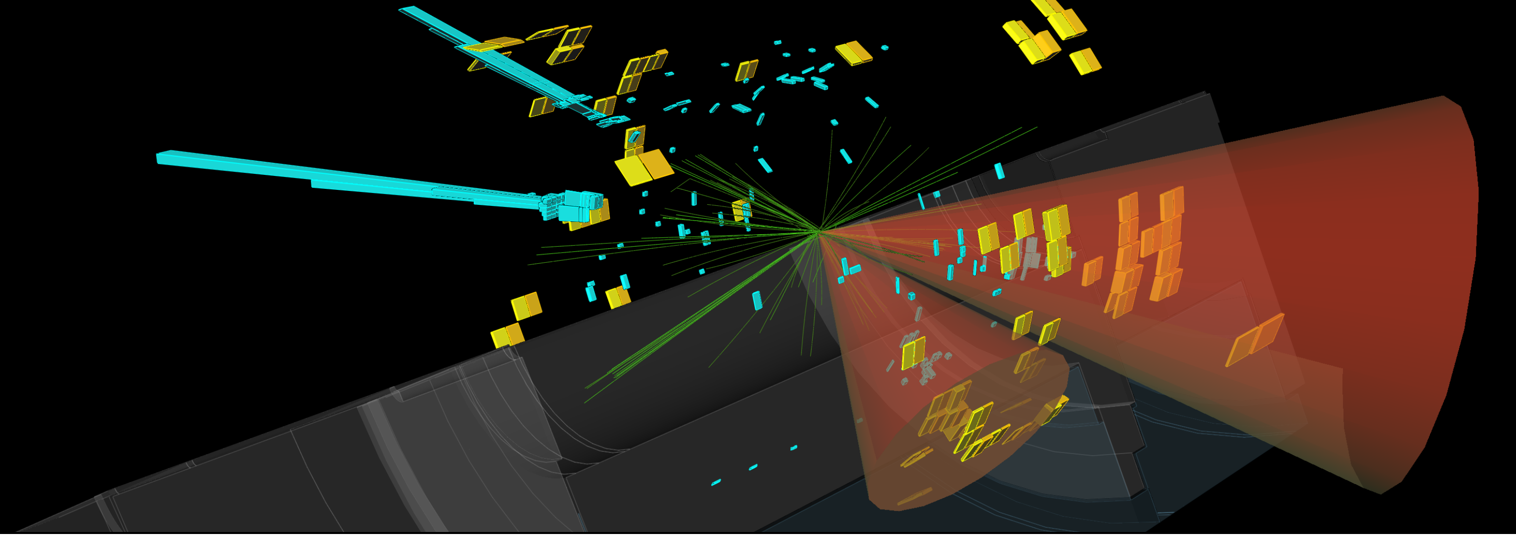




JHEP 03 (2021) 257

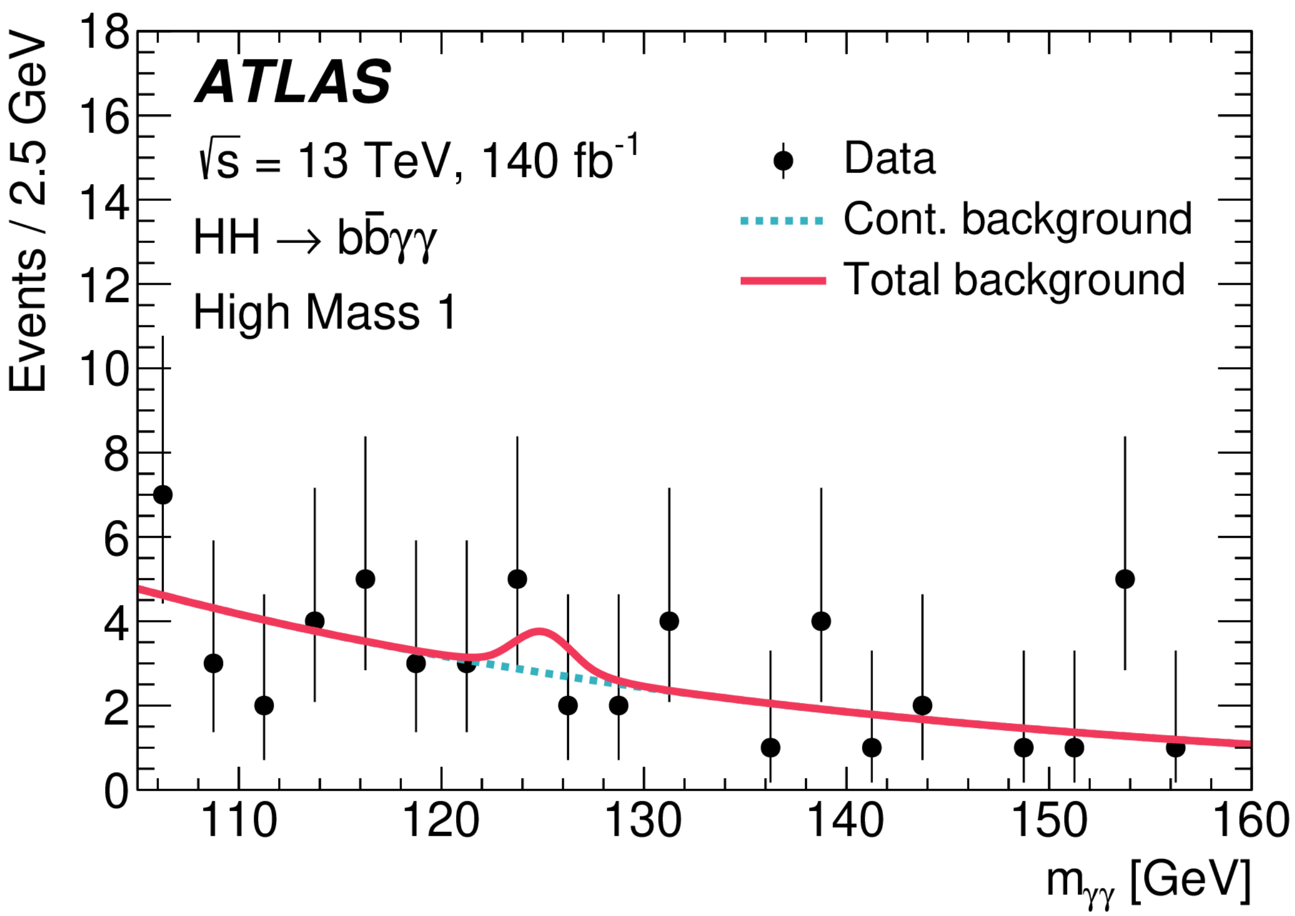
bbγγ

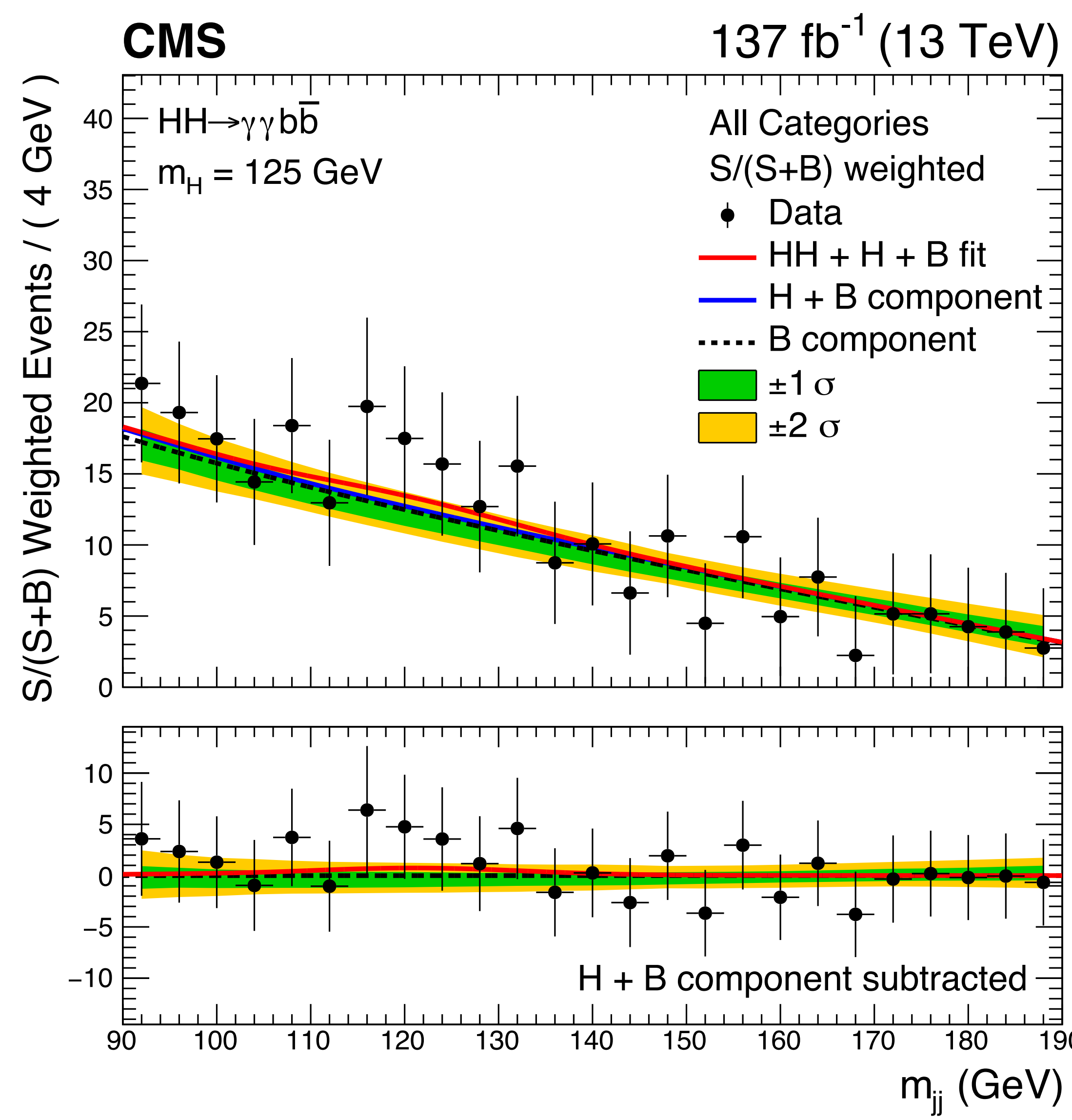
Signal extraction



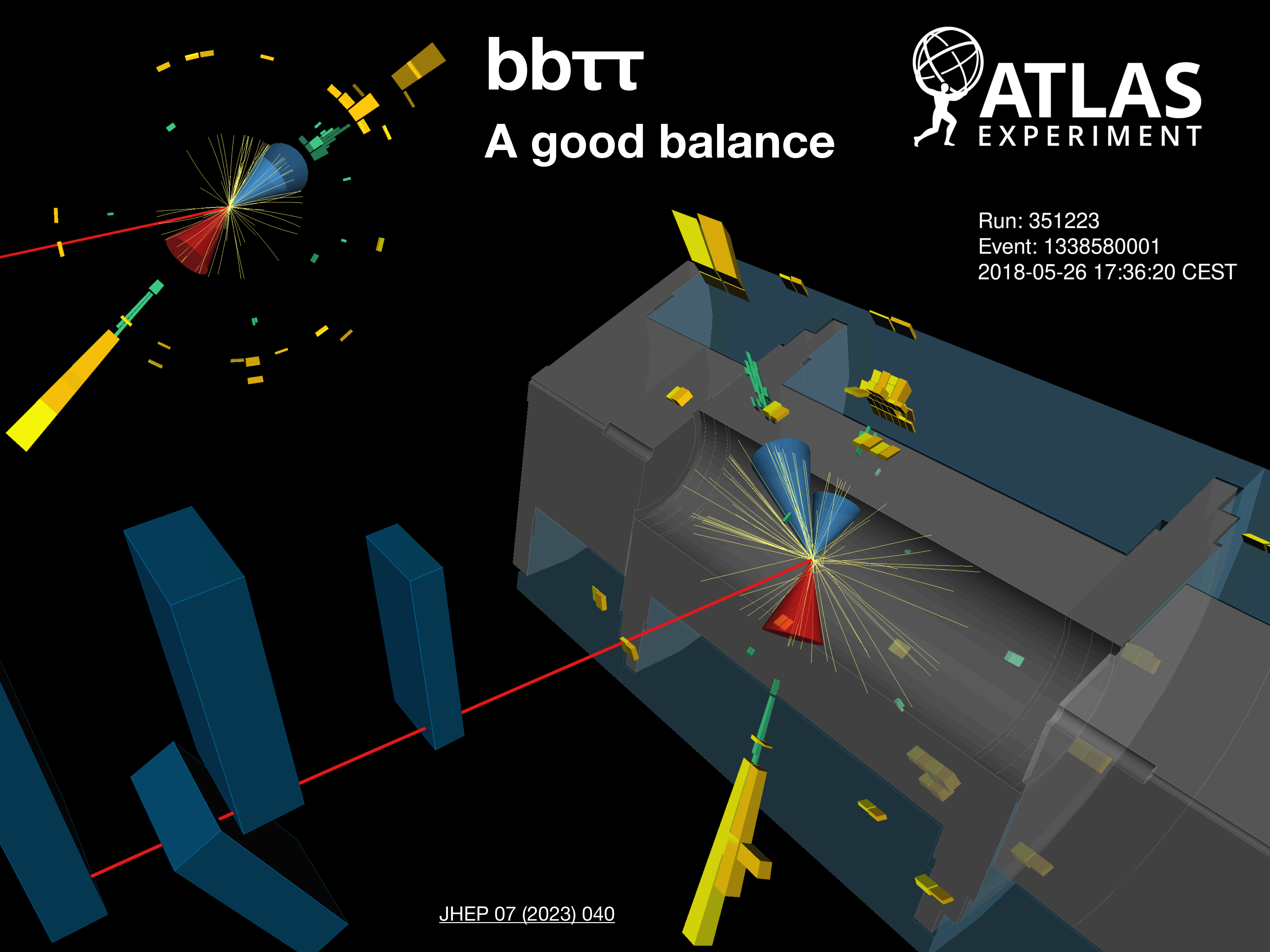
- Invariant mass distributions fit in with signal strength allowed to float
- CMS simultaneously fits $m_{\gamma\gamma}$ and m_{jj} distributions
- ATLAS fits $m_{\gamma\gamma}$ distribution

JHEP 01 (2024) 066



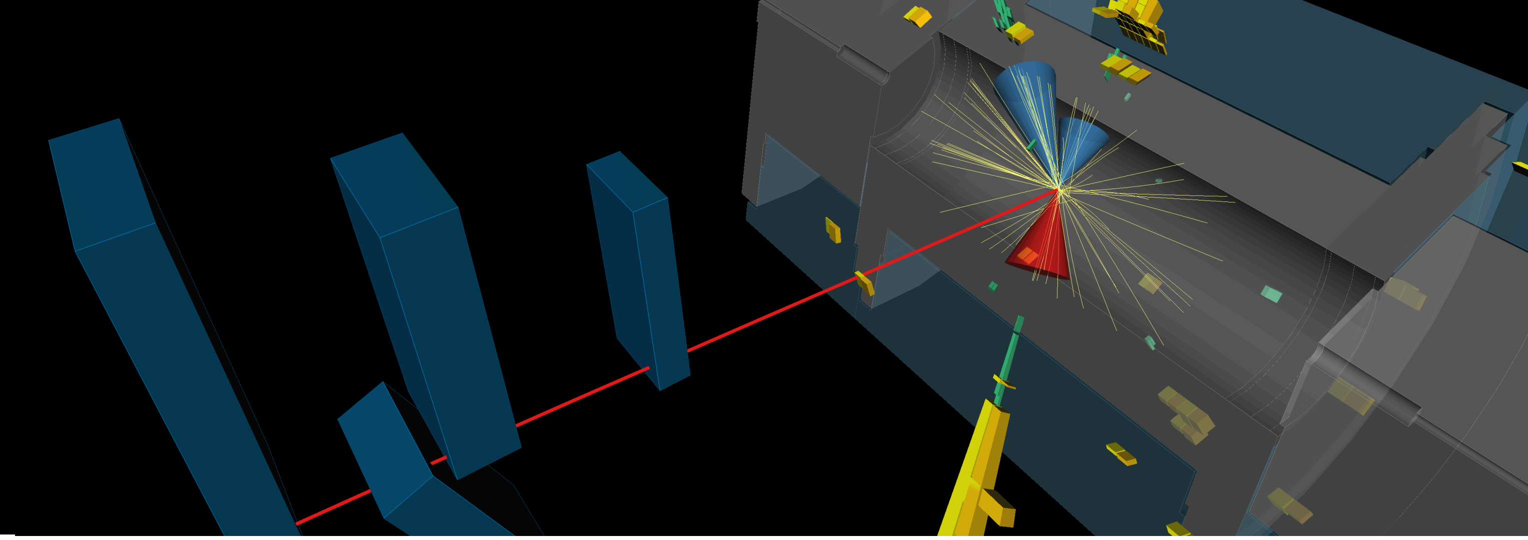


JHEP 03 (2021) 257


bbττ
A good balance
ATLAS
EXPERIMENT
Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST
JHEP 07 (2023) 040

bbττ

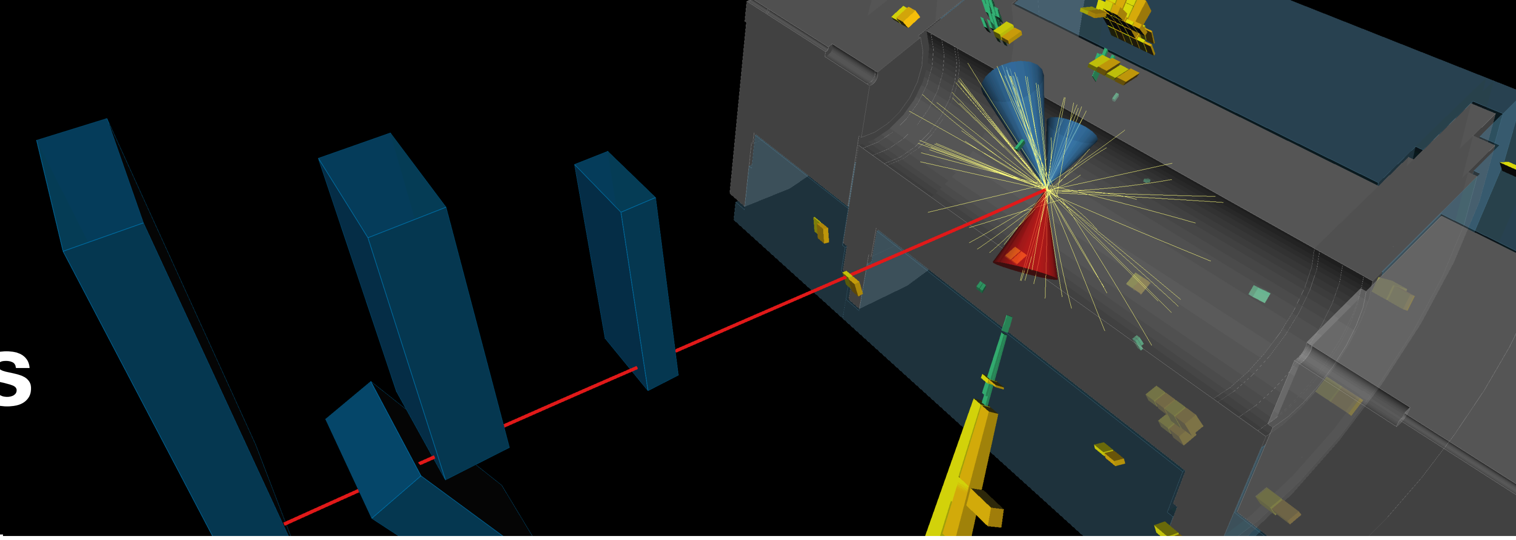
Signature



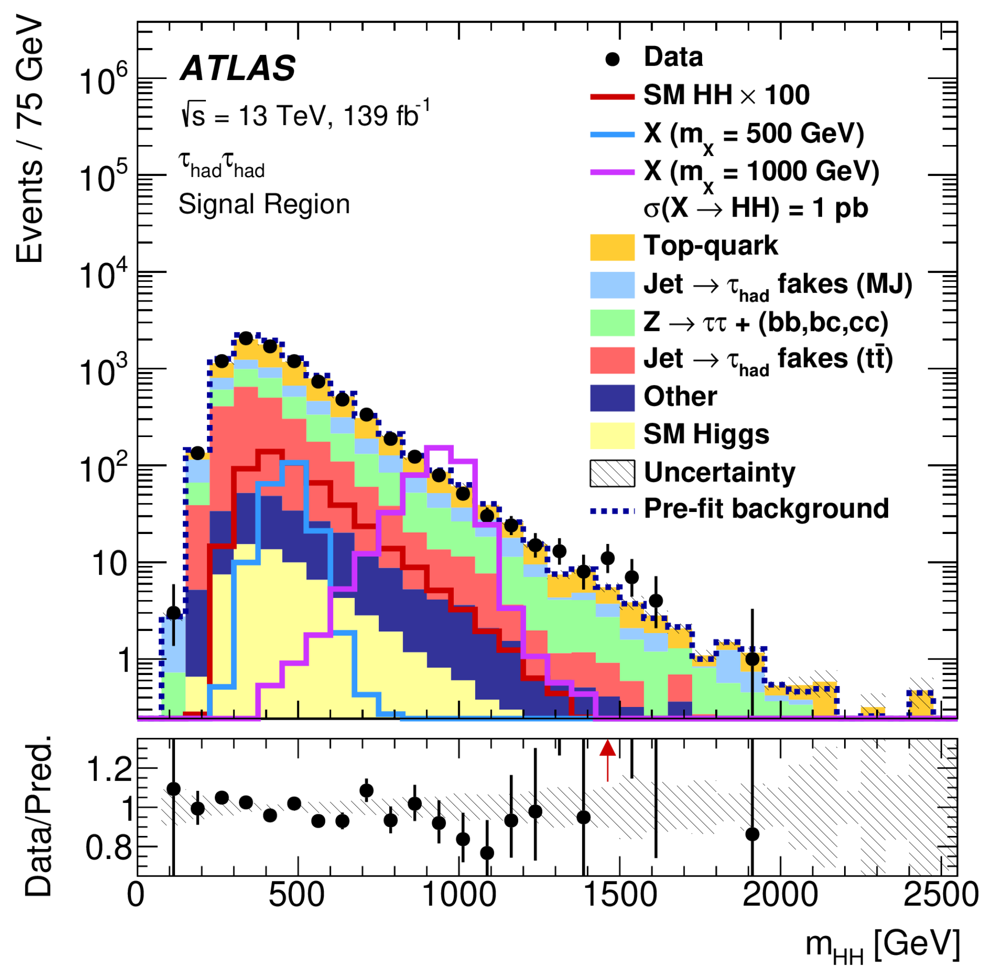
- Moderately large BR with relatively low background
- Fake-τ background challenging to model
- Split analysis based on τ decay modes ($\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$)
- Event selection:
  - Exactly 2 b-tagged jets or one large-R jet with 2 b-tags
    - CMS uses boosted and resolved, ATLAS uses resolved
  - Either 2 hadronic τ or 1 hadronic τ and 1 e/μ

bbττ

Complex backgrounds



$\tau_{had}\tau_{had}$



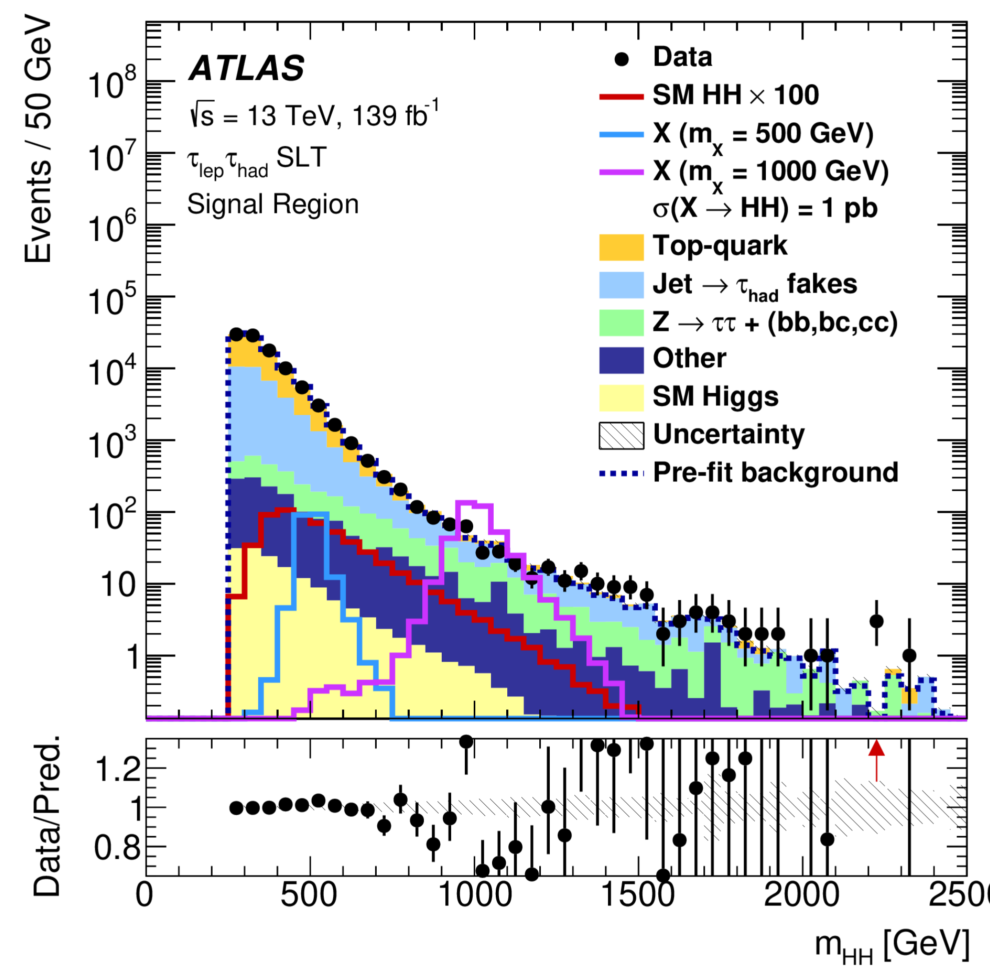
Top quark processes
Shape from MC and normalization from fit

Z→ττ + heavy flavor
Shape from MC and normalization from Z→ee/μμ+HF control region

Fake τ backgrounds
Data-driven estimate

Single Higgs and others
Estimate from MC

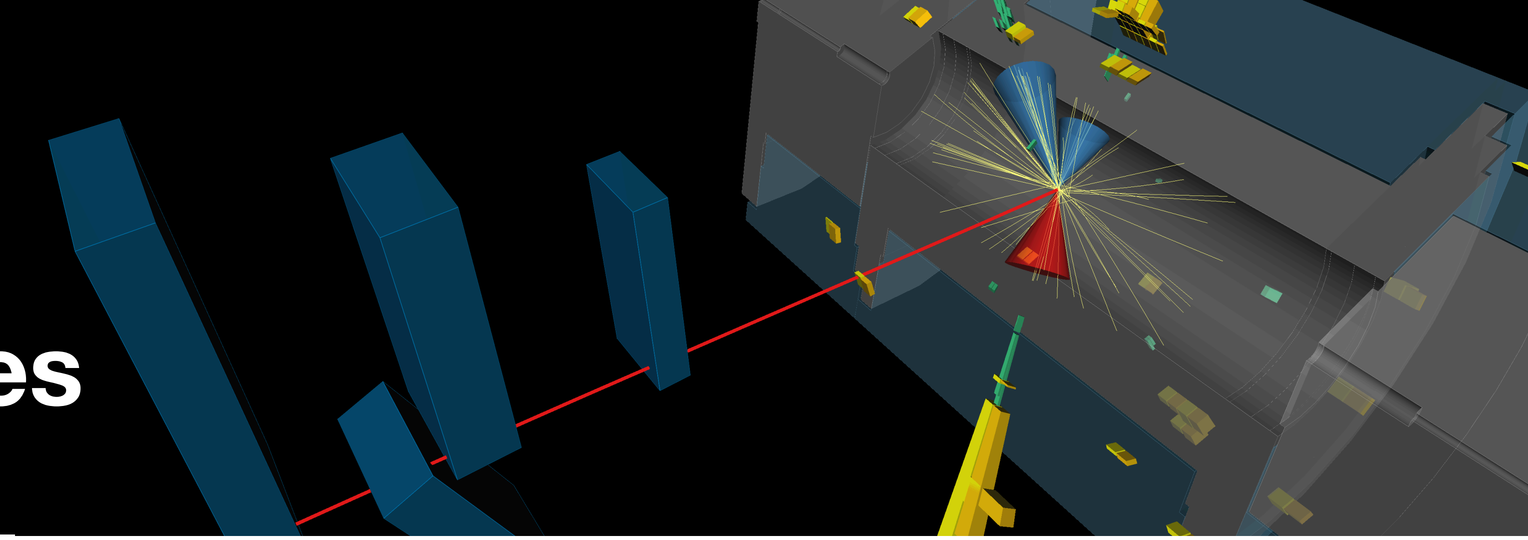
$\tau_{lep}\tau_{had}$



JHEP 07 (2023) 040

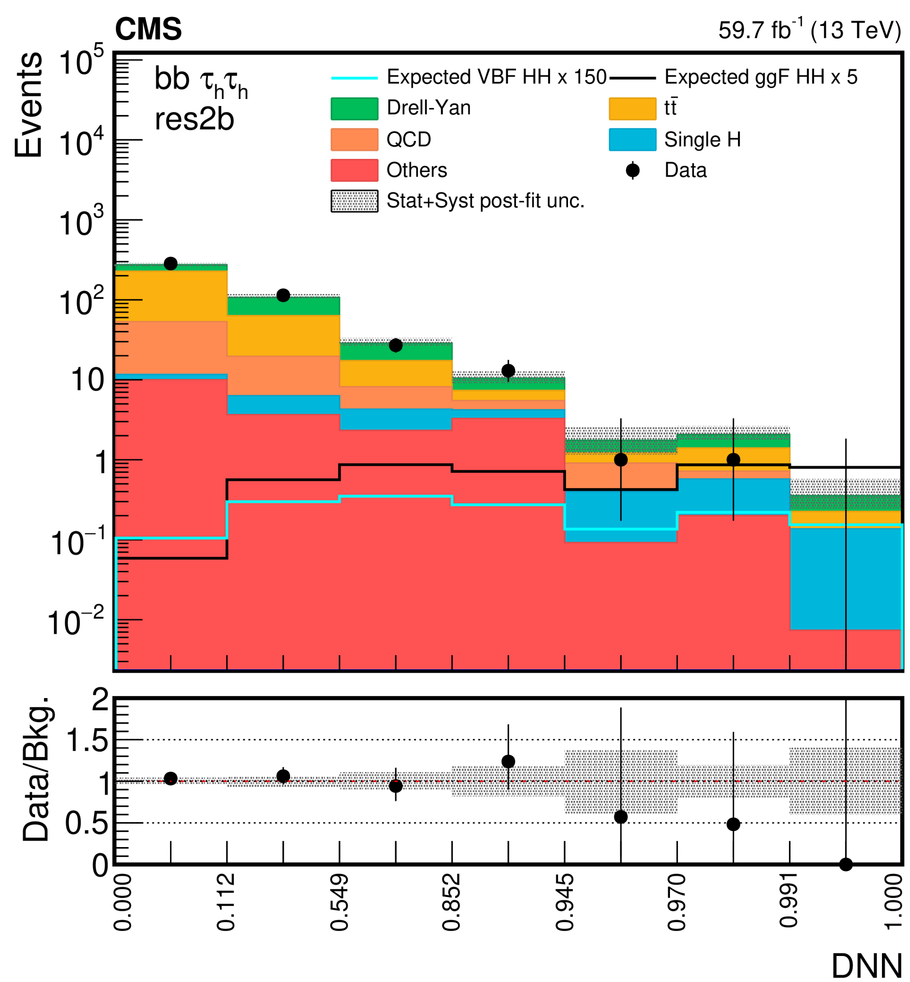
bbττ

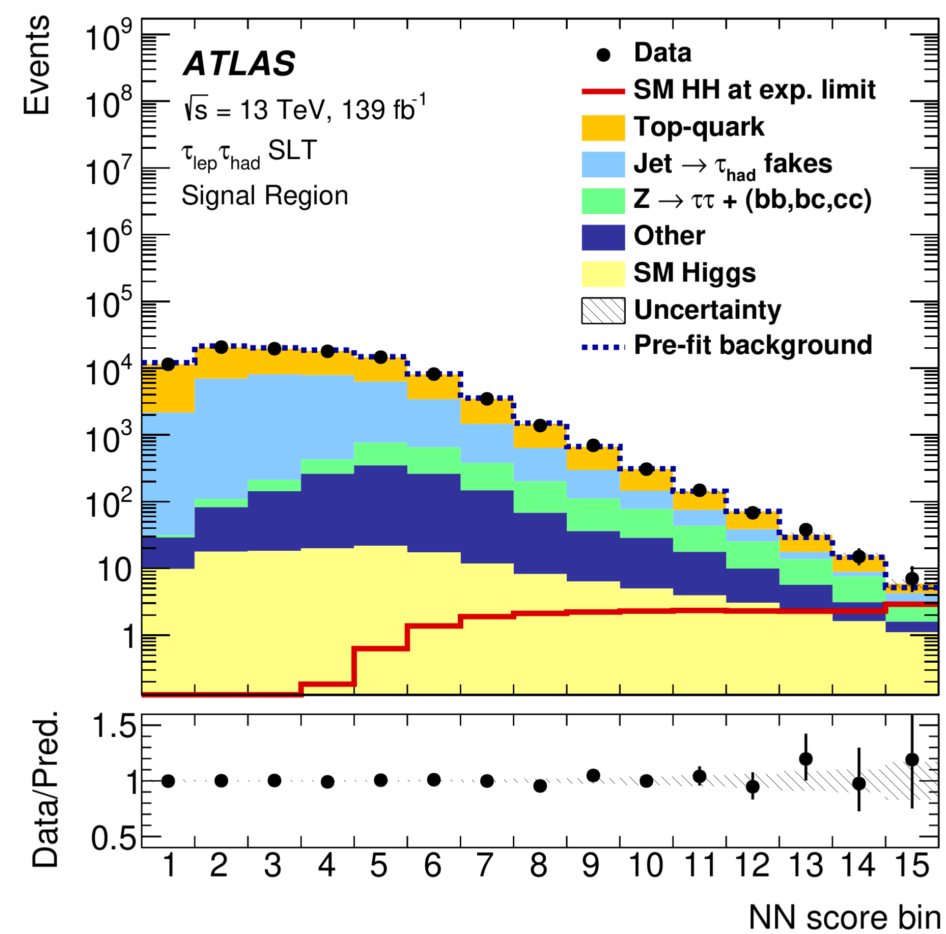
Multivariate techniques



- BDTs and NNs used to distinguish signal from background
- MVA score used as final signal/background discriminant
- Fit multiple categories based on, e.g., τ decay mode (3 in ATLAS, 72 in CMS)

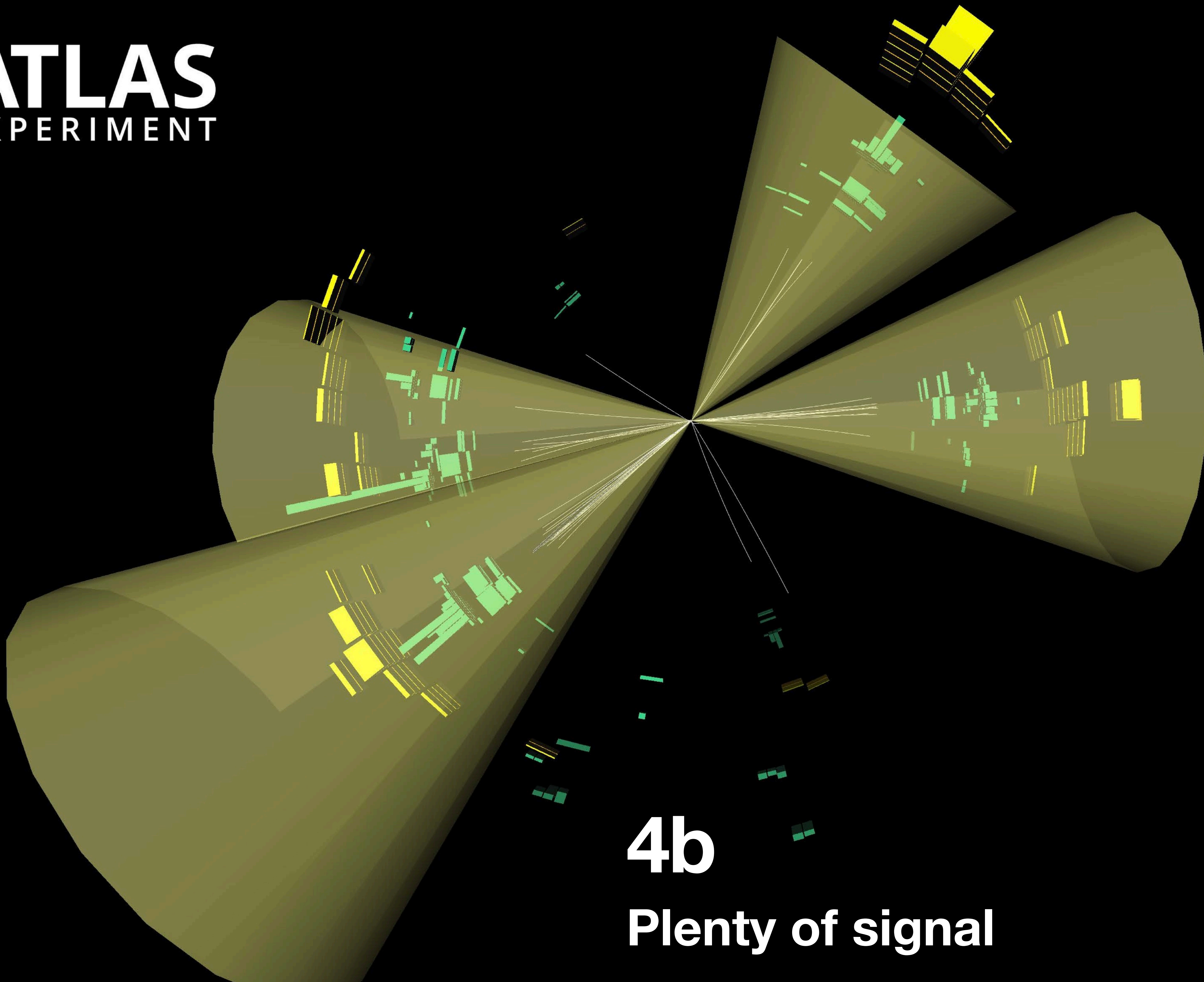
Phys. Lett. B 842 (2023) 137531





JHEP 07 (2023) 040

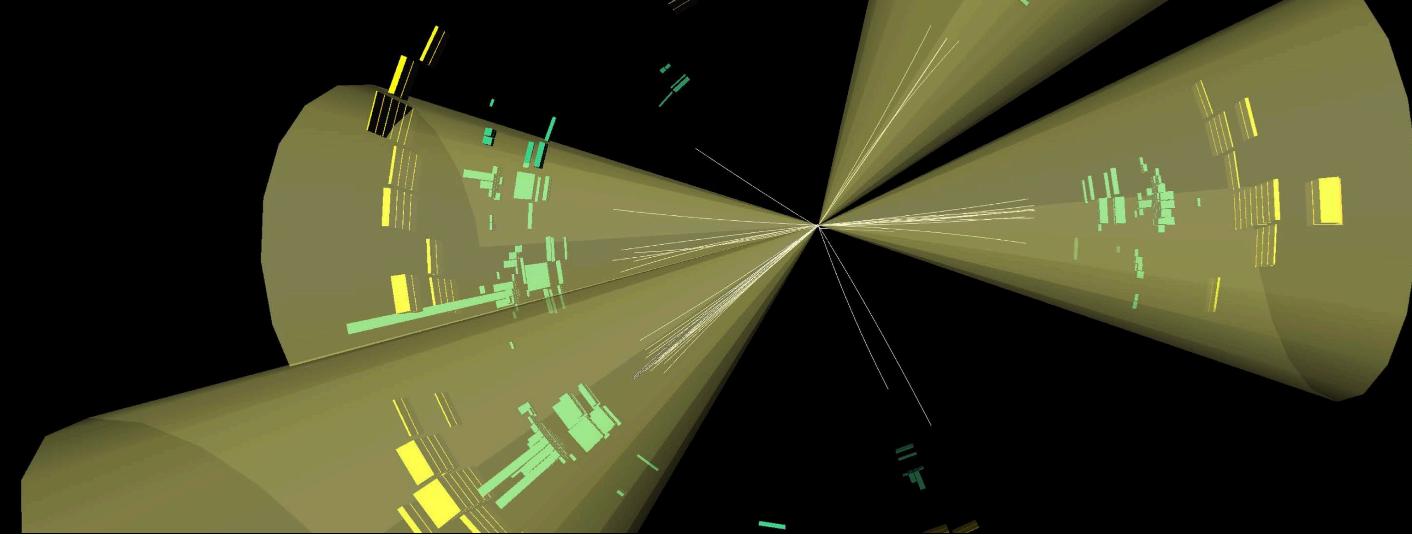
ATLAS EXPERIMENT

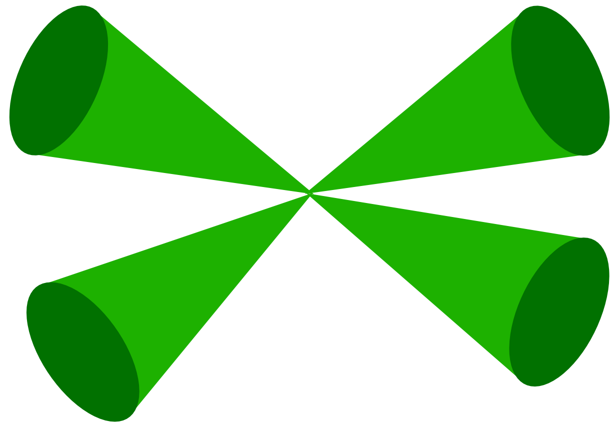


4b

Plenty of signal

4b
Signature

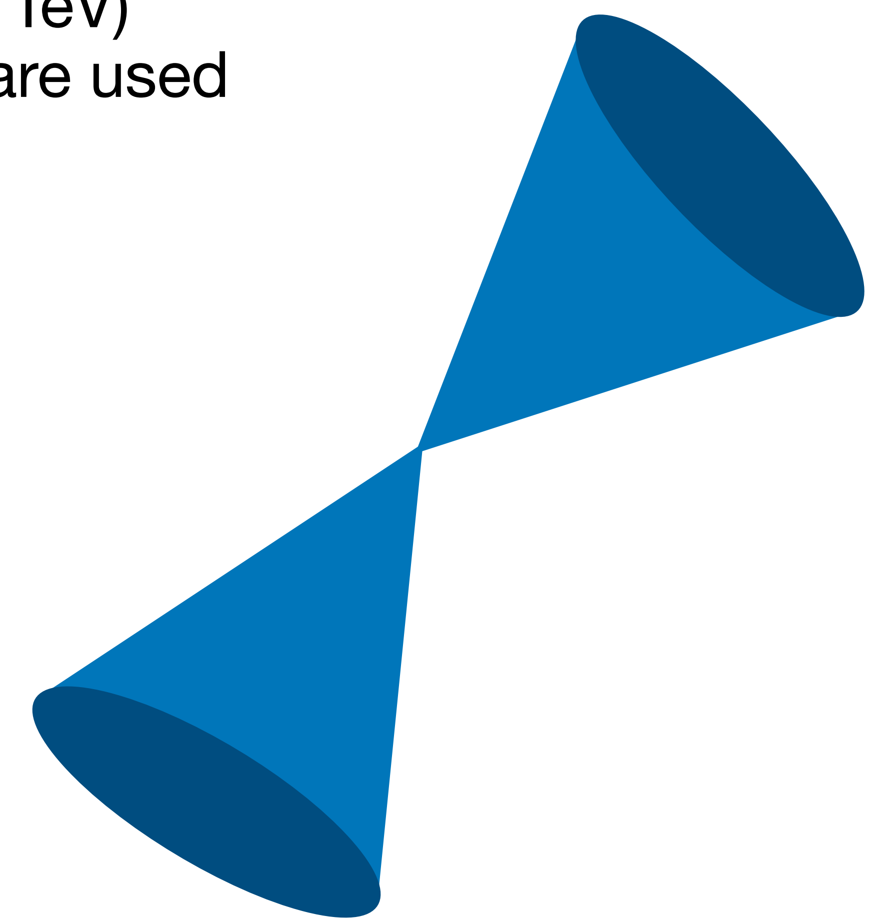




- Largest branching ratio
- Large QCD background
- Resolved (non-resonant and 251 GeV ≤ m_X ≤ 1.5 TeV) and boosted (900 GeV ≤ m_X ≤ 5 TeV) topologies are used
- Event selection:
    - 4 b-tagged jets

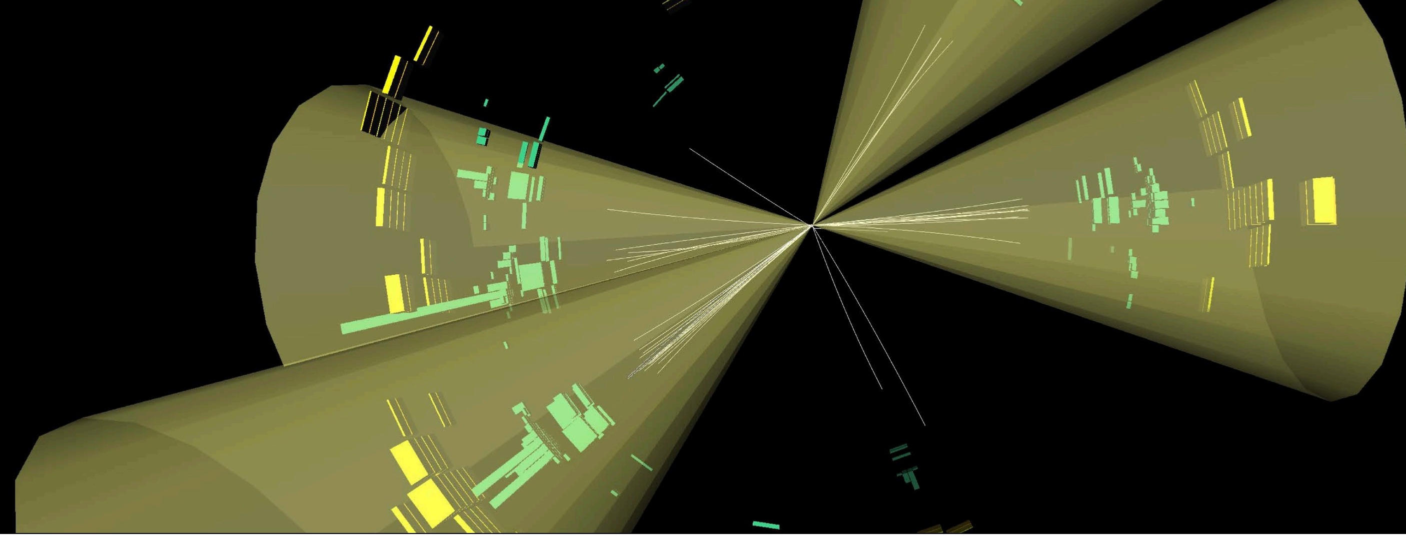
  or

    - 2 large-R jets with 2-4 b-tagged track jets



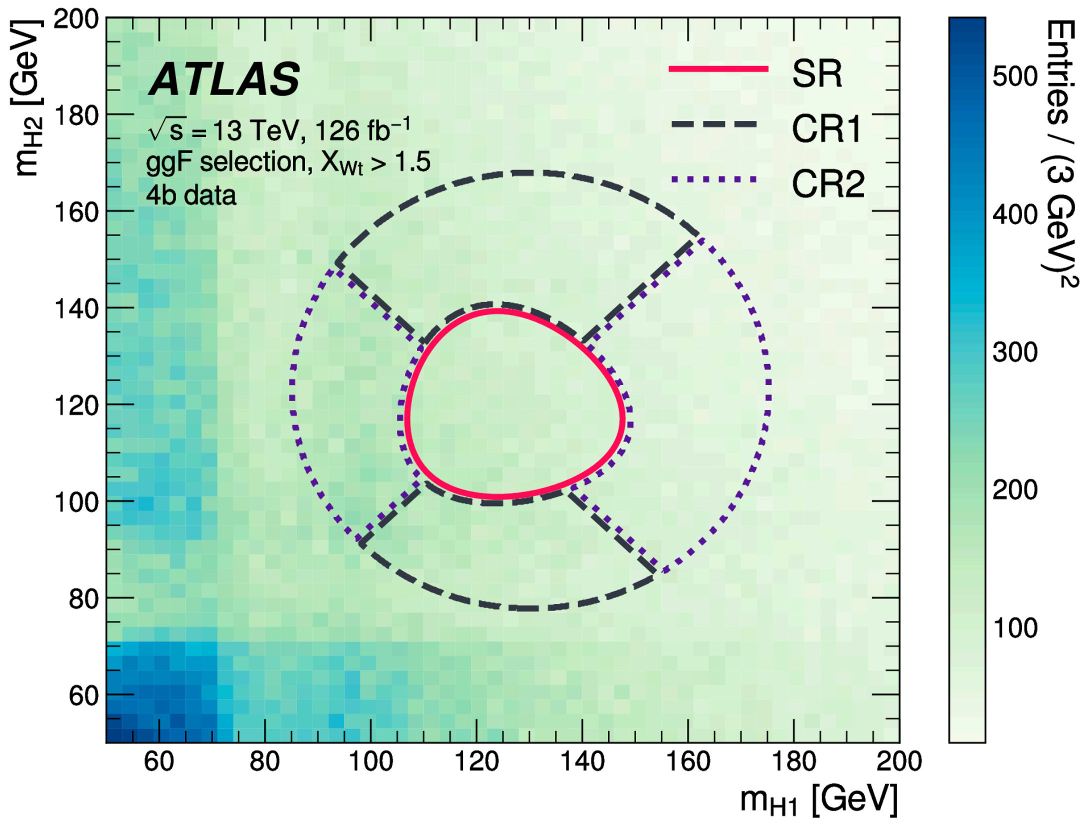
4b

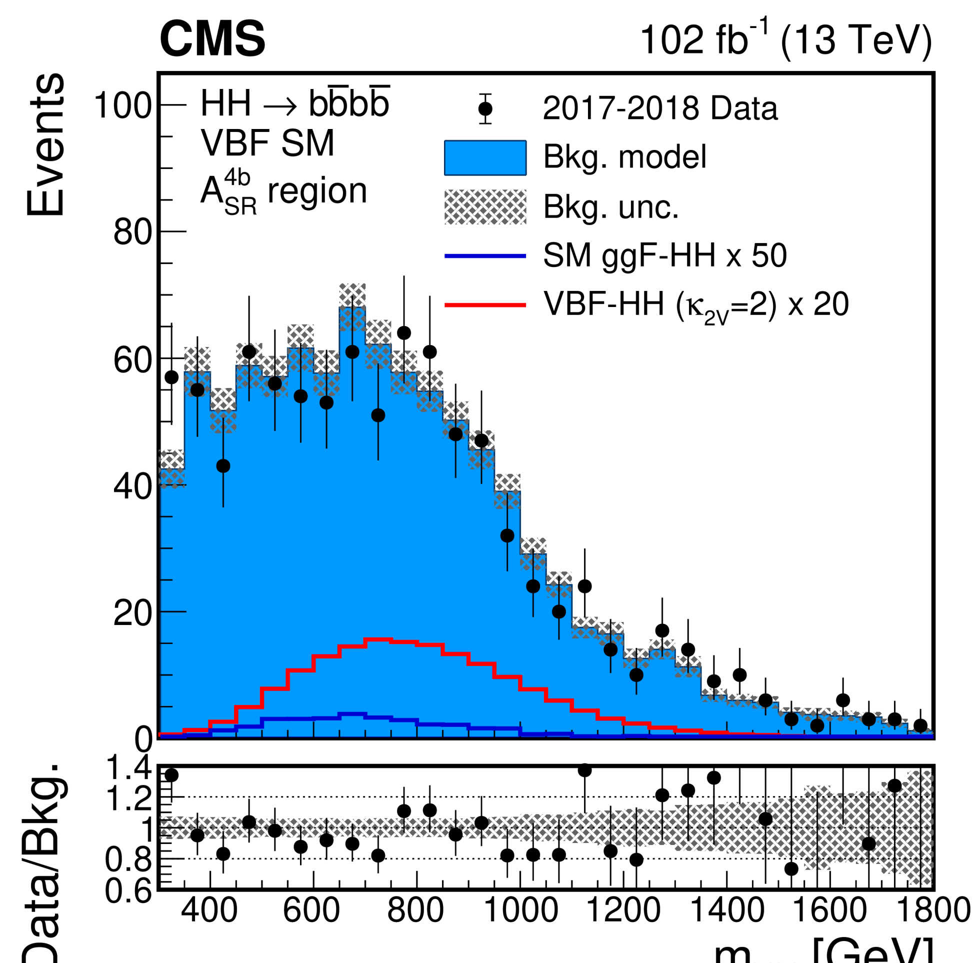
Analysis strategy



- Resolved: 4 b-tagged jets paired to construct Higgs candidates
- Boosted: 2 b-tagged large-R jets used as Higgs candidates
- Primarily data-driven background estimates
- m_{HH} used as final discriminant

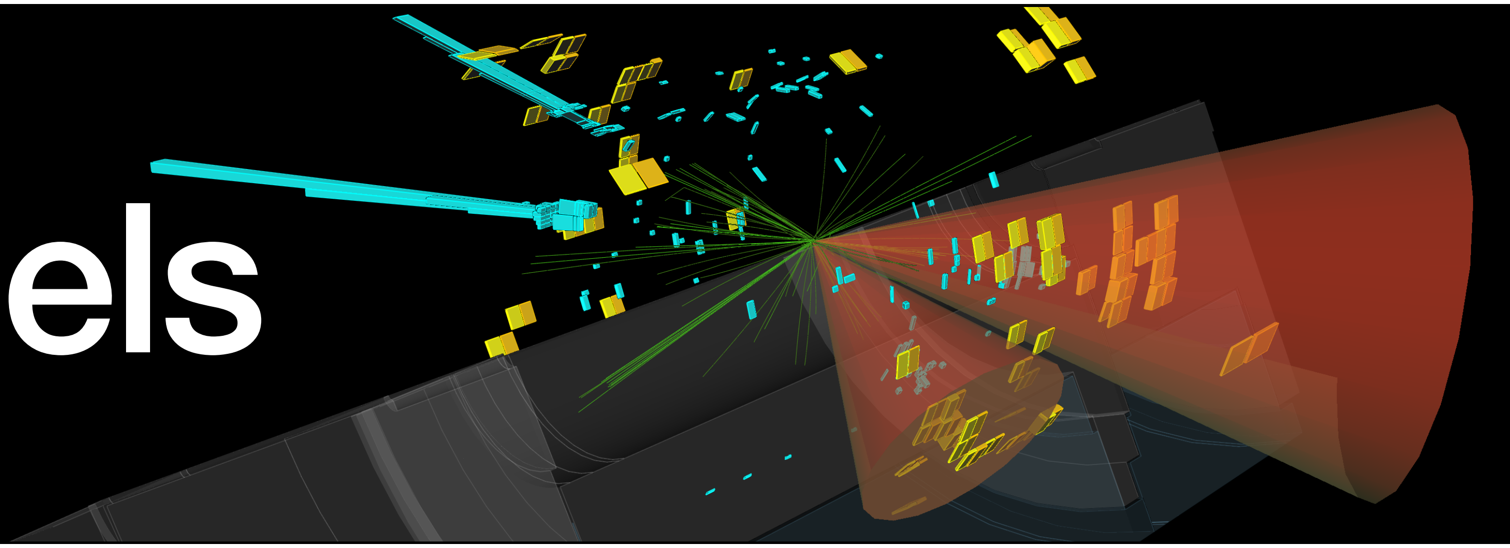
Phys. Rev. D 108 (2023) 052003





Phys. Rev. Lett. 129 (2022) 081802

Other Channels



	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10[illegible]	[illegible]	[illegible]	[illegible]

bb+leptons

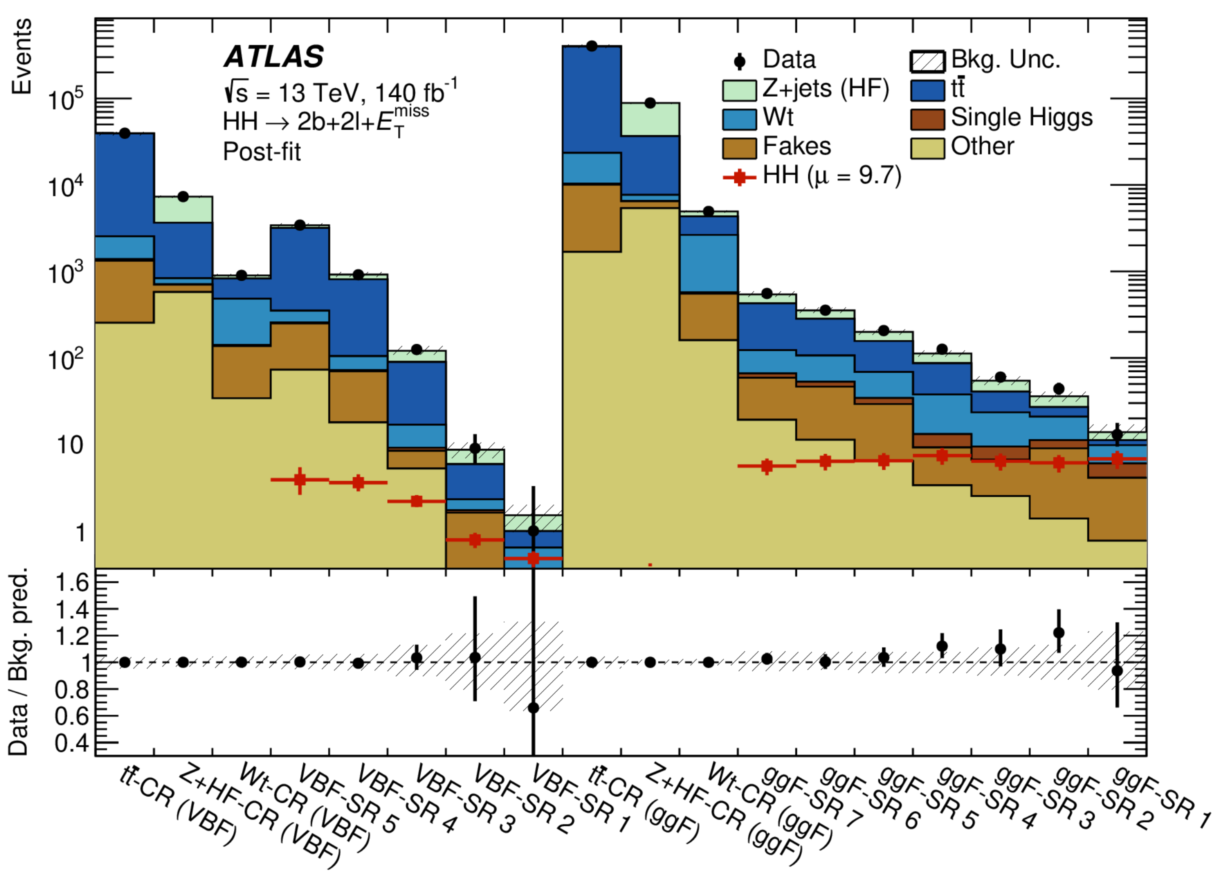
High BR and clean signature

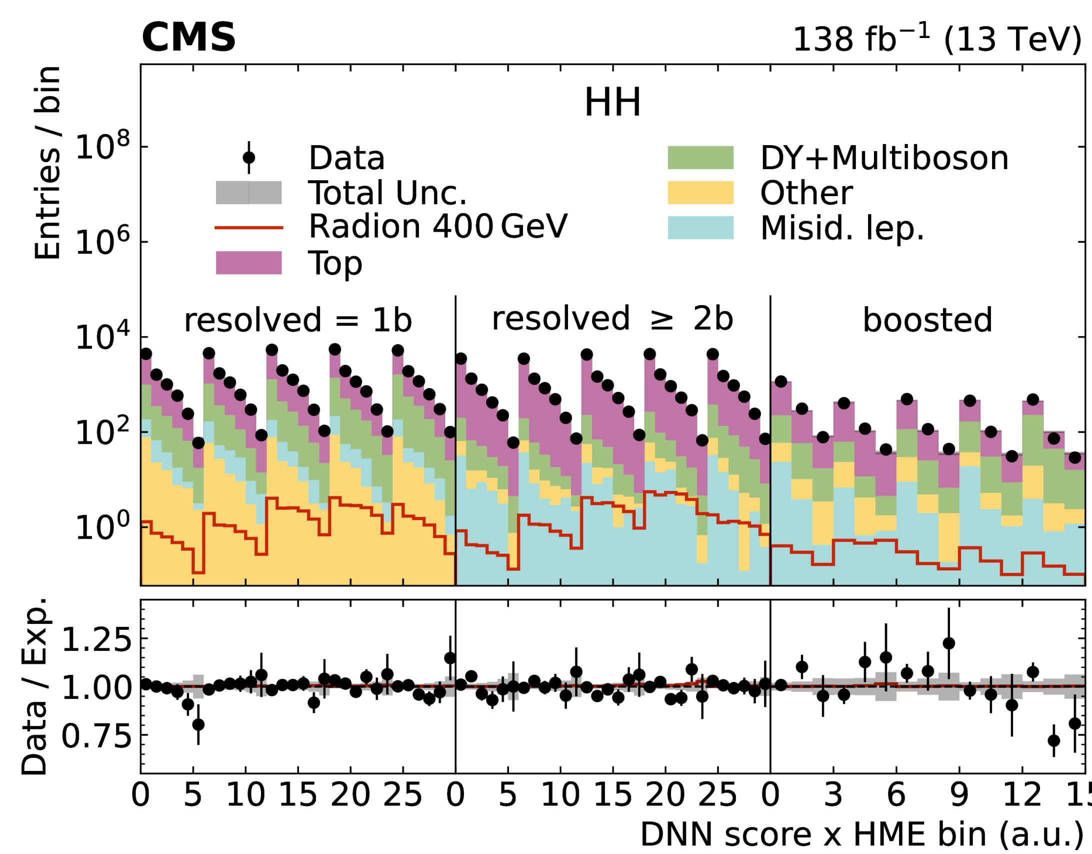
bb+leptons

Analysis strategy

- 2 b-jets and 1 or 2 leptons and MET
- Machine learning techniques used to identify signal
- CMS uses of resolved and boosted topologies, ATLAS uses resolved

JHEP 02 (2024) 037





Submitted to JHEP

Multilepton

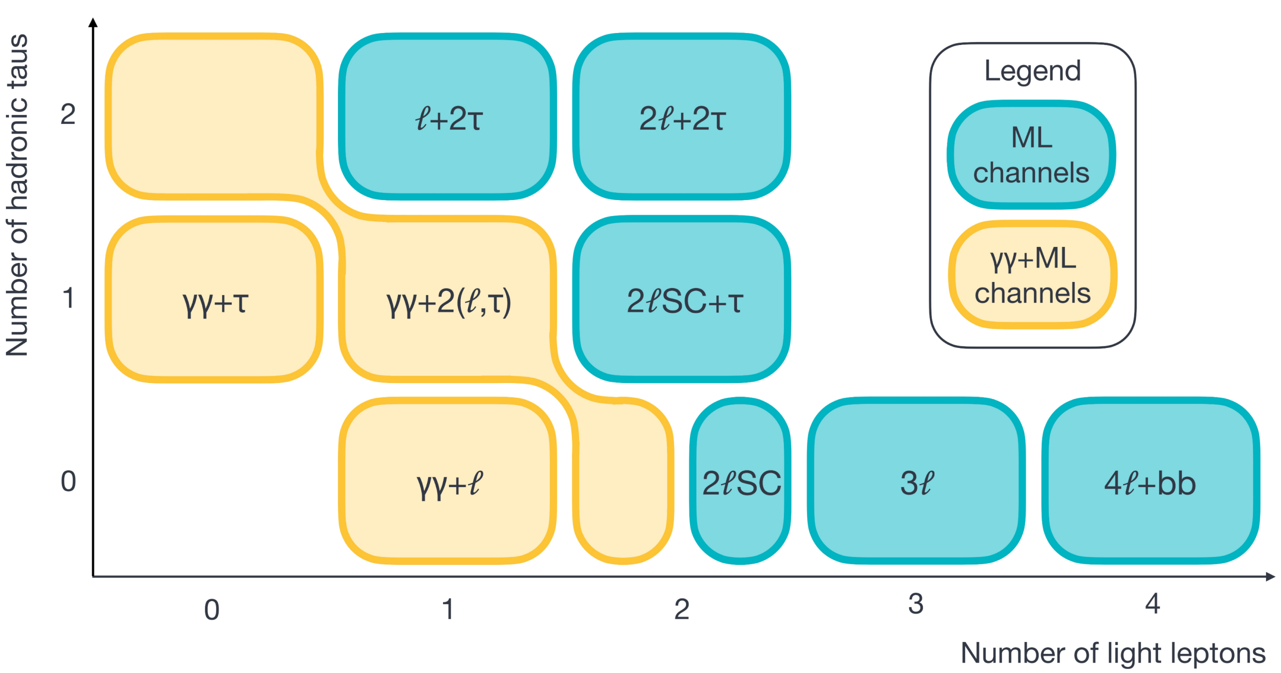
The more the merrier

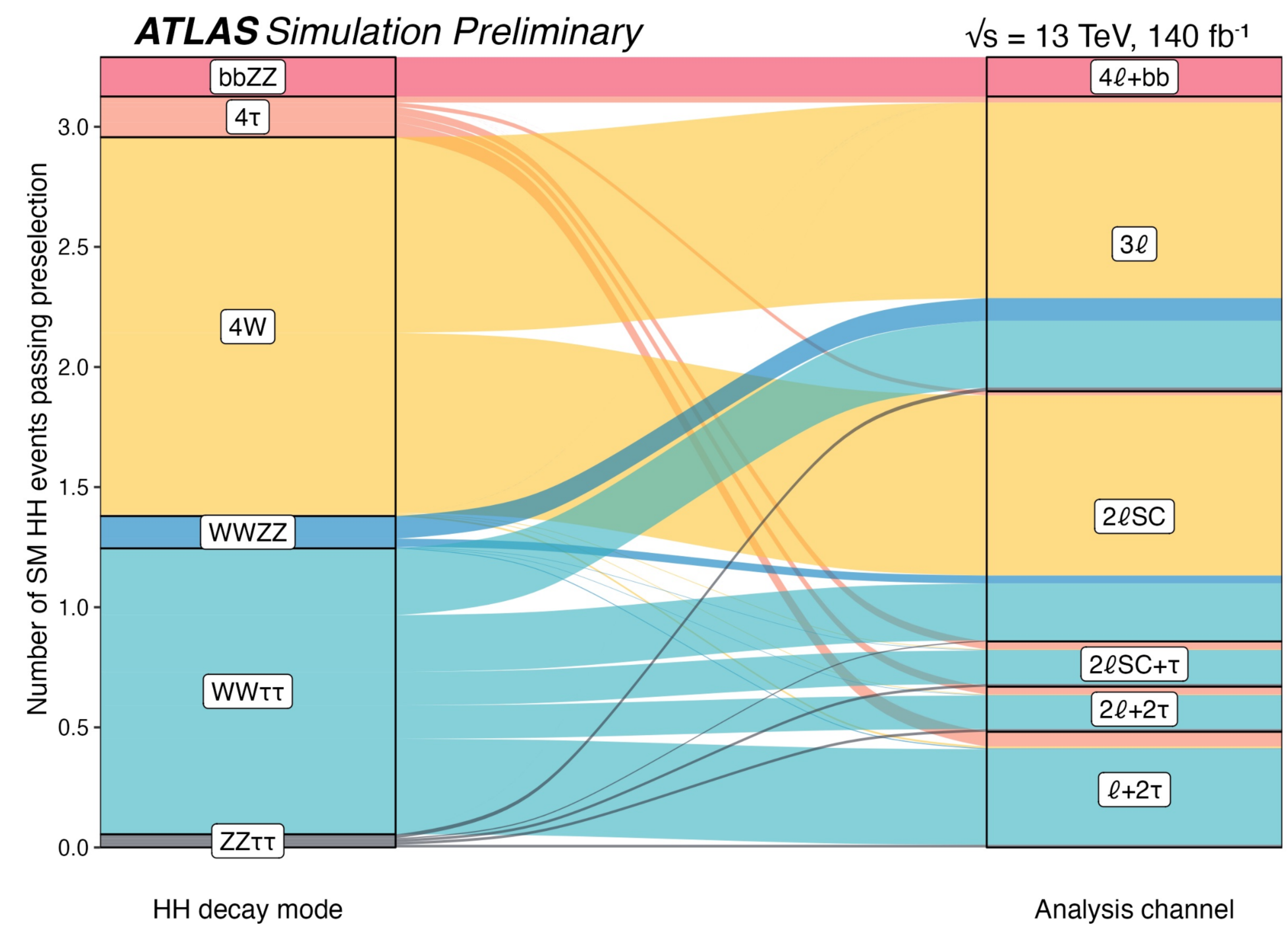
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Multilepton

Analysis strategy

- Combination of channels not covered elsewhere
- Many different multiplicities of leptons, τs, jets and photons used
- Numerous signal regions with dedicated neural networks





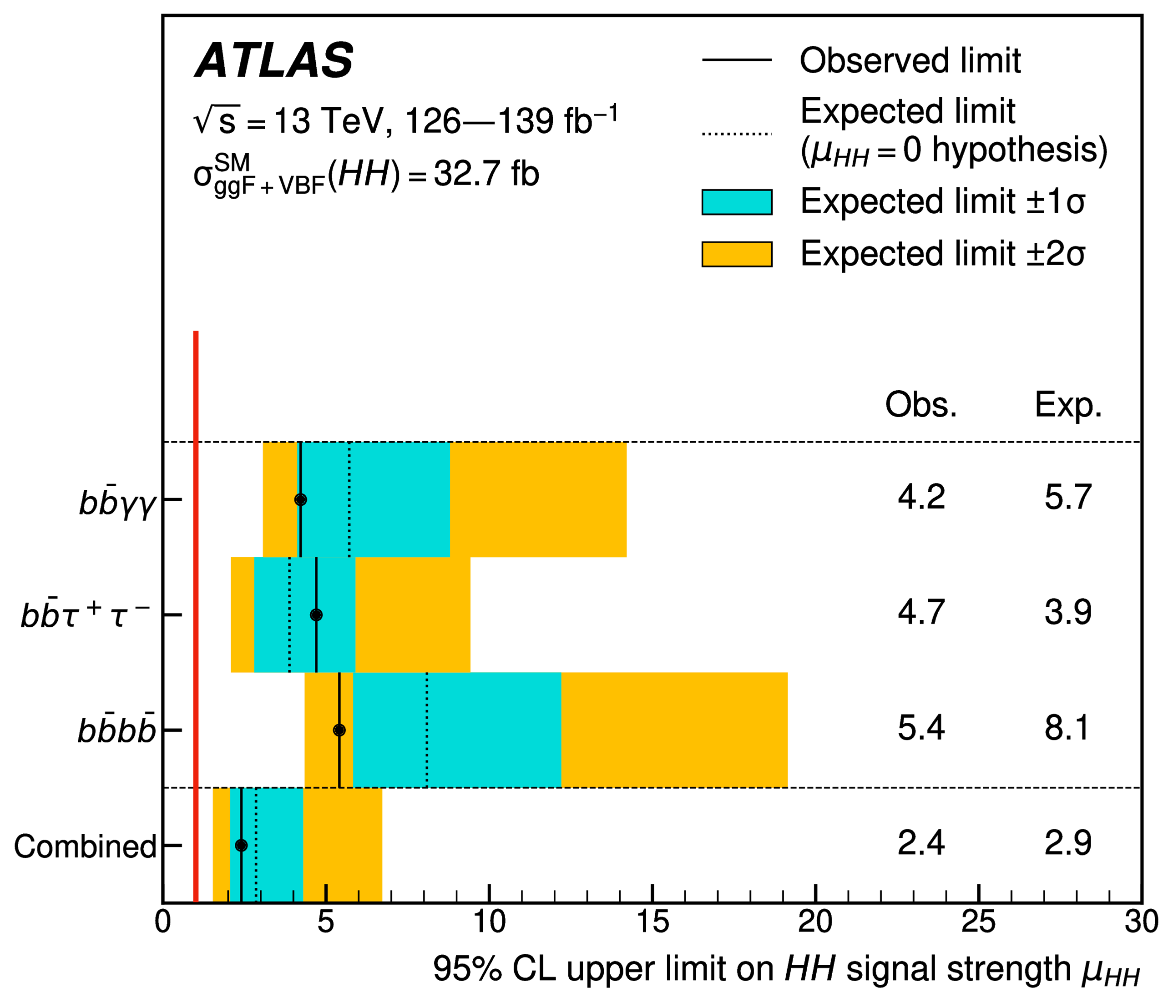
HH Results

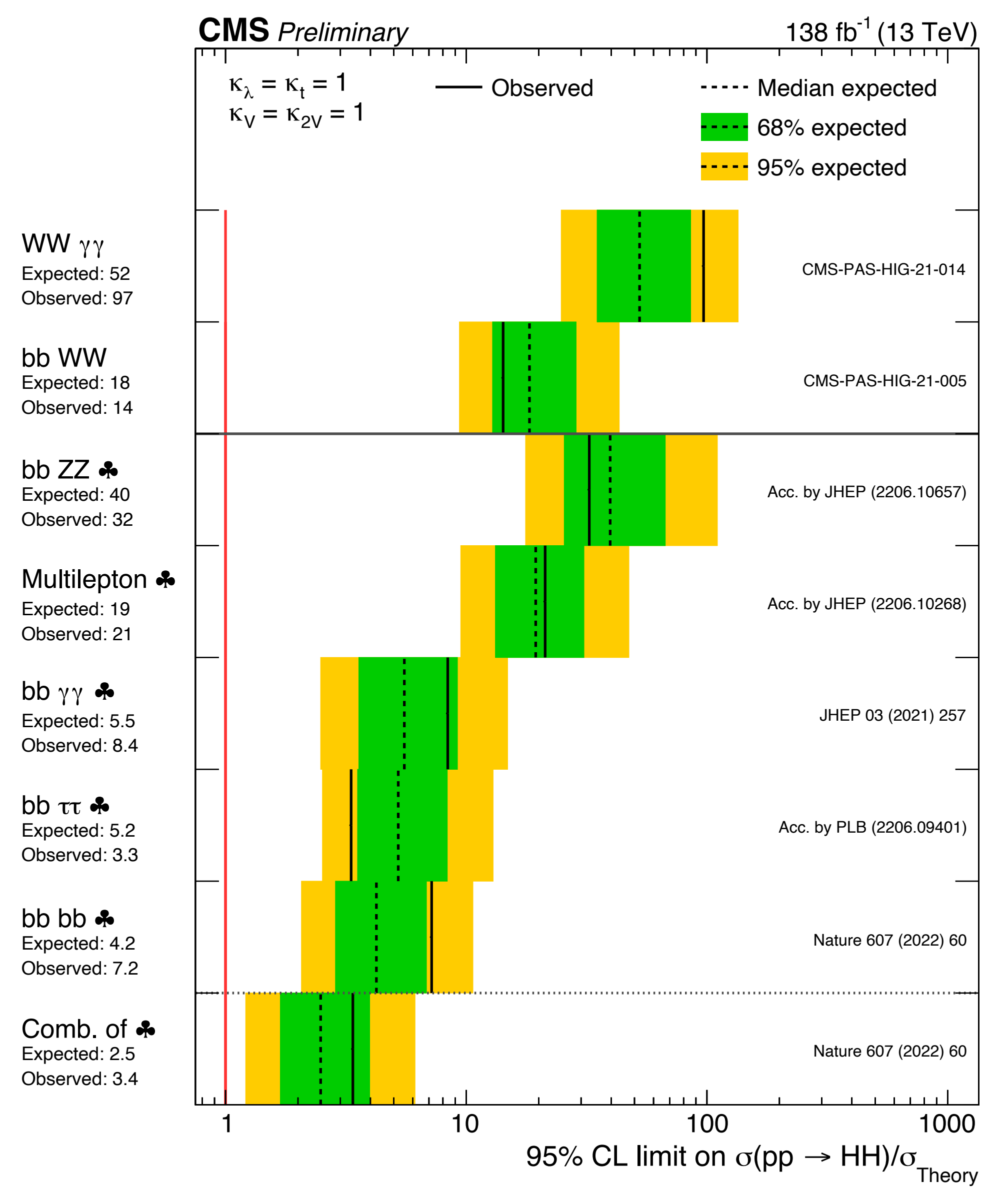
HH Combination

Non-resonant

- Combination of the most sensitive HH channels

Phys. Lett. B 843 (2023) 137745



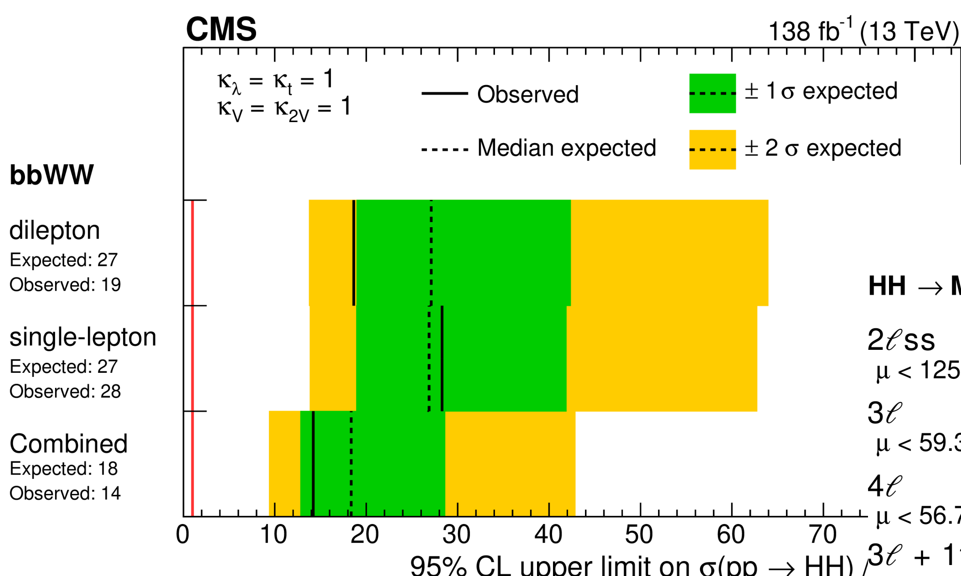


Nature 607, 60–68 (2022)

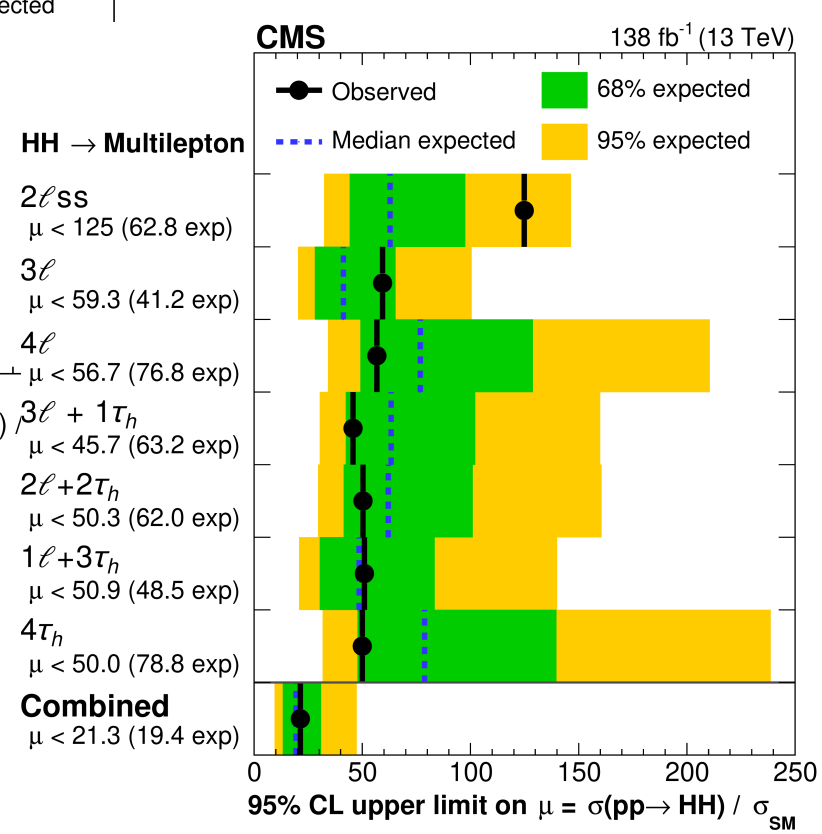
HH with leptons

bb+leptons and multileptons

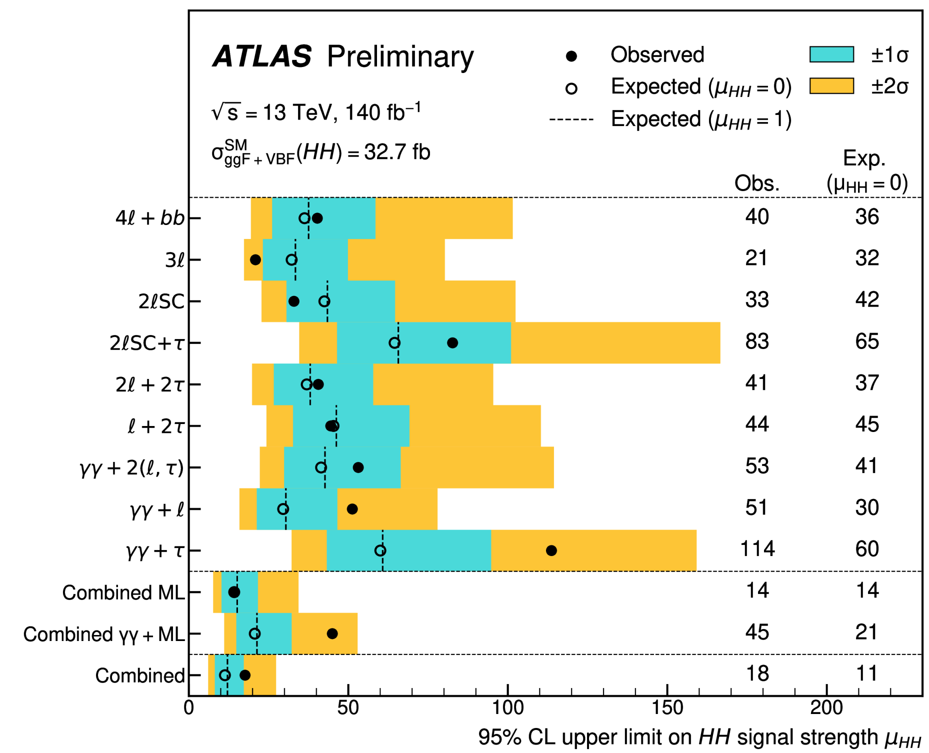
- Novel channels that add additional sensitivity
- Individual sub-channels can be insensitive, but statistical combinations are much stronger



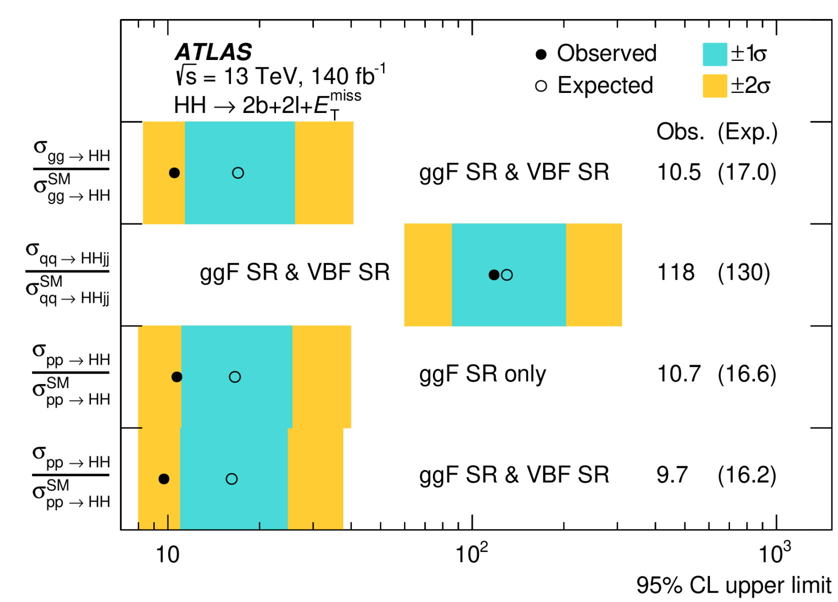
Submitted to JHEP



JHEP 07 (2023) 095



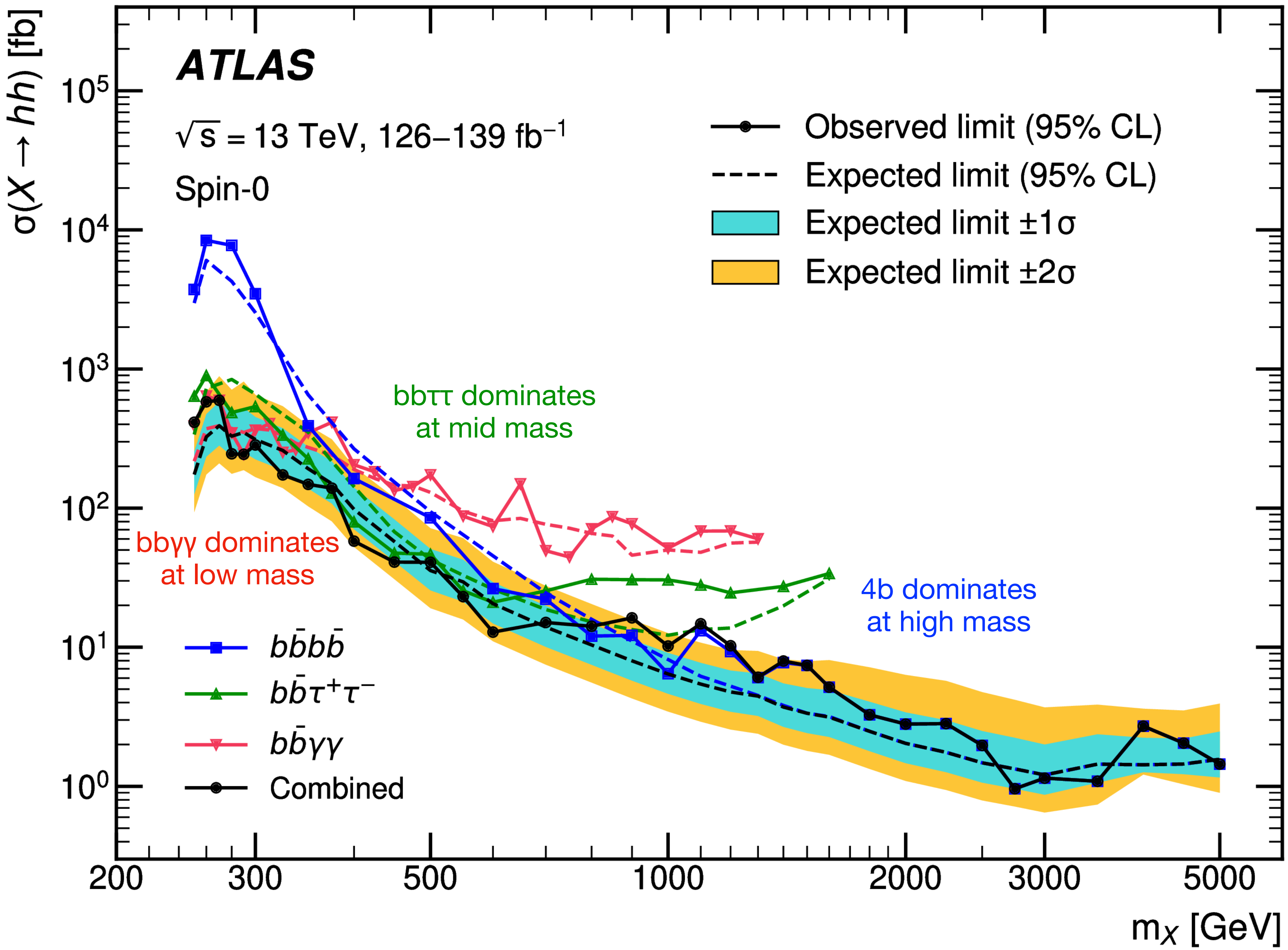
ATLAS-CONF-2024-005



JHEP 02 (2024) 037

HH Combination

Resonant limits

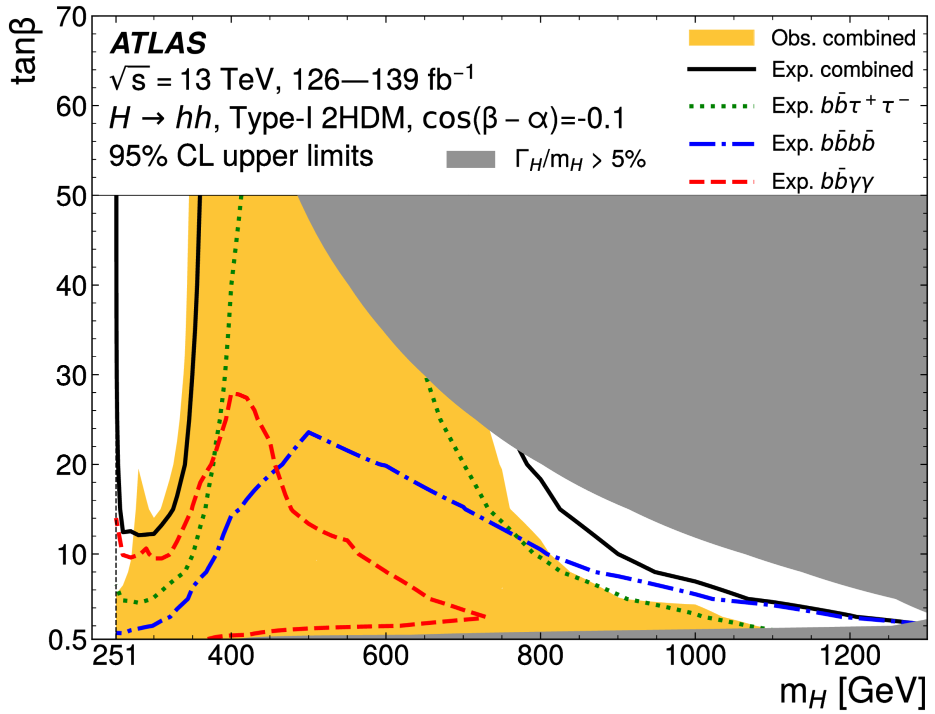


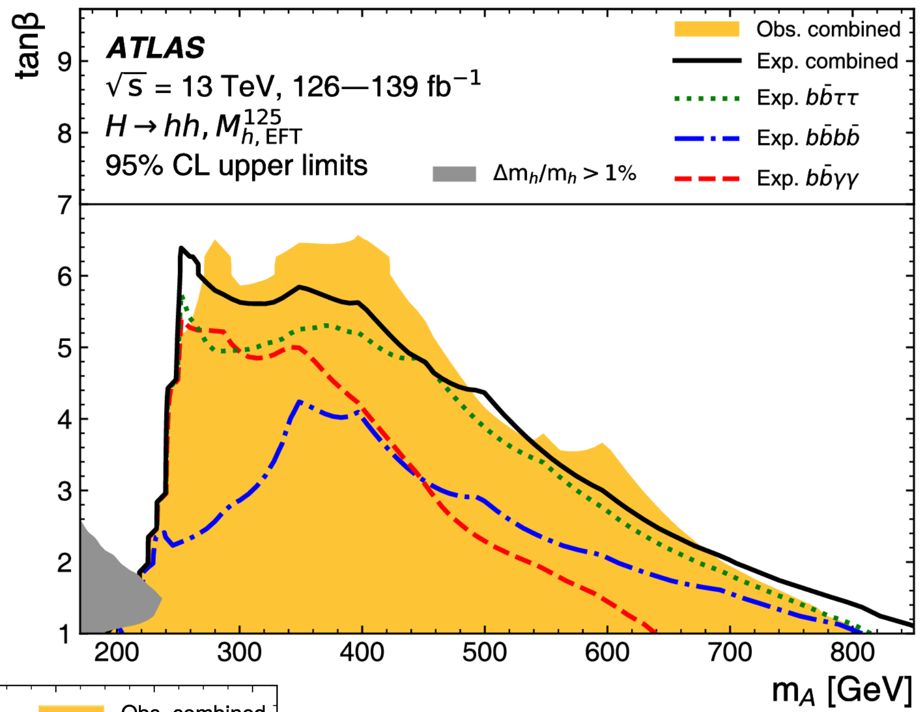
Accepted by PRL

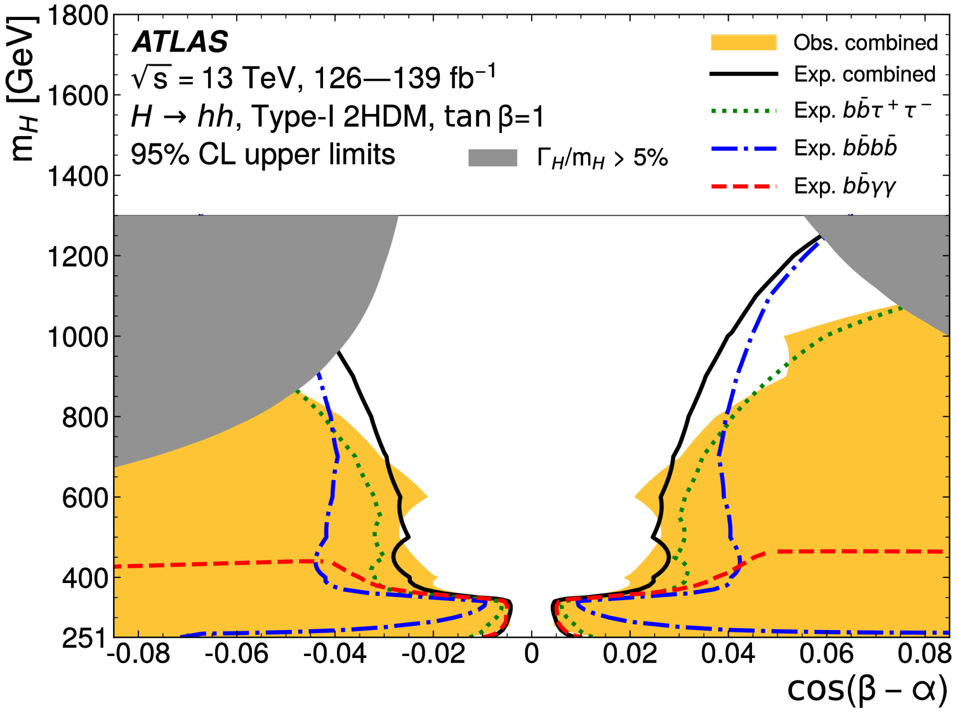
HH Combination

2HDM and MSSM Interpretations

- Limits set on Type-I 2HDM and MSSM







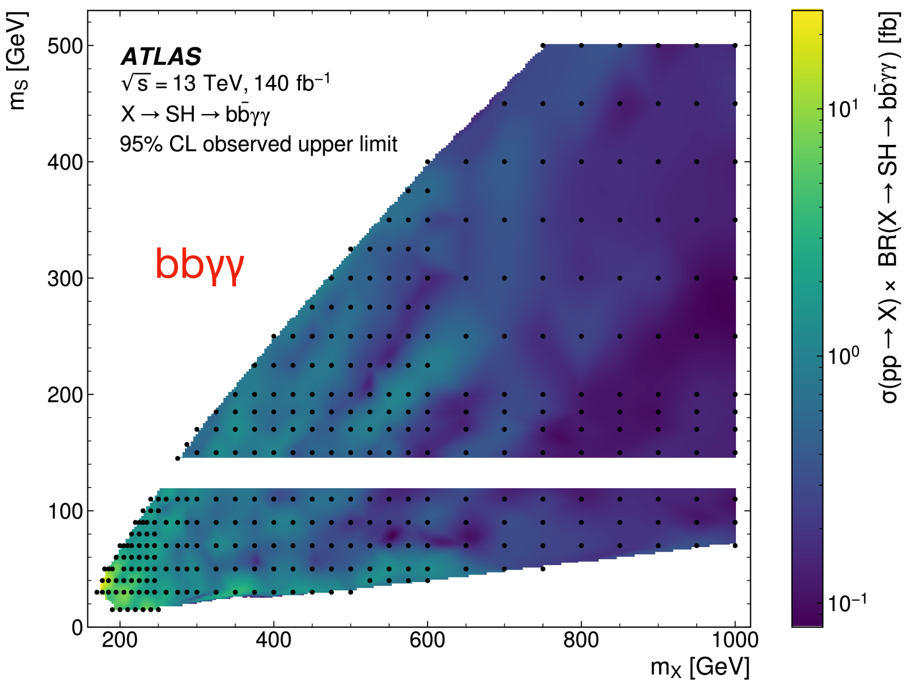
Accepted by PRL

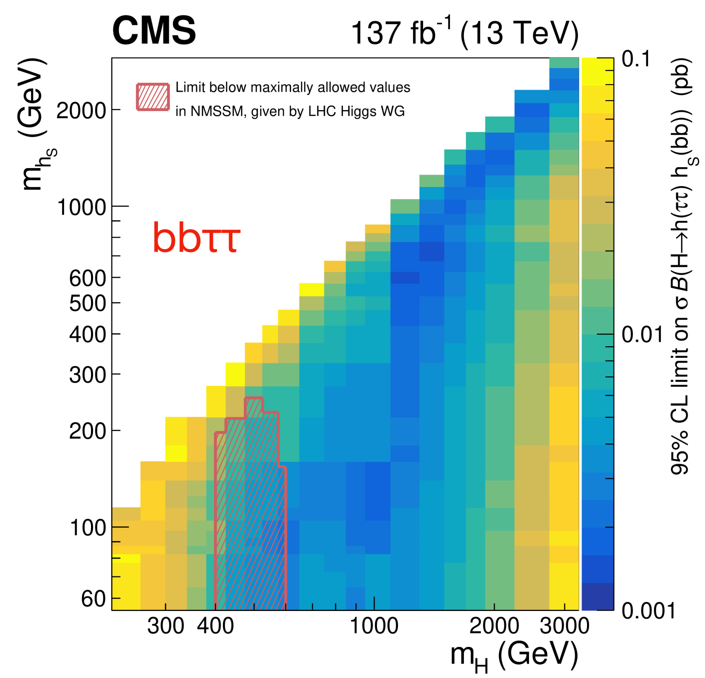
SH results

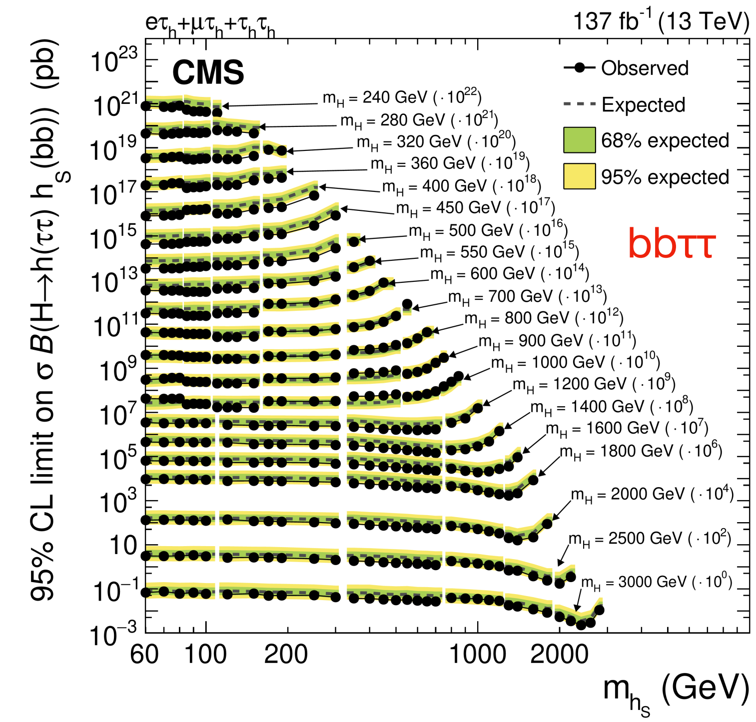
SH Limits

2D limits

Sumitted to JHEP

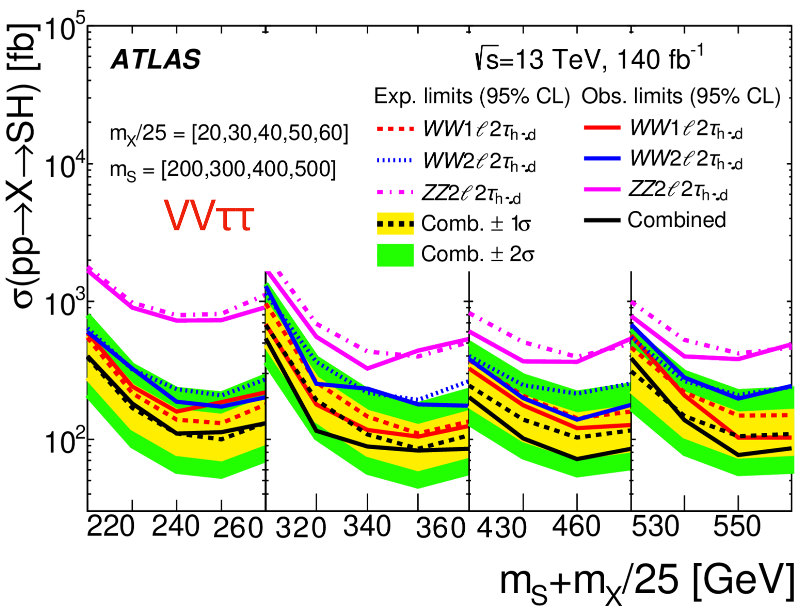


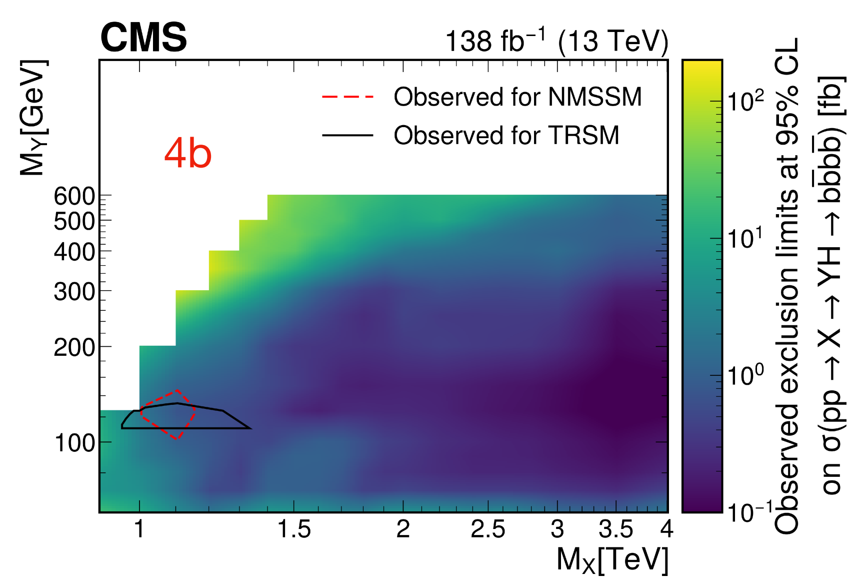




JHEP 11 (2021) 057

JHEP 10 (2023) 009



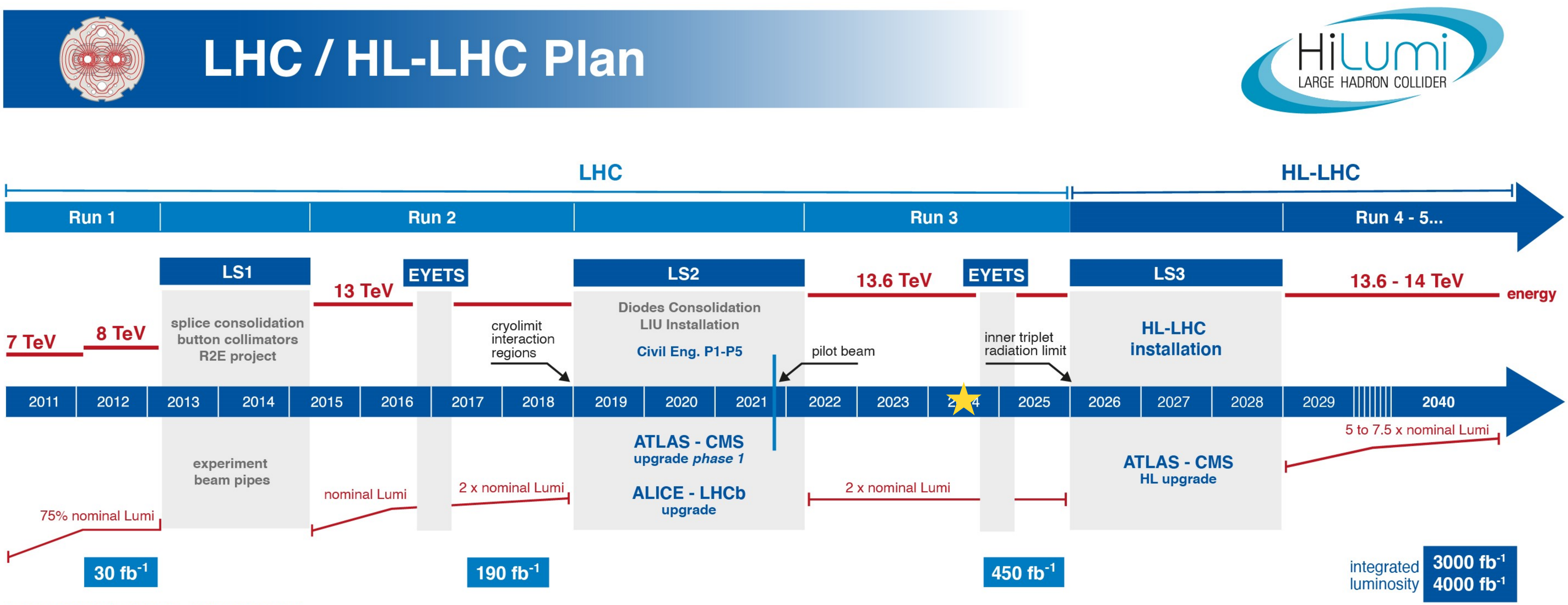


Phys. Lett. B 842 (2023) 137392

Projections

HL-LHC

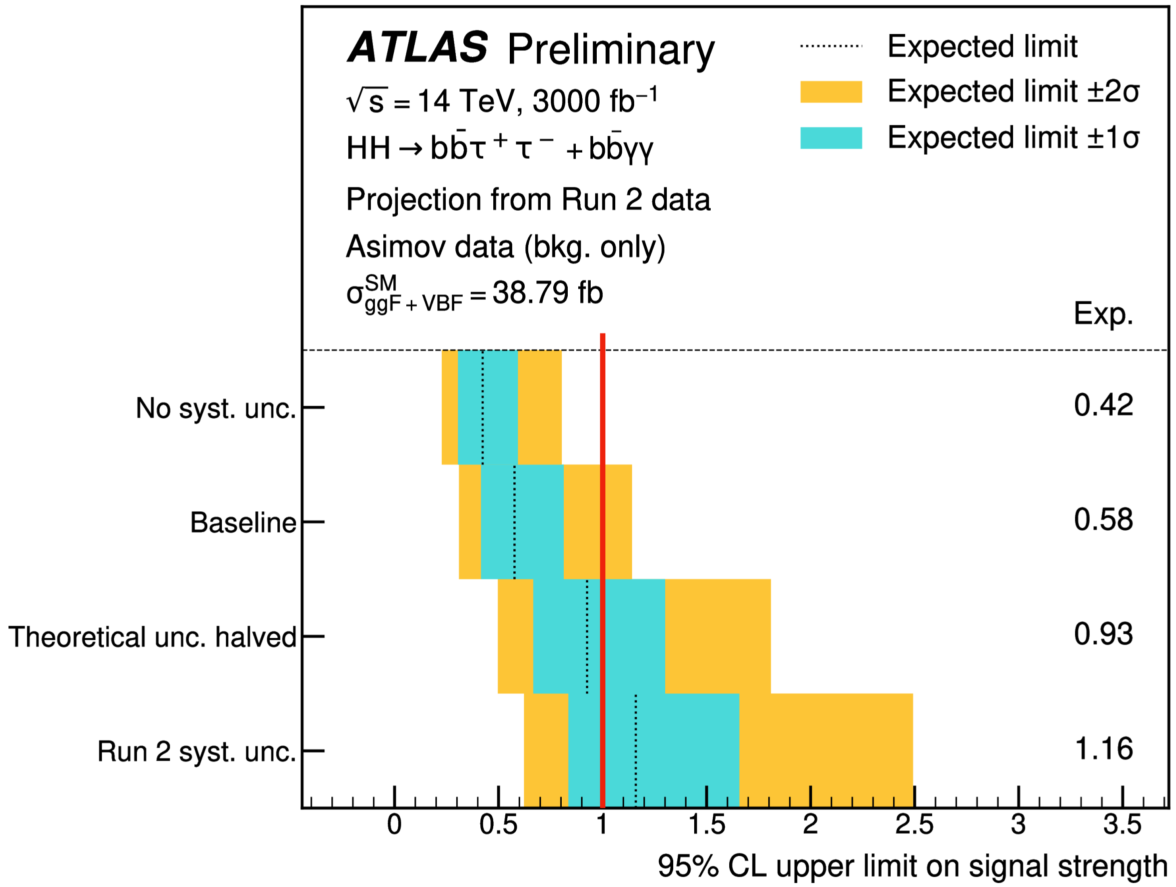
- The High-Luminosity LHC (HL-LHC) will provide $\mathcal{O}$(10x) more collision data
- The increase in data will provide unprecedented physics sensitivity

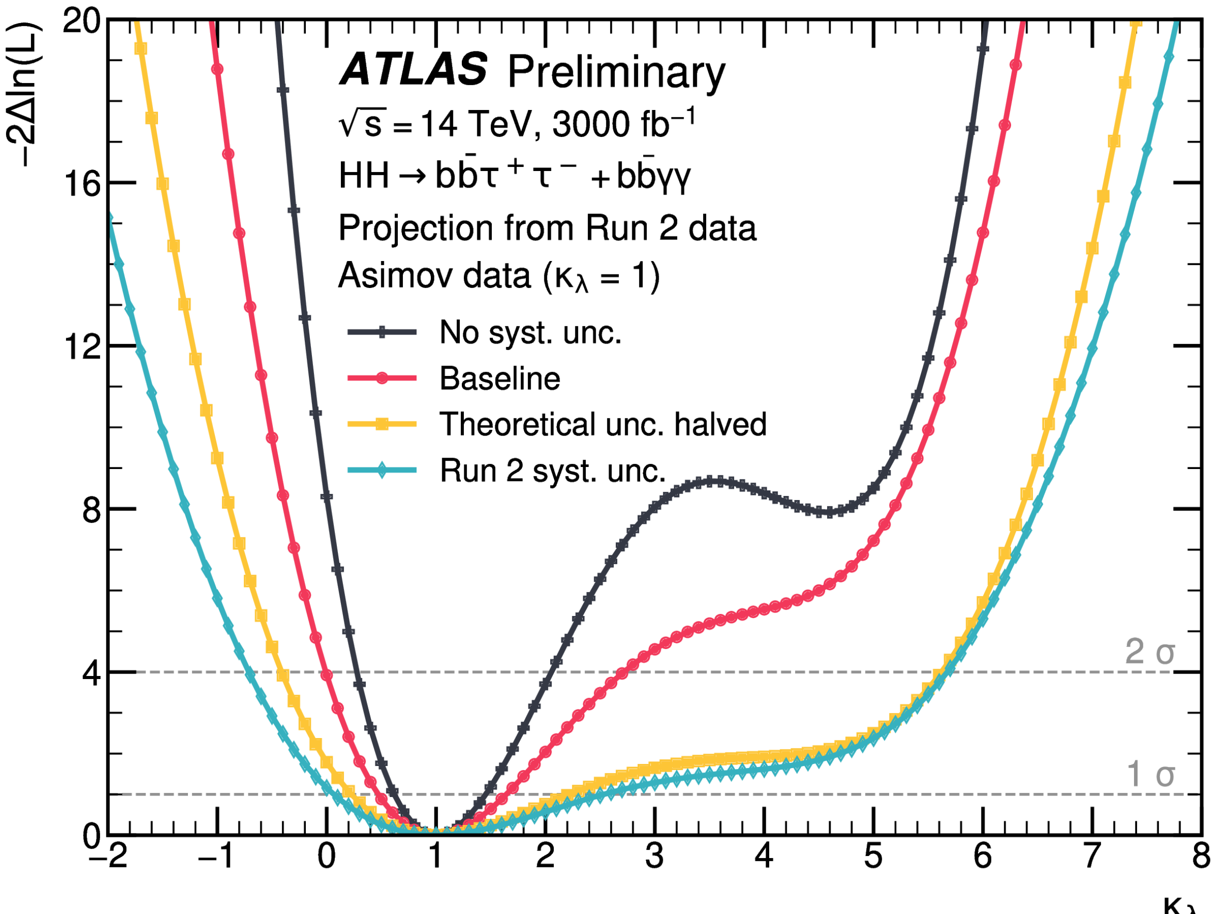


HL-LHC Projections

How well will we do?

- Measuring λ is one of the main physics goals of the HL-LHC
- Use current results to estimate sensitivity using full HL-LHC dataset
  - Scale luminosity and use various assumptions about systematic uncertainties





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HL-LHC Projections

A word of cautious optimism

- Past projections have been shown to be overly pessimistic:

2015 projections for bbττ at the HL-LHC

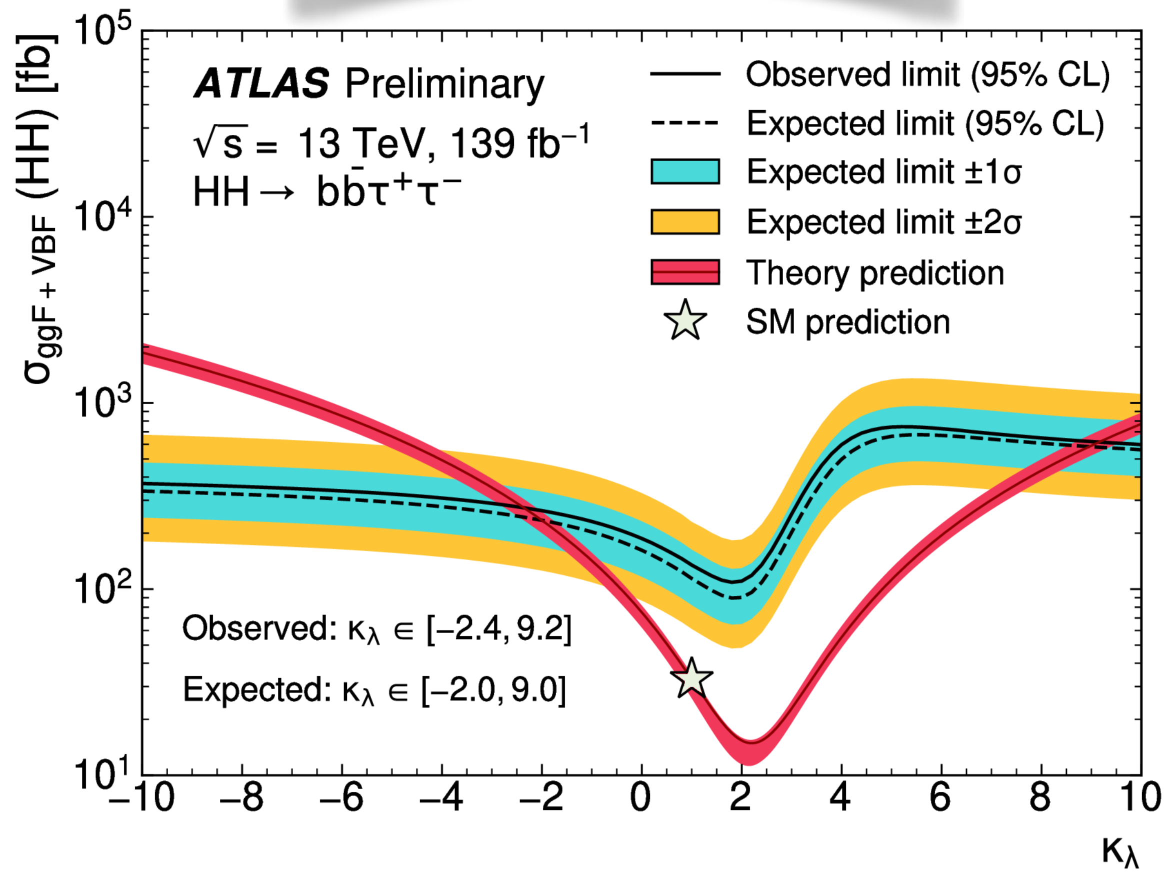
"we can also set an upper limit of **4.3** × σ(HH → bbττ) at 95% Confidence Level on the signal cross section"

"...we can project an exclusion at 95% Confidence Level of BSM HH production with $\lambda_{HHH}/\lambda_{SM} \leq$ **−4** and $\lambda_{HHH}/\lambda_{SM} \geq$ **12**"

ATL-PHYS-PUB-2015-046

bbττ results 6 years later with 5% of the HL-LHC dataset

μ_{SM} < 4.7 observed (3.9 expected)



- It is difficult to predict future innovations in analysis techniques

ATLAS-CONF-2021-052/

Concluding Remarks

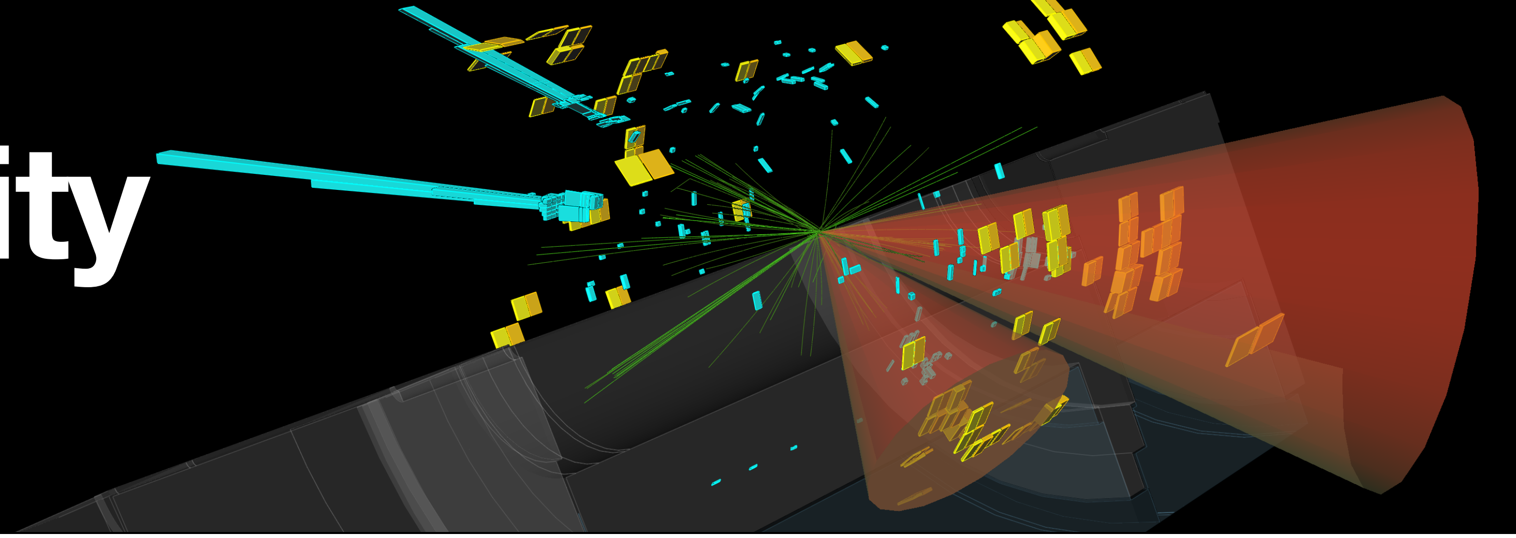
- Non-resonant HH production sensitivity approaching SM level
- Resonant HH and SH production are handles for BSM searches
  - Phase space coverage has significantly improved in the past year
- No single “golden channel” - parallel searches and combination are necessary
- More results expected as Run II analyses wrap up and Run III analyses begin

Thank you for your attention

Backup Slides

Theory details

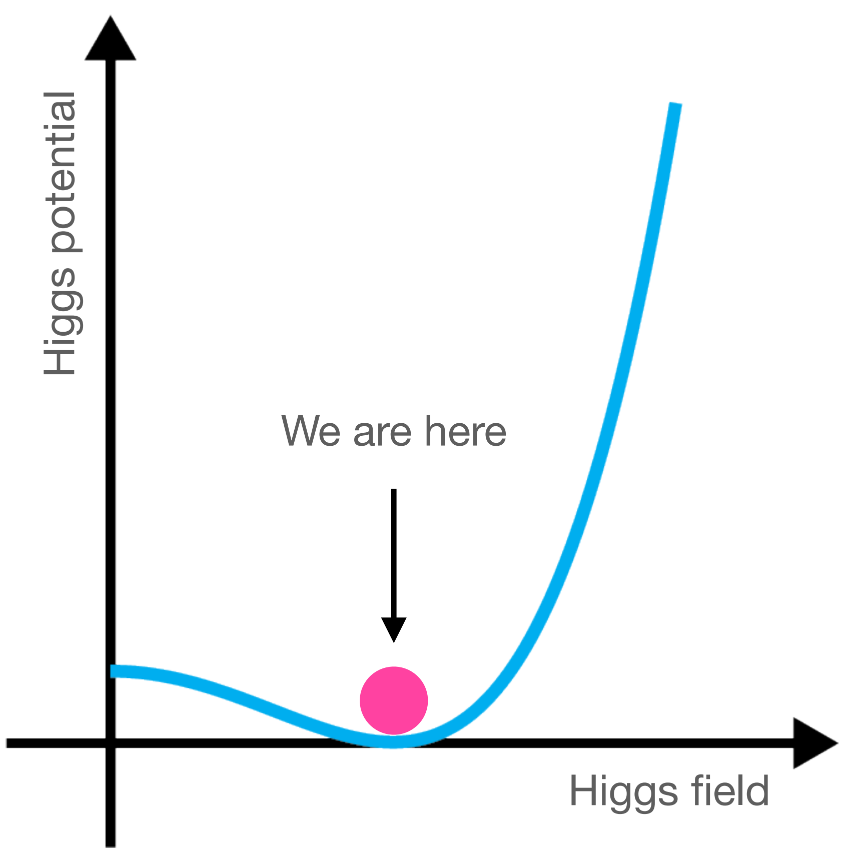
Vacuum Stability



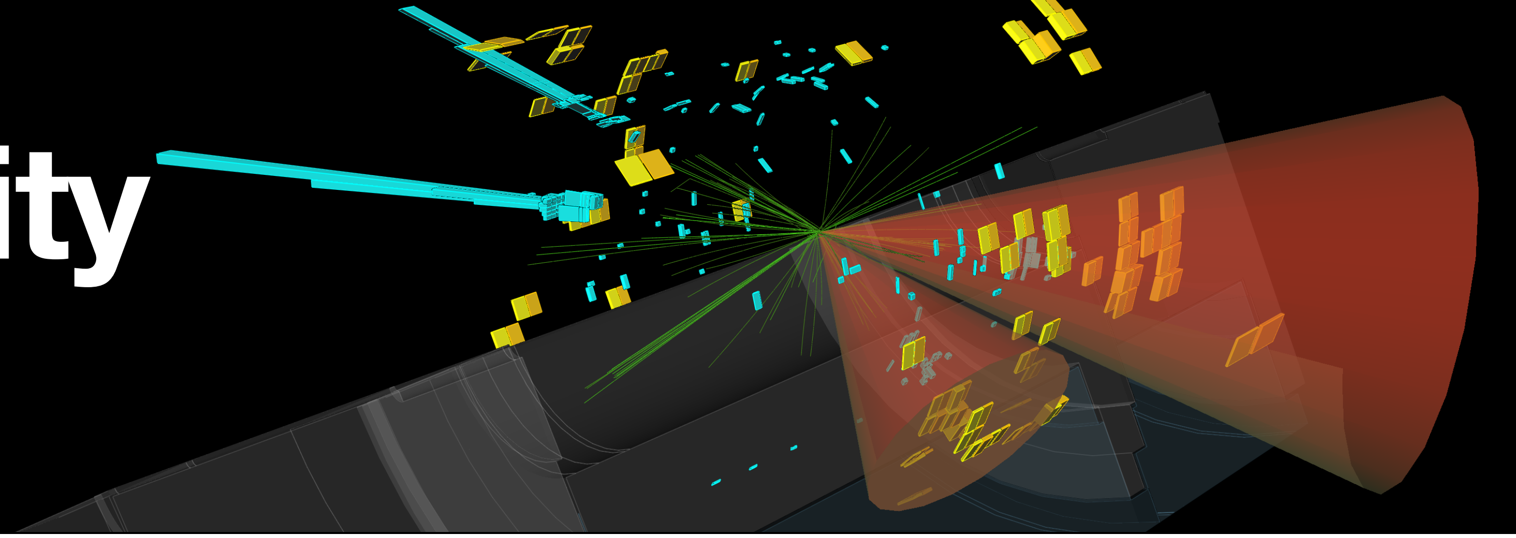
Stable universe

The current state is the absolute minimum

The Higgs field will remain in this state forever



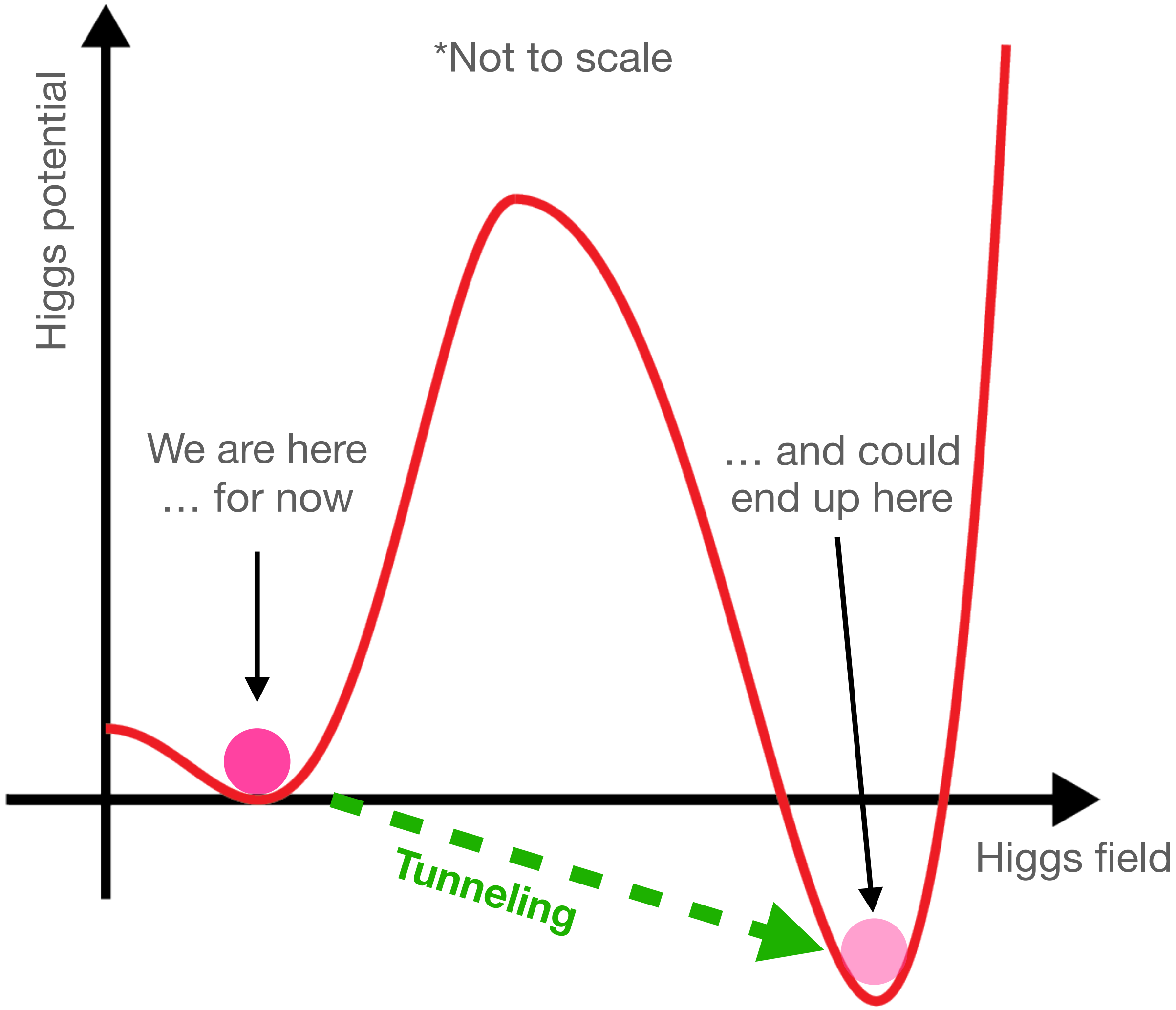
Vacuum Stability



Metastable universe

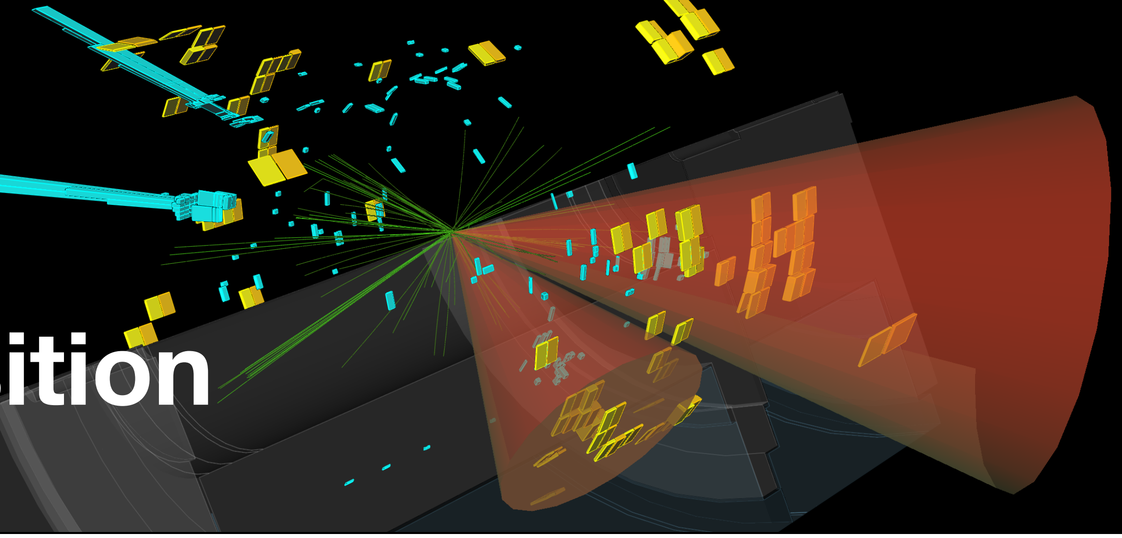
The current state is a local minimum

The vaccuum will eventually decay to a different minimum
(lifetime is longer than the age of the universe)



The Early Universe

The Electroweak Phase Transition



- Baryogenesis requires a first order electroweak phase transition
  - This in turn requires new physics that interacts with the Higgs boson
  - Can lead to an $\mathcal{O}(1)$ modification to the Higgs self-coupling Noble, Perelstein
- Some inflation models require that the Higgs sector couples to gravity
  - This would modify the shape of the Higgs potential Bezrukov, Shaposhnikov

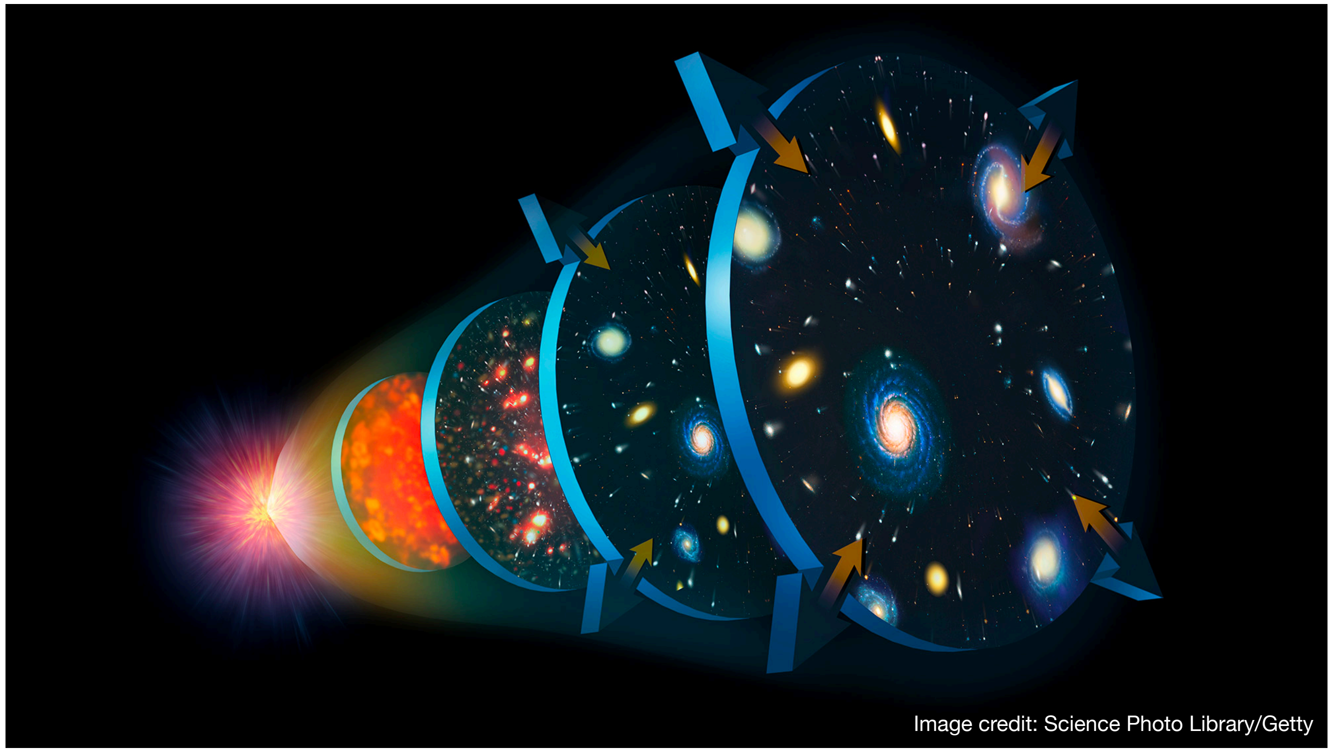
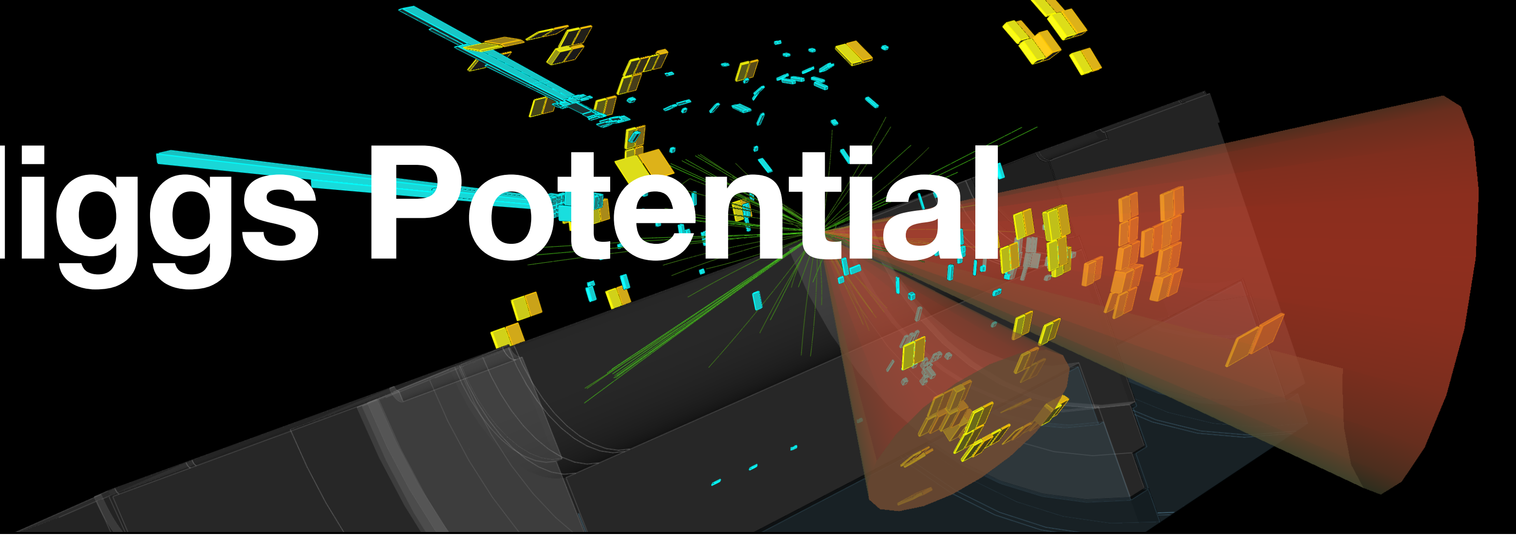
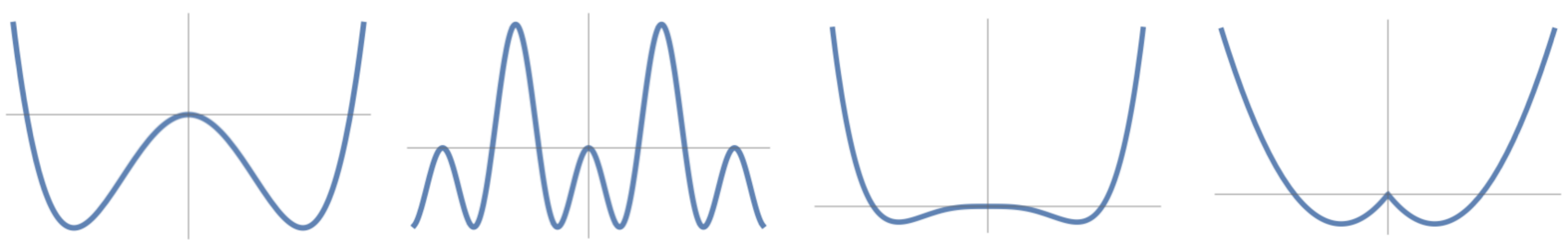


Image credit: Science Photo Library/Getty



Shape of the Higgs Potential

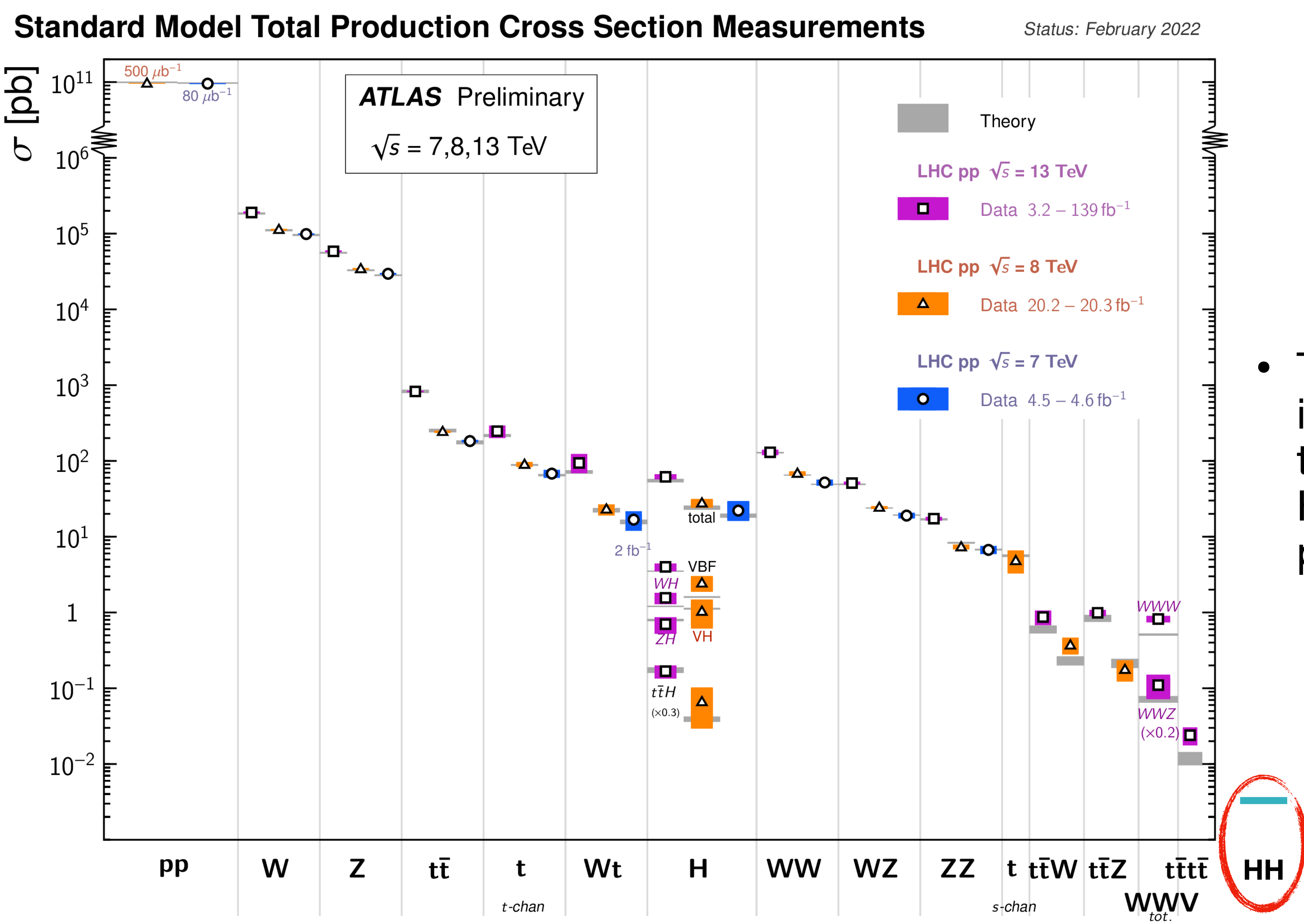
- Otherwise, is the SM Higgs potential correct?
- Numerous BSM models propose alternative Higgs potentials



Landau-Ginzburg Higgs **Nambu-Goldstone Higgs** **Coleman-Weinberg Higgs** **Tadpole-Induced Higgs**

Phys. Rev. D 101, 075023 (2020)

The HH Cross-Section



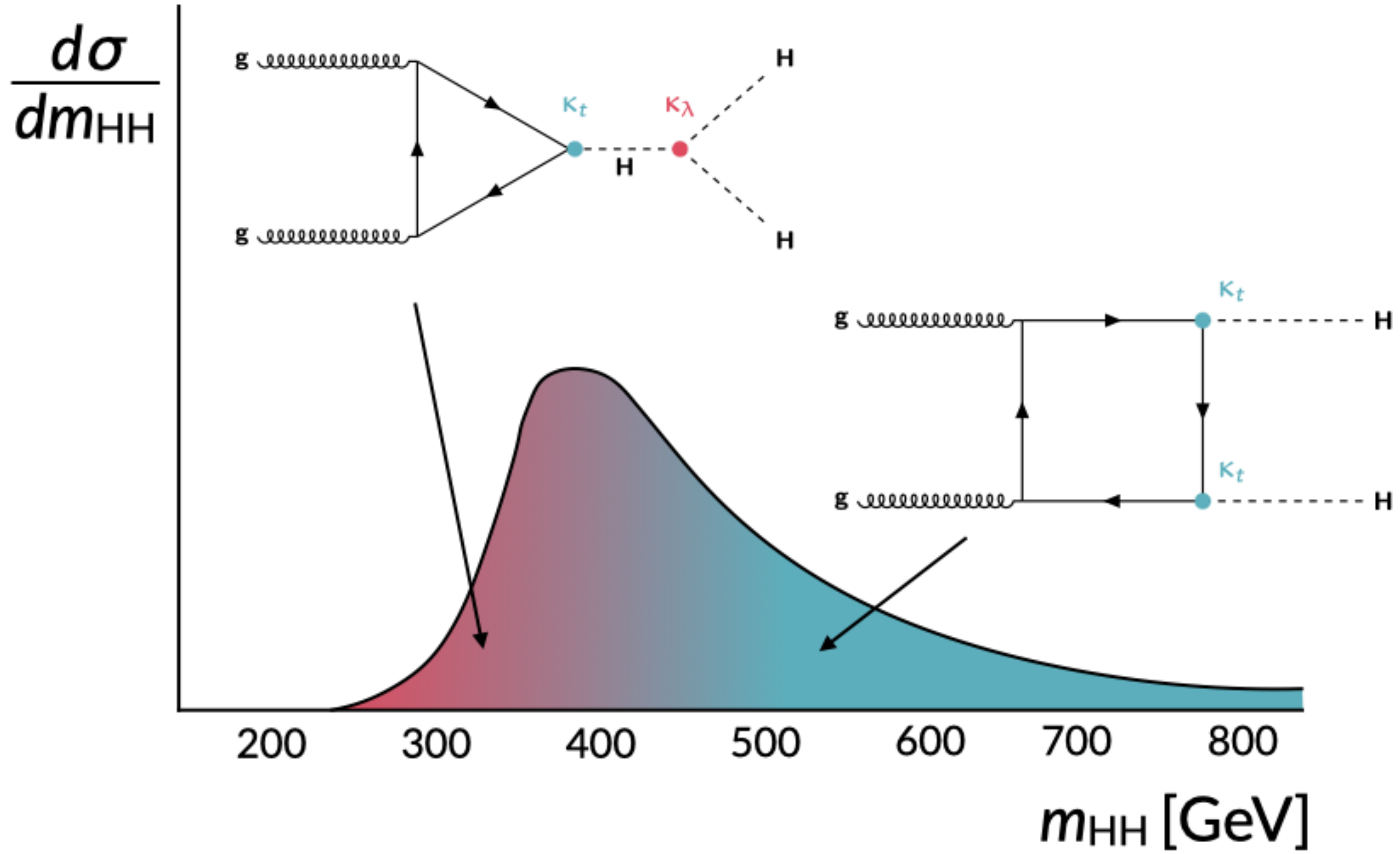
- The HH cross-section is ~1000 times smaller than that of single Higgs boson production

ATL-PHYS-PUB-2022-009

Non-resonant HH Production

HH invariant mass distribution

- The two ggF diagrams contribute to different kinematic regions
- Modifications to κ_λ would modify the cross-section and the m_{HH} distribution



Non-resonant HH Production

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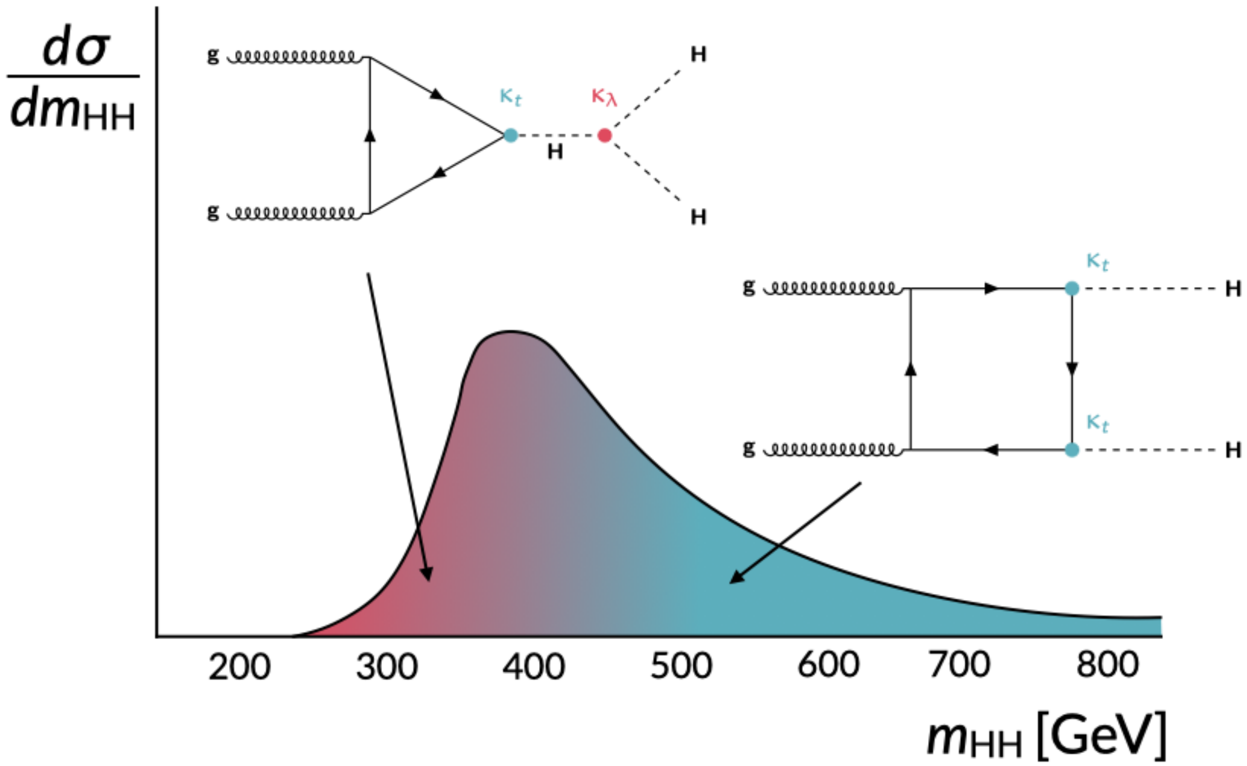
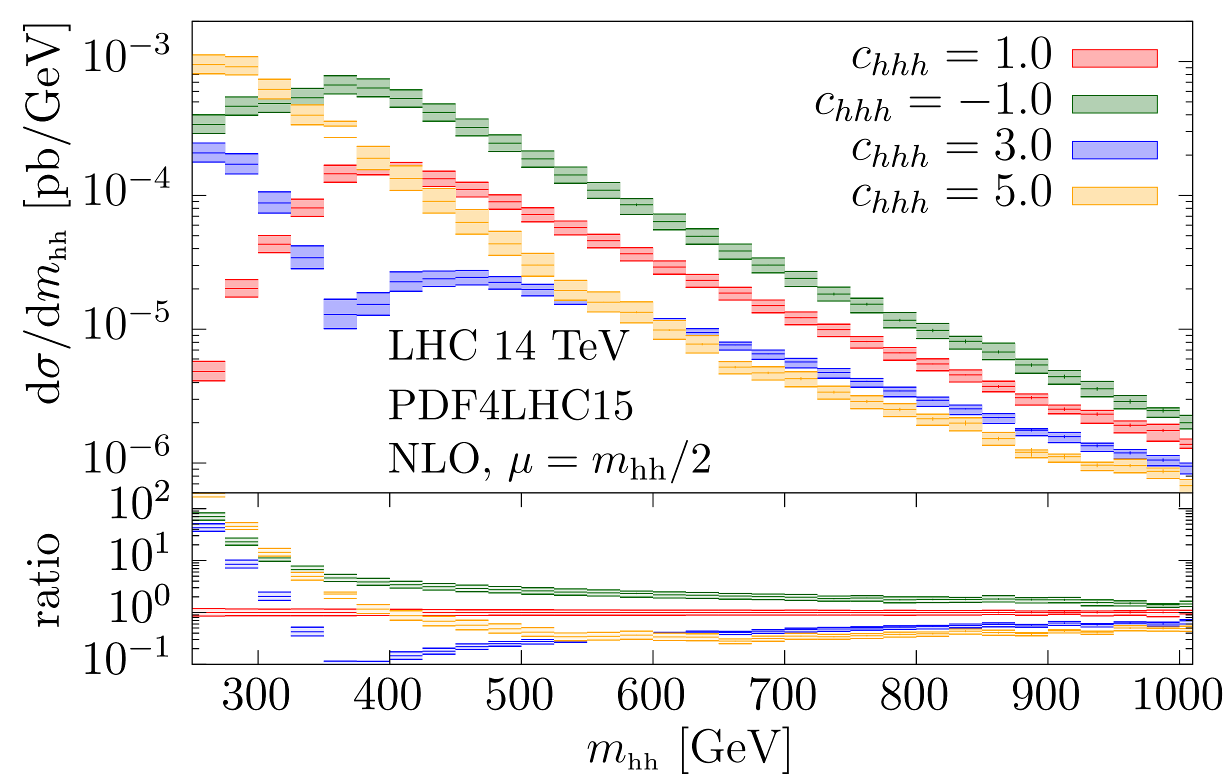


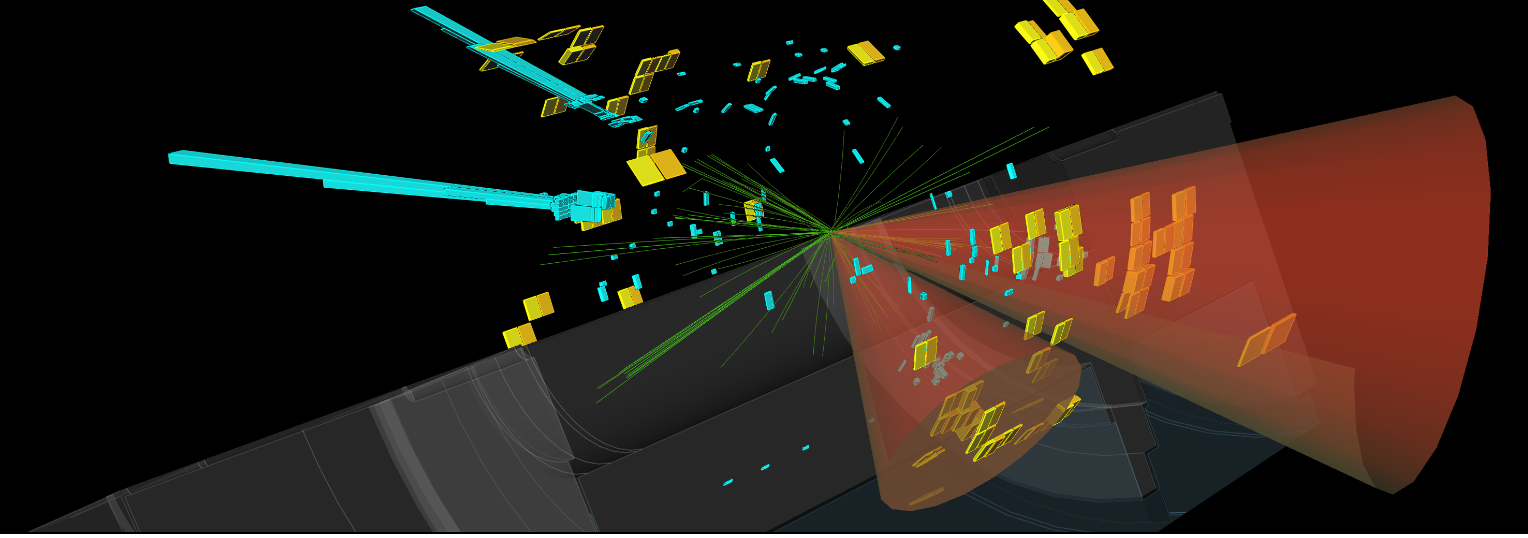


arXiv:1910.00012

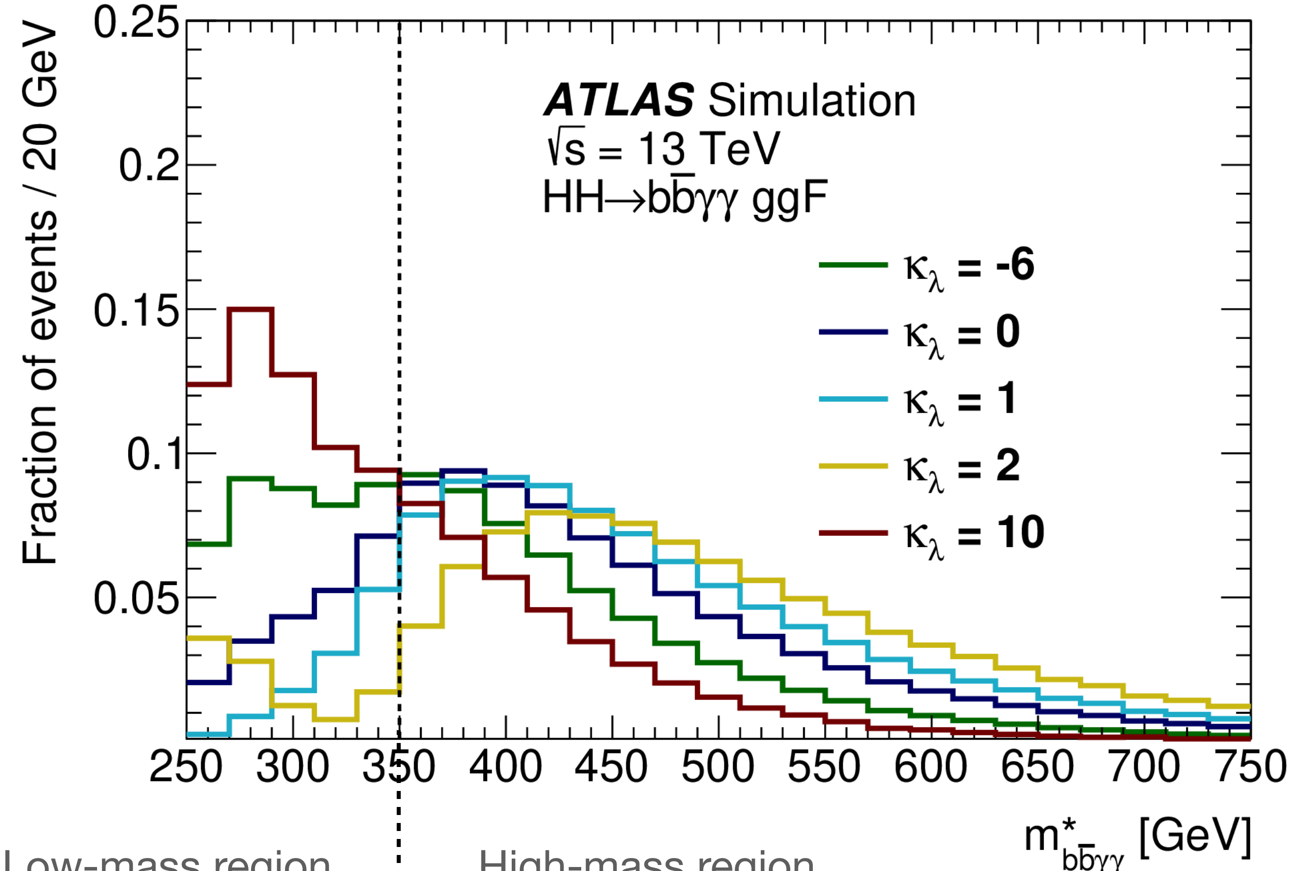
Experimental details

bbγγ

Analysis regions



- Split analysis into categories to maximize sensitivity
- ATLAS uses low- and high-mass regions to target SM and BSM couplings
- CMS uses categories targeting ggF and VBF HH production

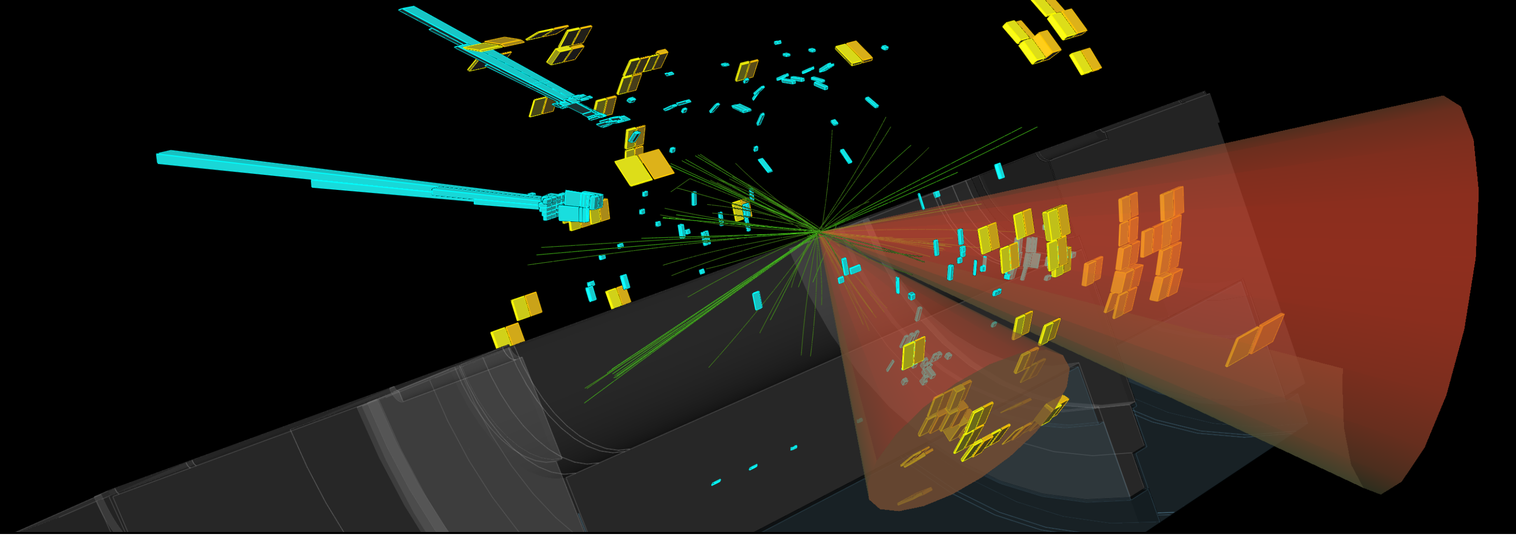


Low-mass region sensitive to large κλ

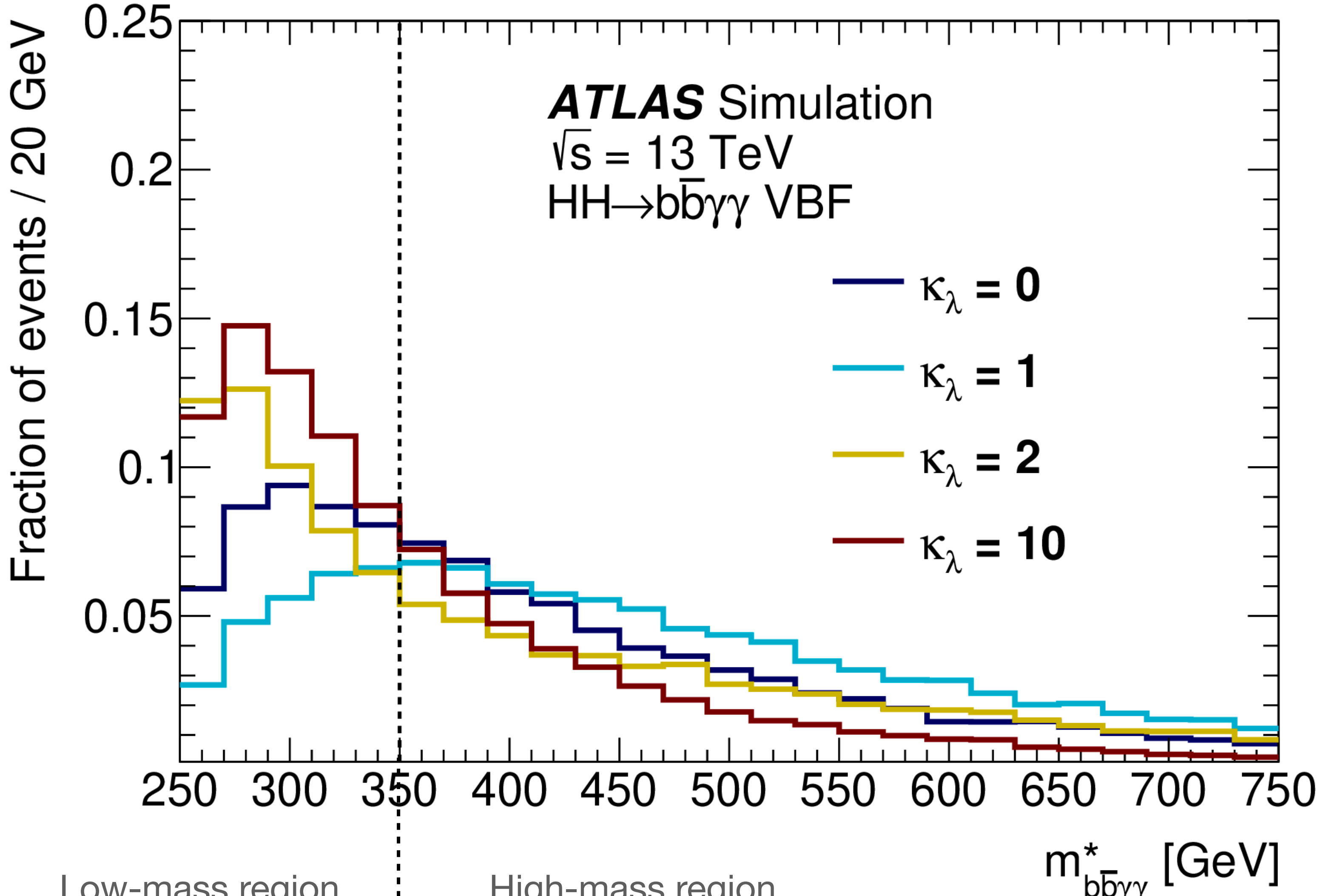
High-mass region sensitive to SM

Phys. Rev. D 106 (2022) 052001

bbγγ
VBF analysis regions



- Split analysis into low- and high-mass regions to target SM and BSM couplings

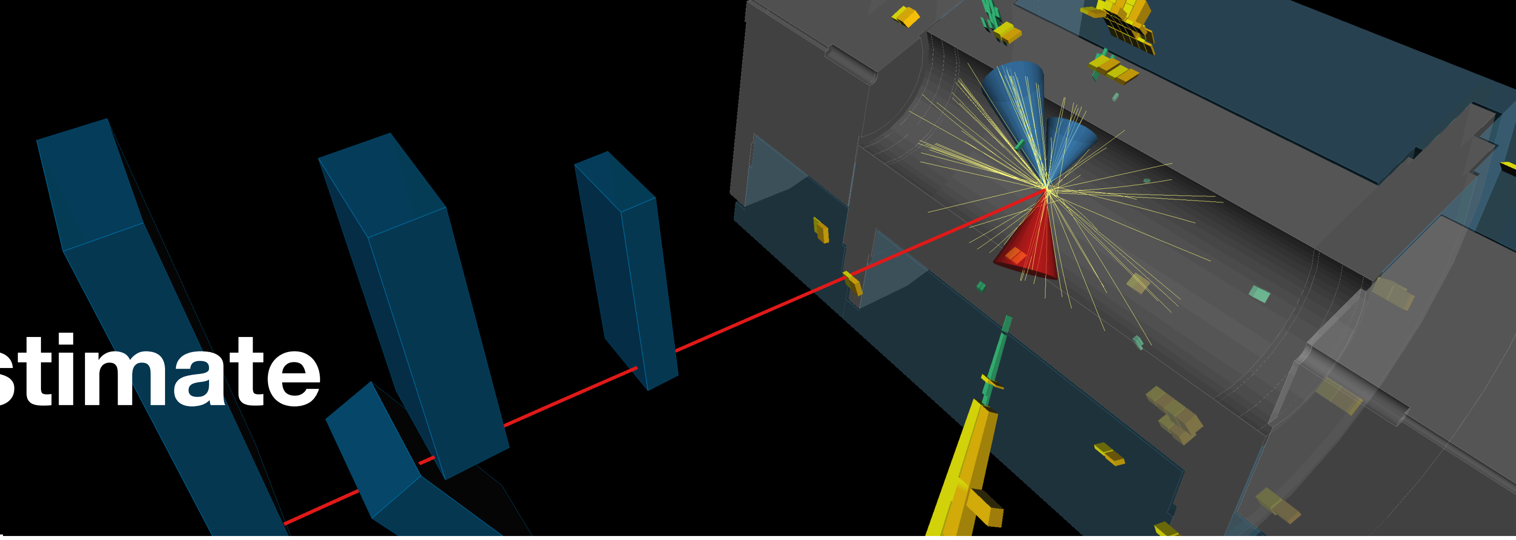


Low-mass region sensitive to large κ_λ

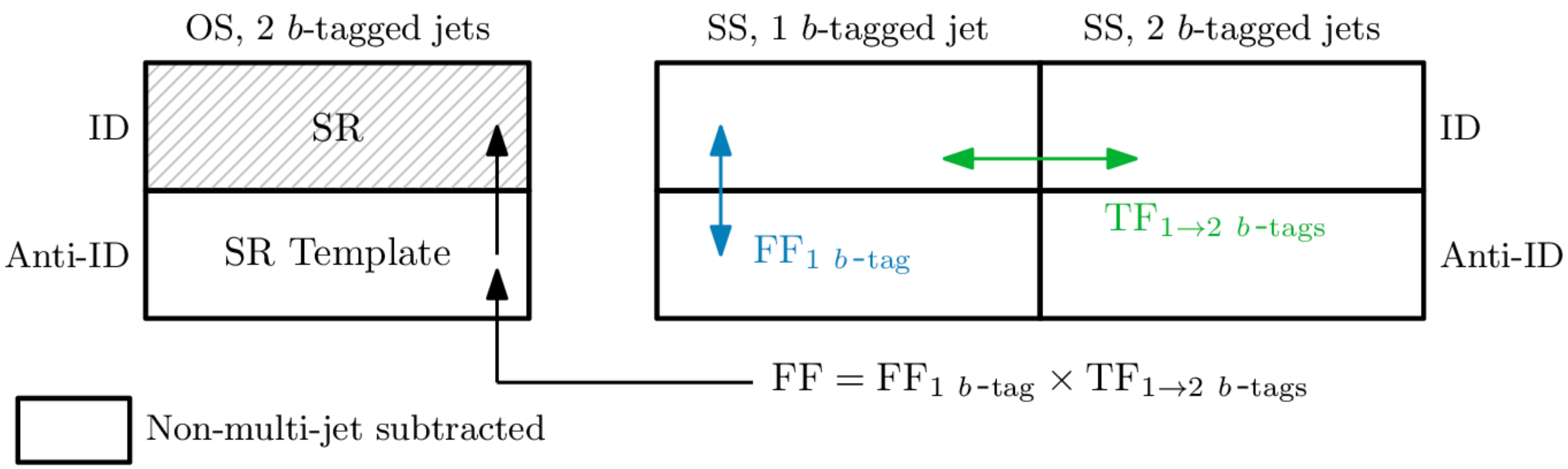
High-mass region sensitive to SM

Phys. Rev. D 106 (2022) 052001

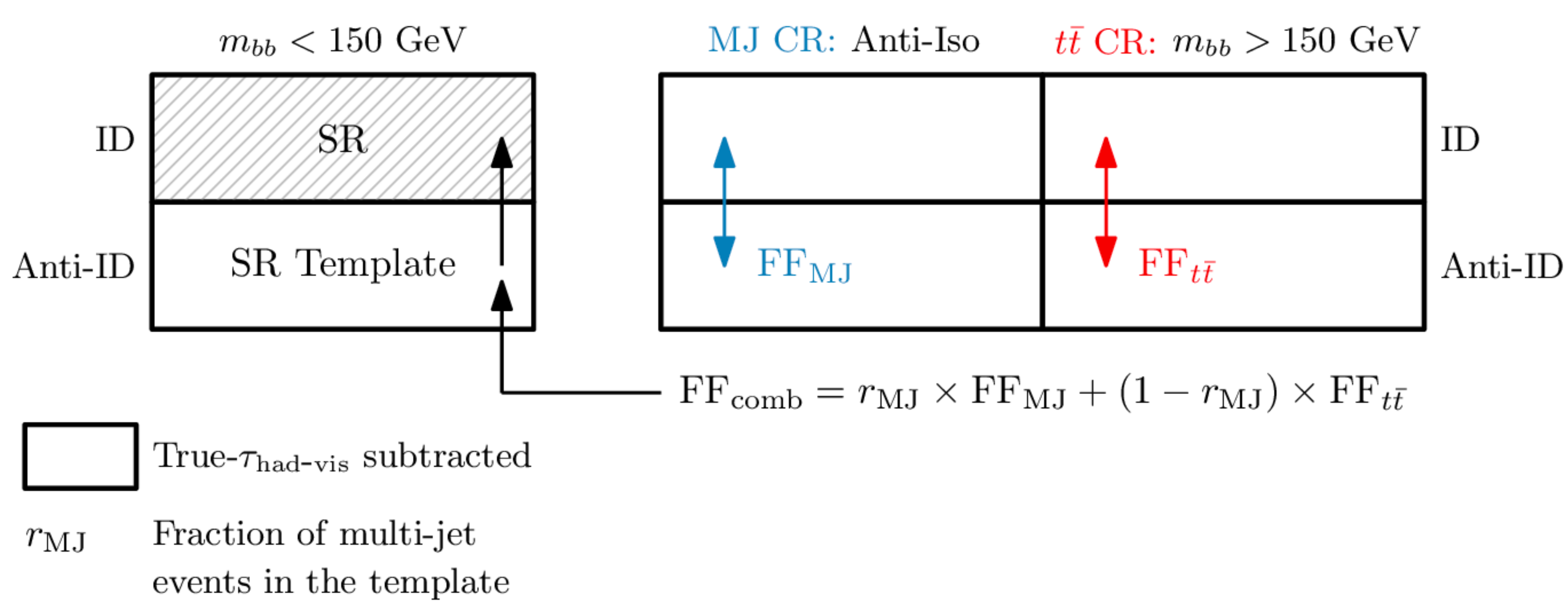
bbττ
Fake-τ background estimate



$\tau_{\rm had}\tau_{\rm had}$ channel

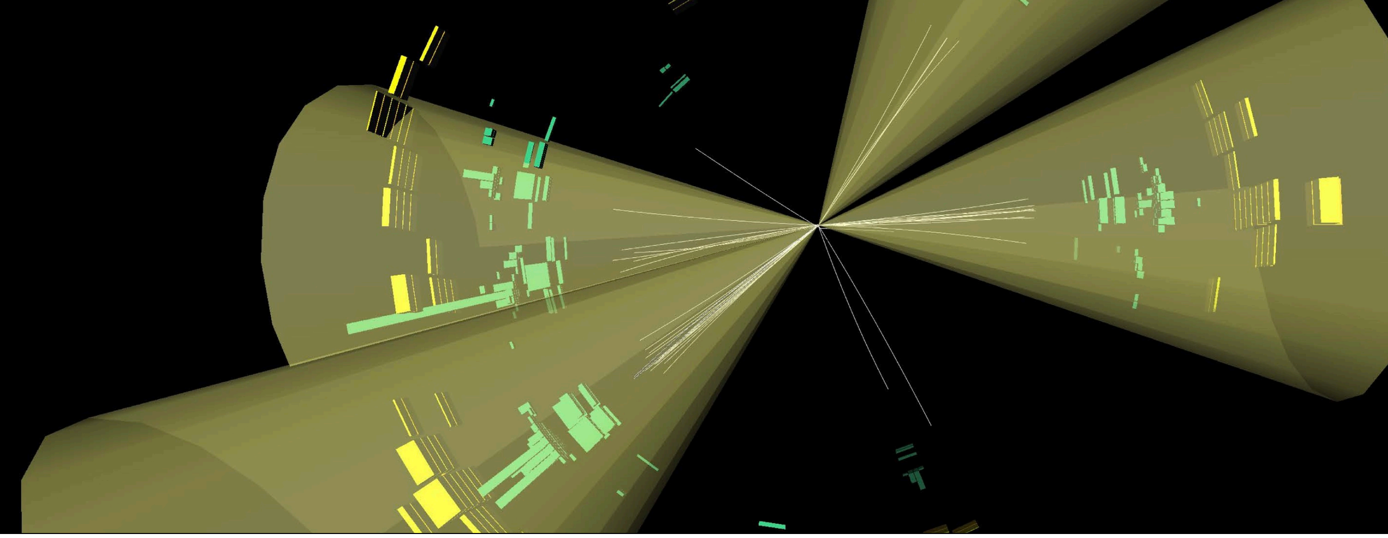


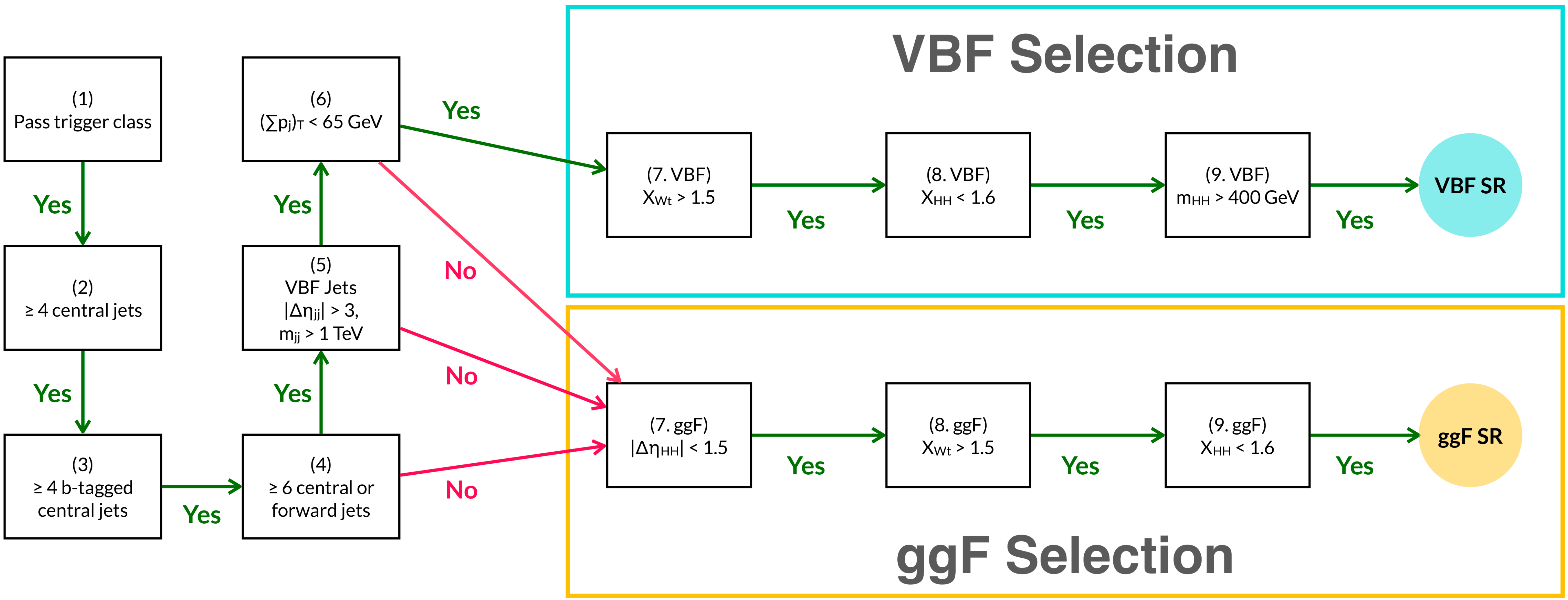
$\tau_{\rm lep}\tau_{\rm had}$ channel



JHEP 07 (2023) 040

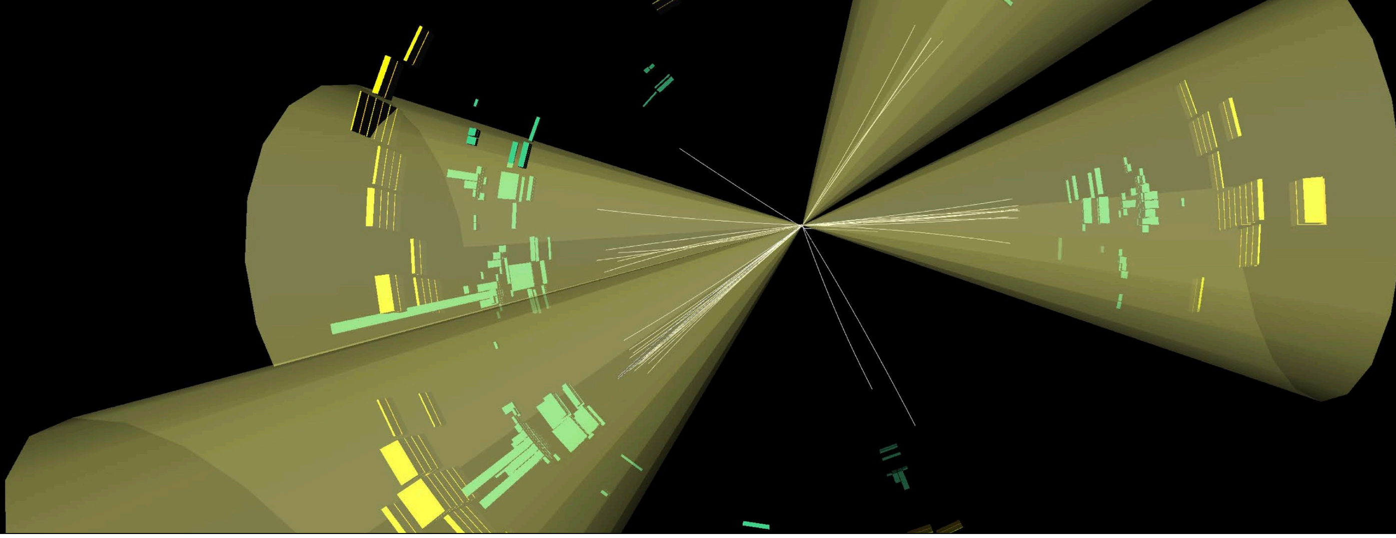
4b
ggF and VBF categories





4b

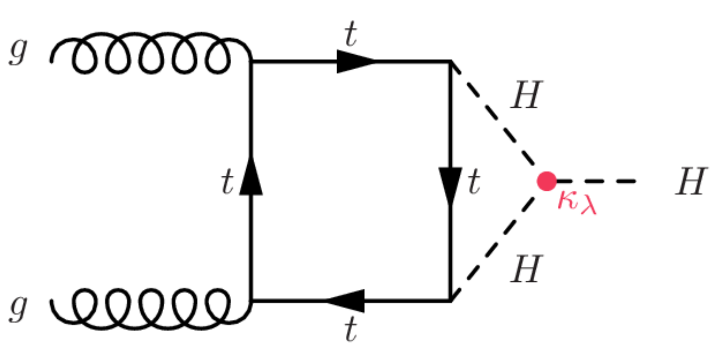
X_{Wt} and X_{HH}

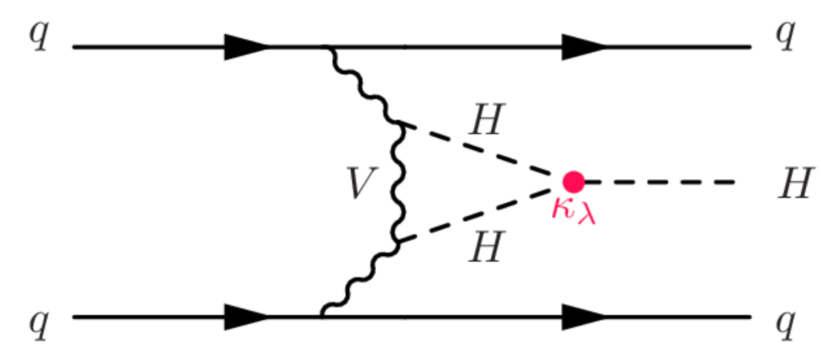


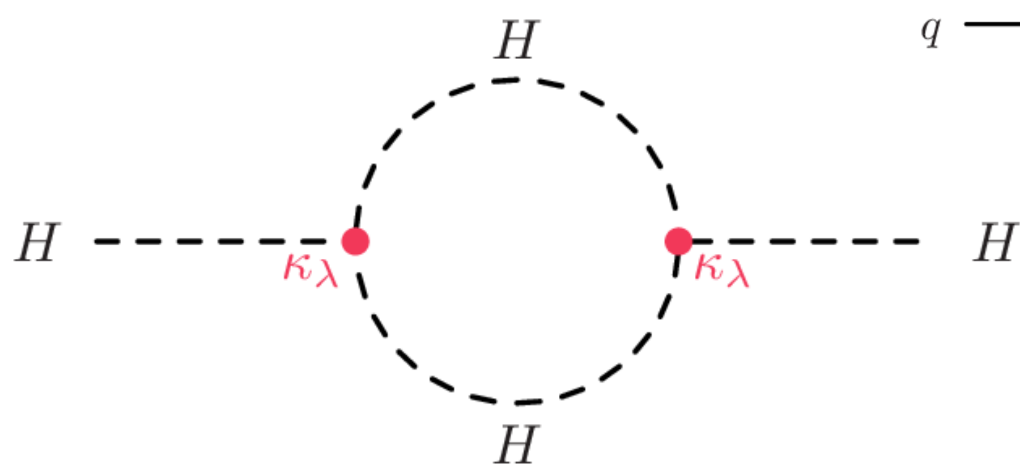
$$X_{Wt} = \sqrt{\left(\frac{m_W - 80.4\,\mathrm{GeV}}{0.1\, m_W}\right)^2 + \left(\frac{m_t - 172.5\,\mathrm{GeV}}{0.1\, m_t}\right)^2}$$

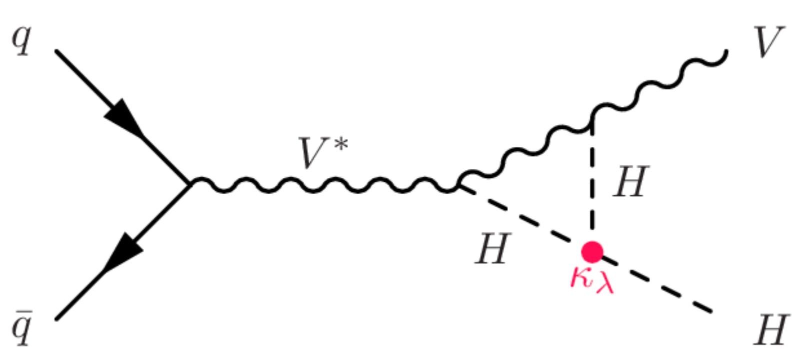
$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\,\mathrm{GeV}}{0.1\, m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\,\mathrm{GeV}}{0.1\, m_{H2}}\right)^2}$$

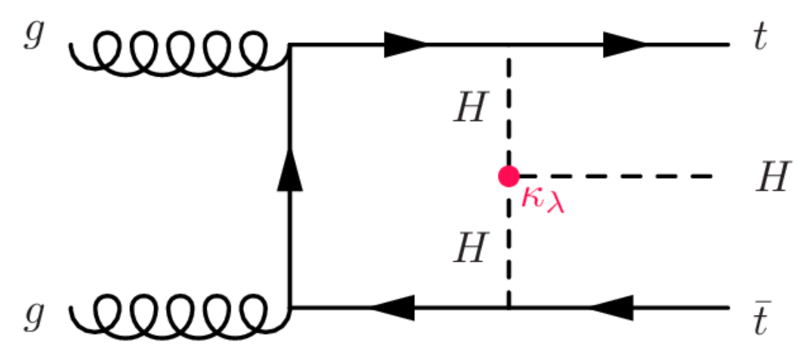
Single Higgs Corrections









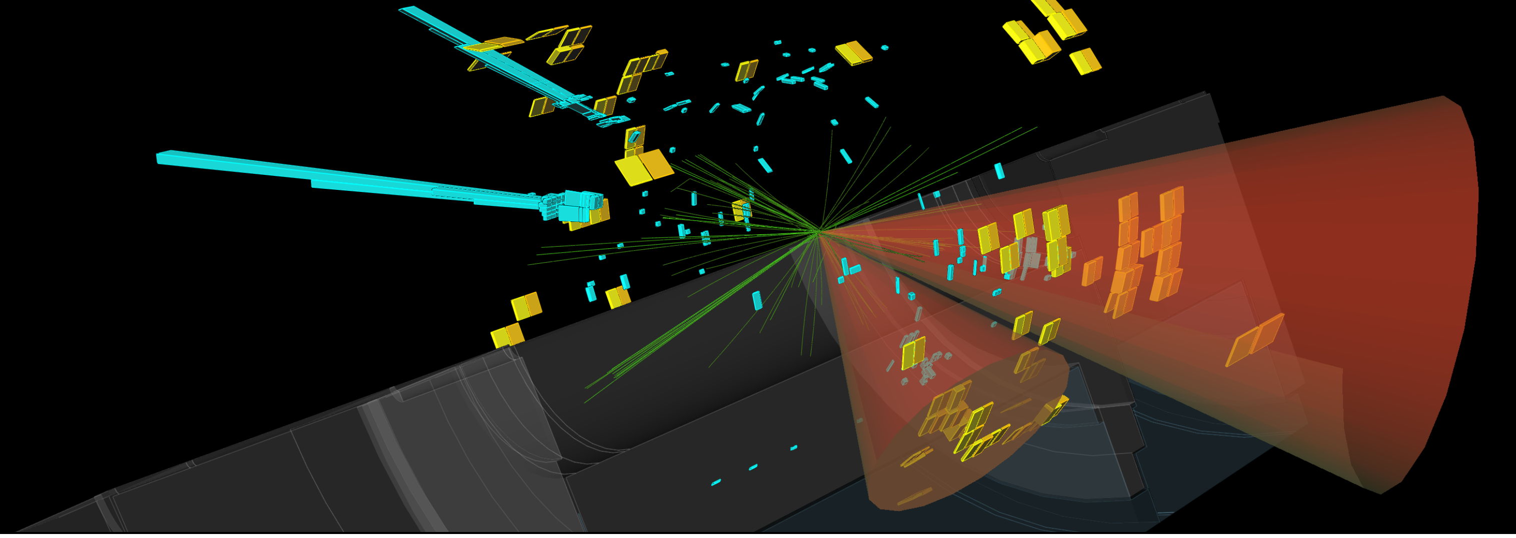


ATLAS-CONF-2022-050

Per channel results

bbγγ

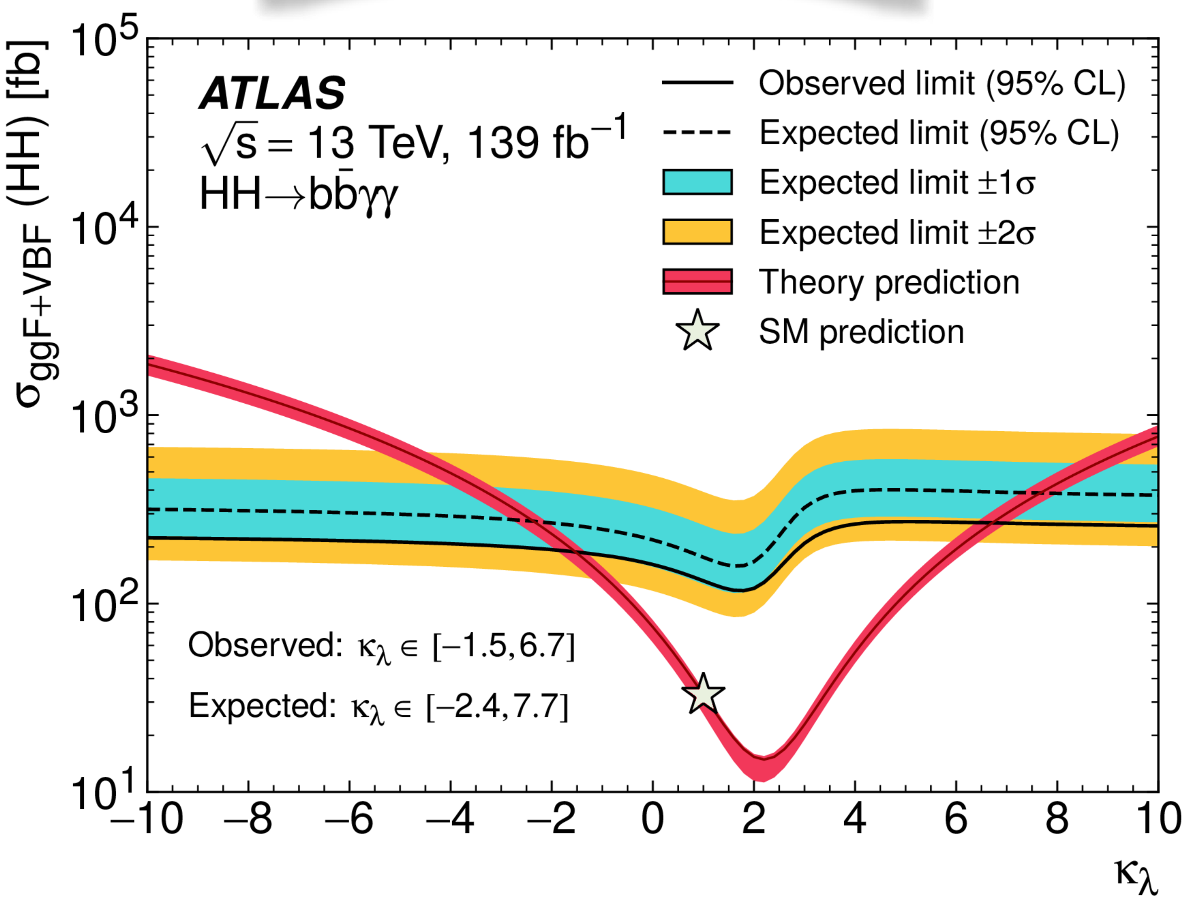
Non-resonant Results



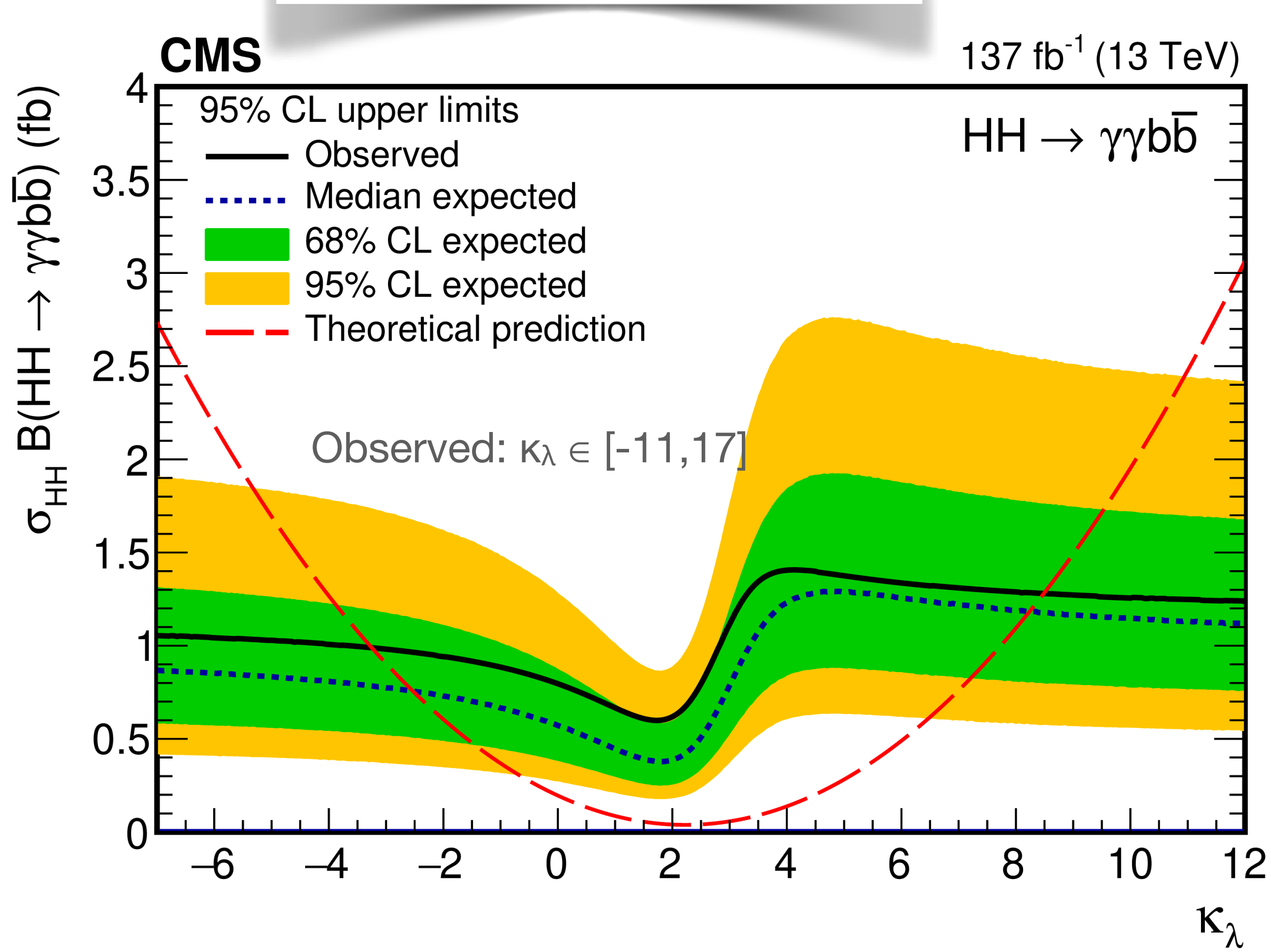
- Limits set on non-resonant μ_{SM} and κ_λ

μ_{SM} < 4.2 observed
(5.7 expected)

μ_{SM} < 7.7 observed
(5.2 expected)



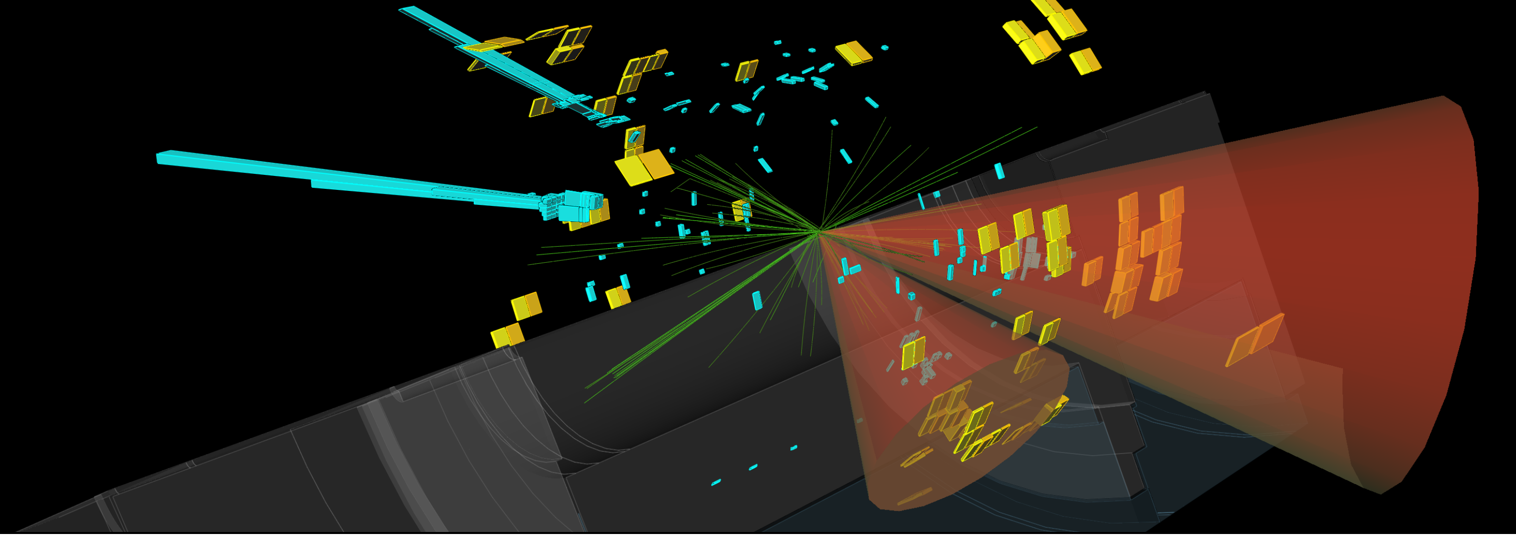
Phys. Rev. D 106 (2022) 052001



JHEP 03 (2021) 257

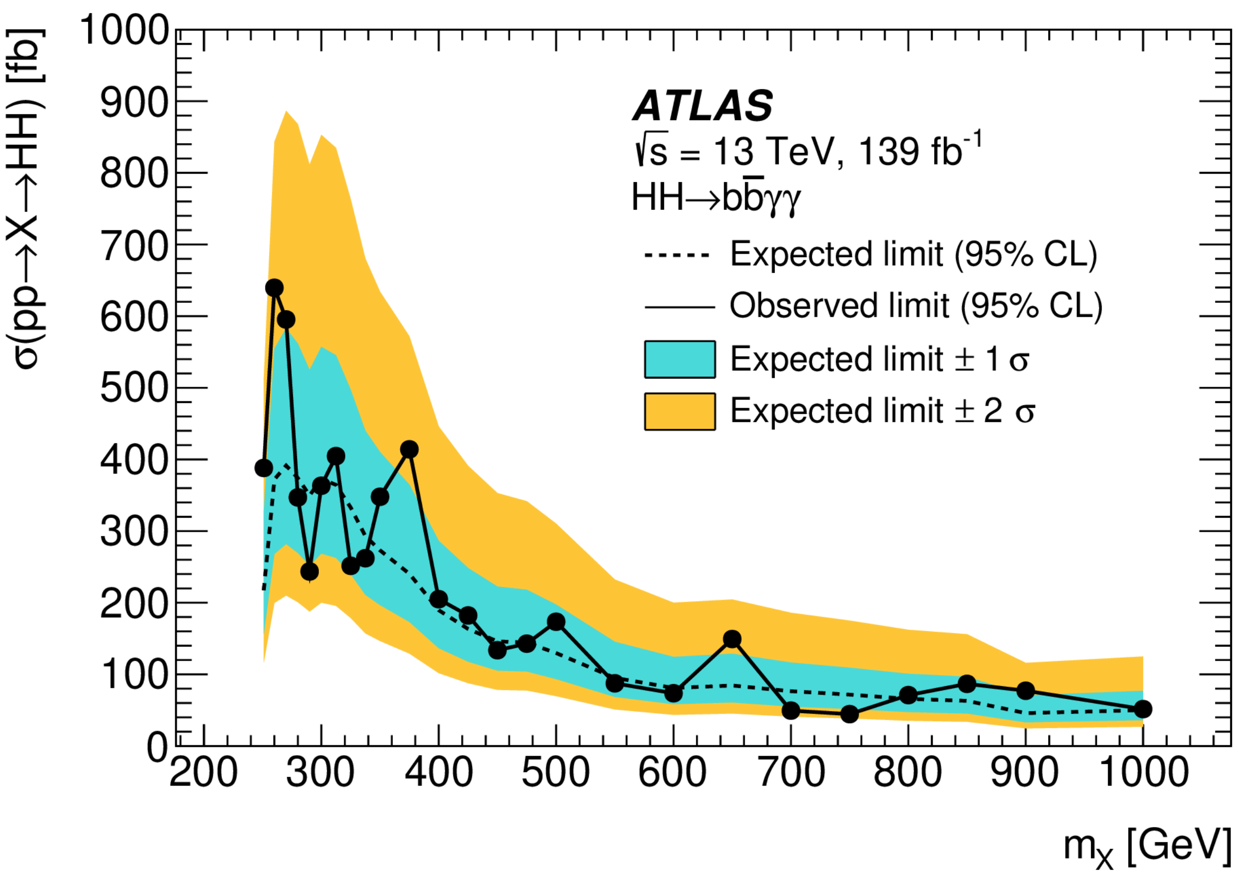
bbγγ

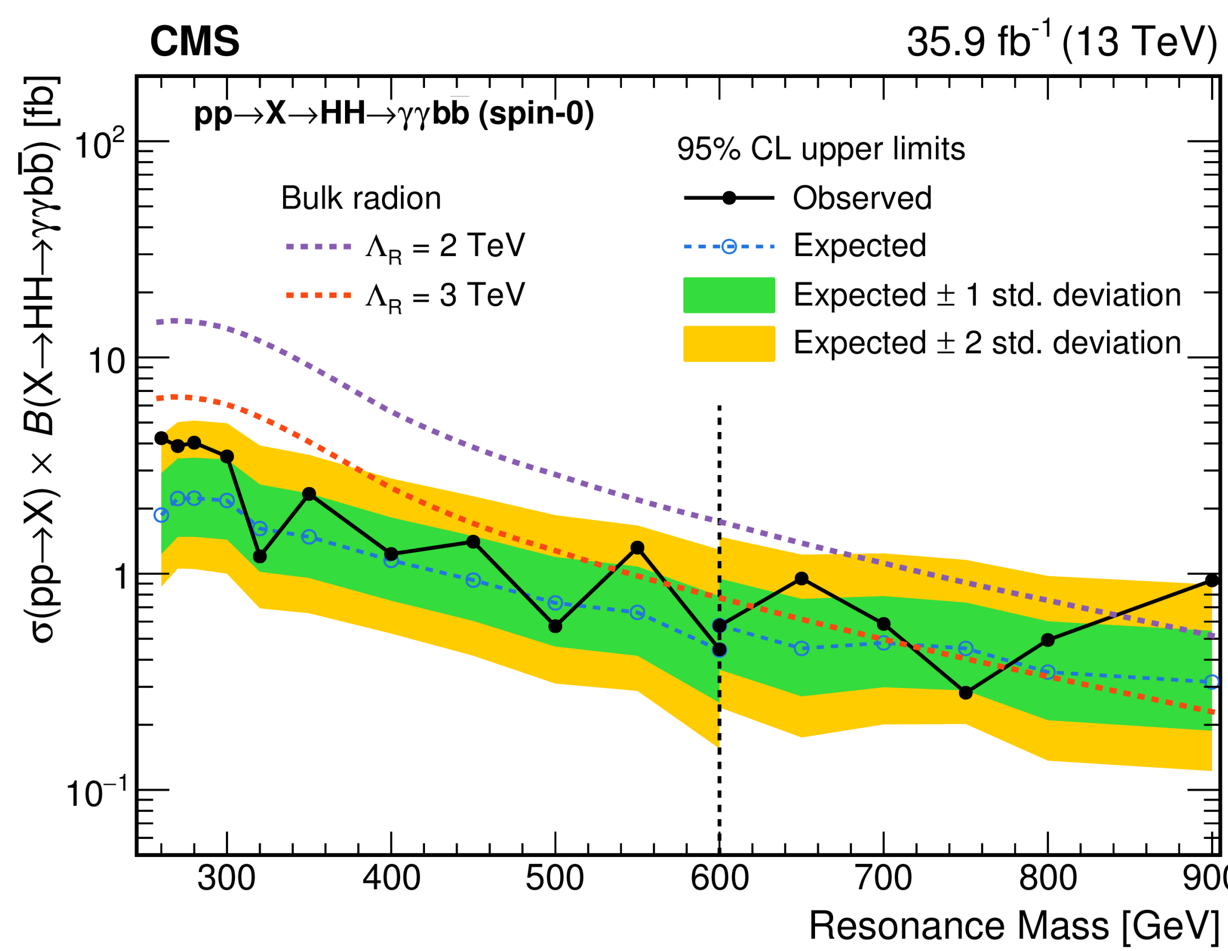
Resonant Results



- ATLAS set limits on spin-0 resonaces
- CMS set limits on spin-0 and spin-2 resonances

Phys. Rev. D 106 (2022) 052001

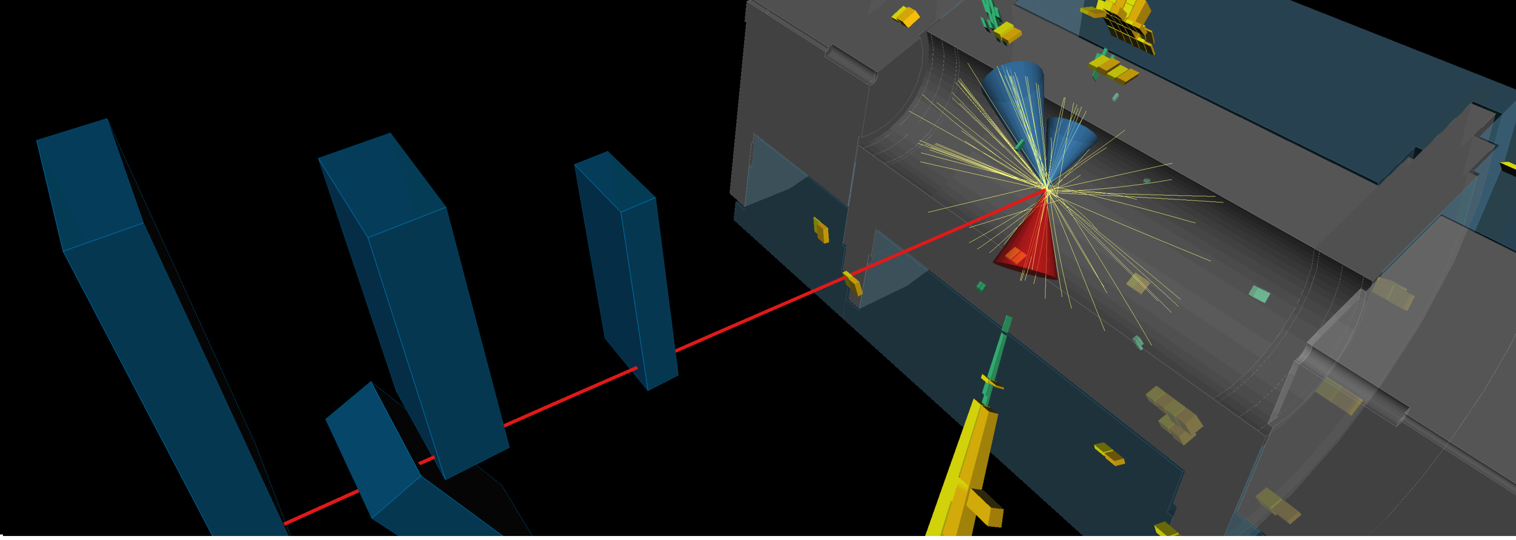




Phys.Lett.B 788 (2019) 7-36

bbττ

Results

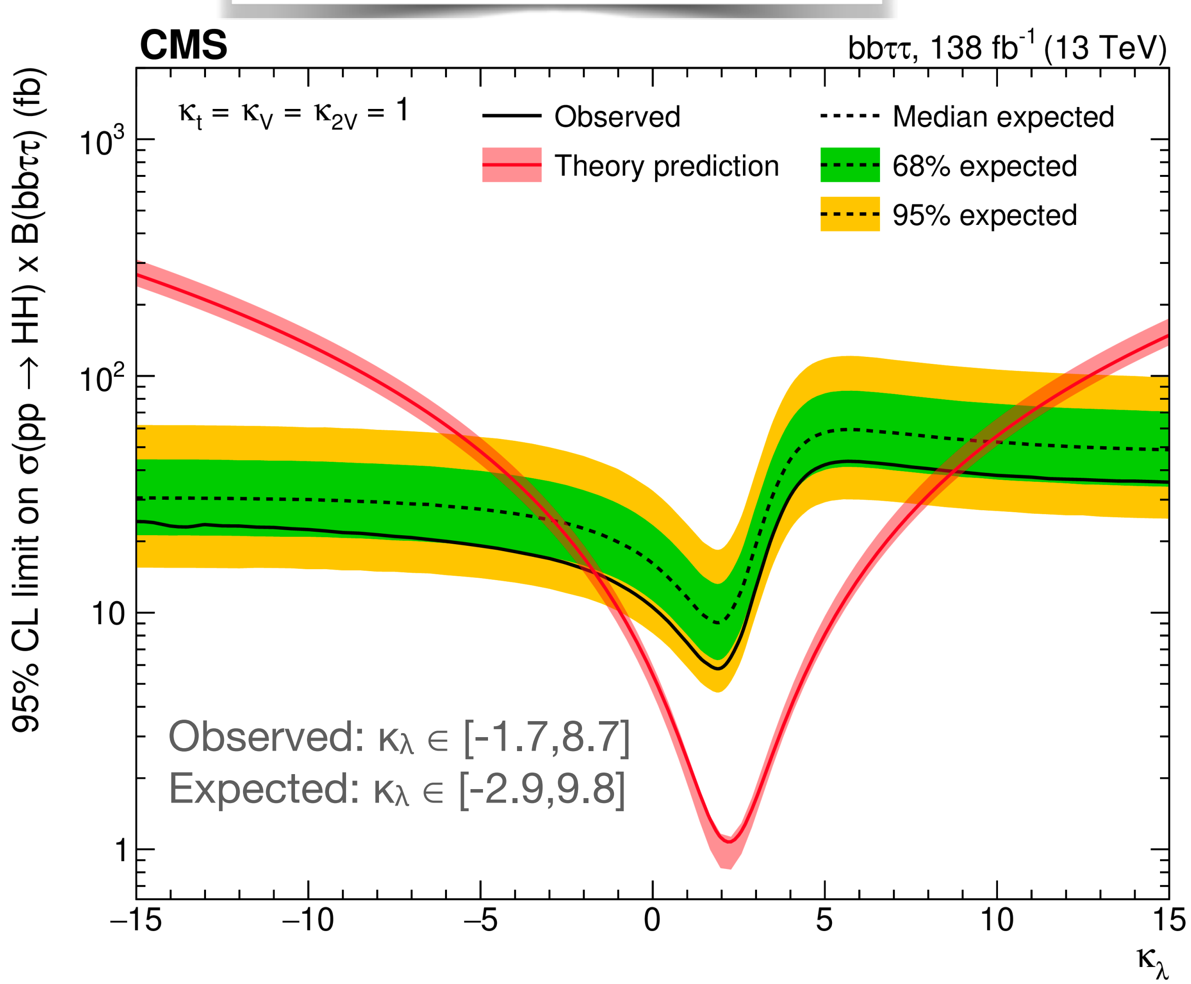


- Limits set on μ_{SM} and κ_λ

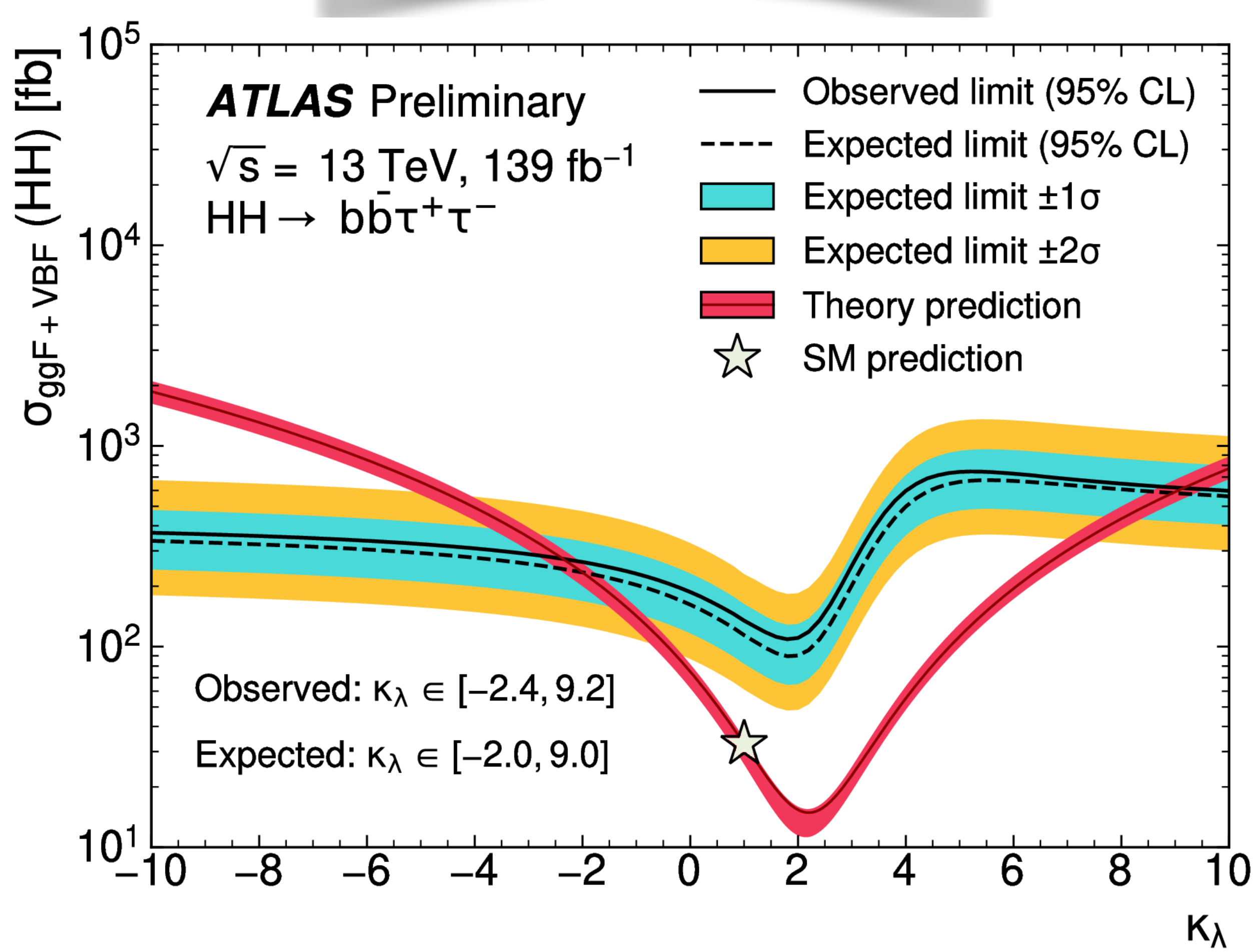
μ_{SM} < 3.3 observed
(5.2 expected)

μ_{SM} < 4.7 observed
(3.9 expected)

Phys. Lett. B 842 (2023) 137531



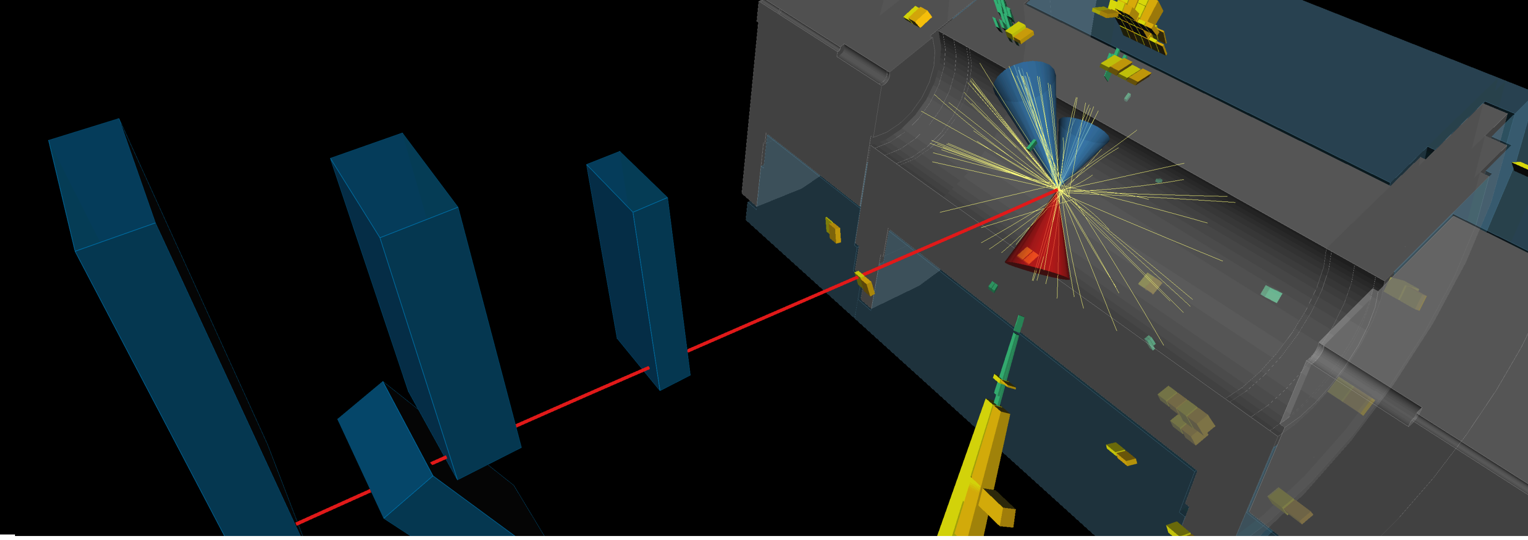
JHEP 07 (2023) 040



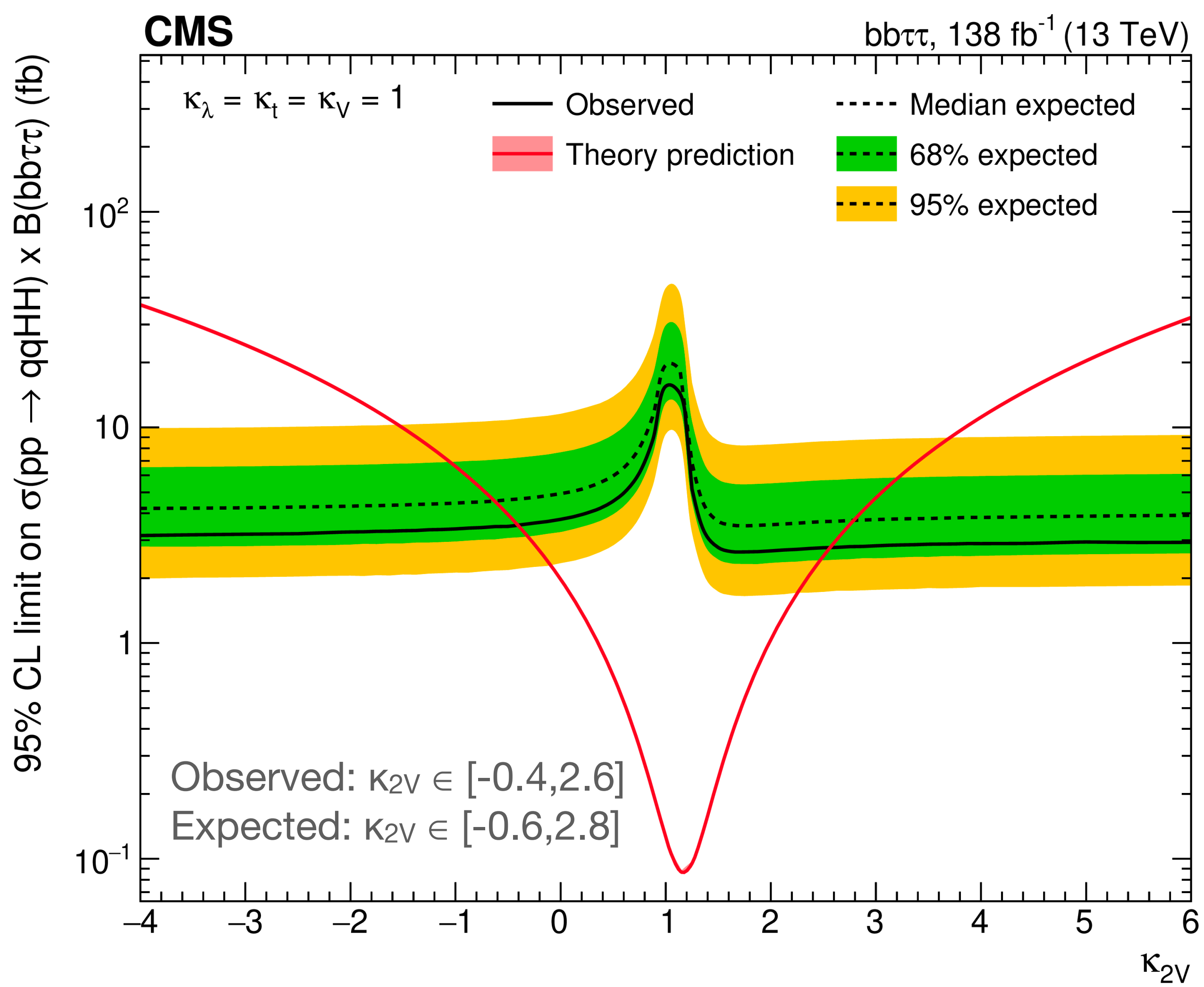
ATLAS-CONF-2021-052

bbττ

κ_{2V} Results



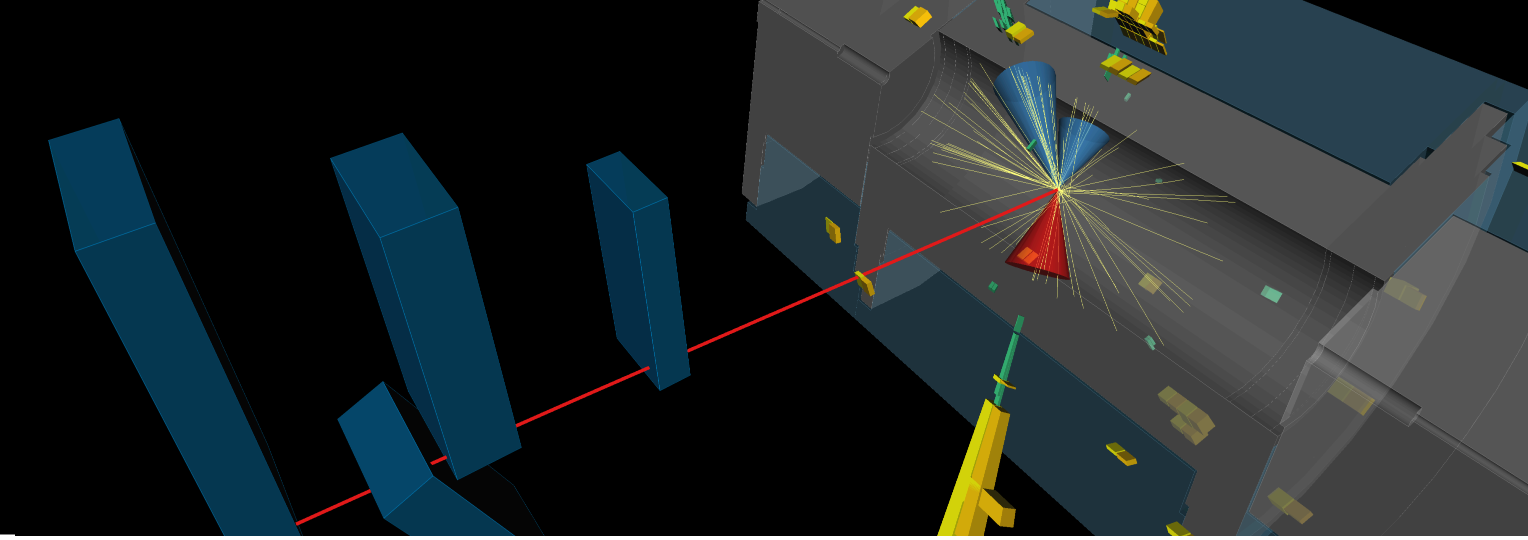
- Limits set on κ_{2V}



Phys. Lett. B 842 (2023) 137531

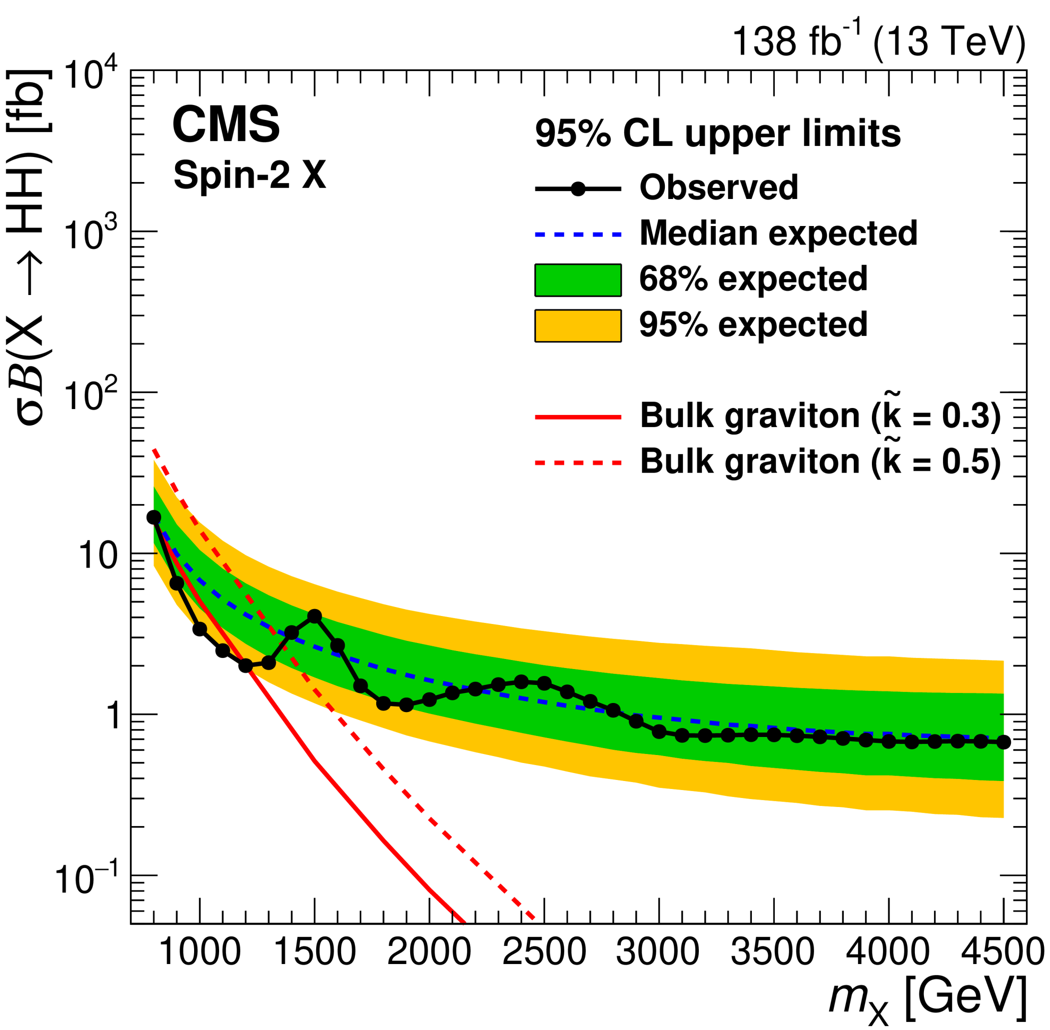
bbττ

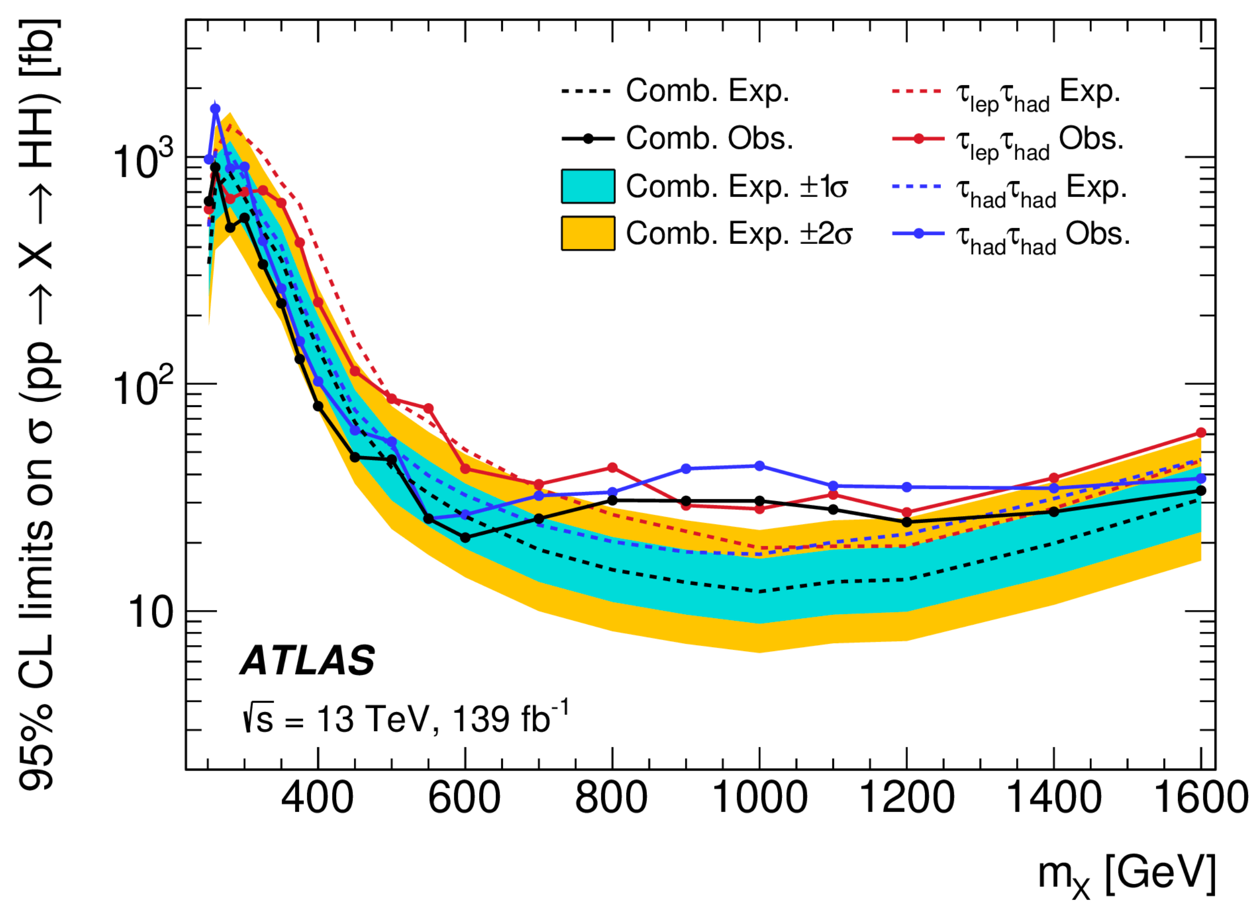
Resonant Results



- Limits set on spin-0 and spin-2 models

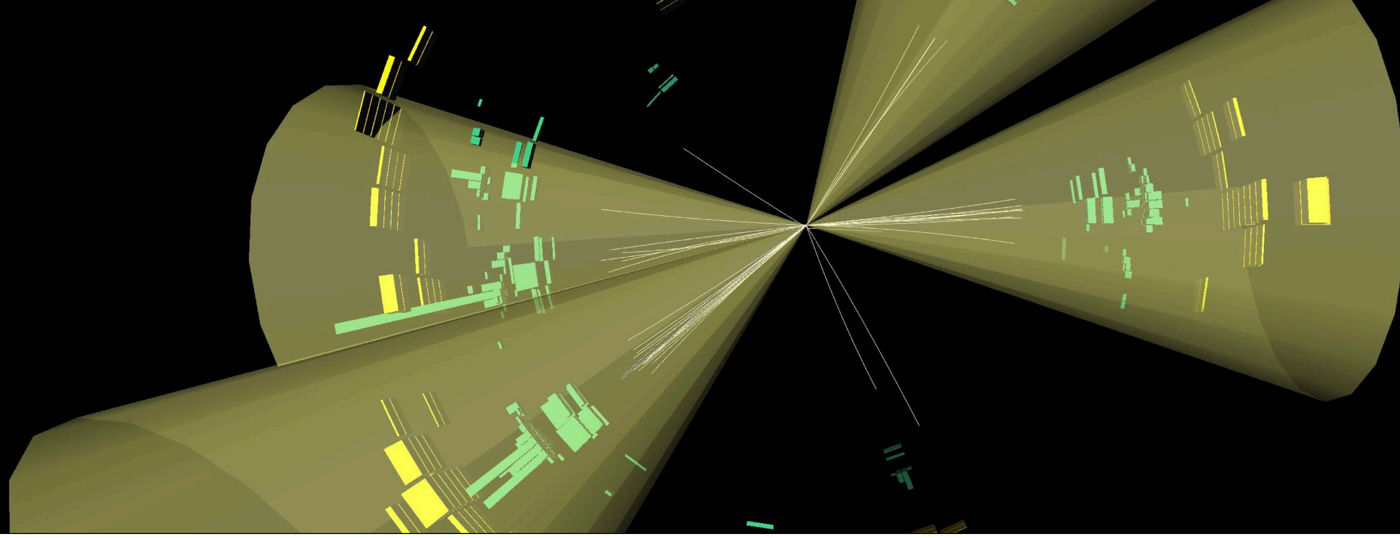
JHEP 05 (2022) 005





JHEP 07 (2023) 040

4b
Results



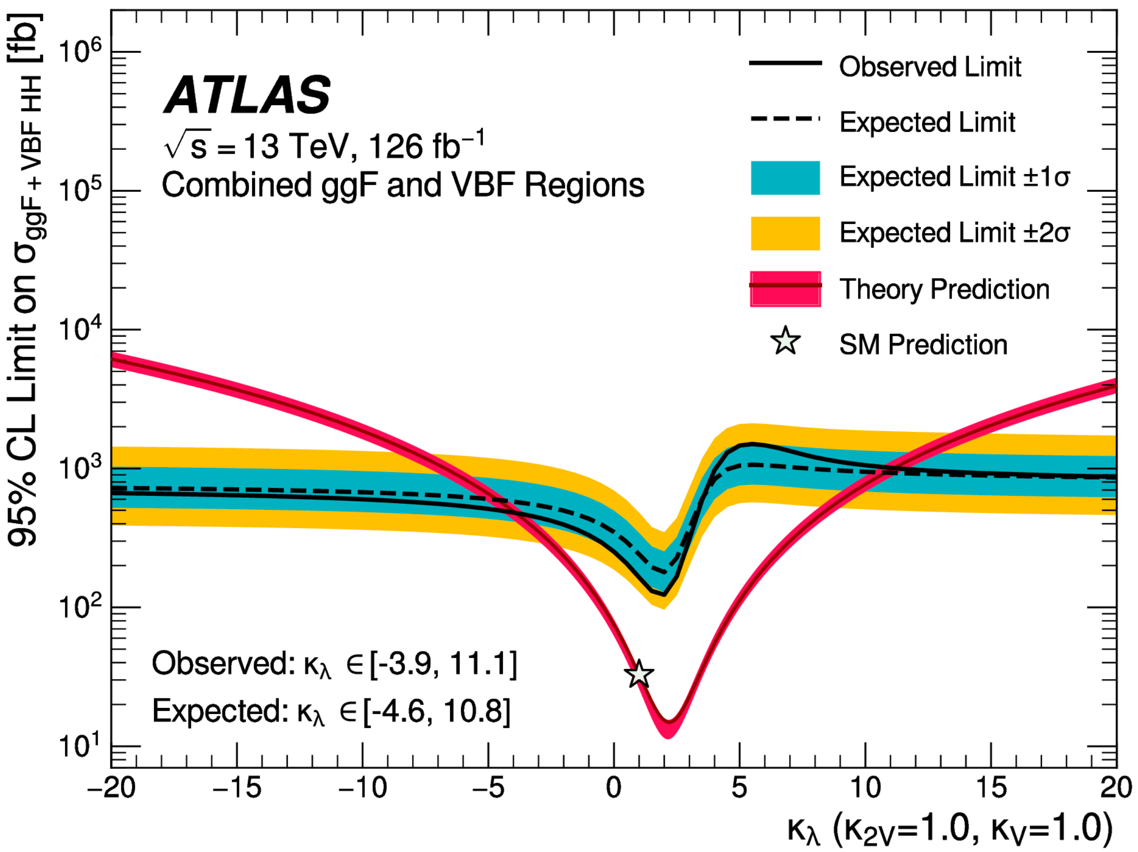
- Limits set on μ_{SM} and κ_λ

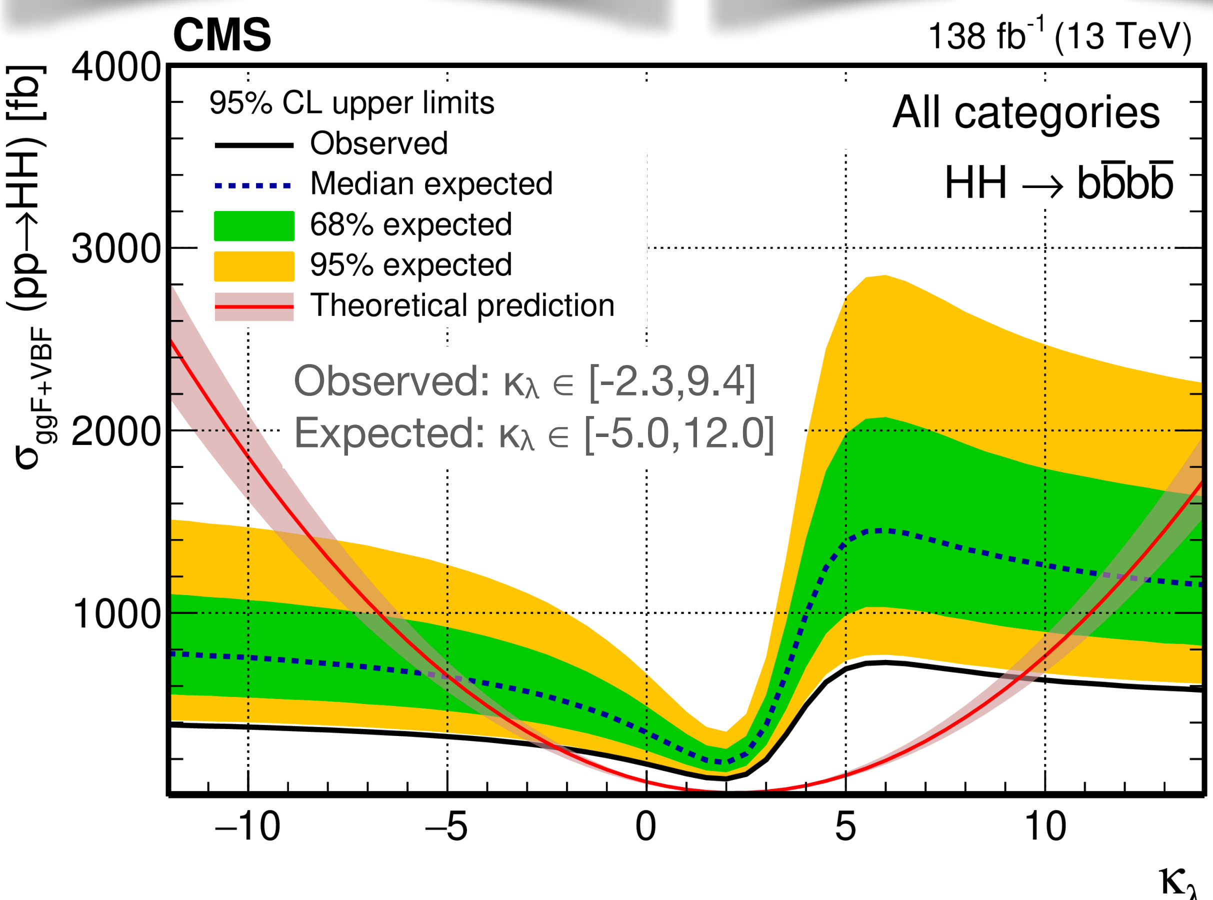
μ_{SM} < 5.4 observed
(8.1 expected)

Resolved
μ_{SM} < 3.9 observed
(7.8 expected)

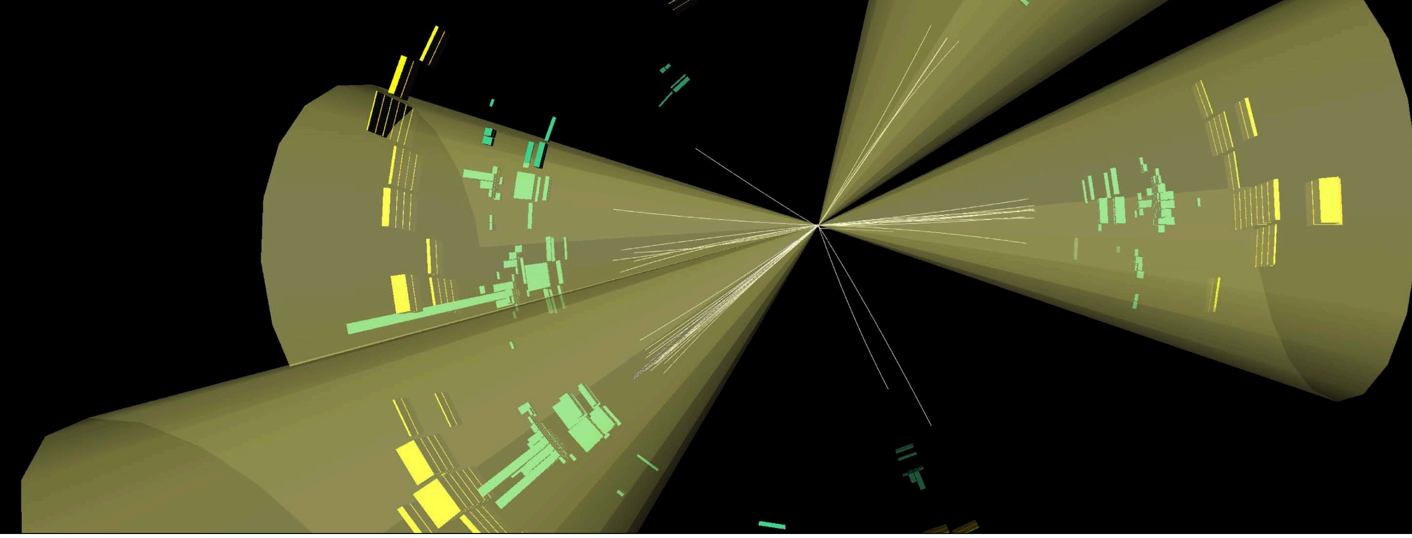
Boosted
μ_{SM} < 9.9 observed
(5.1 expected)

Phys. Rev. D 108 (2023) 052003





Phys. Rev. Lett. 131 (2023) 041803
Phys. Rev. Lett. 129 (2022) 081802

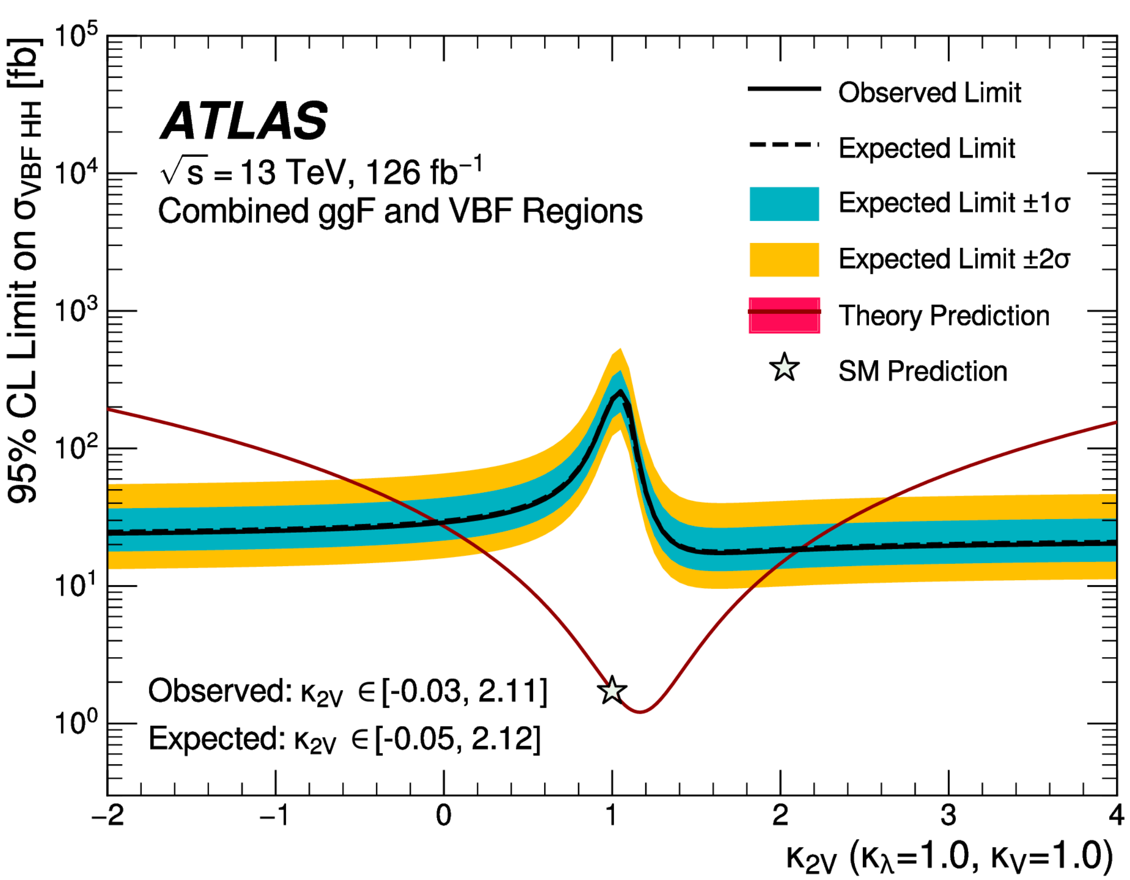


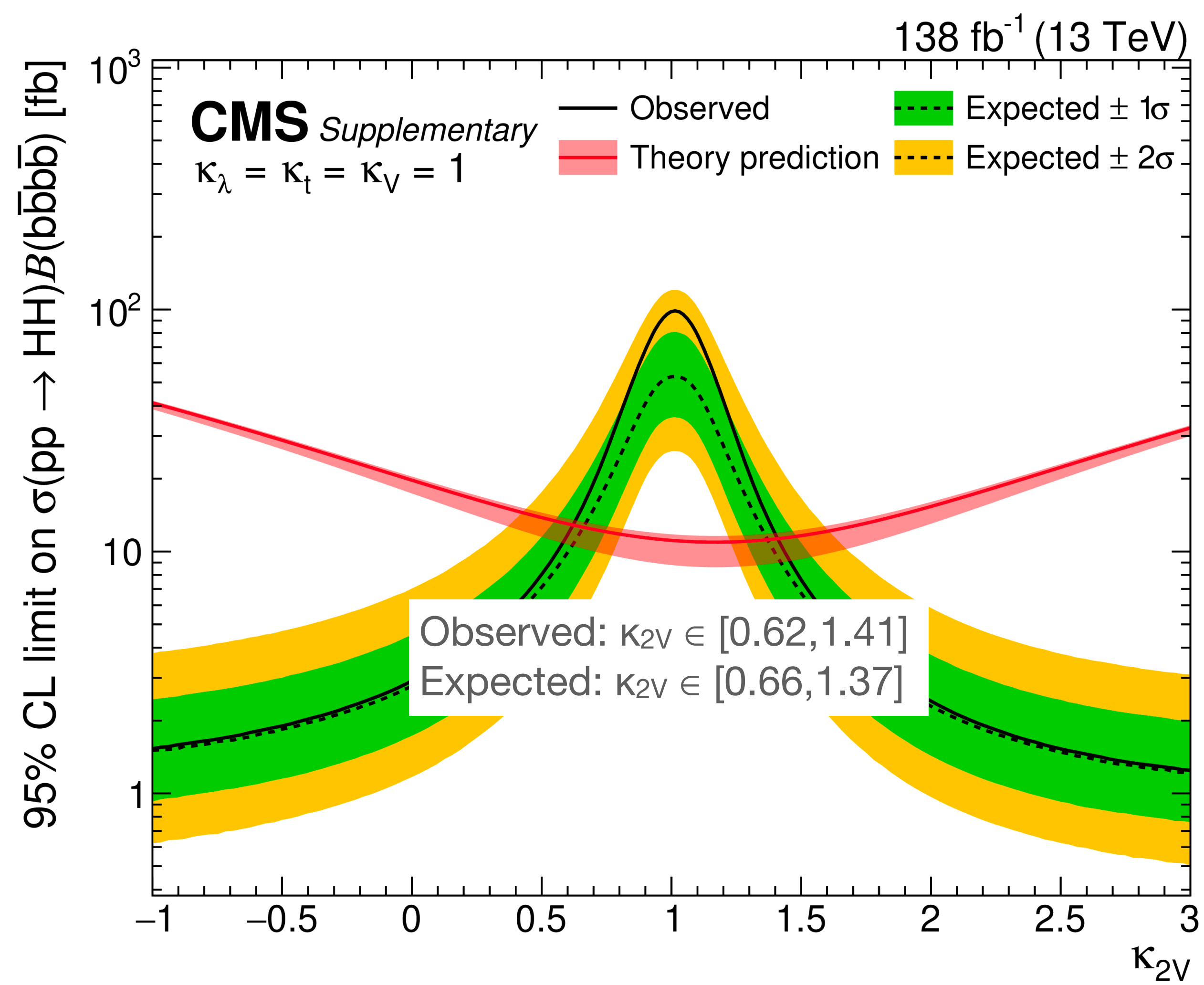
4b

κ_{2V} Results

- Limits set on κ_{2V}
- CMS boosted analysis excludes $\kappa_{2V} = 0$

Phys. Rev. D 108 (2023) 052003

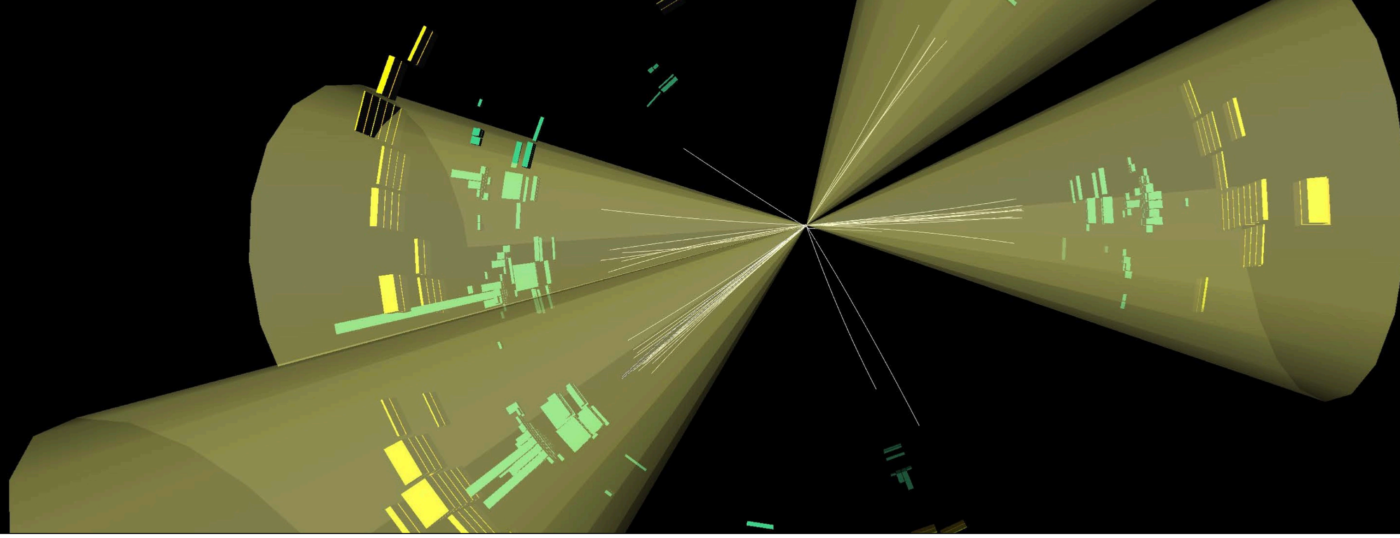




Phys. Rev. Lett. 131 (2023) 041803

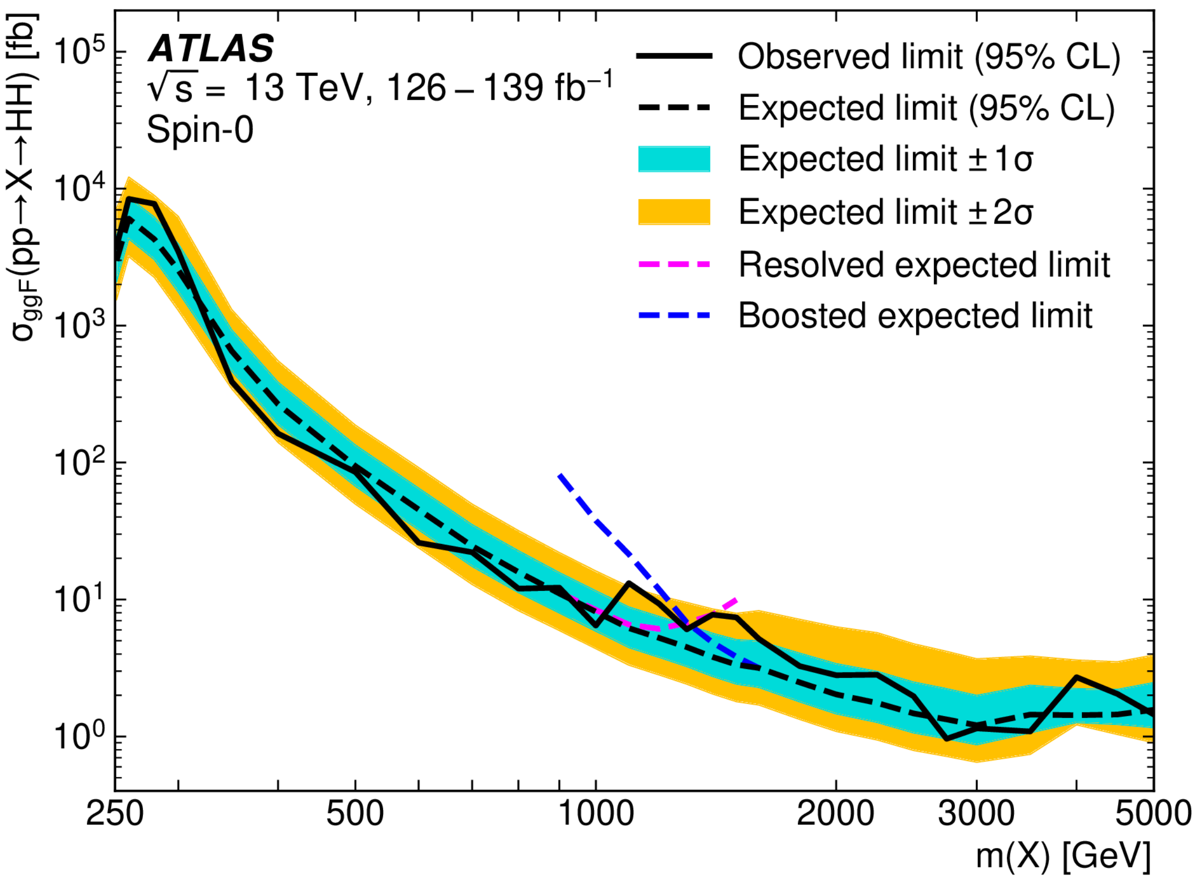
4b

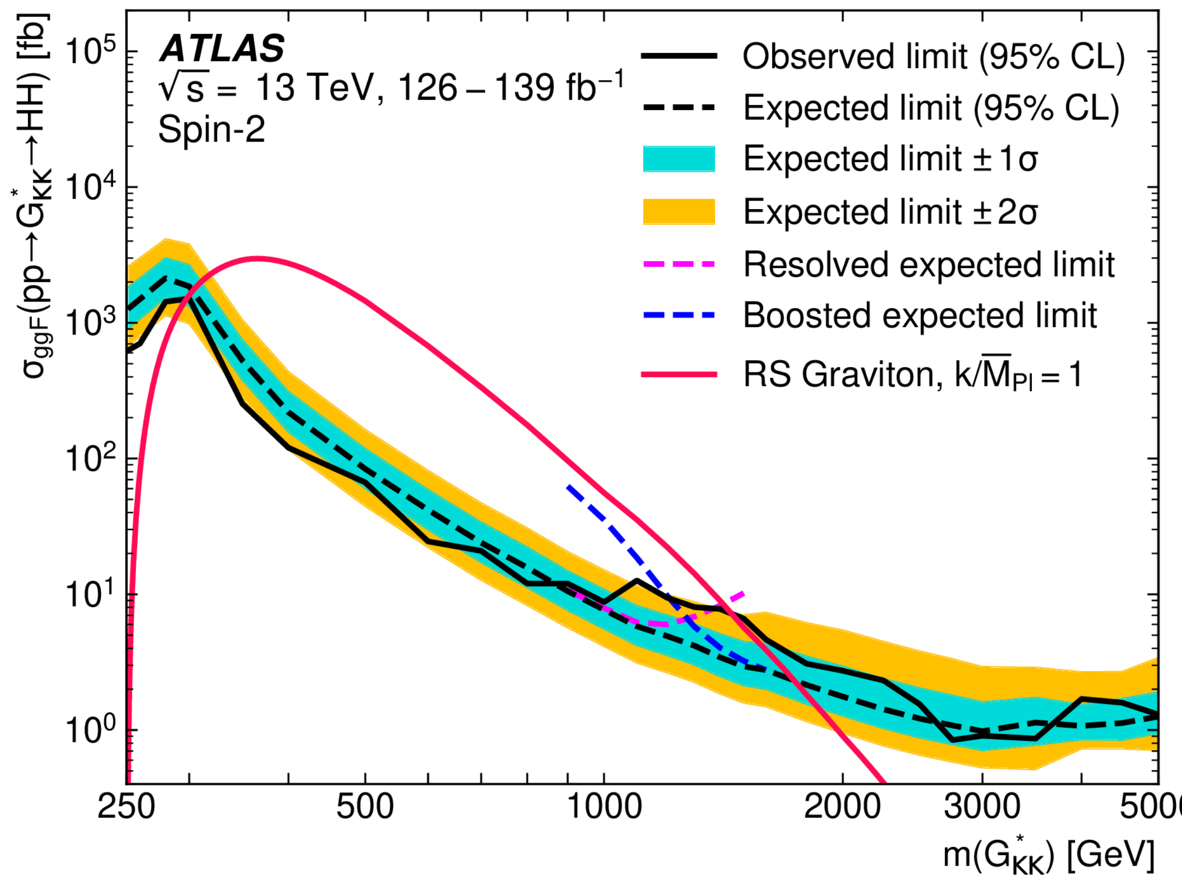
Resonant Results



- Limits set on spin-0 and spin-2 models

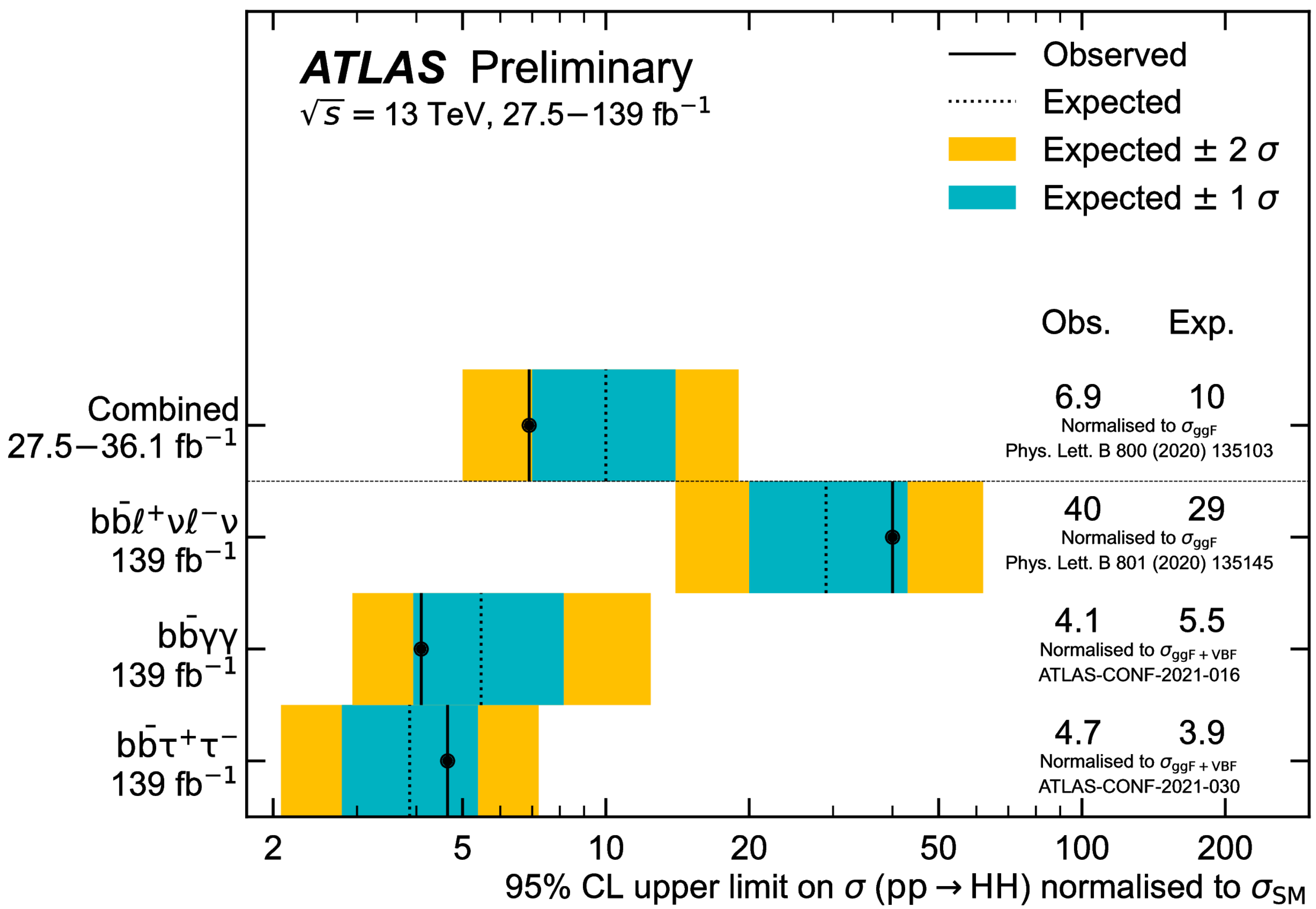
Phys. Rev. D 105 (2022) 092002





Summary Of All Channels

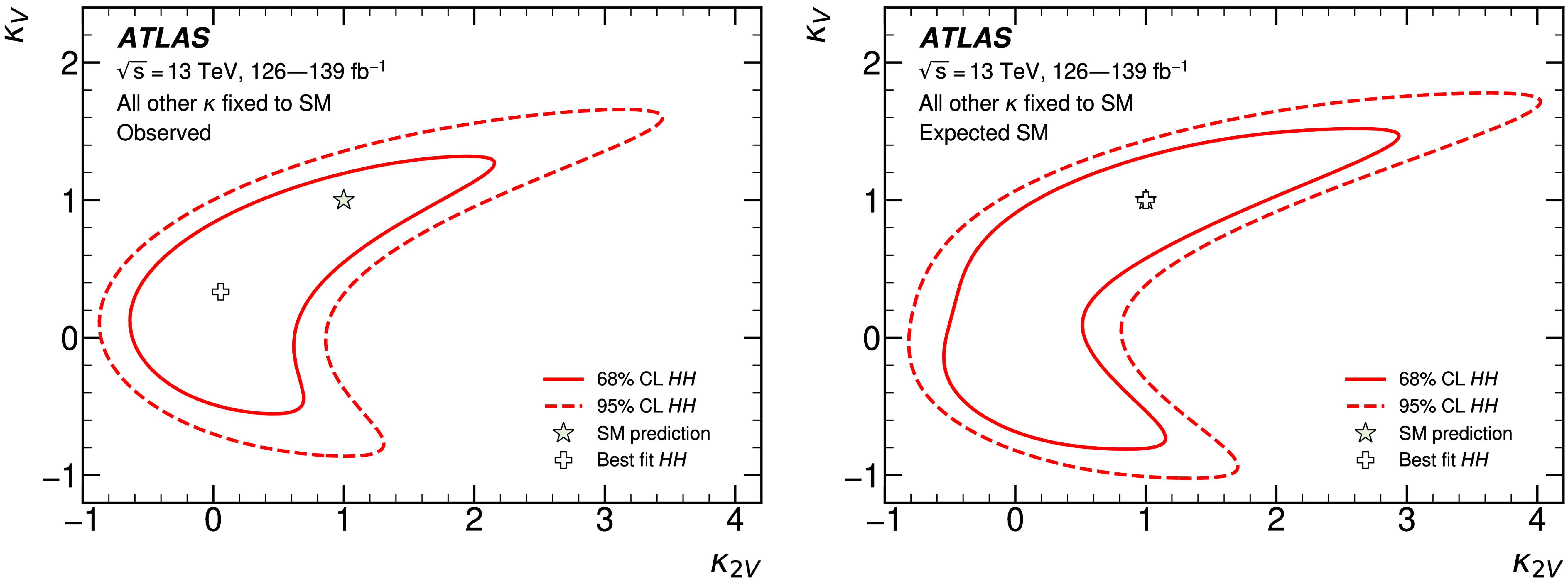
As of July 2021



ATL-PHYS-PUB-2021-031

HH Combination

κ_V-κ_{2V}

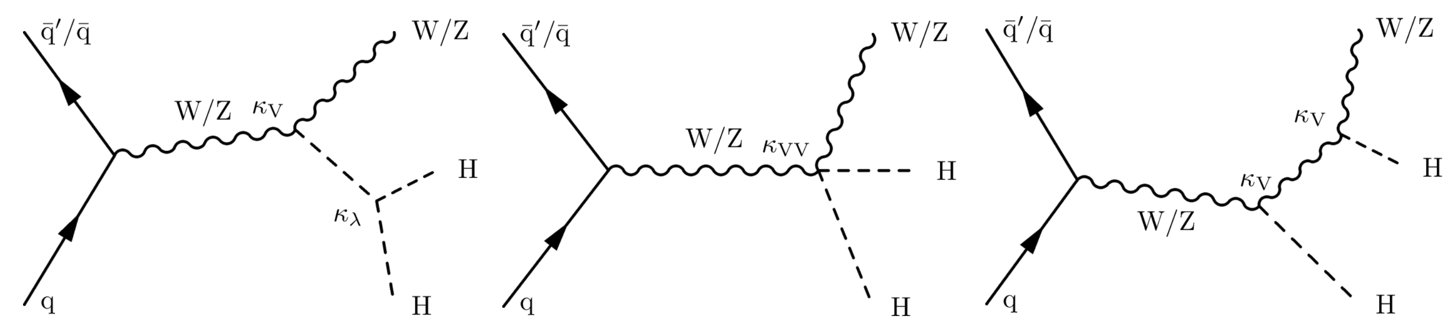


2211.01216

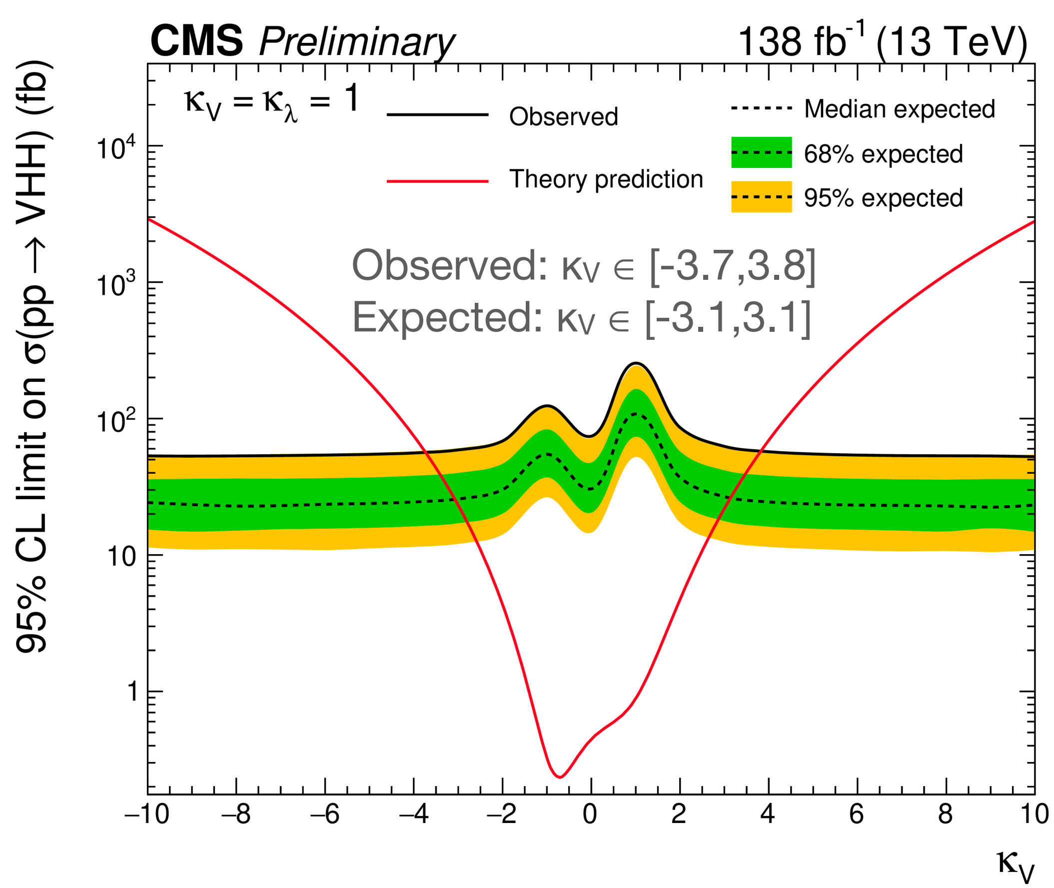
VHH

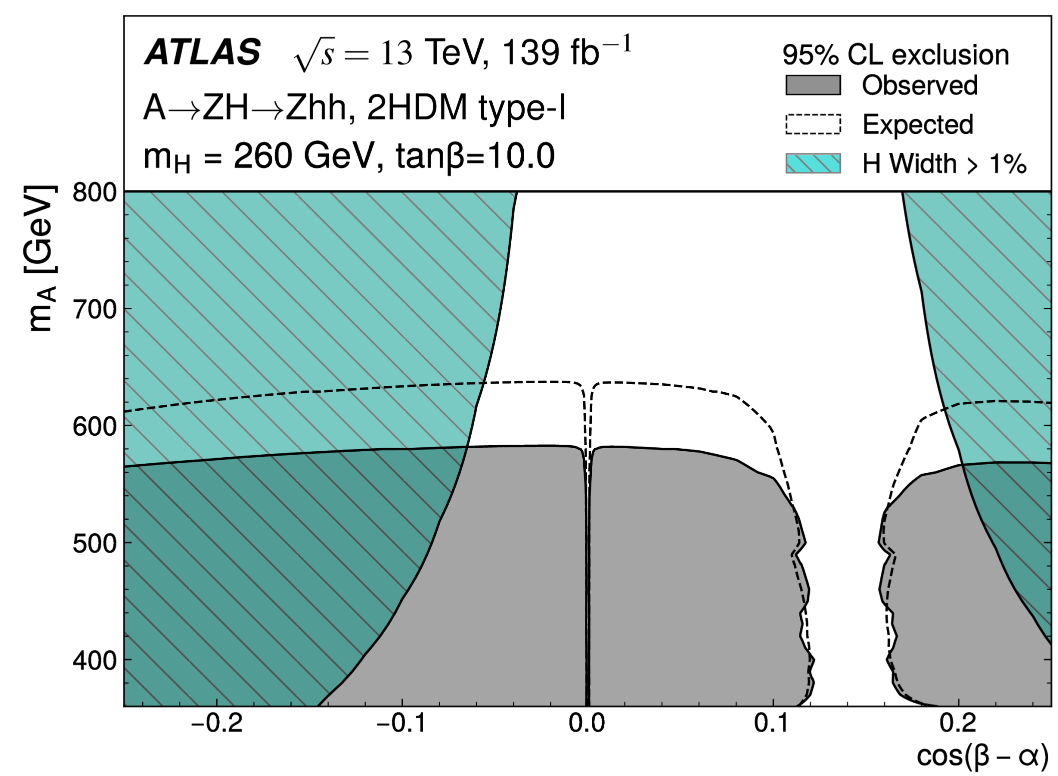
VHH

- HH associated with a vector boson is the next leading production mode
- Offers additional sensitivity to κ_λ, κ_{2V} and κ_V
- Resonant production also possible



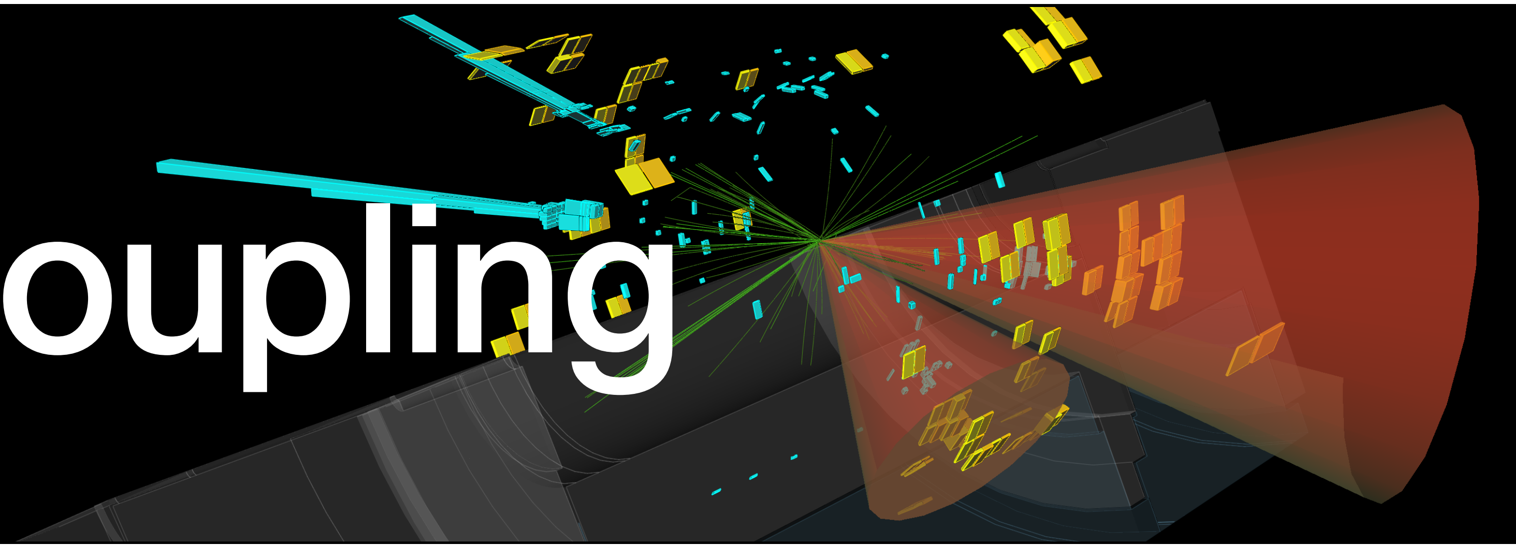
CMS-PAS-HIG-22-006



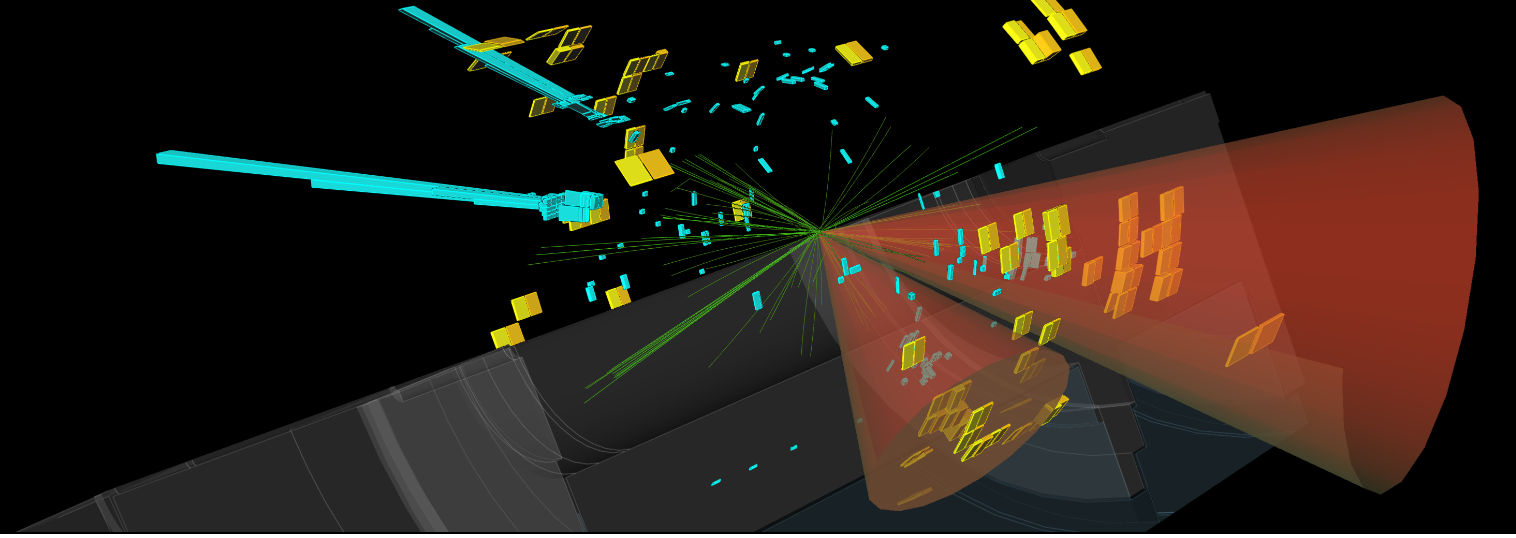


Eur. Phys. J. C 83 (2023) 519

Higgs Self-Coupling



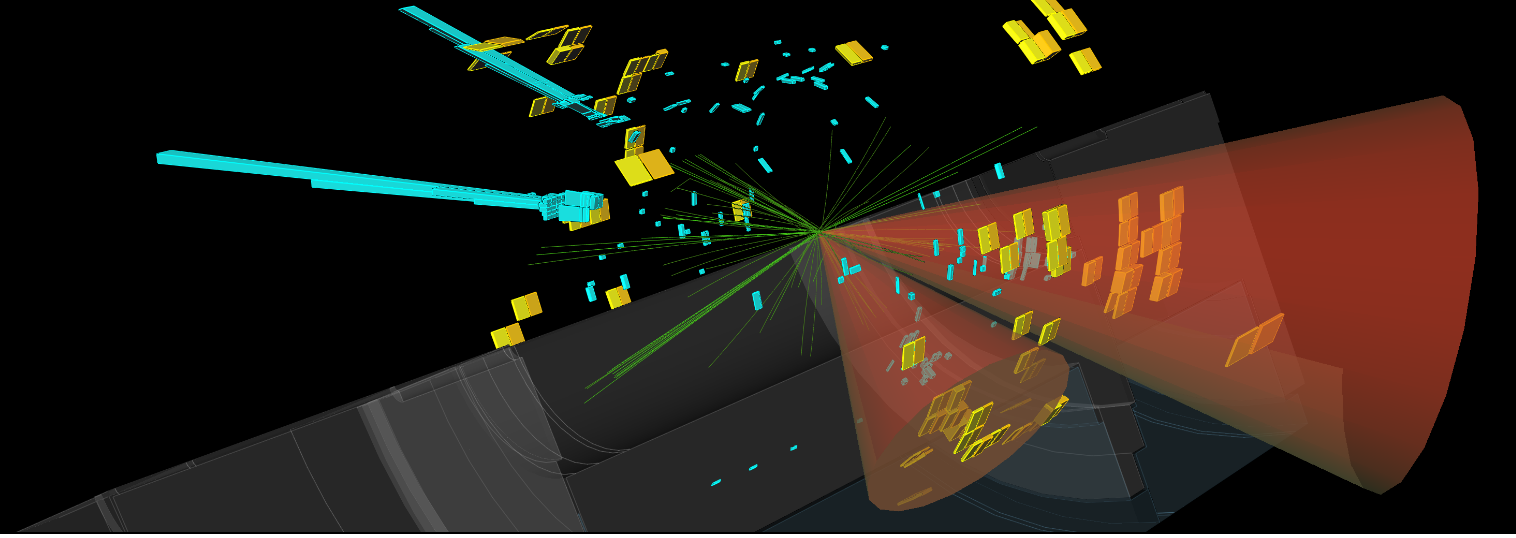
Measuring λ



Writing the Higgs potential as:

$$V(h) \simeq \frac{1}{2}m_H^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

Measuring λ



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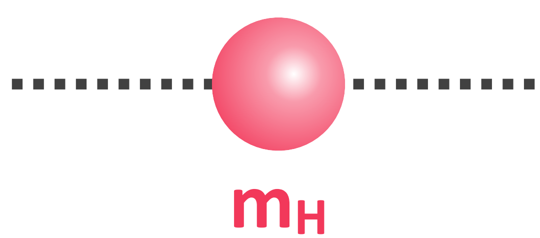
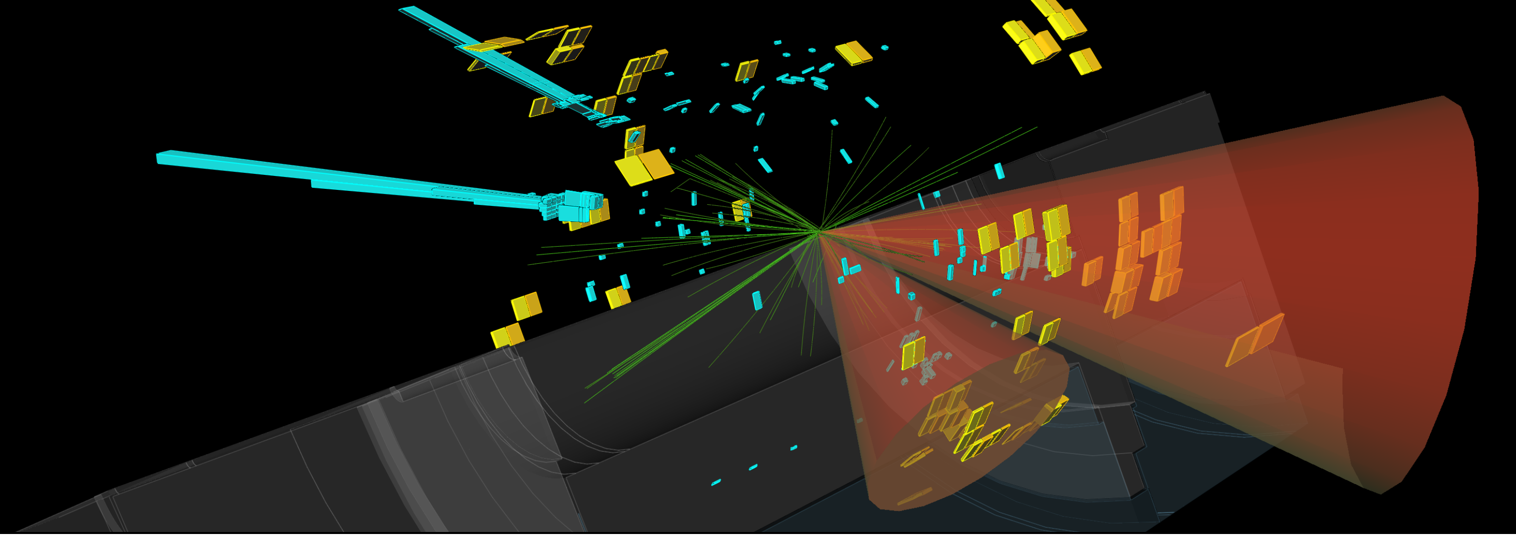


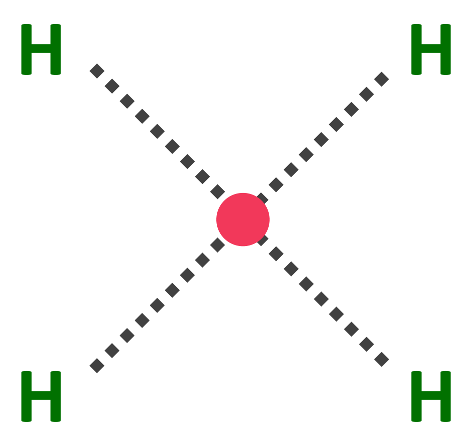
Measuring λ



Writing the Higgs potential as:

$$V(h) \simeq \frac{1}{2}m_H^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

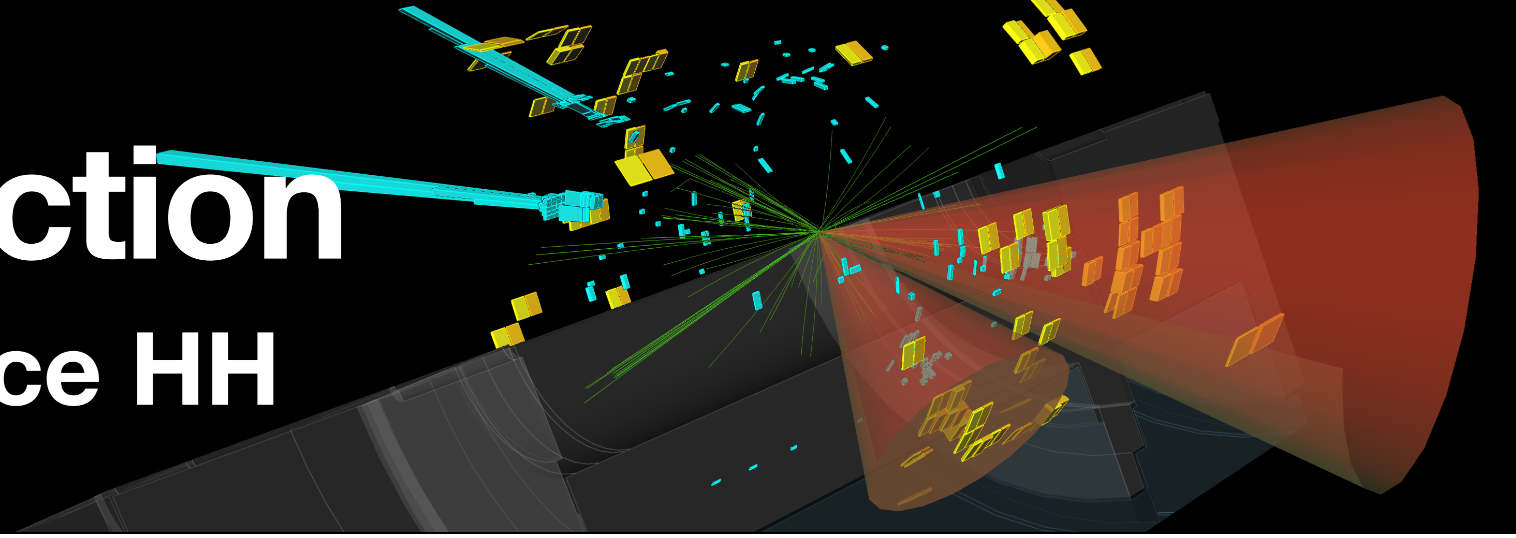
λ also appears in the Higgs quartic coupling



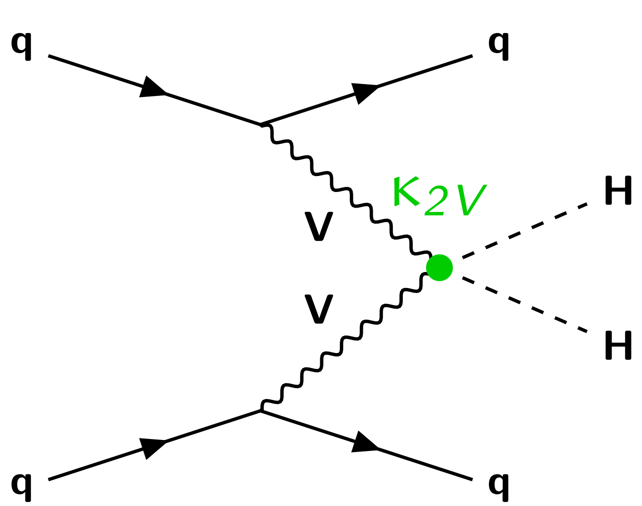
This is unlikely to be reachable by the LHC…

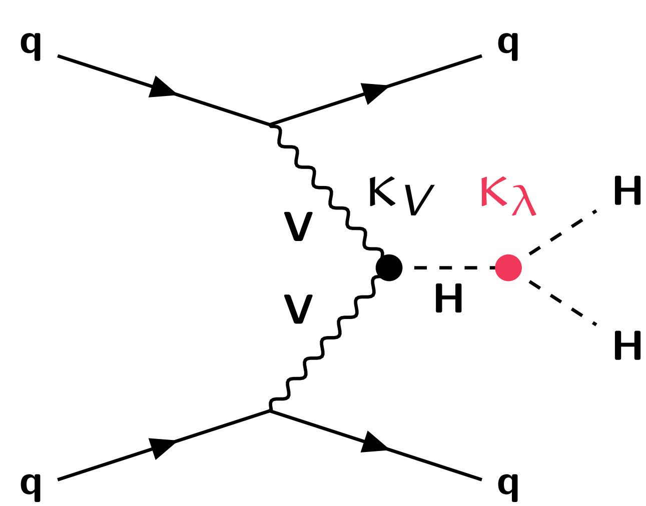
VBF HH Production

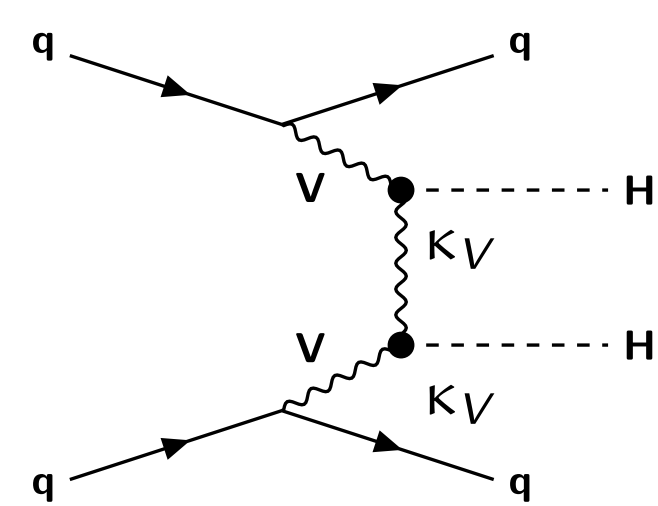
Another way to produce HH



- Vector boson fusion (VBF) is the sub-dominant LHC HH production mode
- Unique signature of two forward jets
- Gives access to the HHVV coupling (κ_{2V} is the coupling modifier)
- Smaller cross-section than gluon-gluon fusion (~1.72 fb)

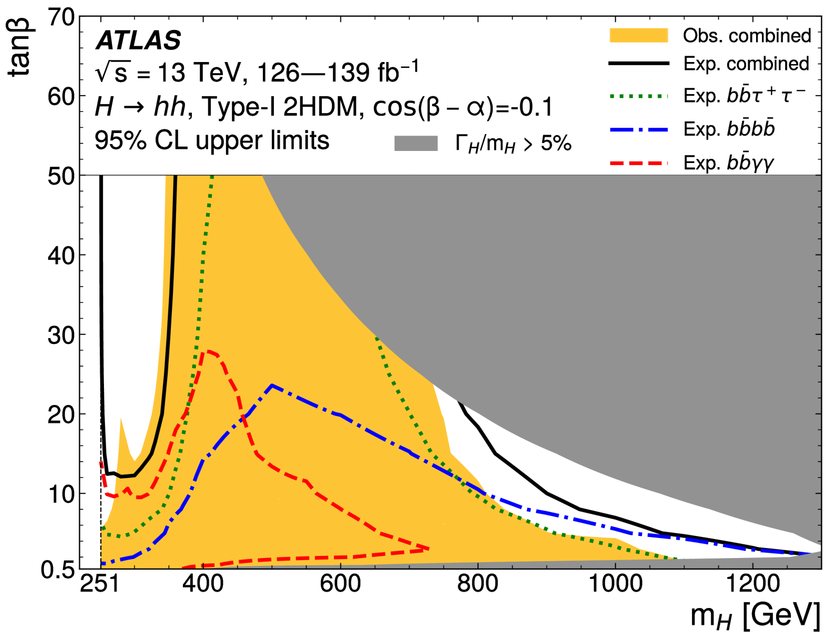


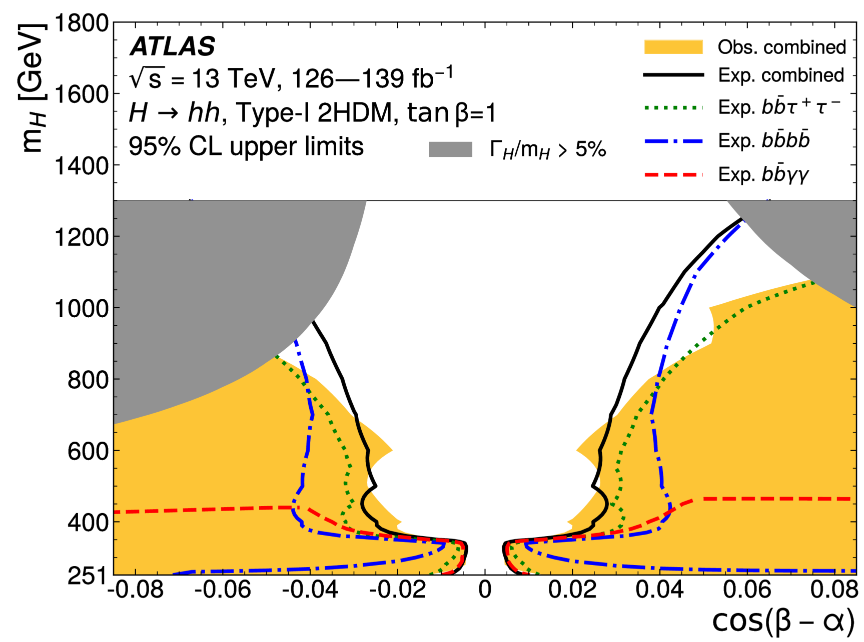


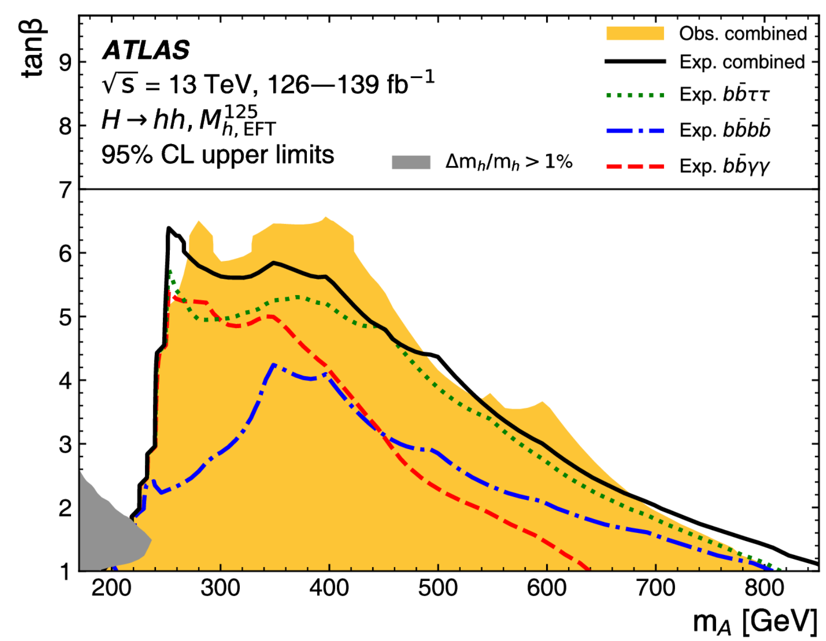


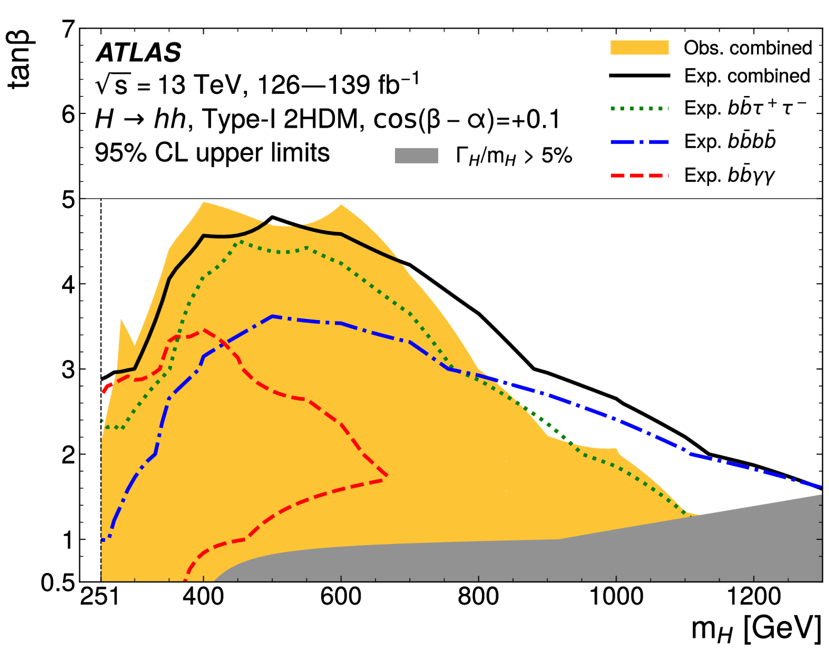
HH Combination

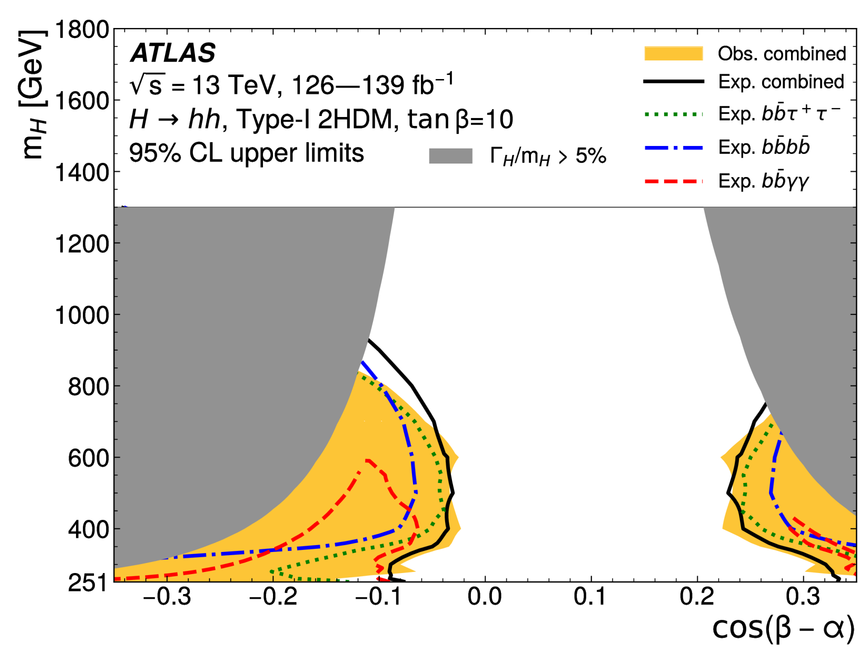
2HDM and MSSM Interpretations

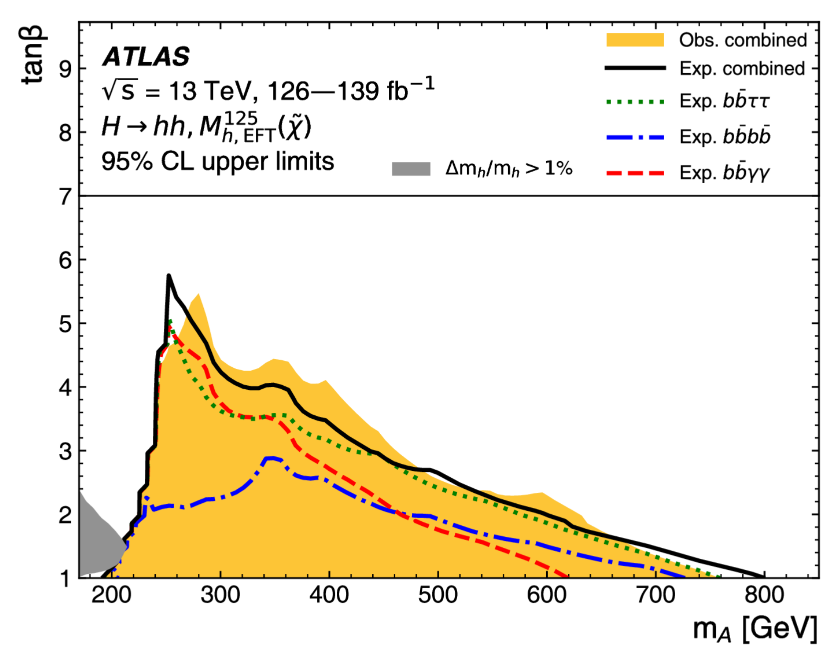








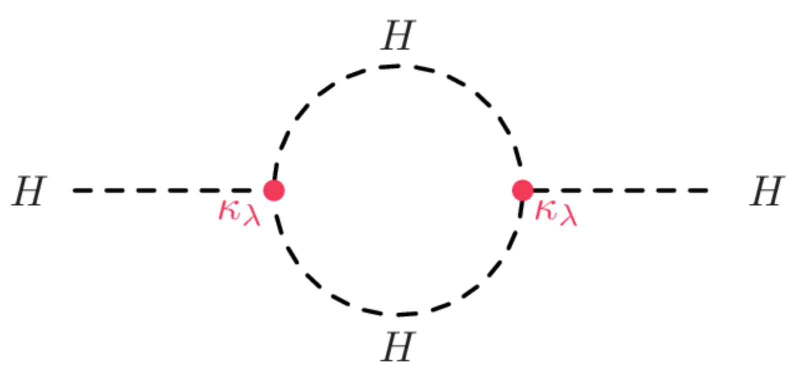


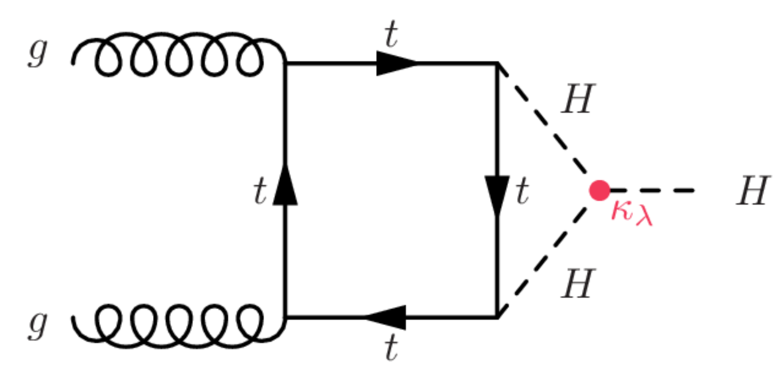


Accepted by PRL

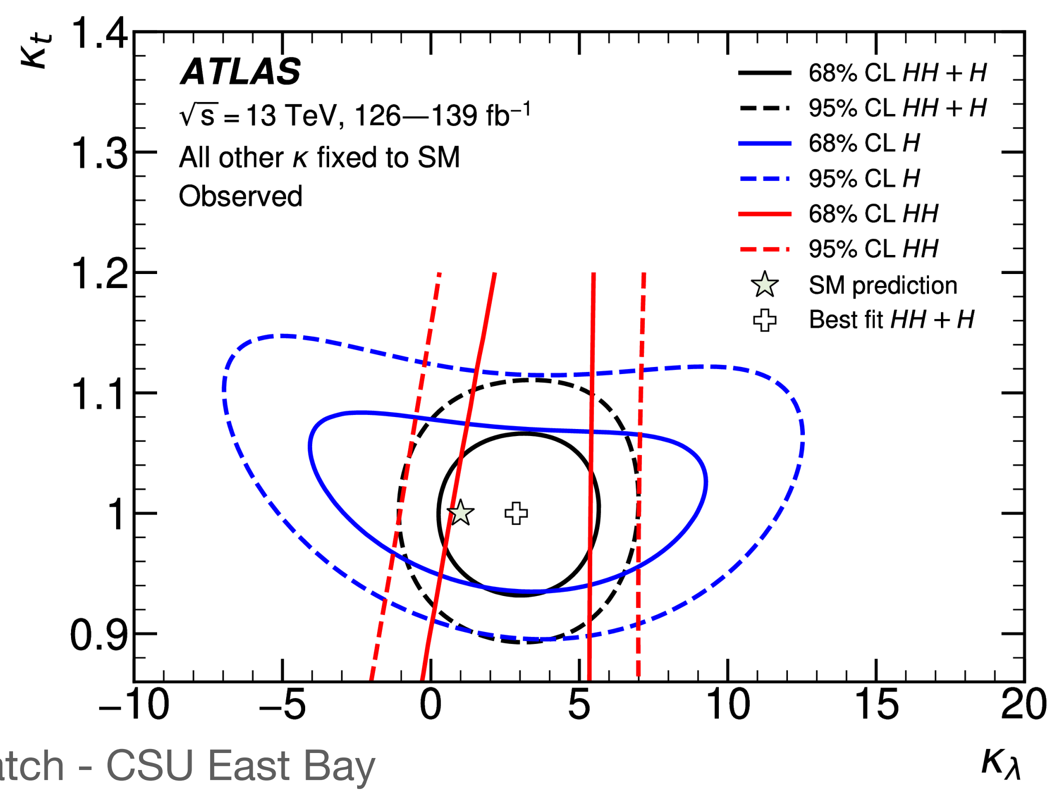
HH+H Combination

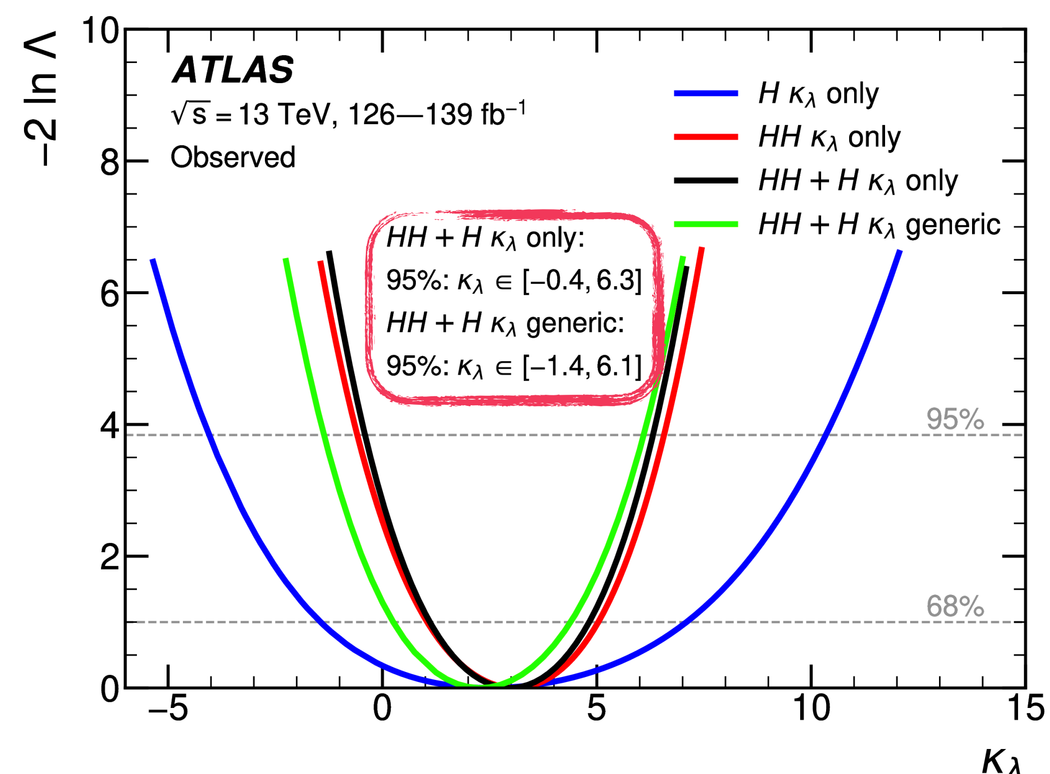
- Single Higgs boson production is also sensitive to λ through loop corrections, e.g.,





- Additional constraints can be achieved by combining HH and H searches





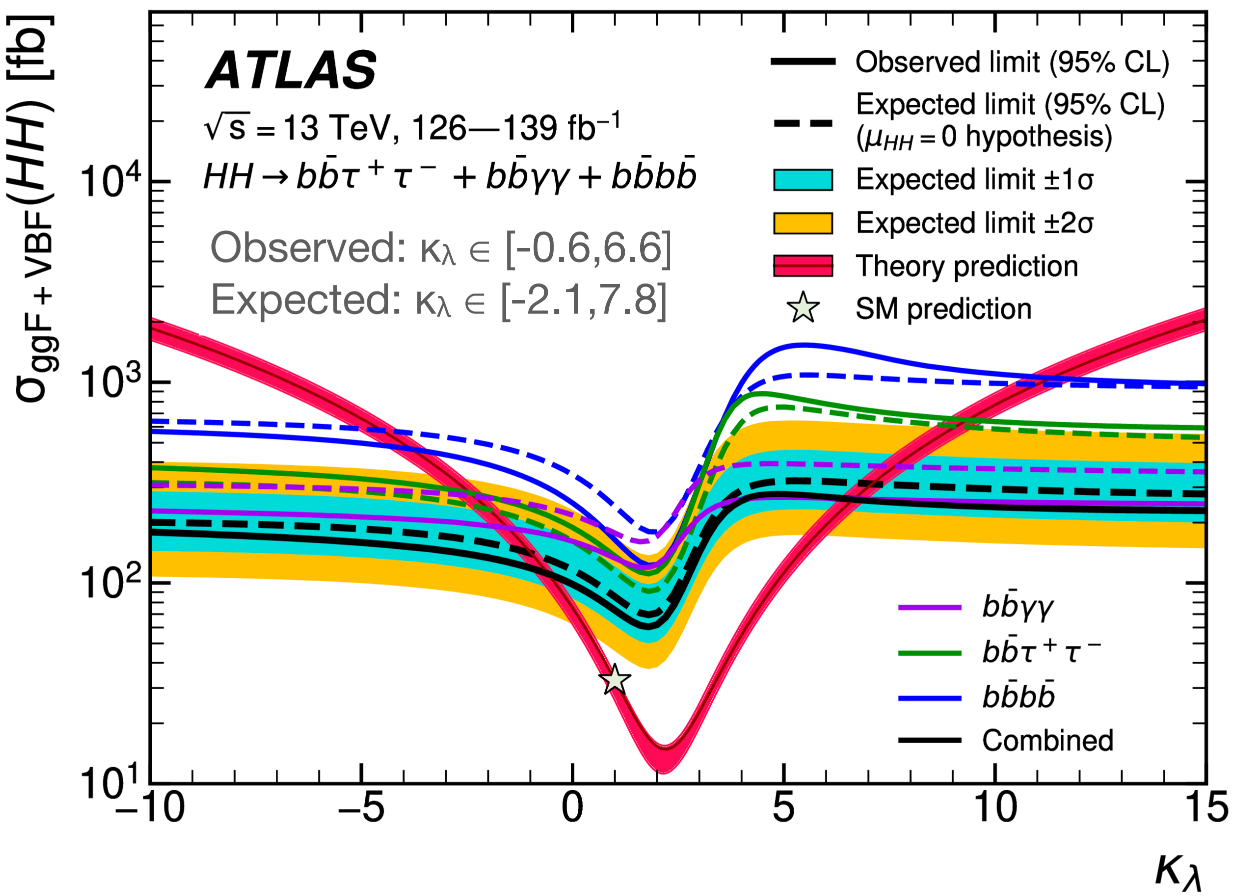
arXiv:2211.01216

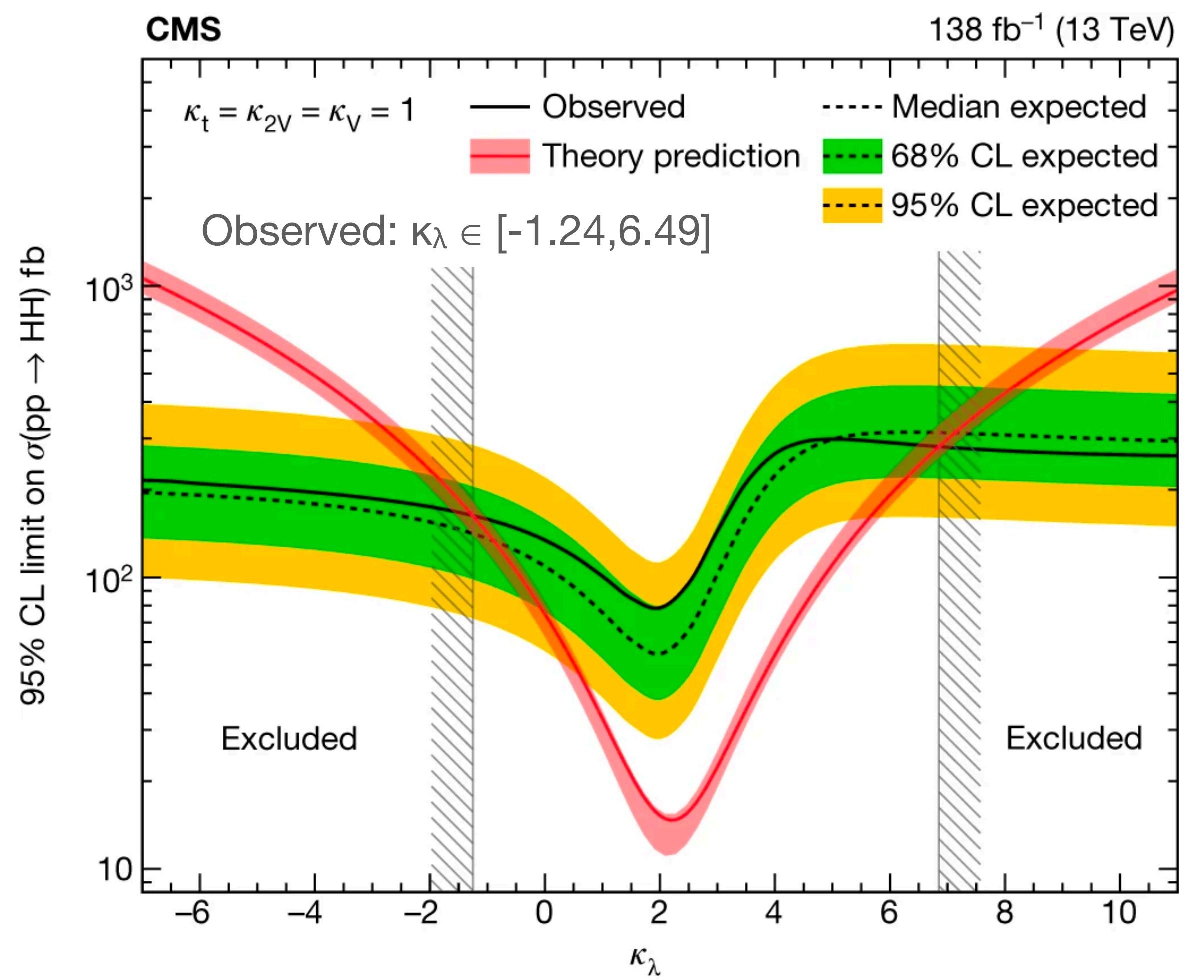
HH Combination

κλ

- Statistically combining channels increases sensitivity
- Combination of the three most sensitive HH channels

Phys. Lett. B 843 (2023) 137745





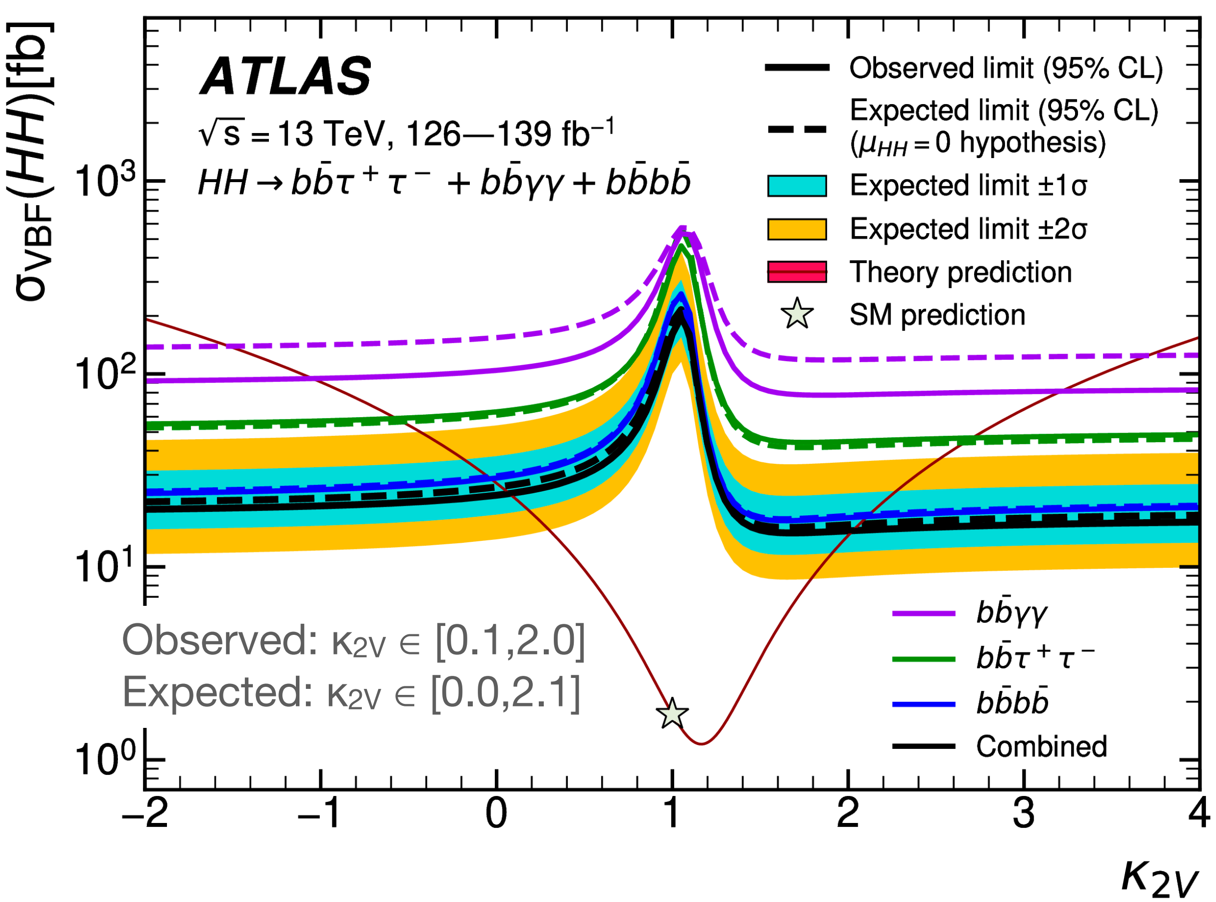
Nature 607, 60–68 (2022)

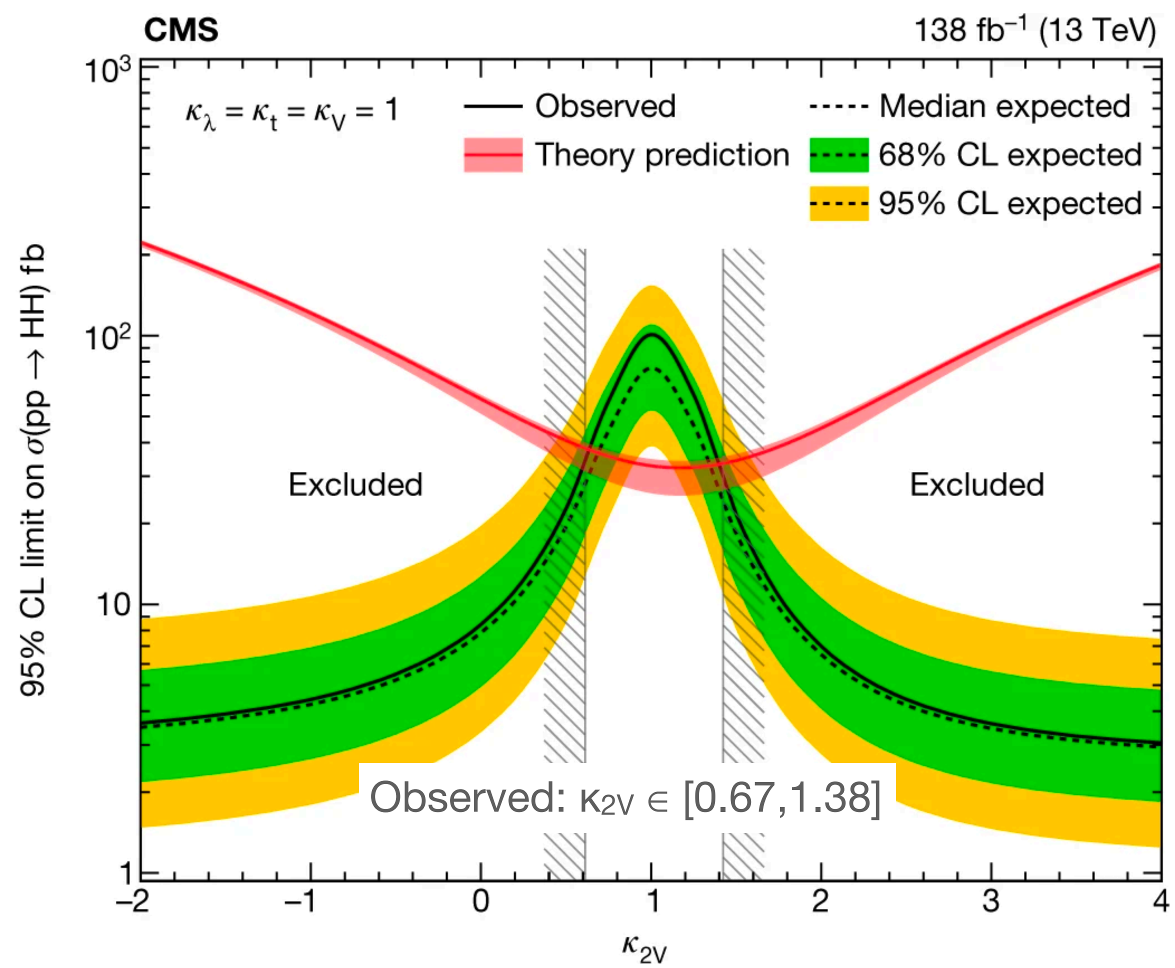
HH Combination

κ_{2V}

- Exclusion of $\kappa_{2V} = 0$

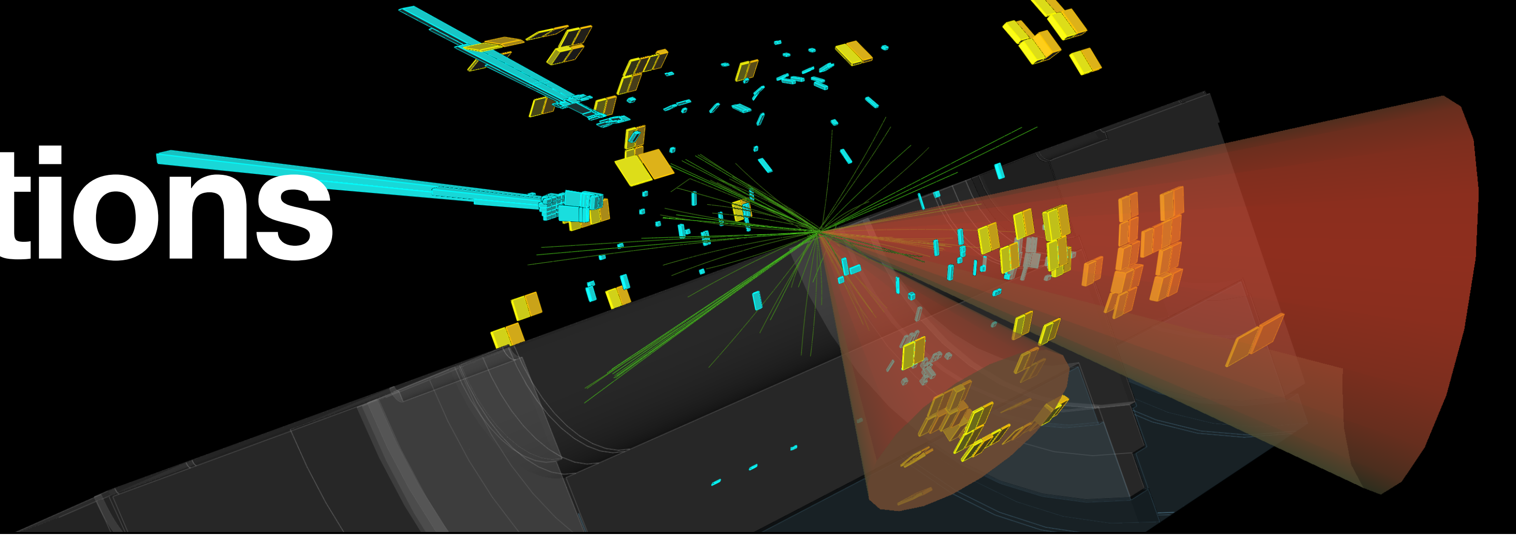
Phys. Lett. B 843 (2023) 137745



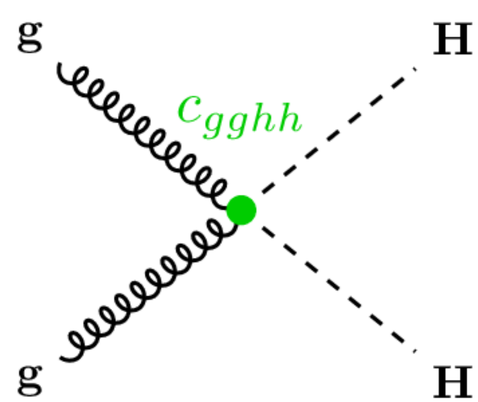


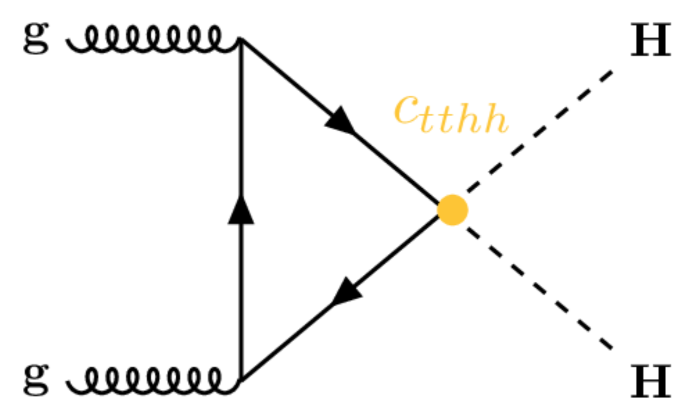
Nature 607, 60–68 (2022)

EFT Interpretations

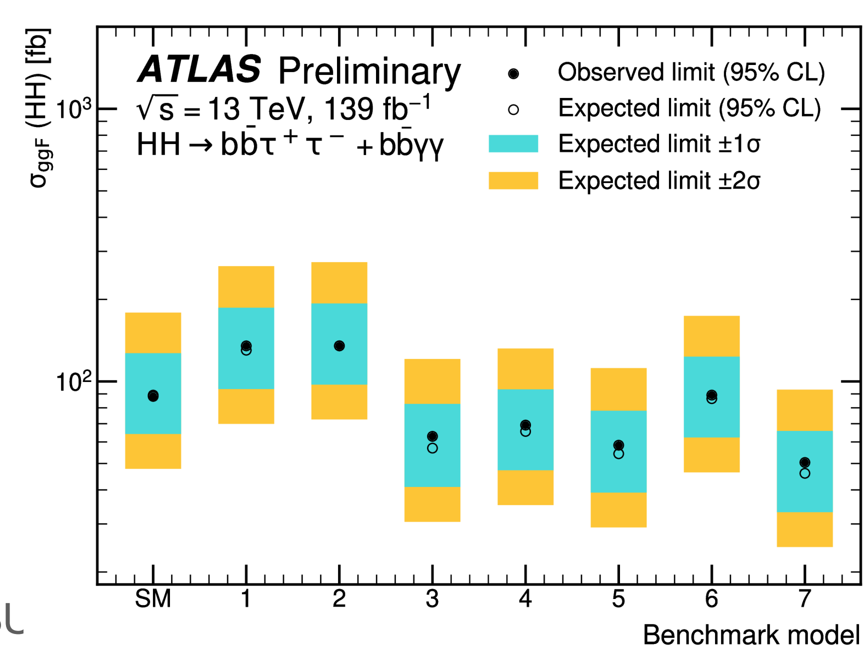


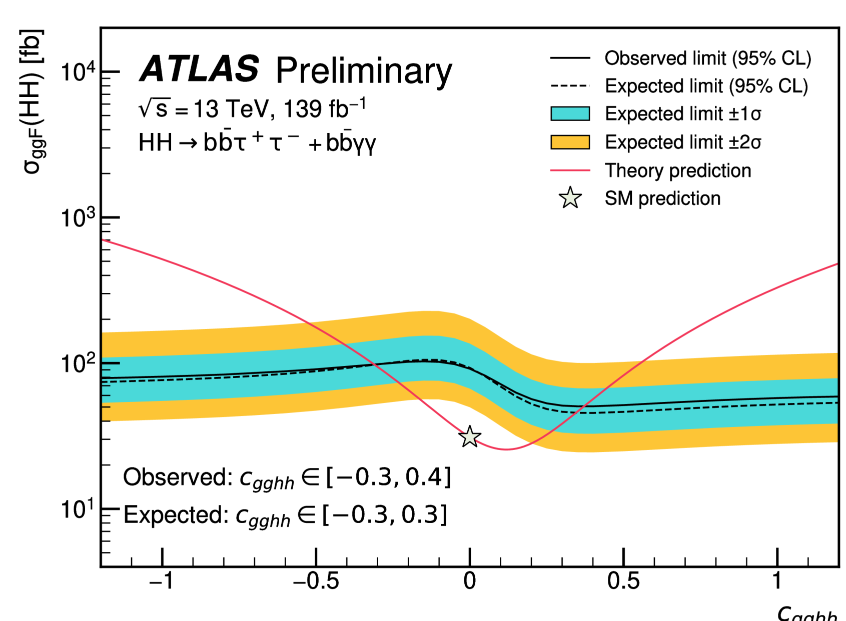
- HH results are also interpreted in the context of Effective Field Theories (EFTs)
- The Higgs EFT (HEFT) includes two additional effective coupling parameters





- bbγγ and bbττ combined limits on HEFT shape benchmarks and couplings





ATL-PHYS-PUB-2022-019