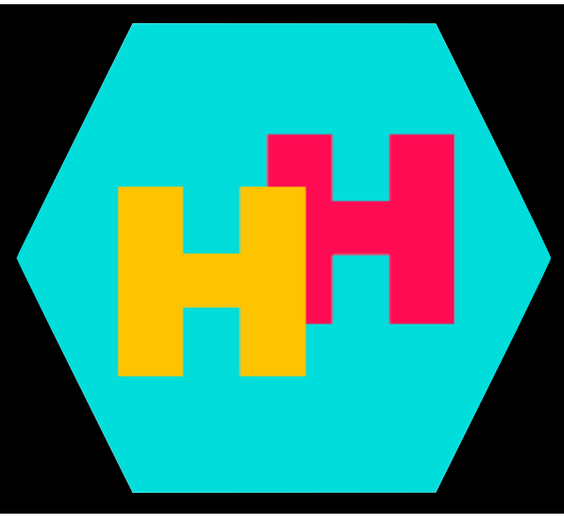
Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

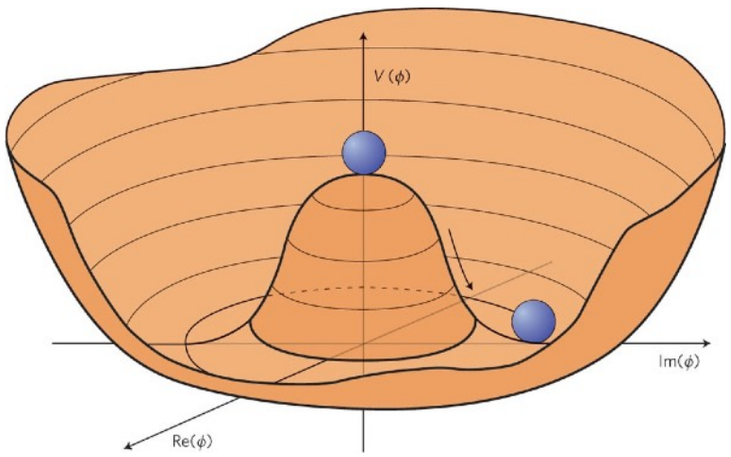
Higgs 2022: November 7th - 11th
Pisa, Italy

Jason Veatch on behalf of the ATLAS Collaboration
CSU East Bay

Higgs Self-Coupling



Measuring λ

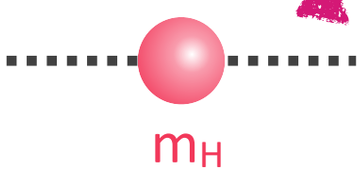


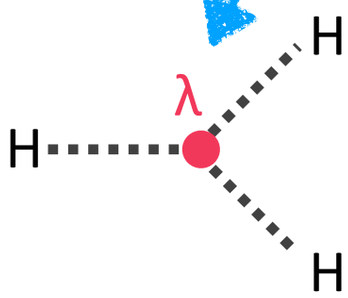
The Higgs potential: $V(\Phi) = \mu^2\Phi^*\Phi + \lambda|\Phi^*\Phi|^2$

λ has not yet been measured **directly**

Expanding around the minimum:

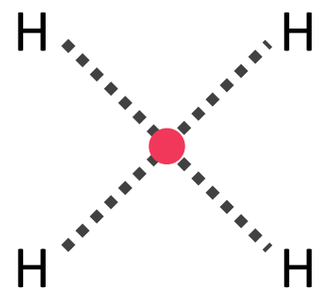
$$V(h) \simeq \frac{1}{2}m_H^2h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$





Measuring the self coupling would give a direct measurement of λ

λ ≠ λ^{SM} could indicate new physics

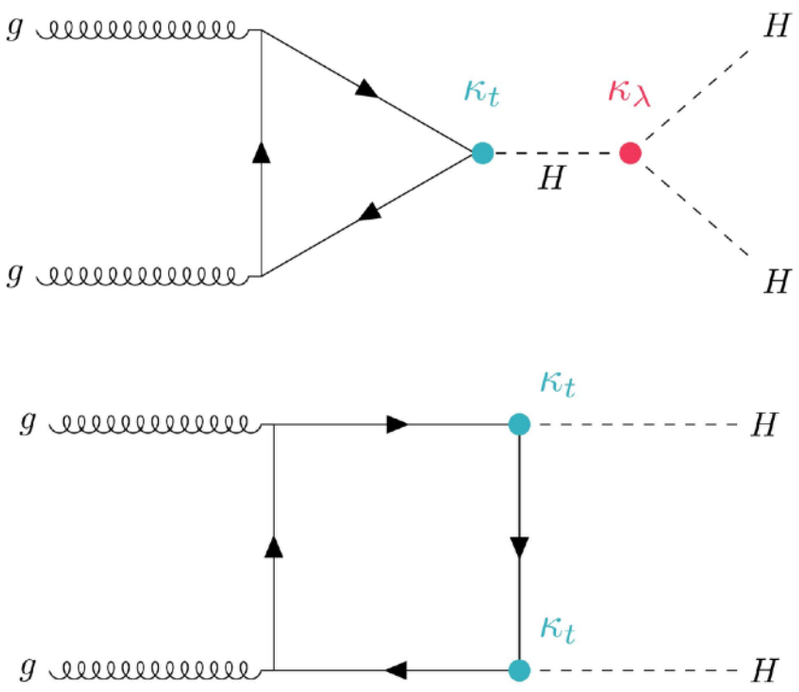


Likely unreachable by the LHC…

HH Production

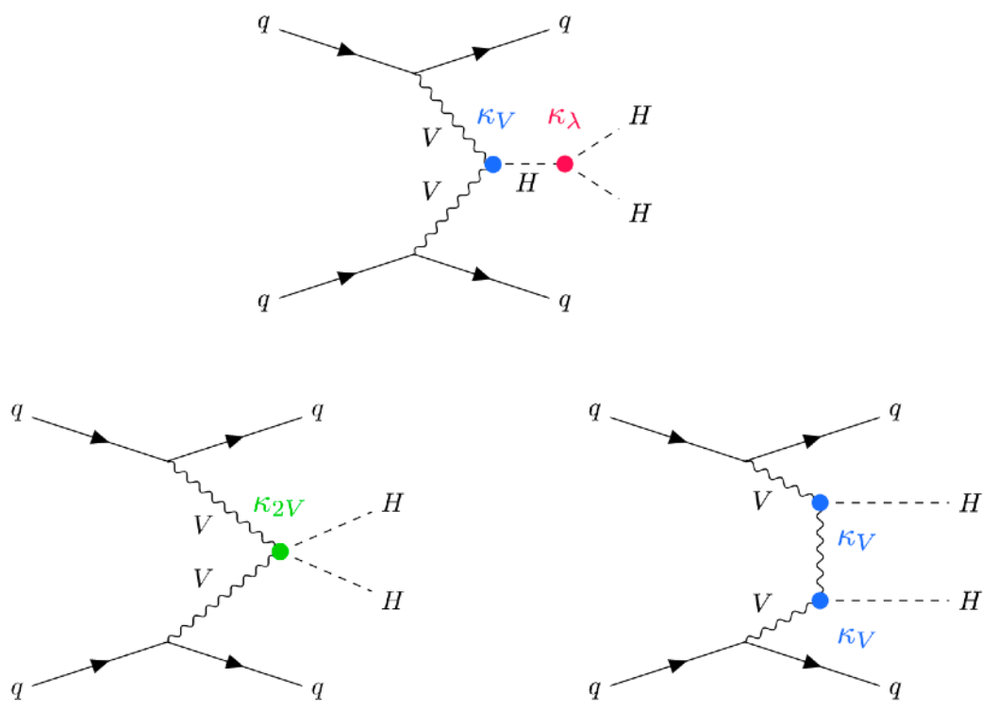
ggF

- The “triangle” diagram involves Higgs boson self-coupling
  - The coupling modifier κ_λ is defined as λ/λ^{SM}
- The “box” diagram interferes destructively, resulting in a small cross-section (~31 fb)

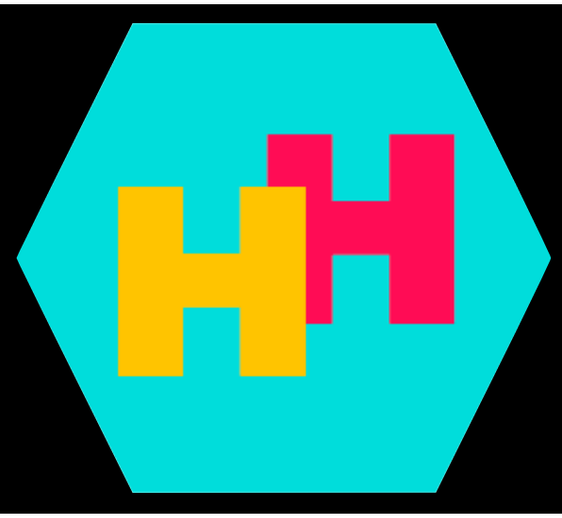


VBF

- Sensitive to κ_λ
- Gives access to the HHVV coupling (κ_{2V} is the coupling modifier)
- Smaller cross-section than gluon-gluon fusion (~1.72 fb)
- Unique signature of two forward jets



ATLAS HH Searches



HH Decay Modes

Available ATLAS results

- The small HH cross-section means multiple final states must be used
- Search channels chosen due to BR and clean final states (low background)

	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%

4b:
ATLAS-CONF-2022-035

bbWW(2l) (not shown):
Phys. Lett. B 801 (2020) 135145

bbττ:
Submitted to JHEP

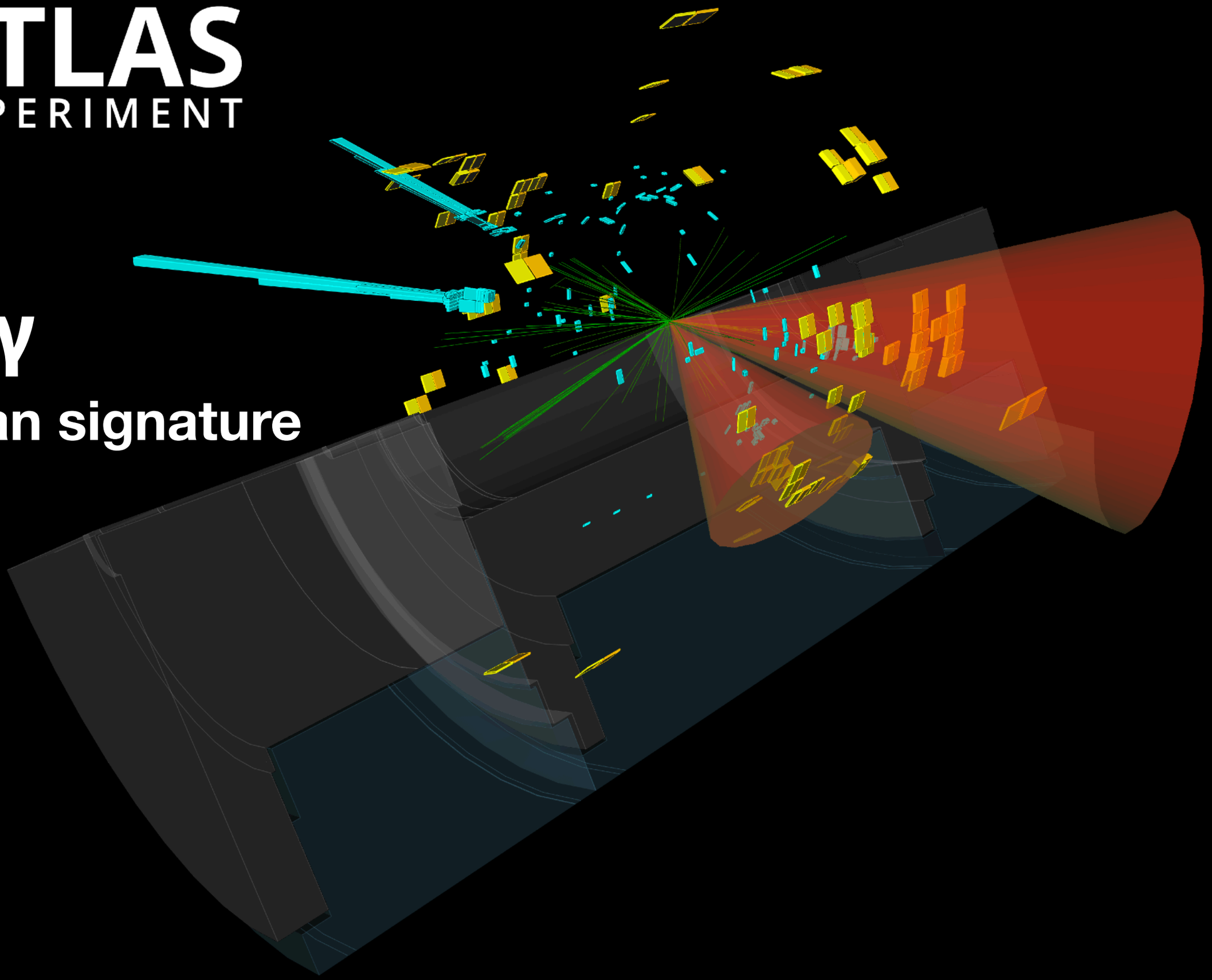
bbγγ:
Phys. Rev. D 106 (2022) 052001

Partial Run 2 results (not shown):
JHEP 05 (2019) 124 and Eur. Phys. J. C 78 (2018) 1007

ATLAS EXPERIMENT

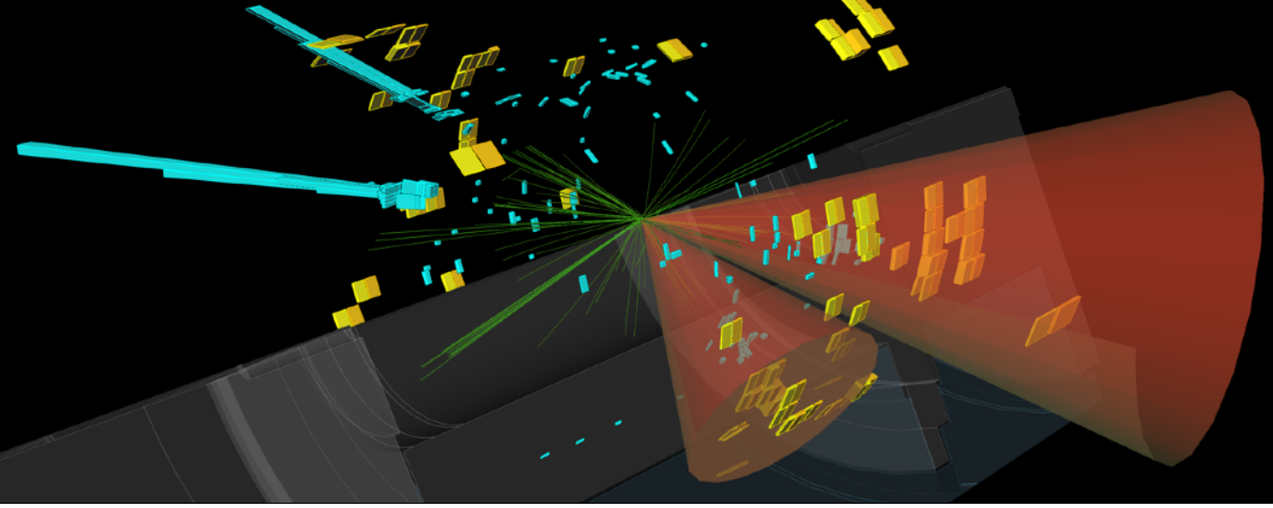
bbγγ

A clean signature

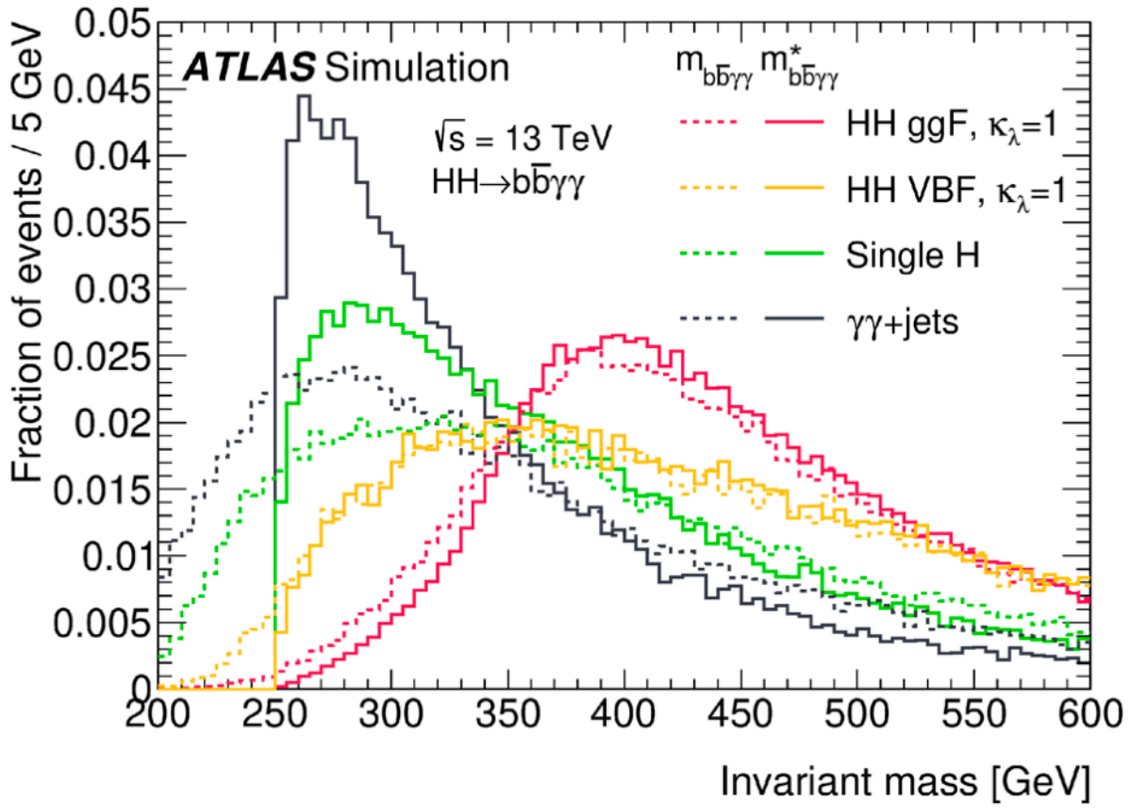


Phys. Rev. D 106 (2022) 052001

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 120 GeV ≤ $m_{\gamma\gamma}$ ≤ 130 GeV
  - Exactly 2 b-tagged jets
  - No e/μ in event



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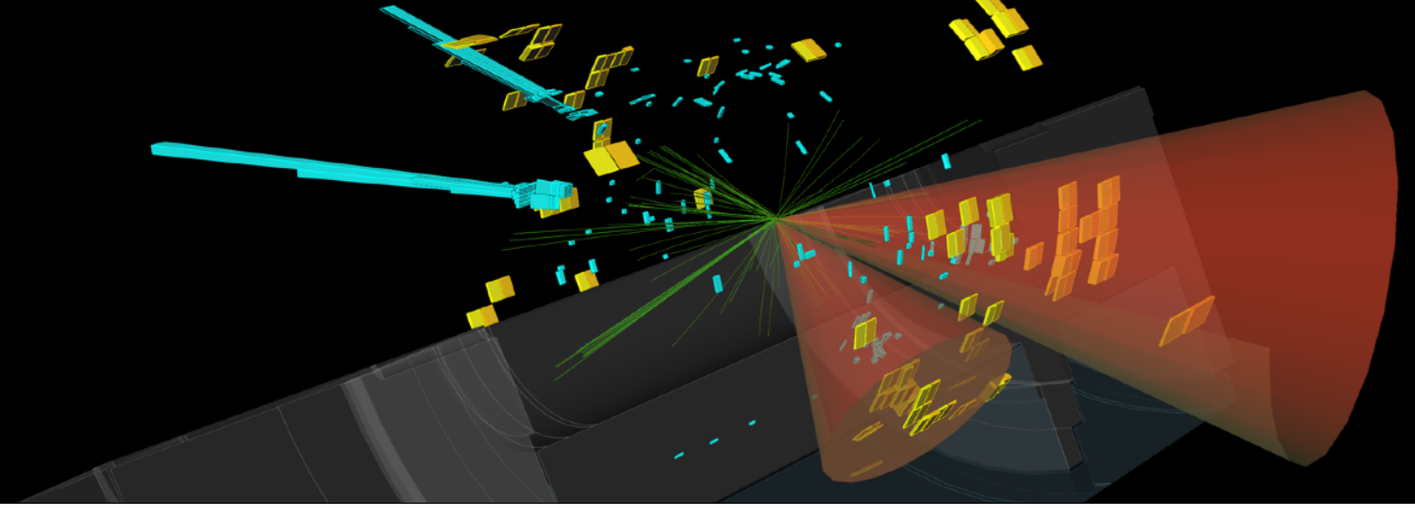
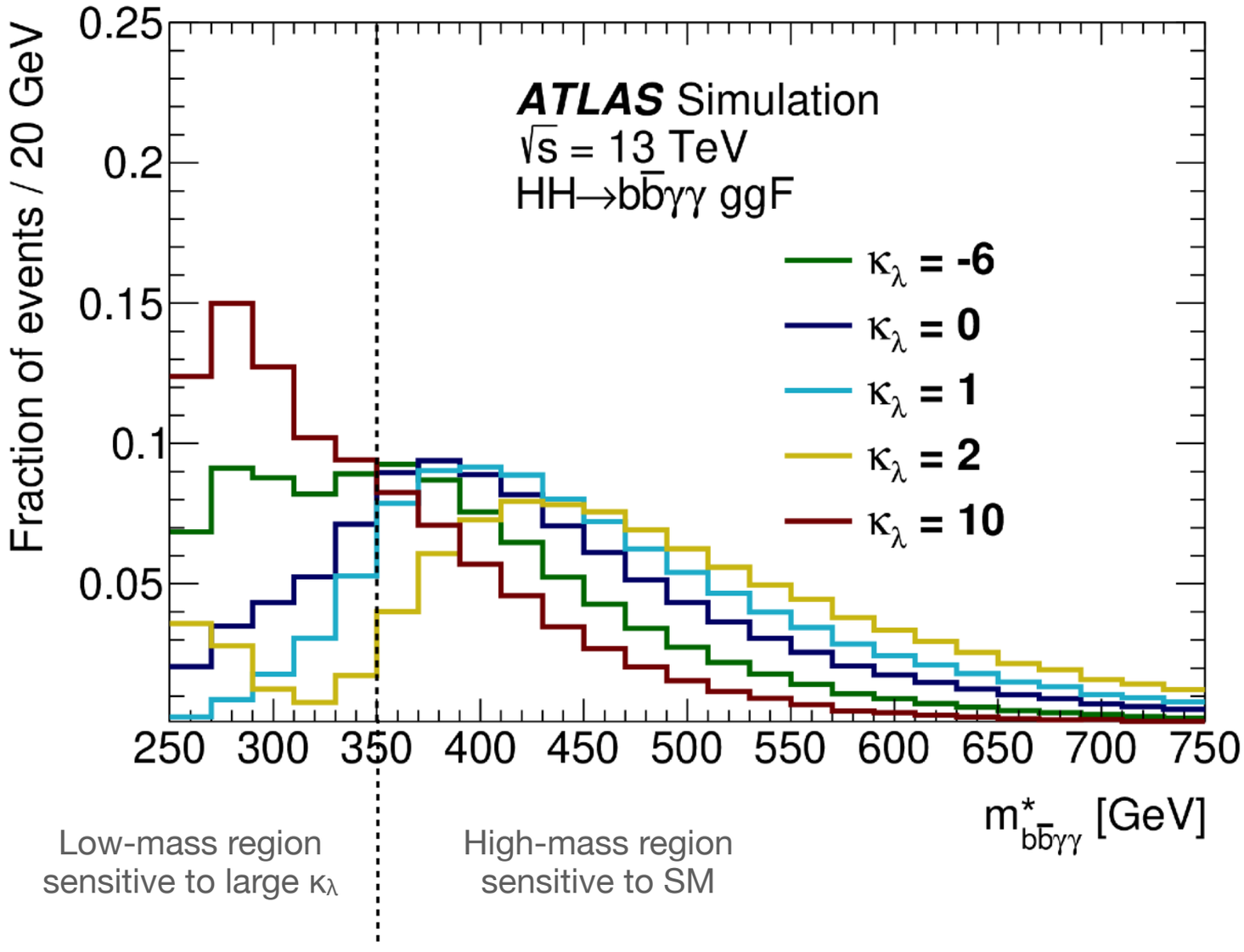
bbγγ
Analysis regions



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



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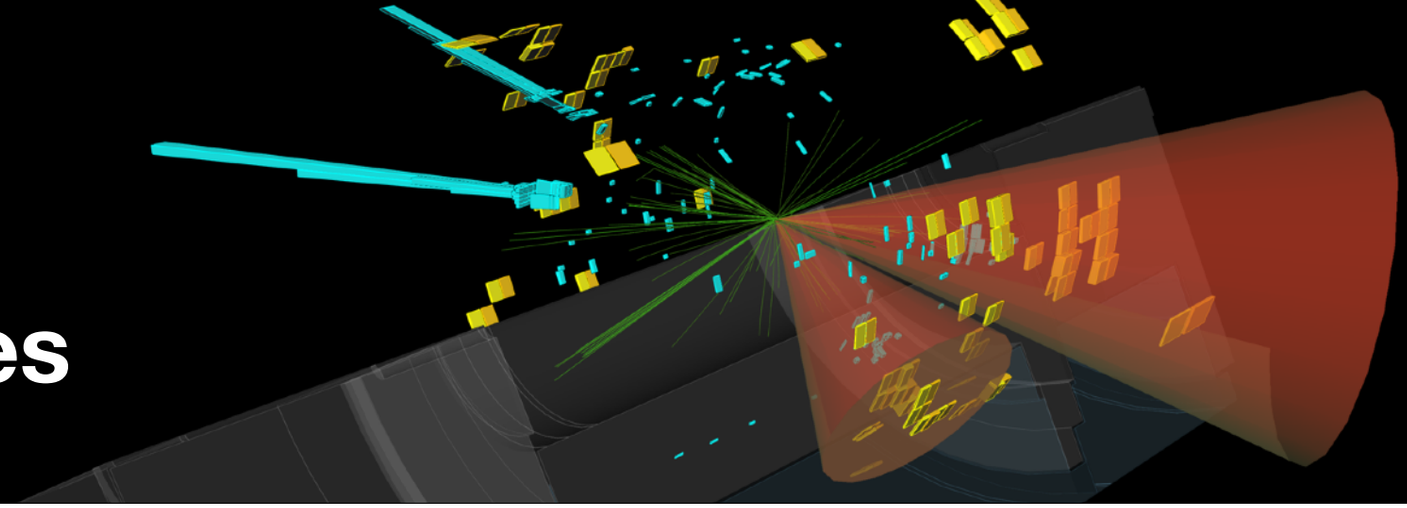
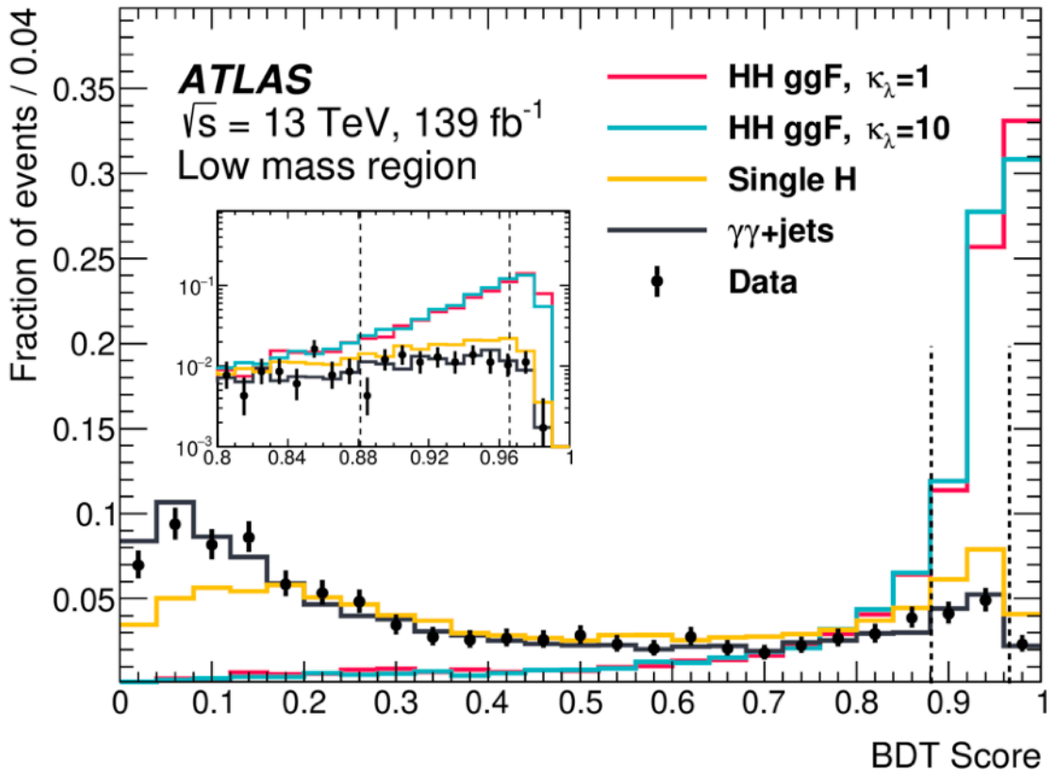
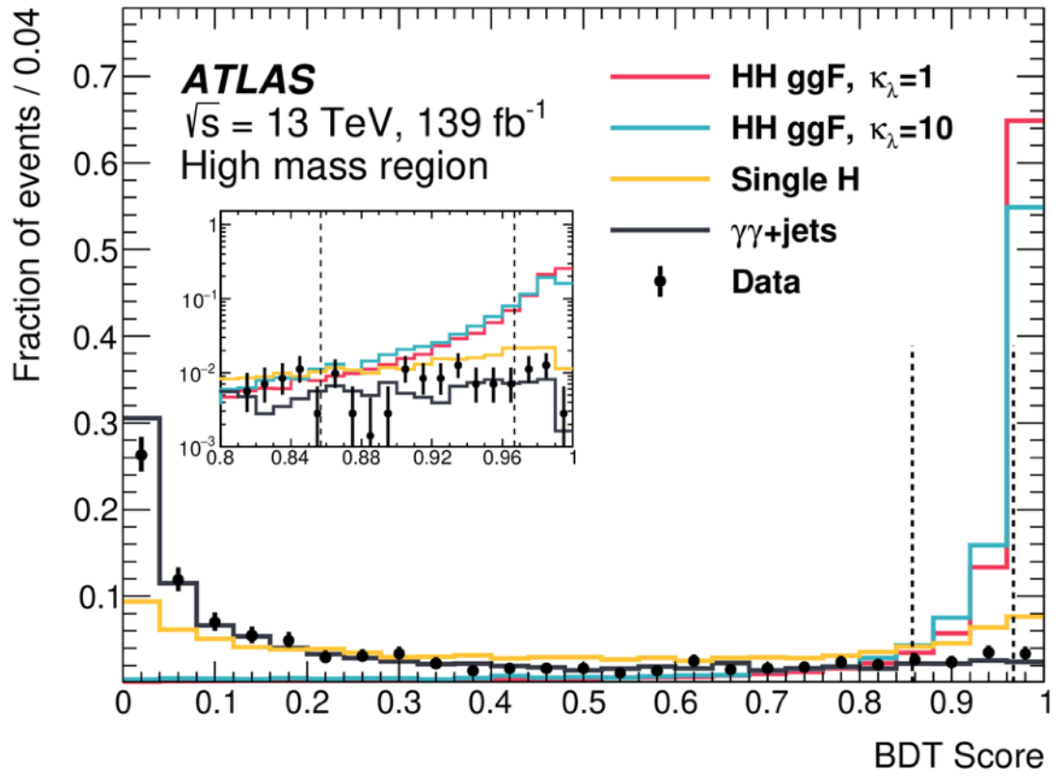
bbγγ
Multivariate techniques



- Use Boosted Decision Trees (BDTs) to distinguish signal from background
  - Combination of 2 BDTs (trained against continuum and single Higgs bkgs)
  - Split into loose- and tight-BDT categories





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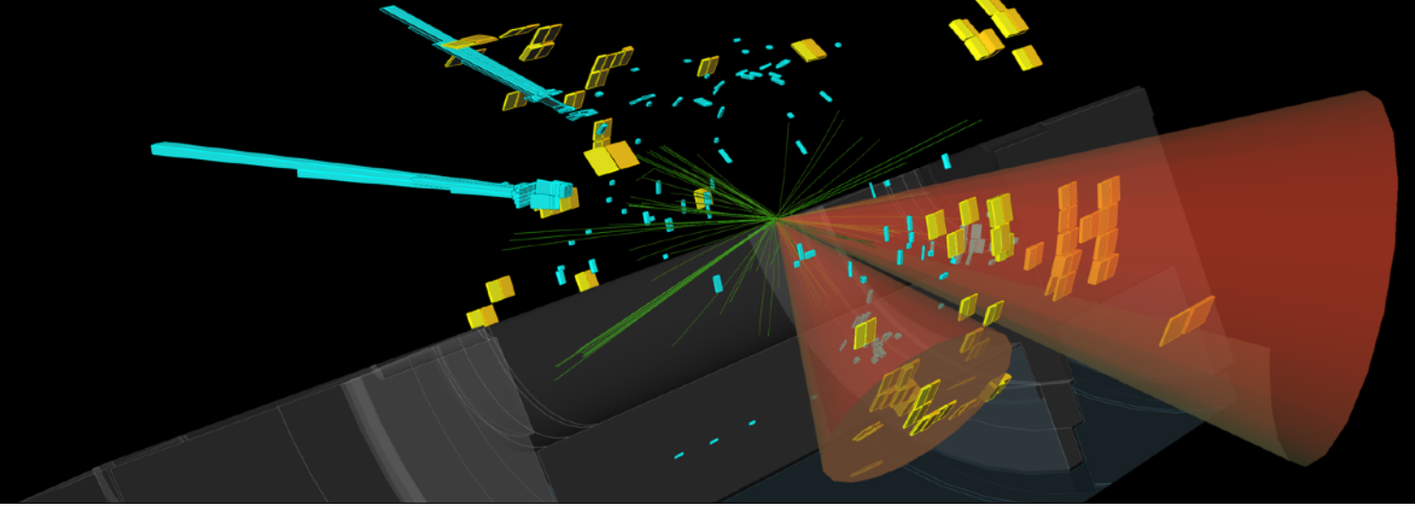
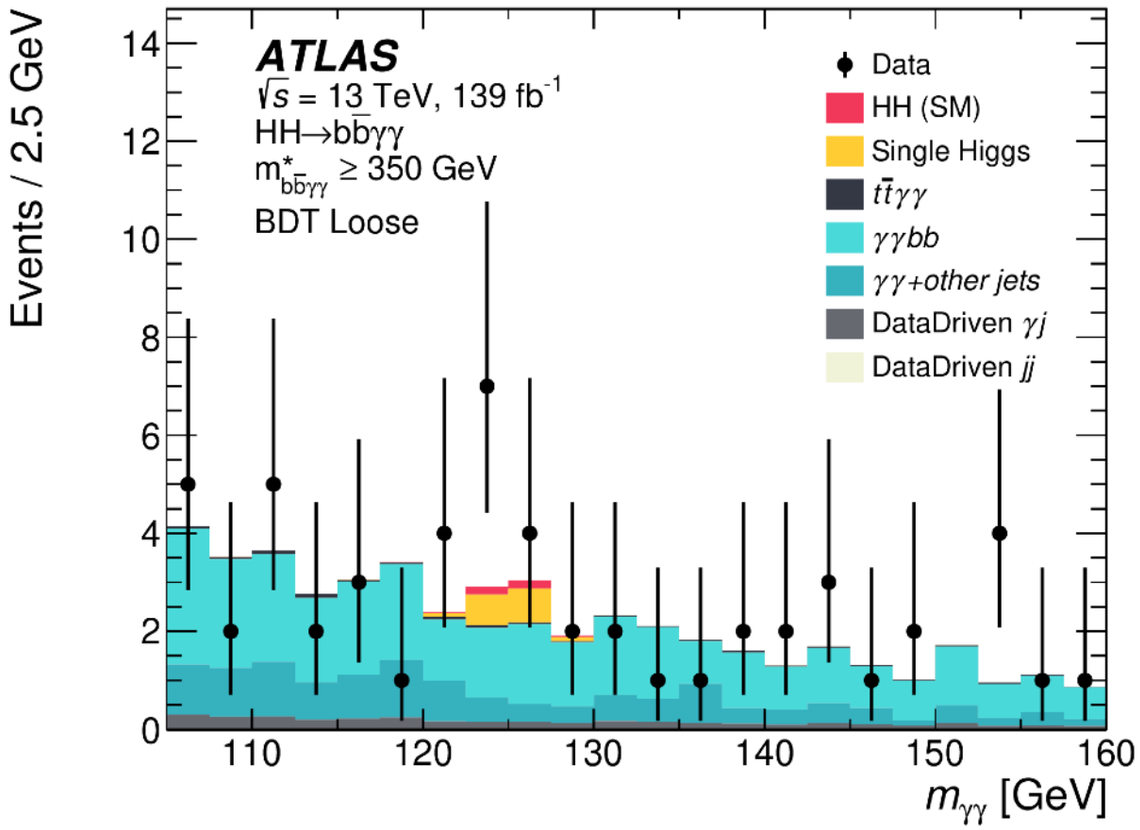
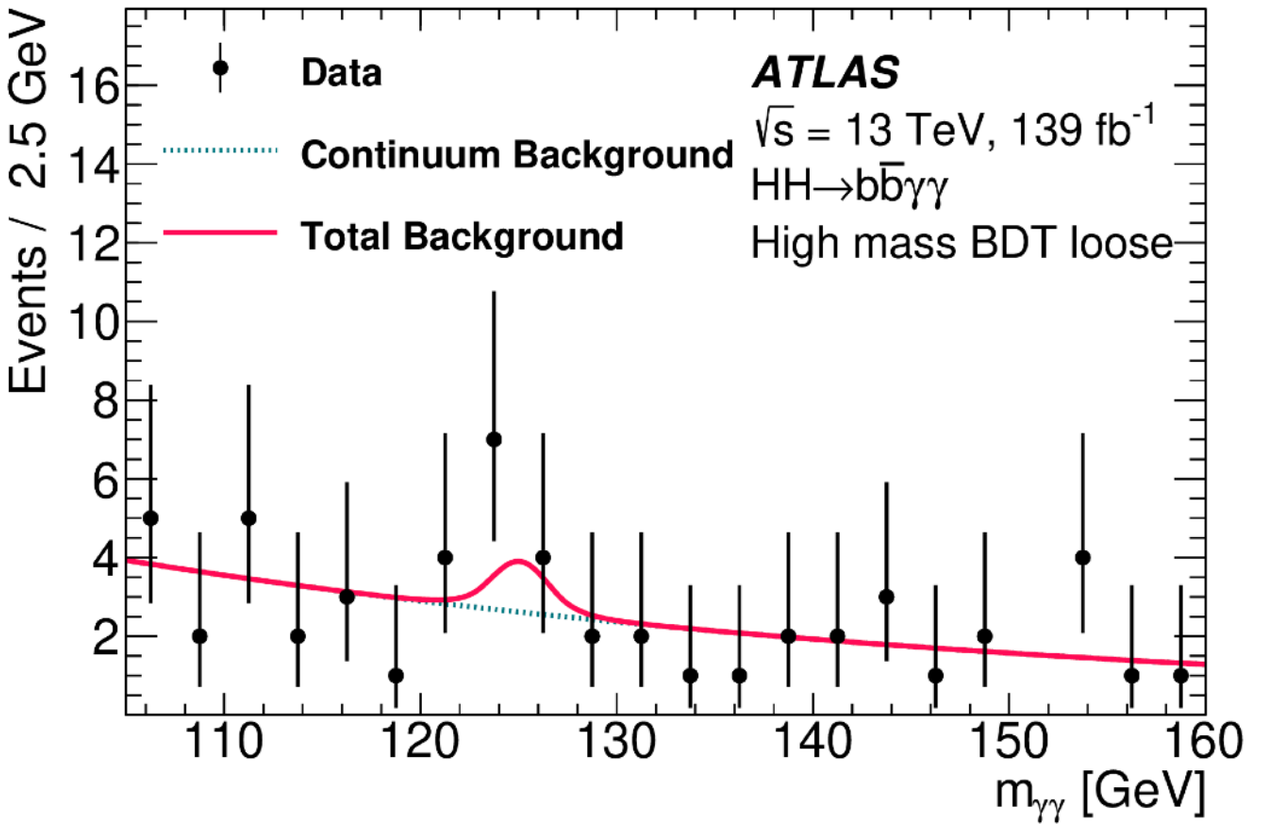
bbγγ
Signal extraction



- $m_{\gamma\gamma}$ distribution fit in each category and signal strength allowed to float





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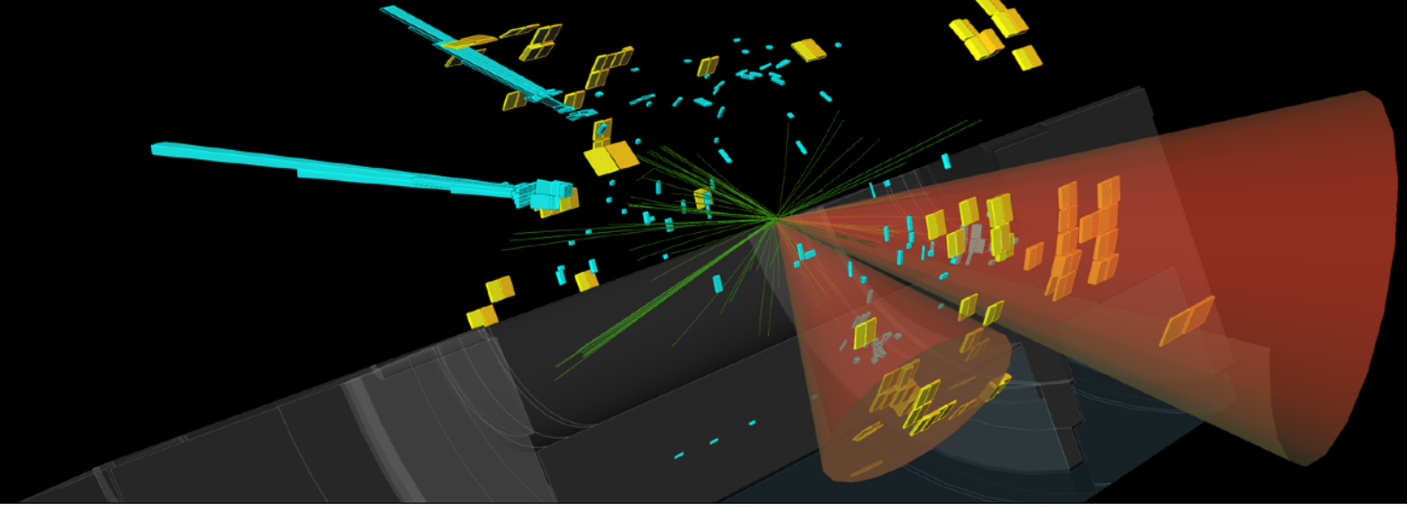
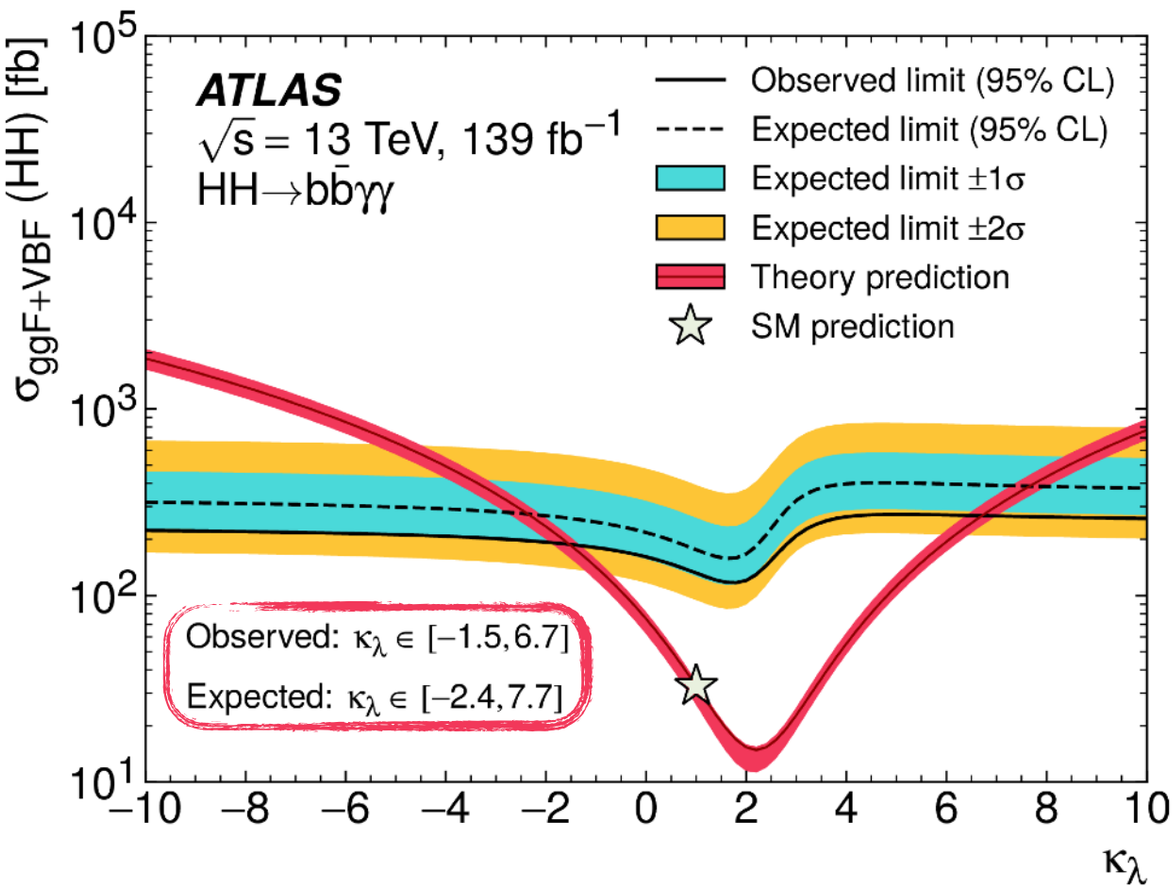
bbγγ
Results



- Limits set on μ_{SM} and κ_λ

$\mu_{SM} < 4.2$ observed
(5.7 expected)



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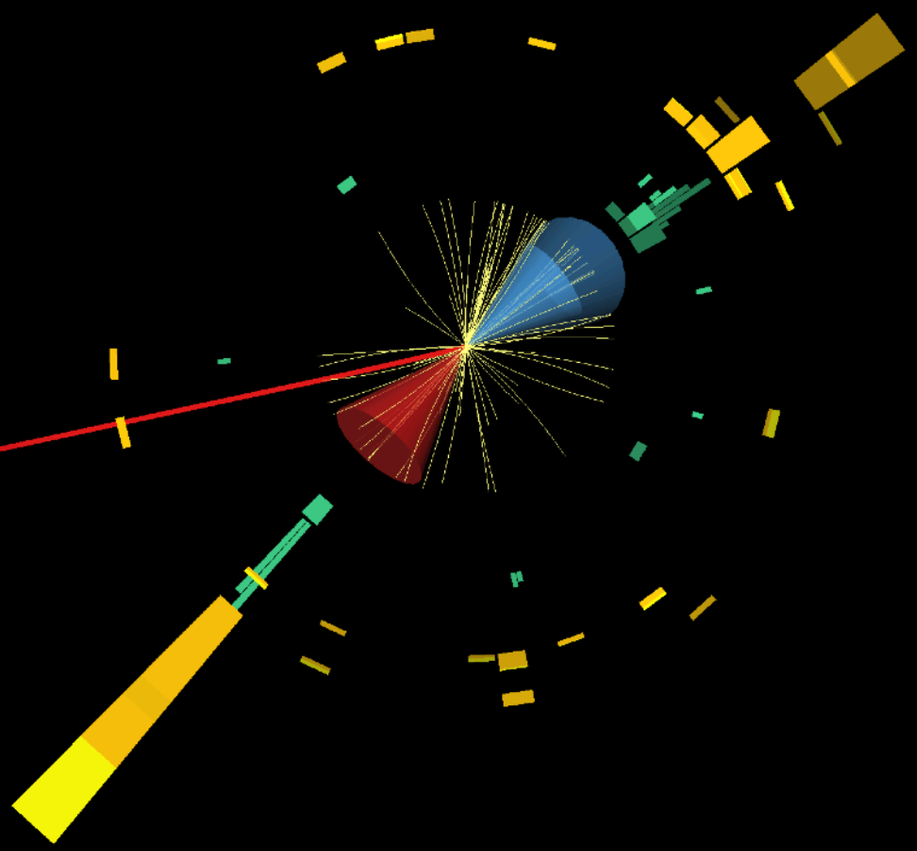
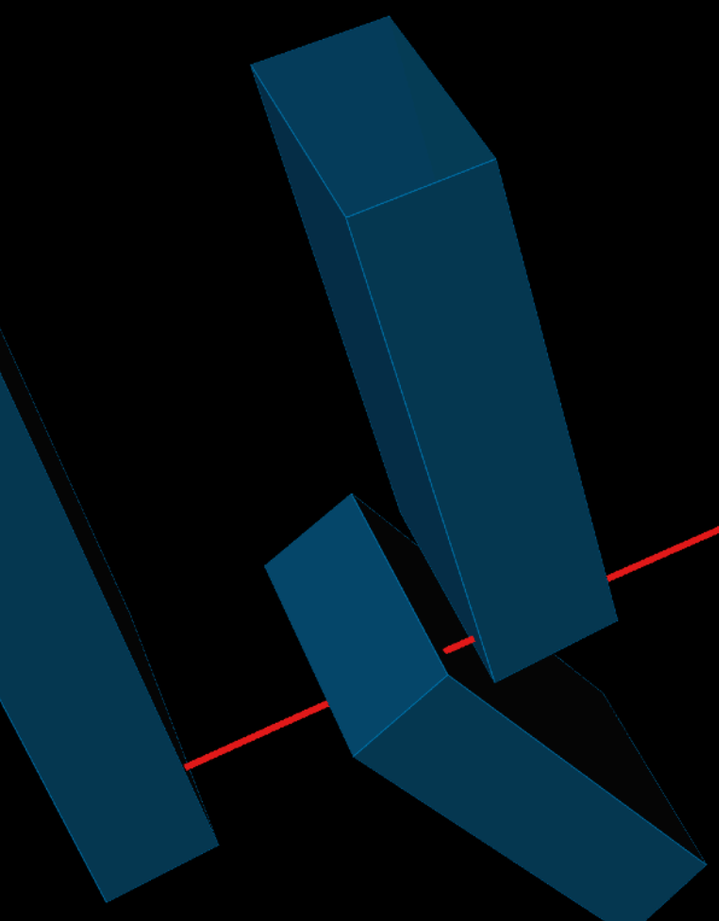
bbττ

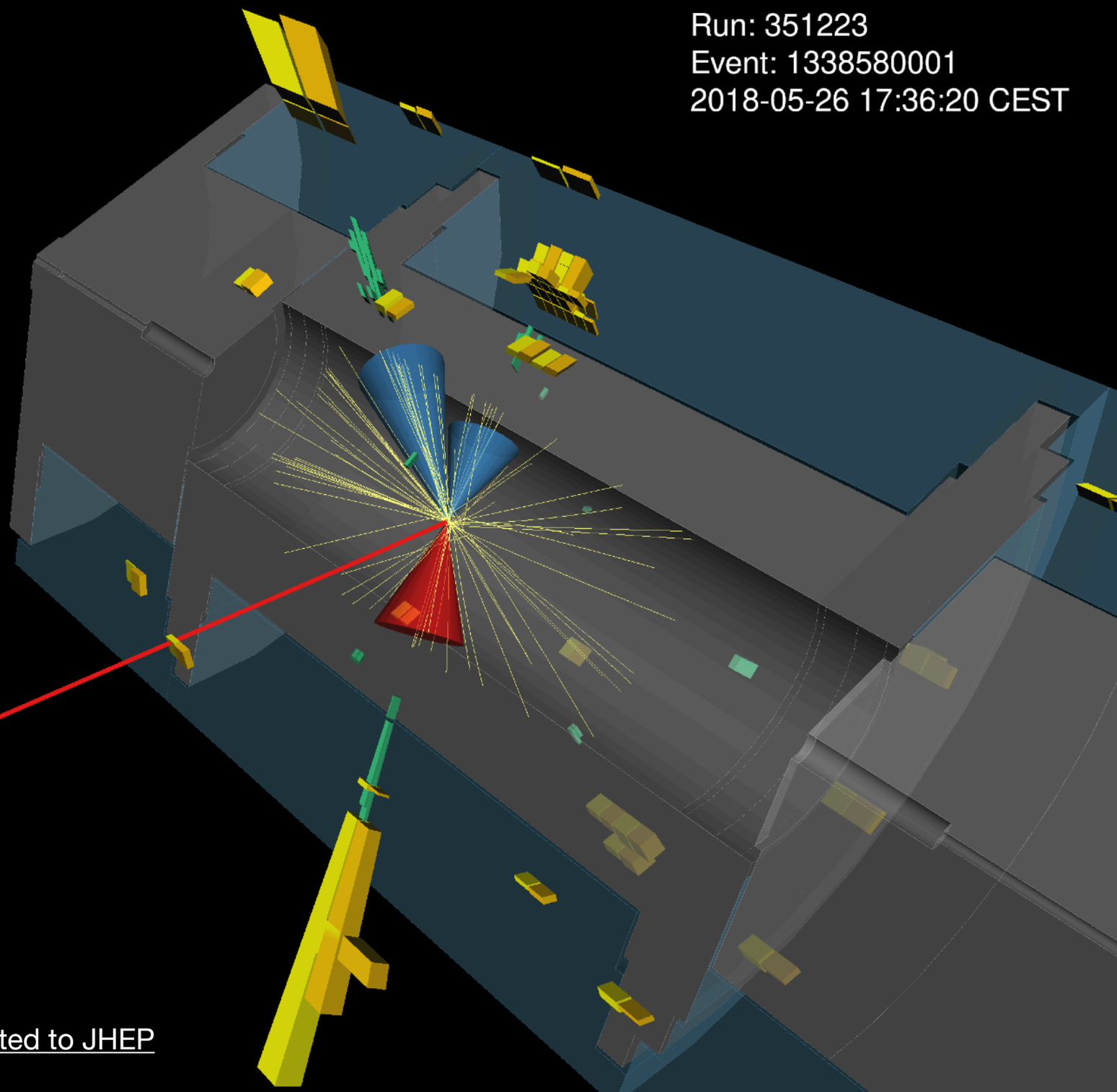
A good balance

ATLAS EXPERIMENT

Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST

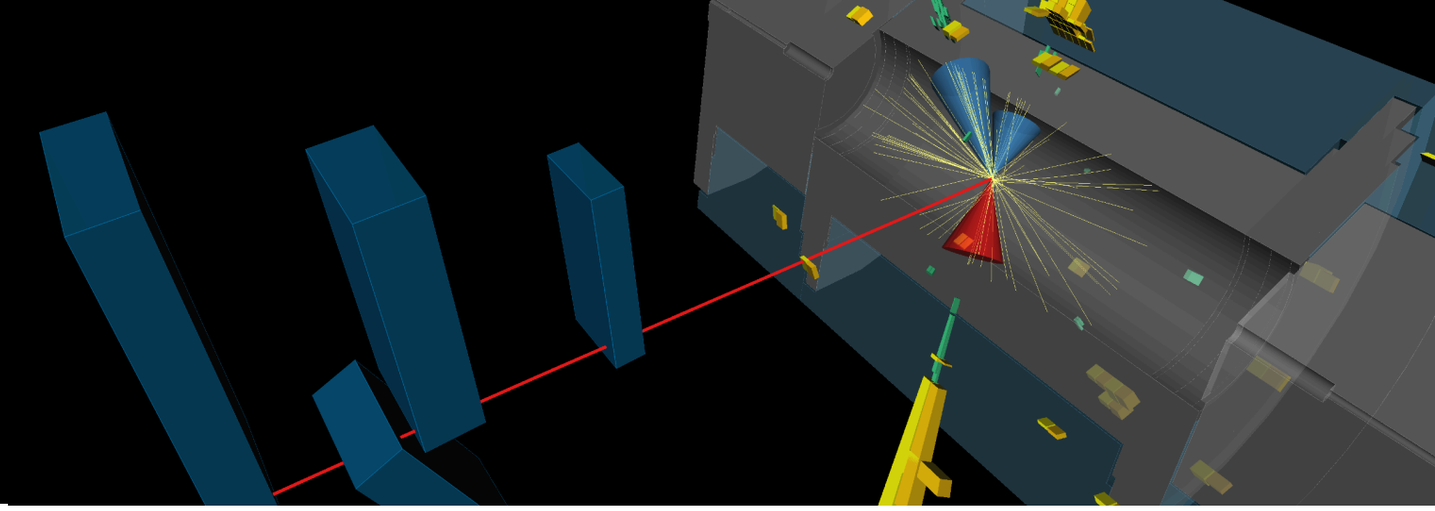






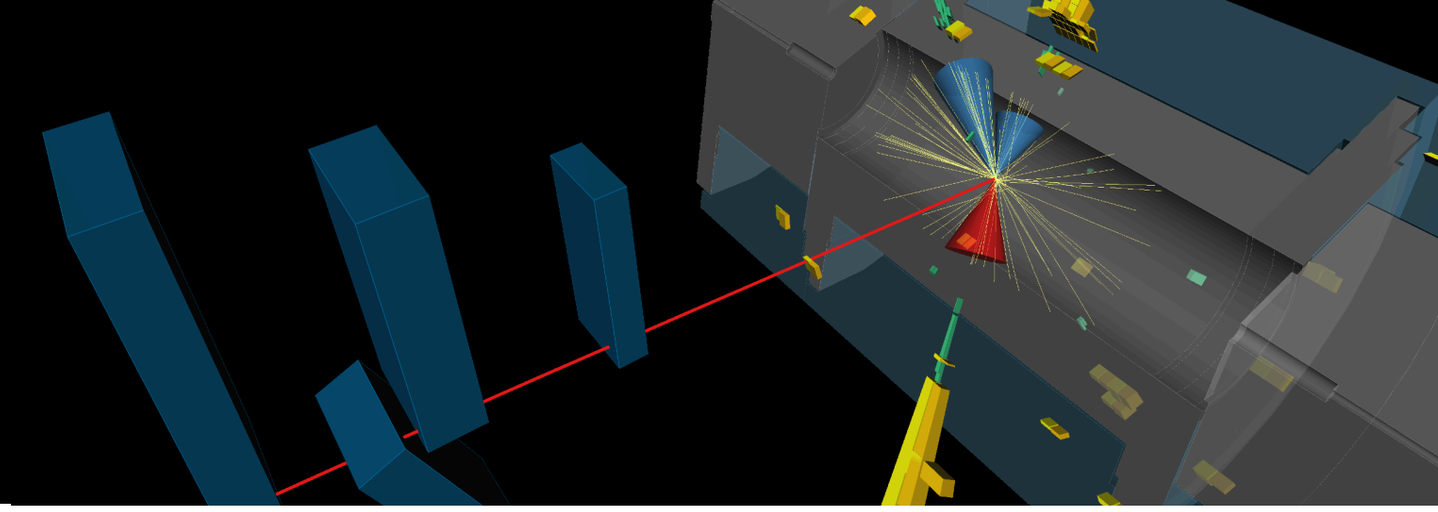
Submitted to JHEP

$bb\tau\tau$
Signature

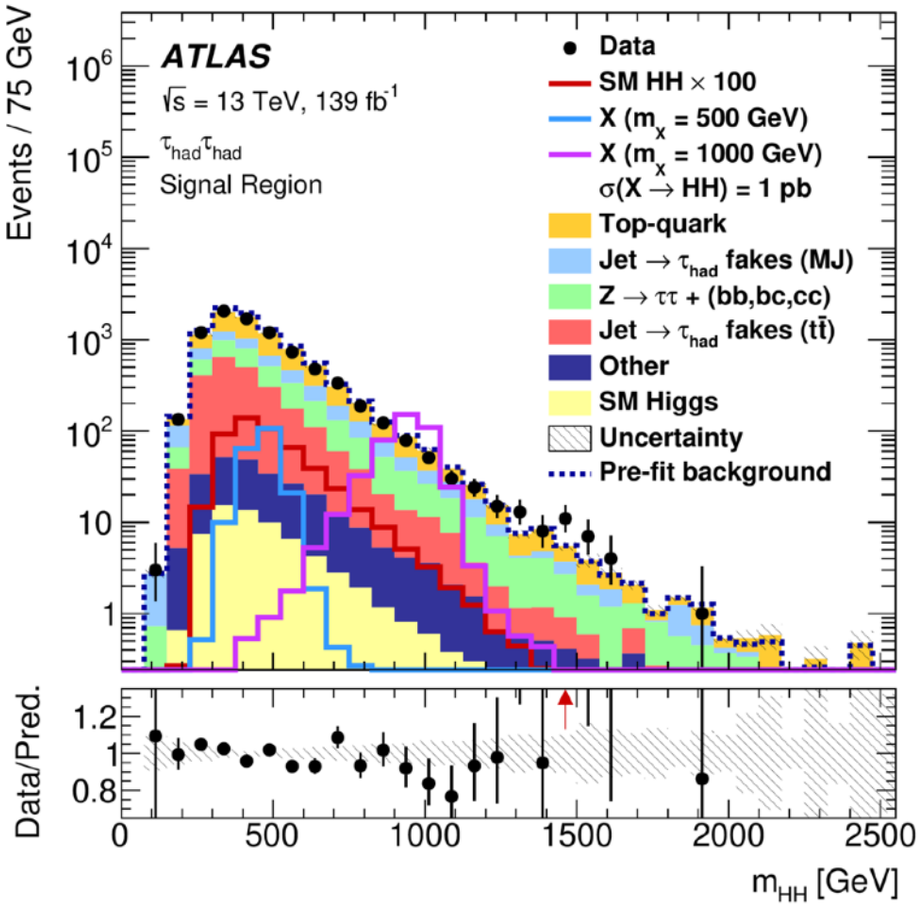


- Moderately large BR with relatively low background
- Fake-τ background difficult to model
- Split analysis based on τ decay modes ($\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$)
- Event selection:
  - Exactly 2 b-tagged jets
  - Either 2 hadronic τ or 1 hadronic τ and 1 e/μ
  - $m_{\tau\tau} > 60$ GeV using Missing Mass Calculator

bbττ
Background estimate



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



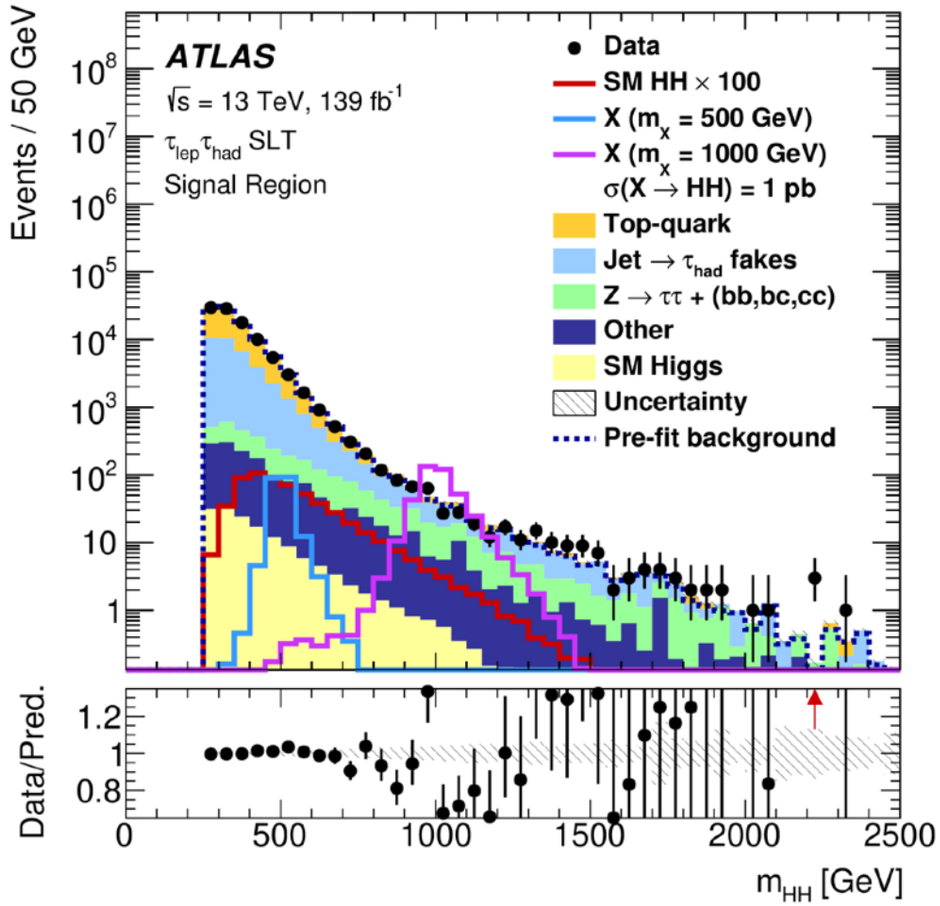
Top quark processes
Shape from MC and normalization from fit

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

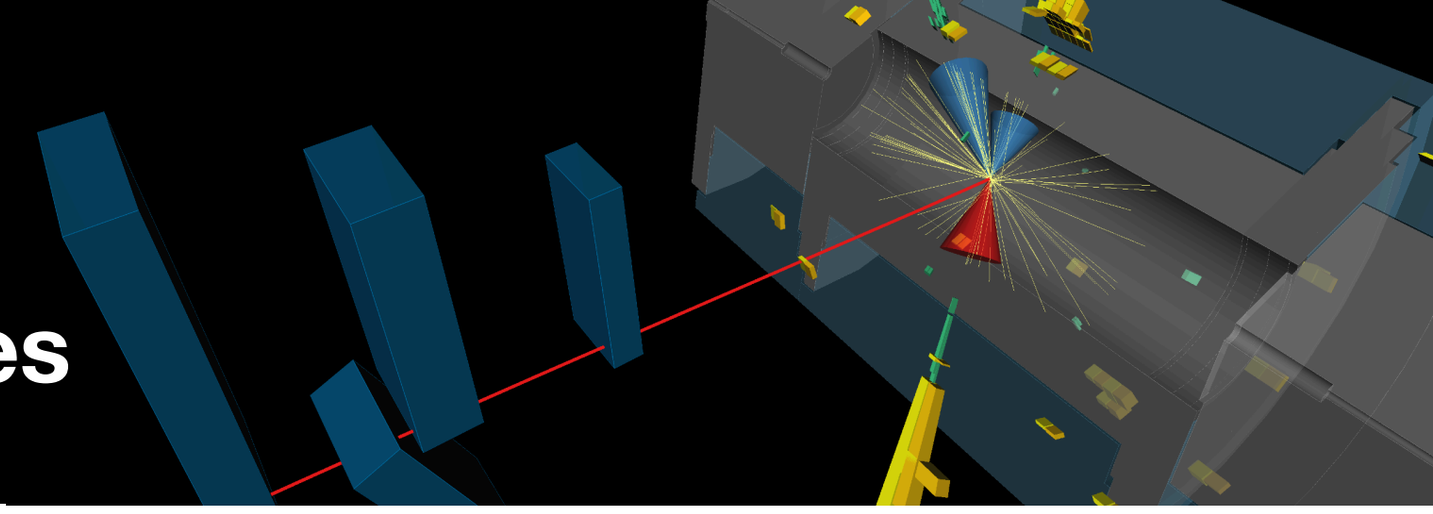
$\tau_{lep}\tau_{had}$



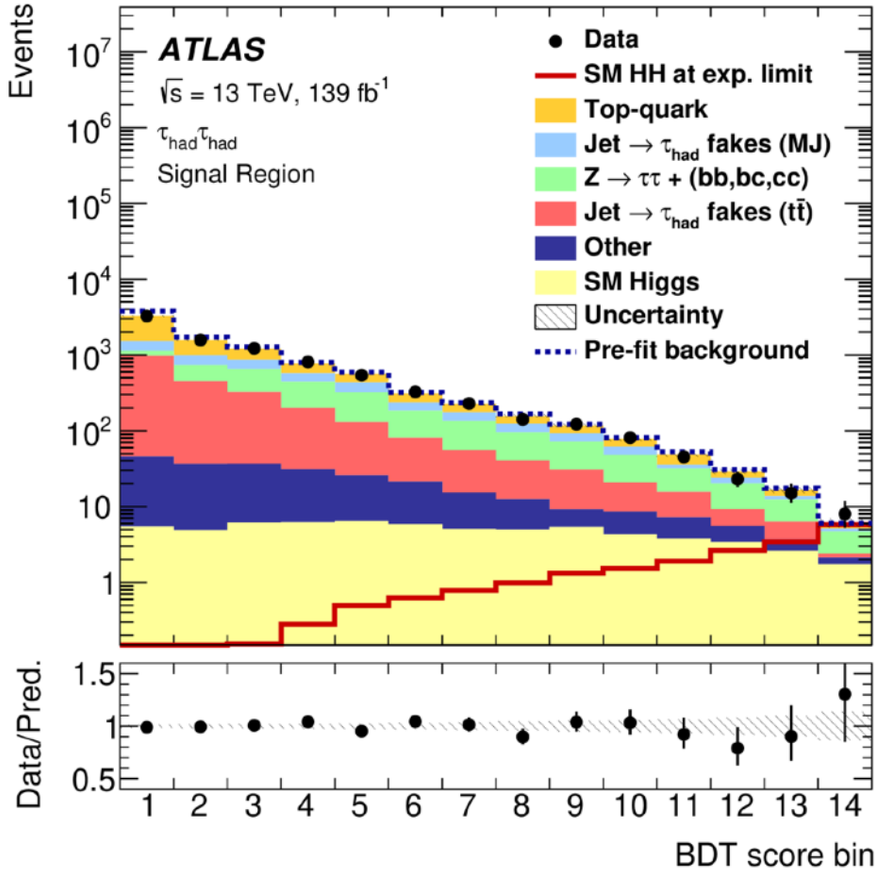
Submitted to JHEP

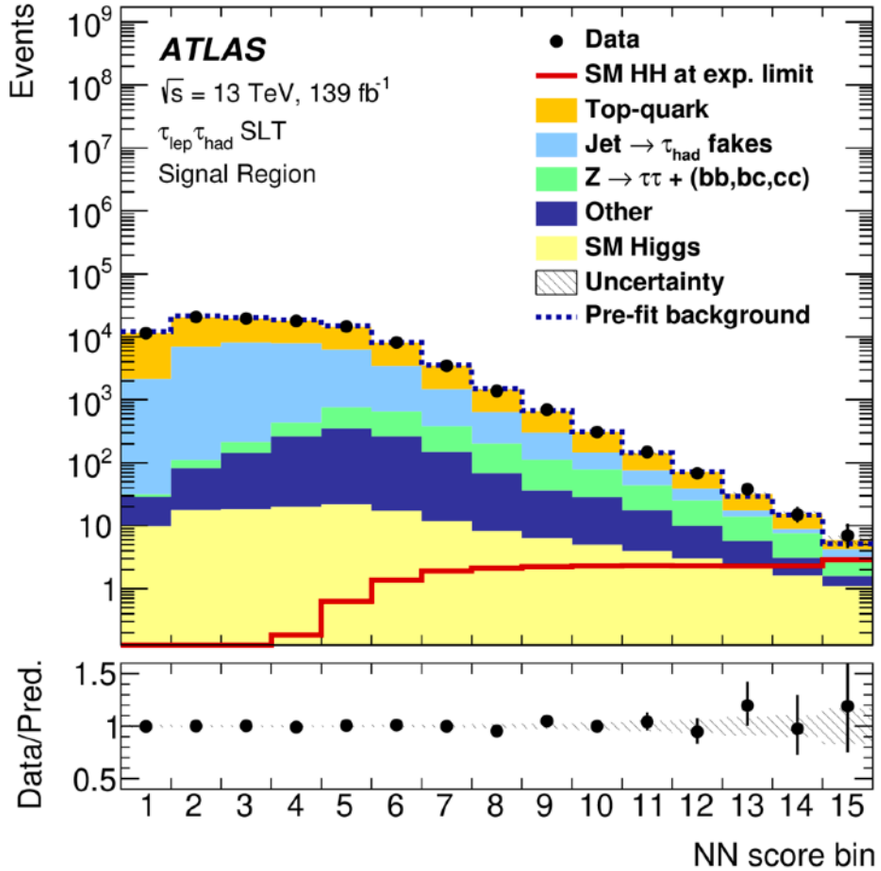
bbττ

Multivariate techniques



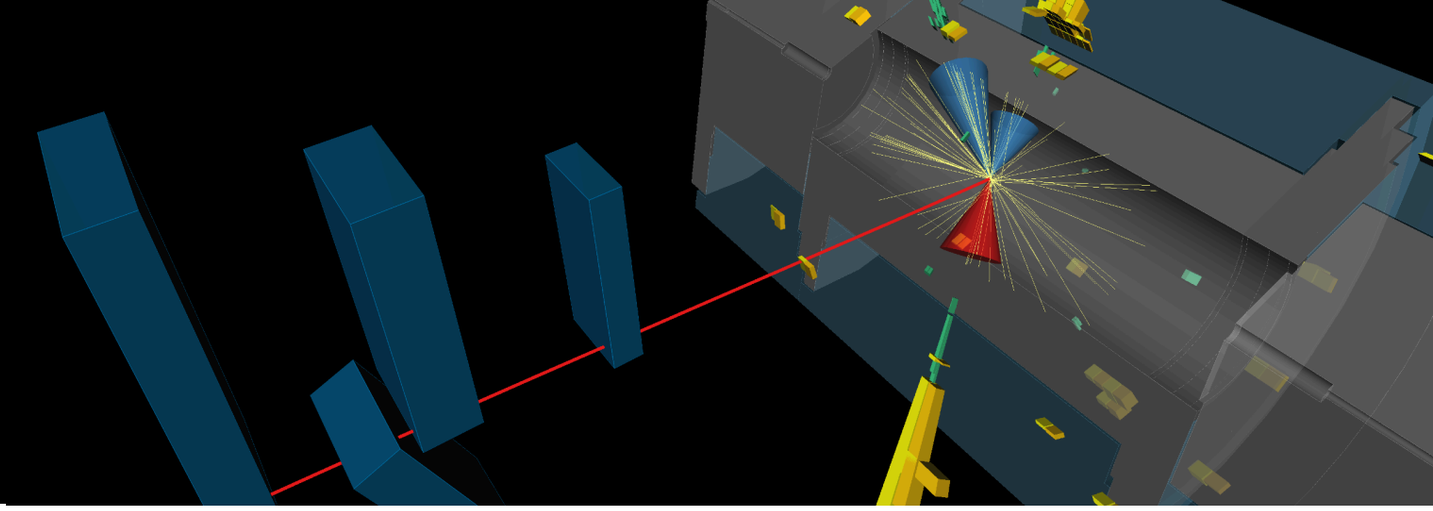
- BDTs and NNs used to distinguish signal from background
- MVA score used as final signal/background discriminant





Submitted to JHEP

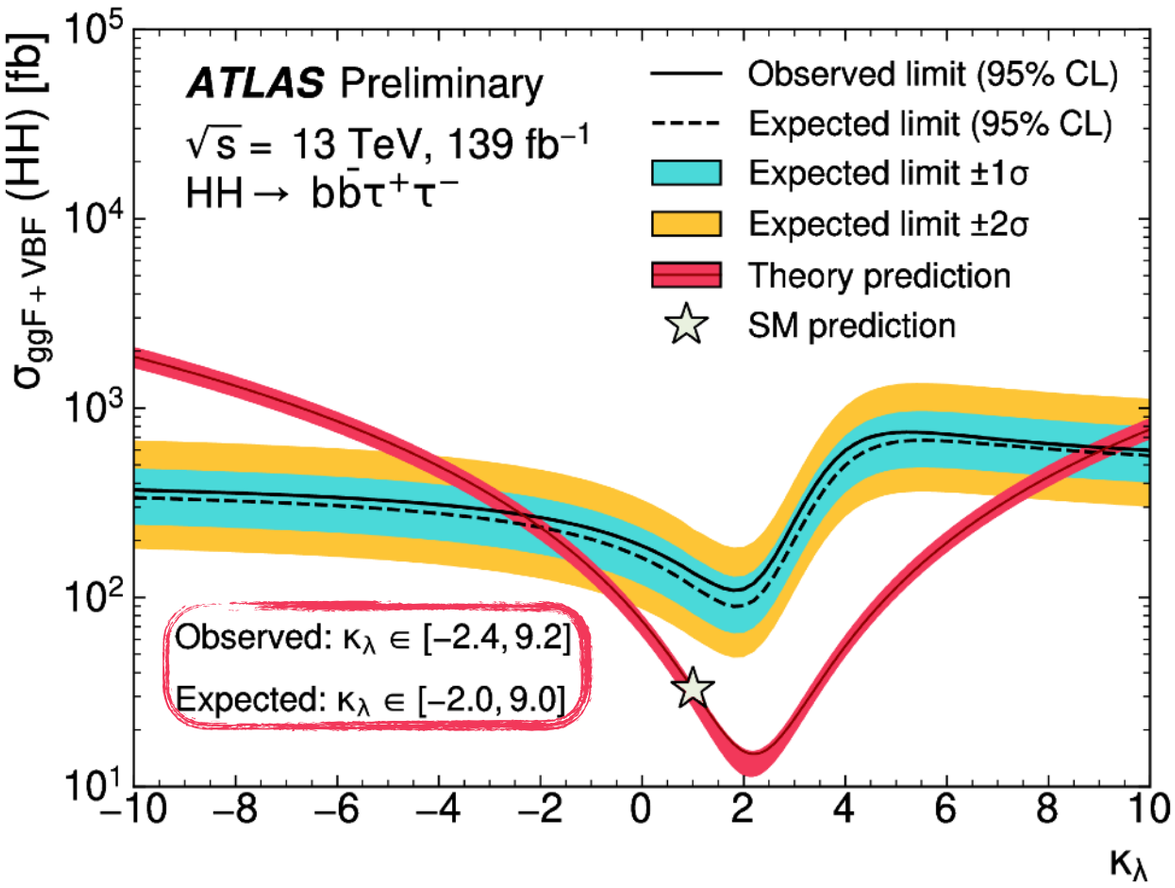
bbττ
Results



- Limits set on μ_{SM} and κ_λ

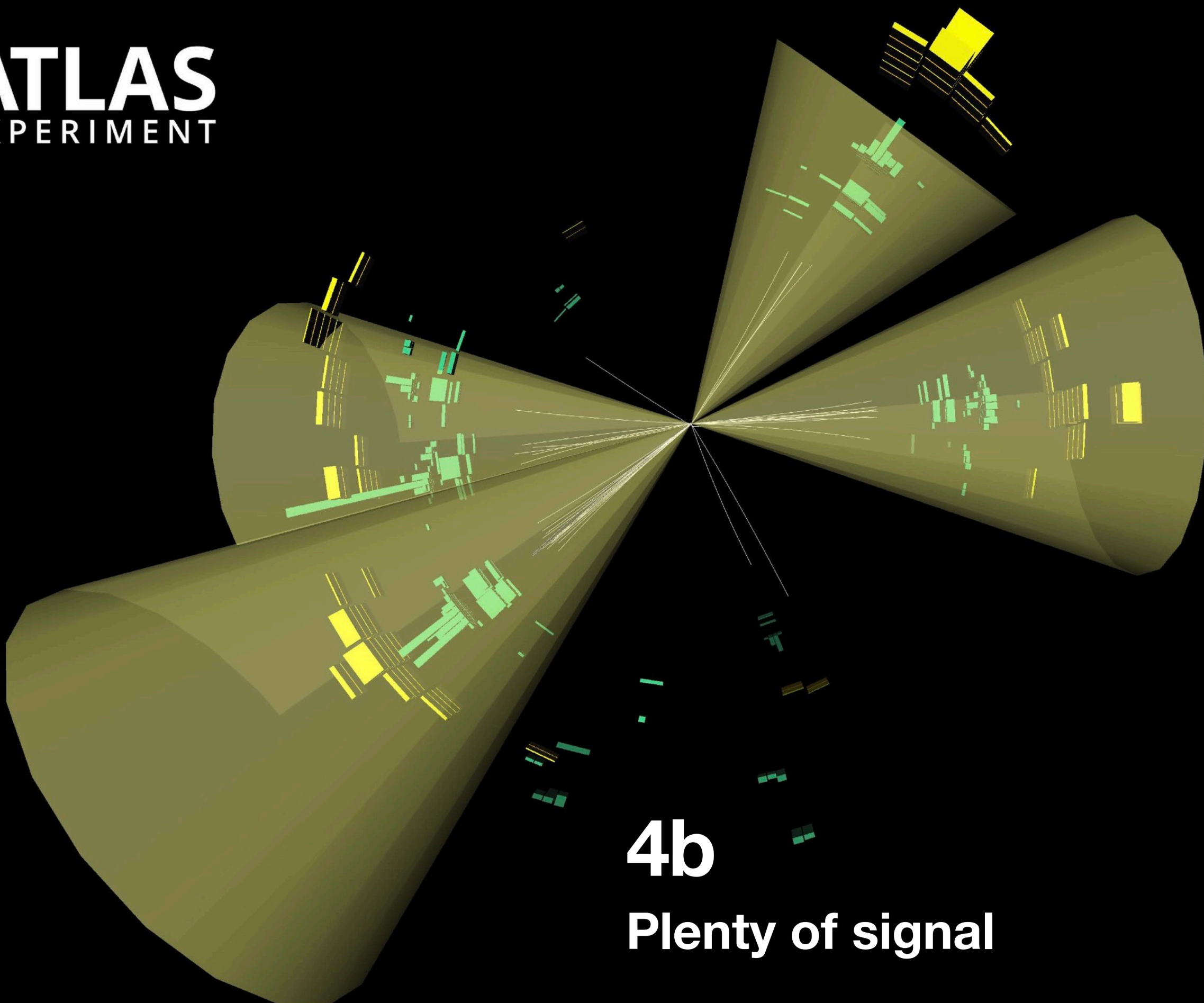
$\mu_{SM} < 4.7$ observed
(3.9 expected)

Submitted to JHEP



ATL-CONF-2021-052

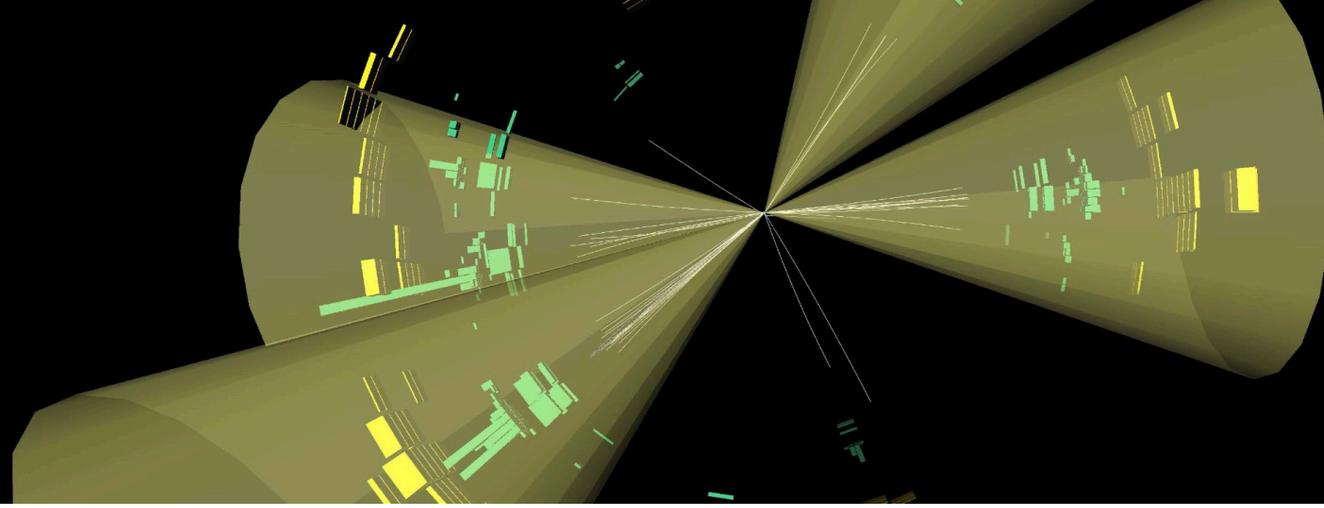
ATLAS EXPERIMENT



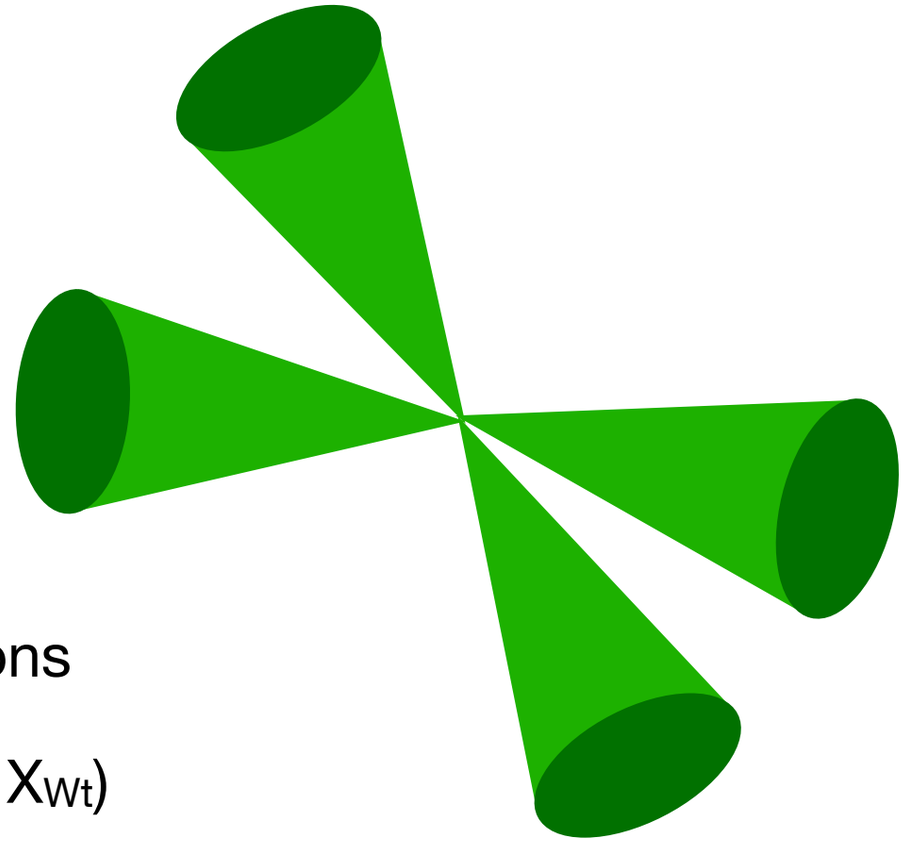
4b

Plenty of signal

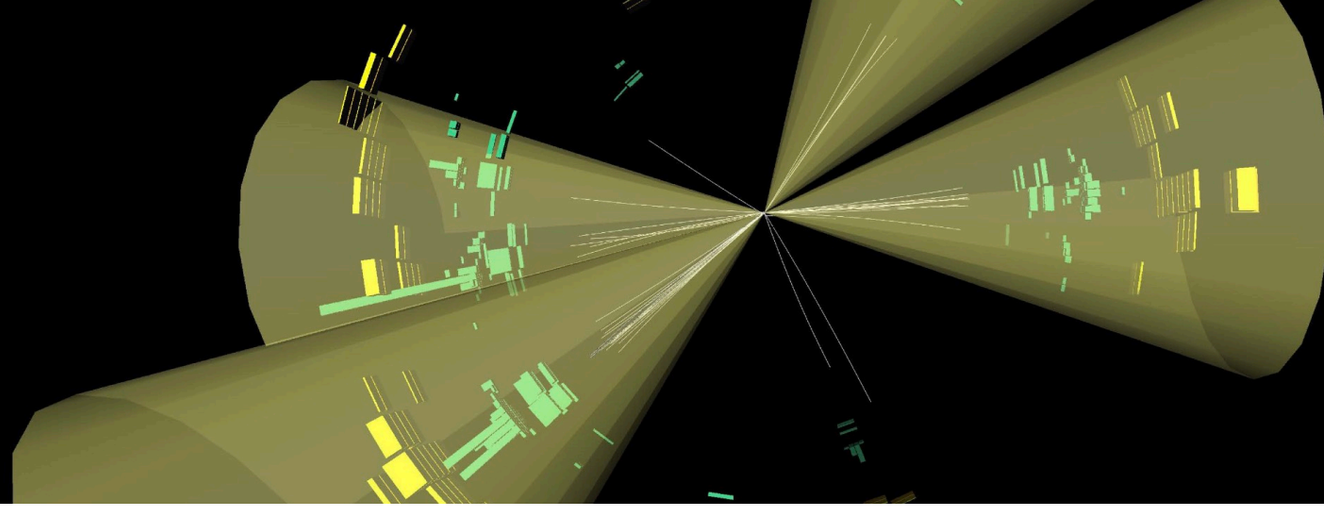
4b
Signature



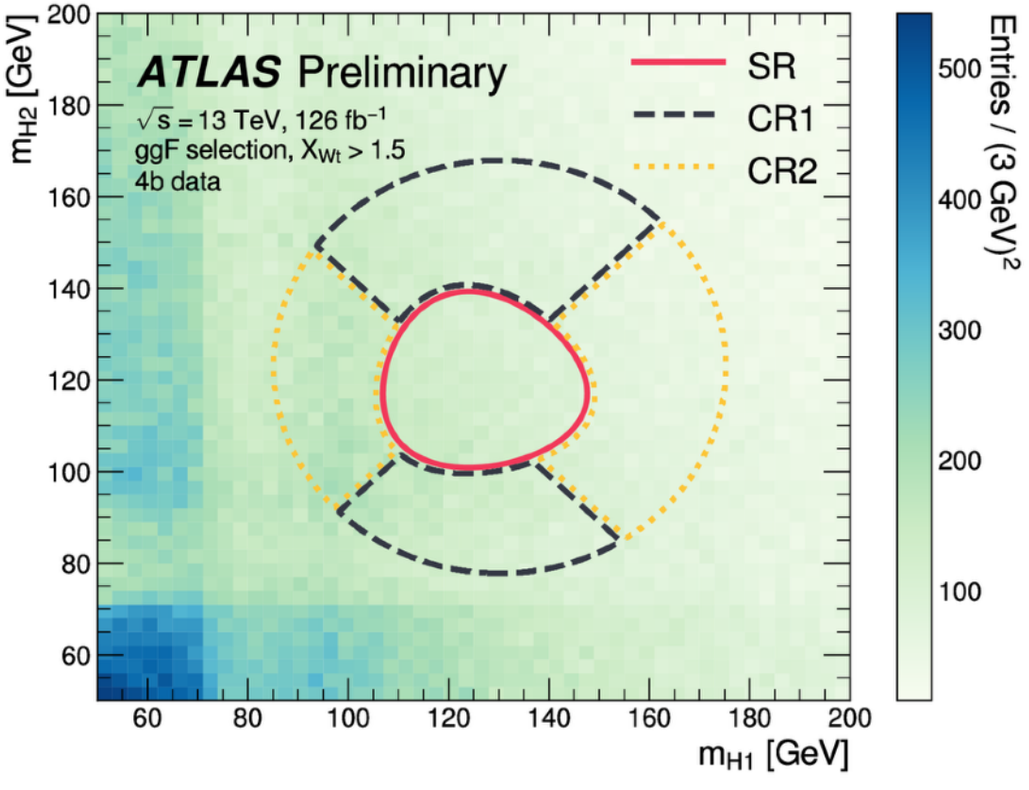
- Largest branching ratio
- Large QCD background
- Event selection:
  - 4 b-tagged jets
  - Forward jets used to split into ggF and VBF regions
  - Cut on HH and ttbar sensitive variables (X_{HH} and X_{Wt})
  - $|\Delta\eta_{HH}|$ and X_{HH} categories to improve κ_λ and κ_{2V} sensitivity

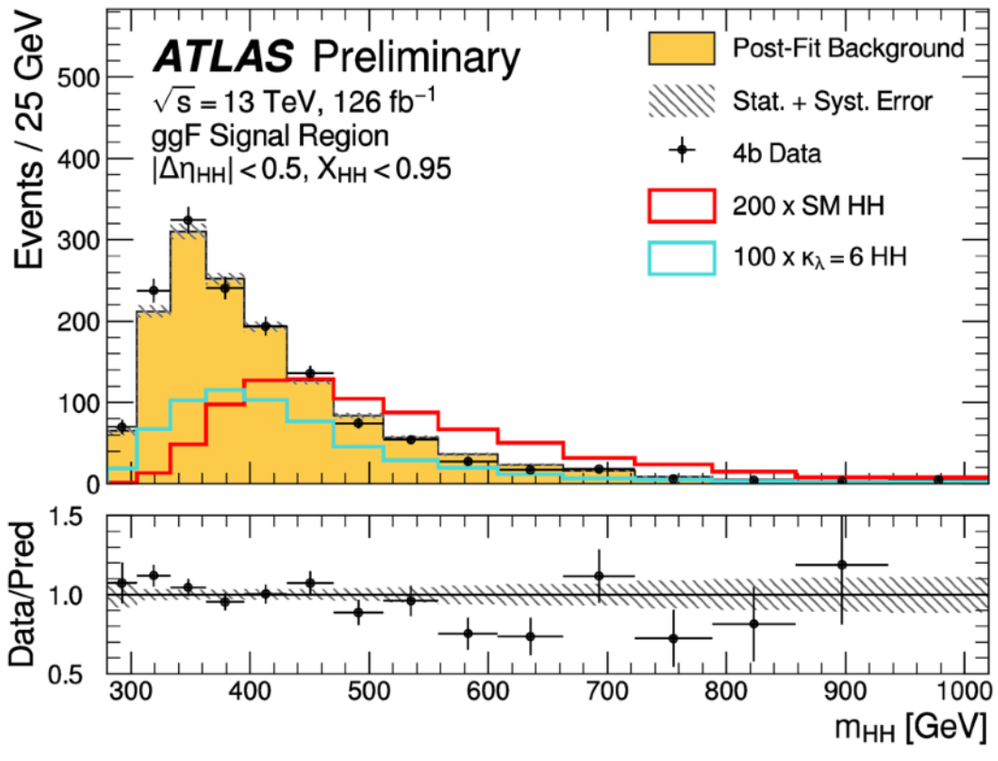


4b
Analysis strategy



- Jets paired to minimize ΔR for p_T-leading dijet system
- Data-driven background estimates
  - Data from 2b region reweighted to 4b SR (defined in m_{H1}-m_{H2} plane)
- m_{HH} used as final discriminant





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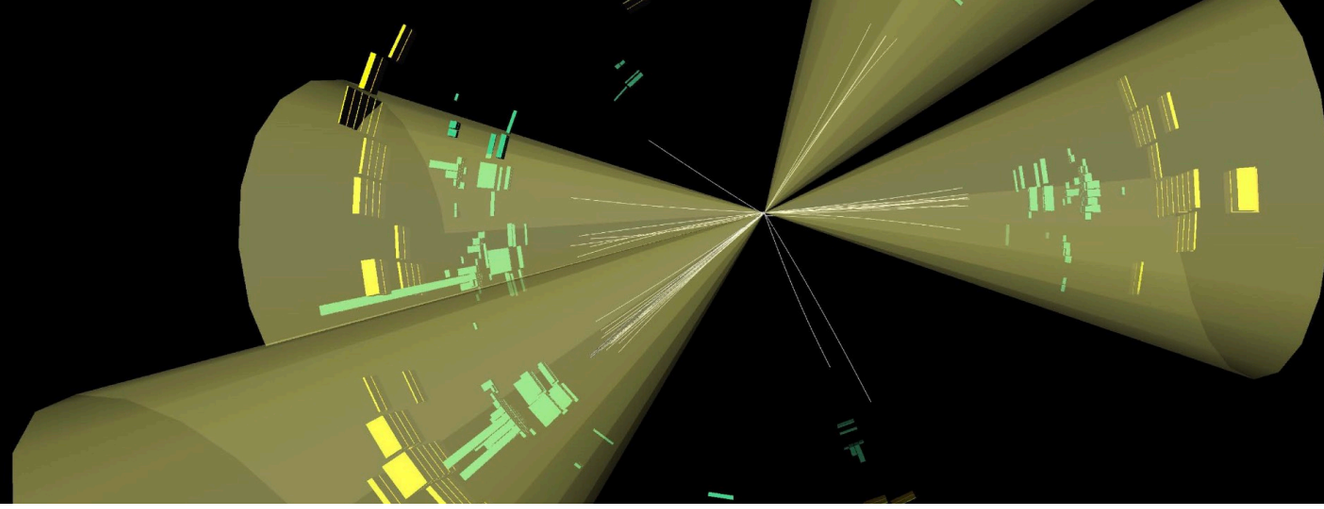
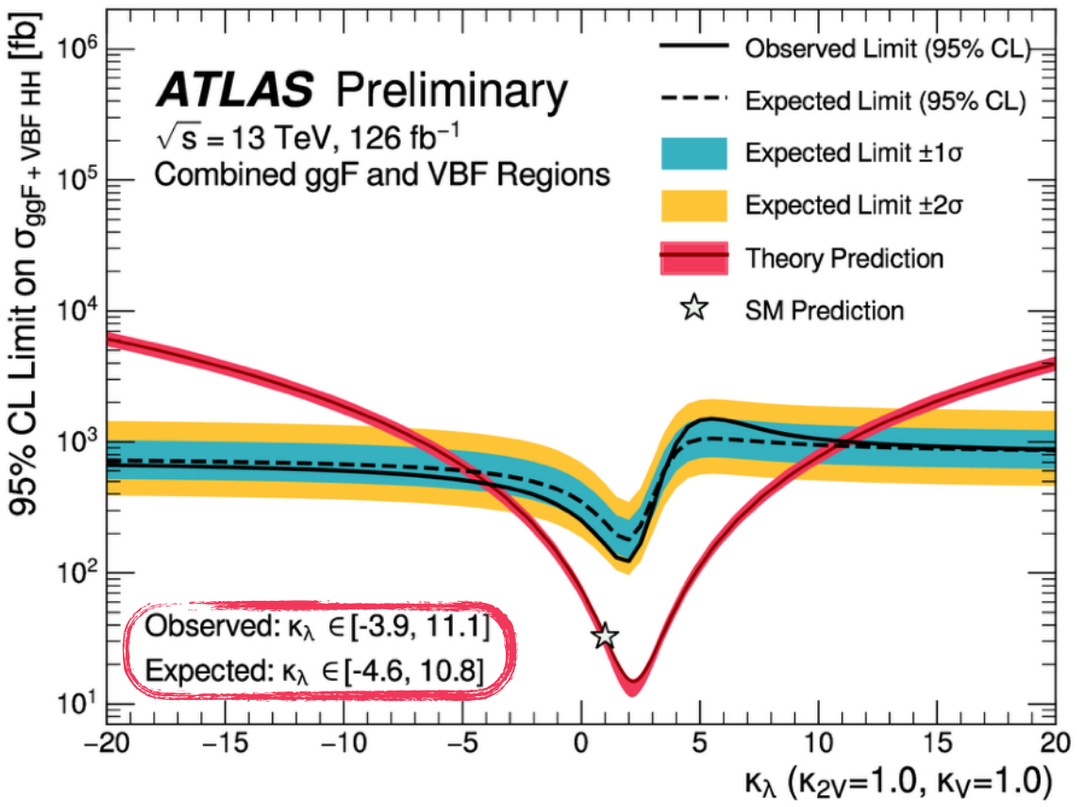
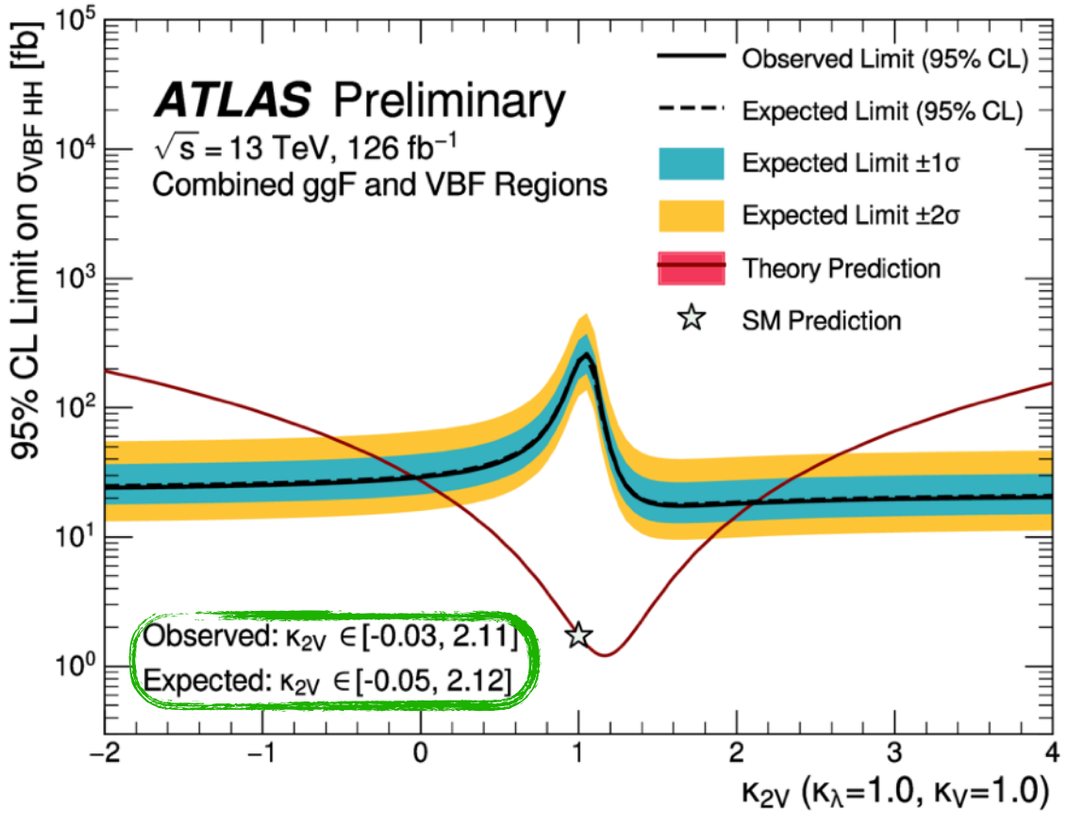
4b
Results



- Limits set on μ_{SM}, κ_λ, and κ_{2V}

$\mu_{SM} < 5.4$ observed
(8.1 expected)





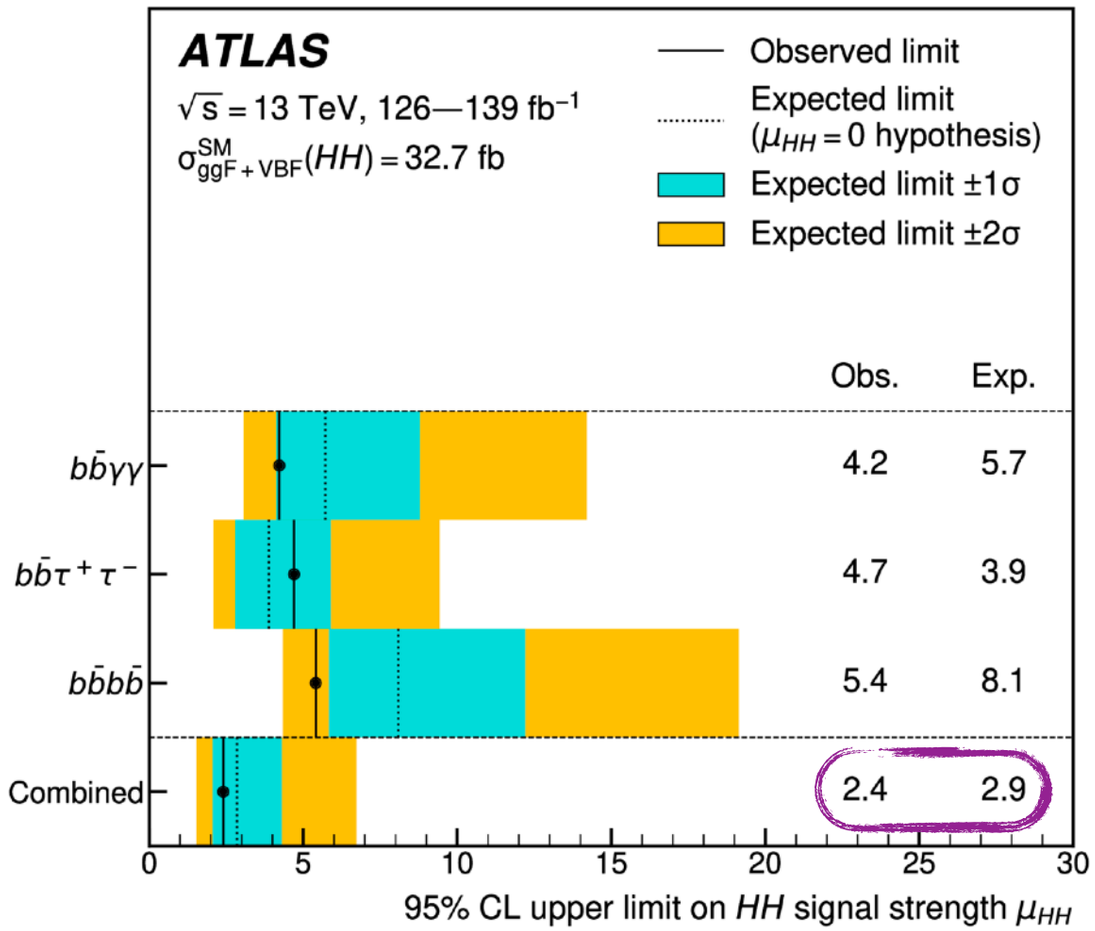
ATLAS-CONF-2022-035

Combinations

HH Combination

Signal strength

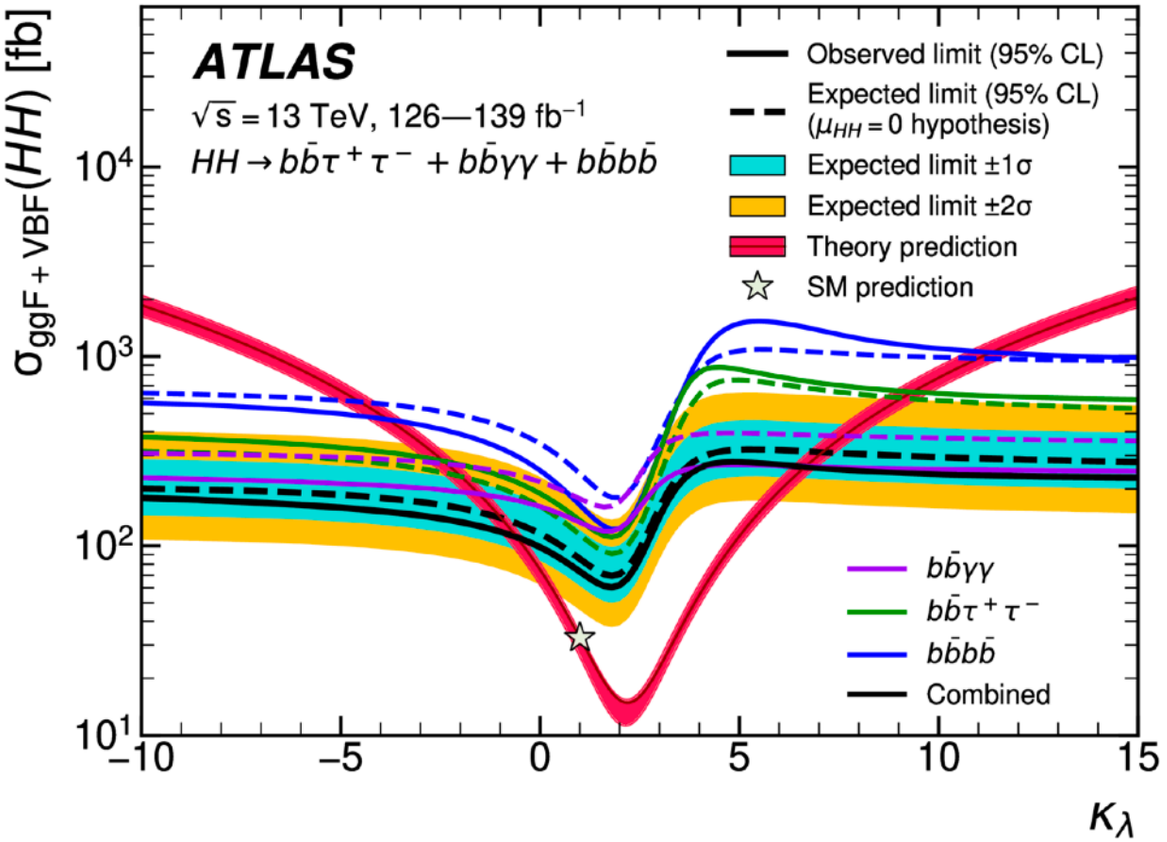
- Statistically combining channels increases sensitivity
- Combination of the three most sensitive HH channels

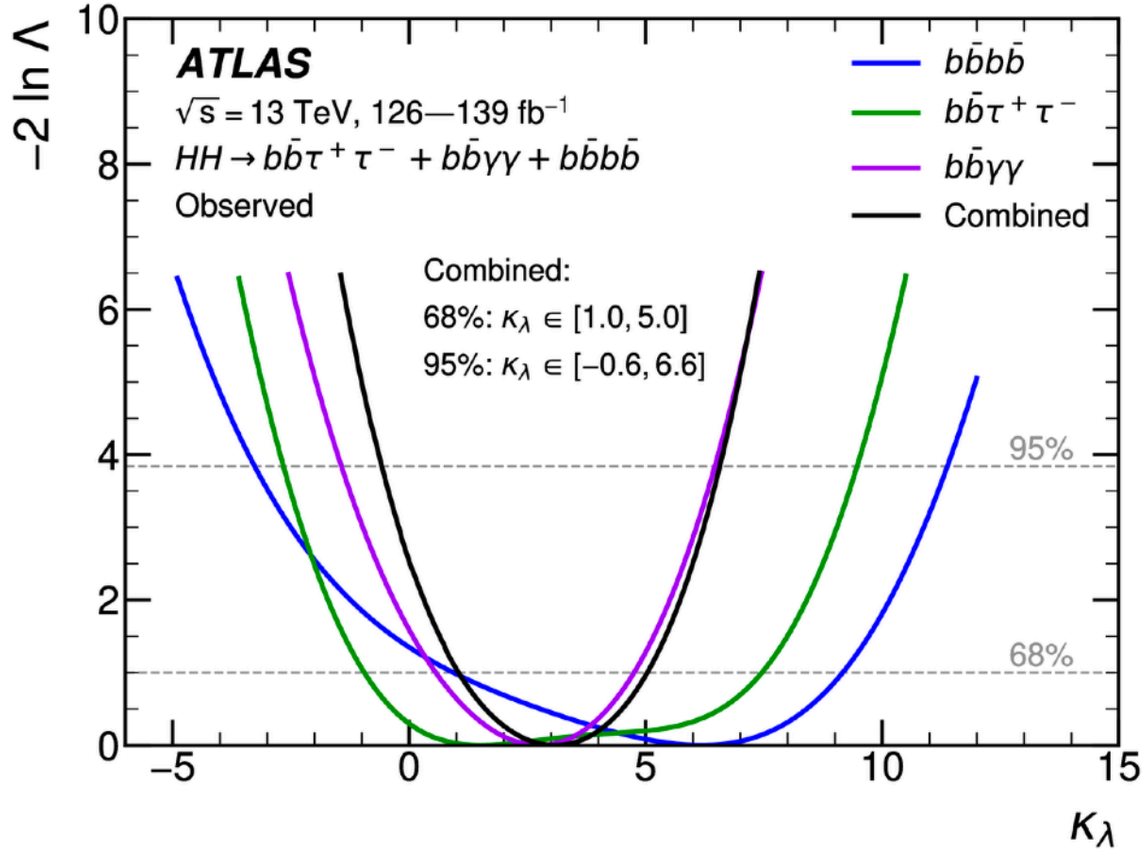


arXiv:2211.01216

HH Combination

κ_λ

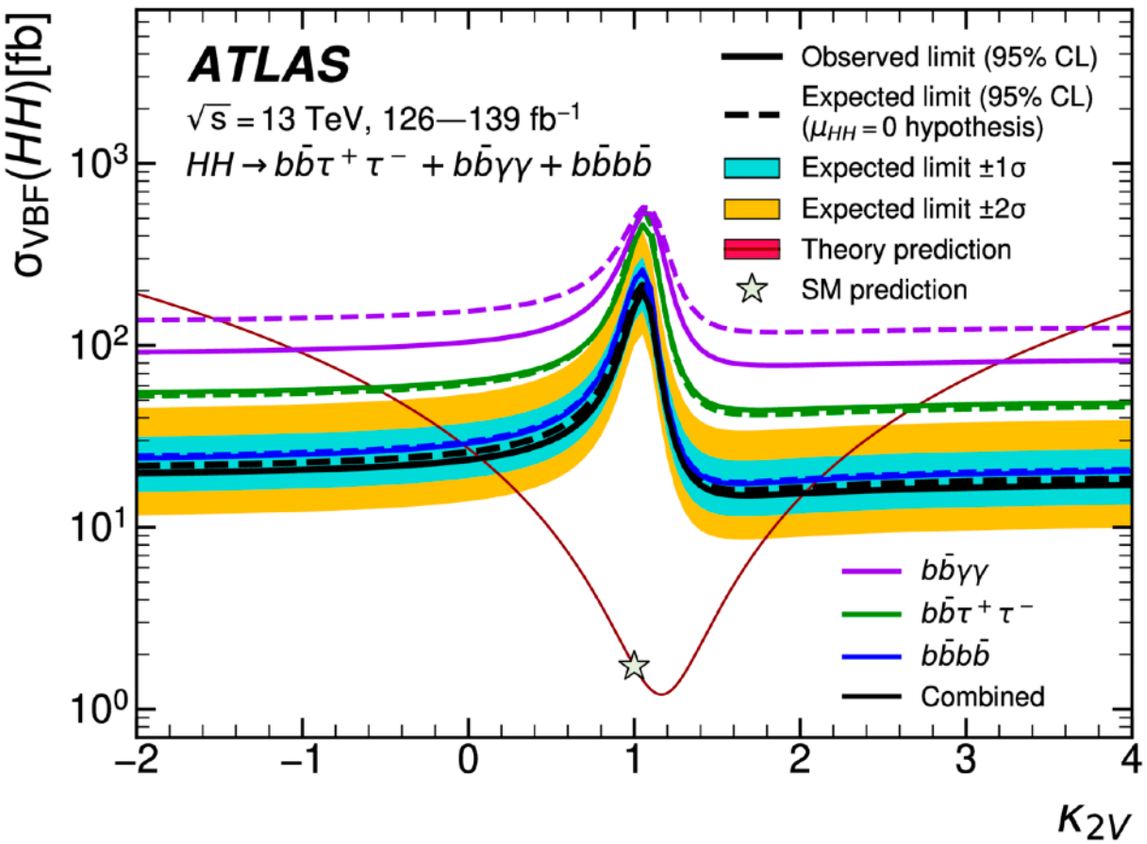


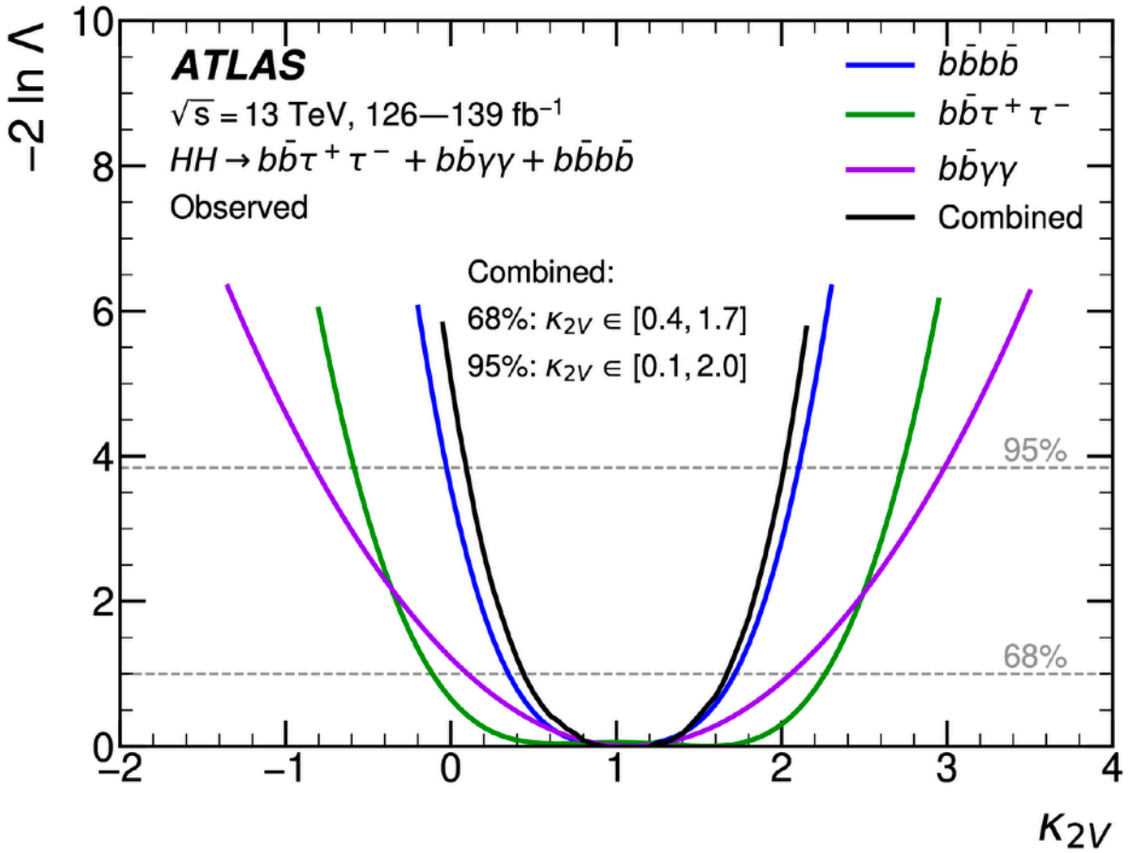


arXiv:2211.01216

HH Combination

κ_{2V}

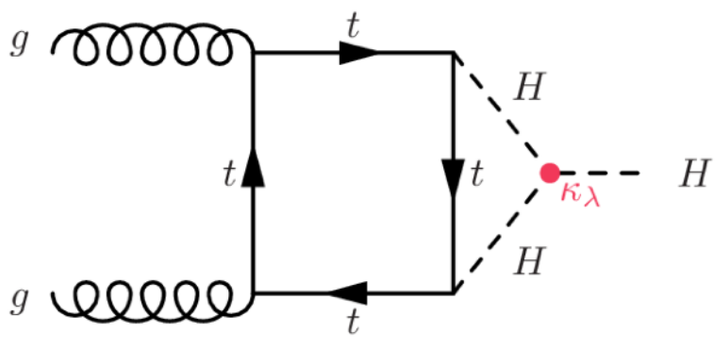


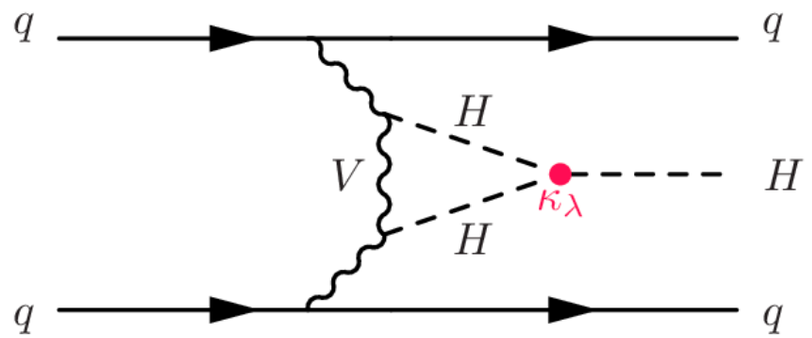


arXiv:2211.01216

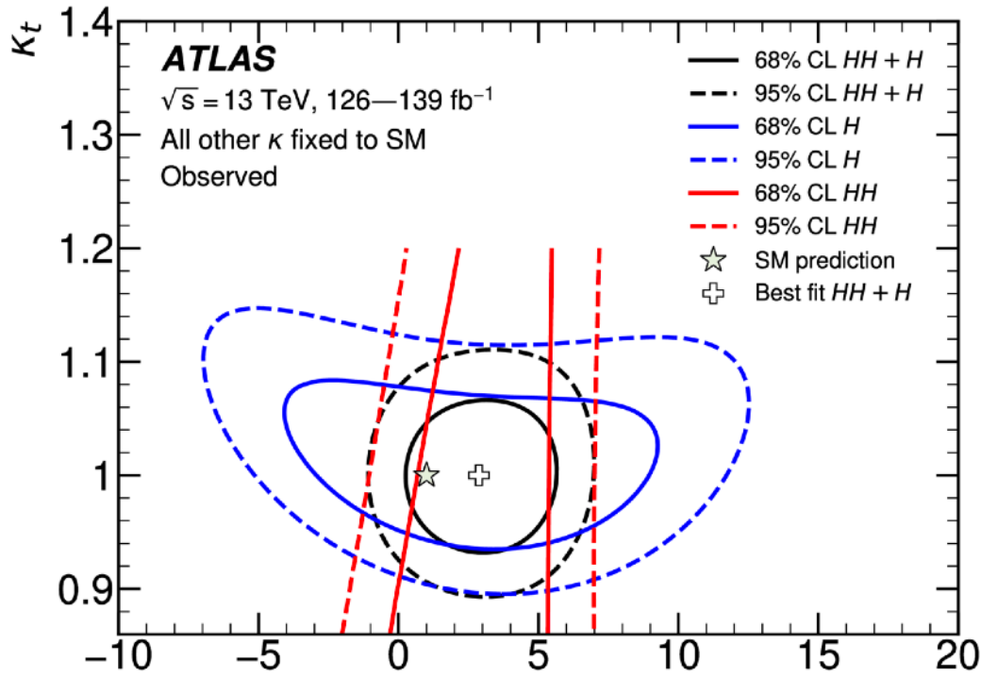
HH+H Combination

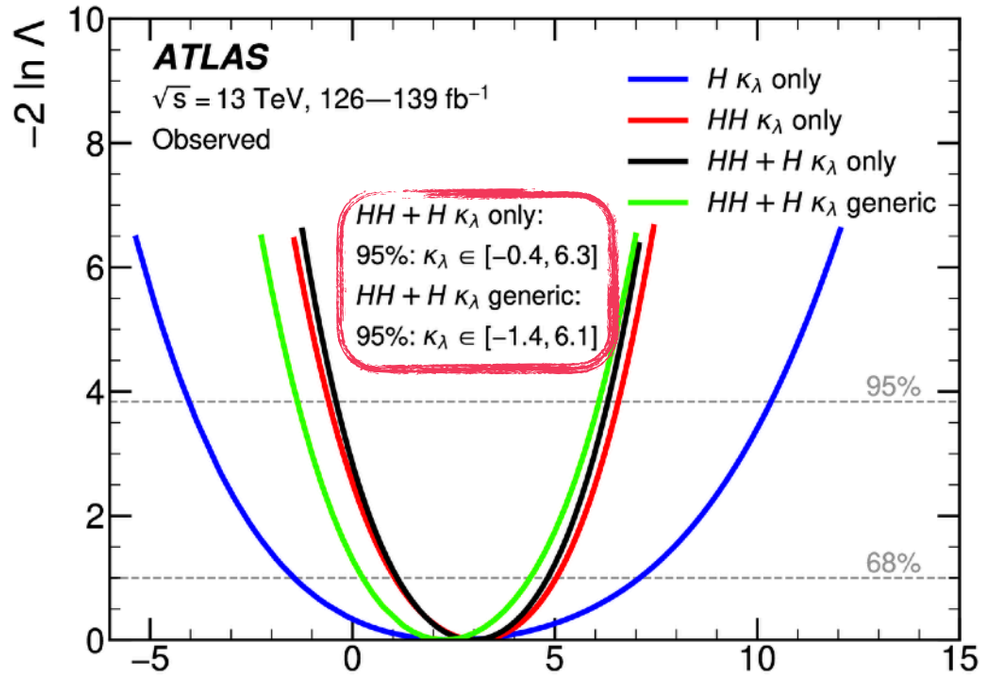
- Single Higgs boson production is also sensitive to λ through loop corrections, e.g.,





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





arXiv:2211.01216

Concluding Remarks

- Searching for HH is one of the most active areas of particle physics research
- No single “golden channel” - parallel searches and combination are necessary
- Higgs boson pair production offers insight into the Higgs mechanism
  - Excellent for heavy resonance searches - see Bill’s talk and Adele's plenary talk
- EFT interpretations available - see Giacinto’s talk
- Promising HL-LHC projections - see Caterina’s talk
- Also see Nicola’s plenary talk
- Many more exciting results expected in the near future…

Thank you for your attention

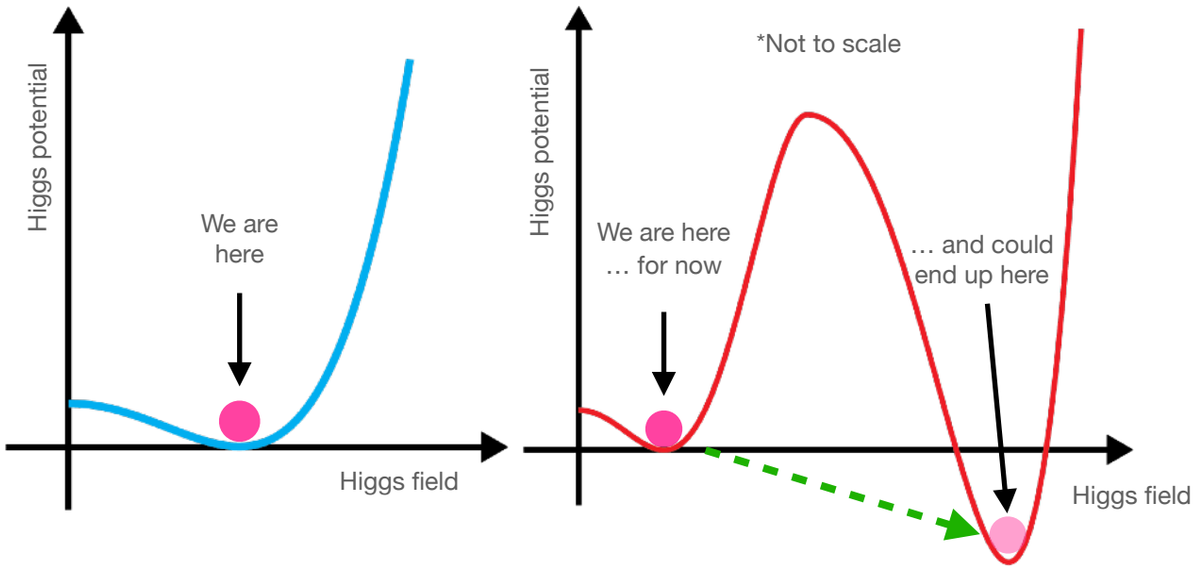
Backup Slides

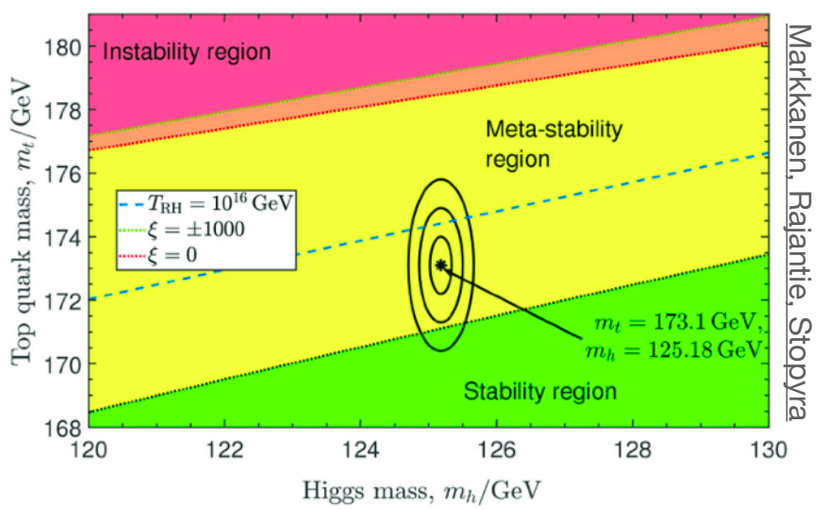
The Higgs Potential

Open Questions

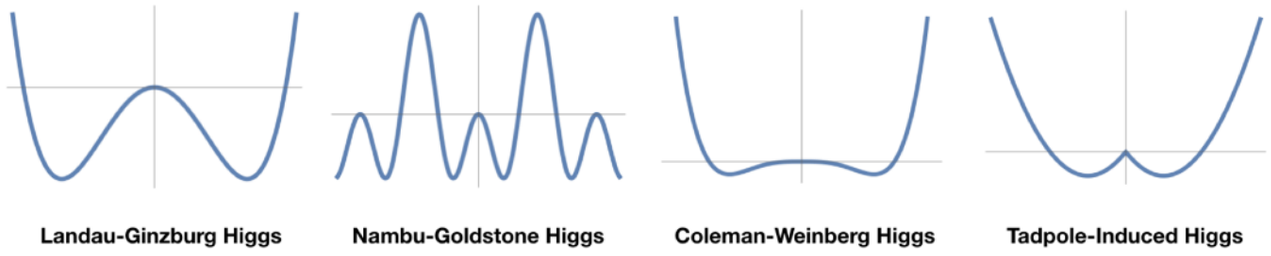
Vacuum Stability

Are we in a local or a global minimum?





Shape of the Higgs Potential



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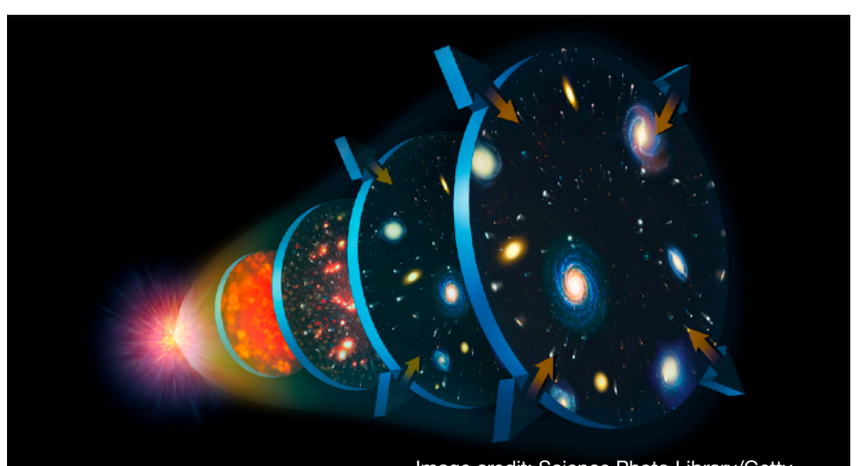
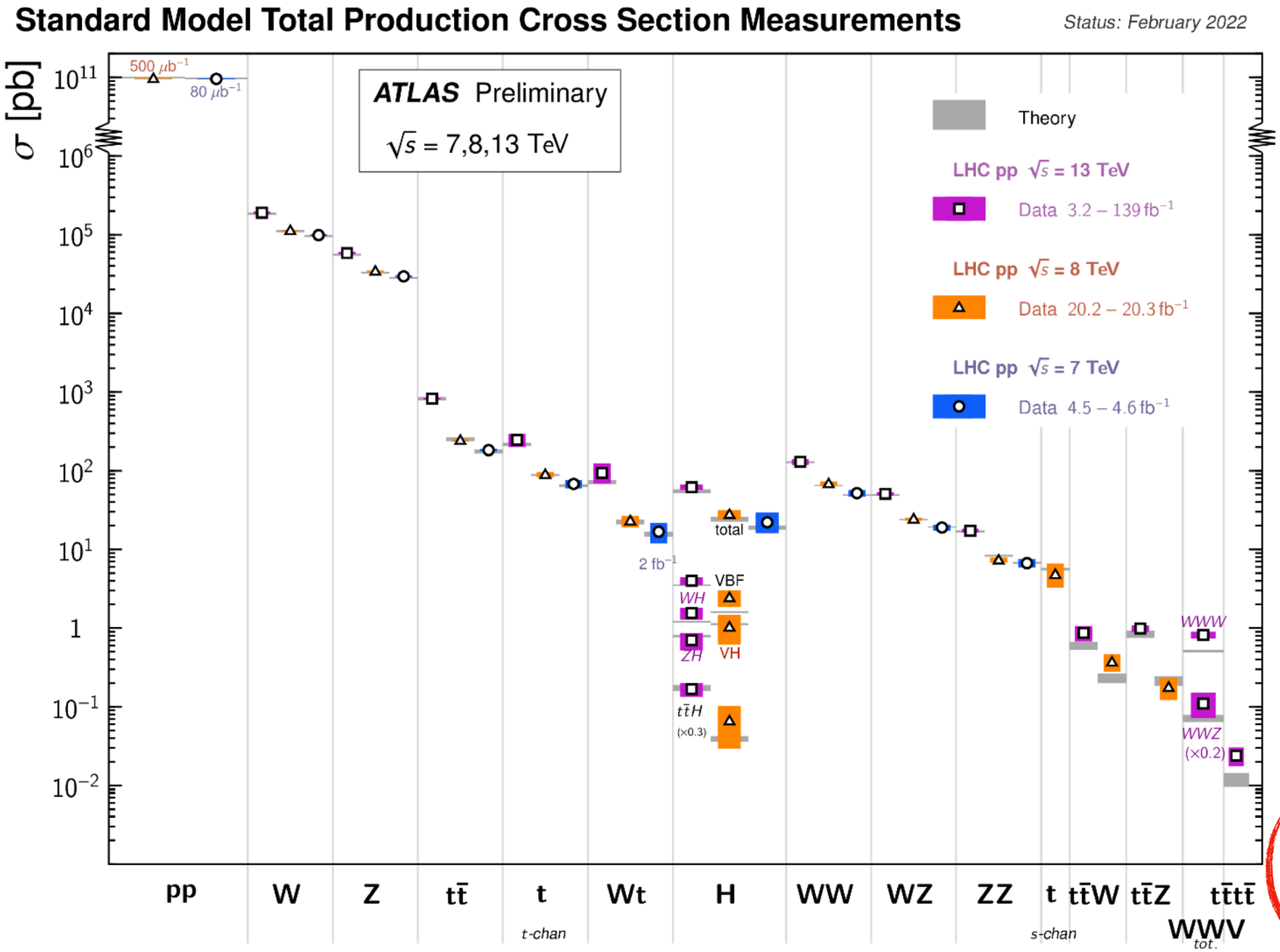
The Early Universe

- 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 HH Cross-Section



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

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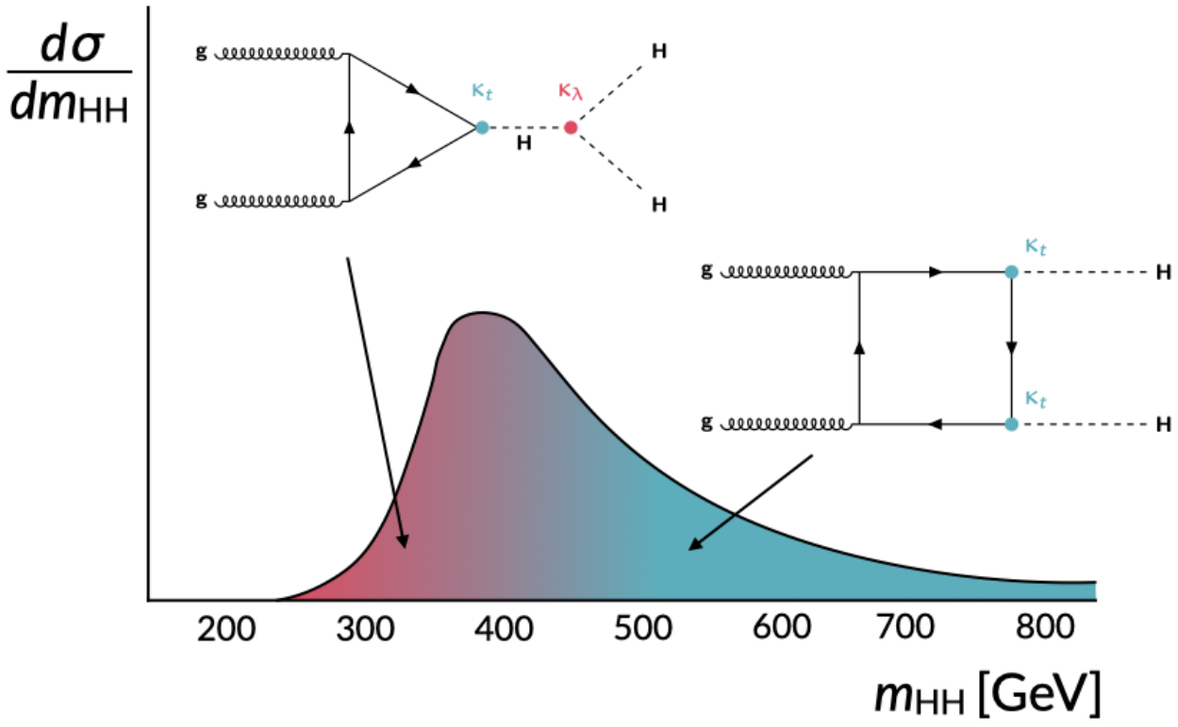
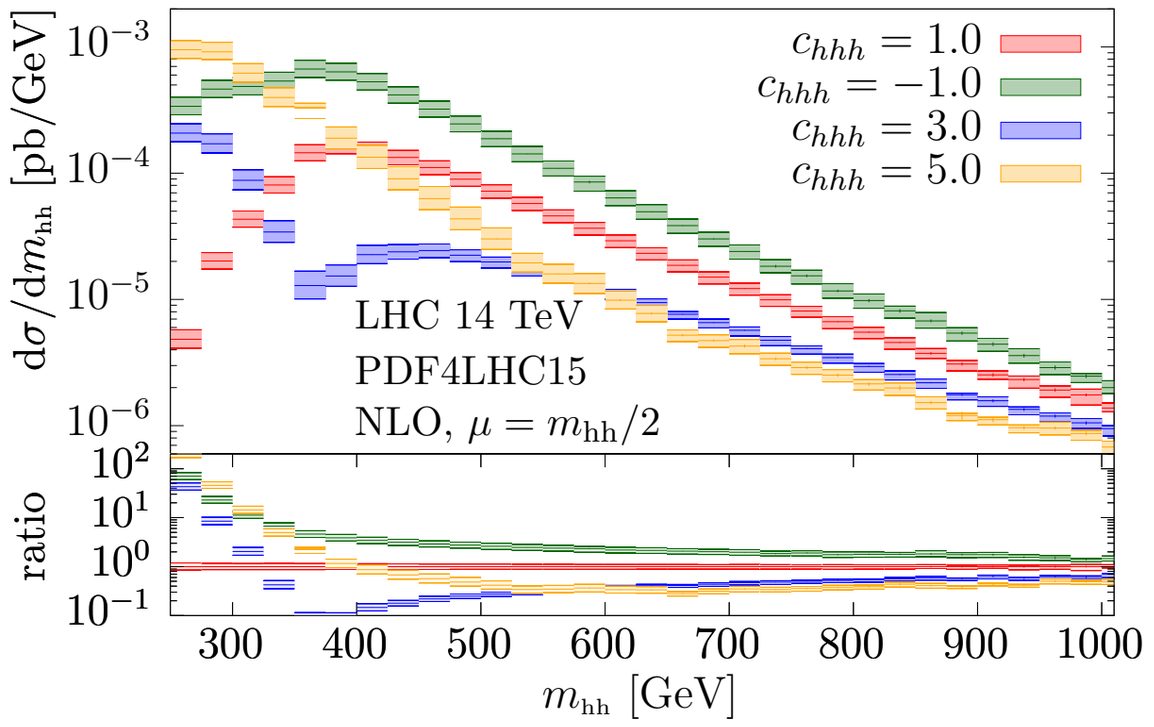
Non-resonant HH Production

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

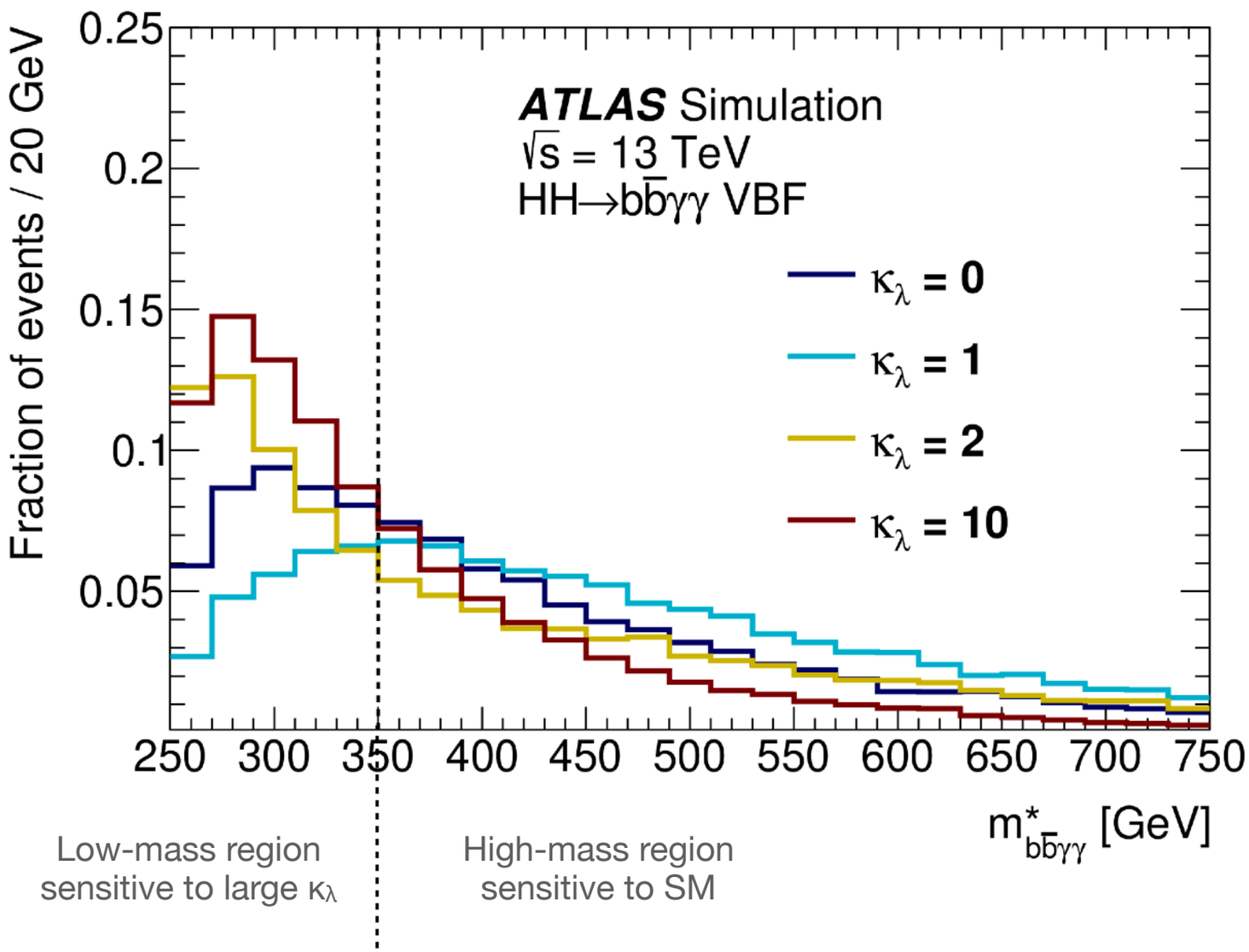




arXiv:1910.00012

bbγγ
VBF analysis regions

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



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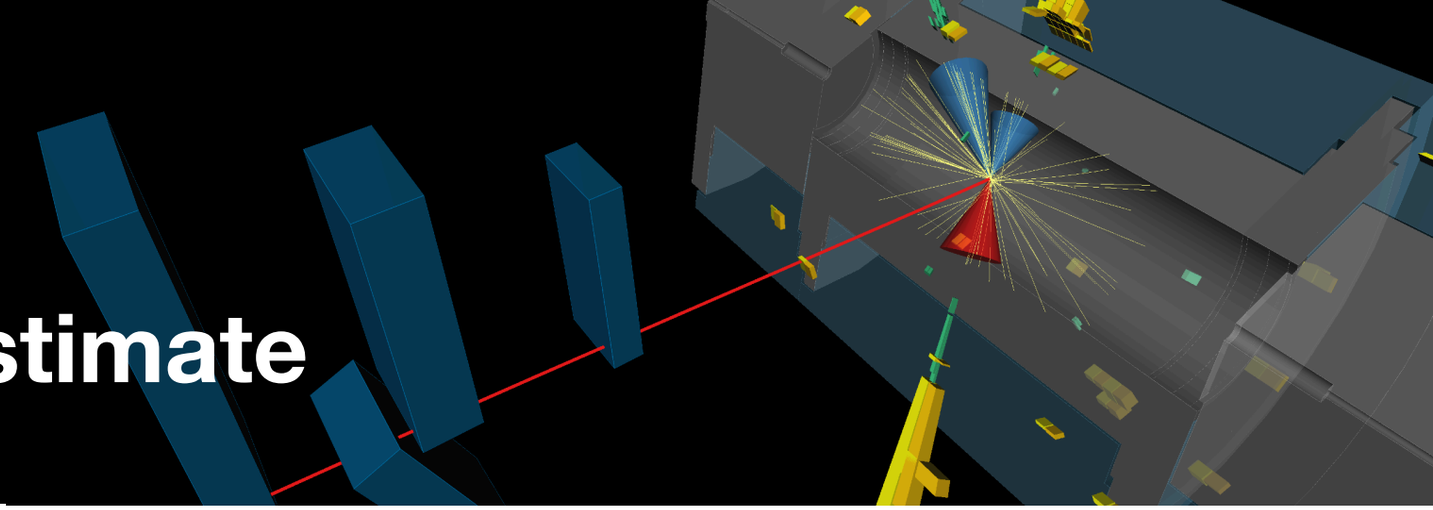
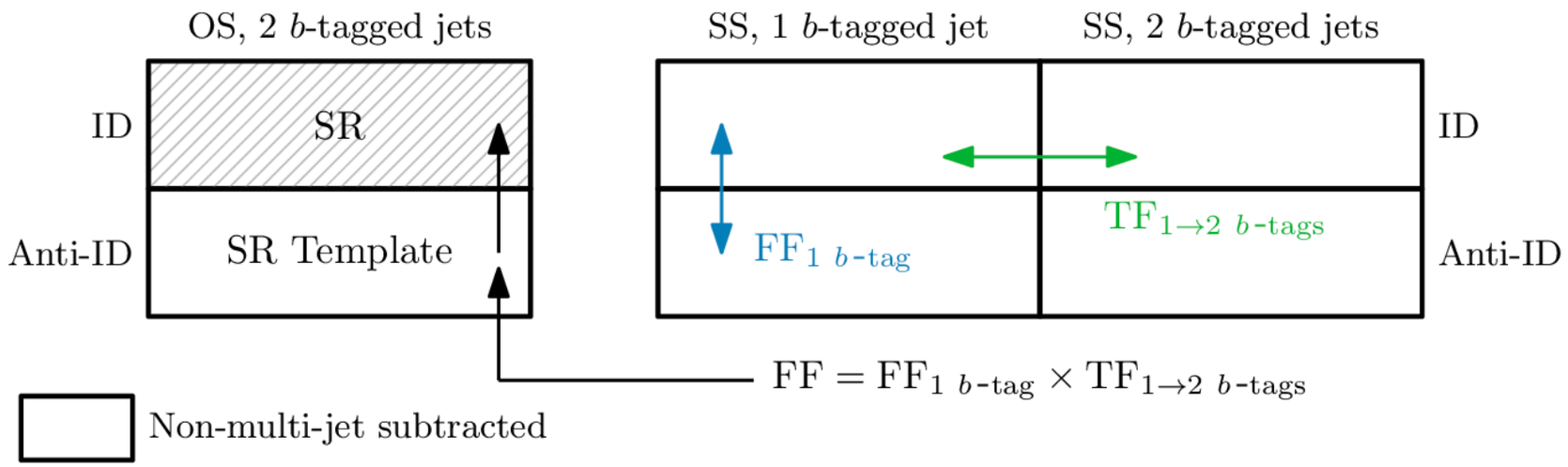
bbττ

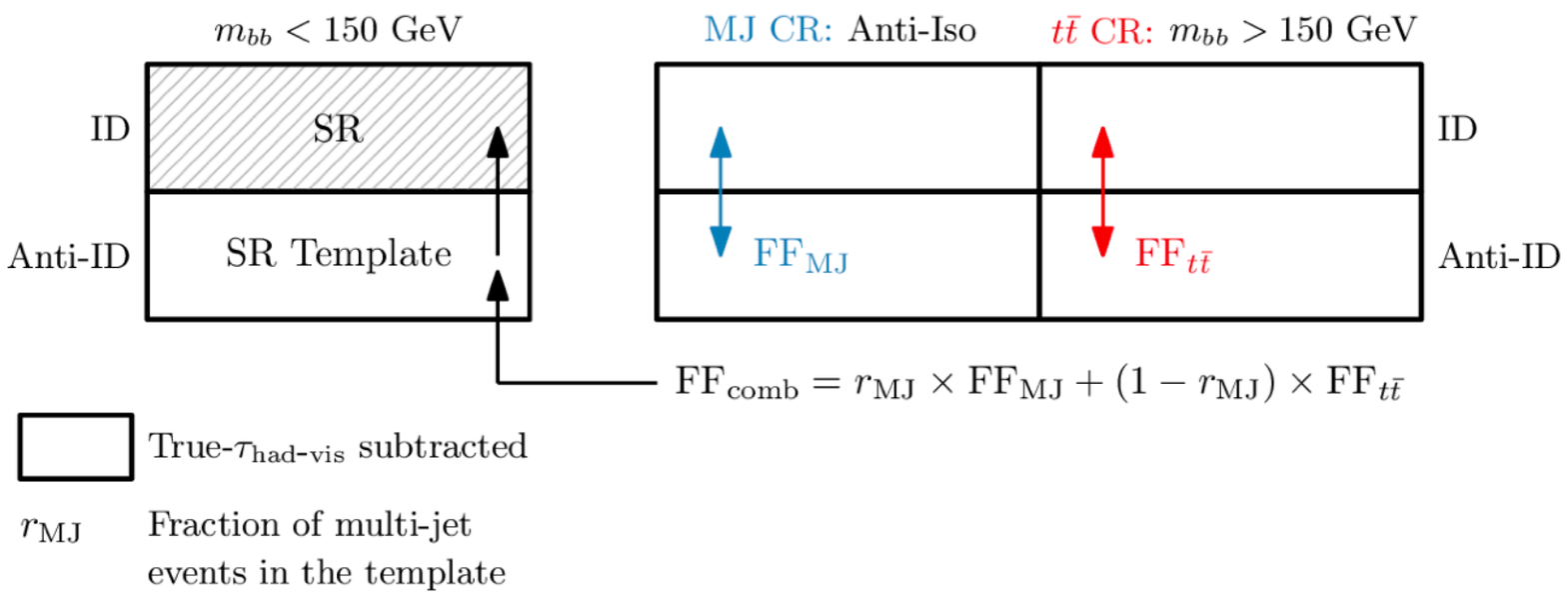
Fake-τ background estimate



$\tau_{\text{had}}\tau_{\text{had}}$ channel

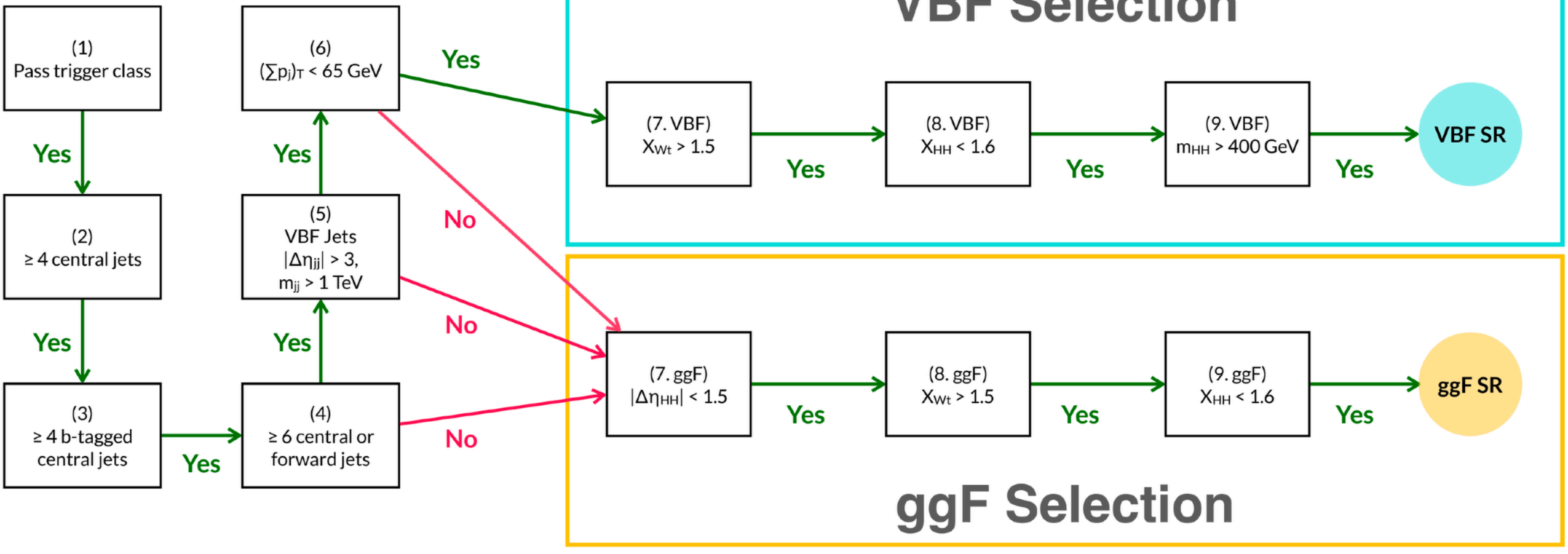


$\tau_{\text{lep}}\tau_{\text{had}}$ channel



Submitted to JHEP

4b
ggF and VBF categories



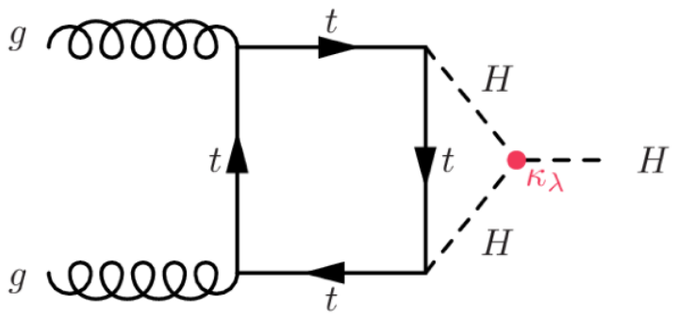
4b

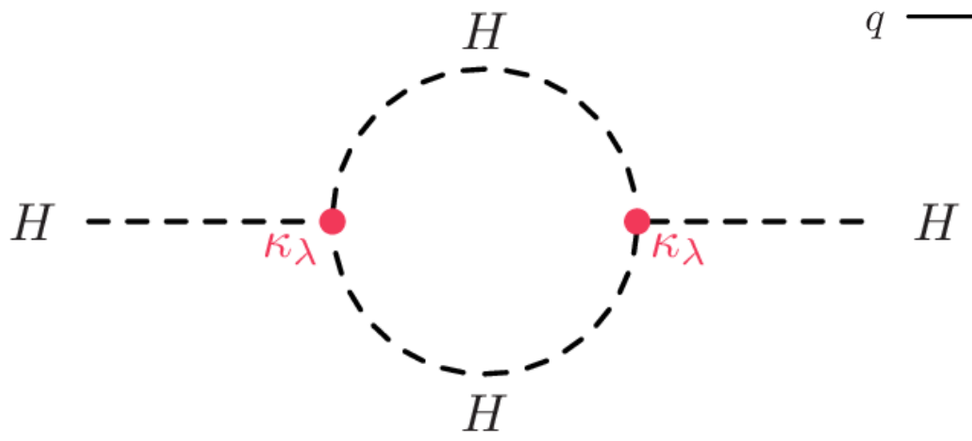
X_{Wt} and X_{HH}

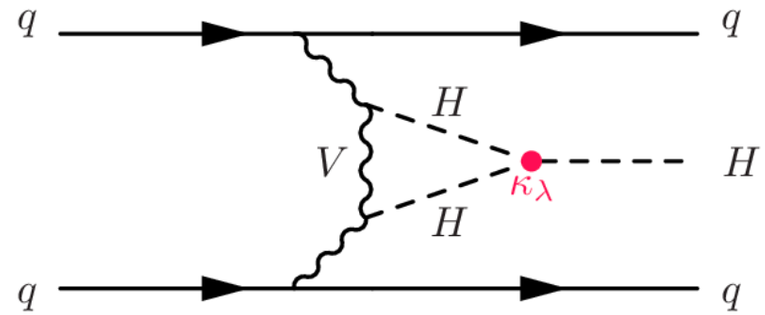
$$X_{Wt} = \sqrt{\left(\frac{m_W - 80.4\,\text{GeV}}{0.1\,m_W}\right)^2 + \left(\frac{m_t - 172.5\,\text{GeV}}{0.1\,m_t}\right)^2}$$

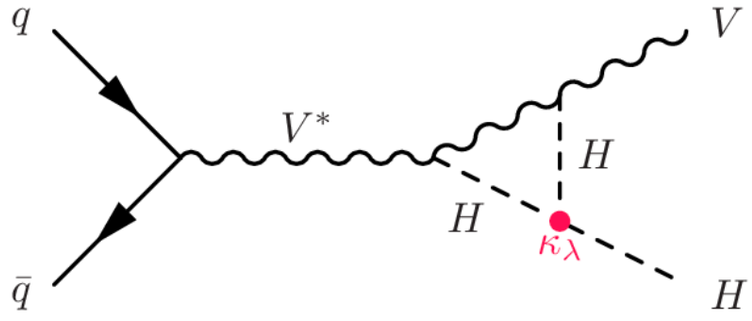
$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\,\text{GeV}}{0.1\,m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\,\text{GeV}}{0.1\,m_{H2}}\right)^2}$$

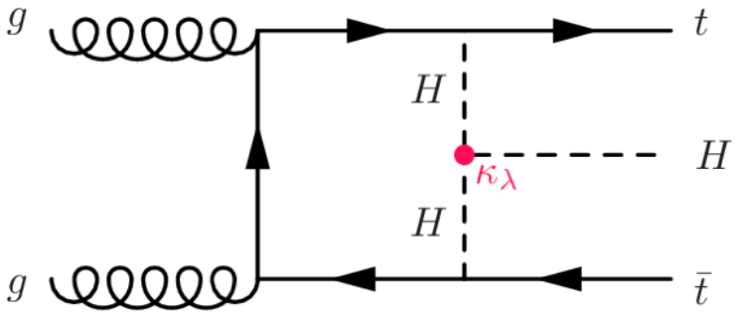
Single Higgs Corrections











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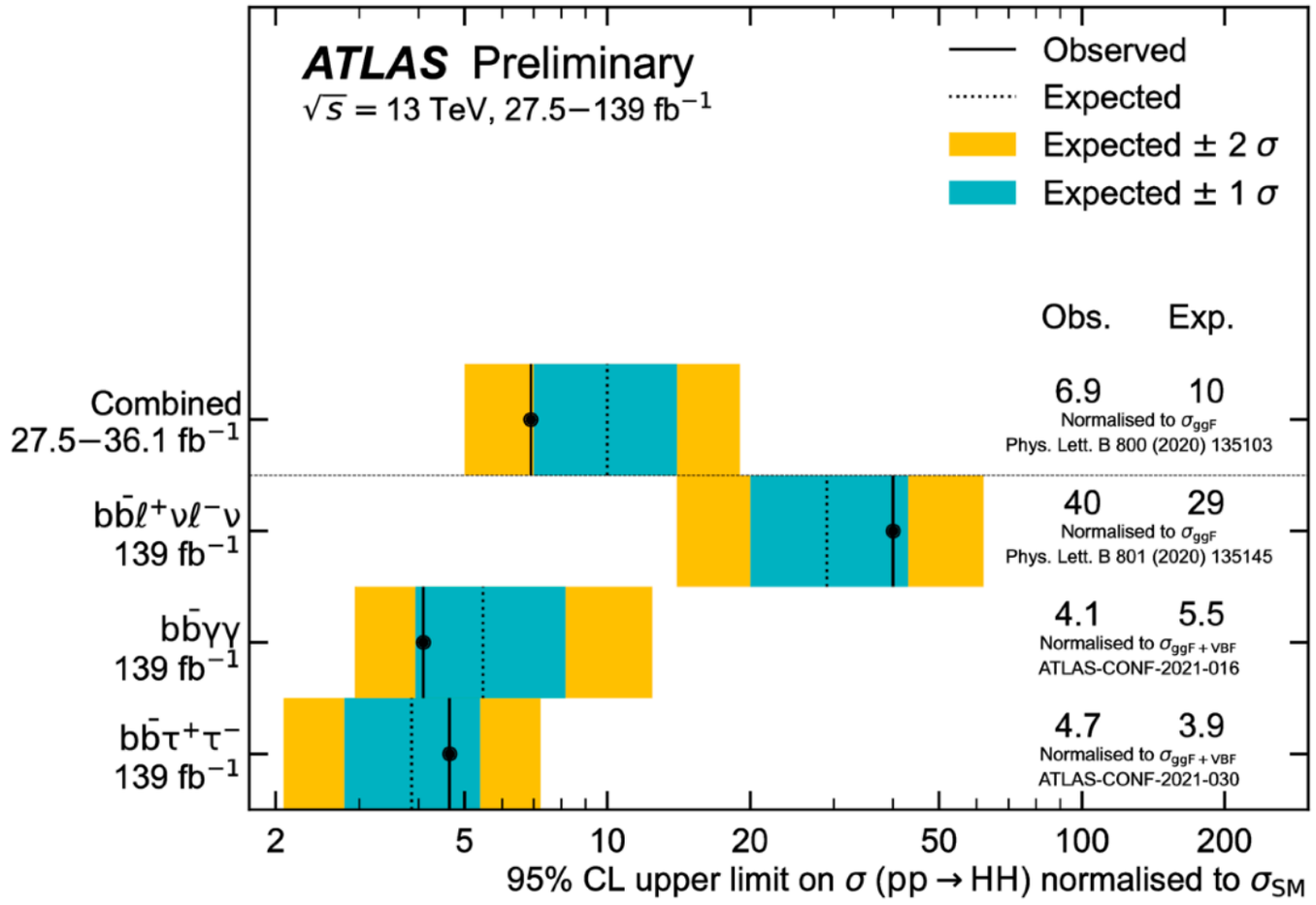
Summary Of All Channels

As of July 2021



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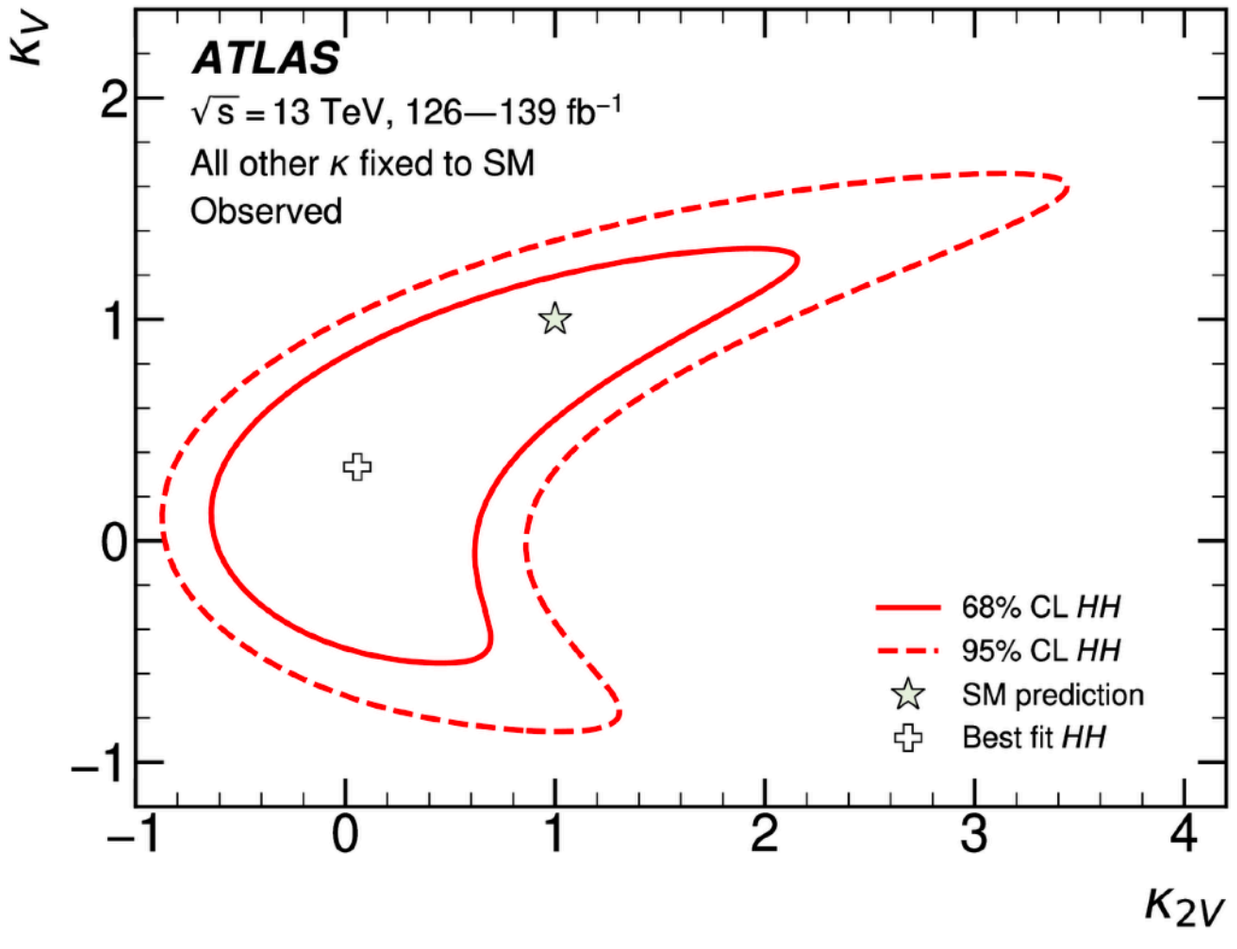
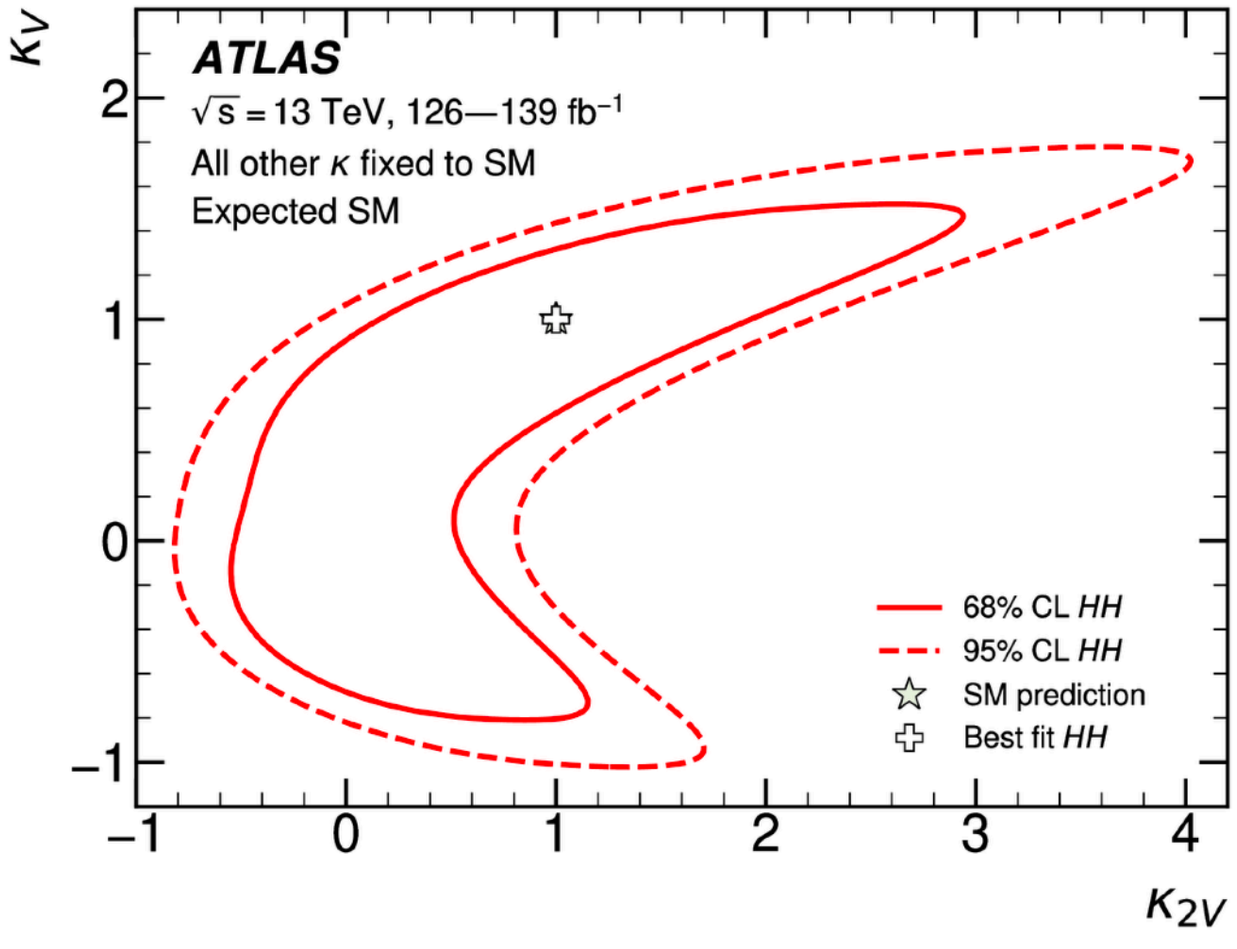
HH Combination

κ_V-κ_{2V}





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