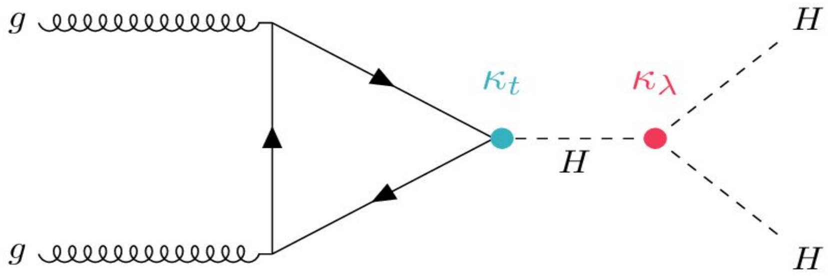
ICHEP 2022 BOLOGNA 07 07 2022

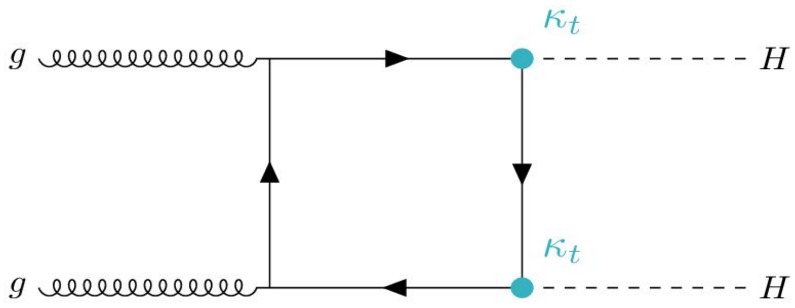
# Probing the nature of electroweak symmetry breaking with higgs boson pairs in ATLAS

Arely CORTES GONZALEZ
on behalf of the **ATLAS Collaboration**

# Non-resonant HH production

Search for non-resonant di-Higgs production allows us to probe the shape of the Higgs potential by measuring the trilinear self-coupling $\kappa_\lambda$ of the Higgs boson.




Higgs potential (minimum)

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \cdots$$

mass term

$$\frac{1}{2} m_H^2$$

trilinear coupling

$$\frac{m_H^2}{2v}$$

$$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{\mathrm{SM}}$$

SM predicts $\kappa_\lambda = 1$

There is however destructive interference between the box and triangle diagrams, thus the cross section is suppressed (~$10^3$ times smaller than single Higgs cross section). Deviations from SM can increase this cross section.

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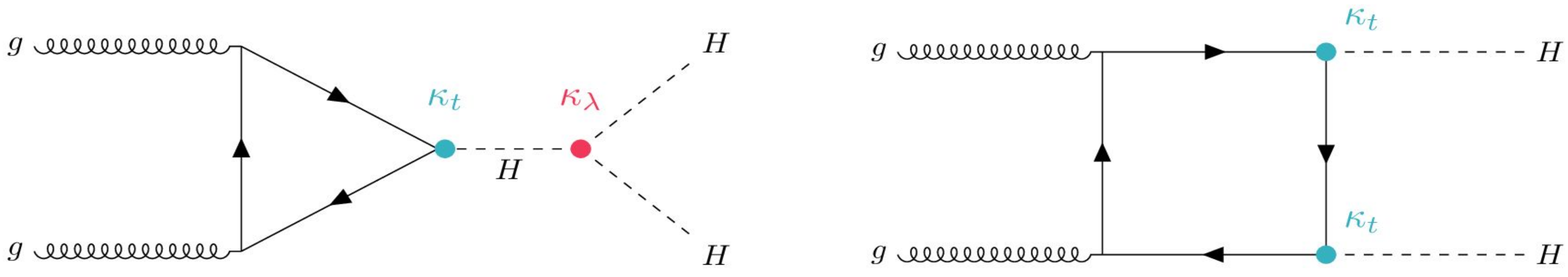
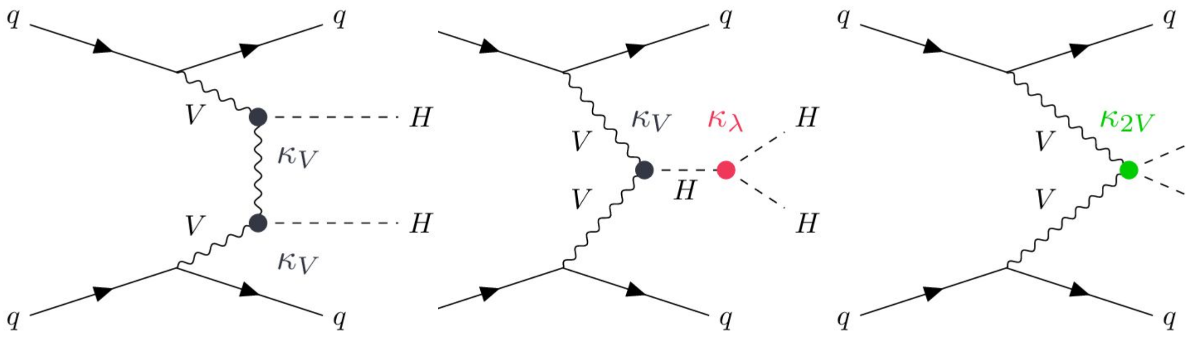


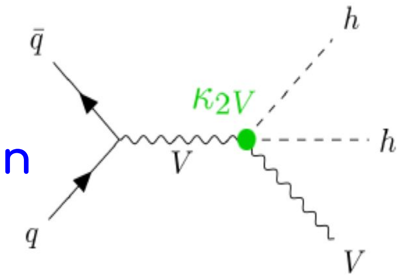

*gluon fusion (ggF) is the main production mechanism.*

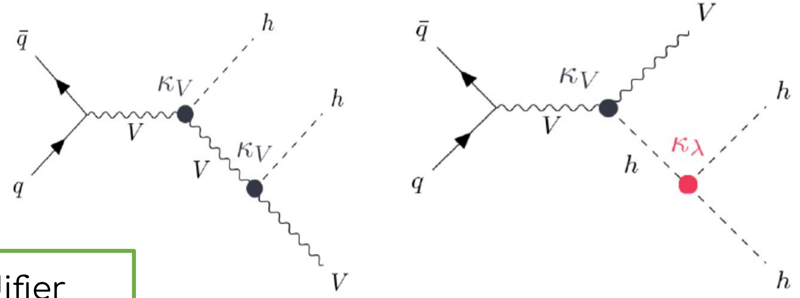
Other production mechanisms also allow us to probe different couplings: $\kappa_{2V}$, $\kappa_V$.

## Vector boson fusion




## Associated production VHH




| VVH coupling modifier<br>SM predicts $\kappa_V$ = 1 |
|---|

| VVHH coupling modifier<br>SM predicts $\kappa_{2V}$ = 1 |
|---|

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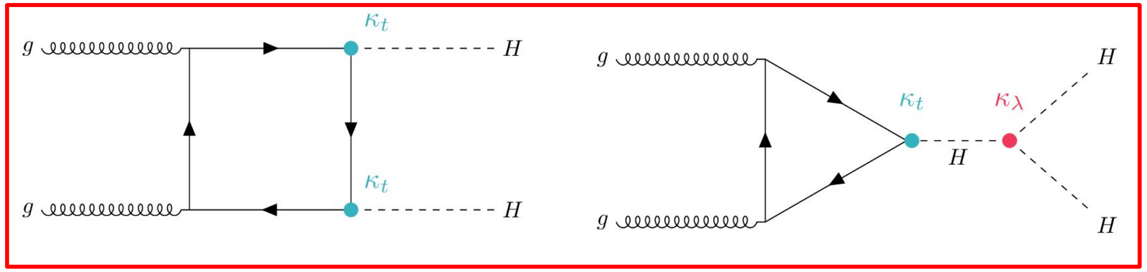
# Non-resonant HH production

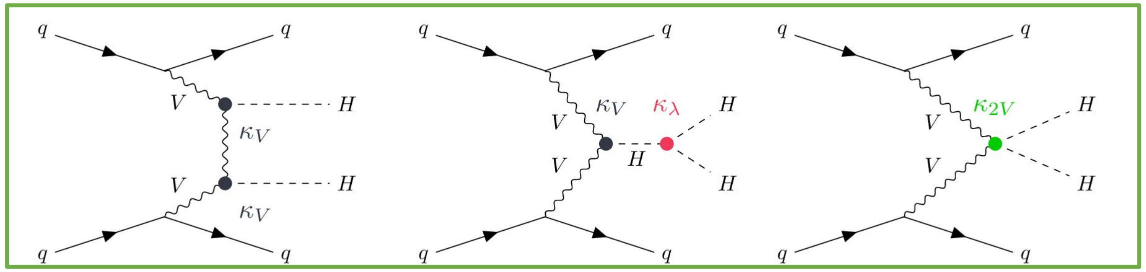
LHCHXSWG-2019-005

Production cross sections at 13 TeV for $m_H$ = 125 GeV



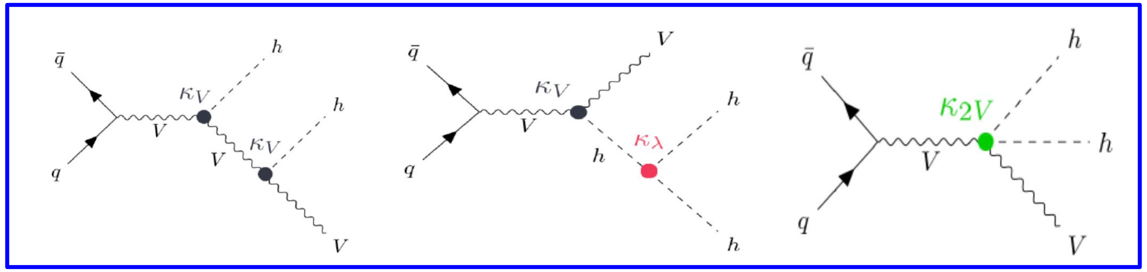

Gluon fusion (NNLO)

$$\sigma^{\mathrm{SM}}_{\mathrm{ggF}} = 31.05^{+6\%}_{-23\%}(\mathrm{scale} + m_{\mathrm{top}}) \pm 3.0\%(\mathrm{PDF} + \alpha_s)\ \mathrm{fb}$$




Vector boson fusion (N$^3$LO)

$$\sigma^{\mathrm{SM}}_{\mathrm{VBF}} = 1.73^{+0.03\%}_{-0.04\%}(\mathrm{scale}) \pm 2.1(\mathrm{PDF} + \alpha_s)\ \mathrm{fb}$$




Associated production, VHH (N$^2$LO)

e.g $\sigma_{ZHH}$

$$\sigma^{\mathrm{SM}}_{\mathrm{ZHH}} = 0.363^{+3.4\%}_{-2.7\%}(\mathrm{scale}) \pm 1.9(\mathrm{PDF} + \alpha_s)\ \mathrm{fb}$$

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# Search channels

| | $b\bar{b}$ | $W^+W^-$ | $gg$ | $\tau^+\tau^-$ | $c\bar{c}$ | $ZZ$ | $\gamma\gamma$ | $Z\gamma$ | $\mu^+\mu^-$ |
|---|---|---|---|---|---|---|---|---|---|
| $b\bar{b}$ | 33.9% | 24.9% | 9.5% | 7.3% | 3.4% | 3.1% | 0.3% | 0.2% | < 0.1% |
| $W^+W^-$ | | 4.6% | 3.5% | 2.7% | 1.2% | 1.1% | < 0.1% | < 0.1% | < 0.1% |
| $gg$ | | | 0.7% | 1.0% | 0.5% | 0.4% | < 0.1% | < 0.1% | < 0.1% |
| $\tau^+\tau^-$ | | | | 0.4% | 0.4% | 0.3% | < 0.1% | < 0.1% | < 0.1% |
| $c\bar{c}$ | | | | | < 0.1% | 0.2% | < 0.1% | < 0.1% | < 0.1% |
| $ZZ$ | | | | | | < 0.1% | < 0.1% | < 0.1% | < 0.1% |
| $\gamma\gamma$ | | | | | | | < 0.1% | < 0.1% | < 0.1% |
| $Z\gamma$ | | | | | | | | < 0.1% | < 0.1% |
| $\mu^+\mu^-$ | | | | | | | | | < 0.1% |

- Decay channels with large branching ratios may lead to challenging signatures.
- Exploring a mixture of different higgs decay channels to increase the sensitivity.
- Different analysis strategies developed.

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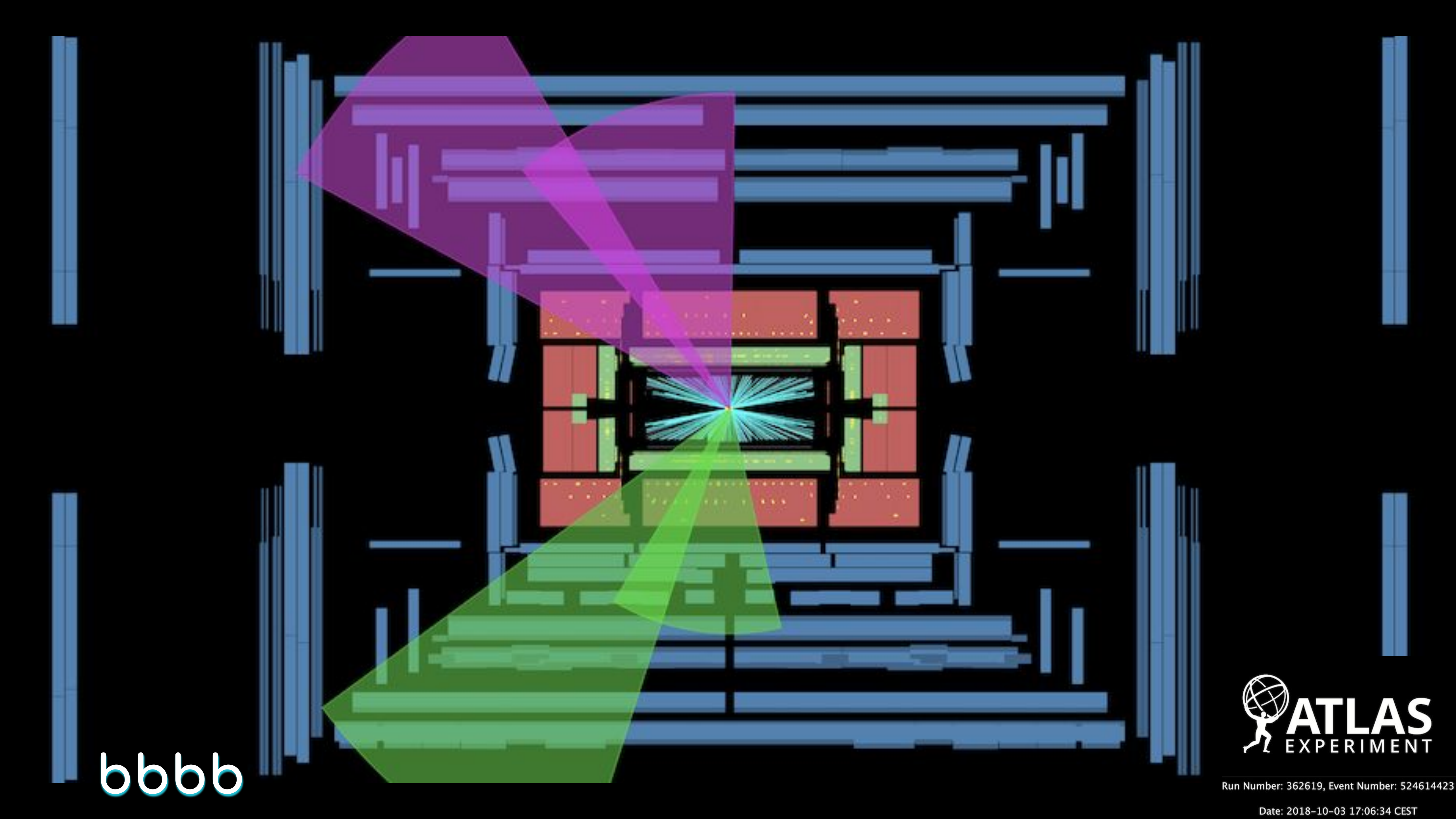
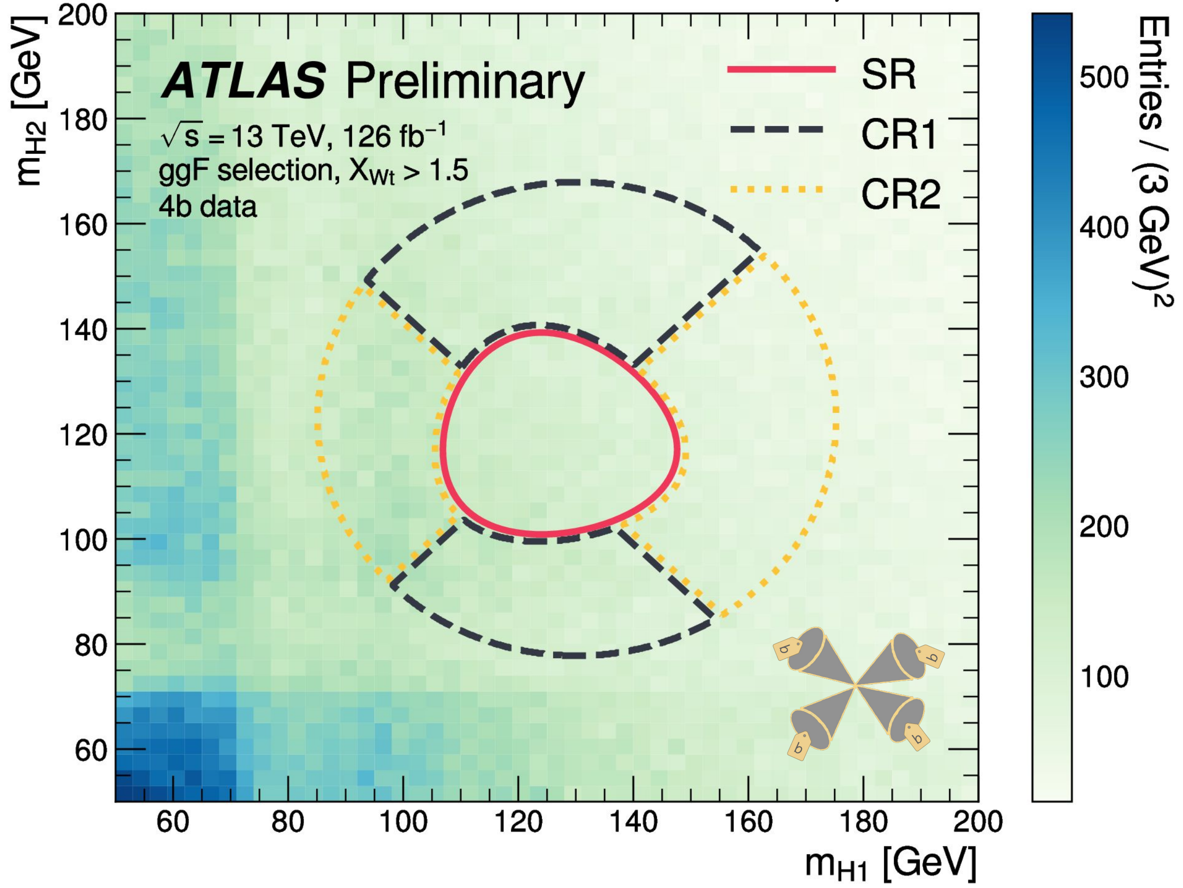
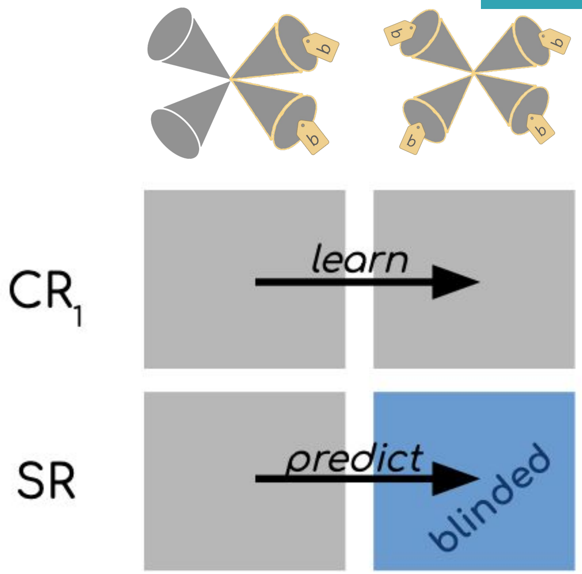

bbbb
ATLAS
EXPERIMENT
Run Number: 362619, Event Number: 524614423
Date: 2018-10-03 17:06:34 CEST

# bbbb



Select 4 b-tagged PFlow jets.
*VBF selection requires two additional jets.*




$X_{Wt}$: top veto cut.

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

$X_{HH}$: SR cut.

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

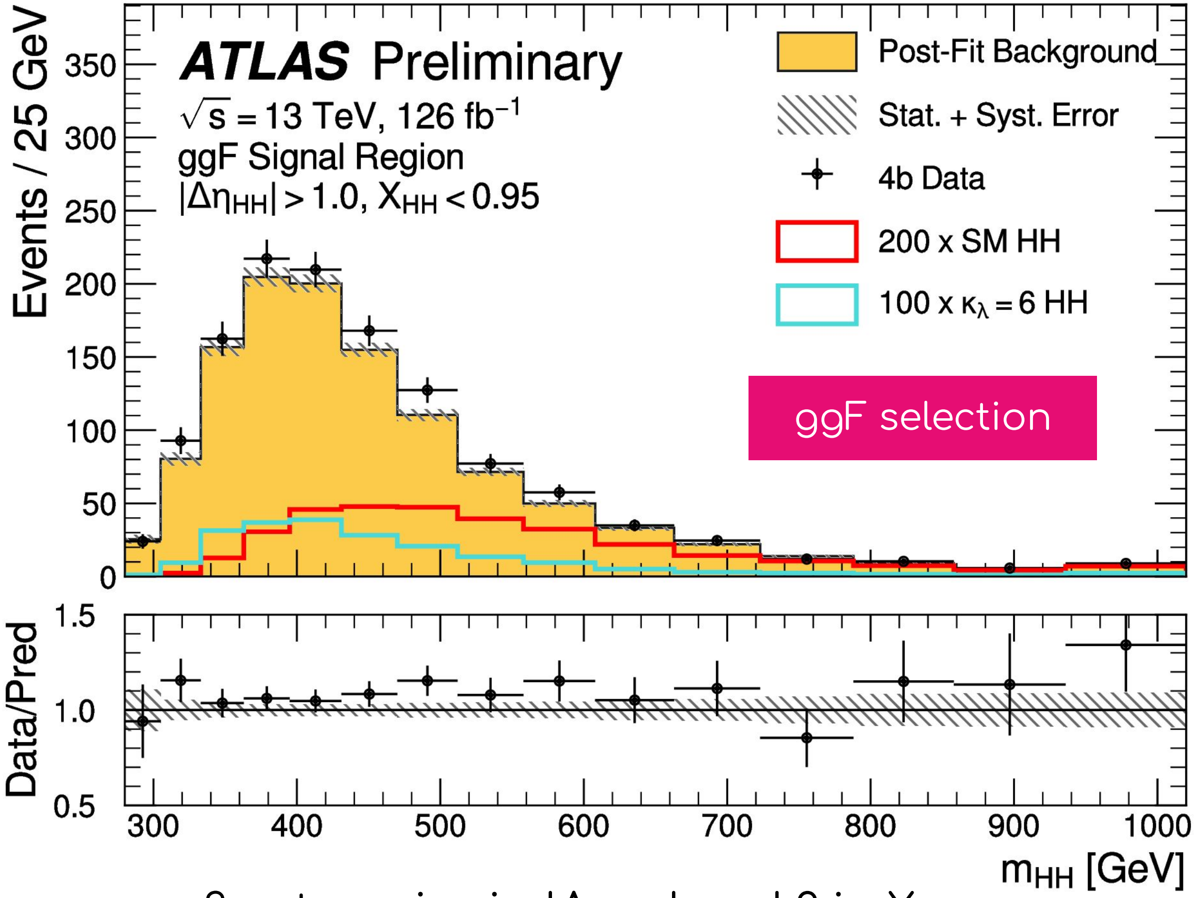
## data-driven bkg estimation

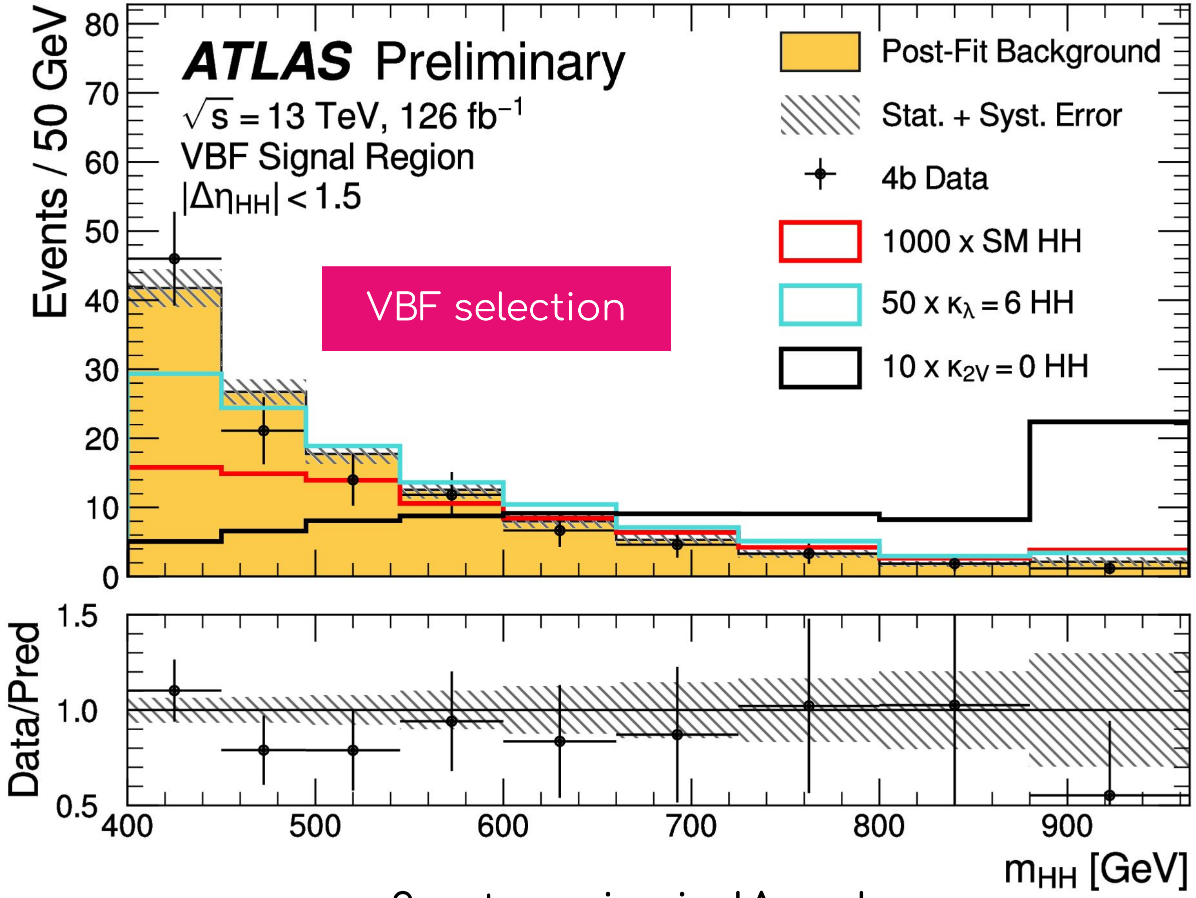
- Use a neural network to learn 2b-to-4b events kinematic re-weighting.
- Train ensemble of 100 NN, use the mean weight as nominal and take the standard deviation as NN statistical uncertainty;
- Systematic uncertainty: compare nominal (CR1) vs alternative (CR2) estimates.

# bbbb

ATLAS-CONF-2022-035

Define different categories to improve analysis sensitivity.




3 categories in $|\Delta\eta_{HH}|$ and 2 in $X_{HH}$

$|\Delta\eta_{HH}| < 0.5$, $0.5 < |\Delta\eta_{HH}| < 1.0$, $|\Delta\eta_{HH}| > 1.0$

$X_{HH} < 0.95$, $X_{HH} > 0.95$

2 categories in $|\Delta\eta_{HH}|$

$|\Delta\eta_{HH}| < 1.5$ and $|\Delta\eta_{HH}| > 1.5$

Analysis dominated by background estimate uncertainties.

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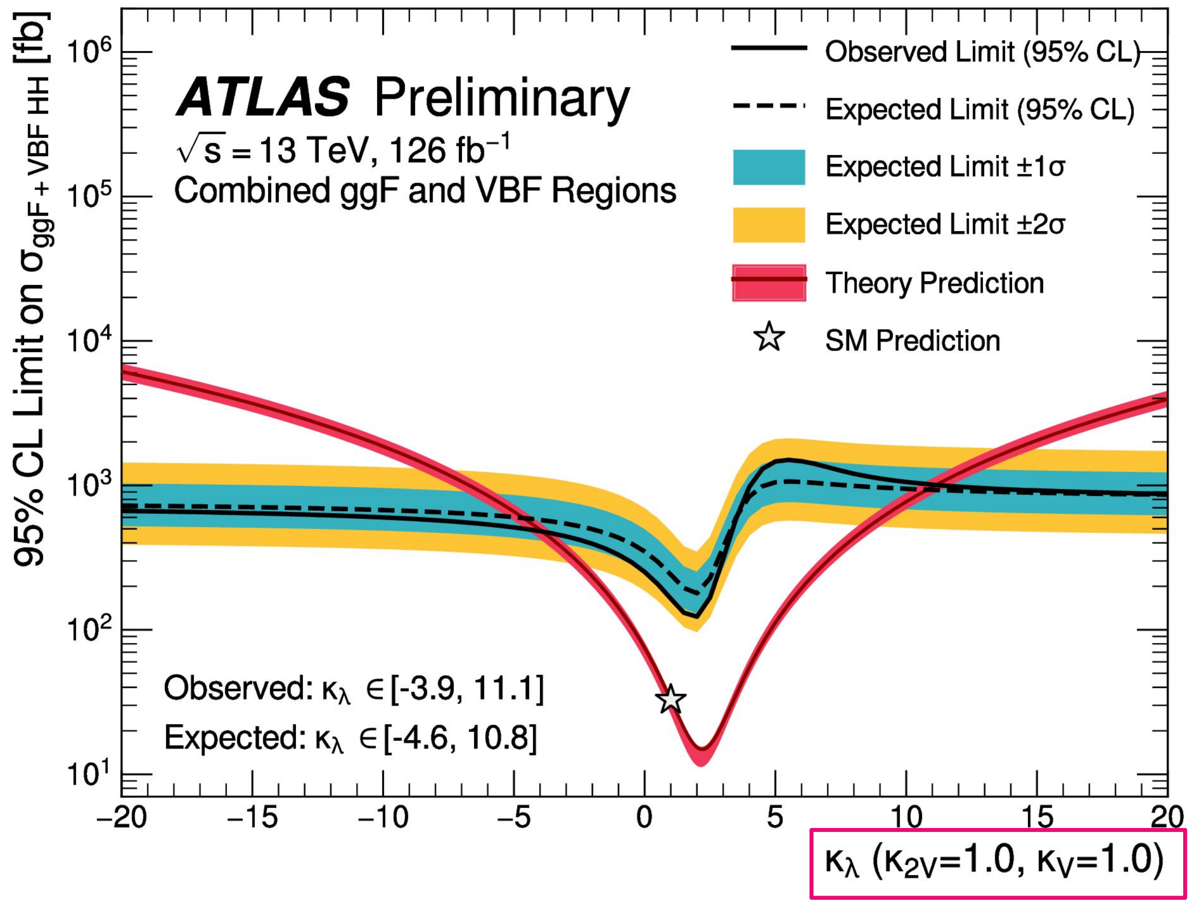
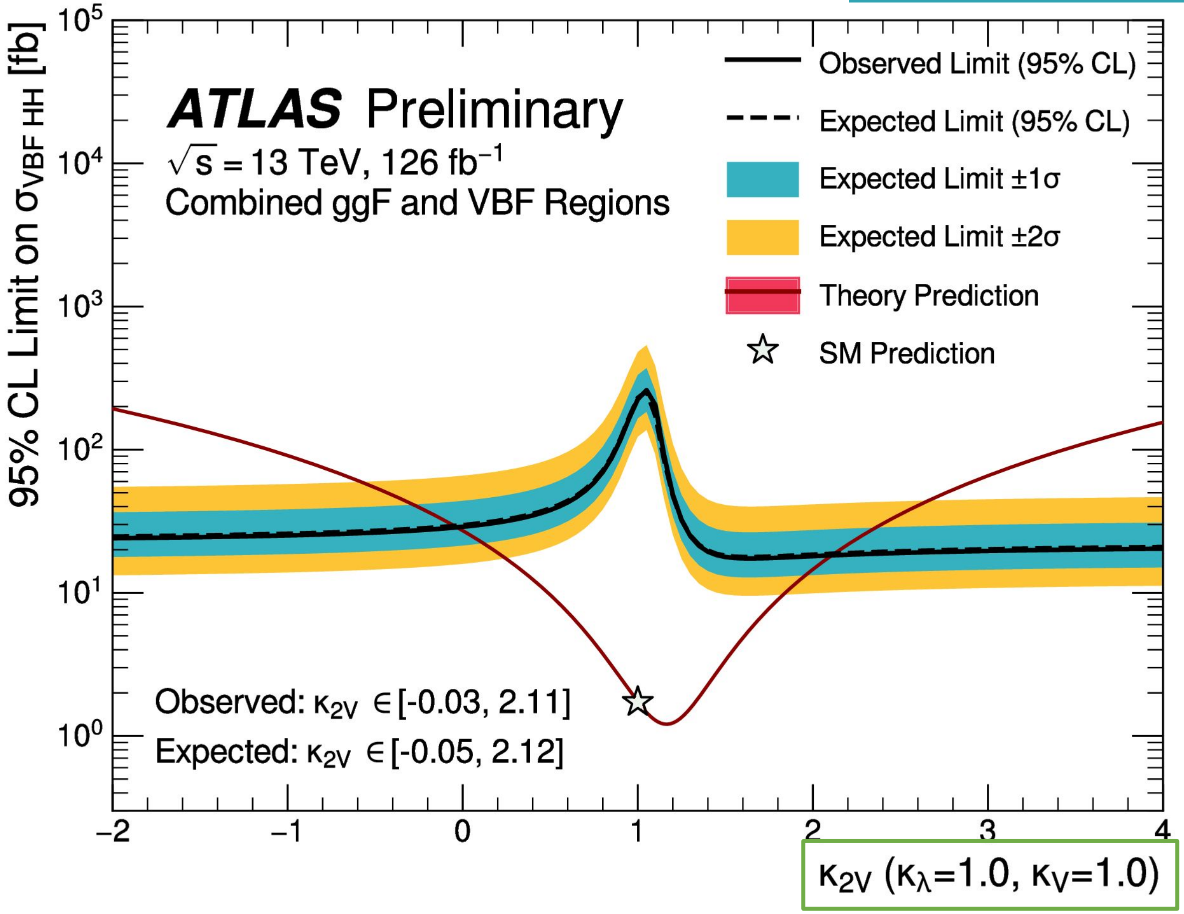
# bbbb

ATLAS-CONF-2022-035




No evidence for a HH(bbbb) signal is found.

Observed (expected) upper limit on the cross section for ggF+VBF production is set to 5.4 (8.1) times the SM predicted cross-section at 95% CL.

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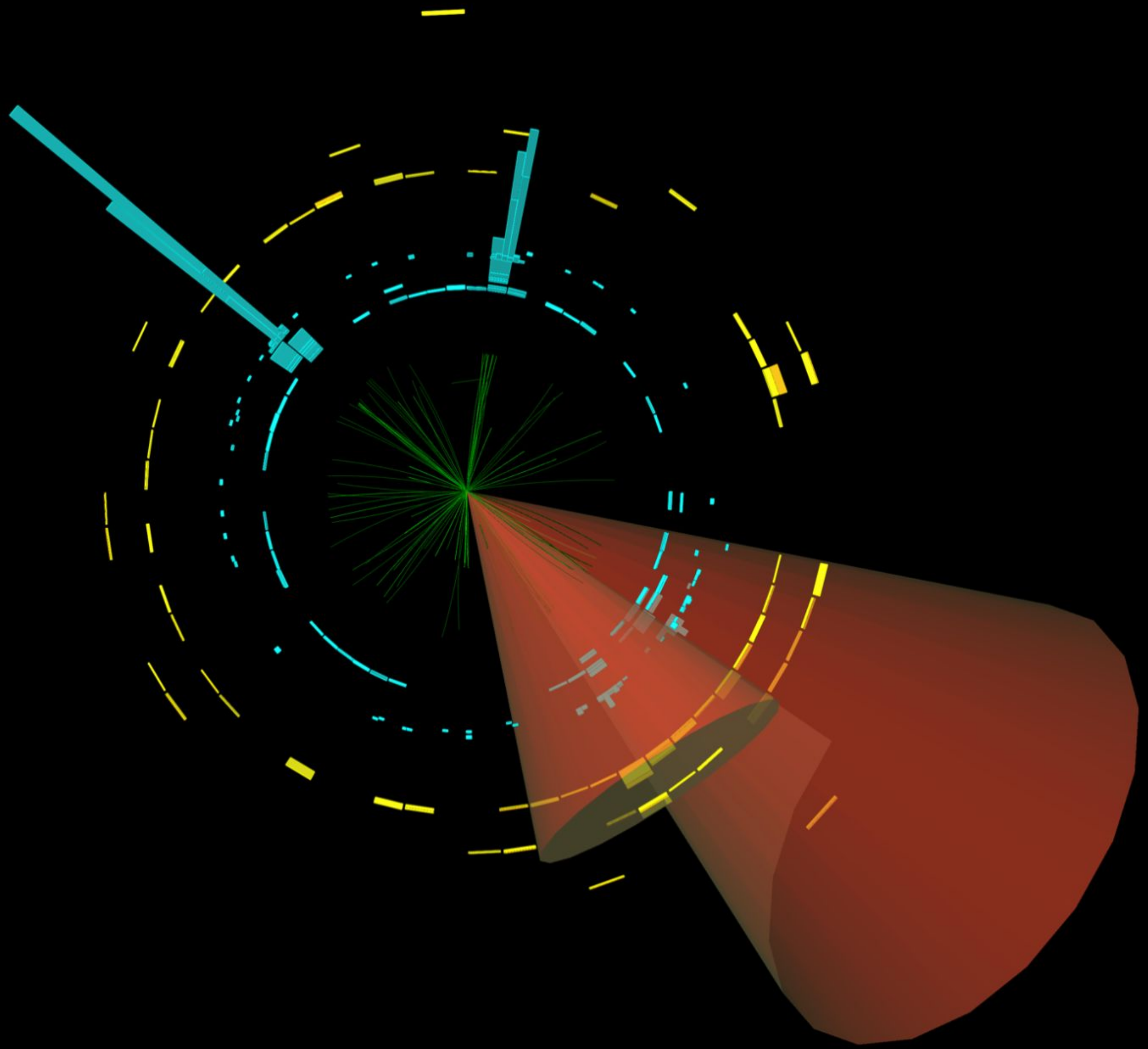
ATLAS EXPERIMENT



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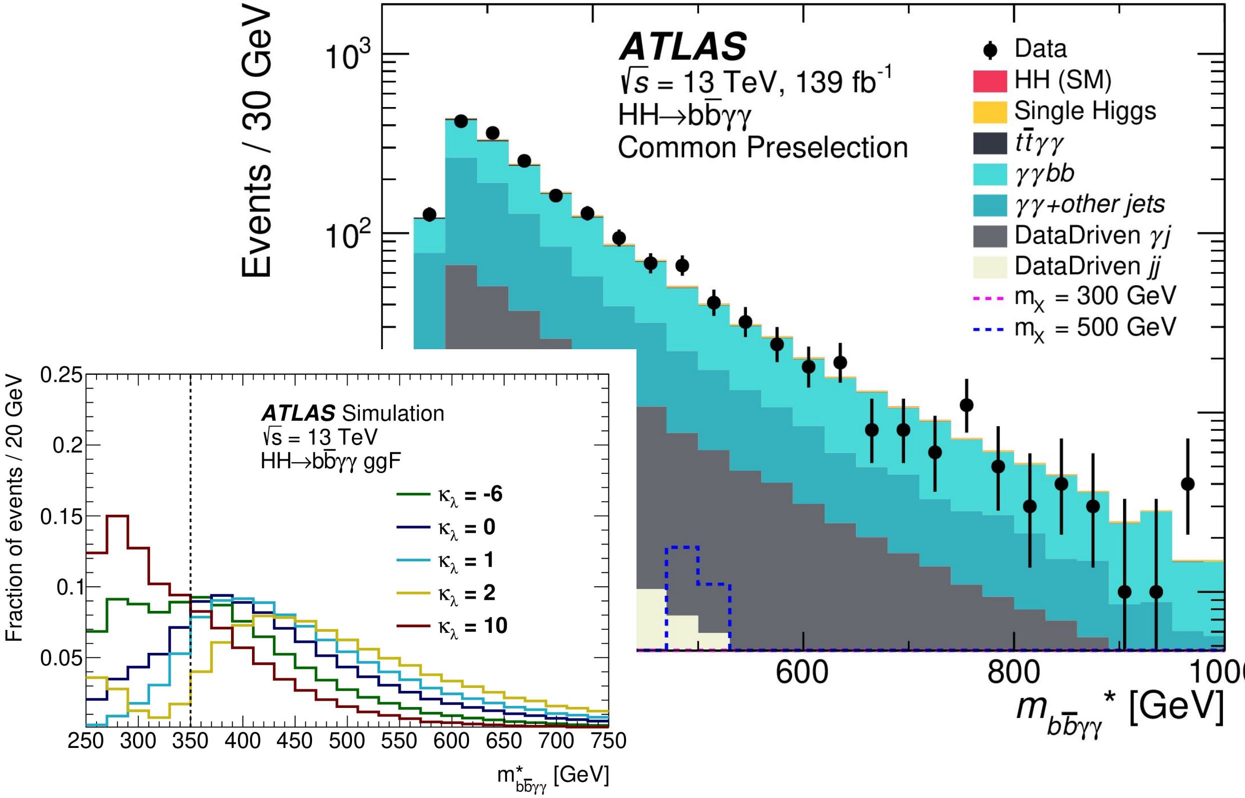
2017-07-17 23:58:15 CEST

bbγγ

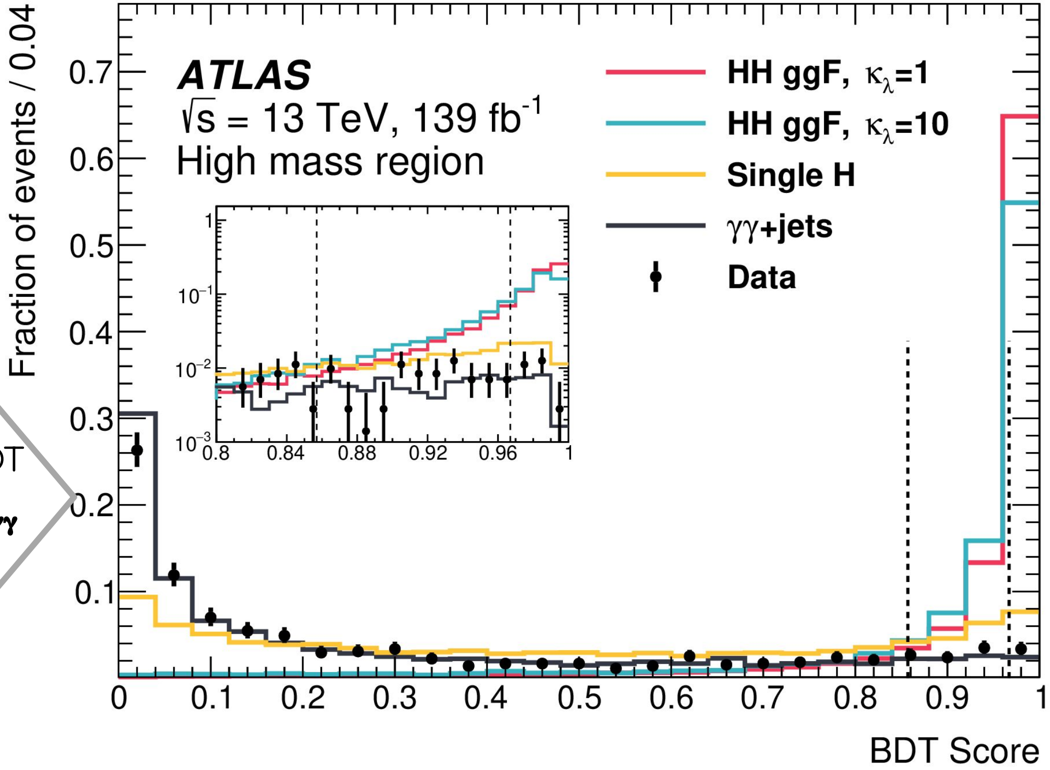
# bbγγ

Submitted to PRD
[arXiv:2112.11876]

Select **2 b-tagged** PFlow jets and **2 high $p_T$ photons**.




train a BDT
per $\mathbf{m^*}_{bb\gamma\gamma}$
region




categories

- High and low $\mathbf{m^*}_{bb\gamma\gamma}$

$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250\ \text{GeV}$$

  - Low mass regions used to retain sensitivity for BSM signals

- For each $\mathbf{m^*}_{bb\gamma\gamma}$ category BDTs are trained.
  - Use BDTs scores to define **tight/loose BDT categories.**

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# bbγγ

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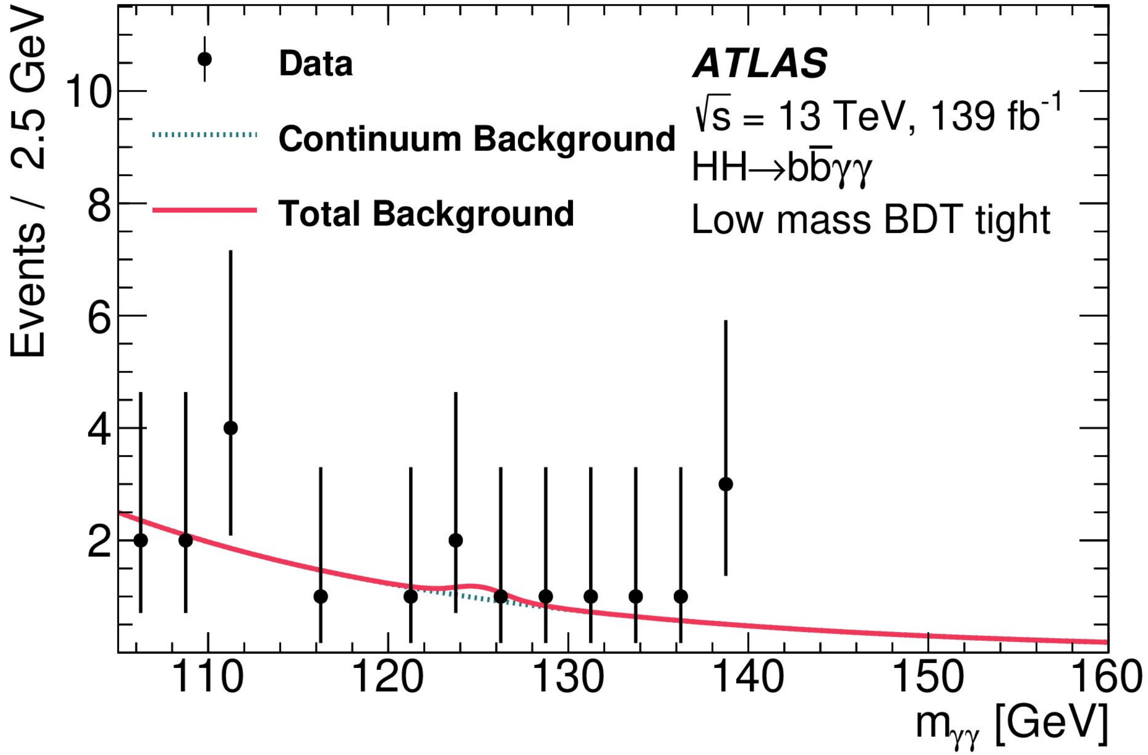
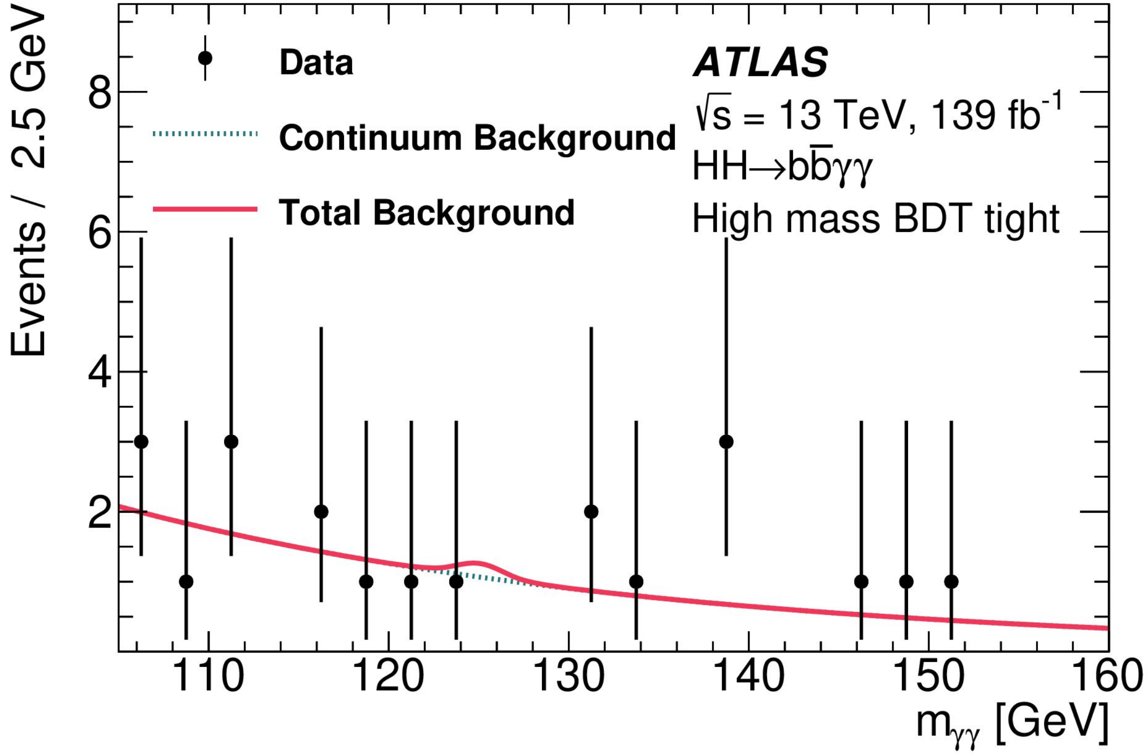
[arXiv:2112.11876]

Select 2 b-tagged PFlow jets and 2 high $p_T$ photons.




data-driven bkg estimation

- Model signal and background $m_{\gamma\gamma}$ shapes with analytic functions.
- Final background prediction comes from $m_{\gamma\gamma}$ fit.

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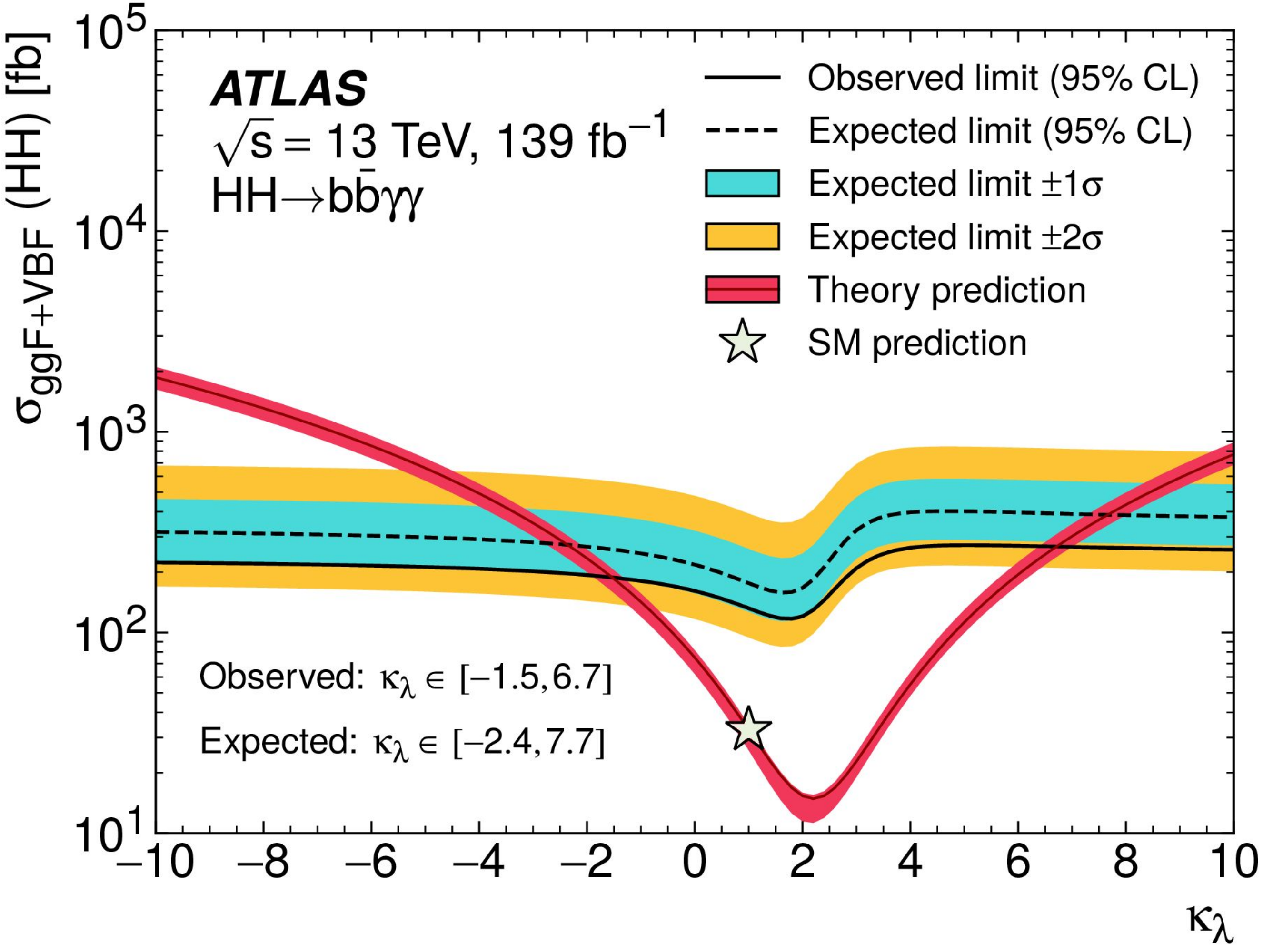
# bbγγ

Submitted to PRD
[arXiv:2112.11876]




- Analysis dominated by statistical uncertainties.
- No evidence for a HH(bbγγ) signal is found.
- Observed (expected) limit on the cross section for ggF+VBF production is set to 4.2 (5.7) times the SM predicted cross section at 95% CL.

ATLAS EXPERIMENT

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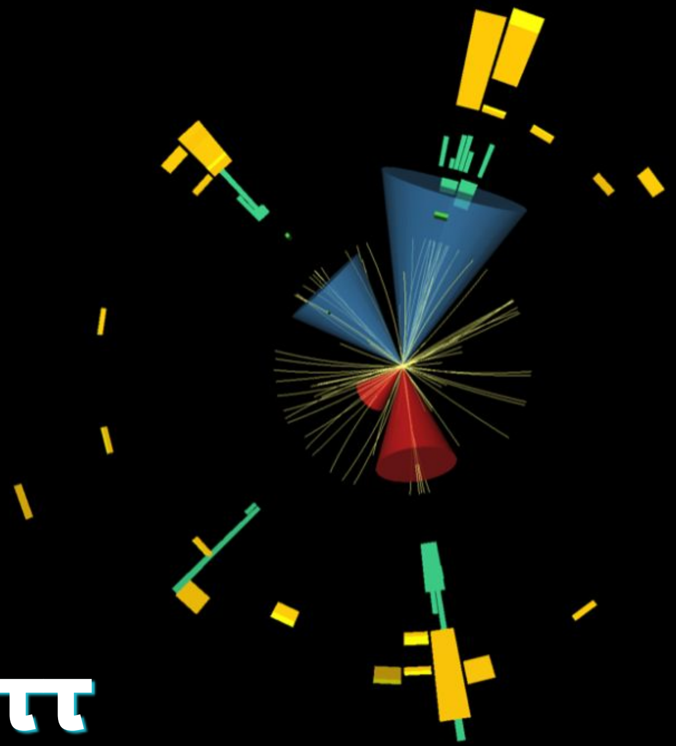
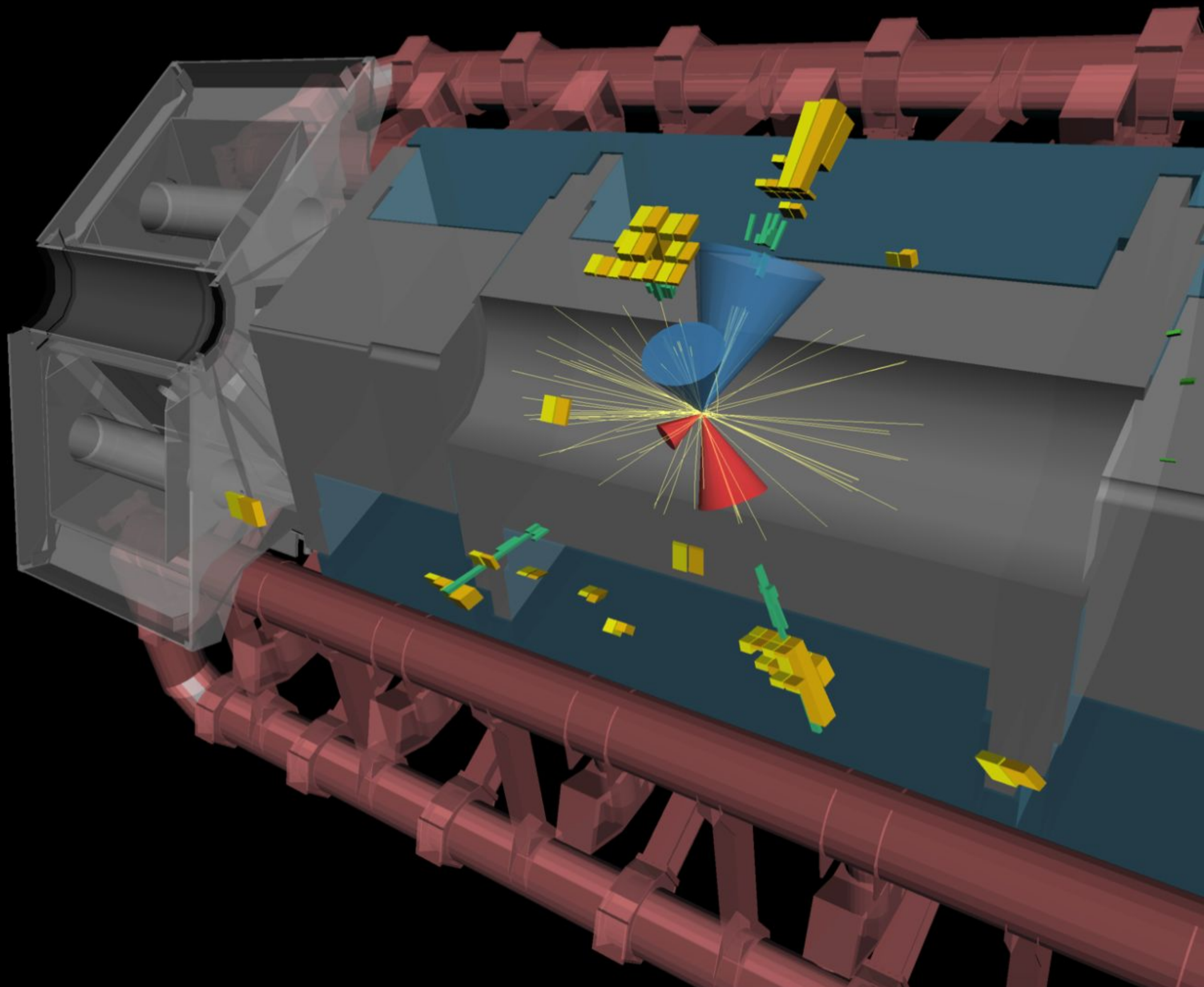
2017-10-31 00:02:20 CEST





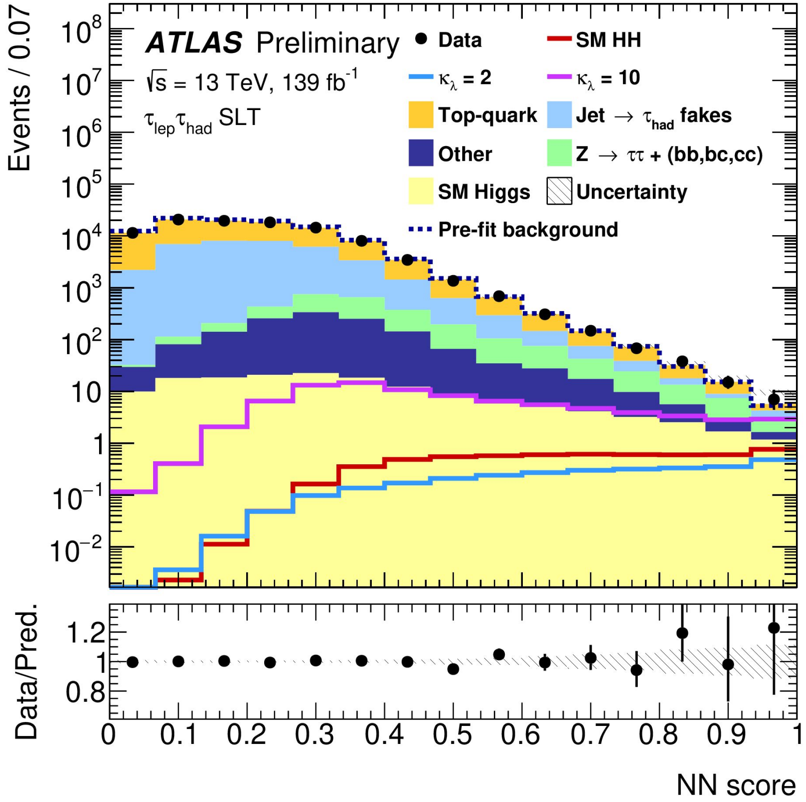
bbττ

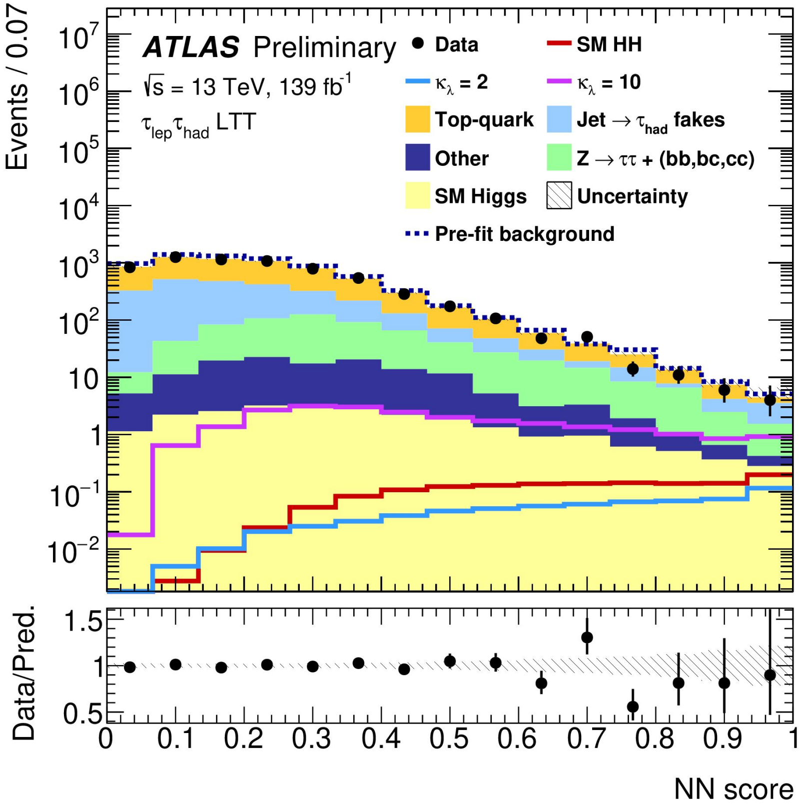
# bbττ

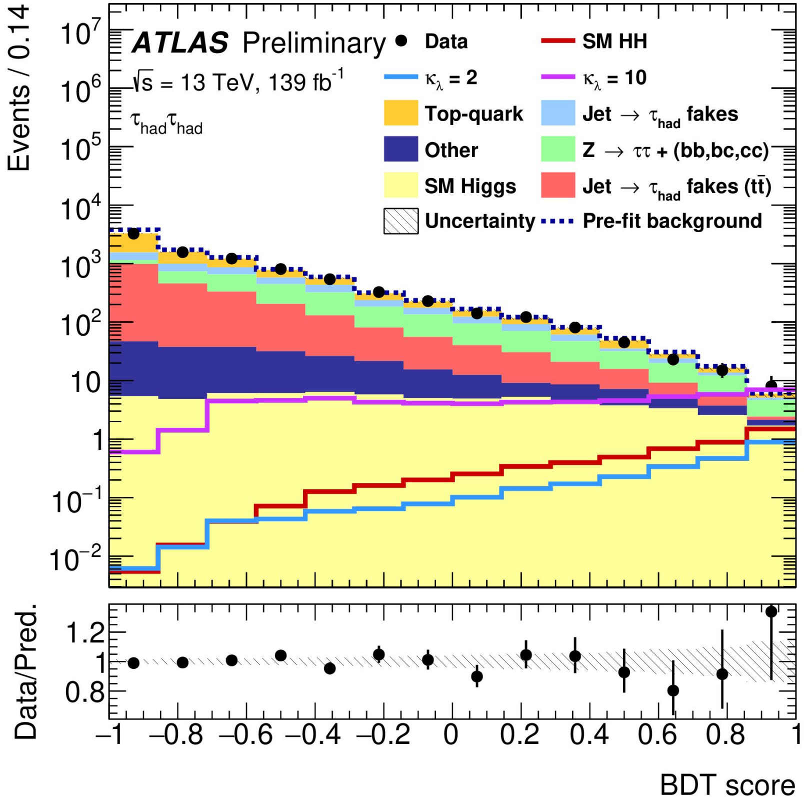
ATLAS EXPERIMENT

ATLAS-CONF-2021-030

Select 2 b-tagged PFlow jets and 2 OS taus ($\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$).




## categorisation (based on triggers)

- $H \to \tau_{lep}\tau_{had}$: single-lepton (SLT) or lepton+tau (LTT) triggers,
- $H \to \tau_{had}\tau_{had}$: combination of single-tau (STT) and di-tau triggers.

## background discrimination

- NN trained in $HH \to bb\,\tau_{lep}\tau_{had}$
- BDT used in $HH \to bb\,\tau_{had}\tau_{had}$

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# $bb\tau\tau$

ATLAS-CONF-2021-030

| | | Observed | $-2\ \sigma$ | $-1\ \sigma$ | Expected | $+1\ \sigma$ | $+2\ \sigma$ |
|---|---|---|---|---|---|---|---|
| $\tau_{had}\tau_{had}$ | $\sigma_{ggF+VBF}$ [fb] | 145 | 70.5 | 94.6 | 131 | 183 | 245 |
| | $\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$ | 4.95 | 2.38 | 3.19 | 4.43 | 6.17 | 8.27 |
| $\tau_{lep}\tau_{had}$ | $\sigma_{ggF+VBF}$ [fb] | 265 | 124 | 167 | 231 | 322 | 432 |
| | $\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$ | 9.16 | 4.22 | 5.66 | 7.86 | 10.9 | 14.7 |
| Combined | $\sigma_{ggF+VBF}$ [fb] | 135 | 61.3 | 82.3 | 114 | 159 | 213 |
| | $\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$ | $\boxed{4.65}$ | 2.08 | 2.79 | 3.87 | 5.39 | 7.22 |

- Analysis dominated by statistical uncertainties.
- No evidence for a HH($bb\tau\tau$) signal is found.
- Observed (expected) limit on the cross section for ggF+VBF production is set to 4.65 (3.87) times the SM predicted cross section at 95% CL.

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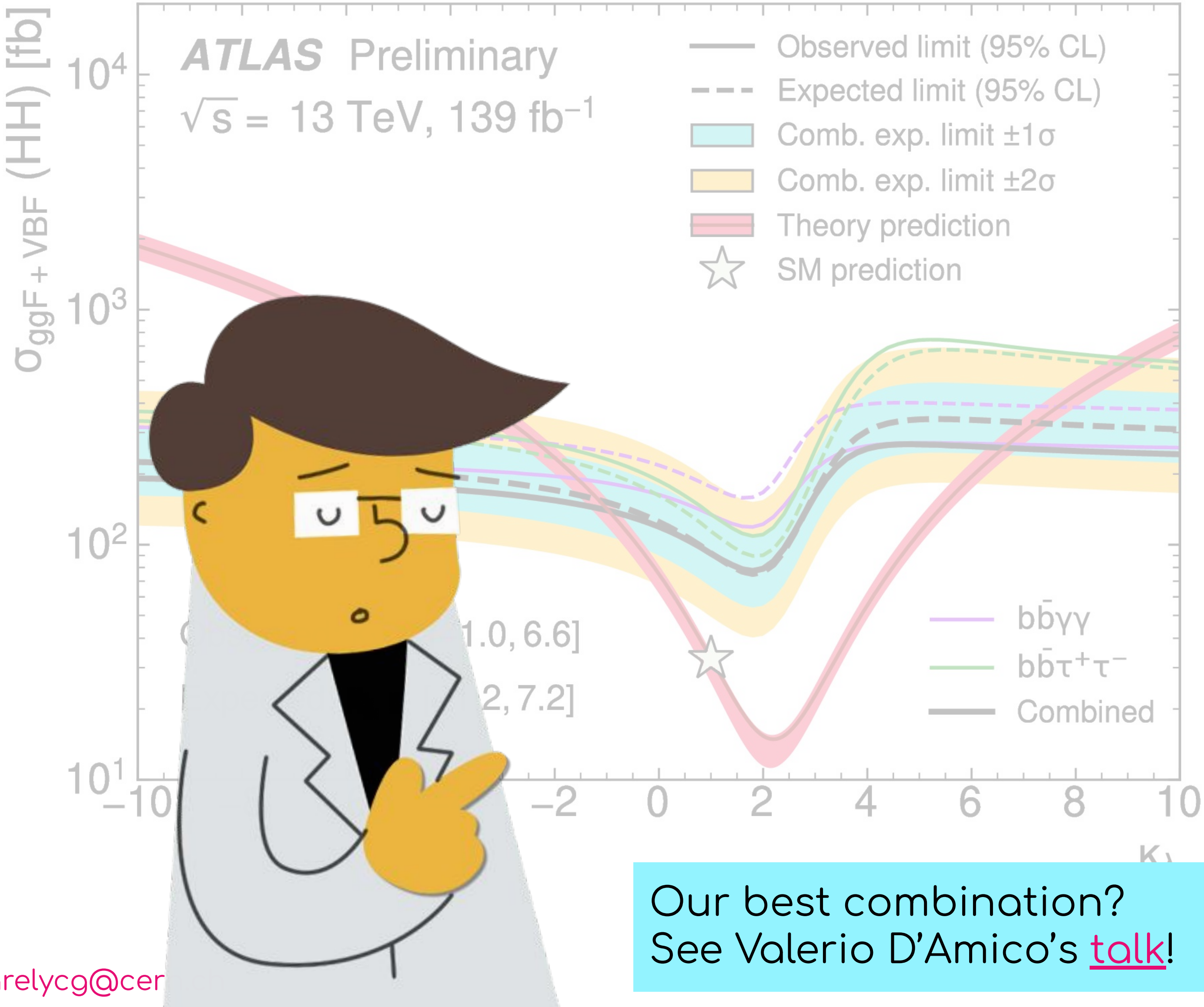
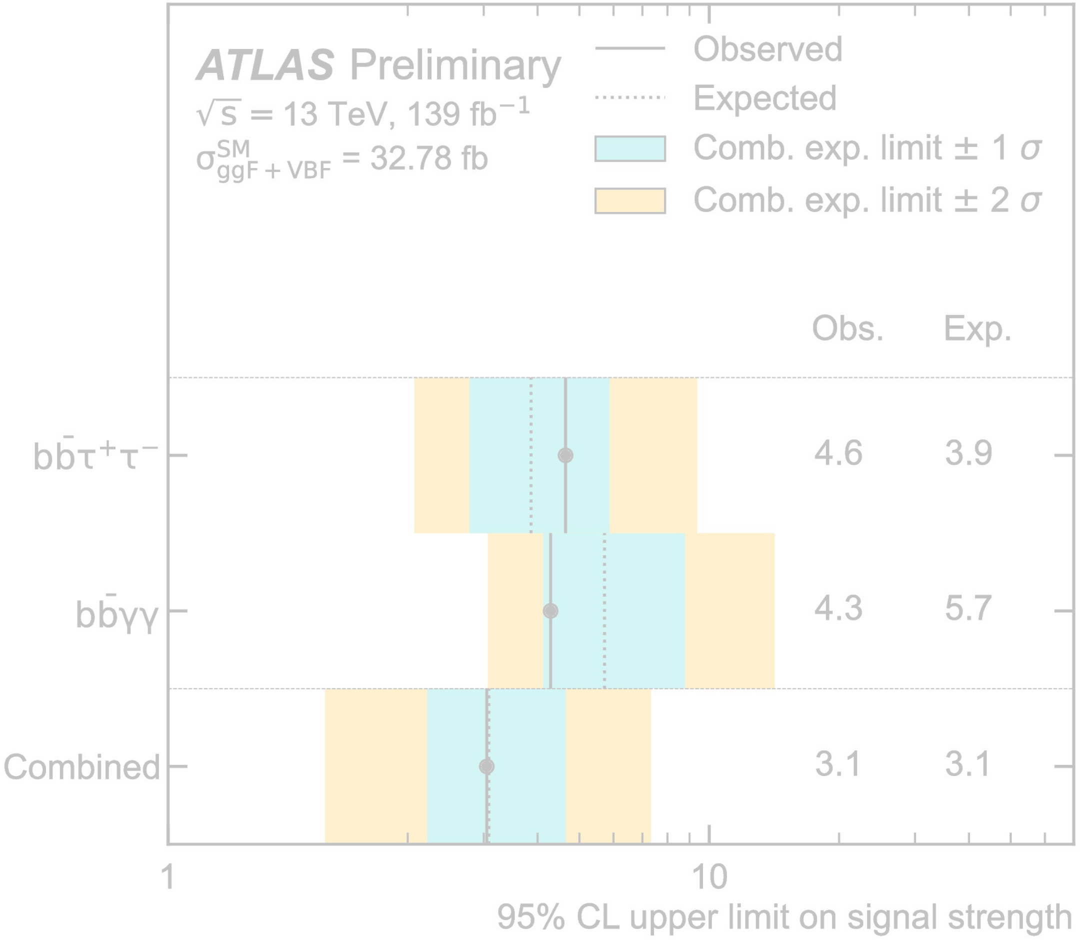
# HH combination?

ATLAS-CONF-2021-052




signal strength for NR HH production with respect to the SM




Our best combination?
See Valerio D'Amico's talk!

# VHH (0L,1L,2L)

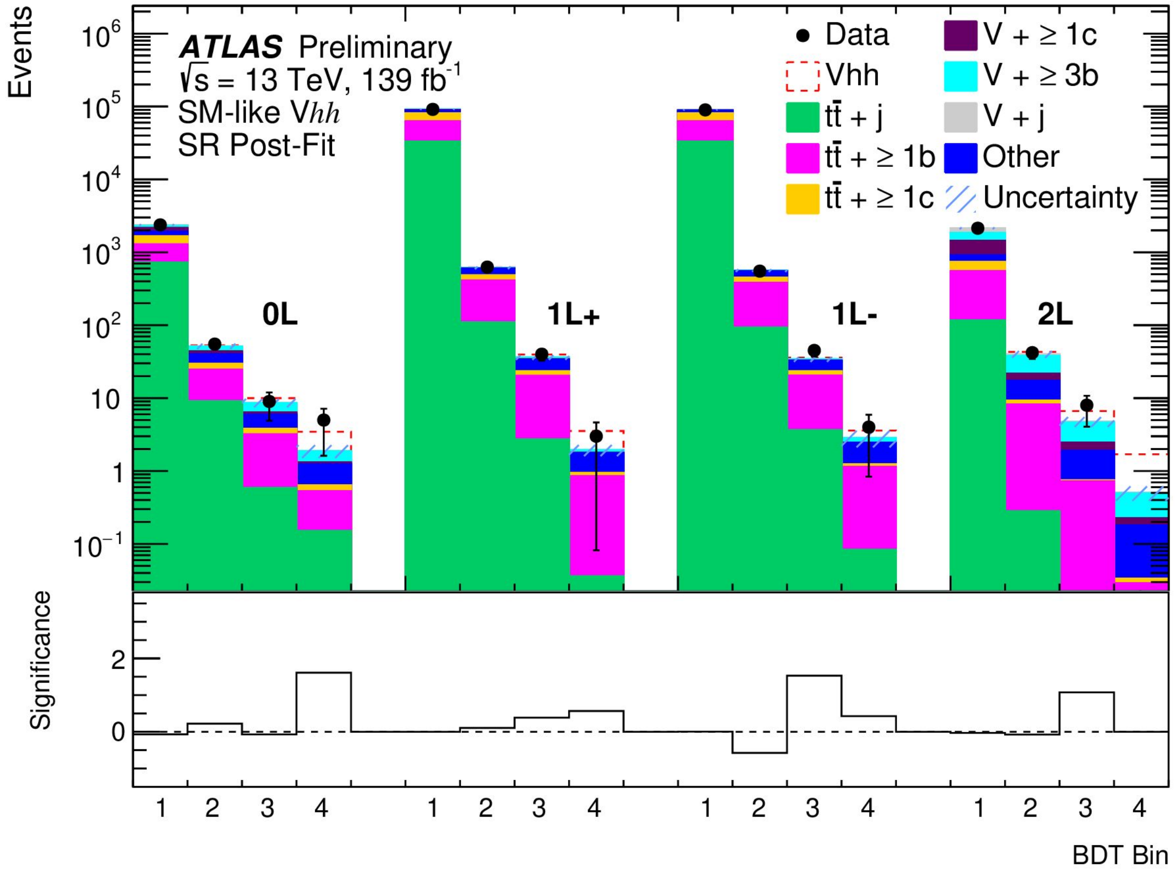
ATLAS-CONF-2022-043/

- Signal regions include:
  - Z(**νν**)hh(bbbb),
  - W(l**ν**)hh(bbbb),
  - Z(ll)hh(bbbb).

- Control regions are constructed to constrain th main backgrounds:
  - γ + jets (to constrain V+jets)
  - e/μ (to constrain ttbar).

- BDT are used for background discrimination. C BDT is constructed for each channel (0L, 1L, 2L).
  - input variables include: $m_{HH}$ and mass difference of the 2 higgs candidates.

- BDT distributions are also used in the fit to extract signal contribution.

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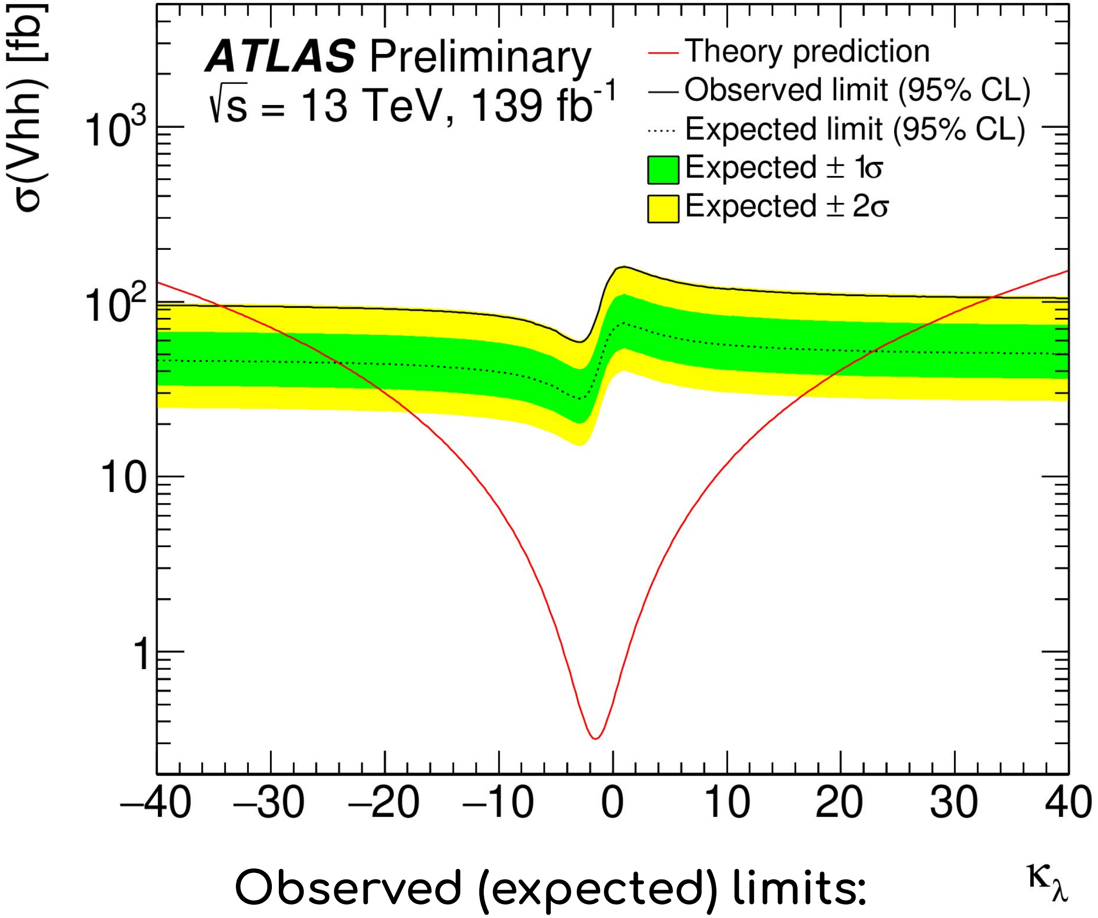
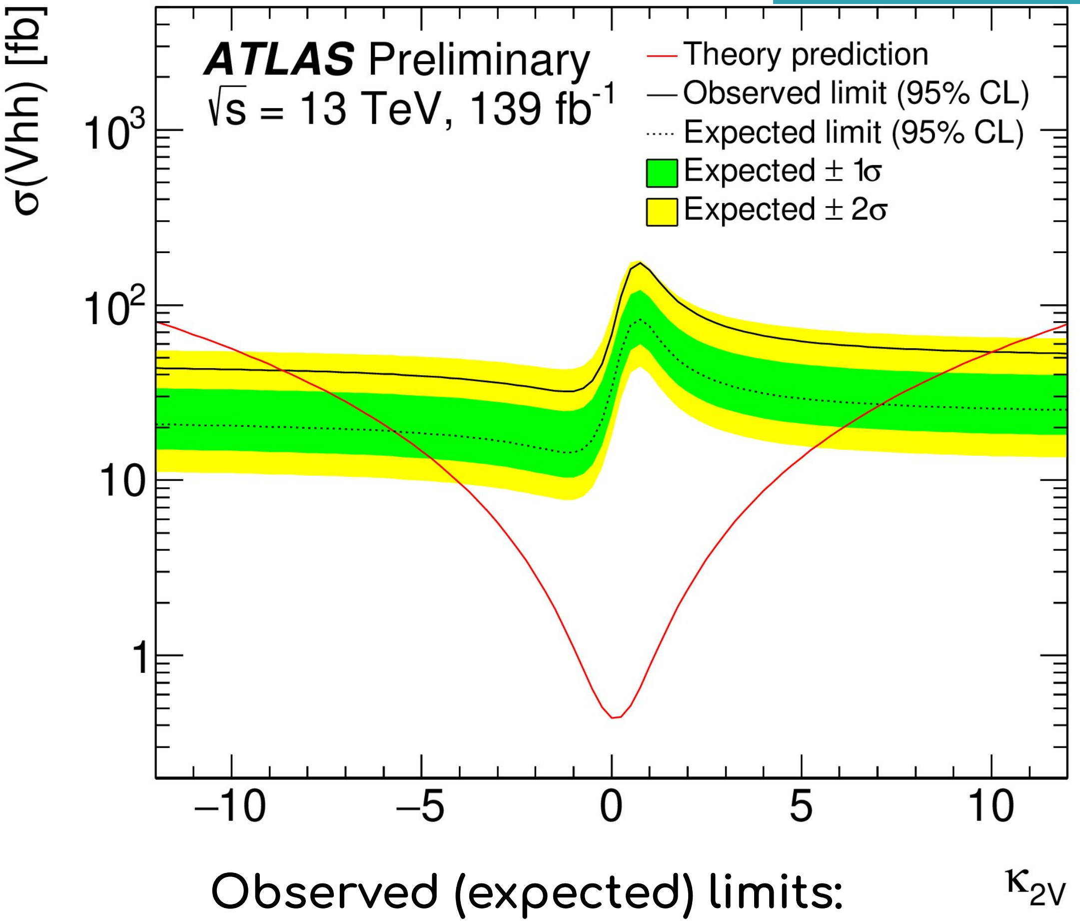
# VHH (0L,1L,2L)

ATLAS-CONF-2022-043/




Observed (expected) limits:

-34.4 (-24.1) < $\kappa_\lambda$ < 33.3 (22.9)




Observed (expected) limits:

-8.6 (-5.7) < $\kappa_{2V}$ < 10.0 (7.1)

An observed (expected) upper limit of 183 (87±41) on the signal strength with respect to the SM.

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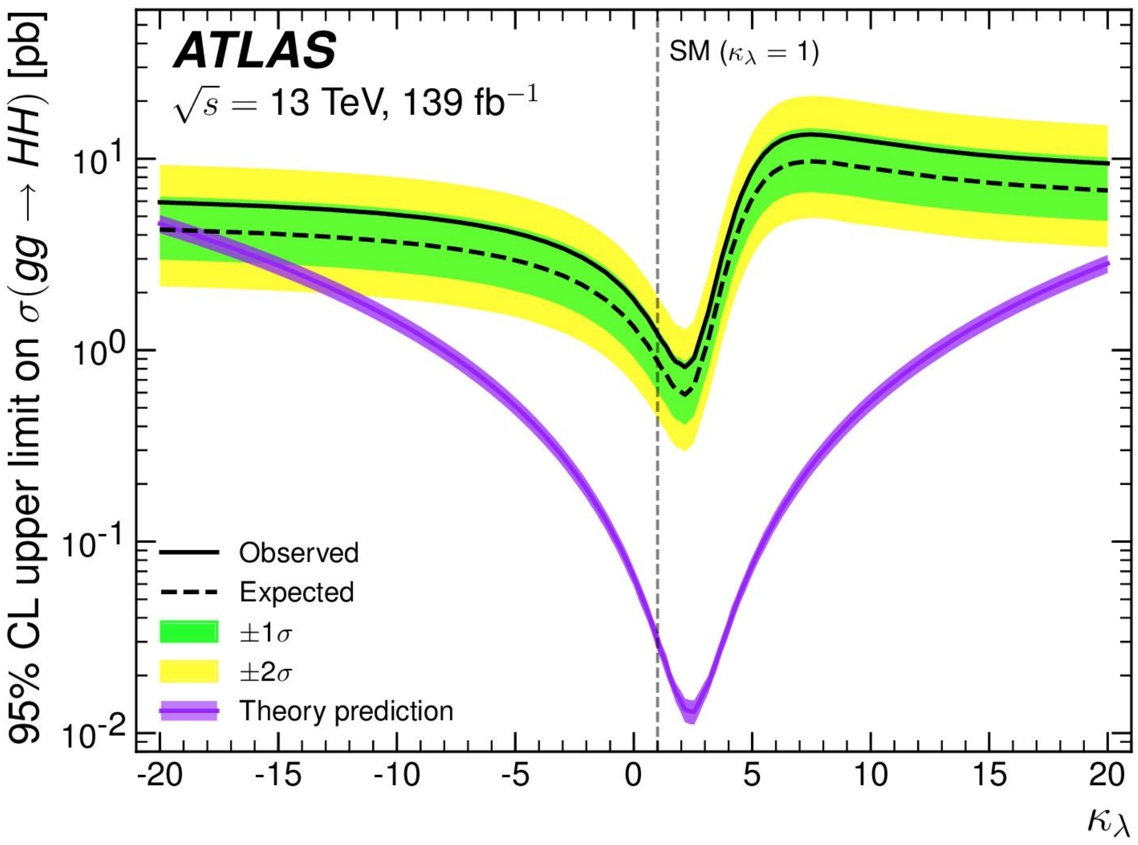
# Other channels

(with full LHC run 2 data)

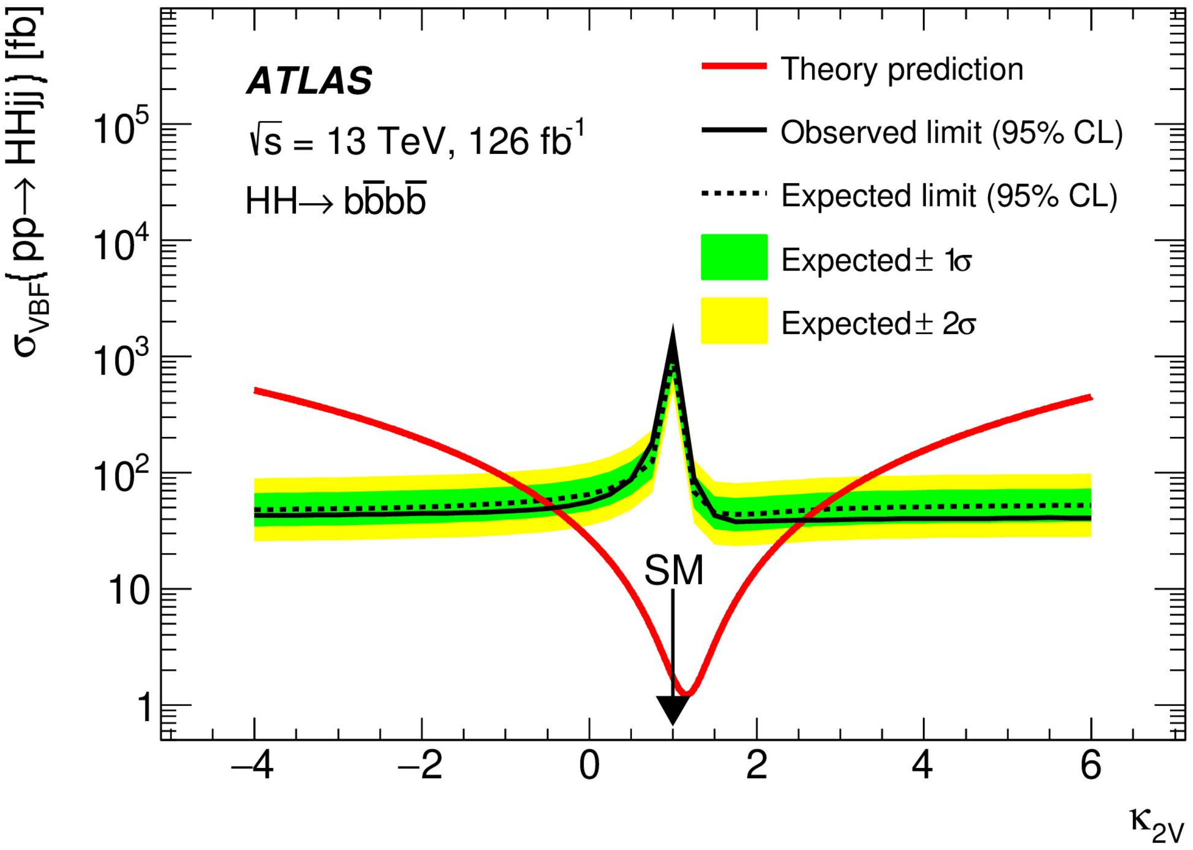
Phys. Lett. B 801 (2020) 135145

JHEP 07 (2020) 108

## HH → bb + ZZ/WW/ττ




## (VBF) HH → bbbb

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# Summary

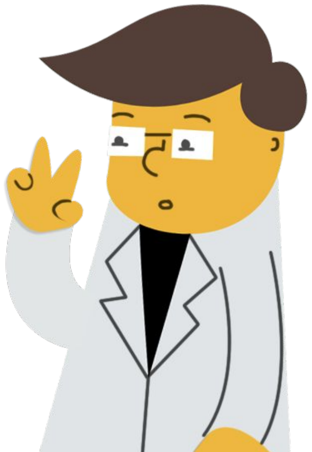
- ATLAS has a strong, and growing, program for HH searches.

- Non-resonant searches have now been performed with the full LHC run 2 data set for bbbb, bb$\tau\tau$, bb$\gamma\gamma$ in different production modes: ggF, VBF and VHH. NEW

- No significant excesses have been found up to now, however strong constraints are set.

- Many other interesting HH-related results by ATLAS (not discussed here):
  - **EFT** interpretations of the Higgs boson measurements→ Sandra Kortner's talk.
  - $\kappa_\lambda$ constraints in a **combined** measurement of single- and di-Higgs channels → Valerio D'Amico's talk.
  - **HL-LHC** prospects for single- and di-Higgs measurements → Tulin Mete's talk.
  - Searches for **resonances** decaying to pair of Higgs bosons → Liaoshan Shi's talk.

Thank you!



# References

| | |
|---|---|
| bbbb non-resonant | ATLAS-CONF-2022-035 |
| bb$\tau\tau$ resonant + NR | ATLAS-CONF-2021-030 |
| VBF bbbb | JHEP 07 (2020) 108 |
| bb$\gamma\gamma$ | Submitted to PRD [arXiv:2112.11876] |
| bbbb, bb$\tau\tau$, bb$\gamma\gamma$ comb. | ATLAS-CONF-2021-052 |
| VHH: | ATLAS-CONF-2022-043/ |

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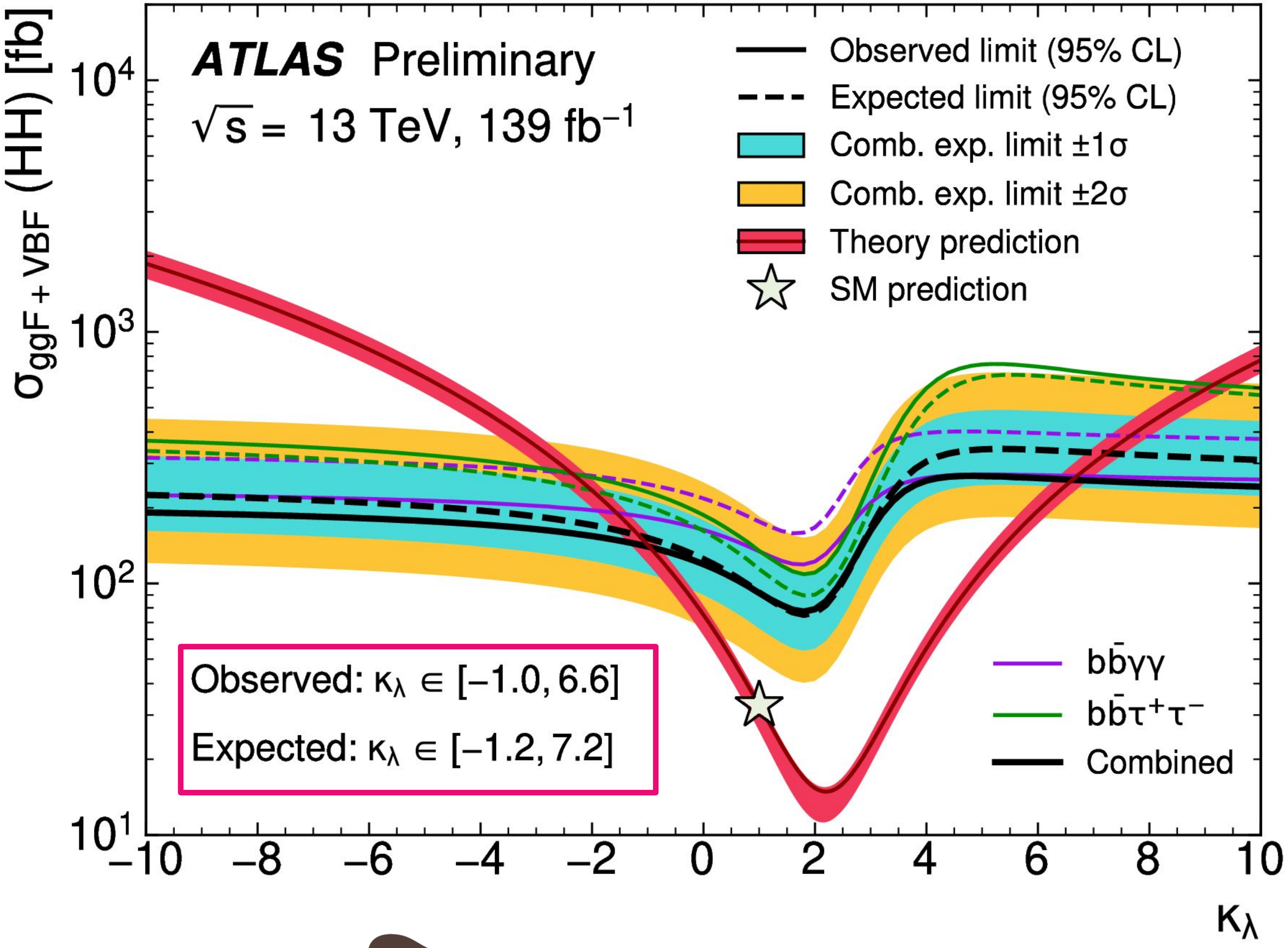
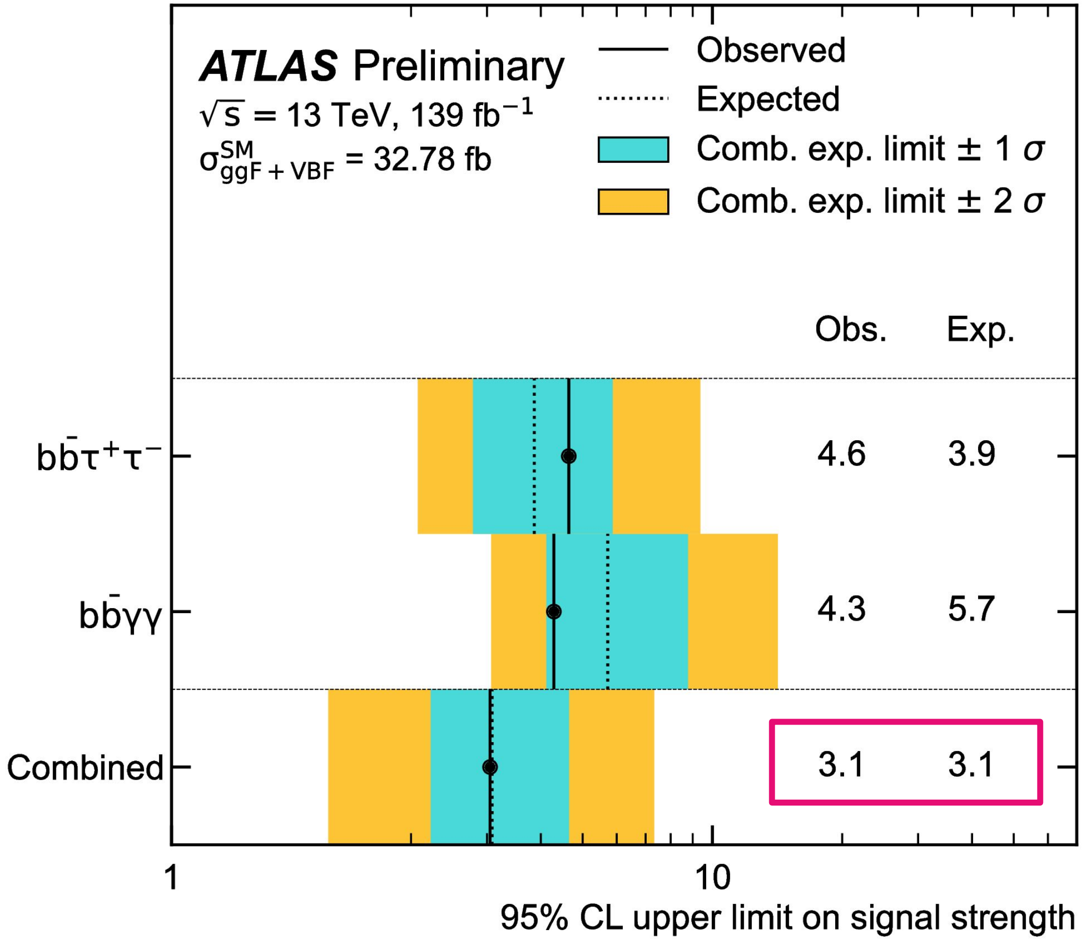
# HH combination

ATLAS-CONF-2021-052




signal strength for NR HH
production with respect to the SM




Other combinations?
See Valerio D'Amico's talk!

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# Non-resonant HH production

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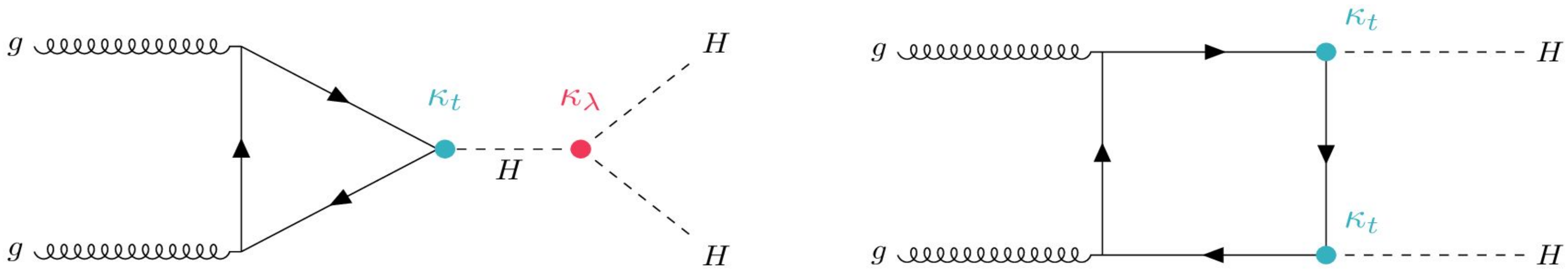
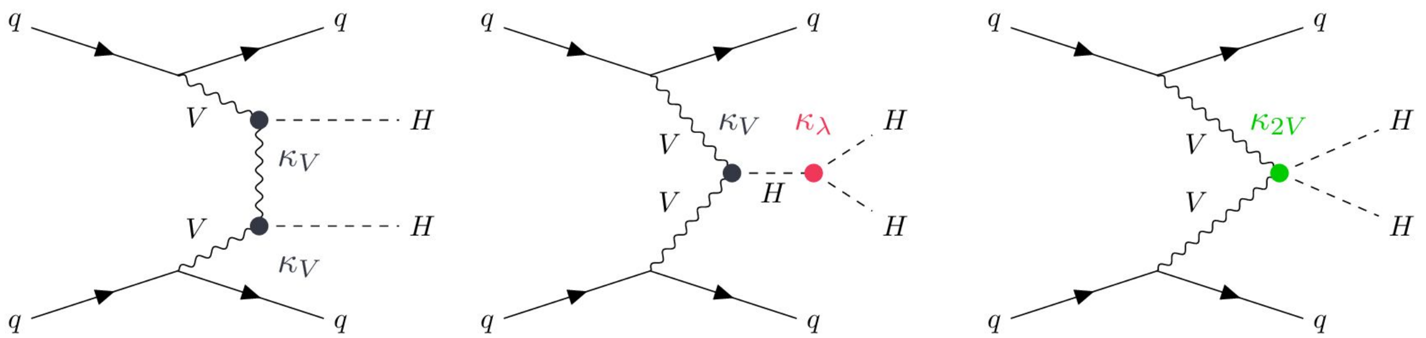



*gluon fusion (ggF) is the main production mechanism.*

Other production mechanisms also allow us to probe different couplings: $\kappa_{2V}$, $\kappa_V$.

Vector boson fusion

VVH coupling modifier
SM predicts $\kappa_V$ = 1




VVHH coupling modifier
SM predicts $\kappa_{2V}$ = 1

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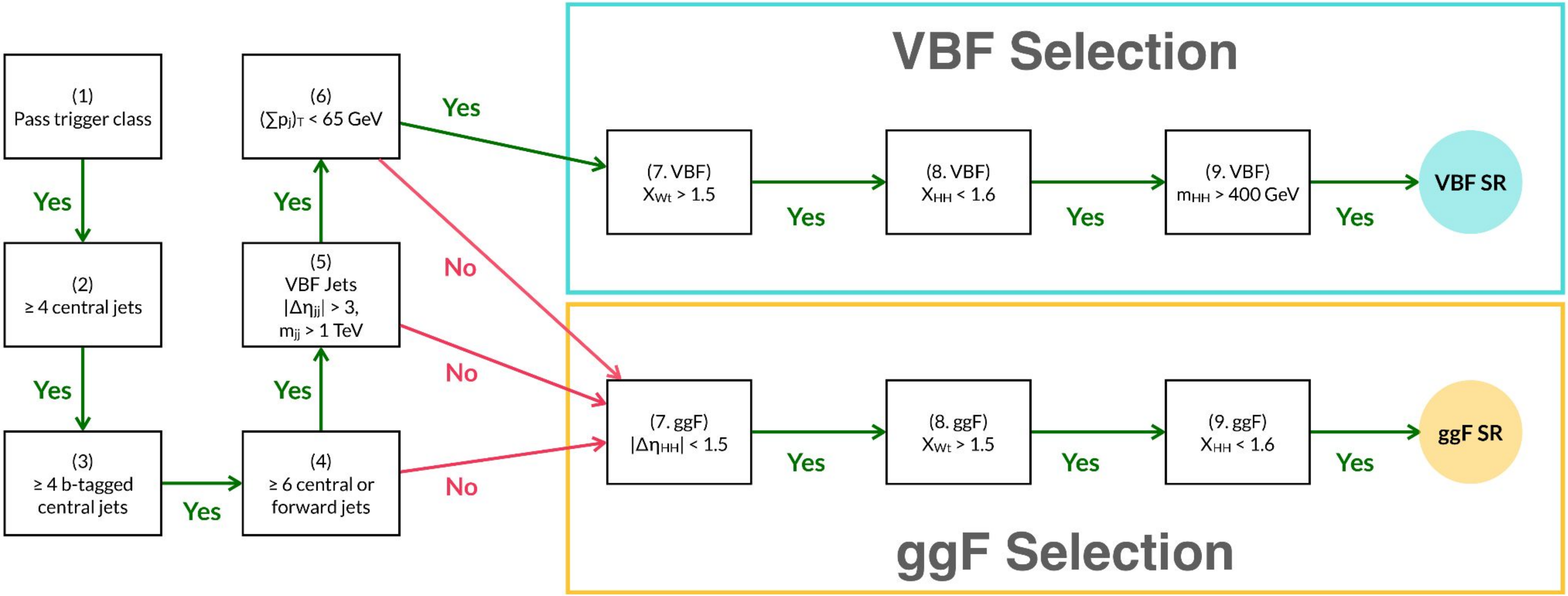
# bbbb

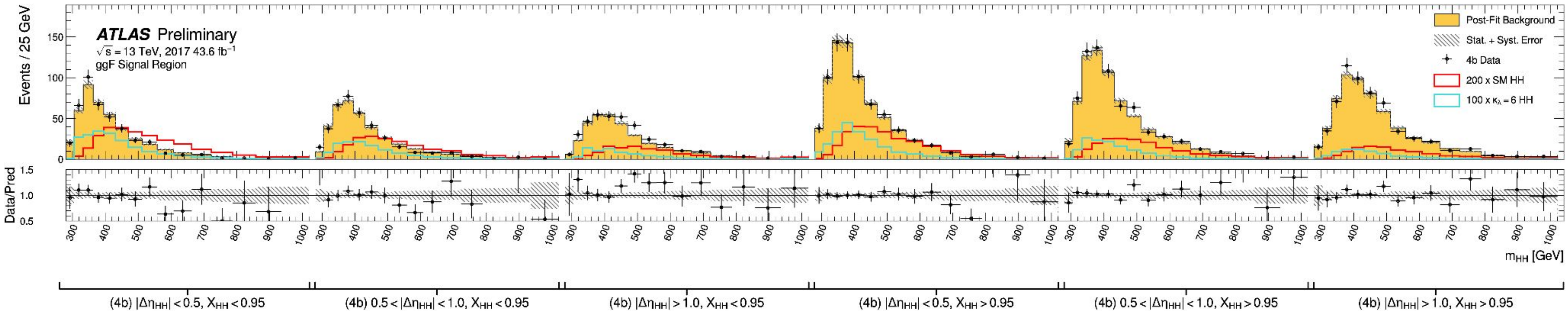
ATLAS-CONF-2022-035

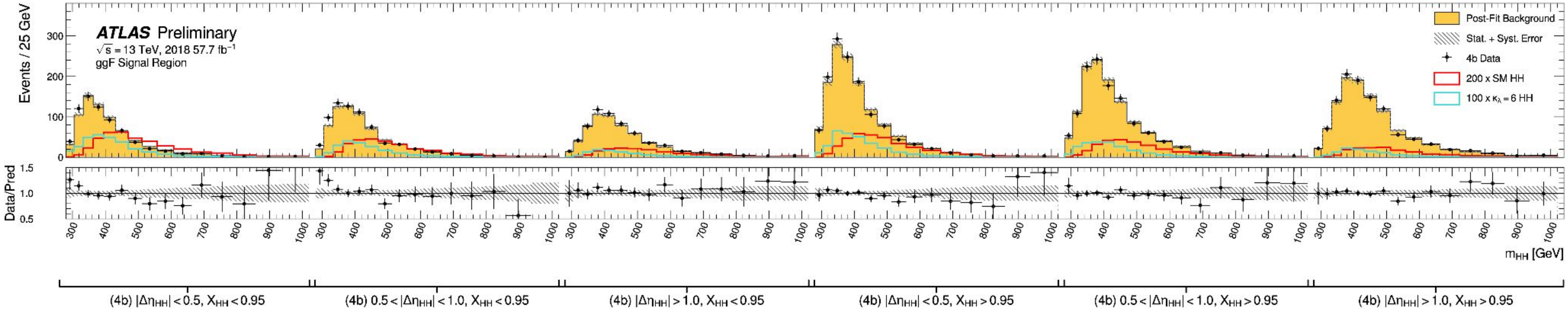


# bbbb

ggF selection

ATLAS-CONF-2022-035

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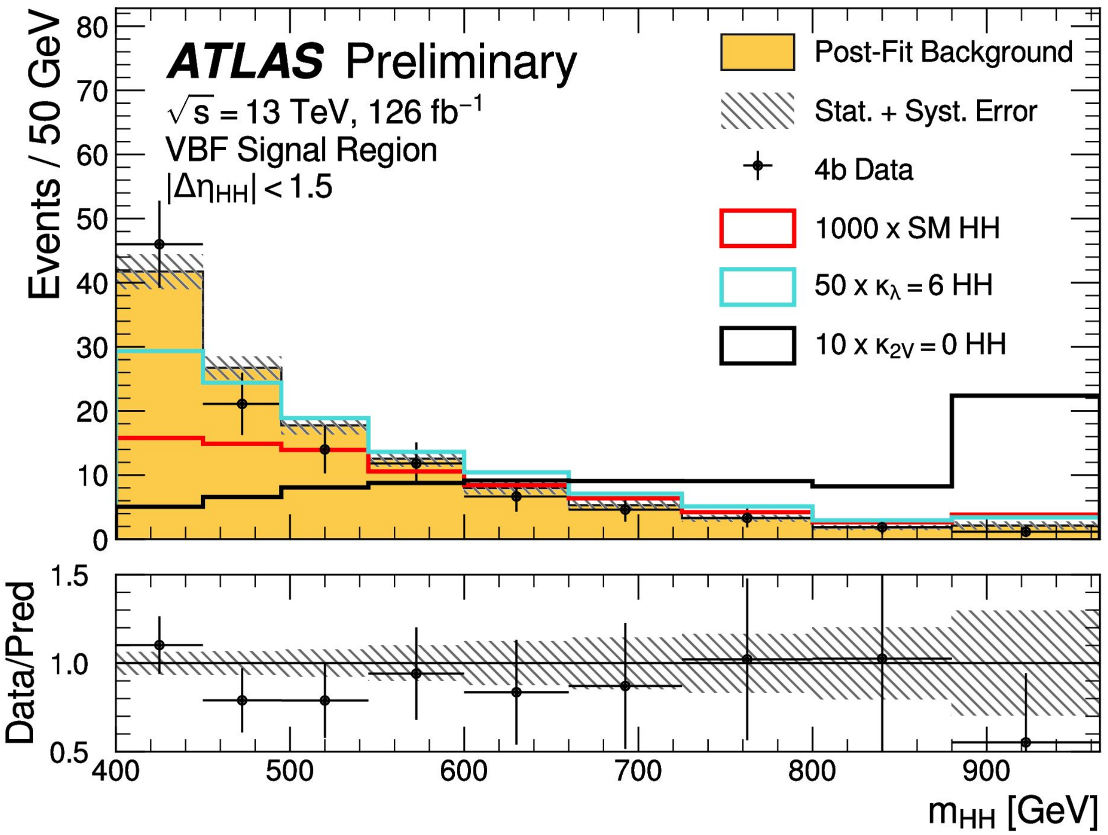
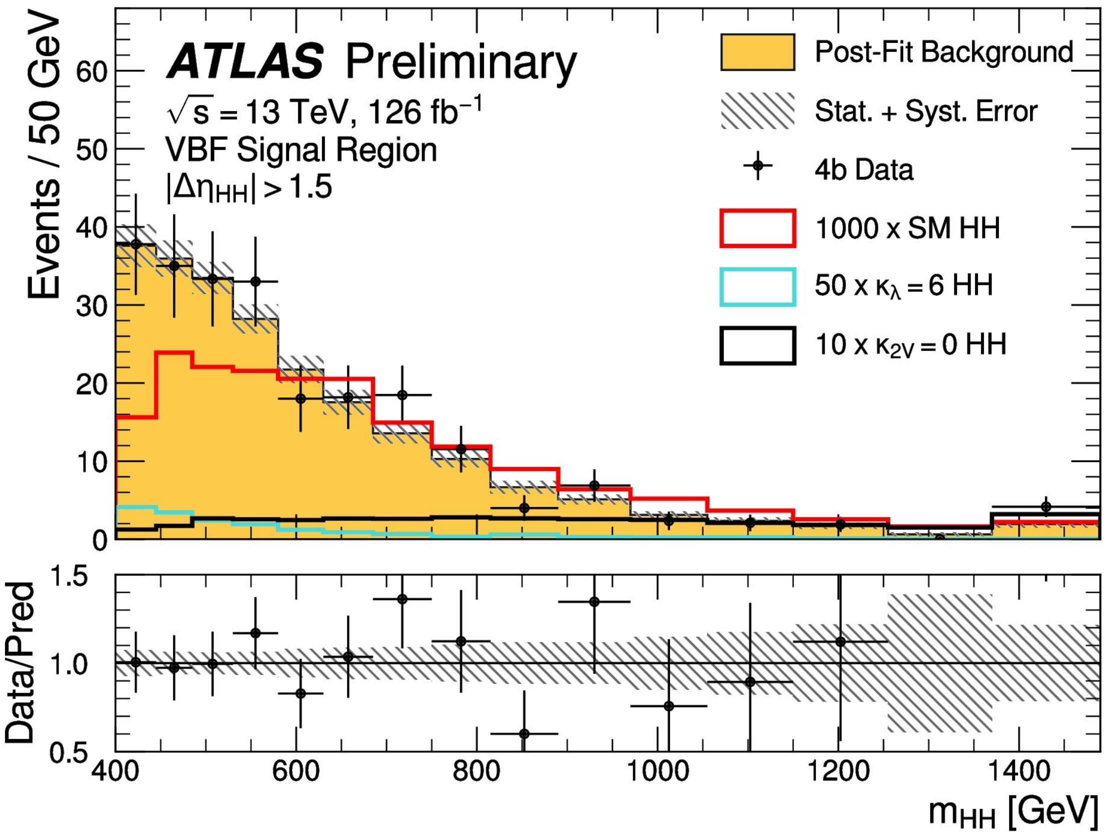
# bbbb

VBF selection

ATLAS EXPERIMENT

ATLAS-CONF-2022-035

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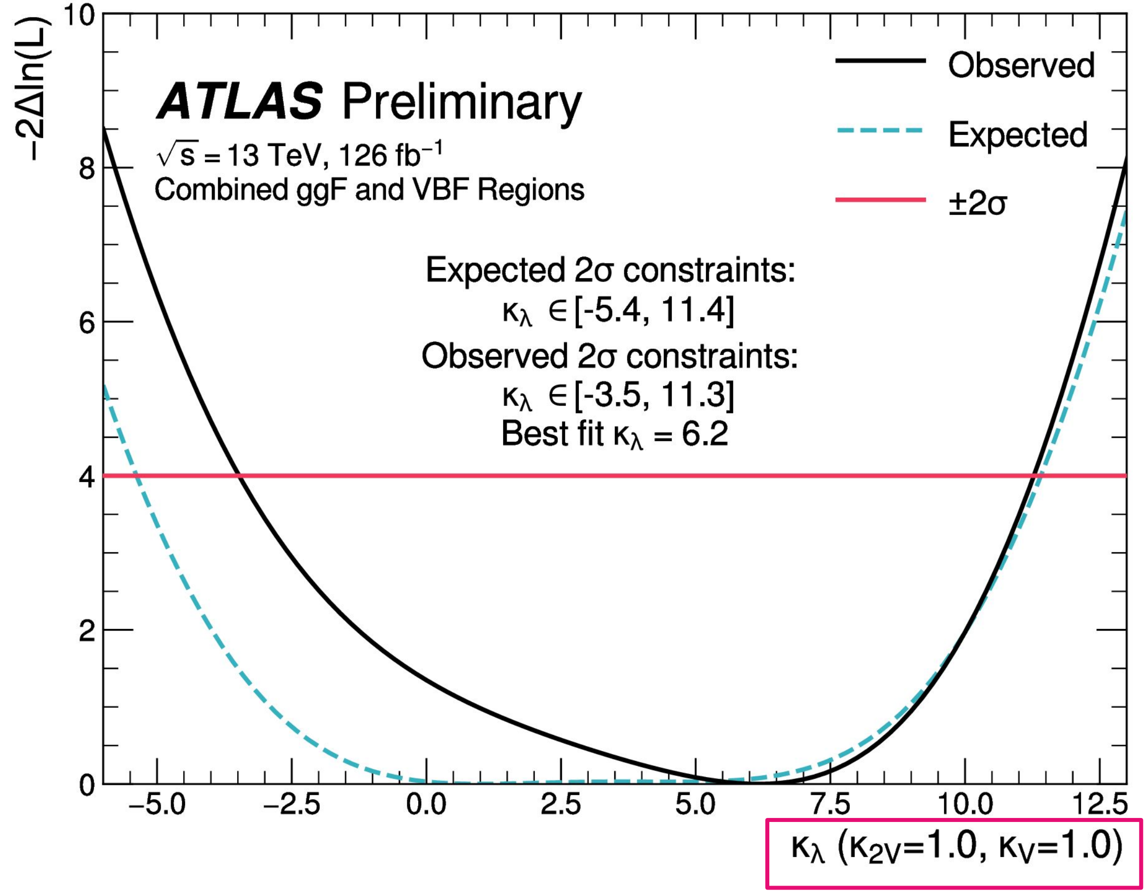
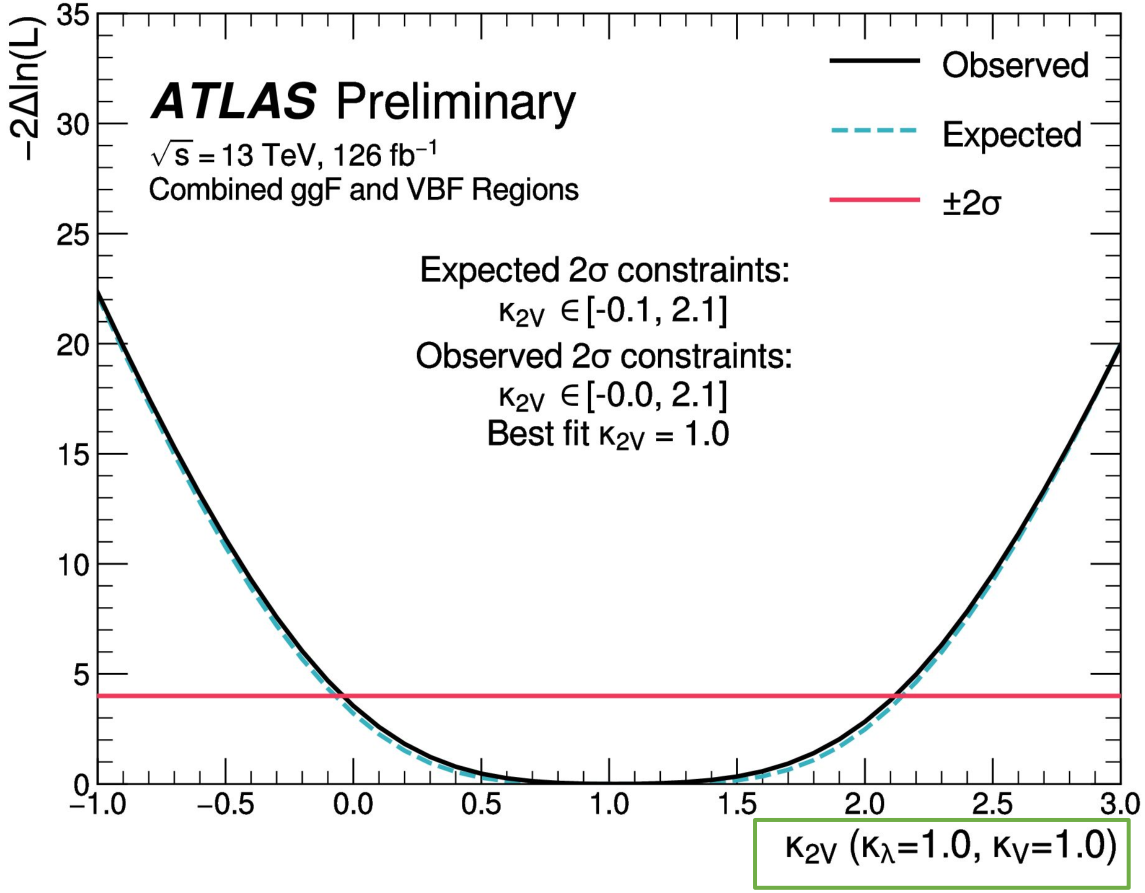
# bbbb



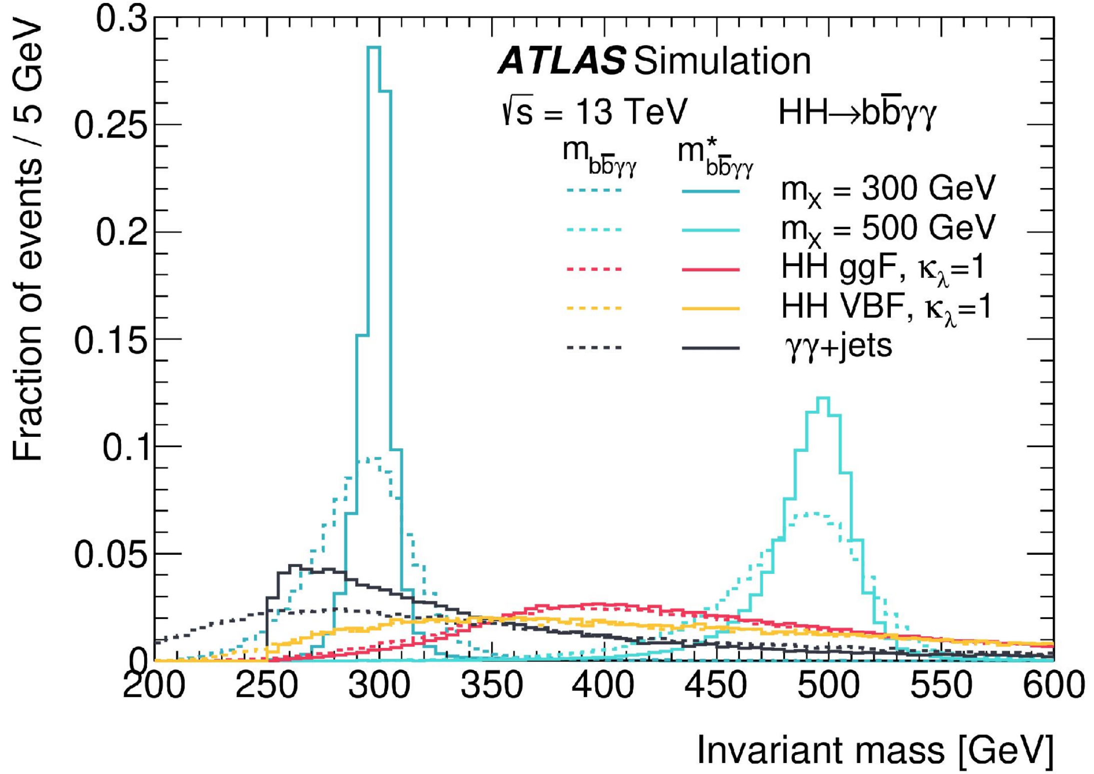


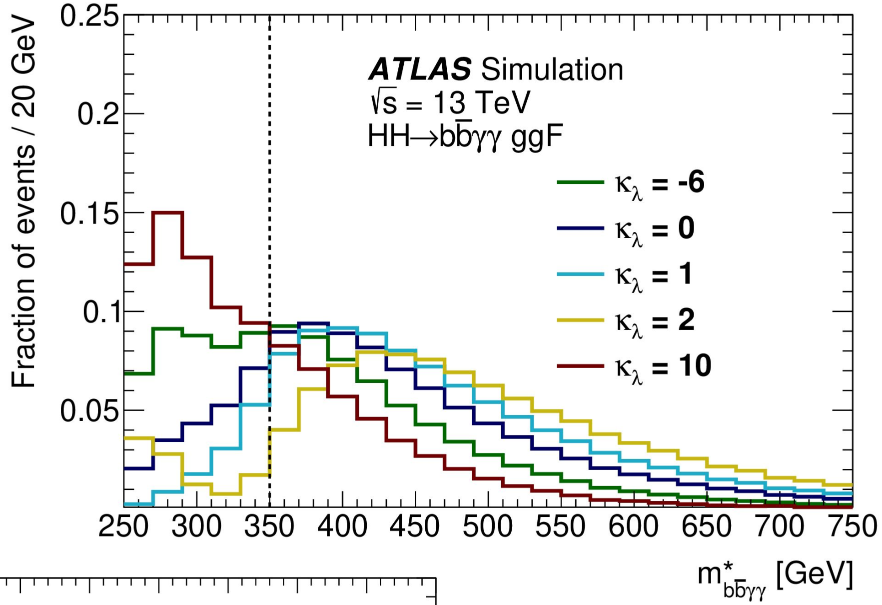



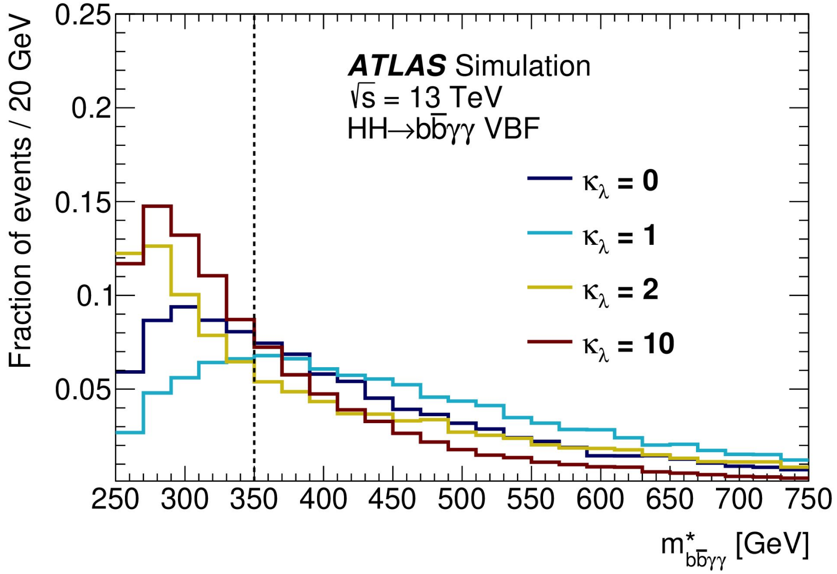

No evidence for a HH(bbbb) signal is found.

# bbγγ

Submitted to PRD
[arXiv:2112.11876]




- High and low $m^*_{bb\gamma\gamma}$

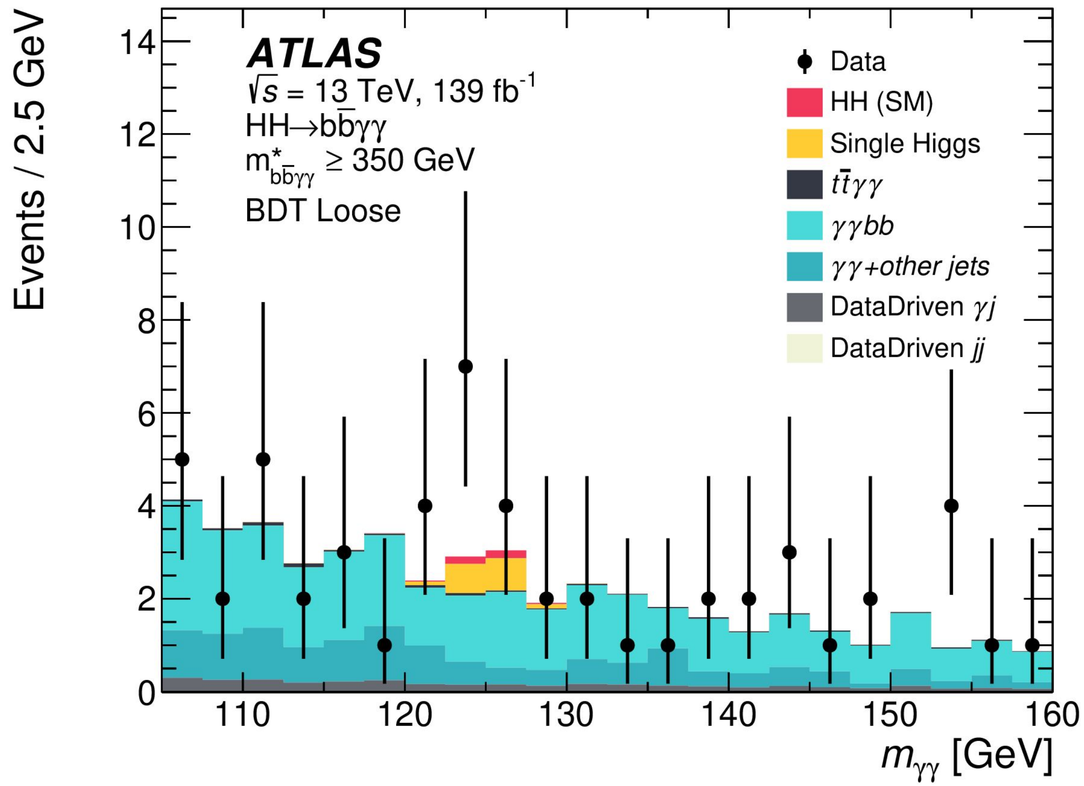
$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250\ \mathrm{GeV}$$

  - BSM expected to be at higher masses.

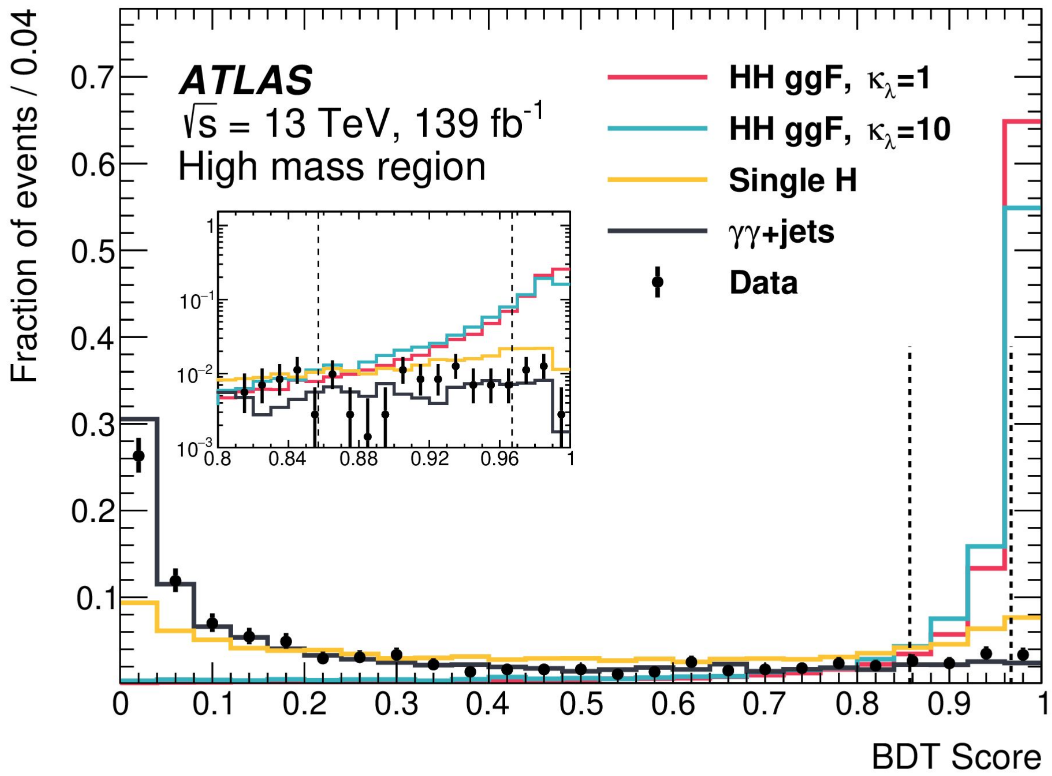
# bbγγ

Submitted to PRD
[arXiv:2112.11876]

Select **2 b-tagged** PFlow jets and **2 high $p_T$ photons**.




train a BDT per $m^*_{bb\gamma\gamma}$ region




categories

- High and low $m^*_{bb\gamma\gamma}$

$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250 \text{ GeV}$$

  - Low mass regions used to retain sensitivity for BSM signals

- For each $m^*_{bb\gamma\gamma}$ category BDTs are trained.
  - Use BDTs scores to define **tight/loose BDT categories.**

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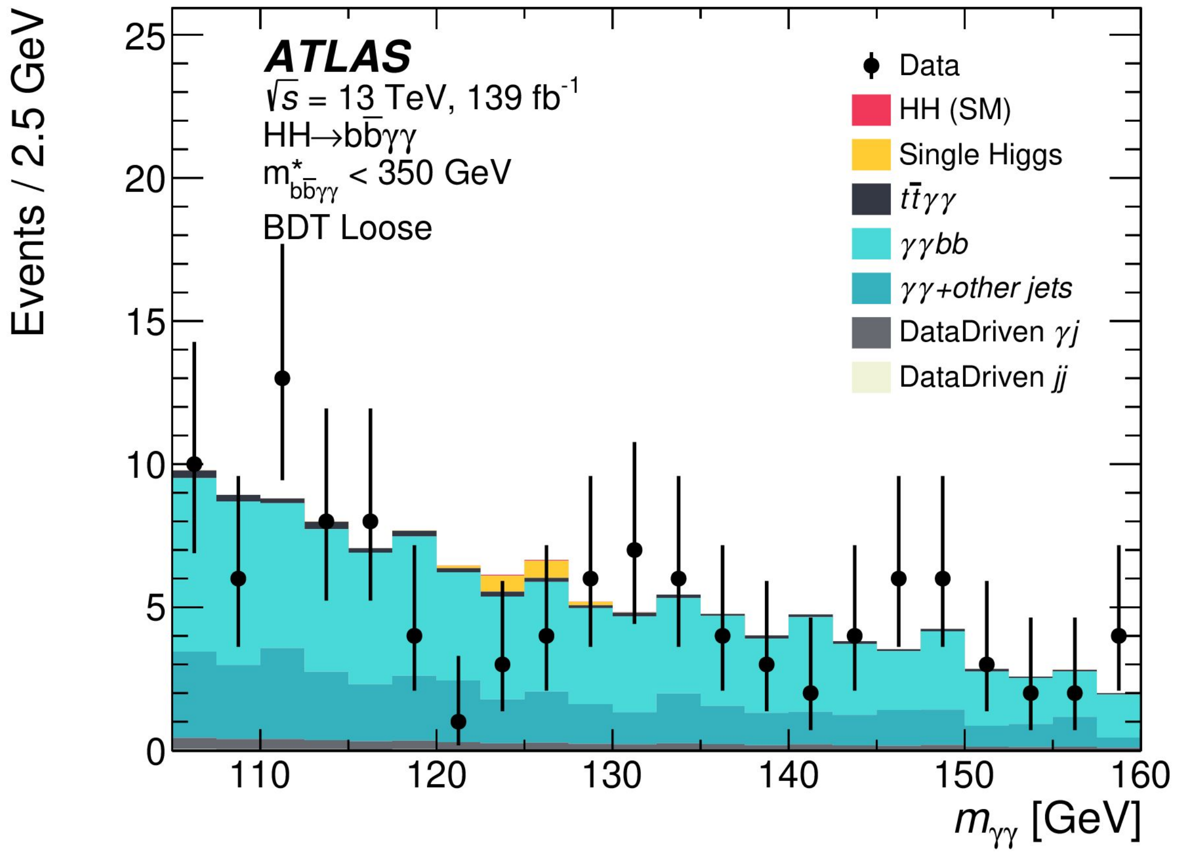
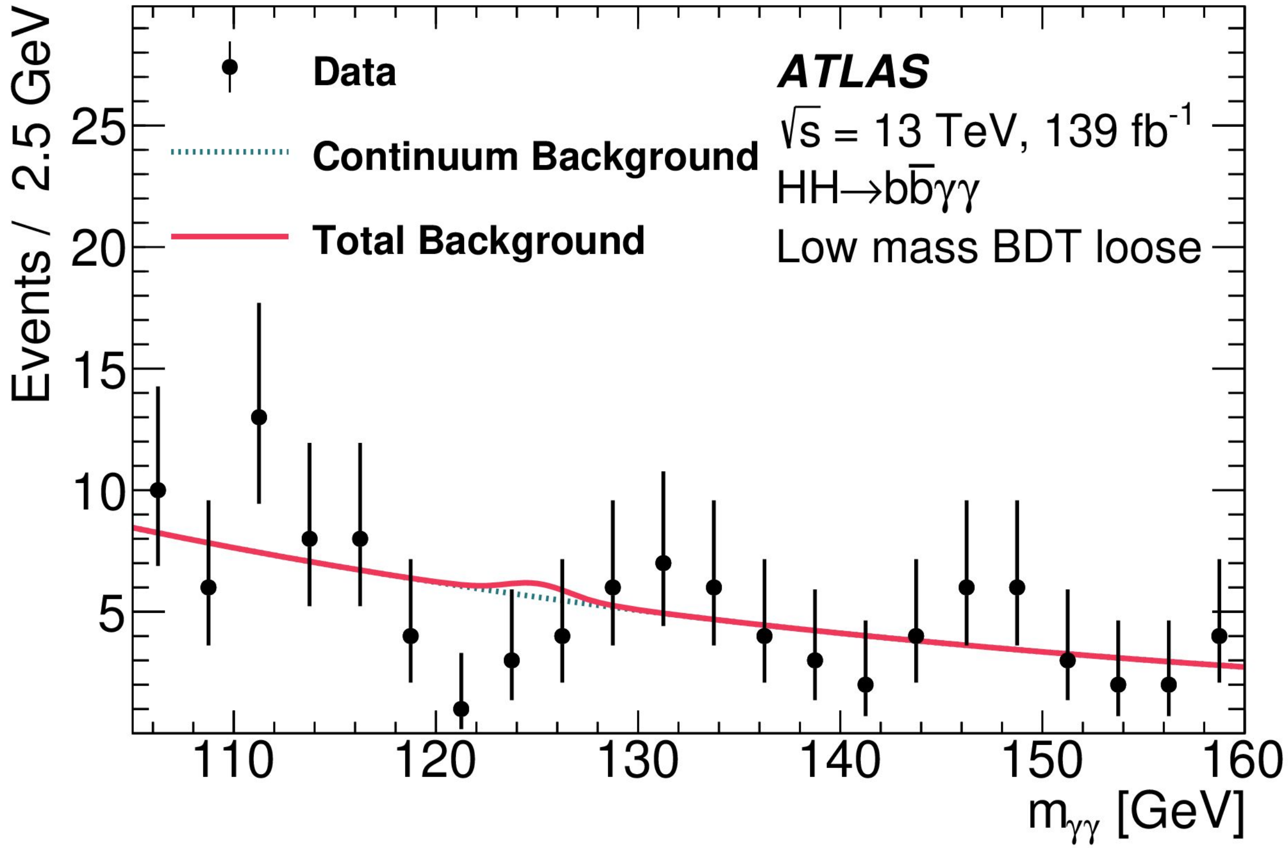
# bbγγ

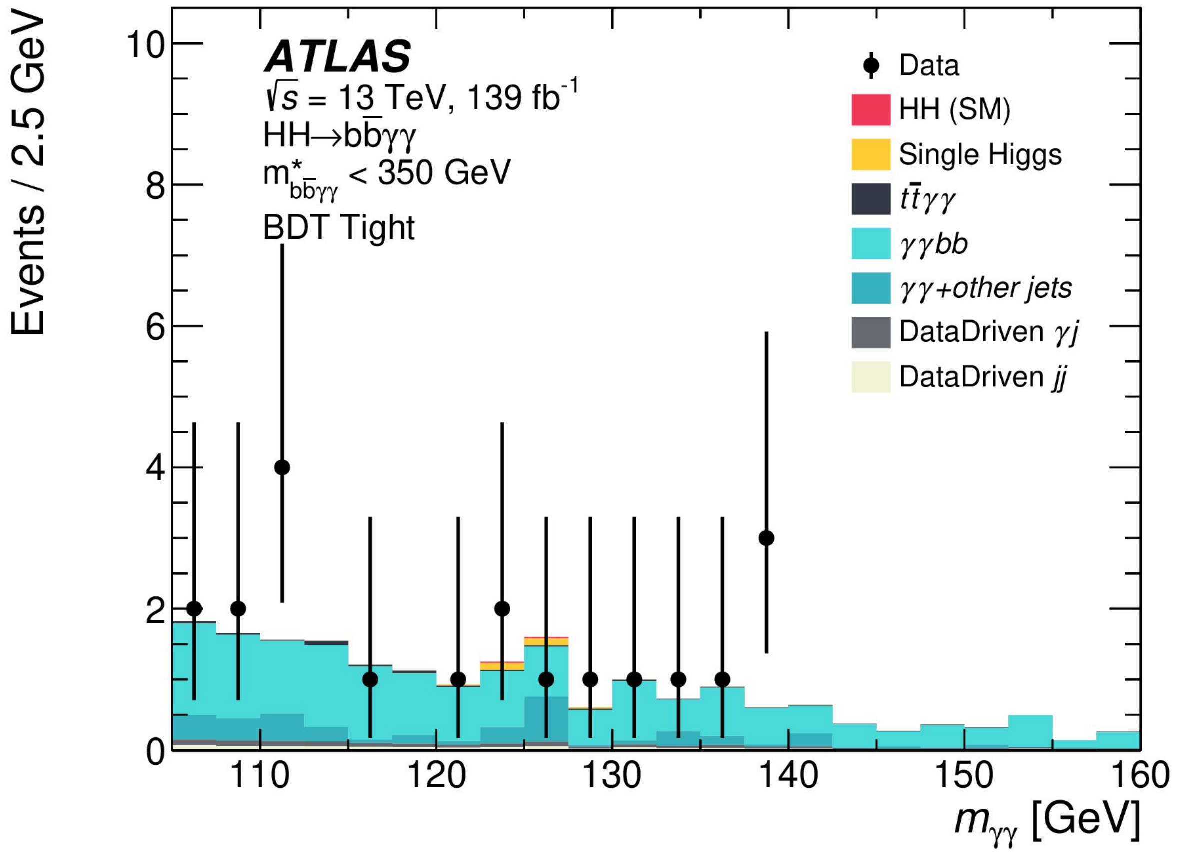
Submitted to PRD
[arXiv:2112.11876]

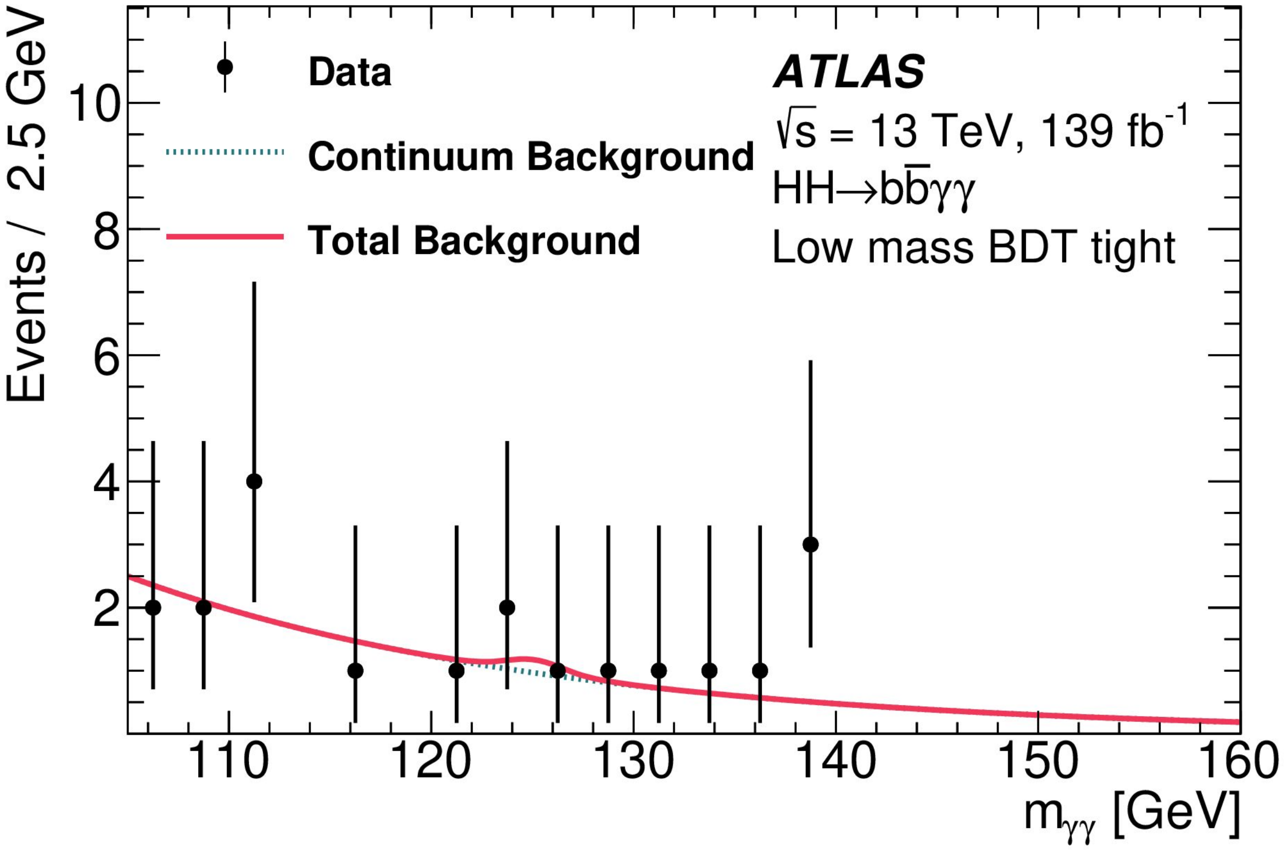


# bbγγ

Submitted to PRD
[arXiv:2112.11876]

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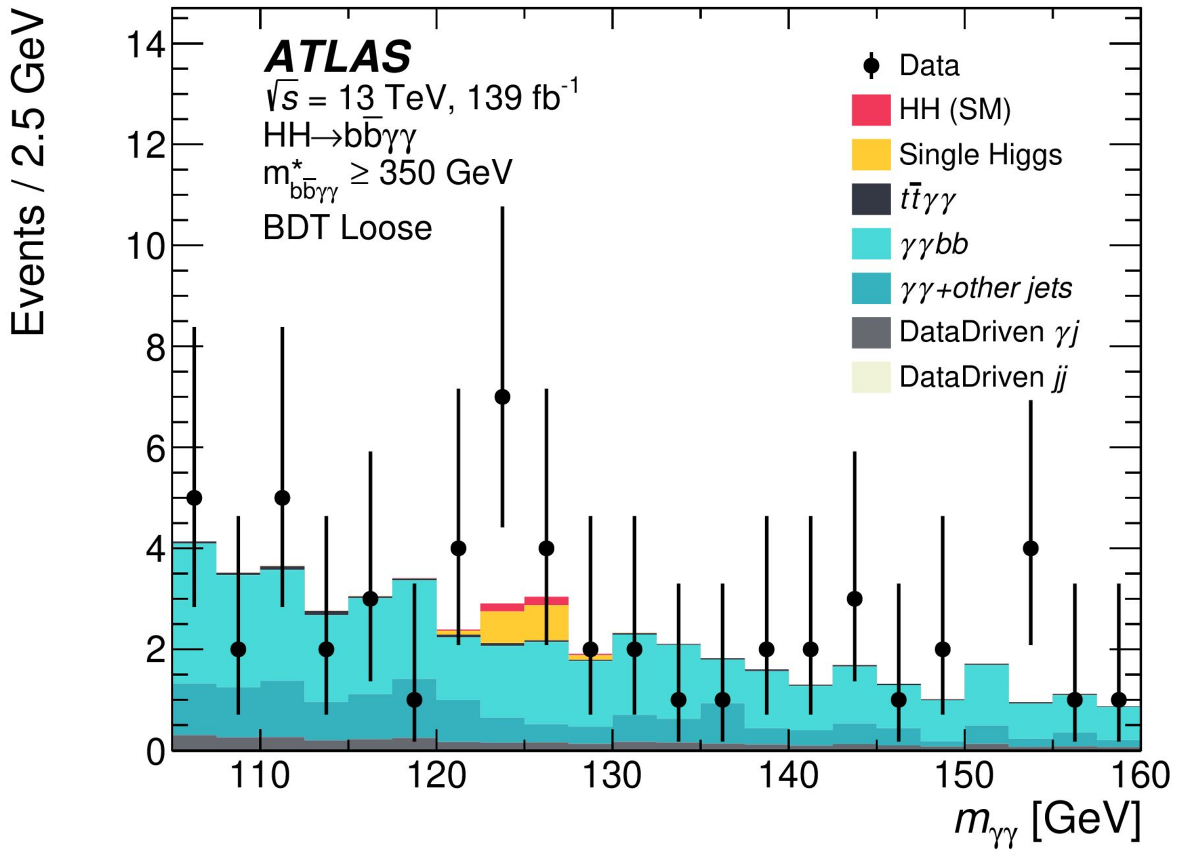
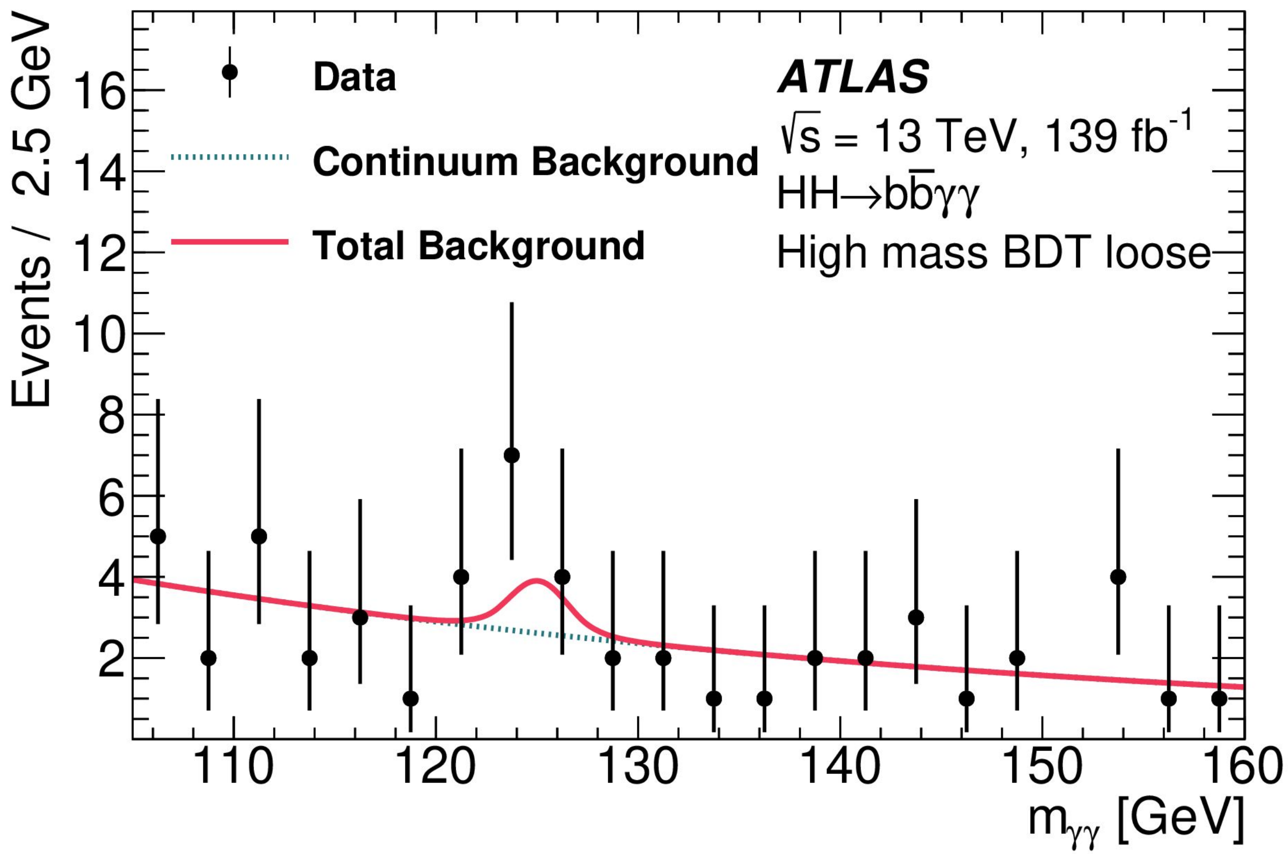
# bbγγ

[Submitted to PRD](#)
[arXiv:2112.11876]

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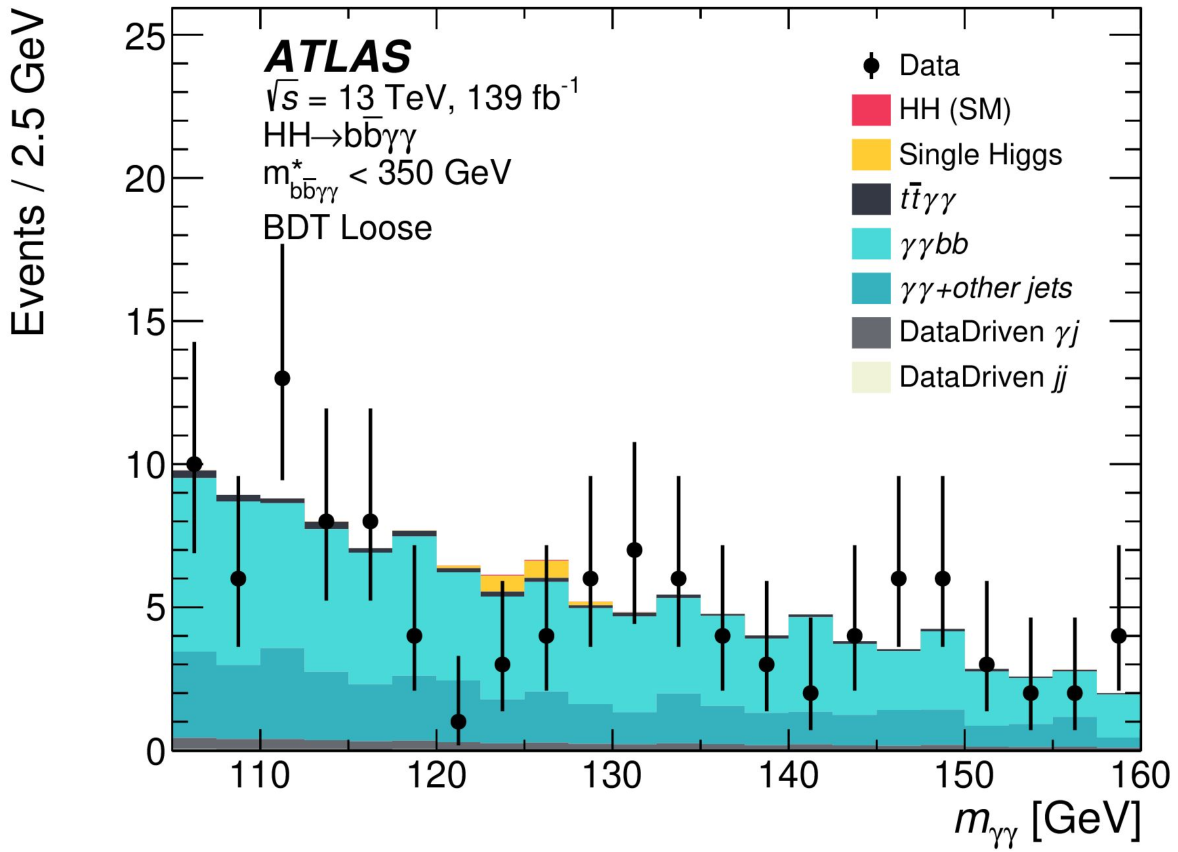
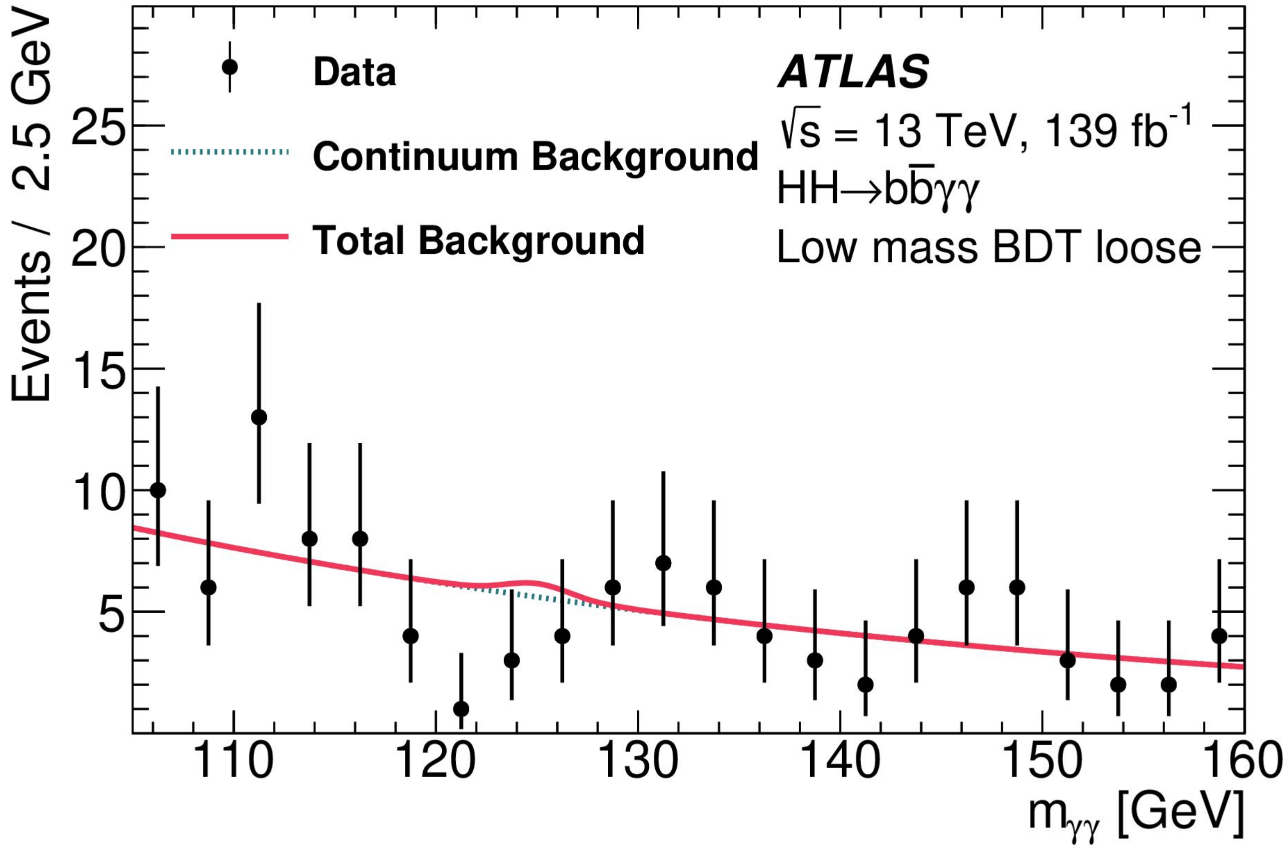
# bbγγ

[Submitted to PRD](#)
[arXiv:2112.11876]

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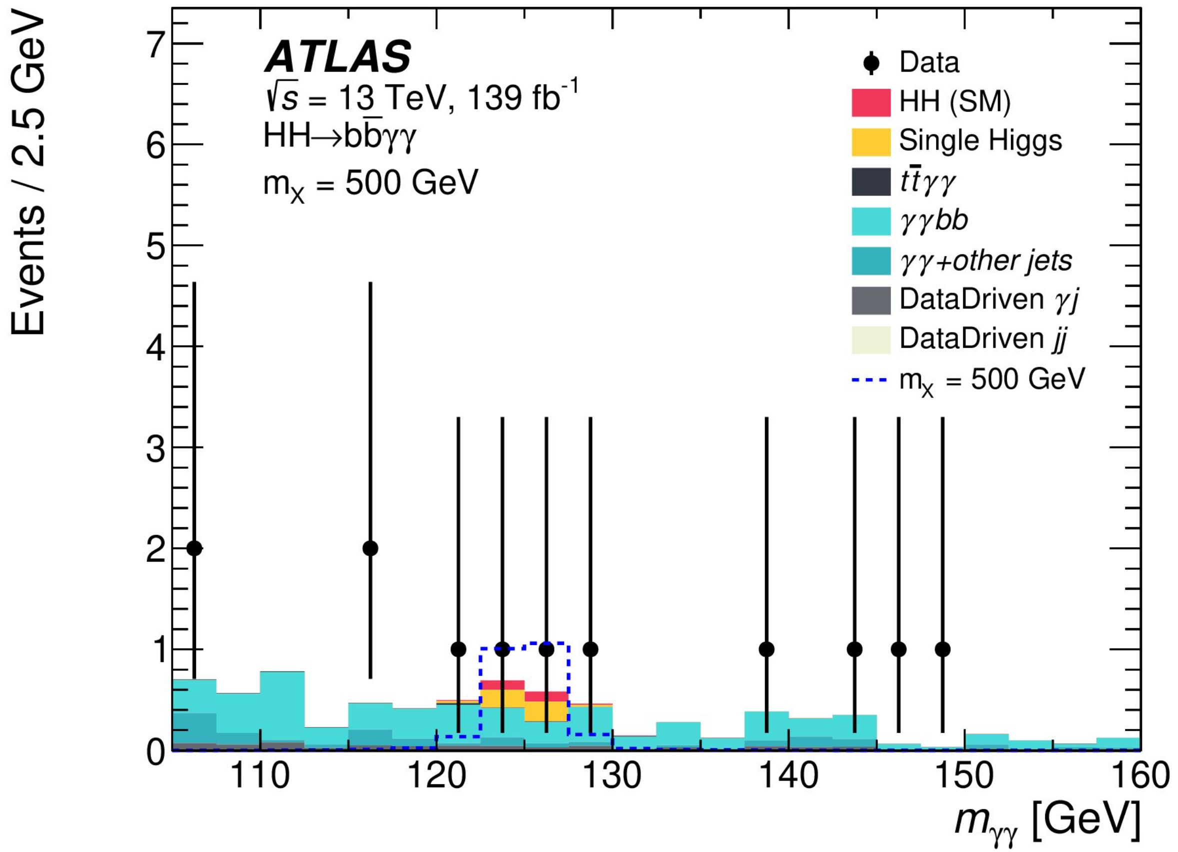
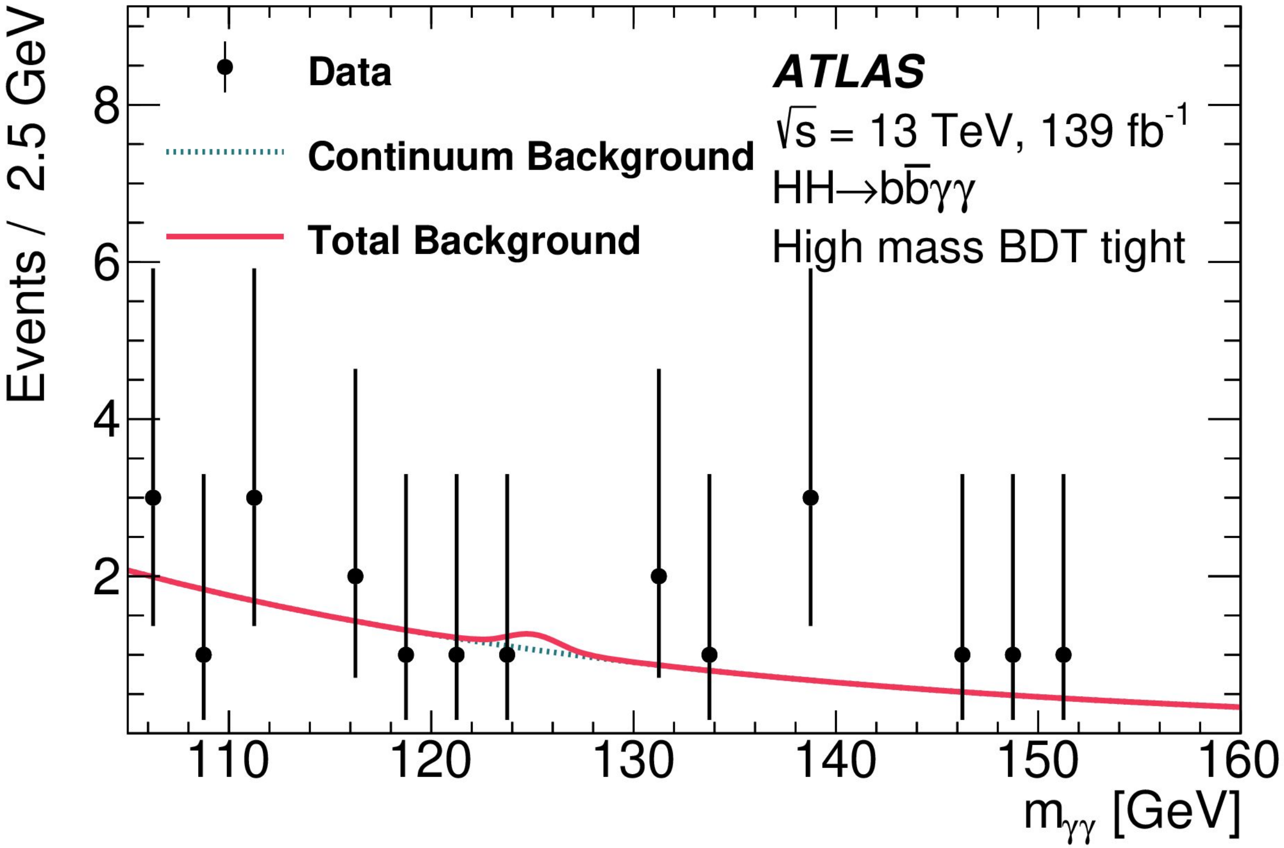
# bbγγ

Submitted to PRD
[arXiv:2112.11876]

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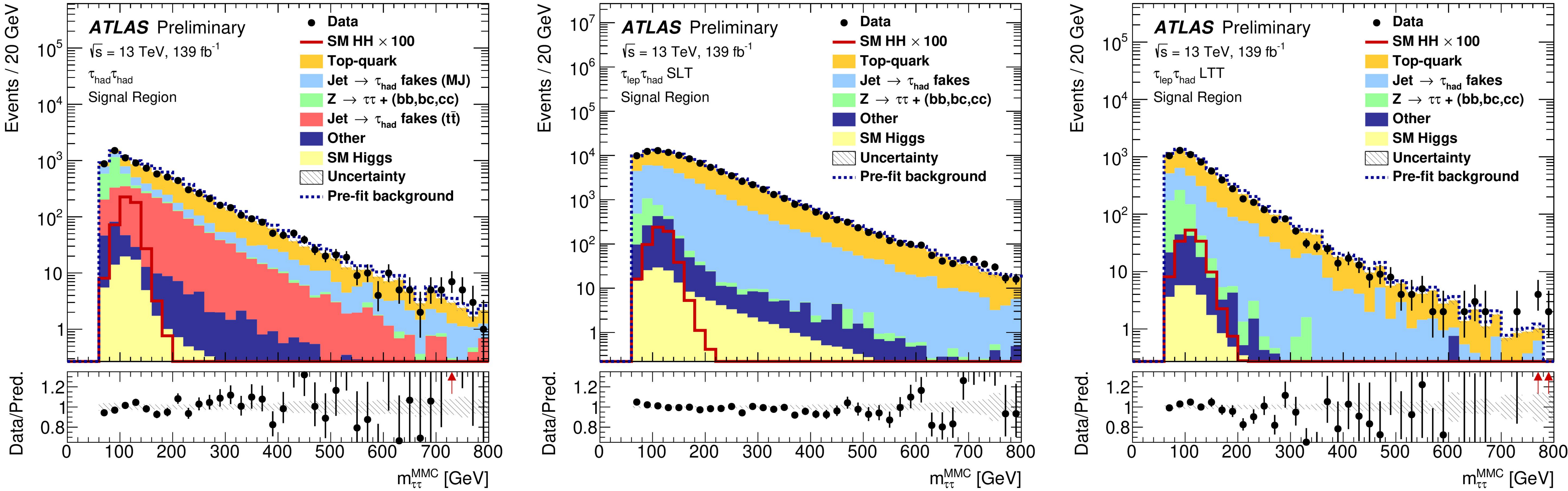
# bbττ

ATLAS-CONF-2021-030

Select 2 b-tagged PFlow jets and 2 taus ($\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$).




## categorisation (based on triggers)

- $H\rightarrow\tau_{lep}\tau_{had}$: single-lepton (SLT) or lepton+tau (LTT) triggers,
- $H\rightarrow\tau_{had}\tau_{had}$: combination of single-tau (STT) and di-tau triggers.

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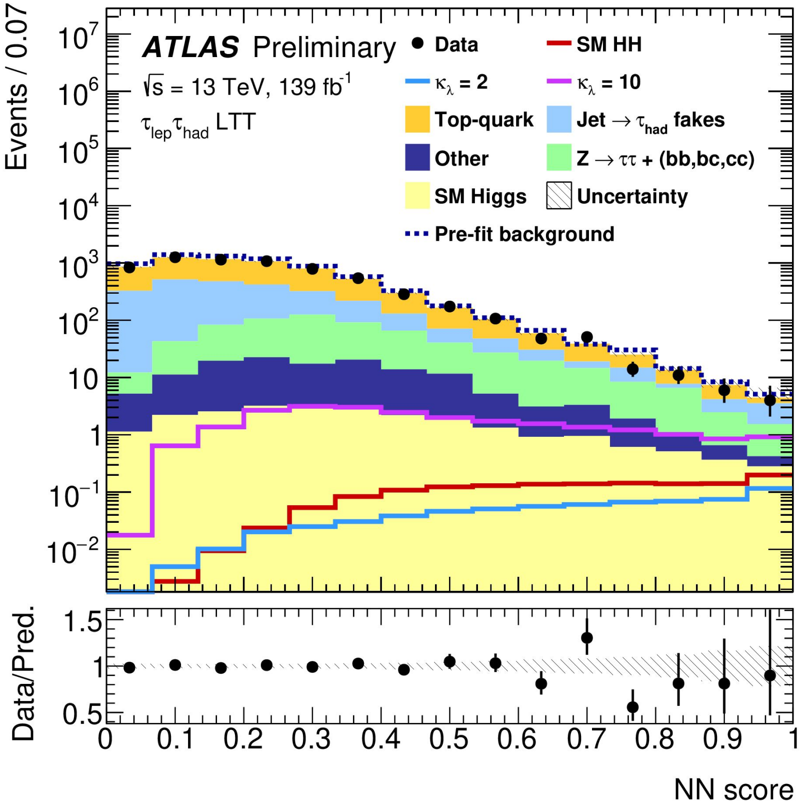
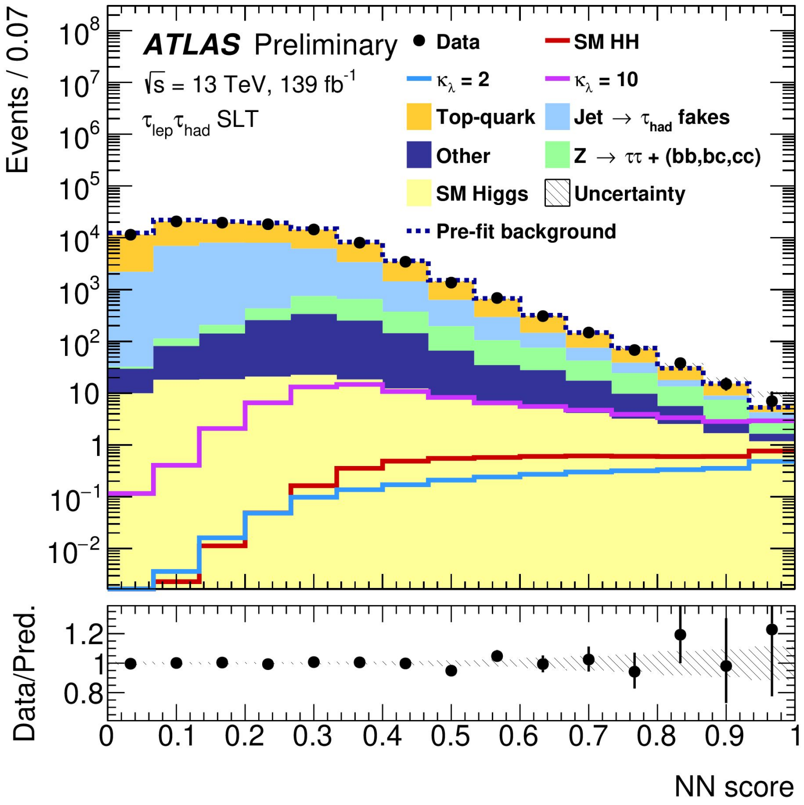
# bbττ

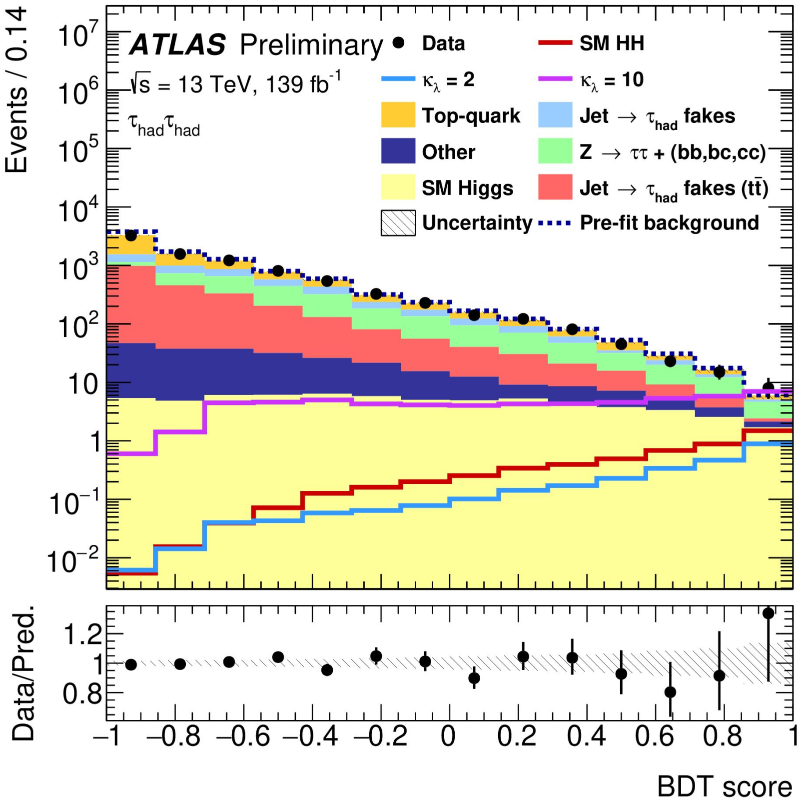
ATLAS EXPERIMENT

ATLAS-CONF-2021-030

Select 2 b-tagged PFlow jets and 2 taus ($\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$).




## background discrimination

- NN trained in HH → bb $\tau_{lep}\tau_{had}$
- BDT used in HH → bb $\tau_{had}\tau_{had}$

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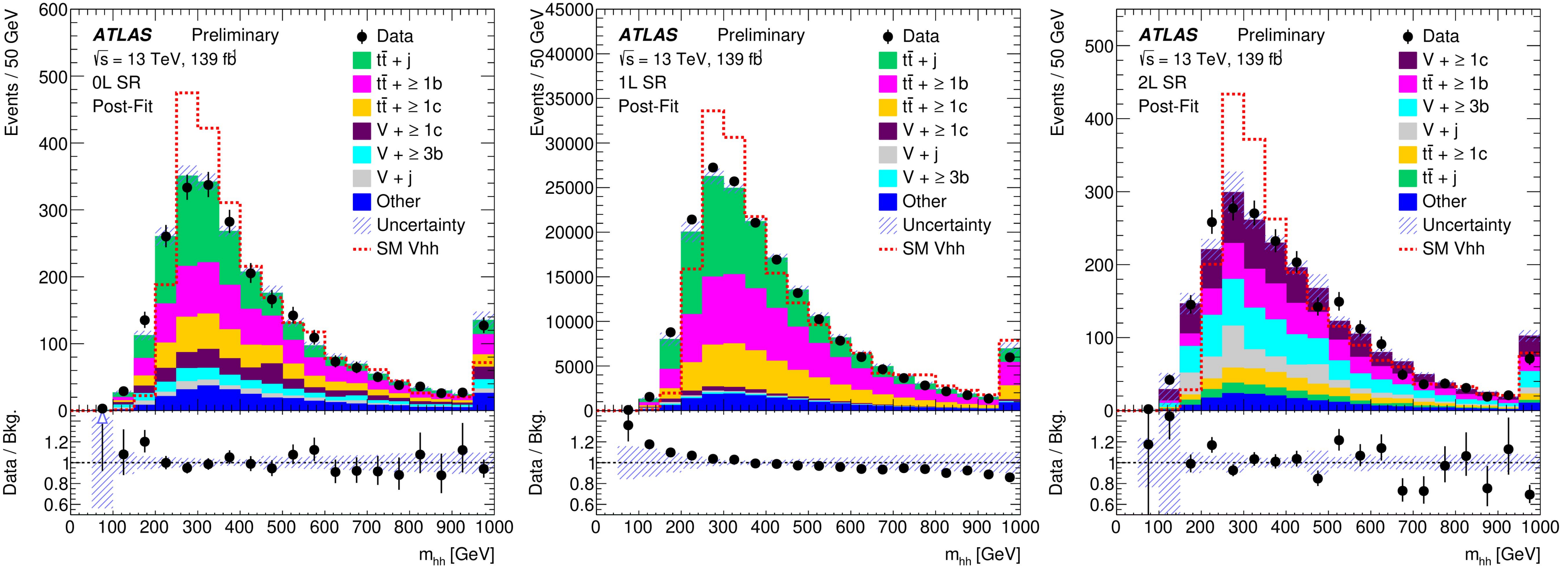
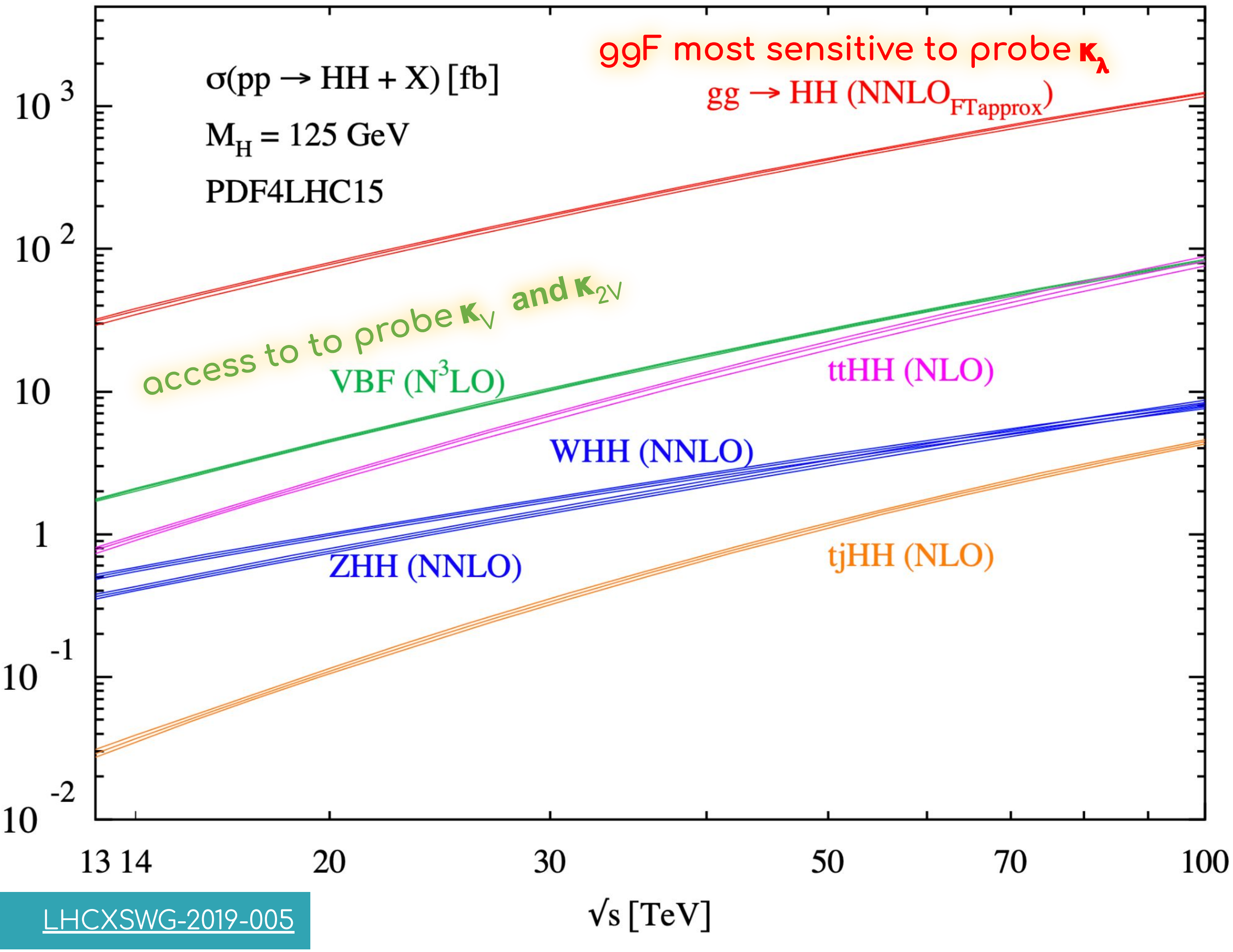
# VHH (0L,1L,2L)

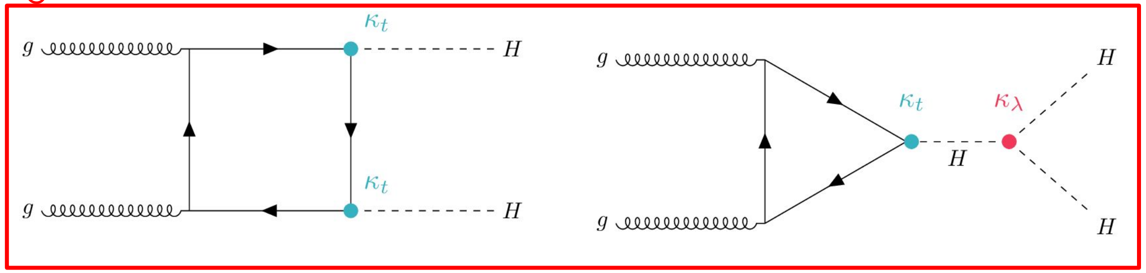
ATLAS-CONF-2022-043/



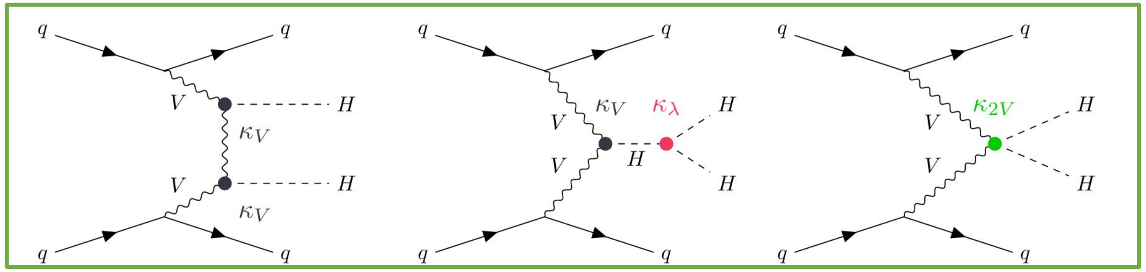
# Non-resonant



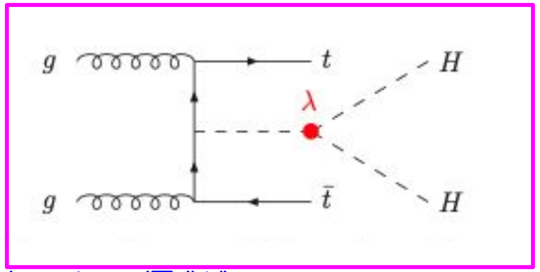

gluon fusion



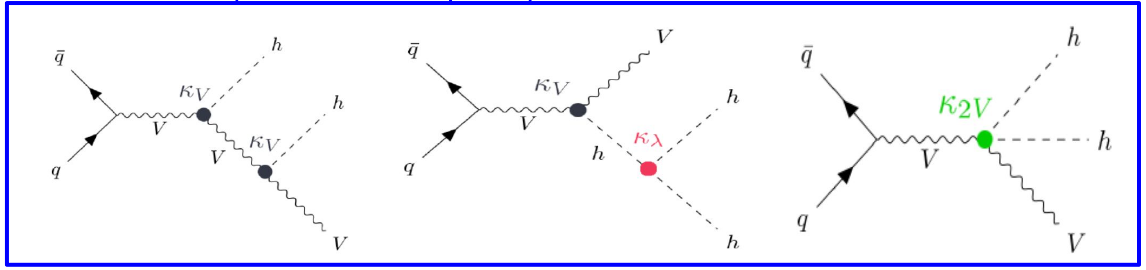
vector boson fusion



associated production (ttbar)



associated production (Z/W)



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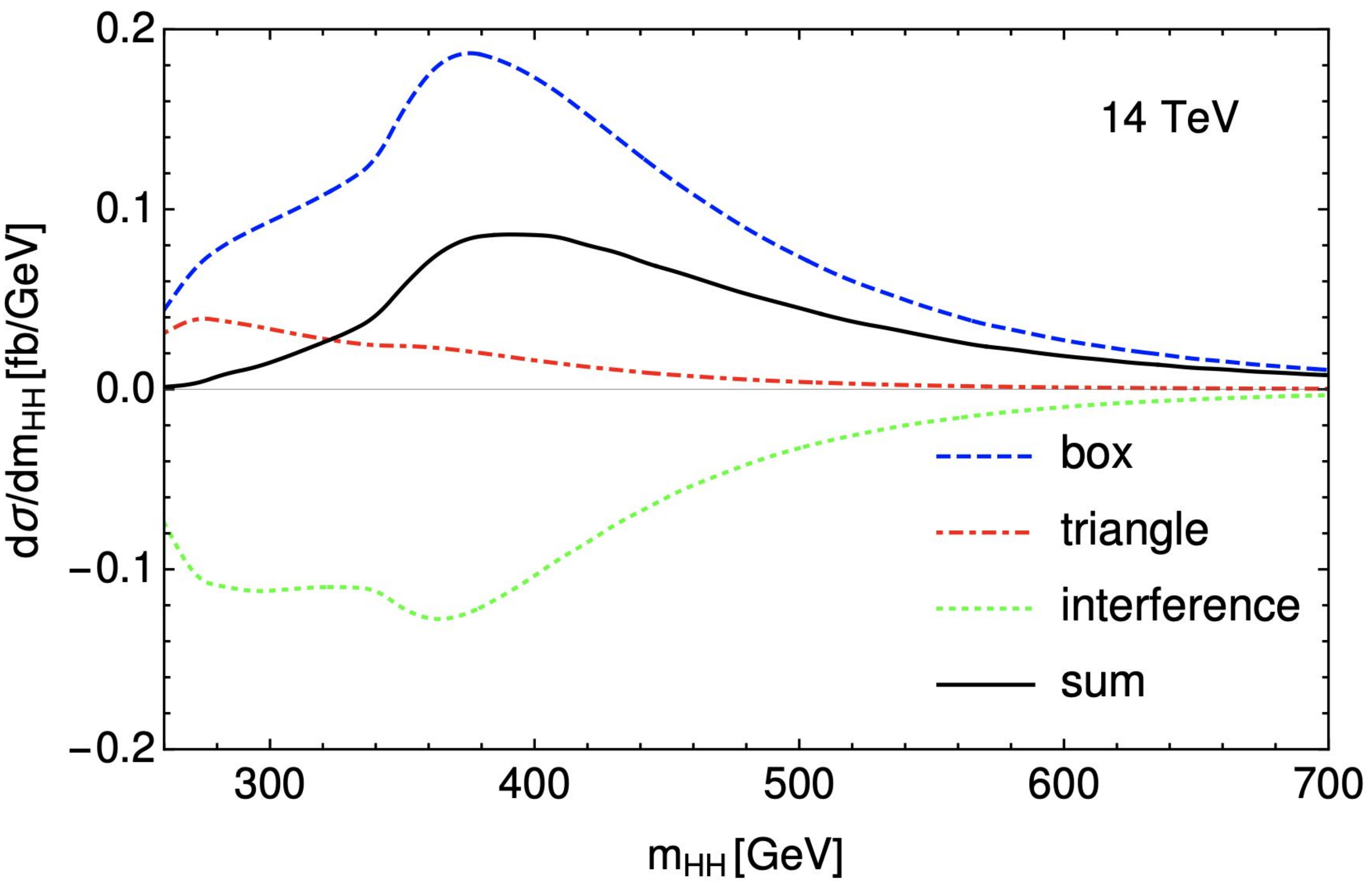
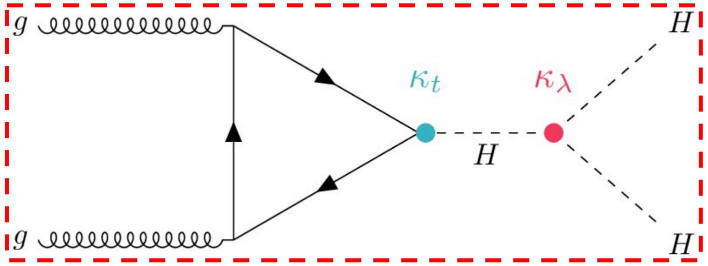
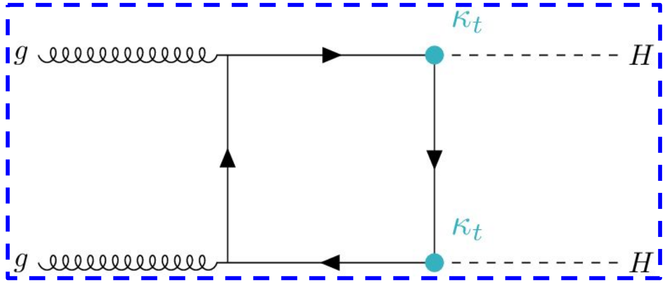
# ggF production

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