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

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On behalf of the ATLAS Collaboration
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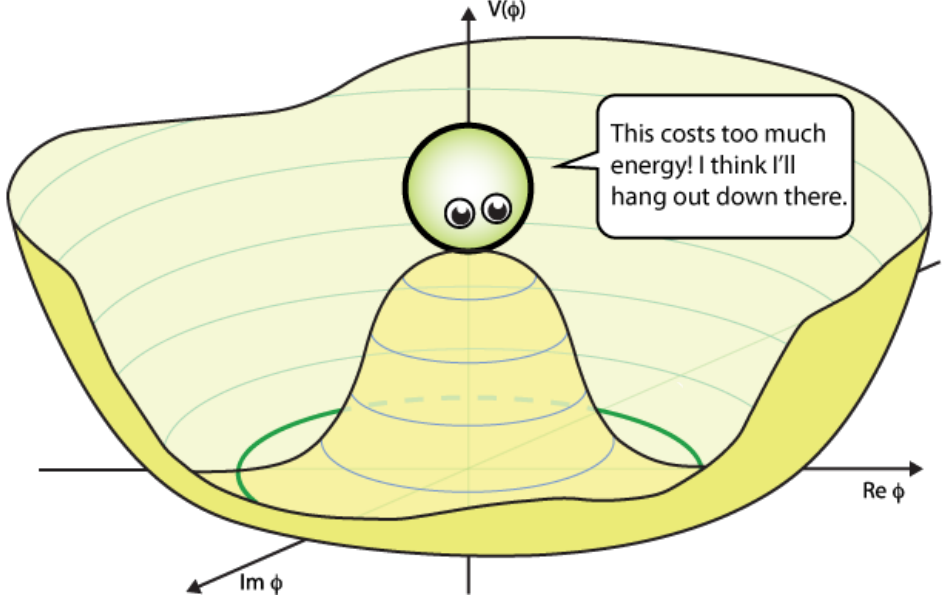
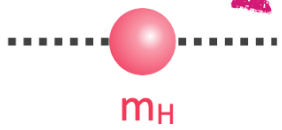
The κ_λ

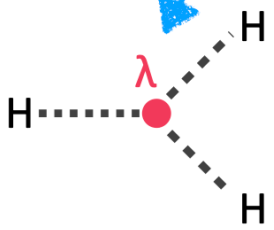
The Higgs potential: $V(\Phi) = \mu^2\Phi^*\Phi + \lambda|\Phi^*\Phi|^2$



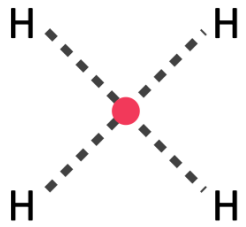
Expanding around the minimum:

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





Measuring the self coupling would give a direct measurement of λ

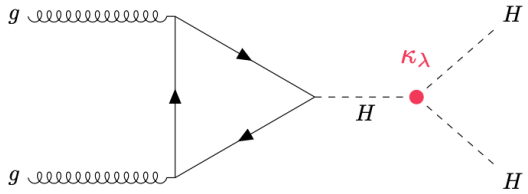


Likely unreachable by the LHC…

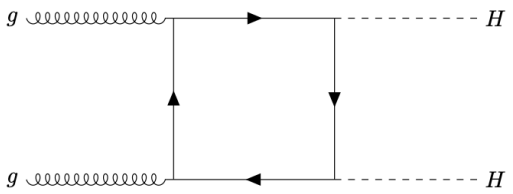
The κ_λ is defined as $\lambda/\lambda_{\mathrm{SM}}$

HH production in SM

- The di-Higgs is dominantly produced by the ggH and VBF processes.
- Di-Higgs production in SM is dominated by non-resonant gluon-fusion process.
  - The triangle diagram involves the Higgs self-coupling and is sensitive to κ_λ.
  - The box diagram involves the Top Yukawa coupling and κ_t.
  - Destructive interference between the triangle and box diagram results in small cross section.
- The vector boson fusion (VBF) process also contributes to the di-Higgs production.
  - Smaller cross section compared with ggF.
  - VBF involves trilinear, $HHVV$ and VVH diagrams.
  - Sensitive to κ_λ and κ_{vv}.
- Small cross-section compared with single Higgs production. Hard to measure.

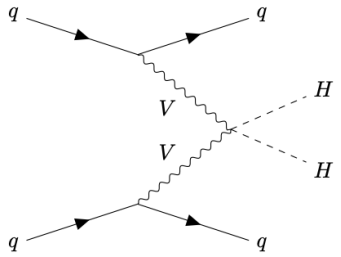


(a) Trilinear coupling

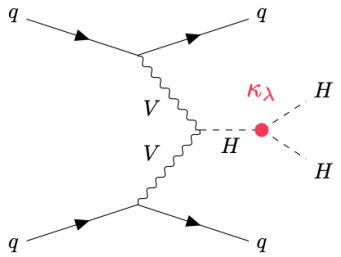


(b) Box diagram

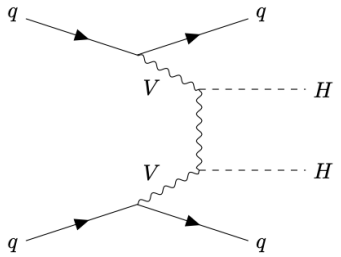
ggH



(a) $HHVV$ vertex



(b) Trilinear coupling



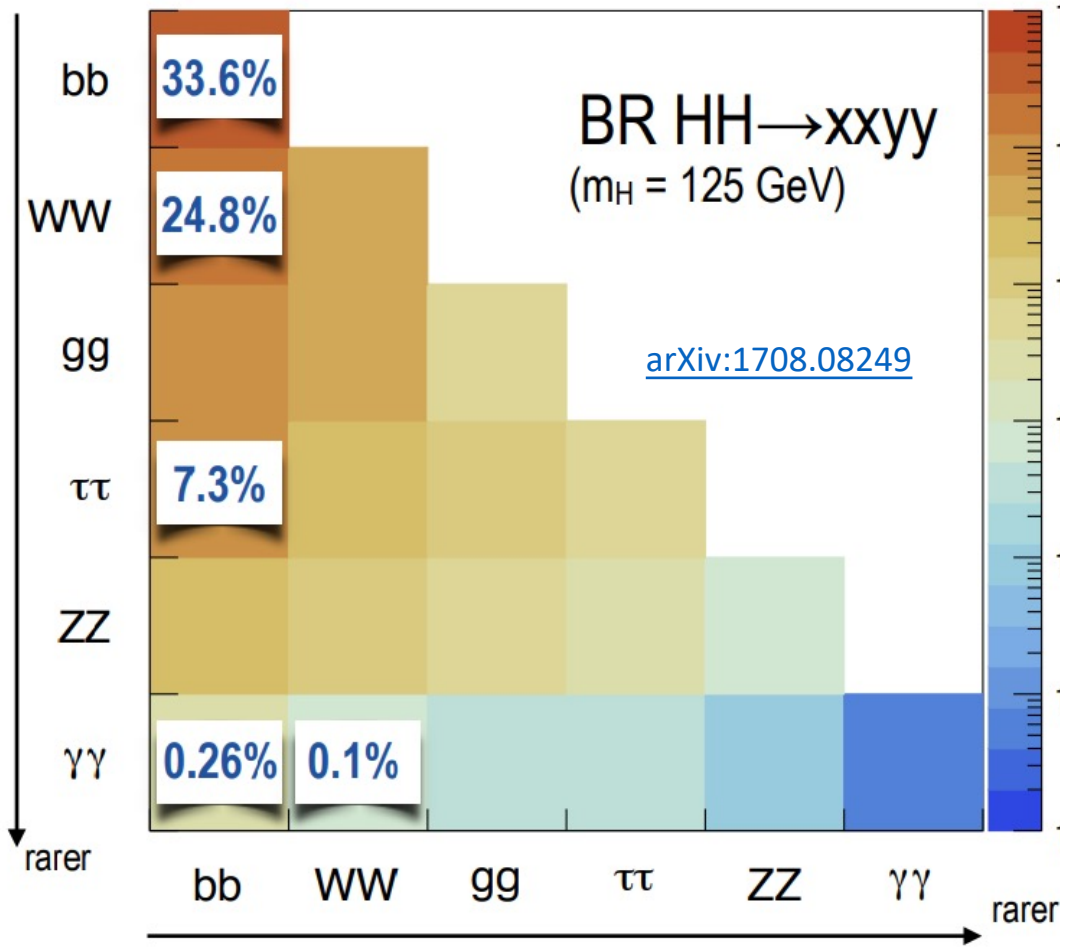
(c) VVH Production mode

VBF

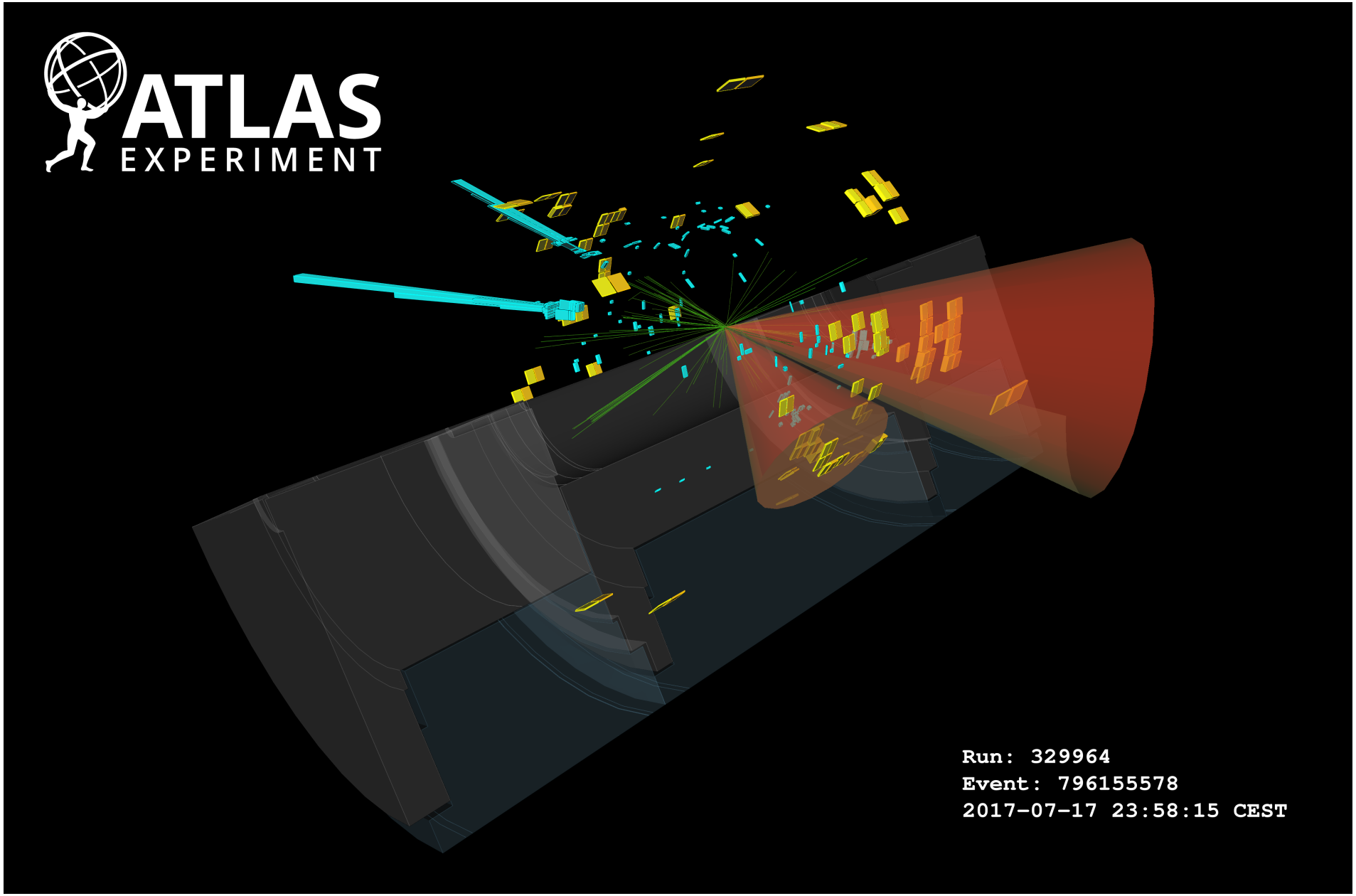
HH decay channels

- **bbbb:** largest branching ratio, large QCD multi-jets and ttbar backgrounds.
- **bbWW:** large branching ratio, large ttbar background (Phys. Lett. B 801 (2020) 135145).
- **bb$\tau\tau$:** relatively small BR and background.
- **bb$\gamma\gamma$:** small BR, good mass resolution, small background.
- **$\gamma\gamma$WW:** small BR, good mass resolution (partial run 2 result: Eur. Phys. J. C 78 (2018) 1007).

In this talk ATLAS measurement on HH production in $bb\gamma\gamma$,$bb\tau\tau$ and $bbbb$ channel using full Run 2 data will be reported.



$HH \rightarrow bb\gamma\gamma$

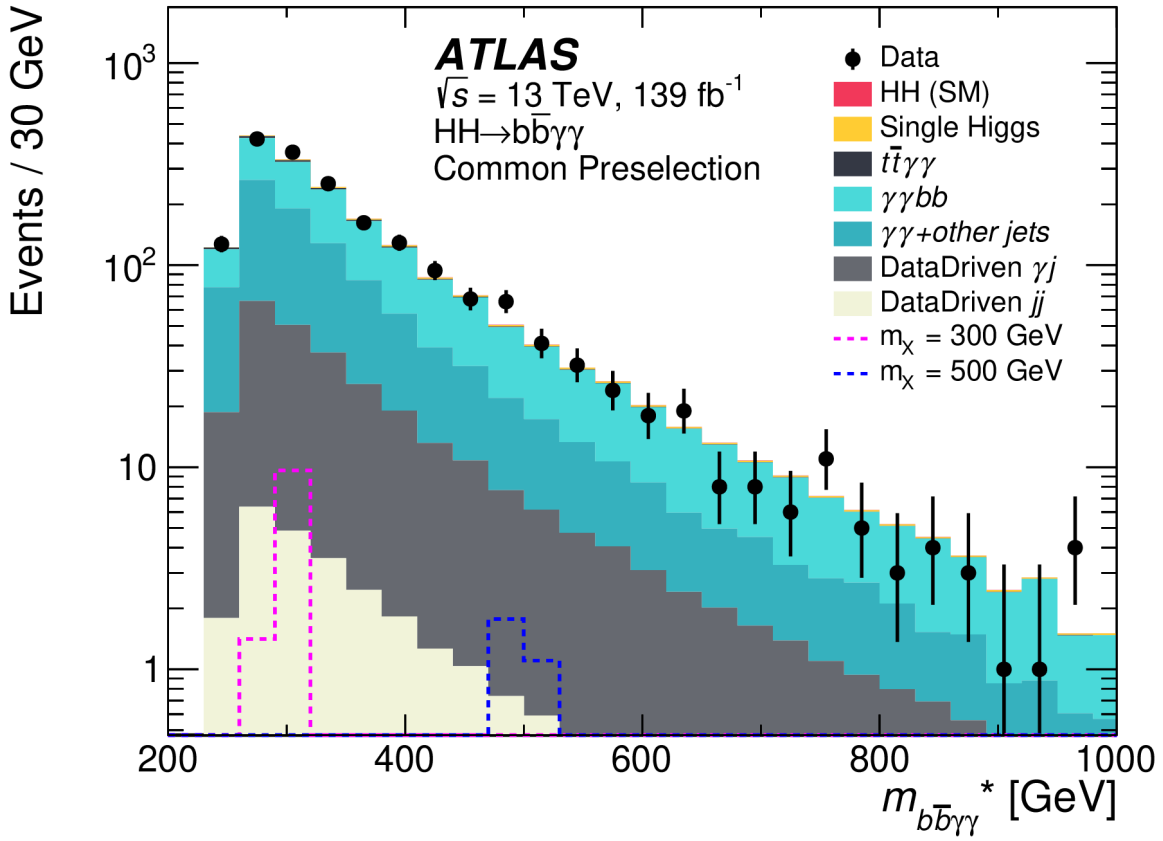


Phys. Rev. D 106, 052001

$HH \rightarrow bb\gamma\gamma$

- Signature of the $bb\gamma\gamma$ channel:
  - A clean channel with small background.
  - $H \rightarrow \gamma\gamma$ decay provides excellent mass resolution.
  - Small branching ratio, ~0.26%.

- Analysis strategy and event selection:
  - Multivariate method (BDT) is used to separate signal from backgrounds.
  - Two photons with invariant mass in the Higgs mass window [120, 130] GeV.
  - Exactly 2 b-tagged jets.
  - No leptons (electron or muon).

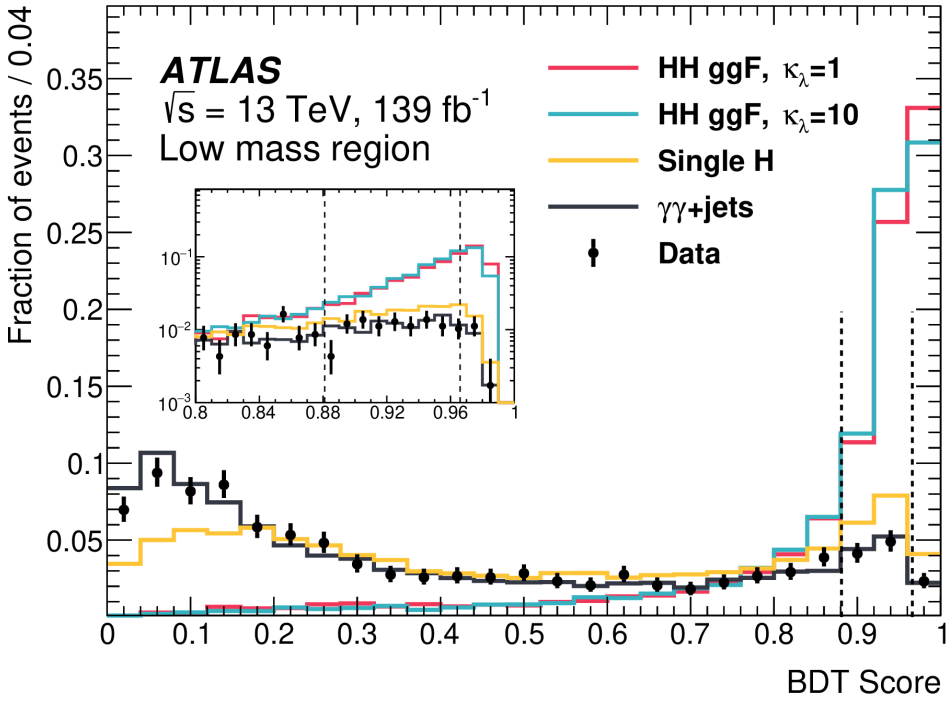


$$m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250 \text{ GeV}$$

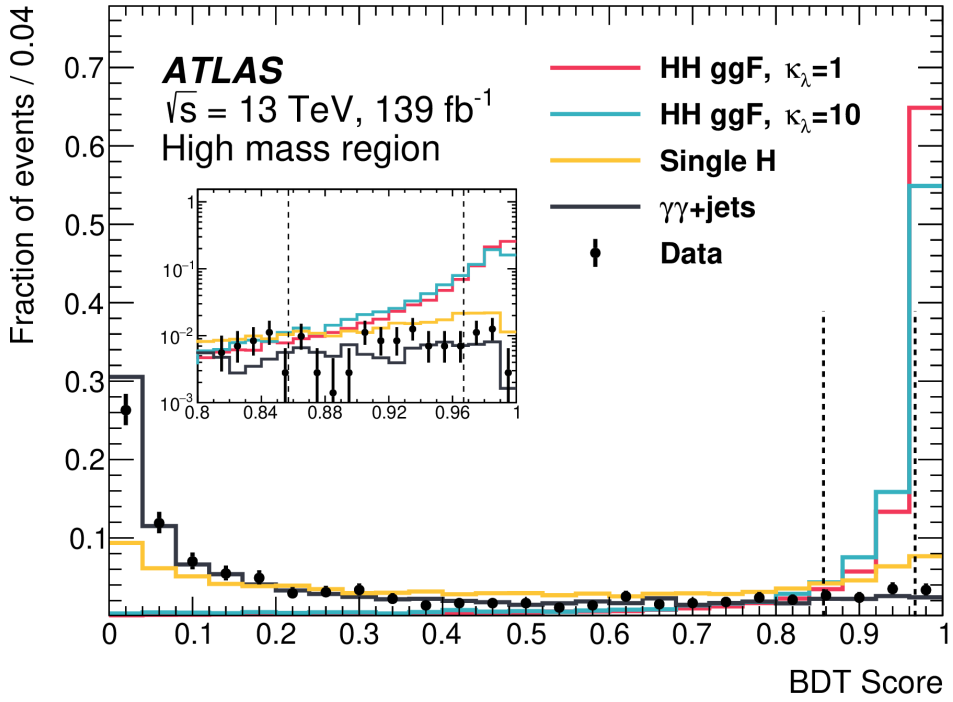
BDT in $HH \rightarrow bb\gamma\gamma$

- Events are split into the low and high mass region according to $m^{*}_{bb\gamma\gamma}$.
- Events are further split into the loose and tight BDT region in both high and low mass region.

Phys. Rev. D 106, 052001



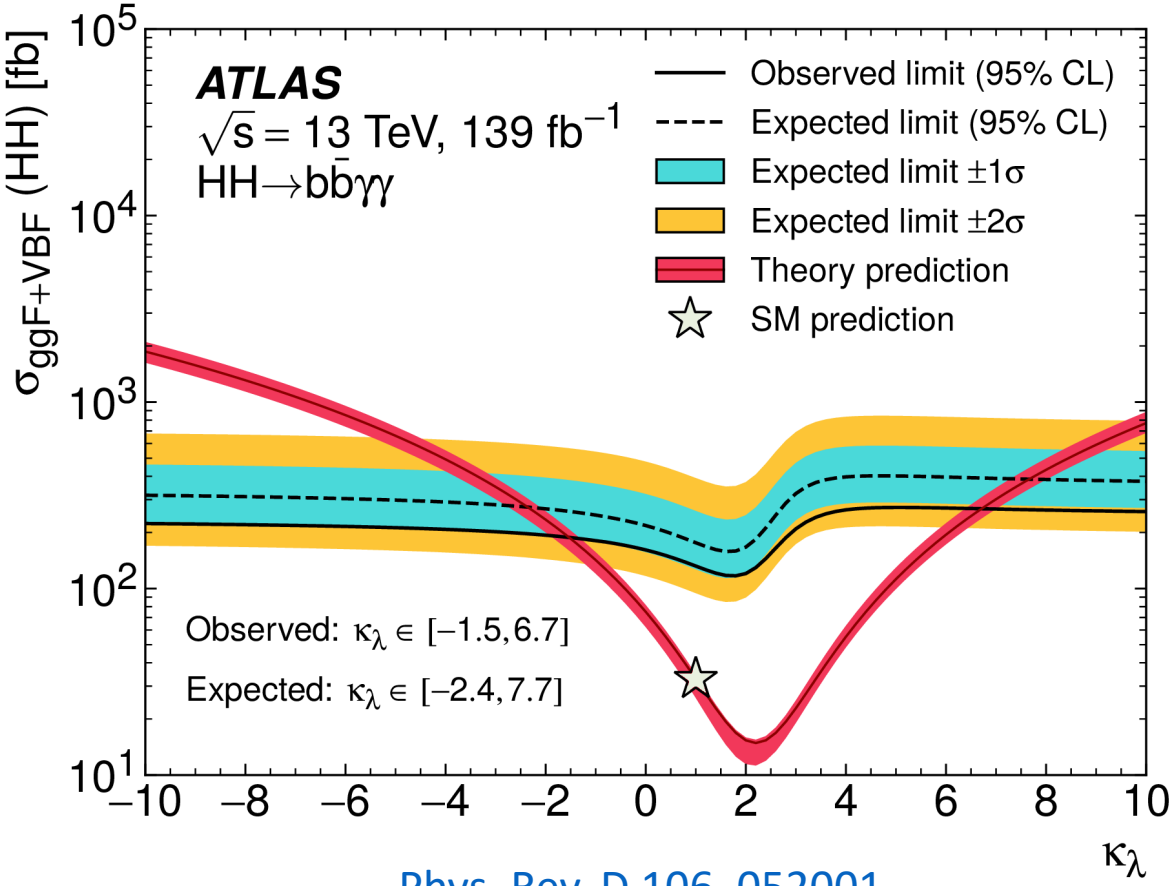
Low mass region: targets to large $\kappa_\lambda = 10$ (BSM)



High mass region: targets to $\kappa_\lambda = 1$ (SM)

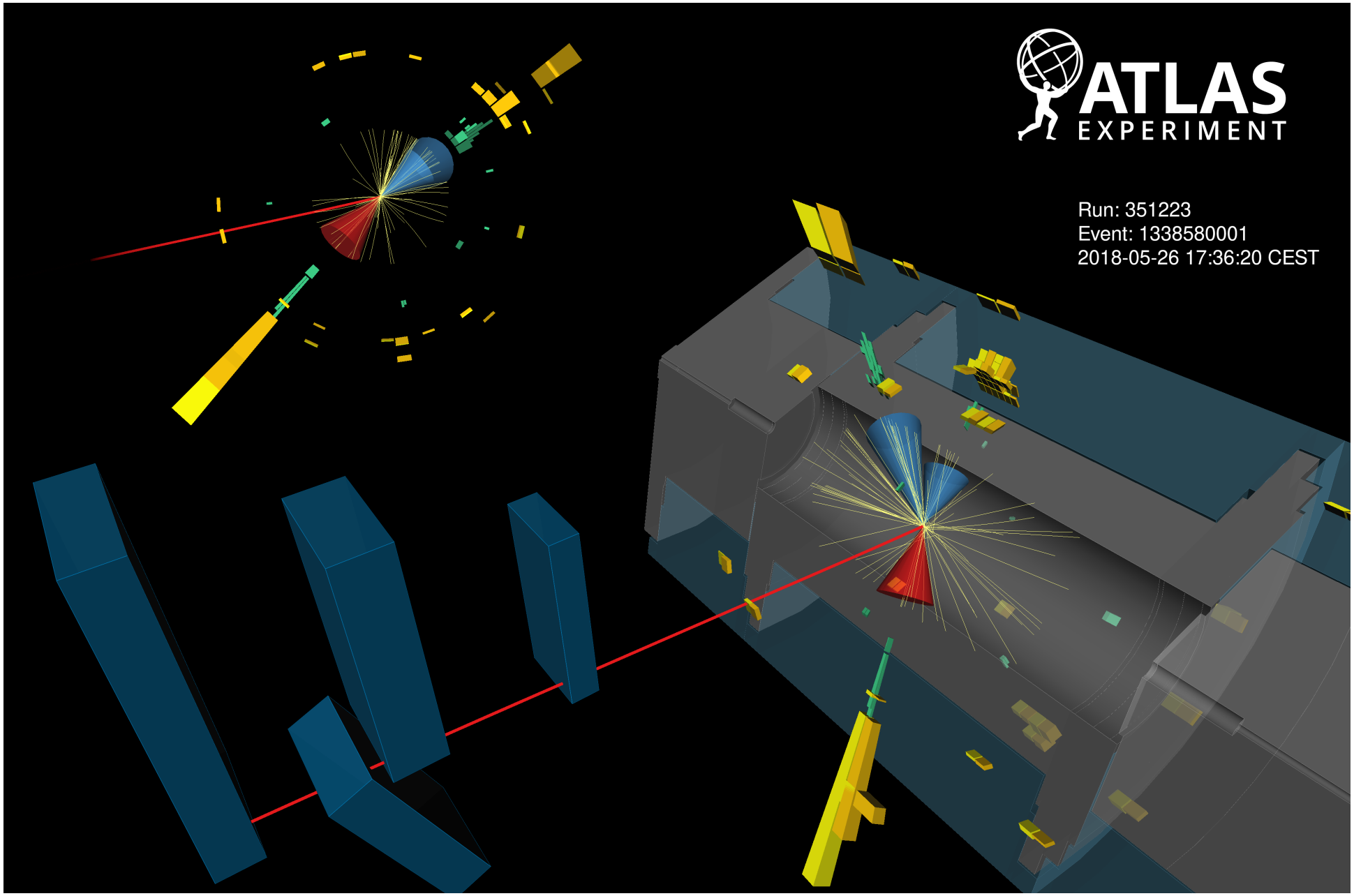
Results of $HH \rightarrow bb\gamma\gamma$

- The statistical fitting is performed on $m_{\gamma\gamma}$ distribution in each category.
- Limits are set on μ_{SM} and κ_λ.
- Observed (expected) μ_{SM} : 4.2 (5.7).



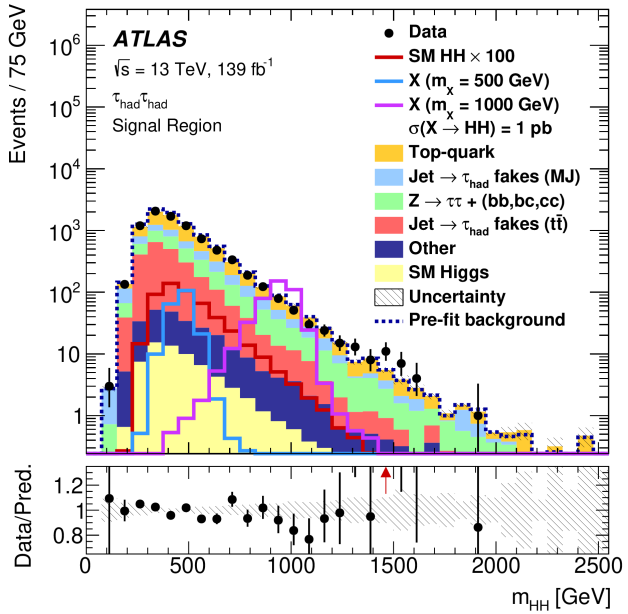
Phys. Rev. D 106, 052001

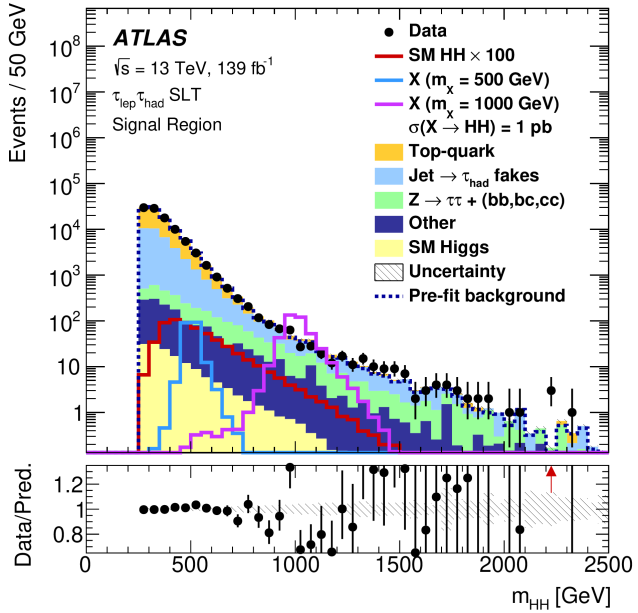
$HH \rightarrow bb\tau\tau$



$HH \to bb\tau\tau$

- Signature of the $bb\tau\tau$ channel:
  - Relative clean background.
  - Moderate branching ratio, ~7.3%
  - Dominate background comes from fake τ, hard to estimate.
- Analysis strategy and event selection:
  - Backgrounds from fake τ are estimated using fake factor method.
  - Events are split into different categories according to the τ decay mode (leptonic or hadronic), based on the type of trigger accepted the event.
  - Exactly 2 b-tagged jets.
  - Require two hardonic τ or τ+e/μ.
  - $m_{\tau\tau} > 60$ GeV.

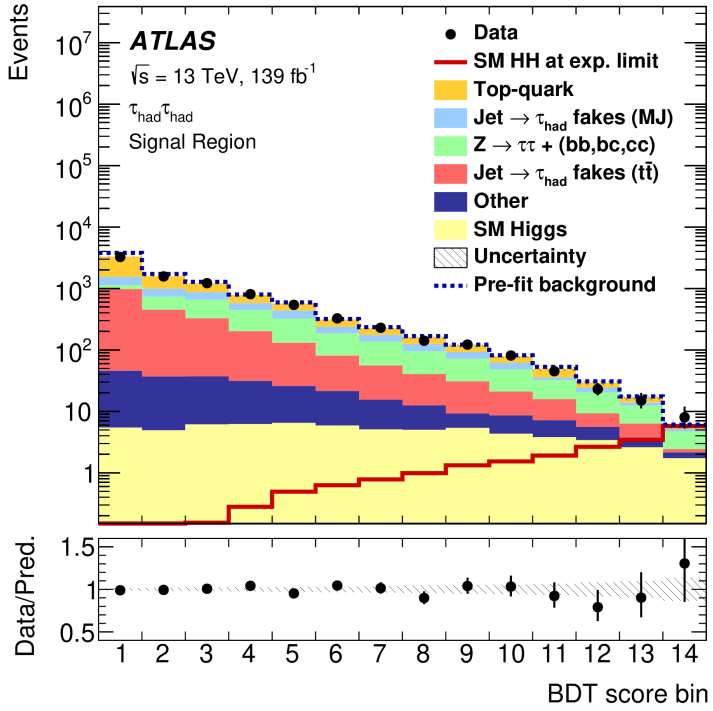


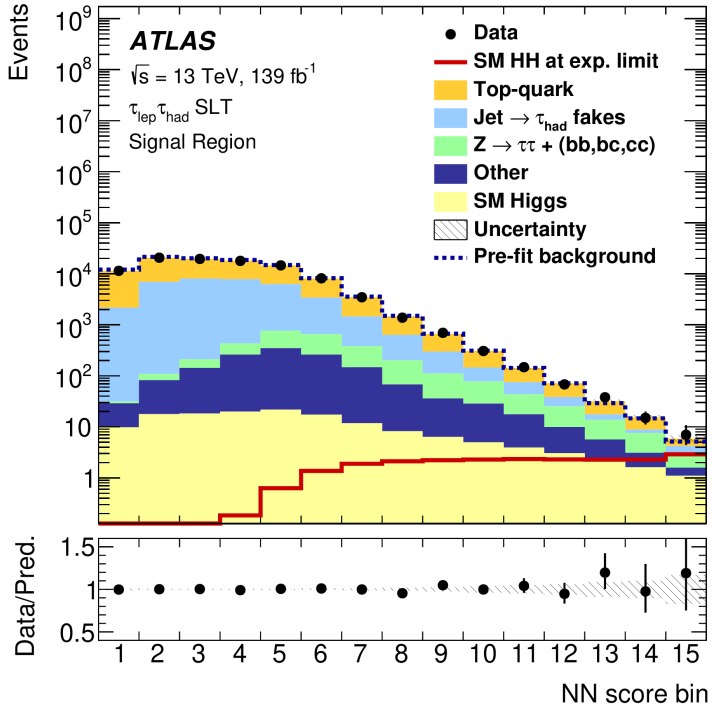


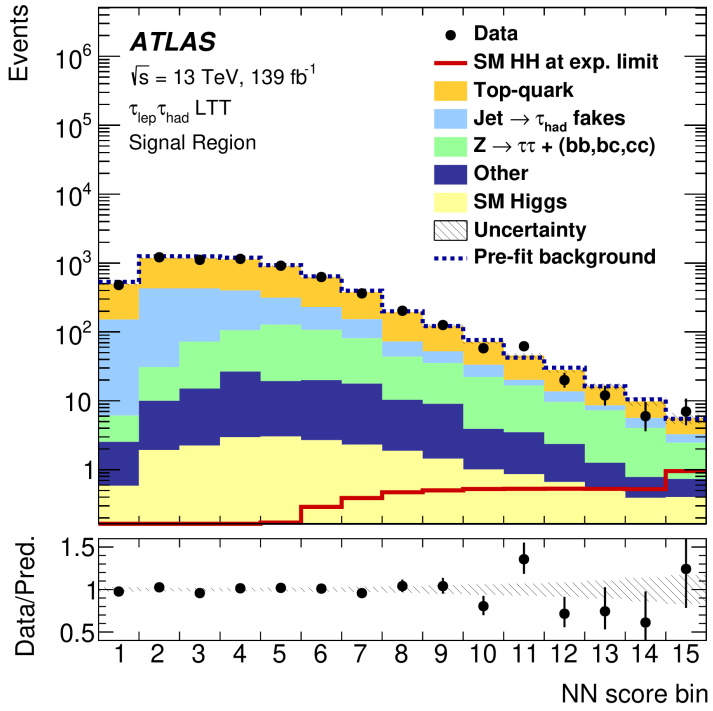
arXiv:2209.10910

MVA and result of $HH \rightarrow bb\tau\tau$

- To improve signal/background ratio, boosted decision tree (BDT) is used in the $\tau_{had}\tau_{had}$ category and neural network is used in the $\tau_{had}\tau_{lep}$ category.
- The statistical fitting is performed on BDT and NN predicted score.
- Observed (expected) upper limits of μ_{SM} : 4.7 (3.9).

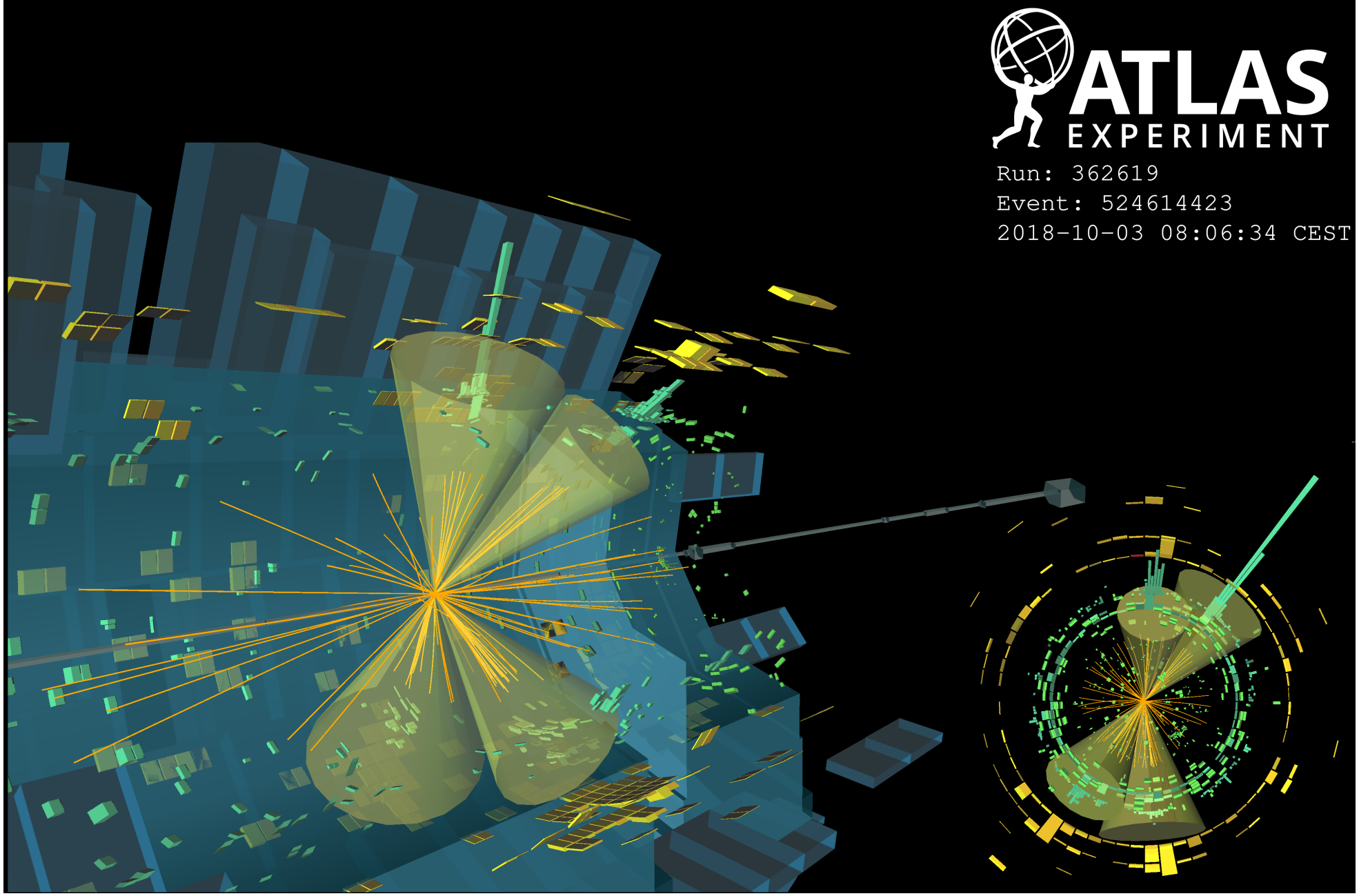






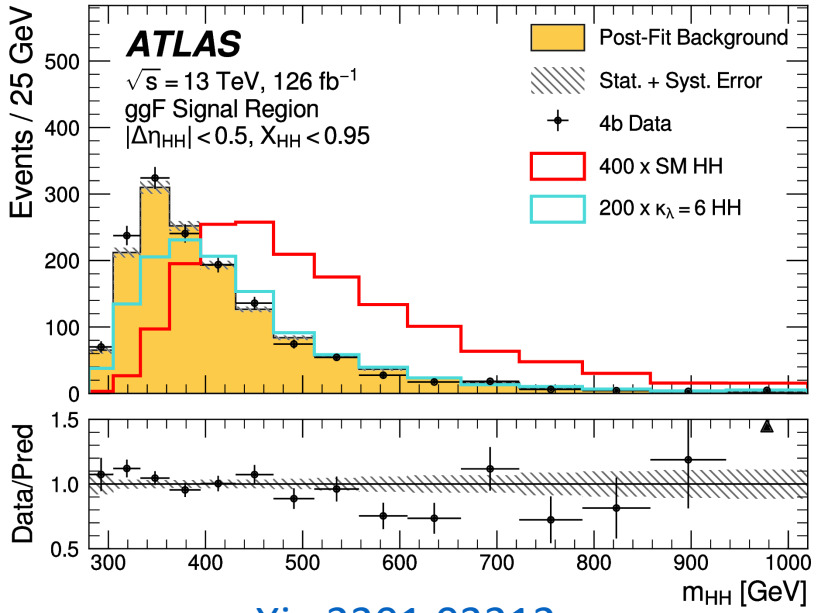
arXiv:2209.10910

$HH \rightarrow bbbb$

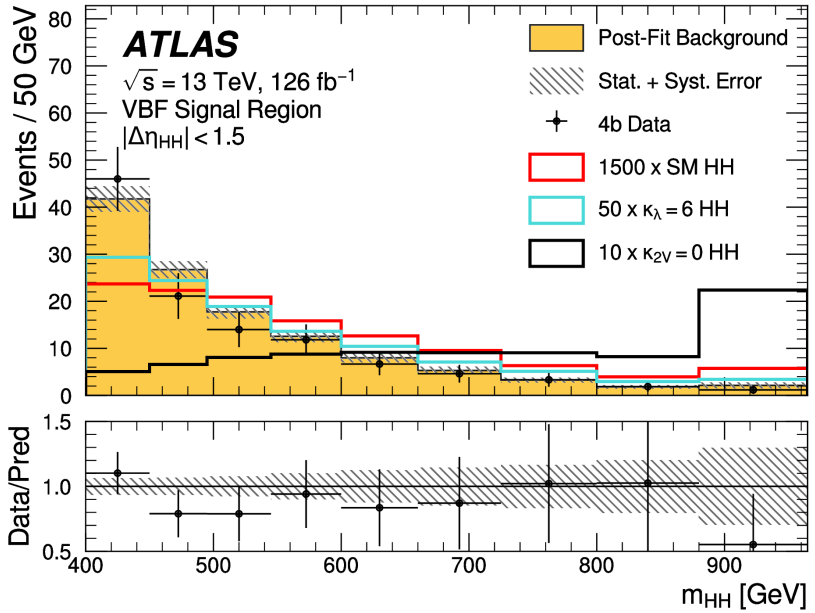


$HH \rightarrow bbbb$

- Signature of the *bbbb* channel:
  - Large background comes from QCD.
  - Largest branching ratio, ~33%
- Analysis strategy and event selection:
  - Both VBF and ggH are included.
  - Fake b-jet backgrounds are estimated using data driven method from a 2b control region.
  - Exactly 4 b-tagged jets.
  - Events are split into six categories according to $\Delta\eta_{HH}$ and X_{HH} in ggH channel, while events are split into two categories according to $\Delta\eta_{HH}$ in VBF channel.

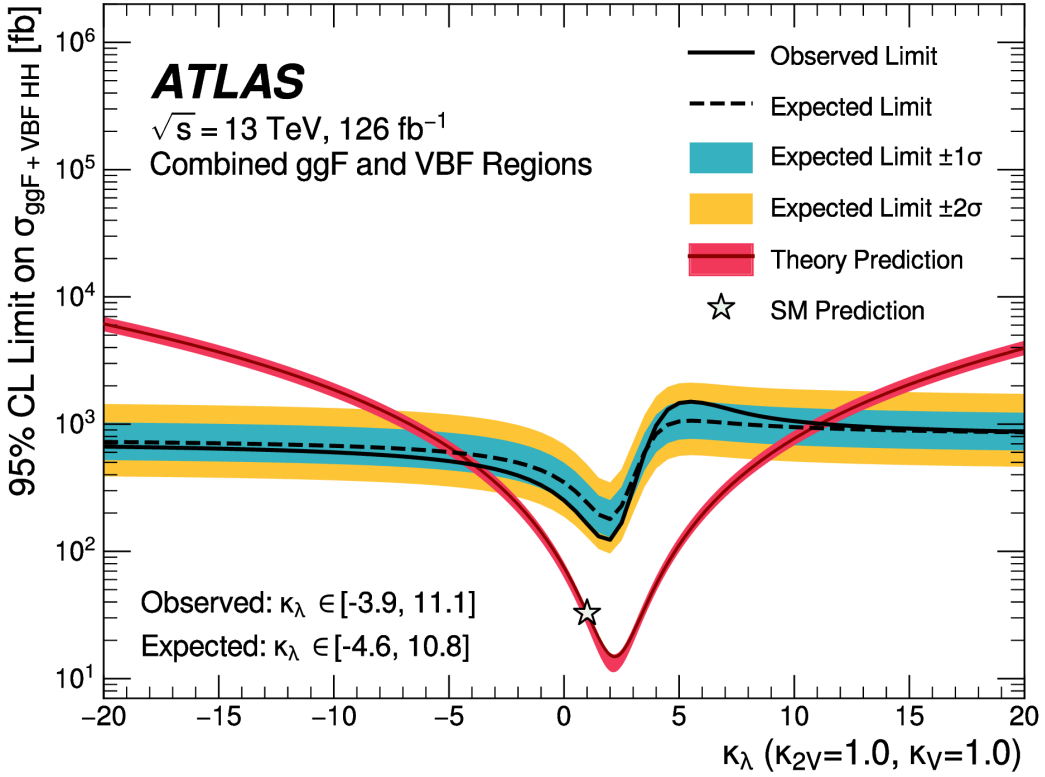


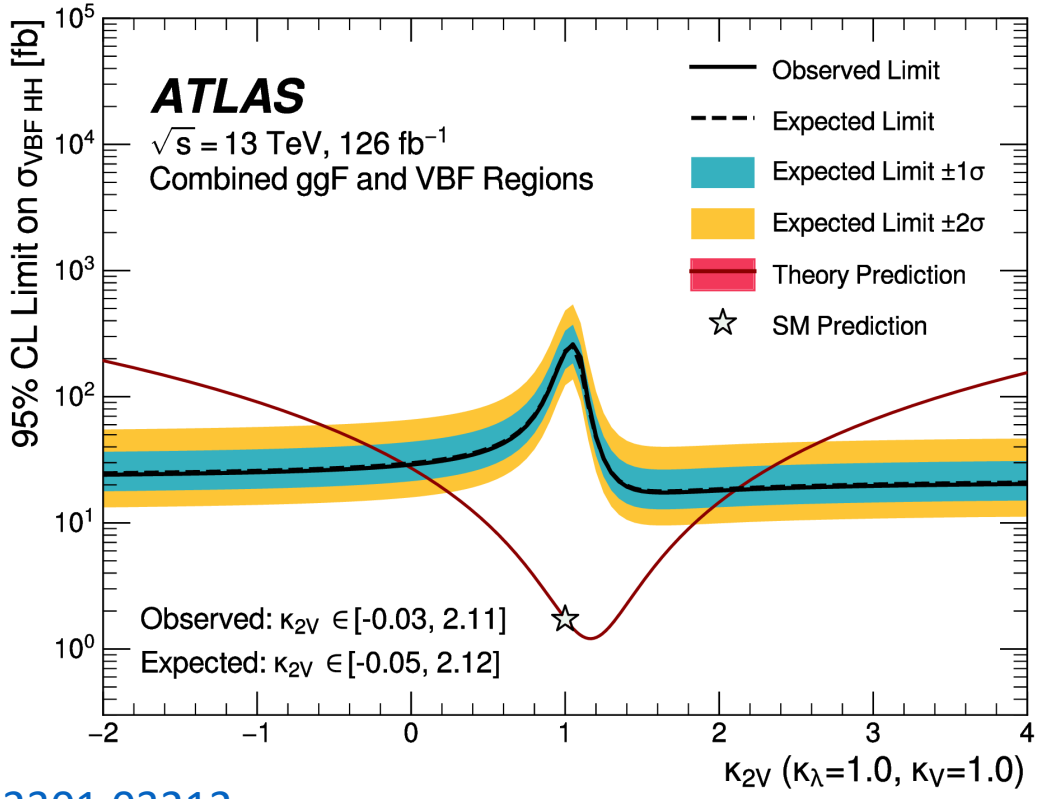
arXiv:2301.03212



Results of $HH \rightarrow bbbb$

- The statistical fitting is performed on m_{HH} distribution in each category.
- Limits are set on μ_{SM} and κ_λ.
- Observed (expected) upper limit on μ_{SM} : 5.4 (8.1)

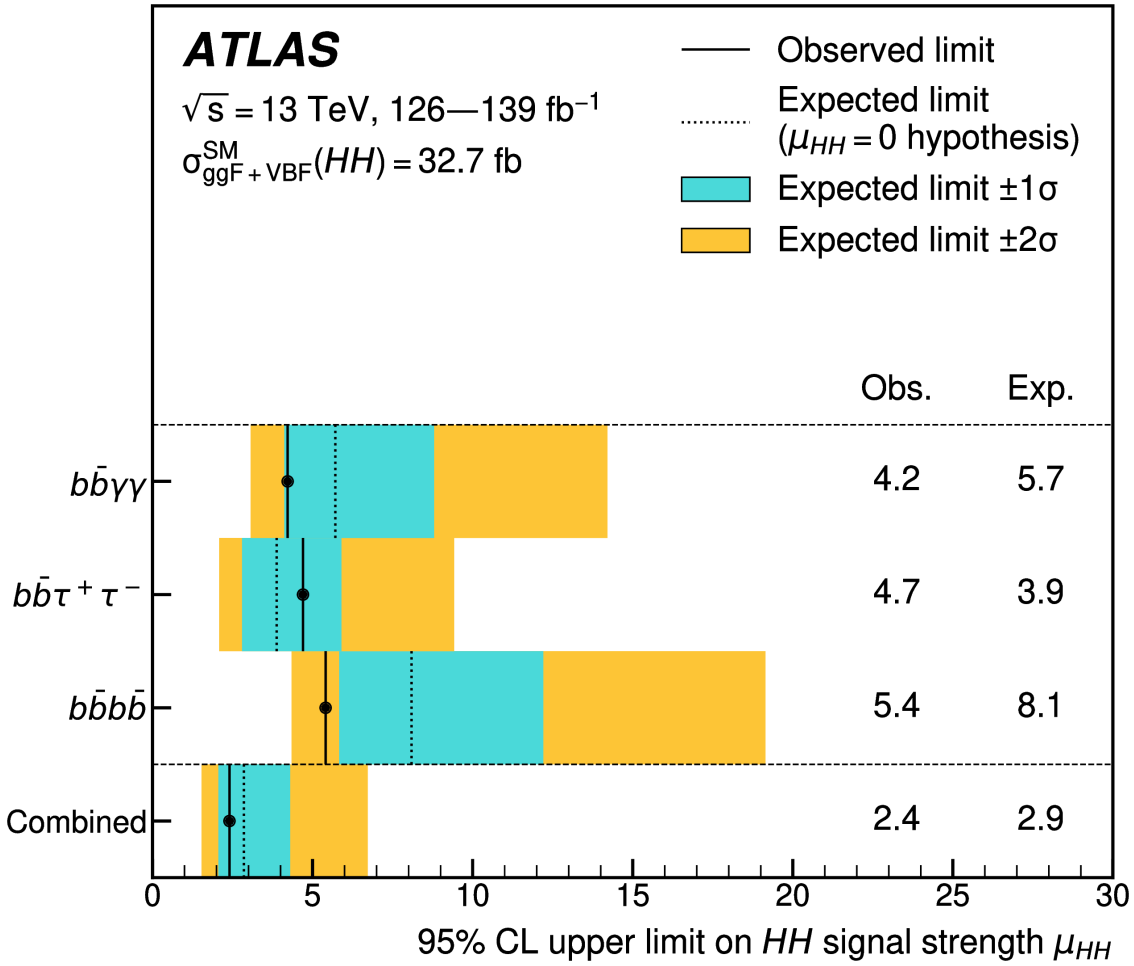




arXiv:2301.03212

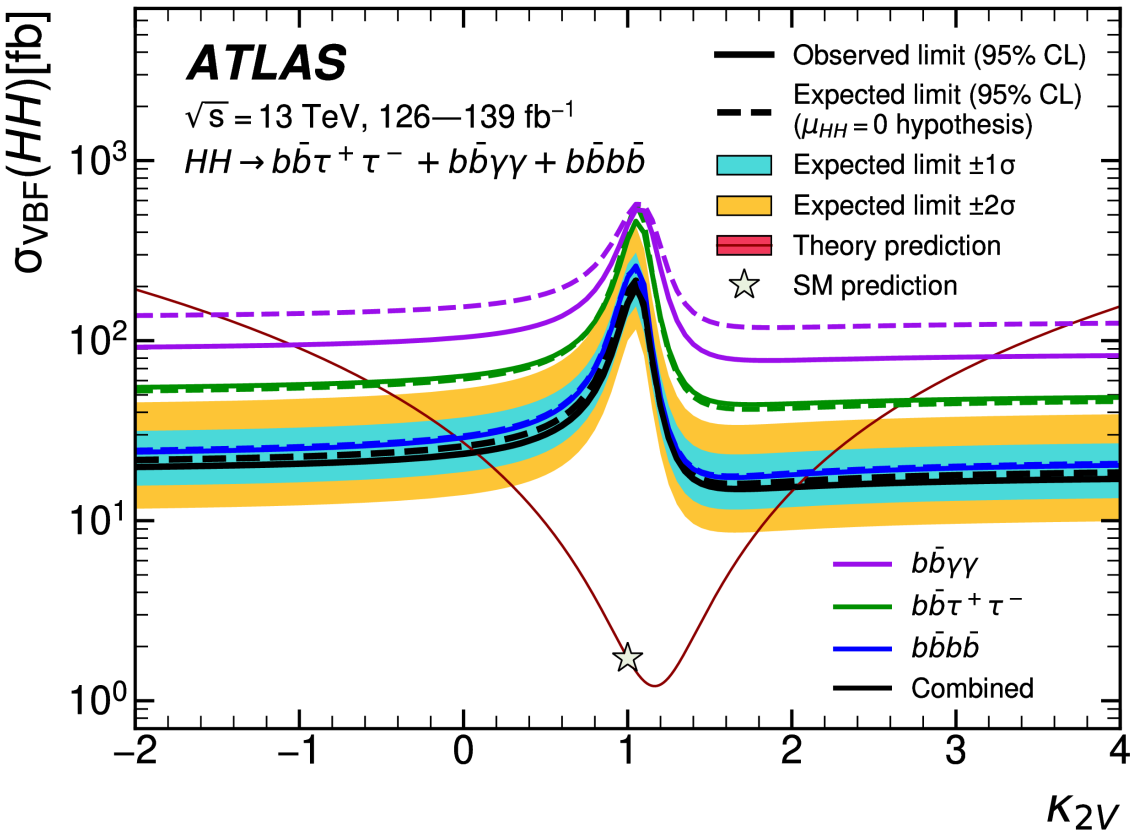
HH combination

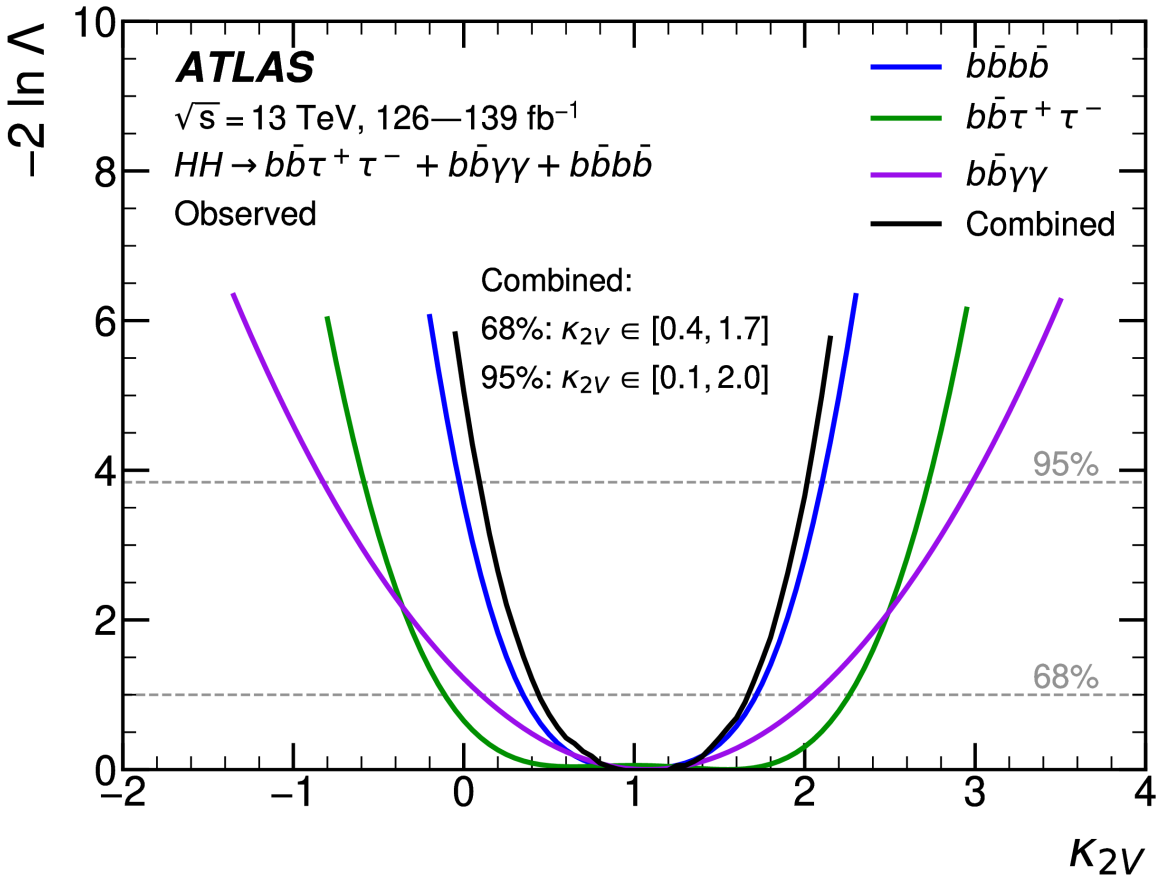
- Combined three most sensitive channel: $bbbb$, $bb\gamma\gamma$ and $bb\tau\tau$.
- Combined 95% upper limits on μ_{HH}: 2.4



arXiv:2211.01216

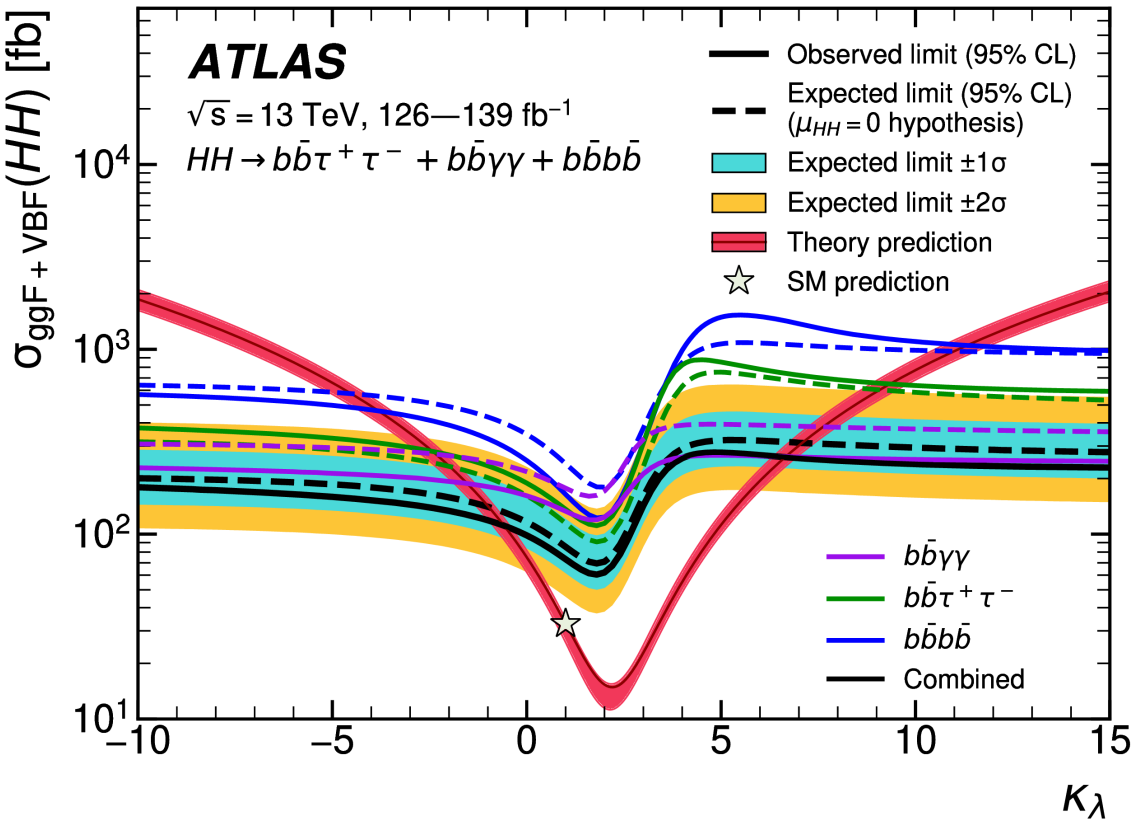
HH combination, κ_{2v}

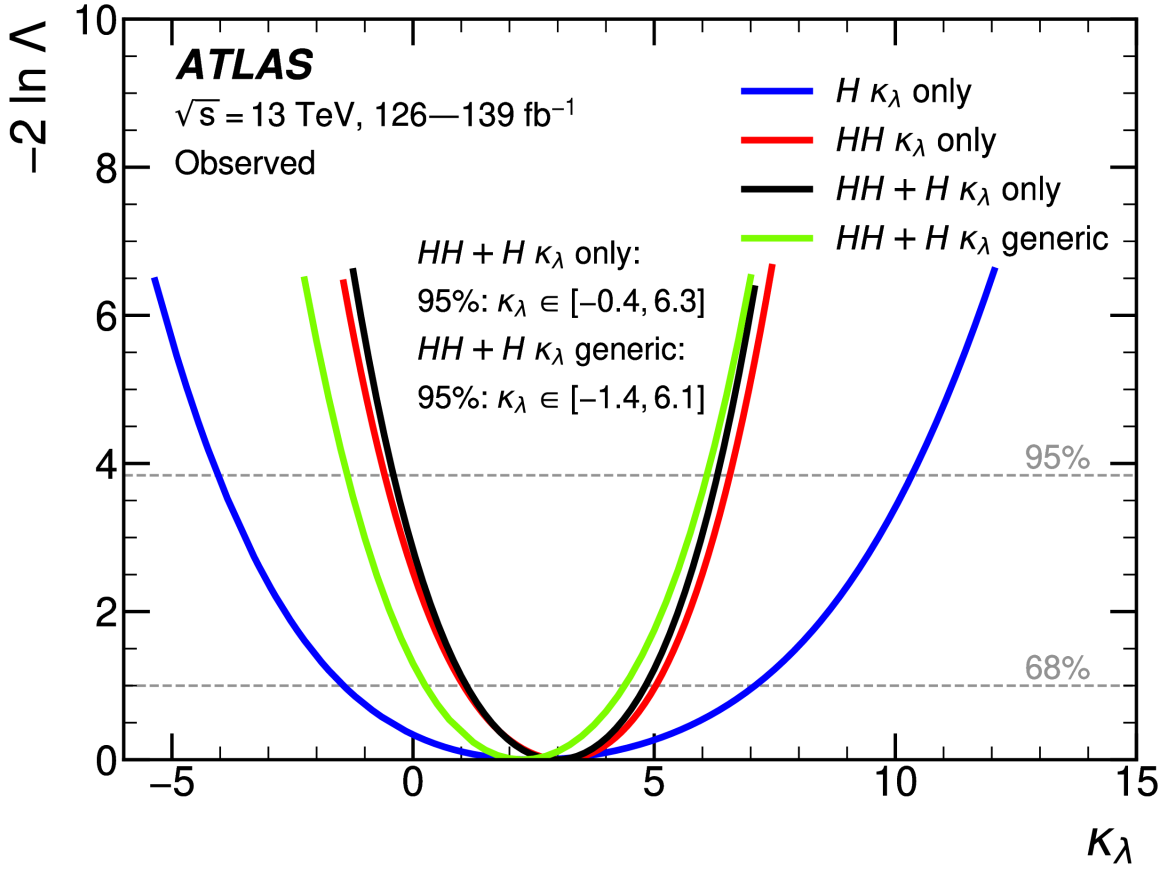




arXiv:2211.01216

HH combination, κ_λ

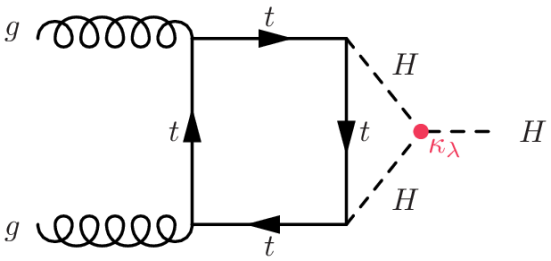


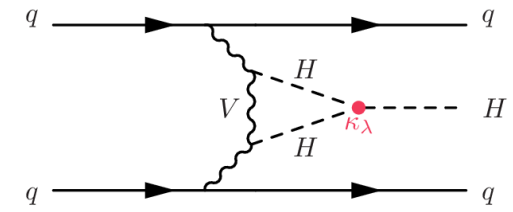


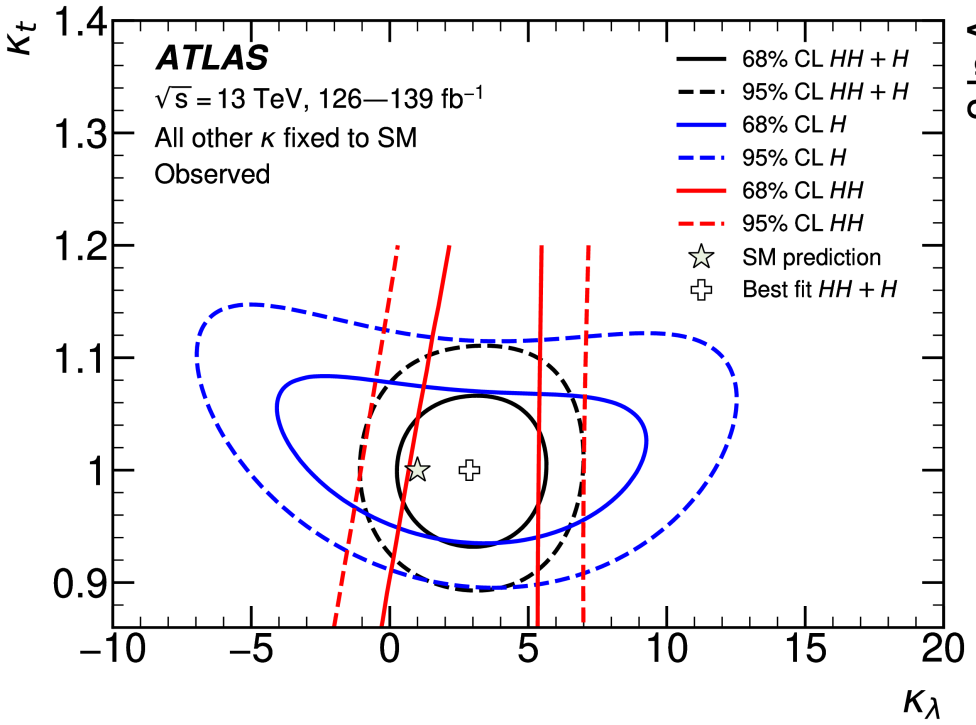
arXiv:2211.01216

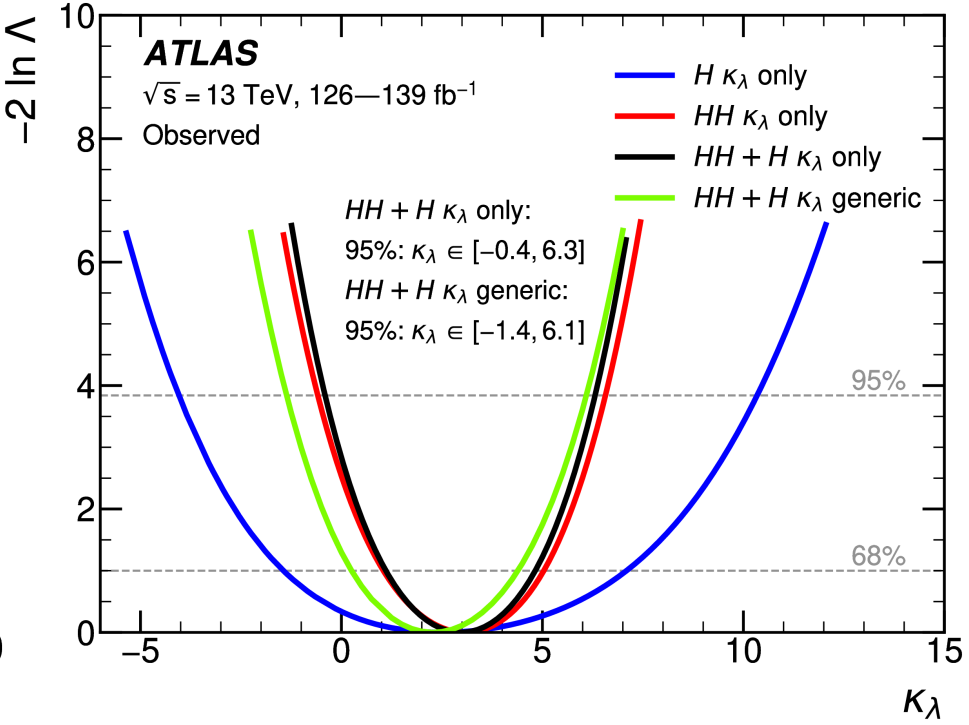
$H + HH$ combination

- Single Higgs boson production is also sensitive to κ_λ when loop corrections are included.
- Combined limits from single and double Higgs production:





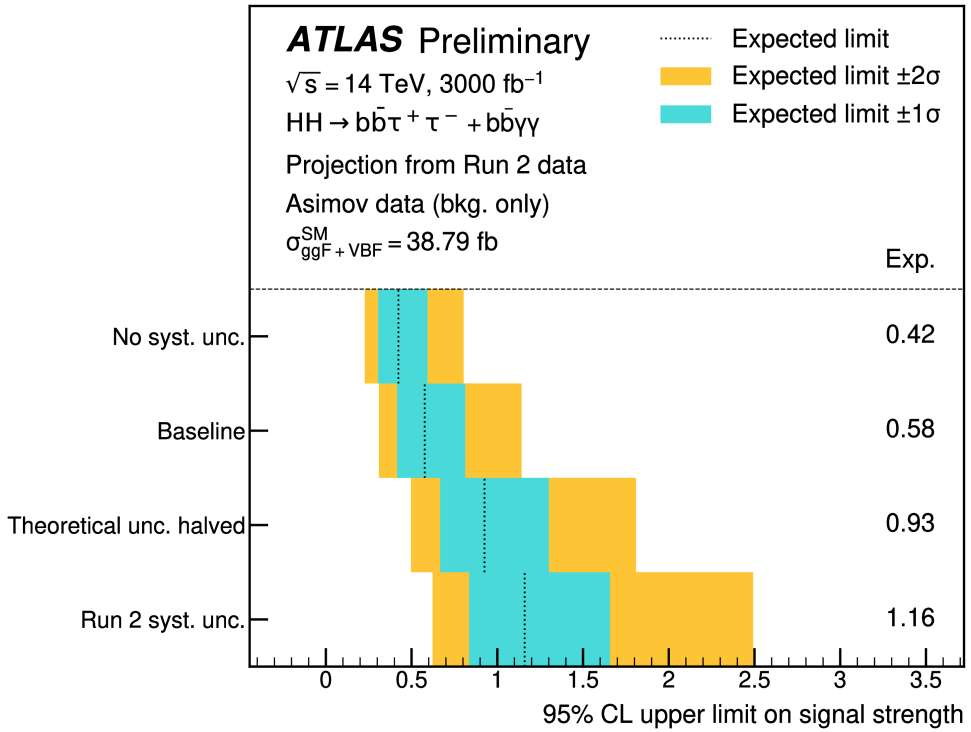


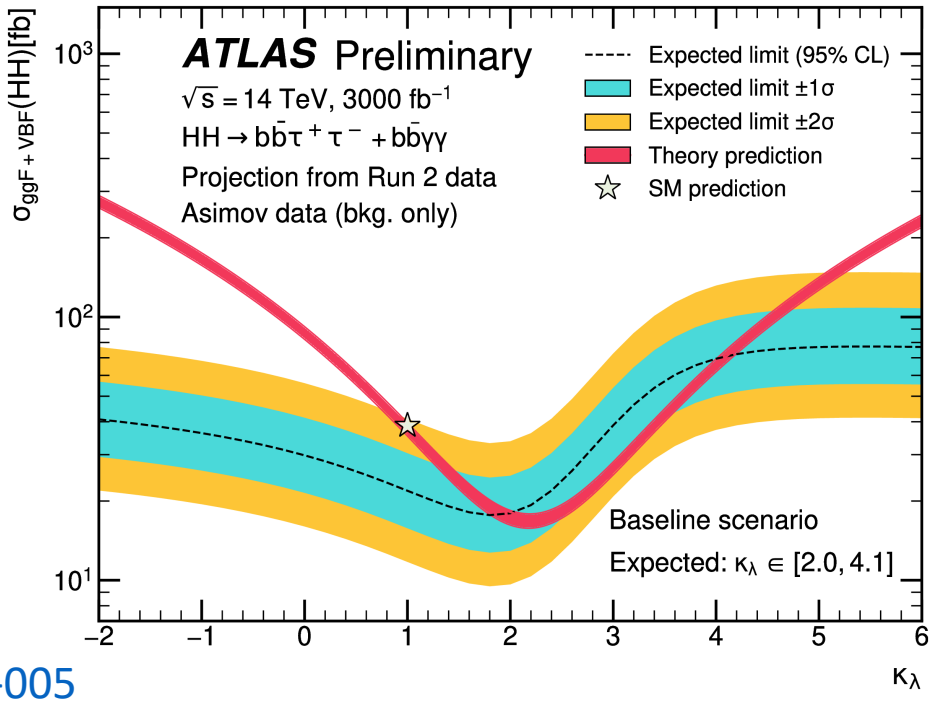


arXiv:2211.01216

Projected result at HL-LHC ($bb\gamma\gamma + bb\tau\tau$)

- Measurement from Run 2 data with integrated luminosity of 139 fb^{-1} at 13 TeV are projected to the HL-LHC at 14 TeV and total integrated luminosity of 3000 fb^{-1} .
- The estimated significance of the SM HH production is 3.2 σ with systematic uncertainties included.

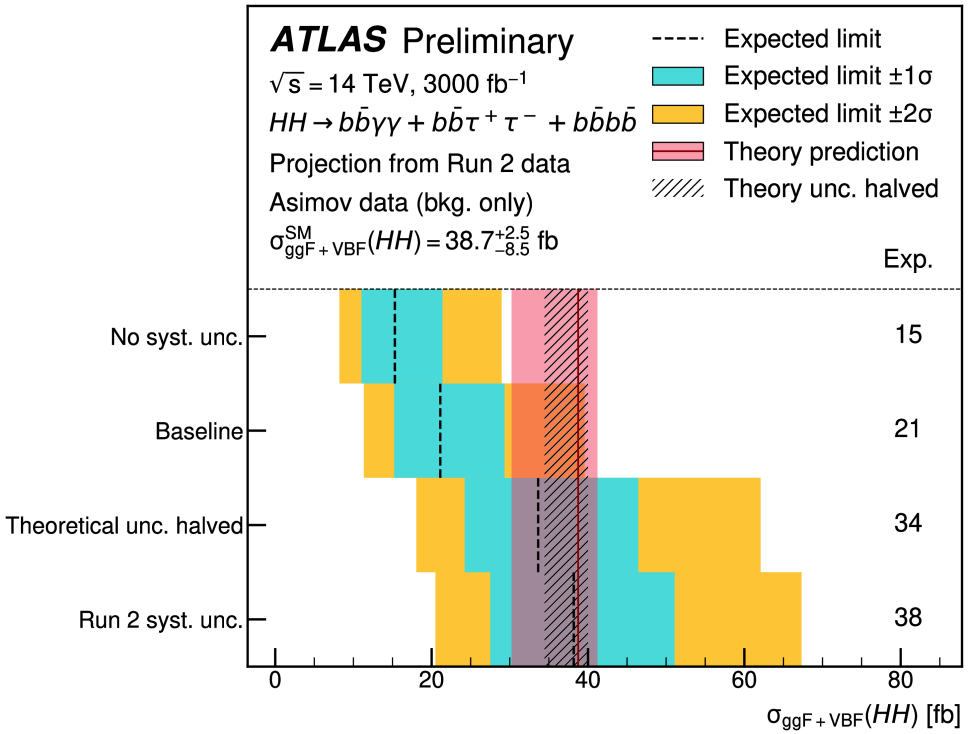


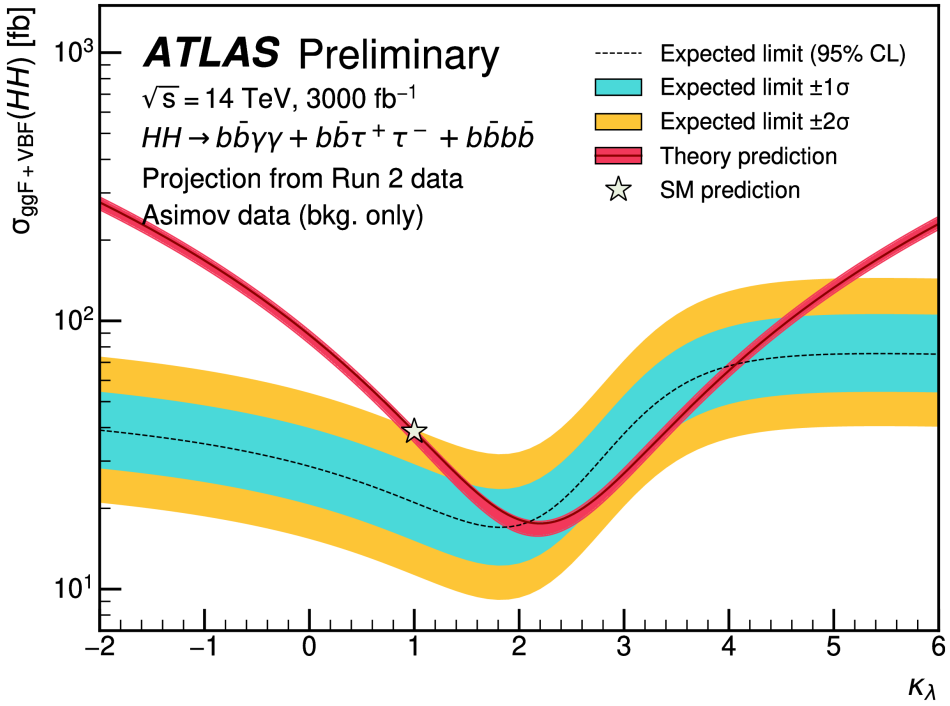


ATL-PHYS-PUB-2022-005

Projected result at HL-LHC ($bb\gamma\gamma + bb\tau\tau + bbbb$)

- The estimated significance of the SM HH production is 3.4 σ with systematic uncertainties included after the including the $bbbb$ channel.





ATL-PHYS-PUB-2022-005

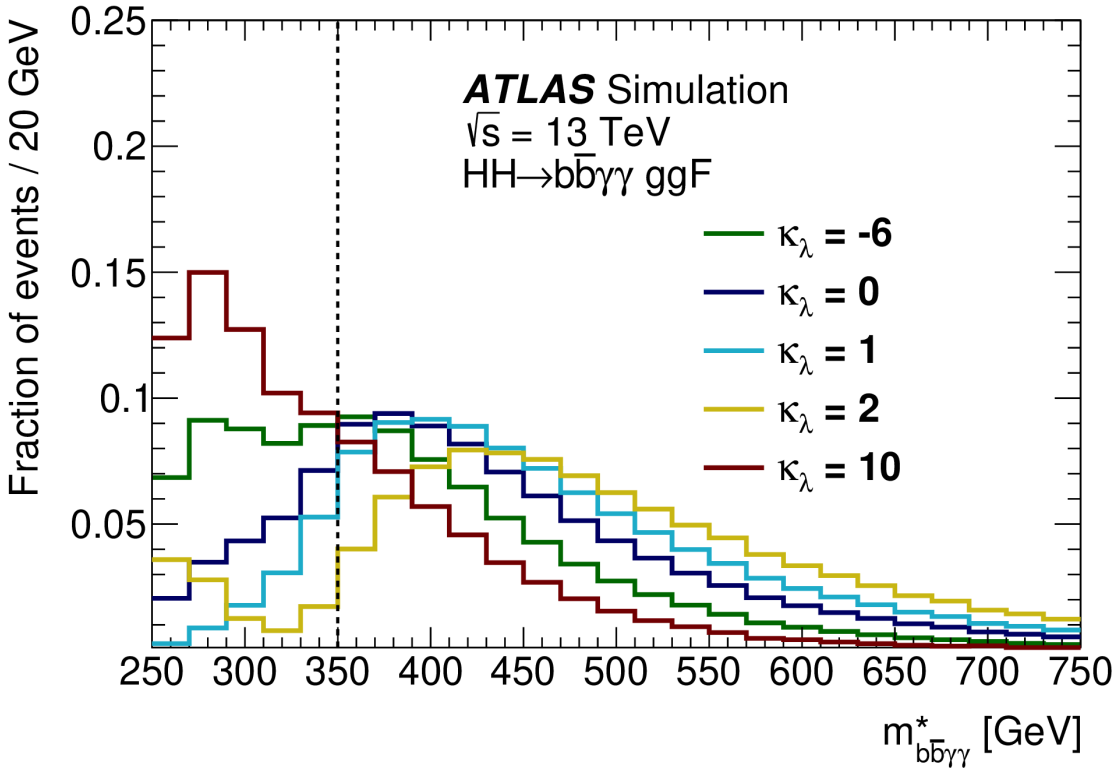
Summary

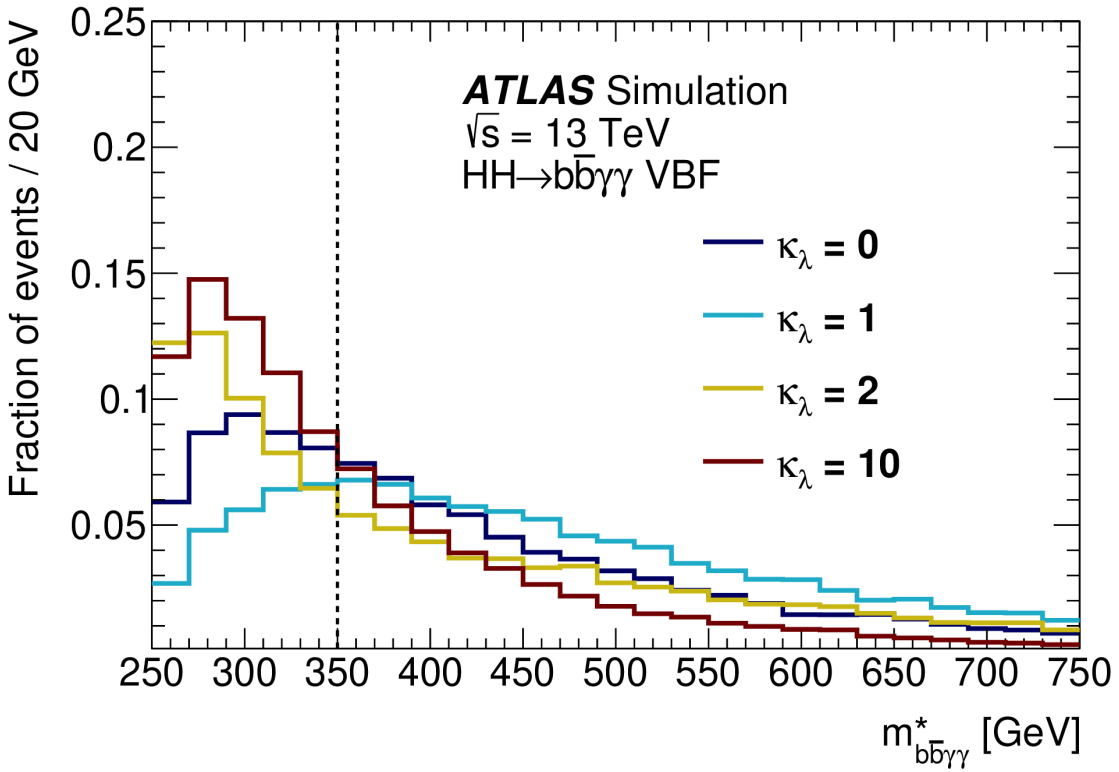
- Searches for HH production in the three most sensitive channels by ATLAS are reported.
  - $bb\gamma\gamma$: observed (expected) upper limit on μ_{HH}: 4.2 (5.7).
  - $bb\tau\tau$: observed (expected) upper limit on μ_{HH}: 4.7 (3.9).
  - $bbbb$: observed (expected) upper limit on μ_{HH}: 5.4 (8.1).
- Combined HH measurement result is also reported:
  - Combined upper limit on μ_{HH}: 2.4.

- Projected measurement result of HH production on the HL-LHC is also reported.

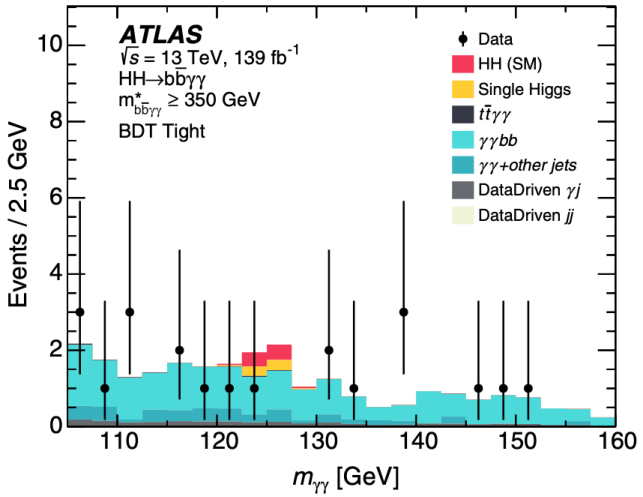
Back up

$HH \rightarrow bb\gamma\gamma$

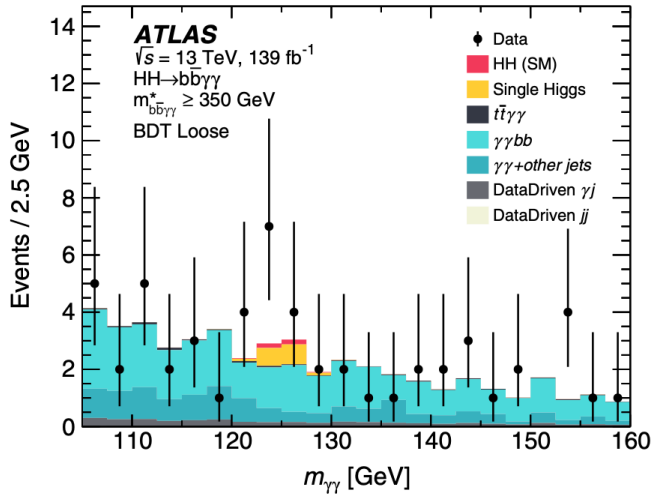




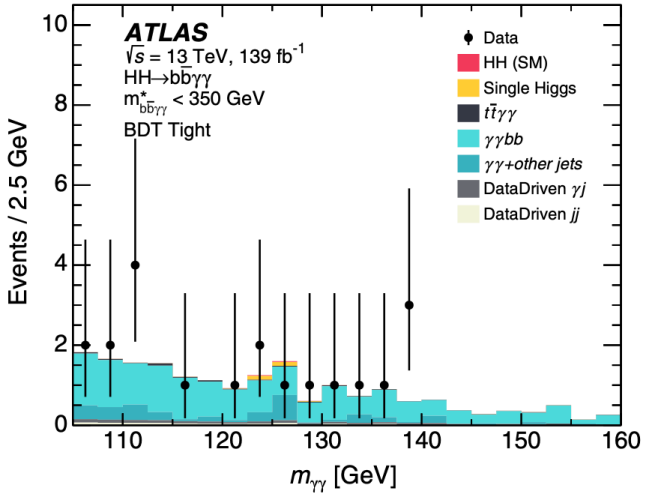
$HH \rightarrow bb\gamma\gamma$



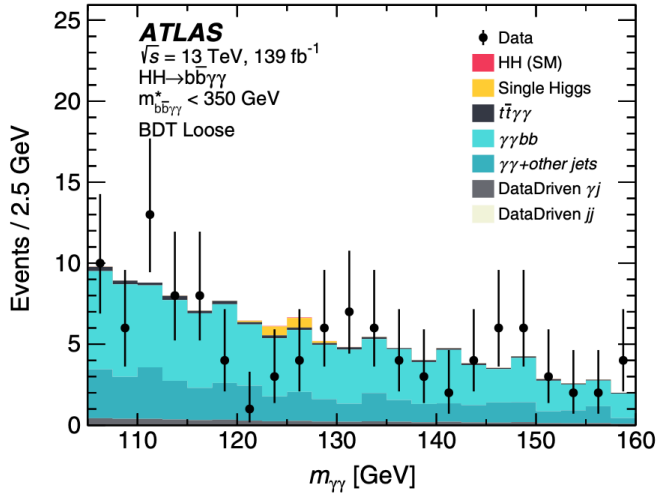
(a) High mass BDT tight selection



(b) High mass BDT loose selection



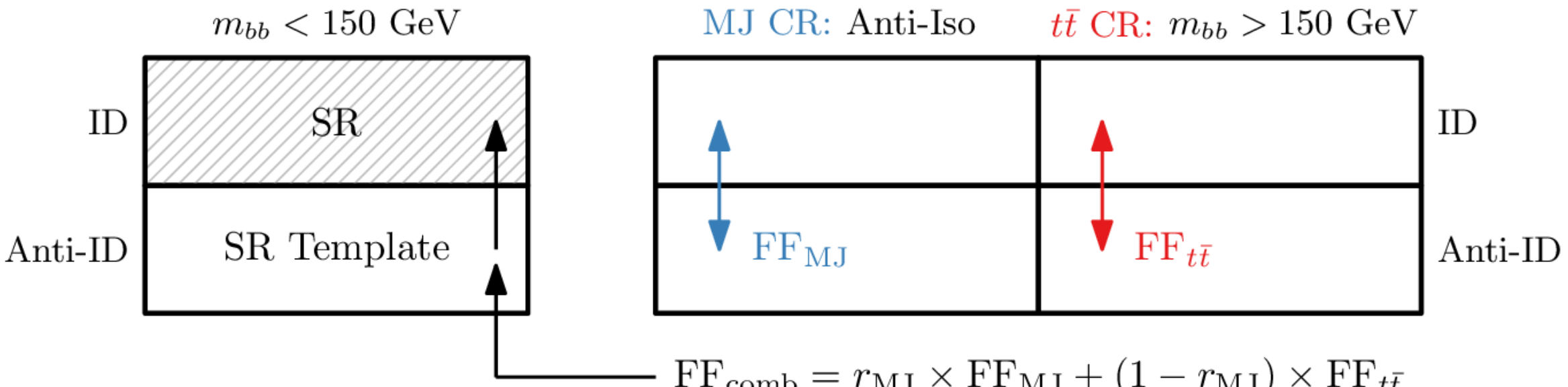
(c) Low mass BDT tight selection



(d) Low mass BDT loose selection

$HH \to bb\tau\tau$

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

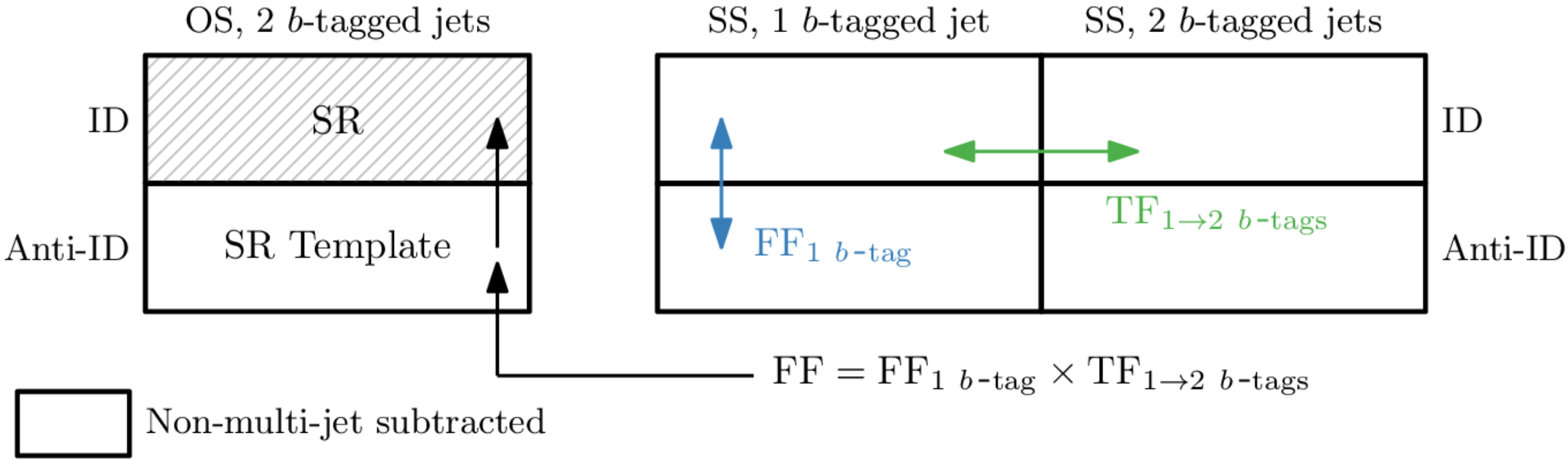


True-$\tau_{\text{had-vis}}$ subtracted

r_{MJ} Fraction of multi-jet events in the template

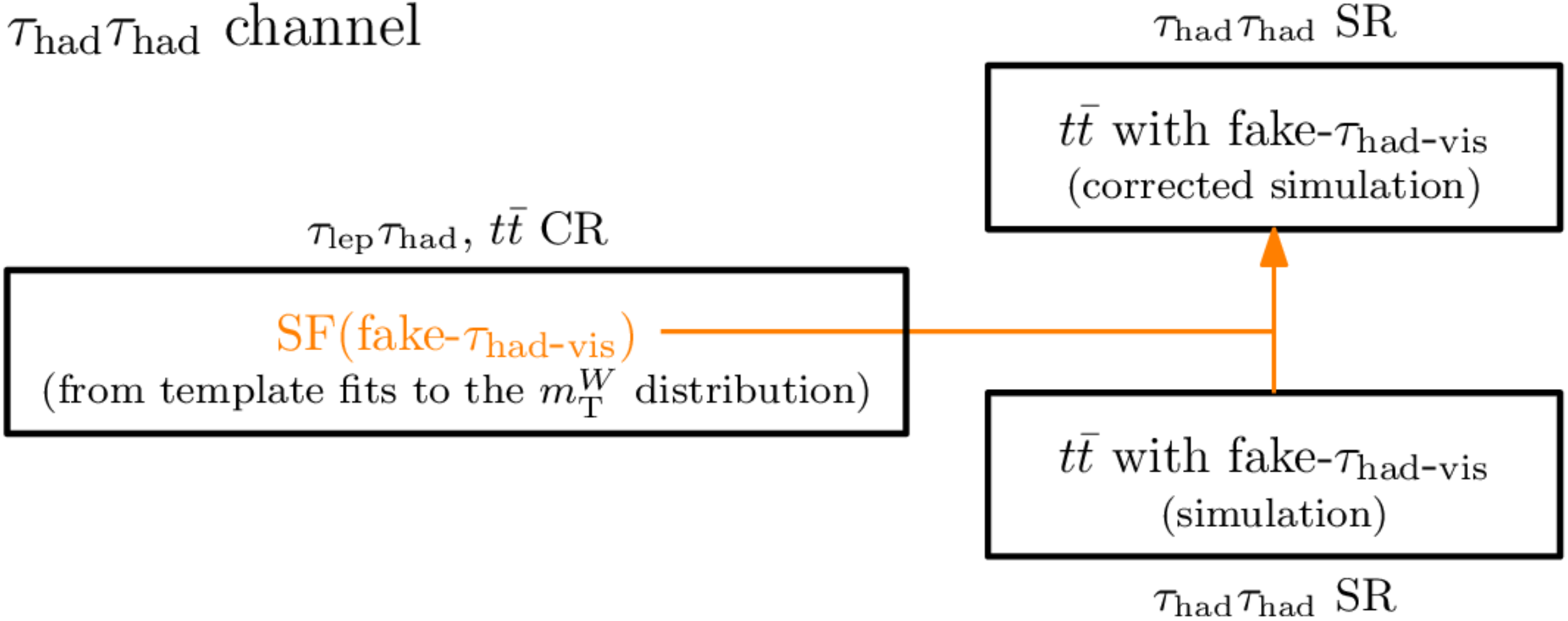
$HH \to bb\tau\tau$

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

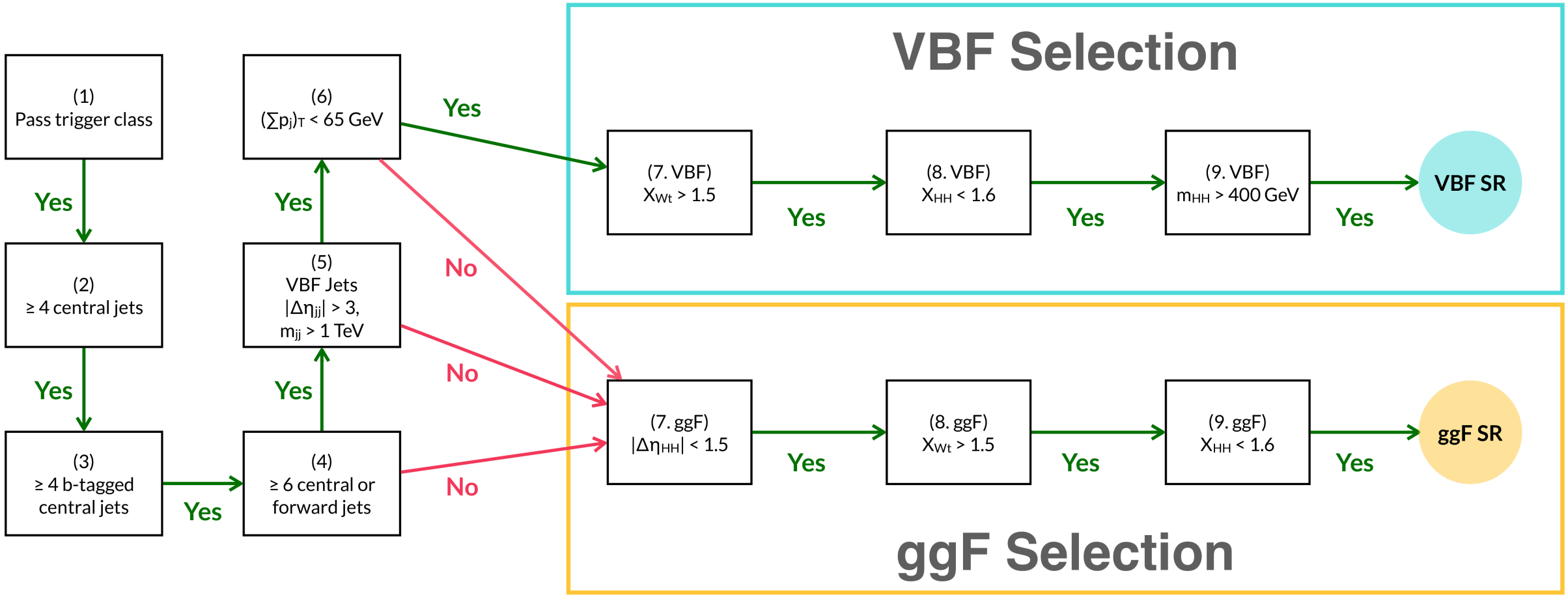


$HH \to bb\tau\tau$

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



$HH \rightarrow bbbb$ categories



$HH \rightarrow bbbb$

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

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

$H + HH$ combination