LHCP Boston 2024

Non-resonant di-Higgs search/measurements, ATLAS

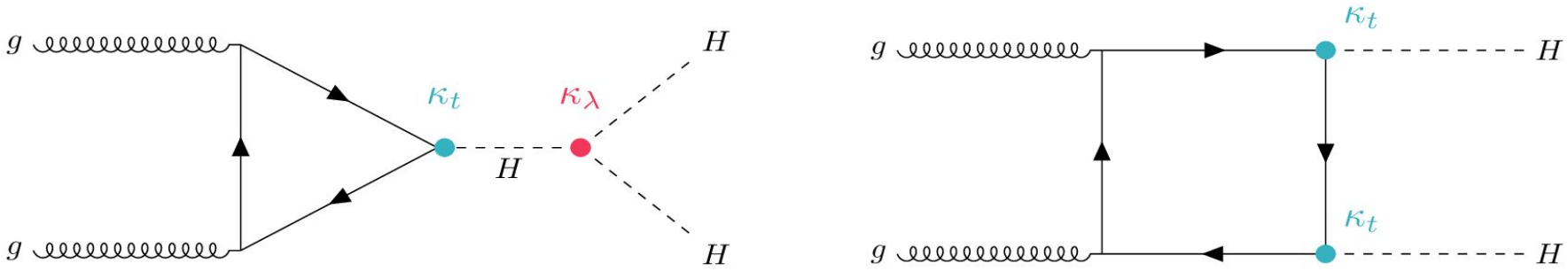
Arely CORTES GONZALEZ
on behalf of the **ATLAS Collaboration**

erc

HUMBOLDT-UNIVERSITÄT ZU BERLIN

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 κ_λ 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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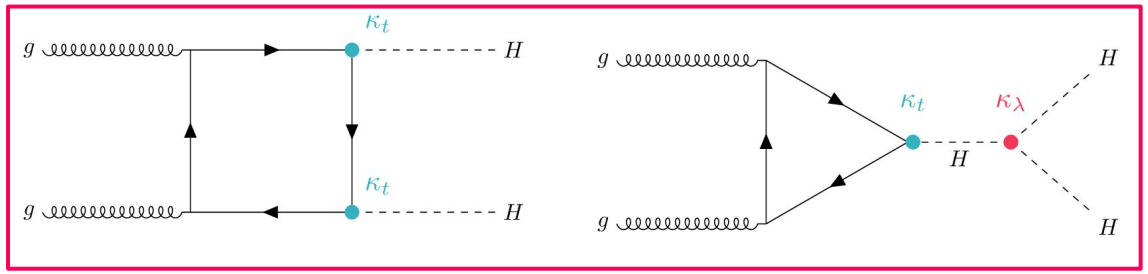
Non-resonant HH production

LHCHXSWG-2019-005

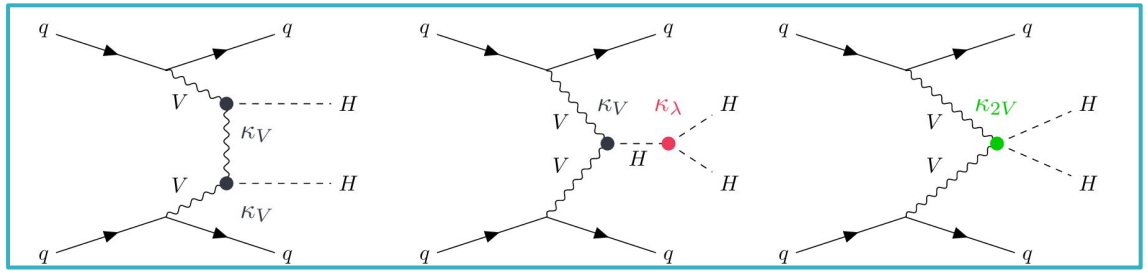
Production cross sections at 13 TeV for m_H = 125 GeV



Gluon fusion (NNLO)

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

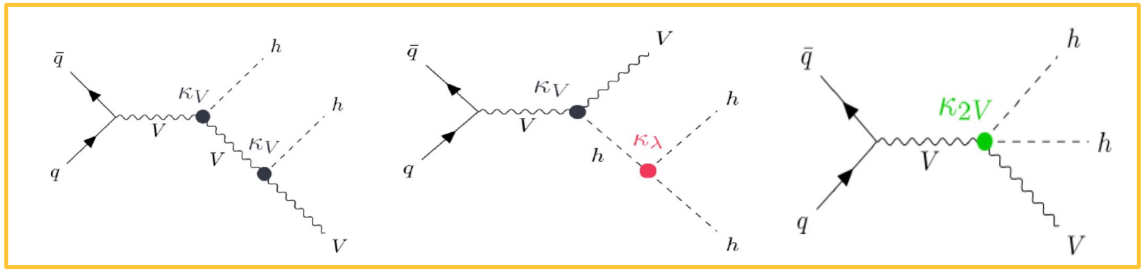
Trilinear self-coupling modifier: κ_λ



Vector boson fusion (N^{3}LO)

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

VVHH coupling modifier κ_{2V}



Associated production, VHH (N^{2}LO)

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

VVH coupling modifier κ_V

SM predicts $\kappa_\lambda = 1$, $\kappa_{2V} = 1$, $\kappa_V = 1$

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Search 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%	0.028%	0.012%	0.0005%

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

Combination is key in this search!

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Search channels

	bb	WW	ττ	ZZ	γγ
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- [bbbb] Largest decay fraction, exploit data driven techniques to estimate dominant multijet background.

  Resolved — Phys. Rev. D 108 (2023) 052003

  Boosted VBF — Submitted to Phys. Lett. B

  VHH — Eur. Phys. J. C 83 (2023) 519

- [bbττ] Medium decay fraction, good signal selection purity.

  JHEP 07 (2023) 040

  Submitted to Physical Review D

- [bbγγ] Lower decay fraction, but excellent $m_{\gamma\gamma}$ mass resolution.

  Phys. Rev. D 106 (2022) 052001

  JHEP 01 (2024) 066

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Search channels

	bb	WW	ττ	ZZ	γγ
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- [bb$\ell\ell$ + MET] Targeting multiple decay fractions, with one Higgs not decaying into bb (bbWW/bbττ/bbZZ).

  JHEP 02 (2024) 037

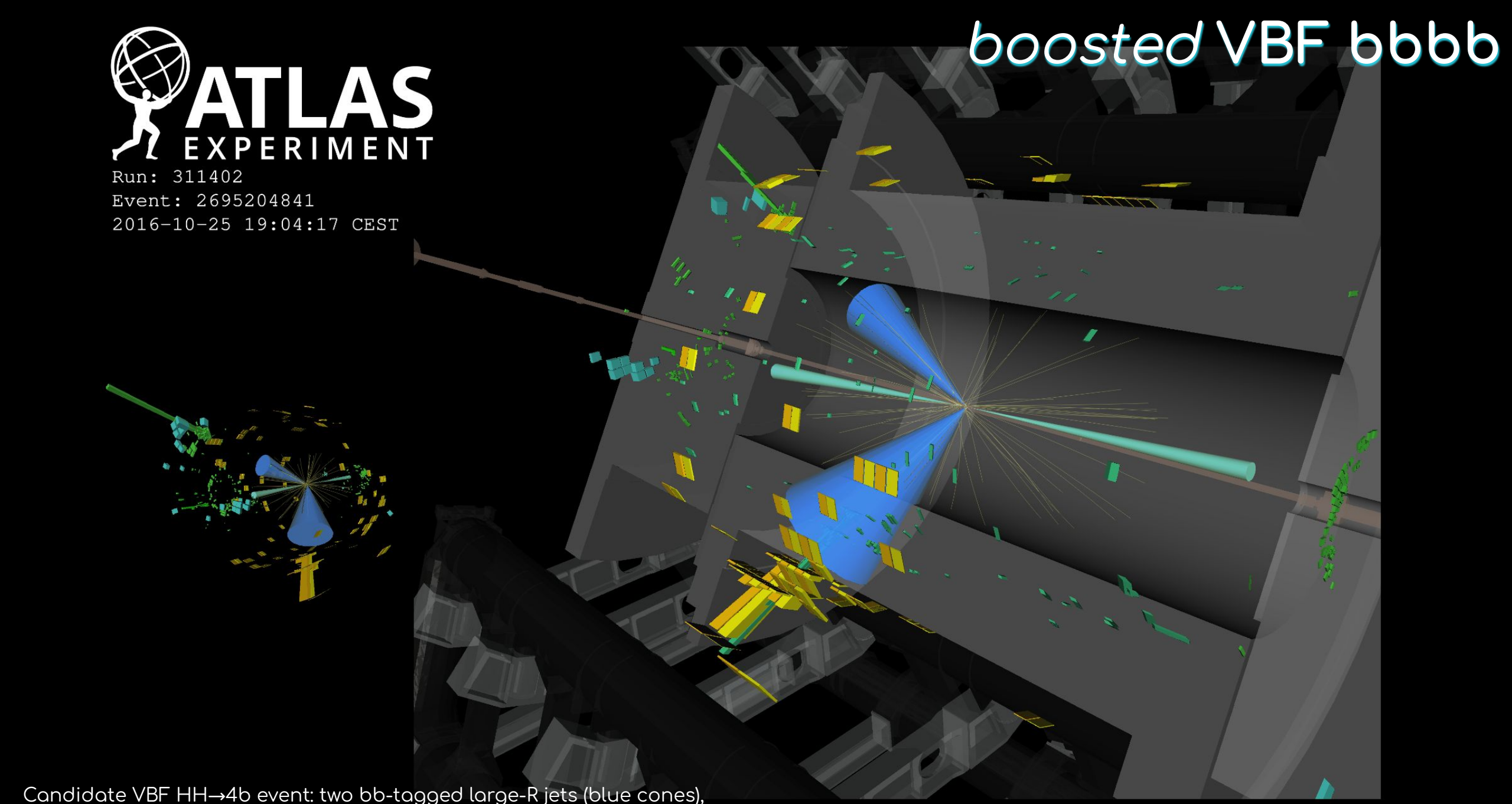
- [($\gamma\gamma$) multi-lepton] Covering multiple decay modes, where both Higgs don't decay into bb (and bbZZ(4ℓ)).

  ATLAS-CONF-2024-005

NEW Combination!

ATLAS-CONF-2024-006

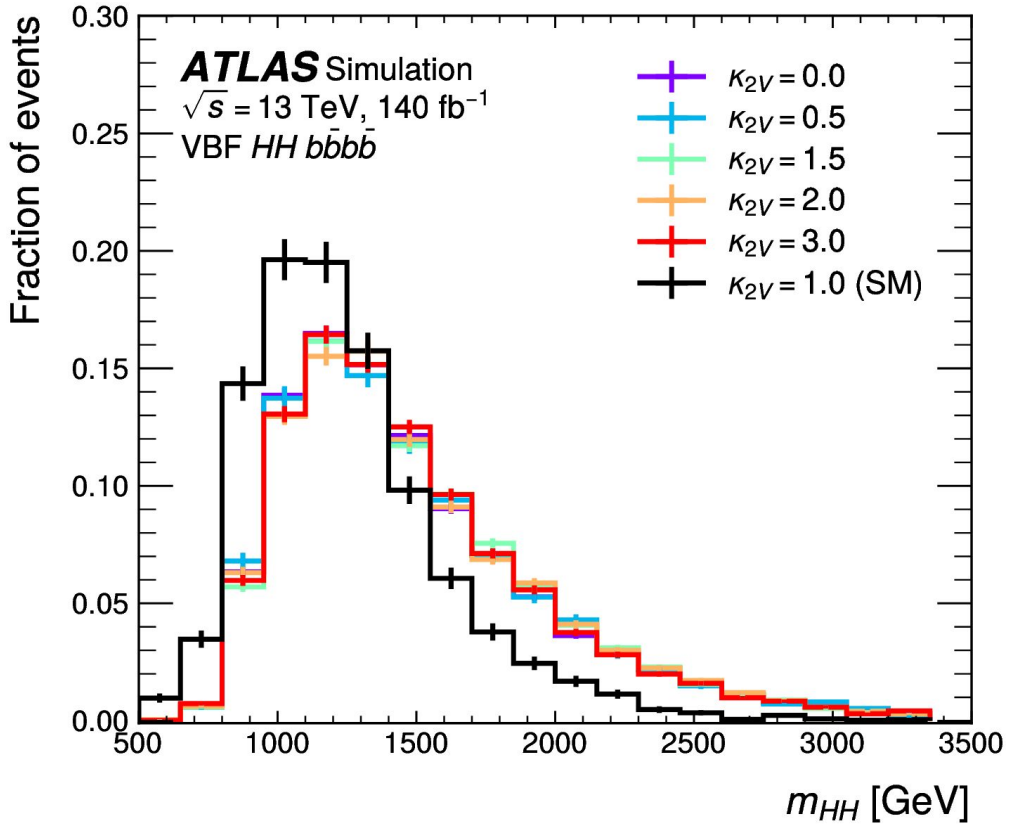
boosted VBF bbbb



Candidate VBF HH→4b event: two bb-tagged large-R jets (blue cones), two small-R jets (green cones) well separated in η.

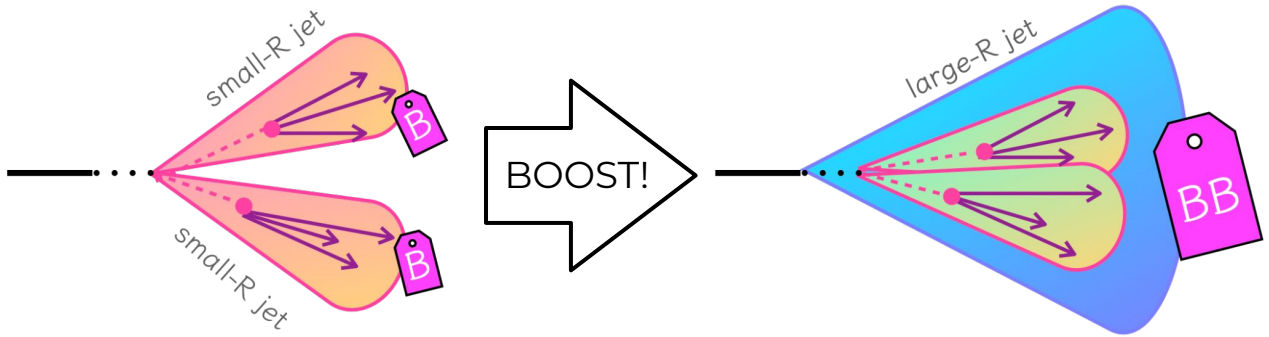
New reconstruction techniques

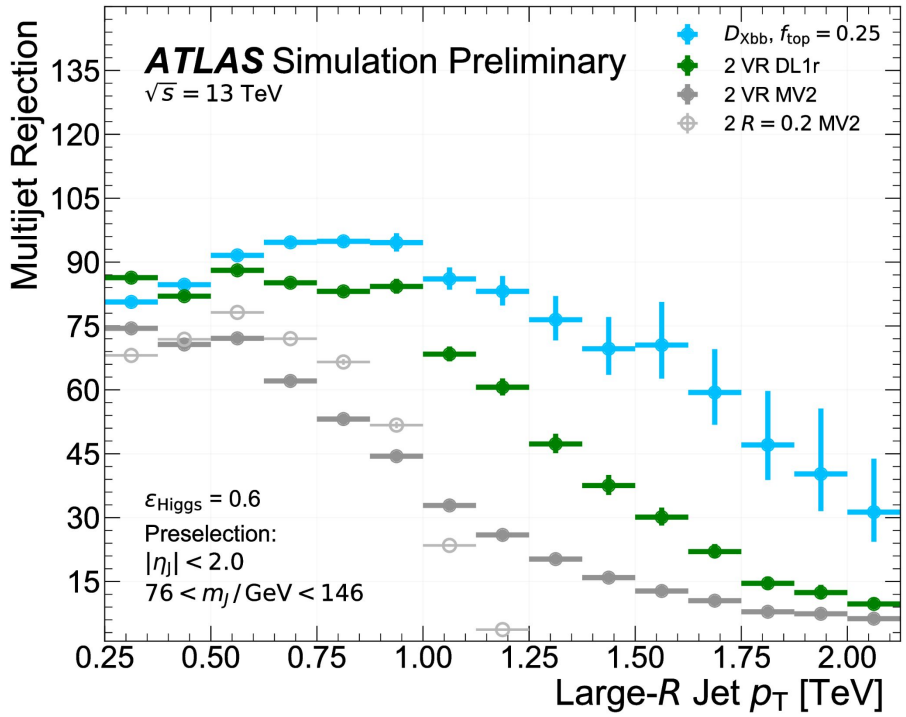
ATL-PHYS-PUB-2020-019
ATL-PHYS-PUB-2021-035



Non-SM κ_{2V} values are characterised by harder m_{HH} spectra. We can exploit boosted signatures.

Develop new techniques to improve our H→bb signal identification in this boosted regime.





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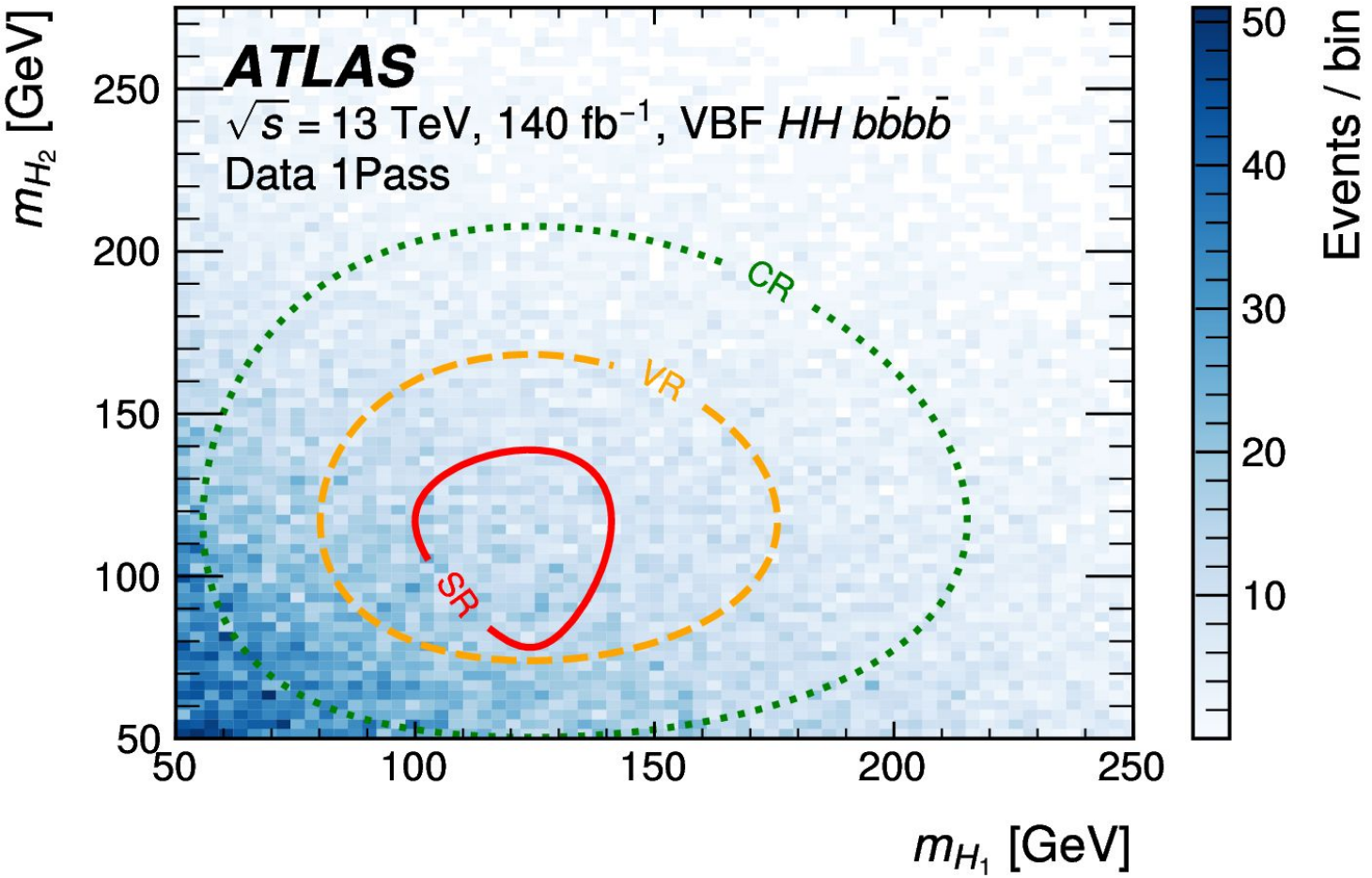
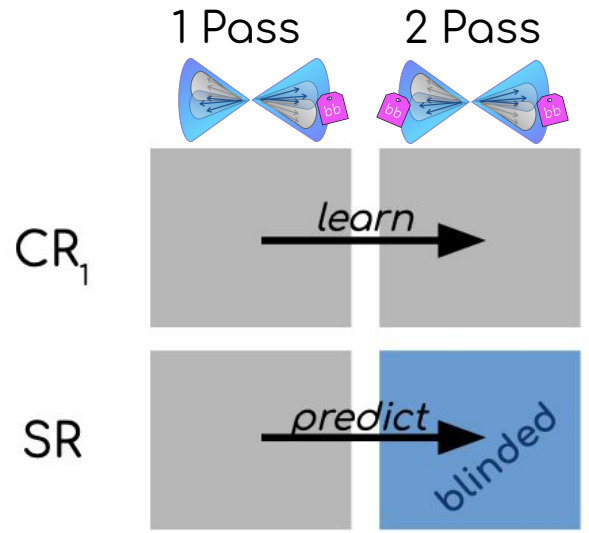
boosted VBF bbbb

Submitted to Phys. Lett. B

Select 2 Xbb-tagged jets and two additional VBF jets.



Define SR/CR/VR in the mass plane of the two Higgs candidates.



data-driven bkg estimation

- Use the CR to extract a 1Pass-to-2Pass **normalisation**. Apply this to SR-1Pass, to predict background in SR-2Pass.
- Validation region is used to obtain a systematic uncertainty.

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boosted VBF bbbb

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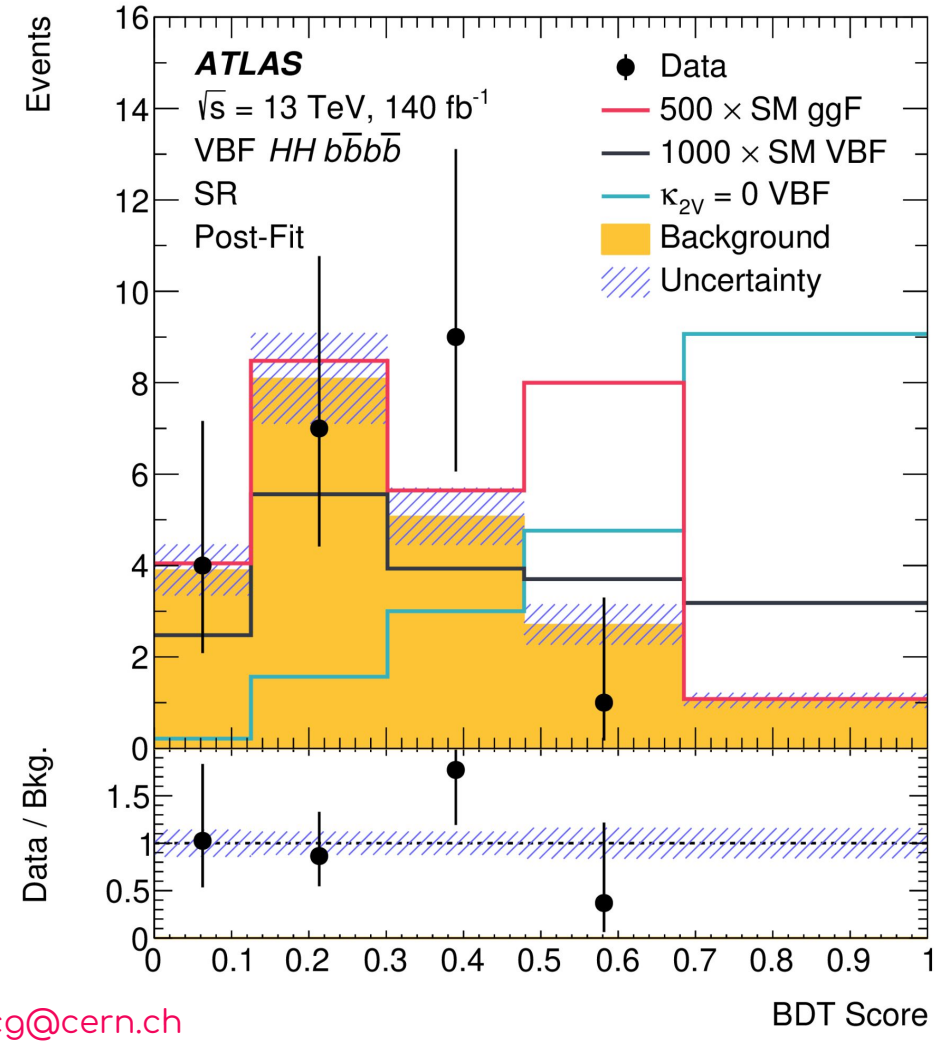
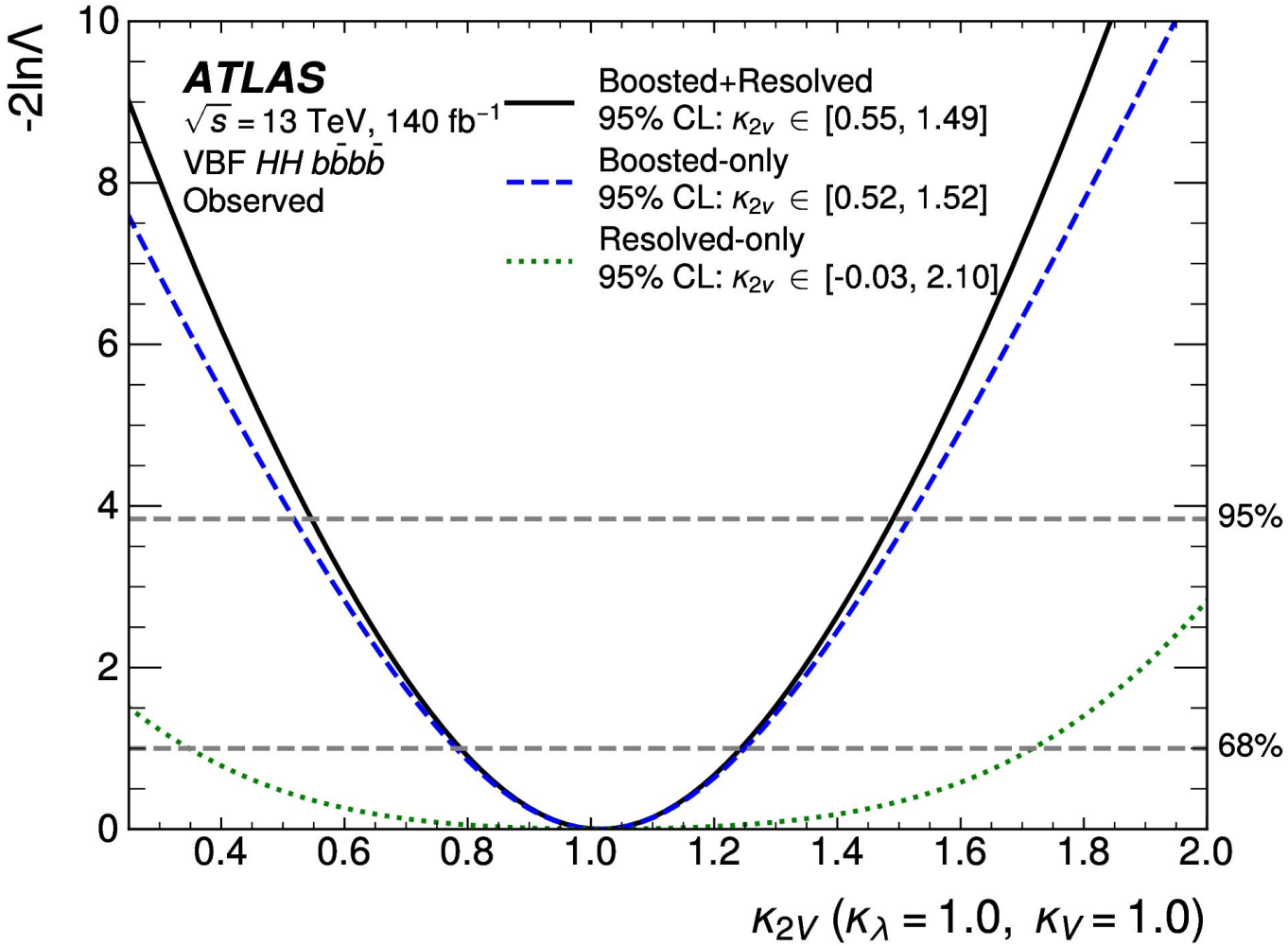
Employ a BDT to further enhance signal-to-background discrimination.



This channel dominates our sensitivity to κ_{2V}



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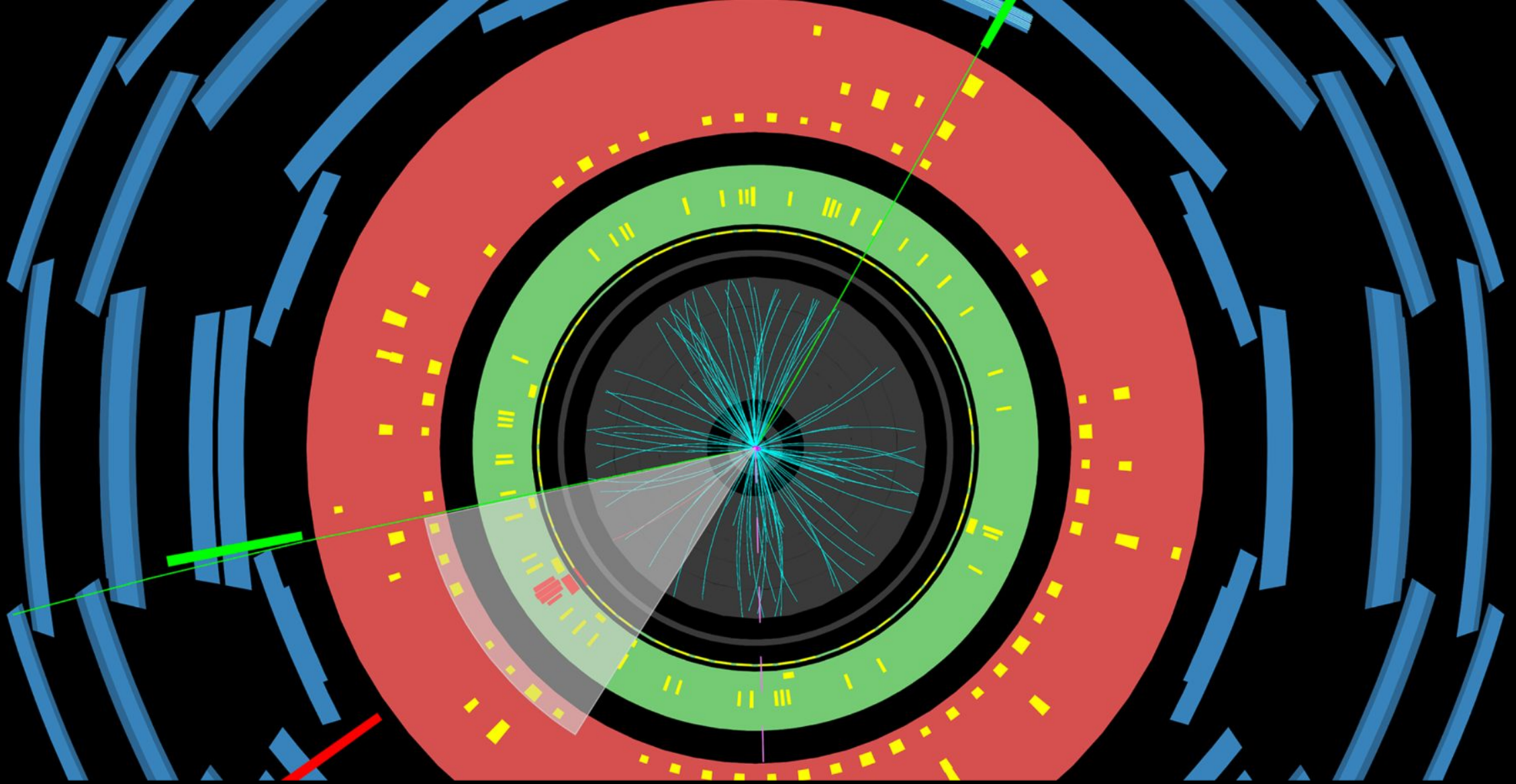


multi-leptons (3ℓ)

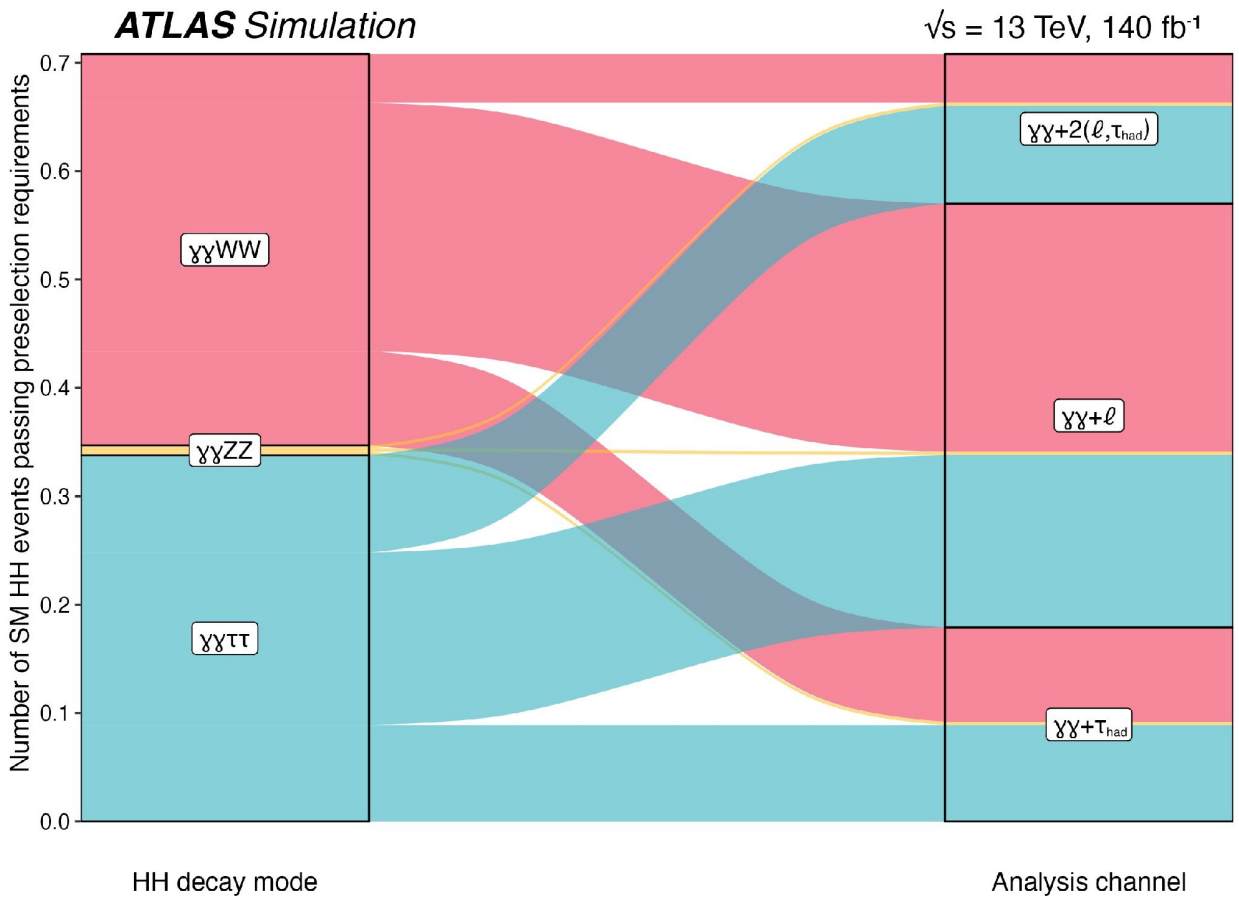
Candidate HH→multilepton event: two muons (green lines), one electron (red line), one jet (grey cone) and missing transverse energy (dashed magenta line).

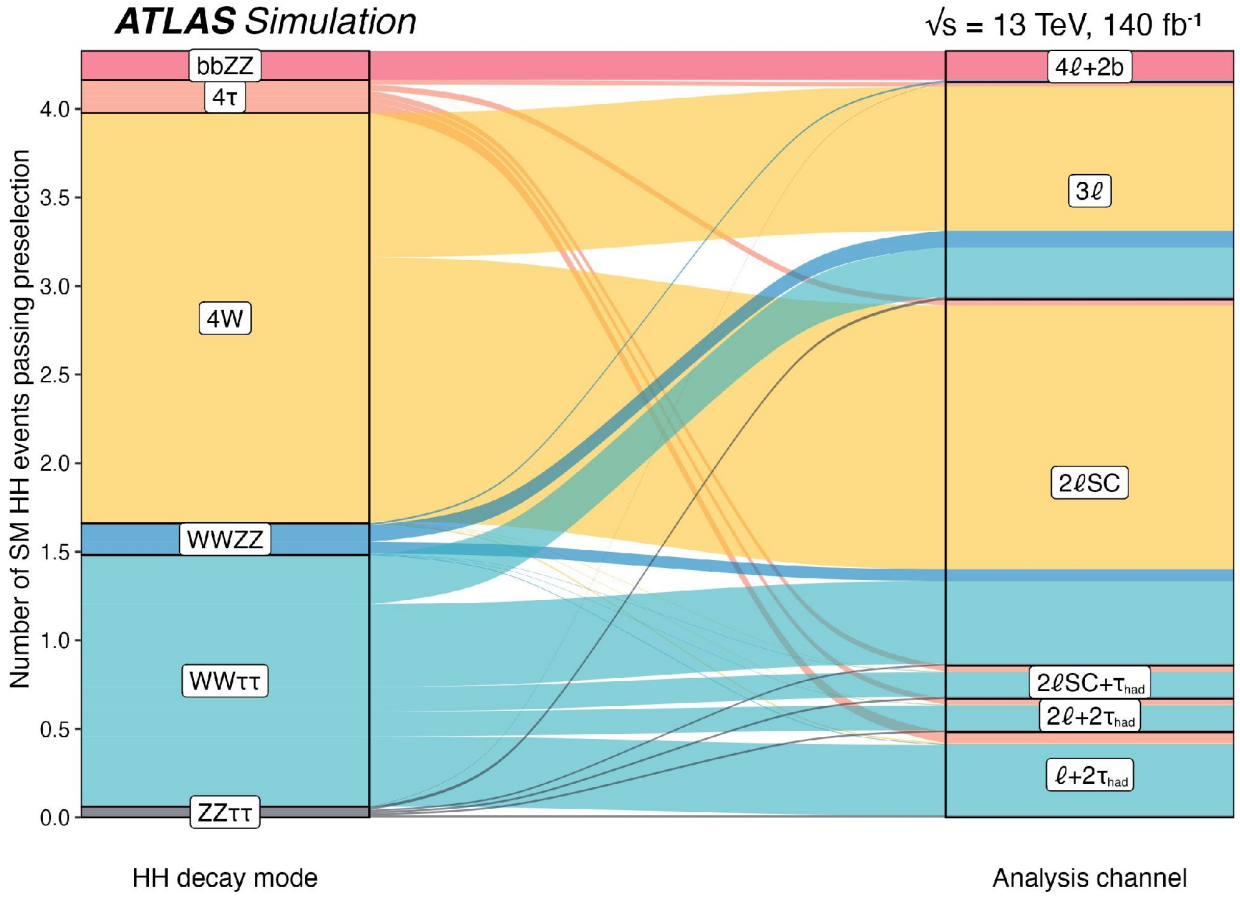
Check out the briefing!

More decay channels

Submitted to JHEP

Include many HH decay modes: multiple selections based on number of leptons (e, μ, τ) and photons.

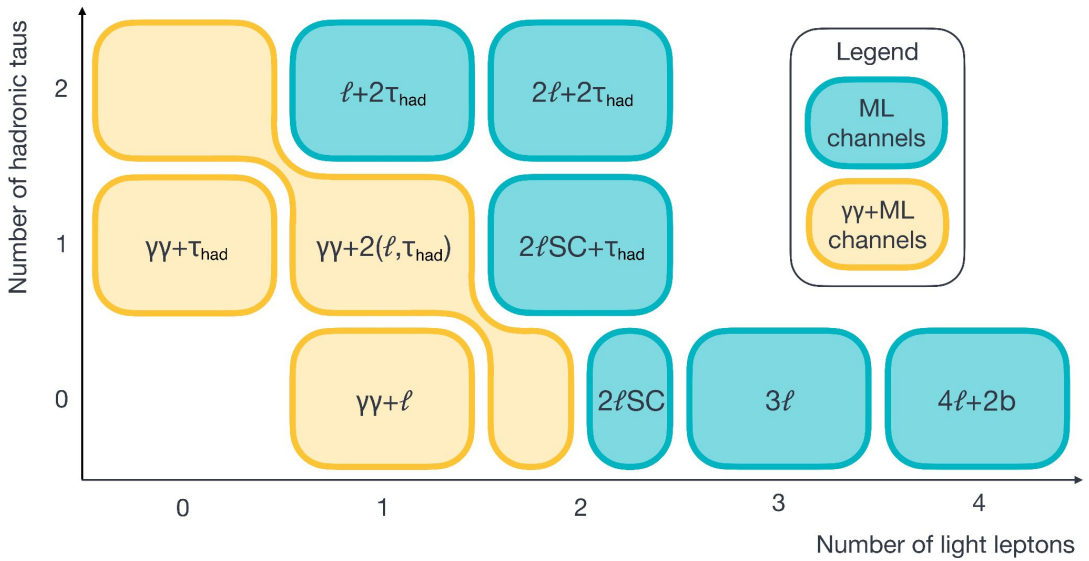




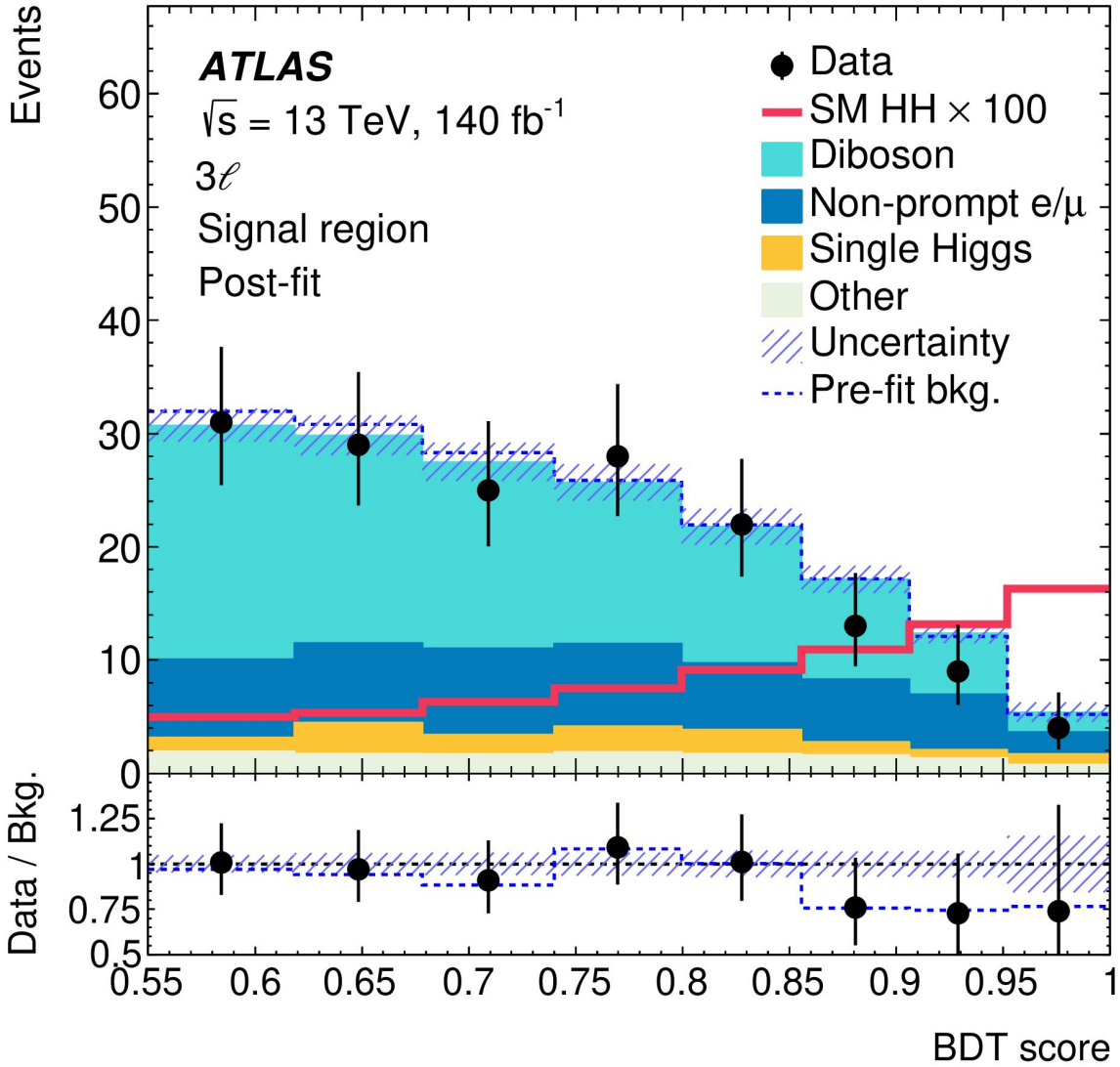
multi-lepton

Submitted to JHEP

Define different signal extraction strategies for each channel.



ML channels
use a BDT score for the final discriminant.
Control regions are define to normalised the prompt lepton backgrounds.



multi-lepton

Submitted to JHEP

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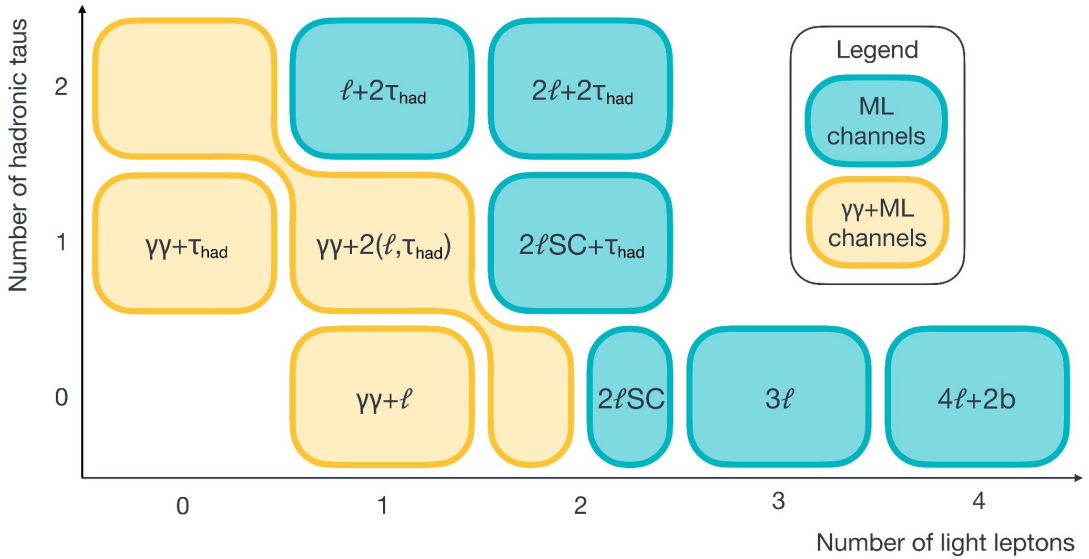
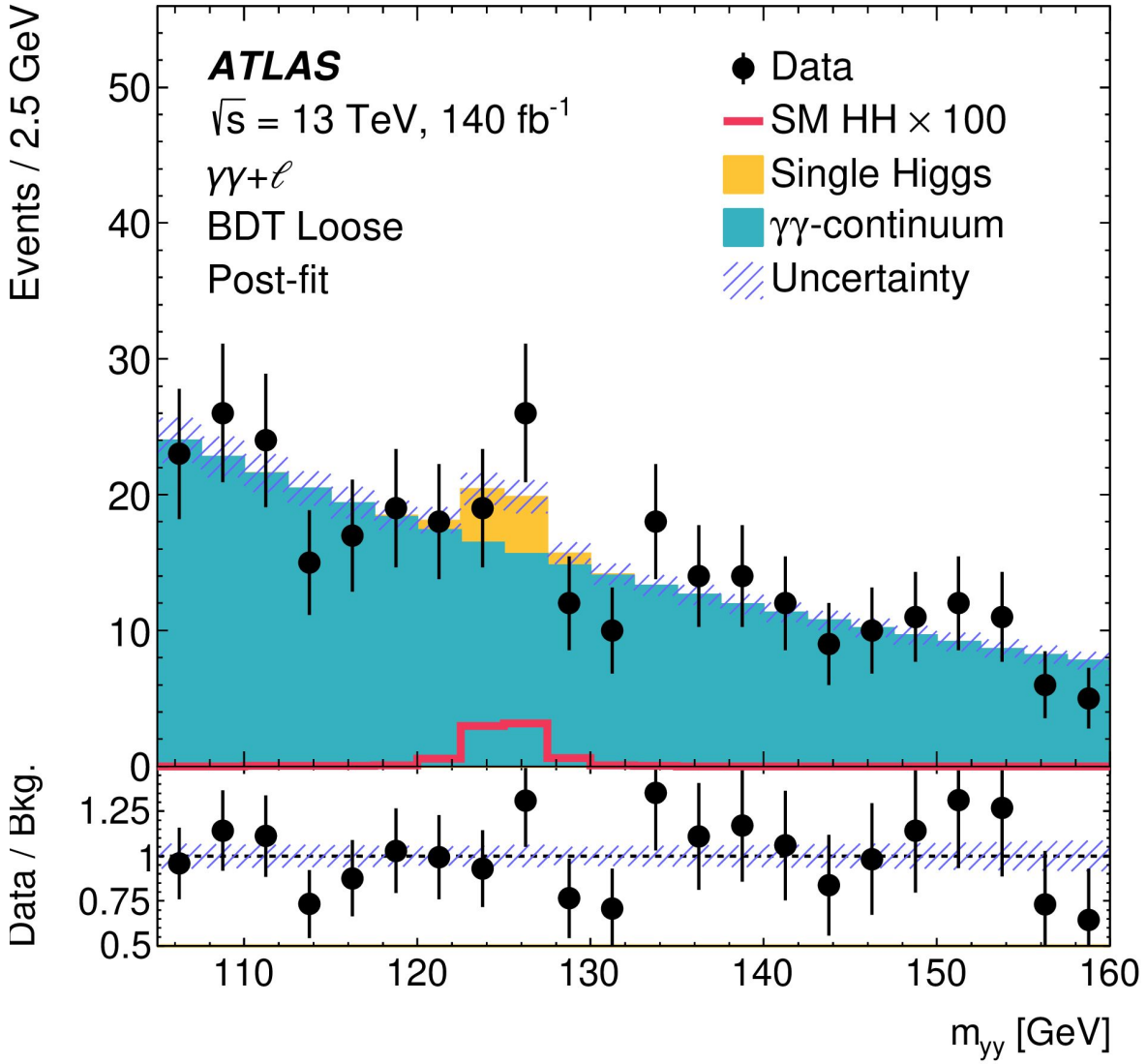


γγ+ML channels

BDT to define categories and $m_{\gamma\gamma}$ distributions used as final discriminant. Sidebands use to determine the functional form of the non-resonant γγ production.



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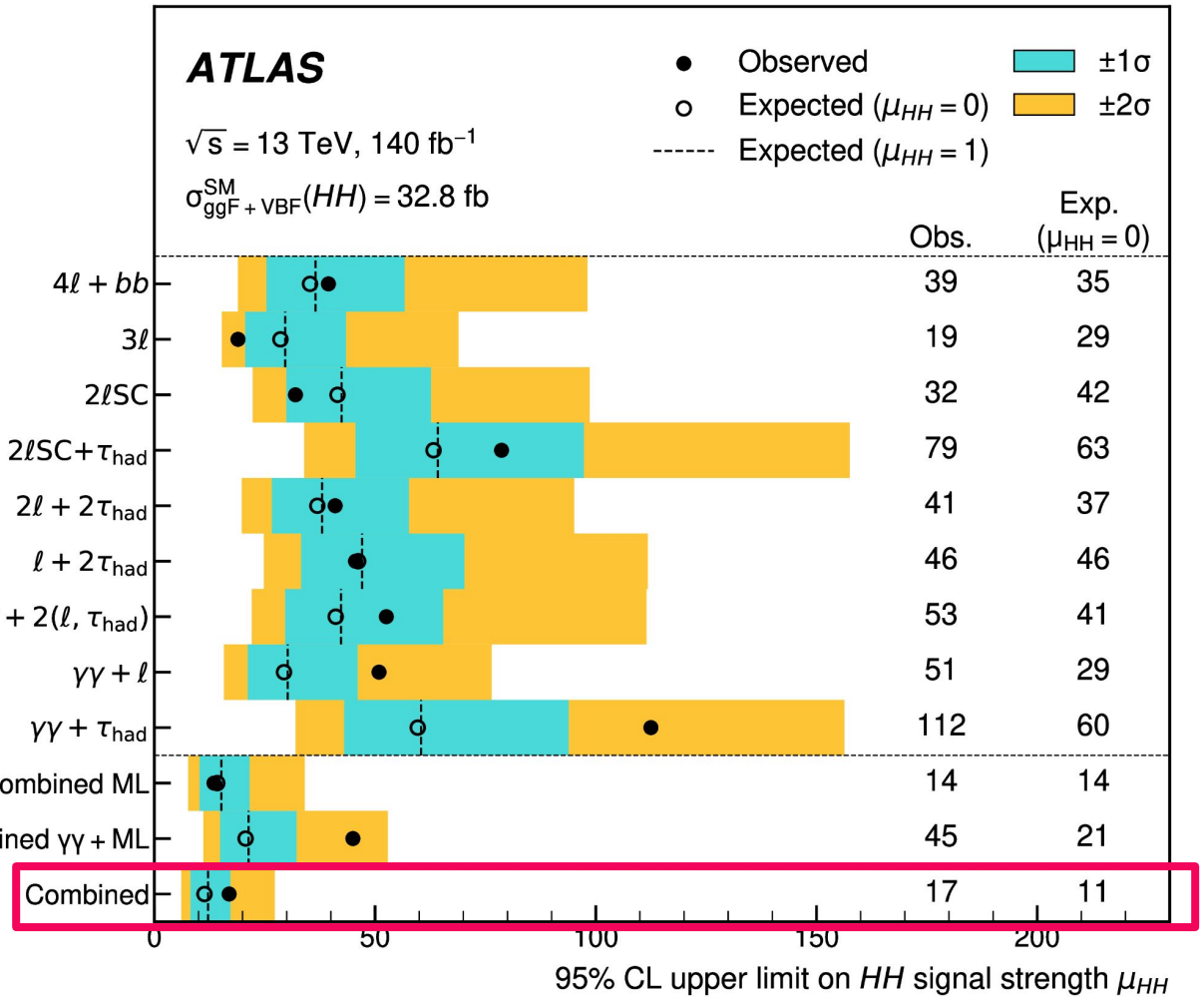
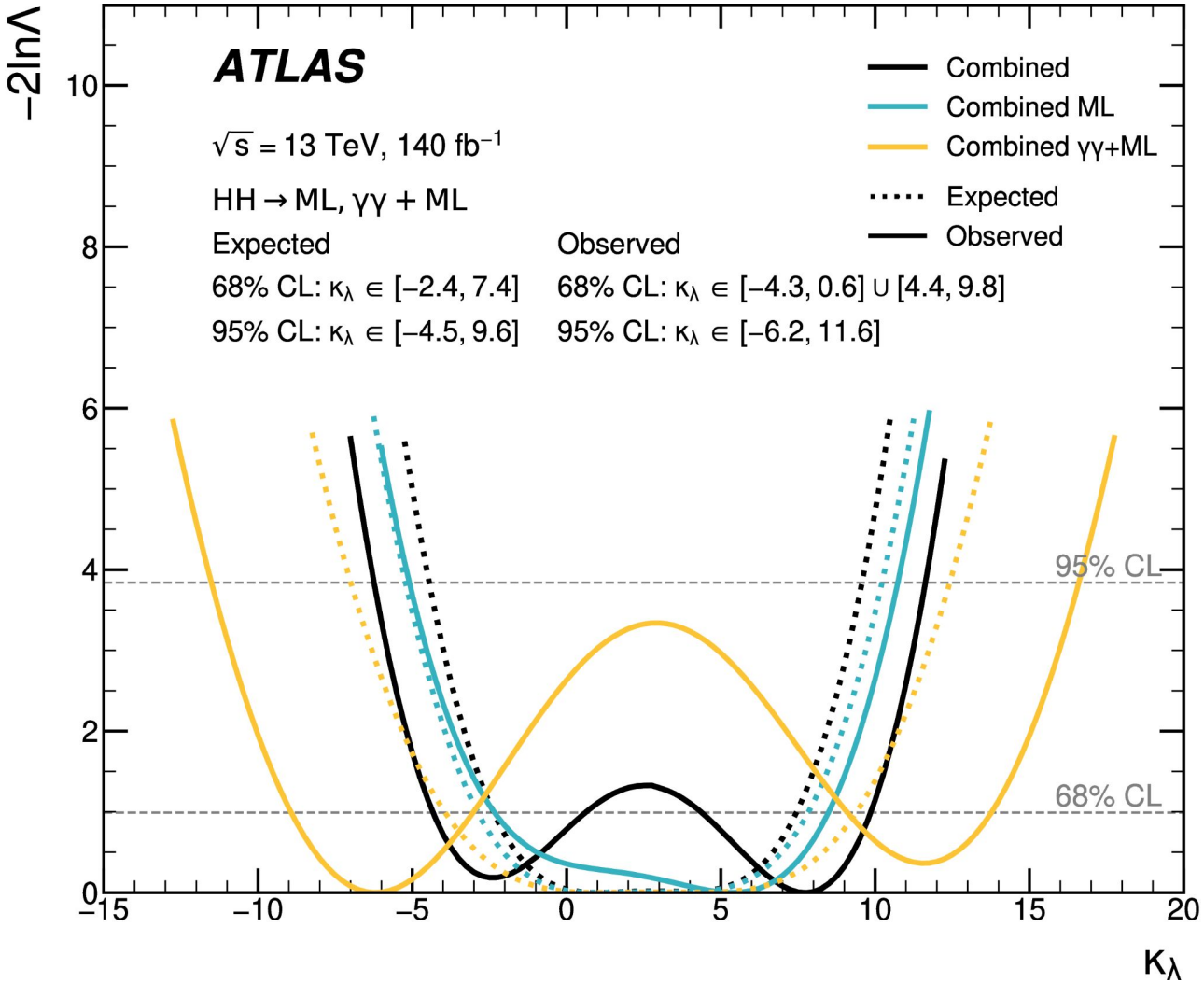
multi-lepton

Submitted to JHEP

Strength in numbers!





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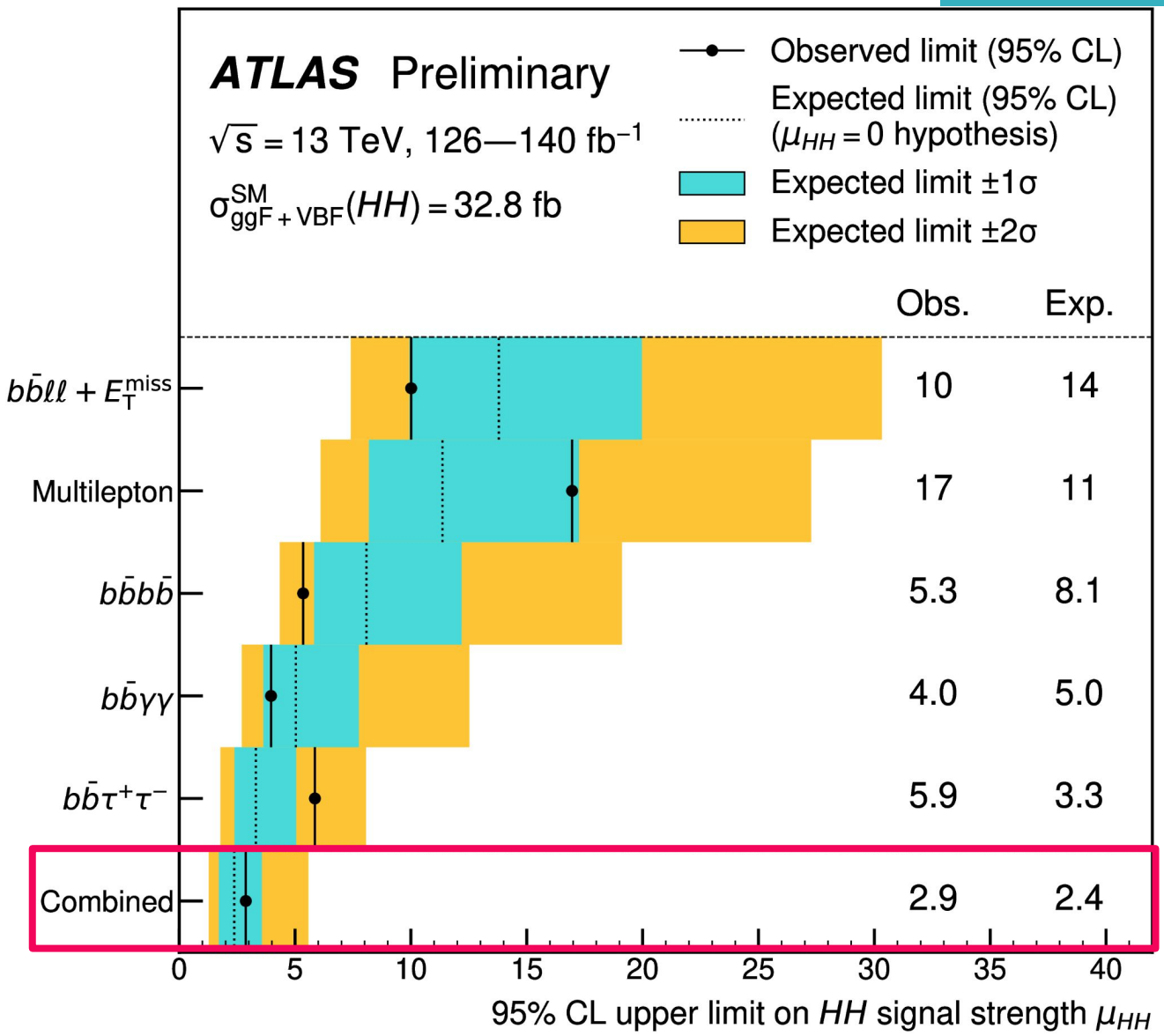
NEW Combination

ATLAS EXPERIMENT

ATLAS-CONF-2024-006

- New ATLAS combination for searches of Higgs boson pair production!
  - Previous HH search combination only included bbbb, bbττ, bbγγ.
- Updates:
  - Improved results for bbττ, bbγγ,
  - New *boosted* VBF bbbb,
  - New decay modes: multi-leptons and bbℓℓ+MET.
- Best expected sensitivity to date on HH cross section:
  - $\mu_{HH} < 2.9$ (2.4 exp.)
  - $\mu_{HH} < 2.9$ (44.3) for ggF (VBF) production
  - $\sigma_{HH} < 85.8$ (71.1 exp) fb
- Dominant uncertainty: HH theory cross section uncertainty.



NEW Combination

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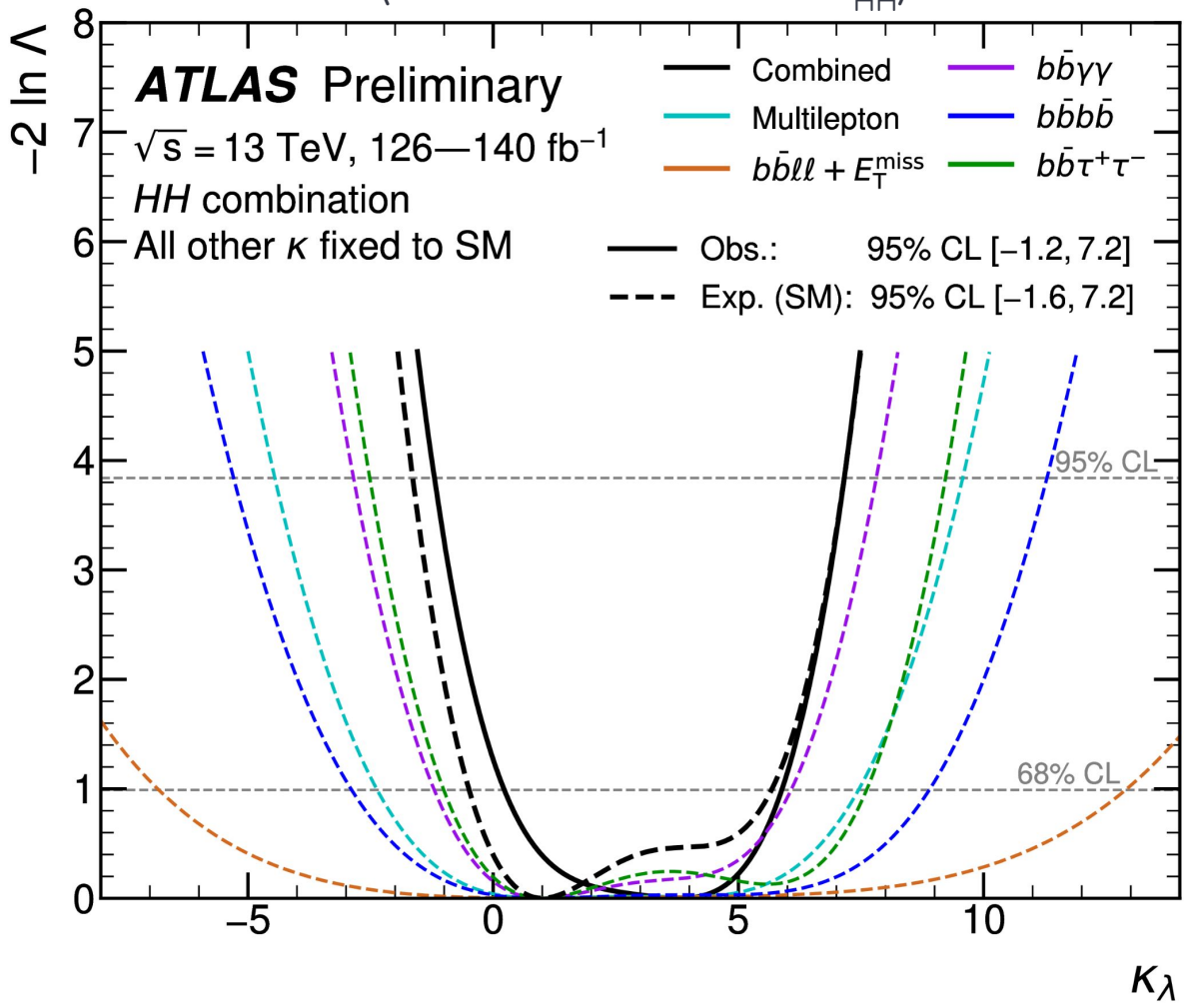
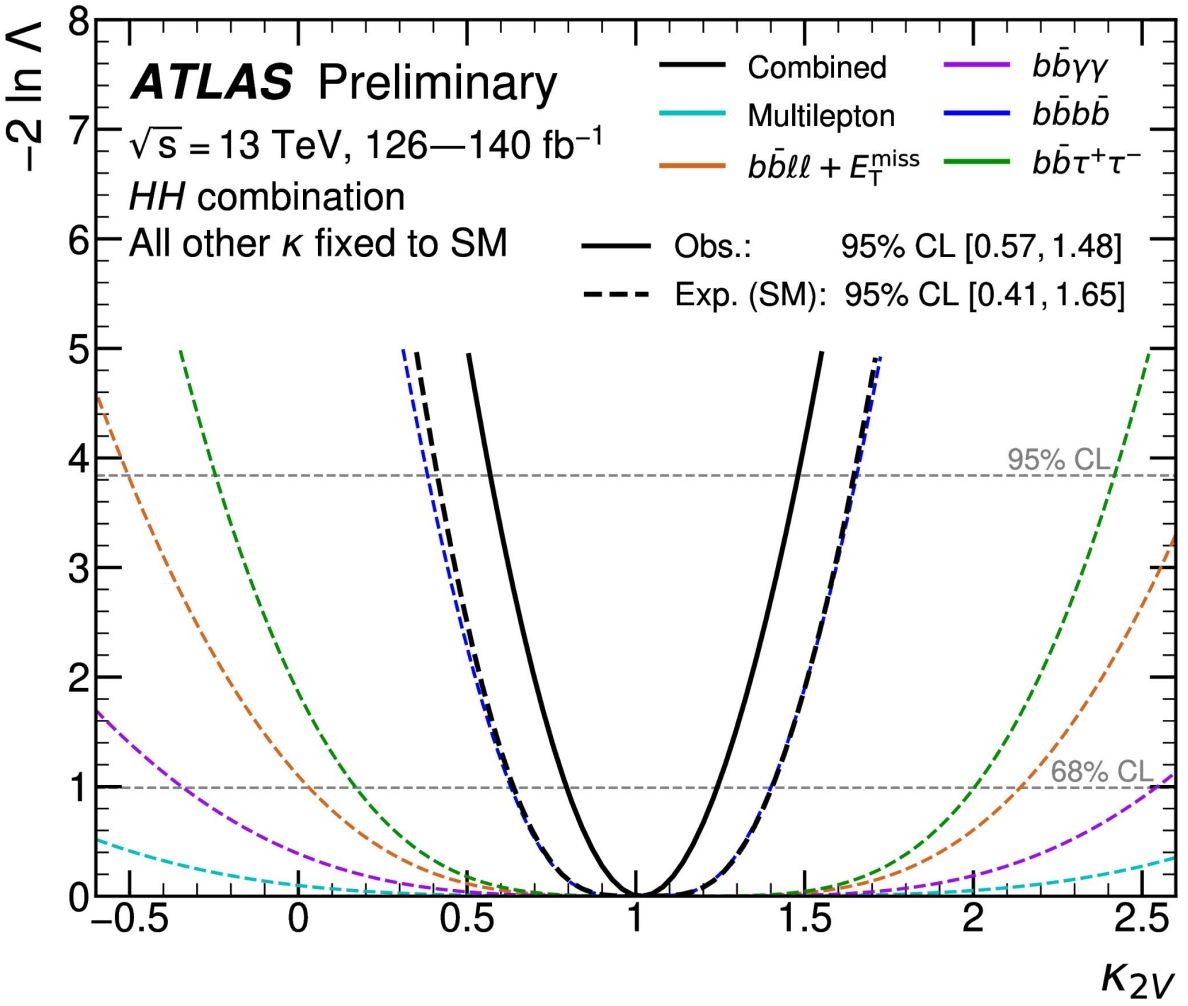
ATLAS-CONF-2024-006

Leading sensitivity by bbττ, bbγγ (better access to low m_{HH}).



Dominant channel: boosted VBF bbbb



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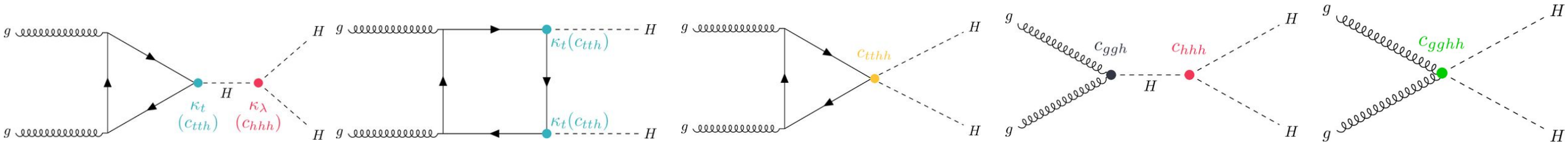
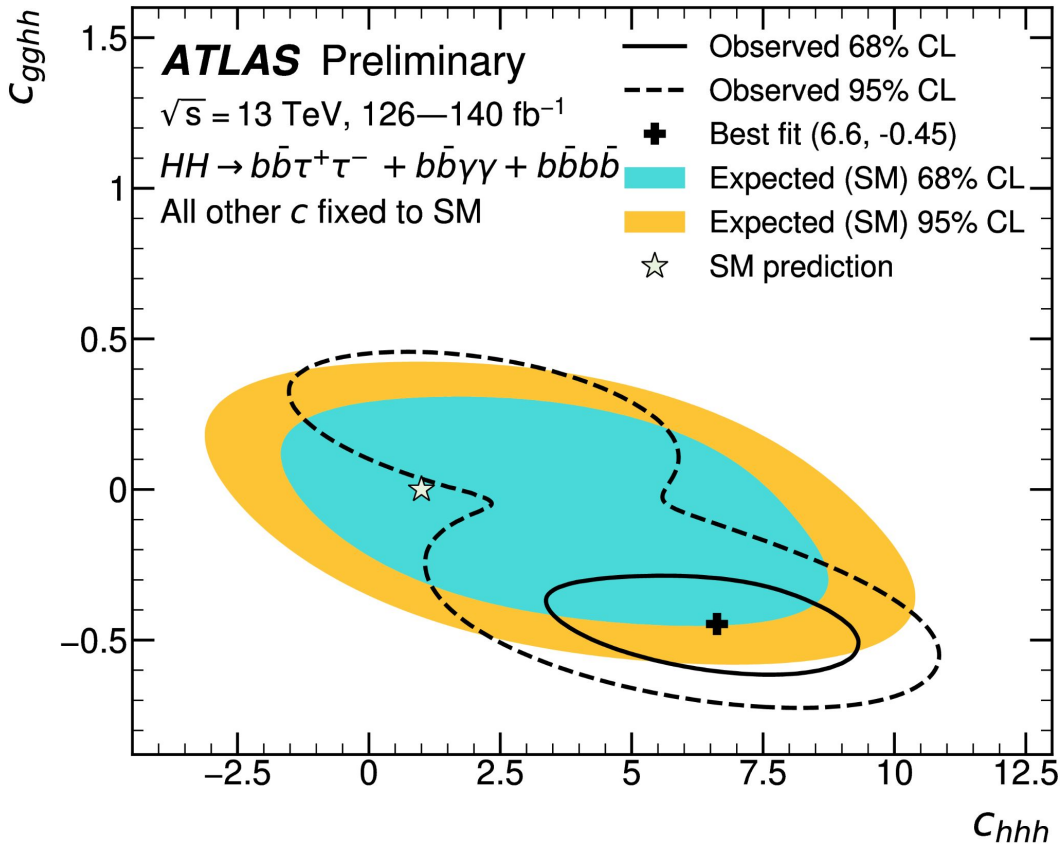
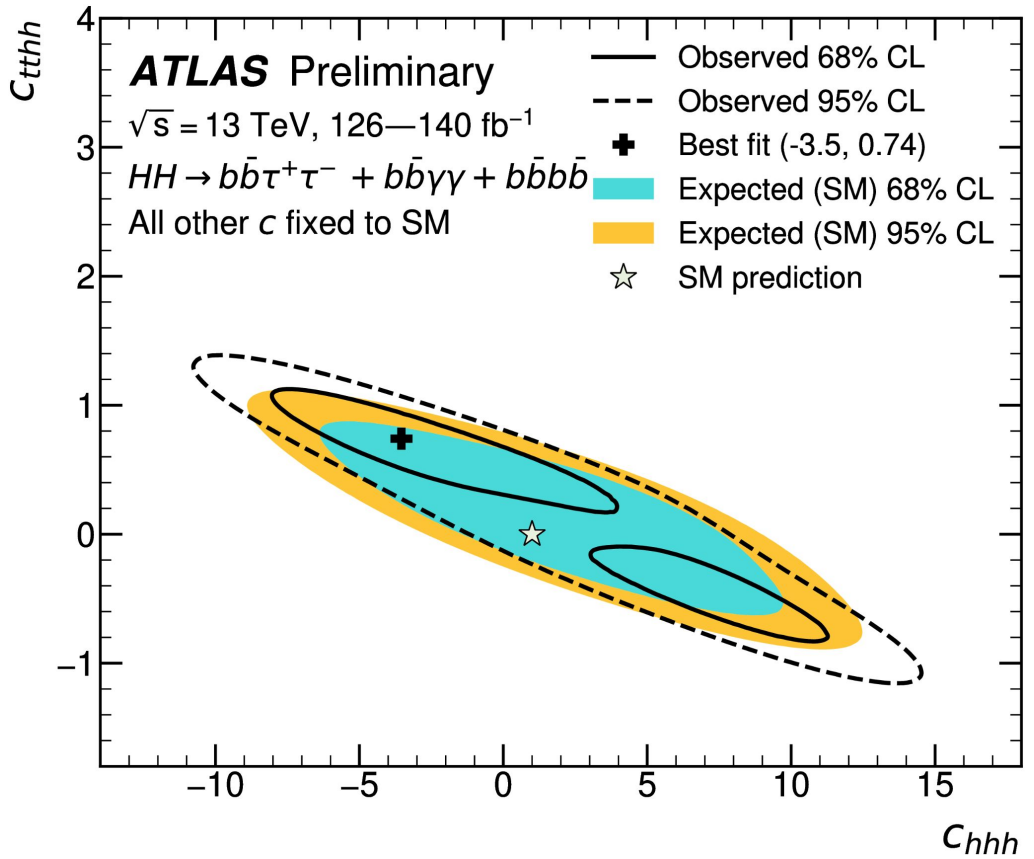
HEFT

Use an effective Lagrangian in a EFT relevant to the H boson pair production.

ATLAS-CONF-2024-006







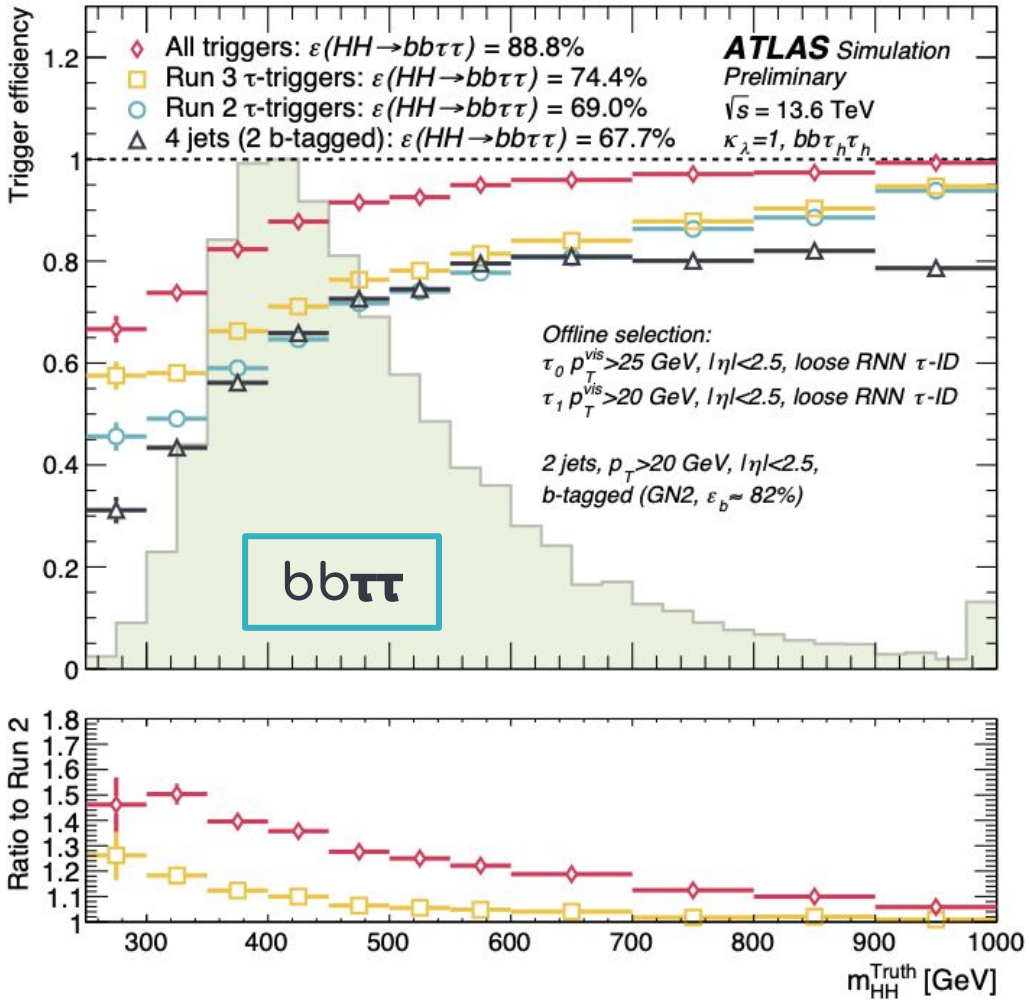
SM predicts $C_{hhh} = 1$, $C_{tth} = 1$ (equivalent to κ_λ and κ_t in this formalism)

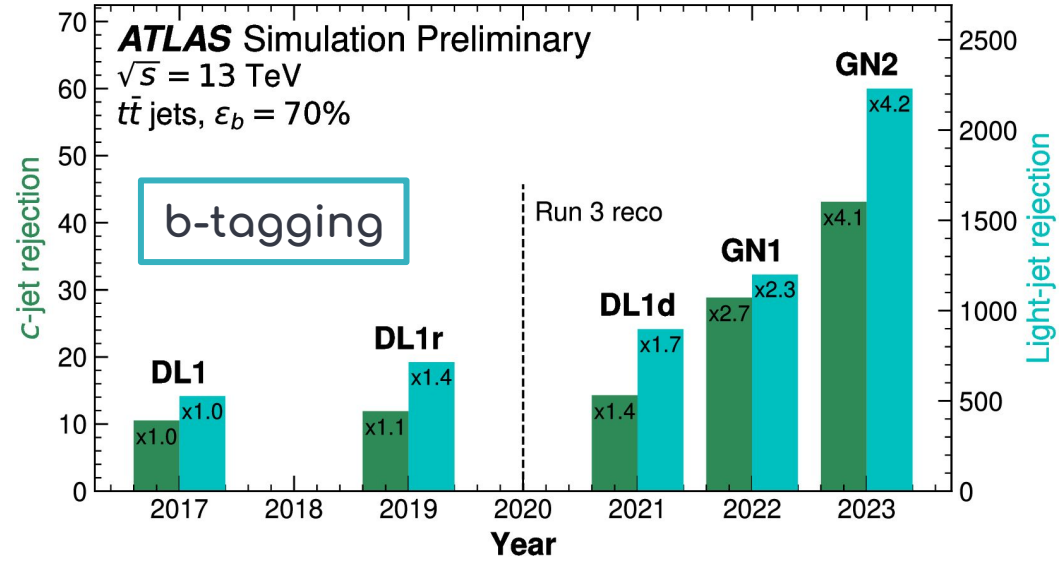
Towards the future

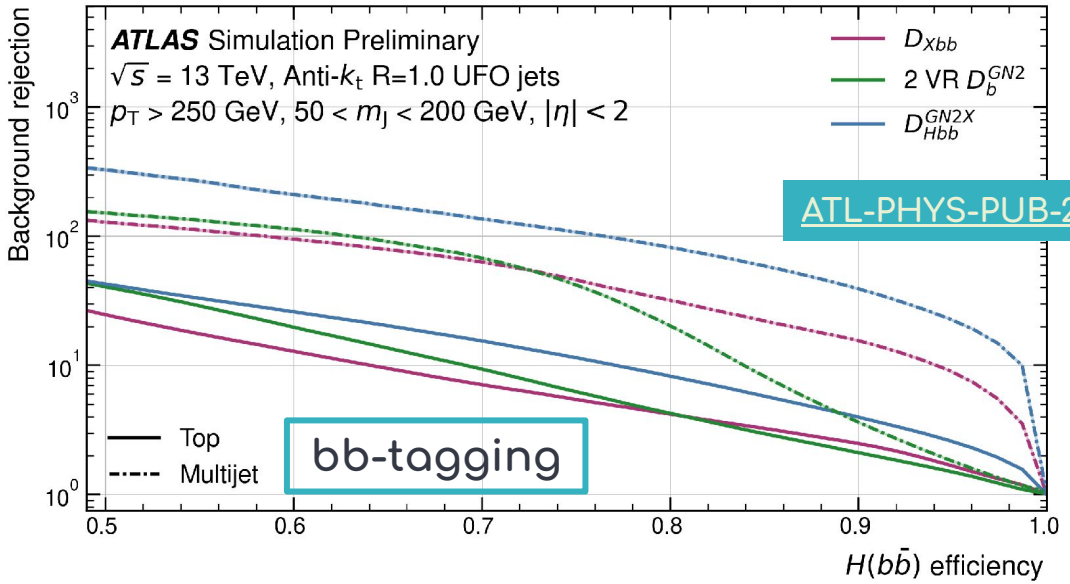
More data, better triggers, better taggers, better performance!

FTAG-2023-01

Tau Trigger Plots







ATL-PHYS-PUB-2023-021

Conclusions

- Very rich Higgs boson pair production search program in ATLAS
  - Searches for resonant HH/SH production shown by Pawel Bruckman and Shigeki Hirose.

- New combination for searches of Higgs boson pair production!
  - Previous HH search combination only included bbbb, bbττ, bbγγ.

- New results!:
  - Improved results for bbττ, bbγγ,
  - *New* boosted VBF bbbb,
  - *New* decay modes: multi-leptons and bbℓℓ+MET.

- Best expected sensitivity to date on HH cross section:
  - $\mu_{HH} < 2.9$ (2.4 exp)
  - $\sigma_{HH} < 85.8$ (71.1 exp) fb

- And most stringent expected constraints to the Higgs boson self-coupling:
  - $\mathbf{-1.2 < \kappa_\lambda < 7.2}$ ($-1.6 < \kappa_\lambda < 7.2$ exp) 95% CL

- Promising outlook for Run 3 results:
  - New triggers,
  - improved b(b)-taggers,
  - better object identification,
  - analysis techniques.

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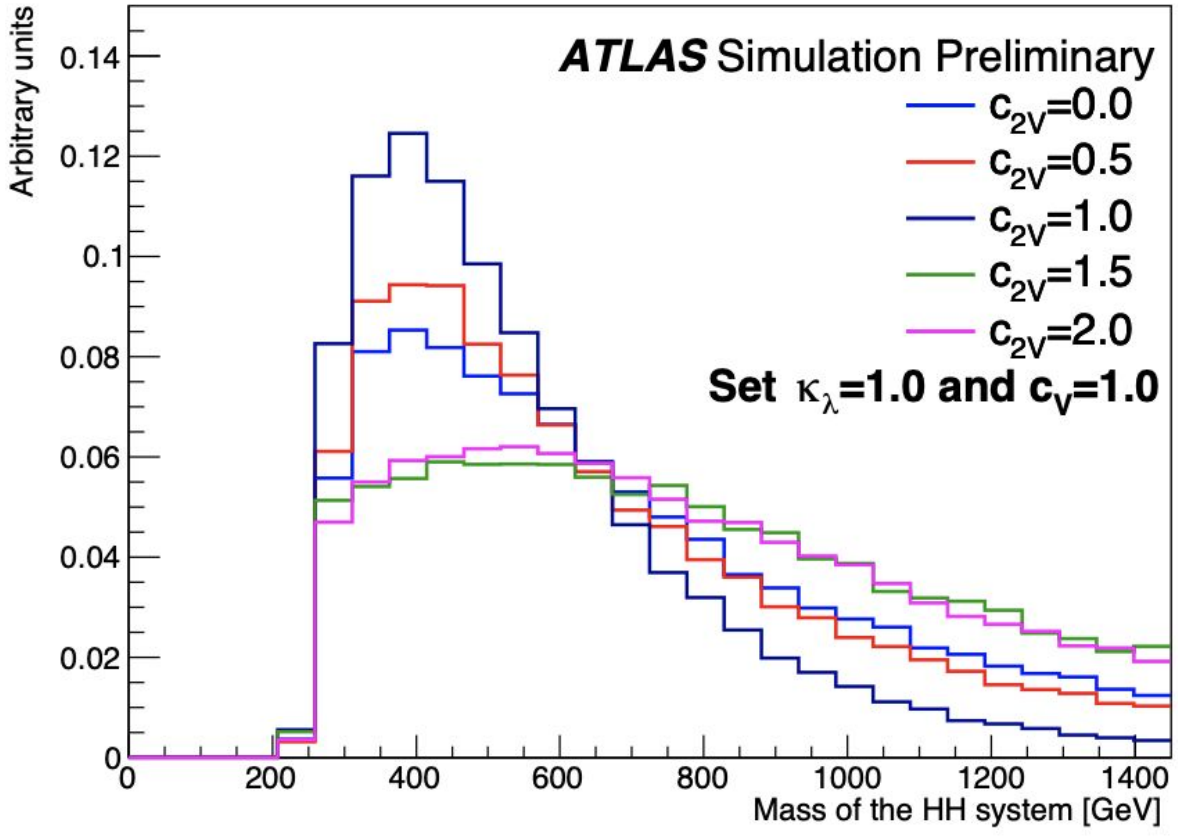
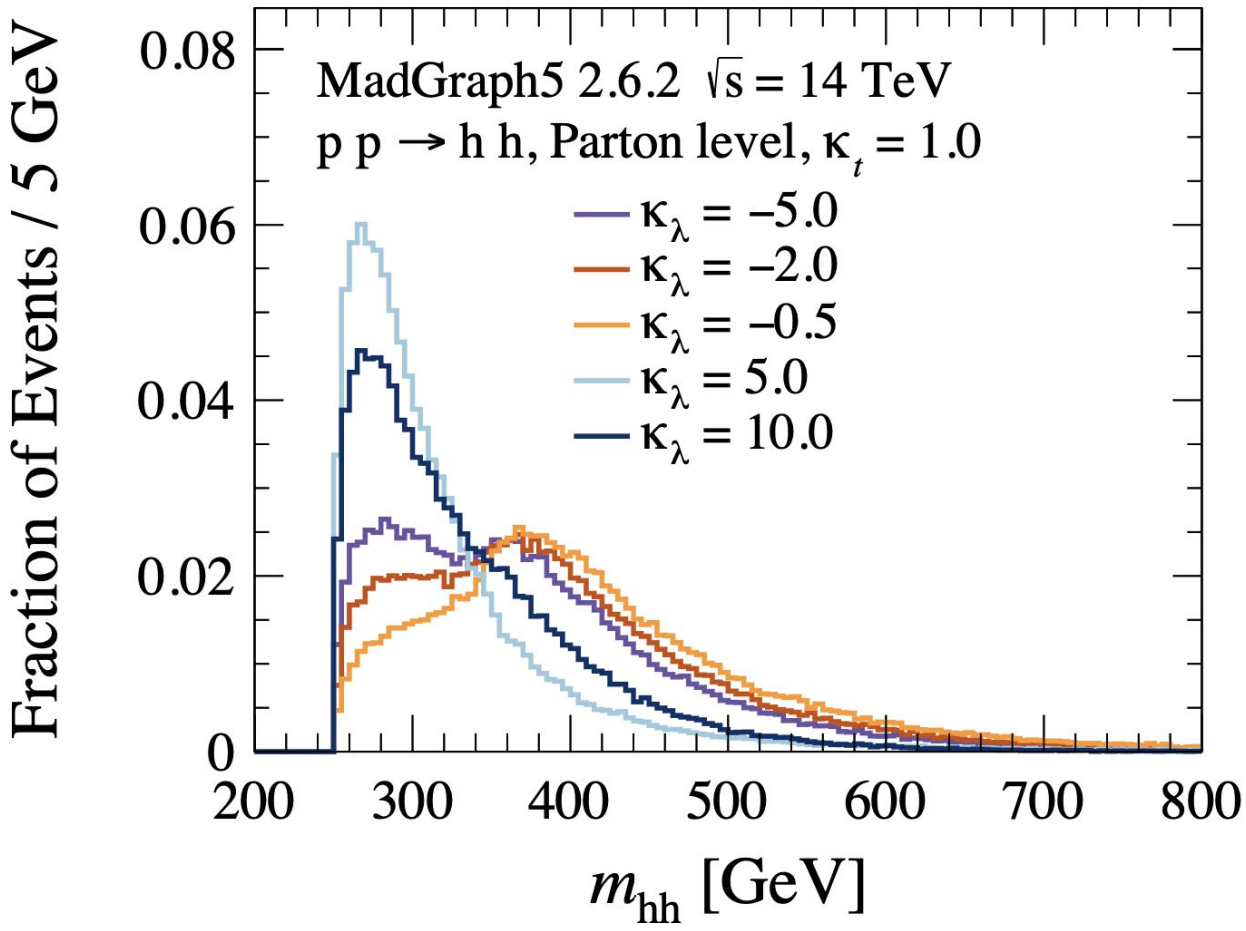
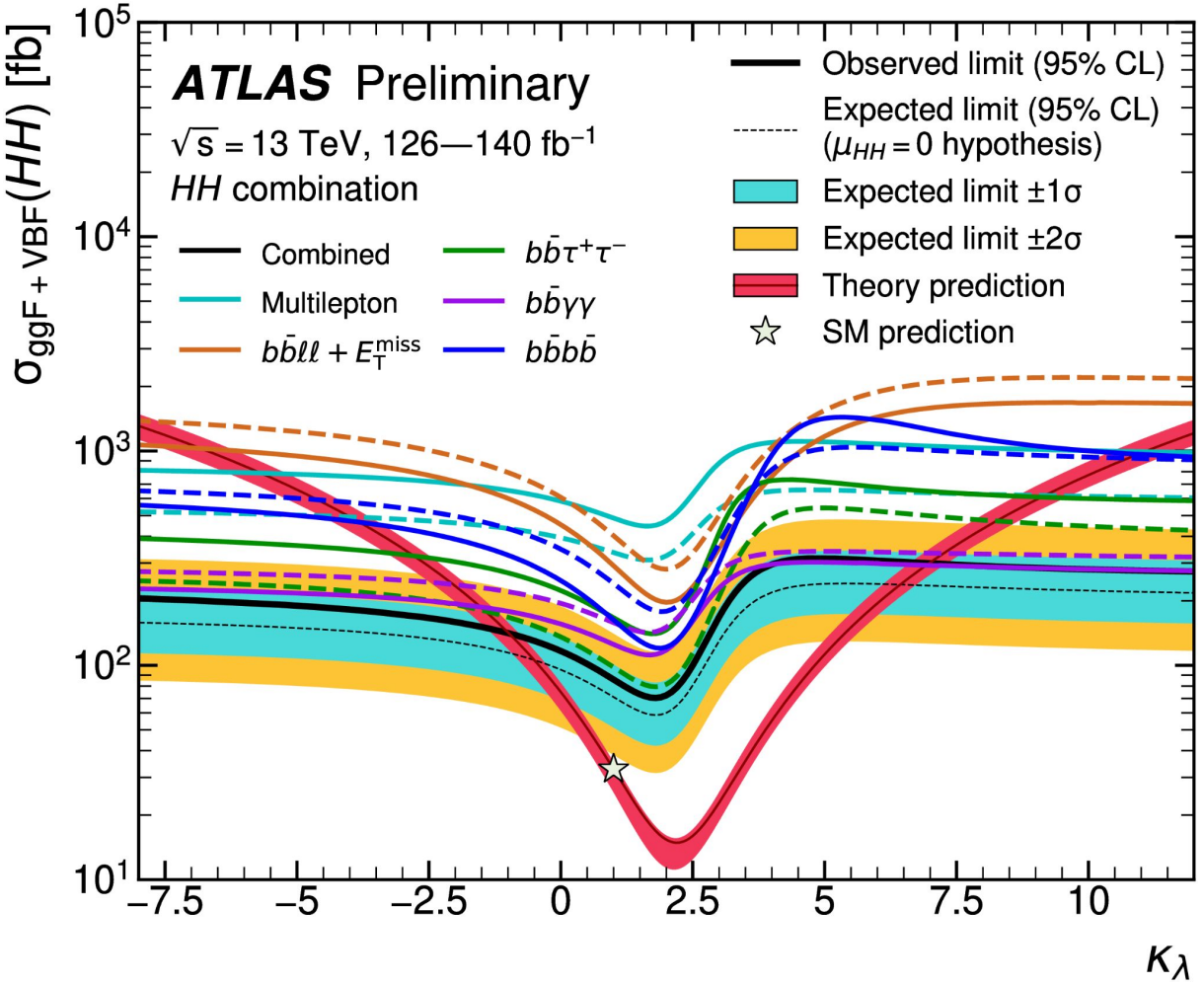
Thank you!

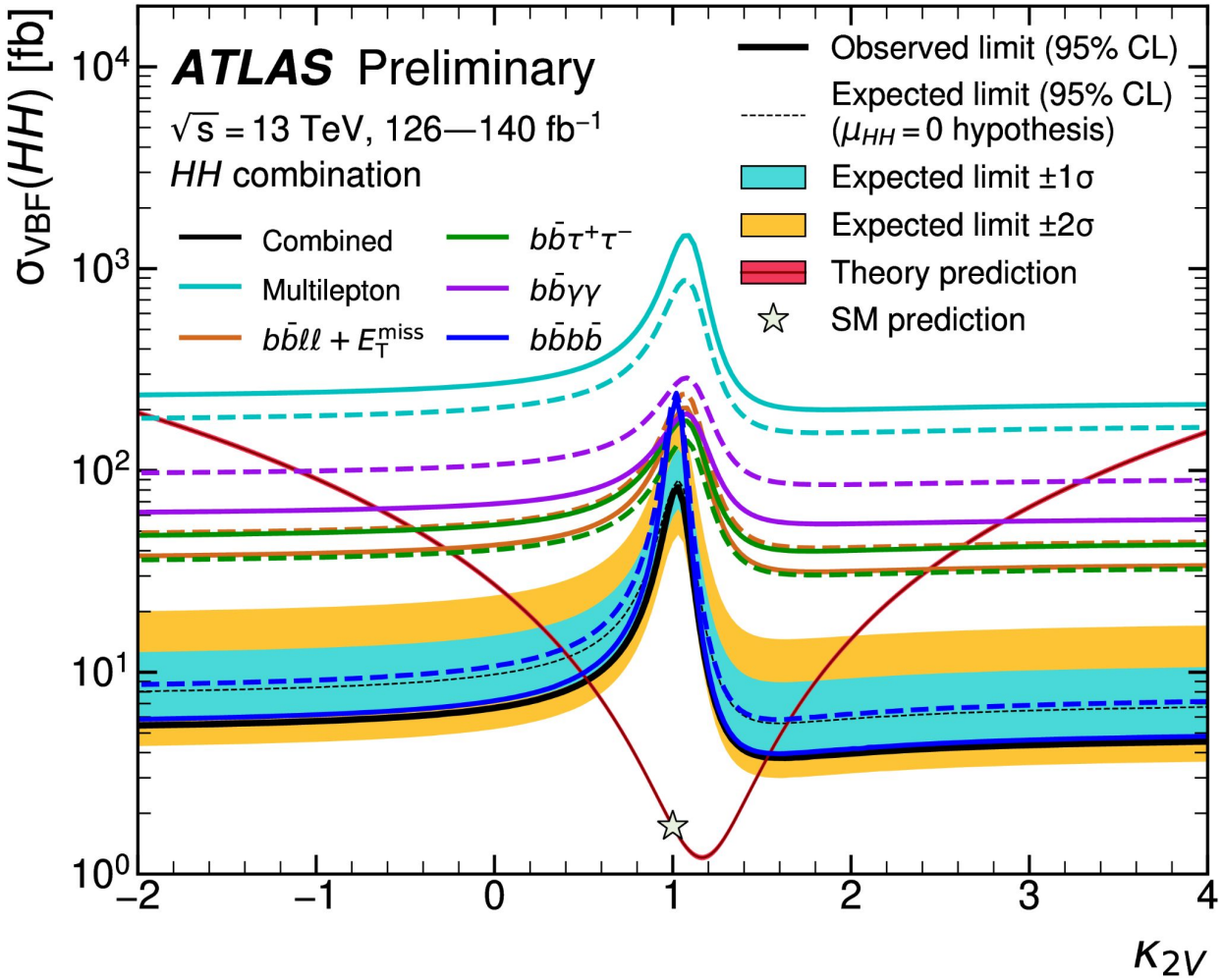
Higgs boson pair production





NEW Combination



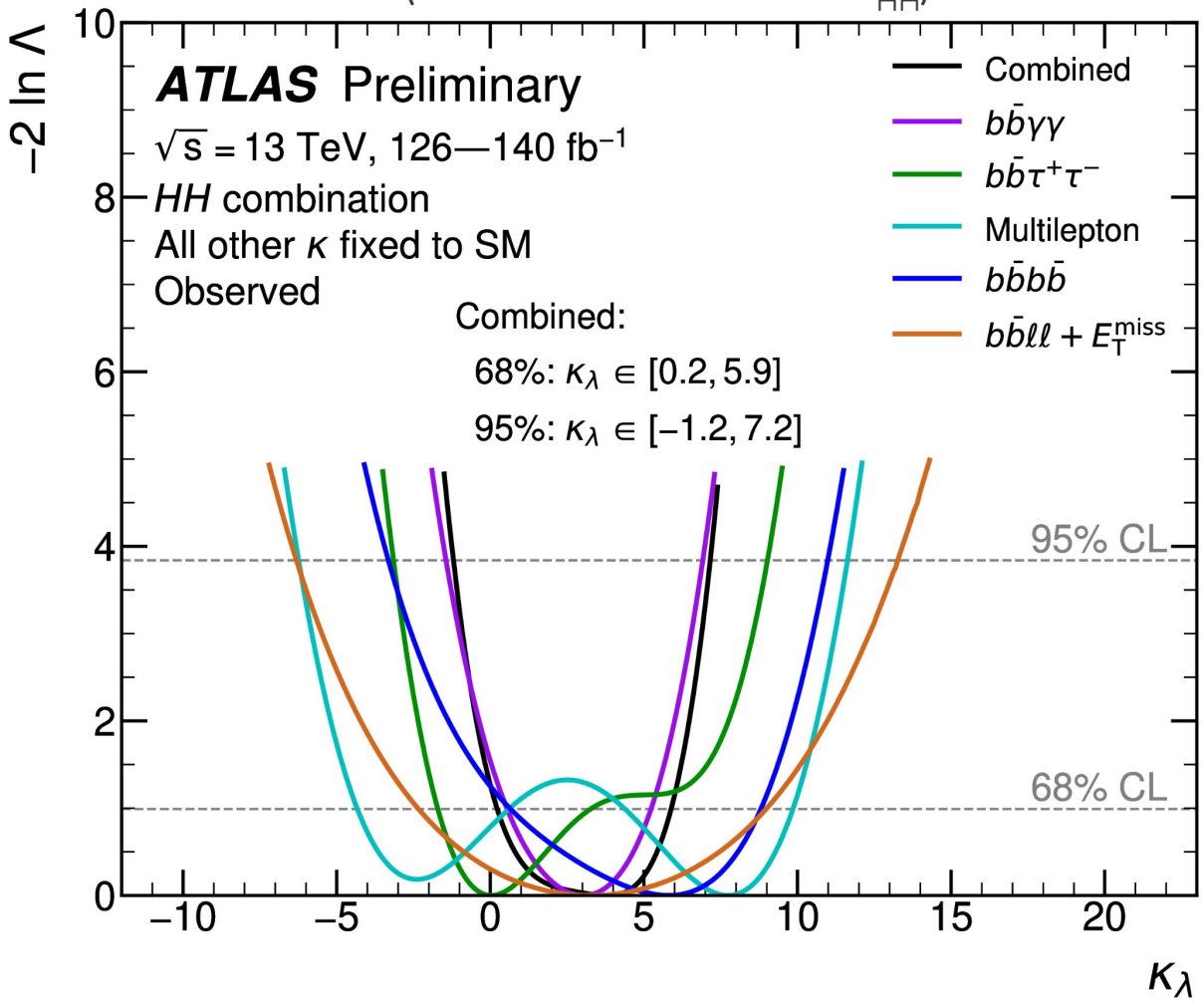


NEW Combination

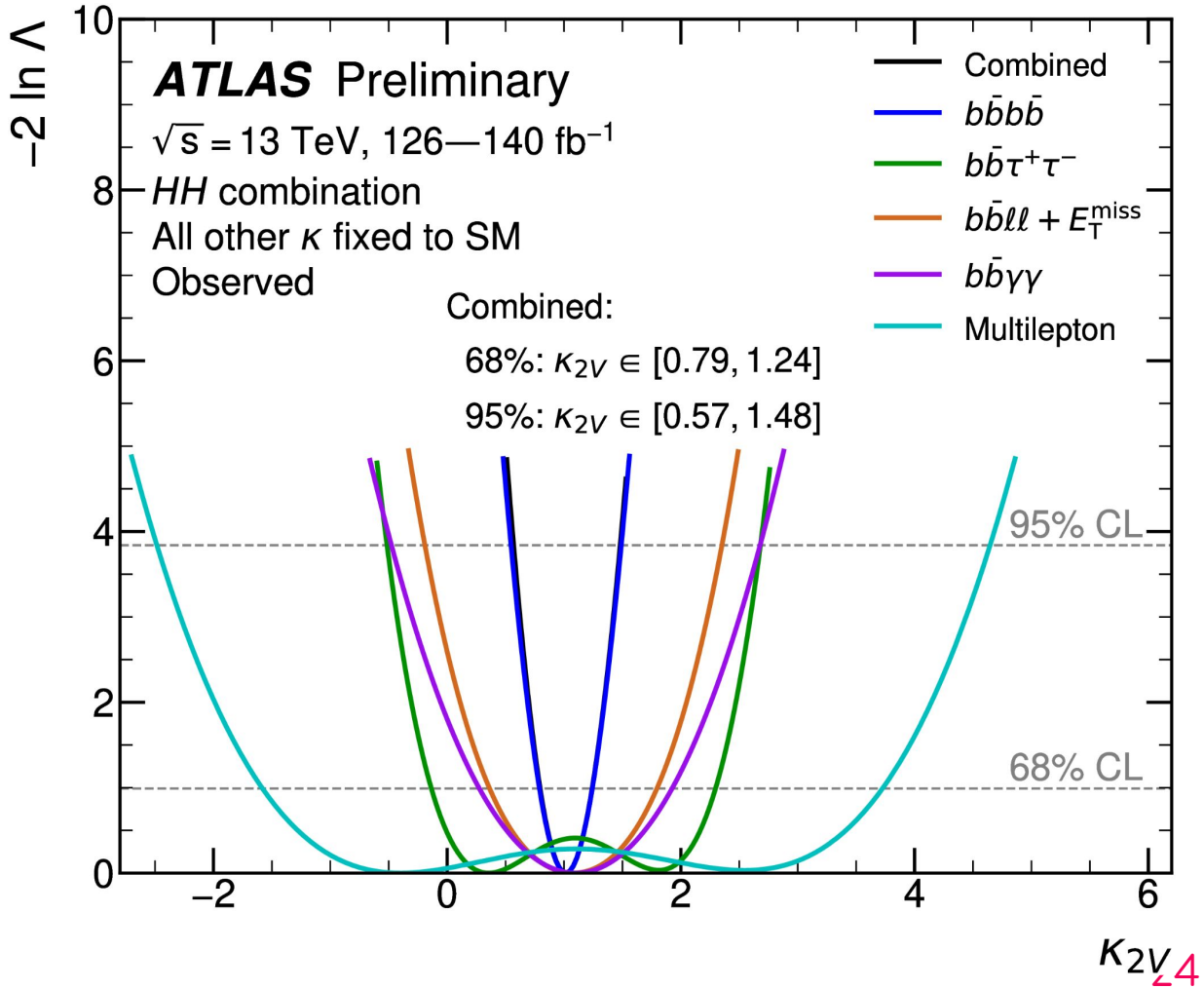
ATLAS EXPERIMENT

ATLAS-CONF-2024-006

Leading sensitivity by bbττ, bbγγ
(better access to low m_{HH}).



Dominant channel: boosted VBF bbbb



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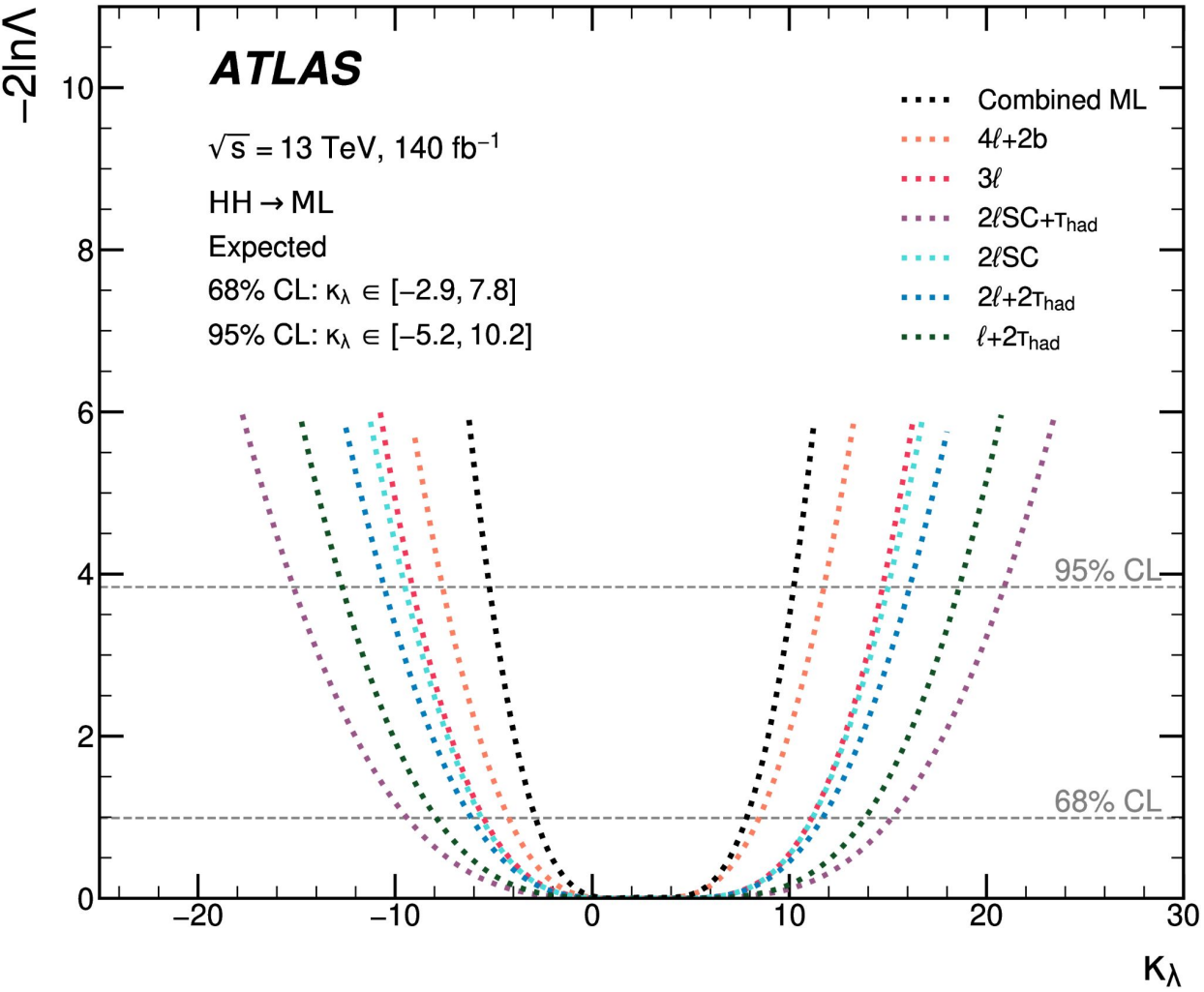
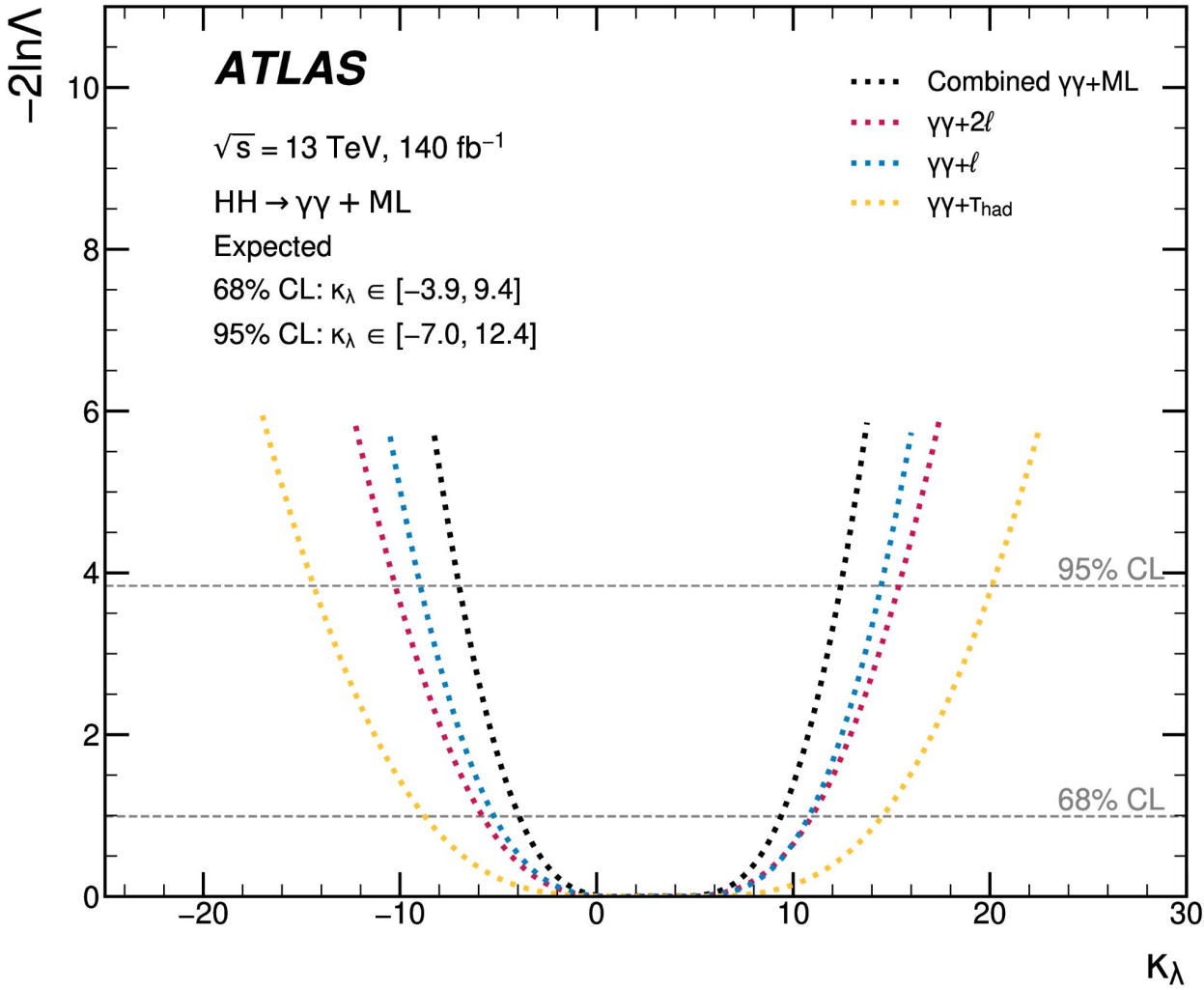
multi-lepton

Submitted to JHEP





multi-lepton

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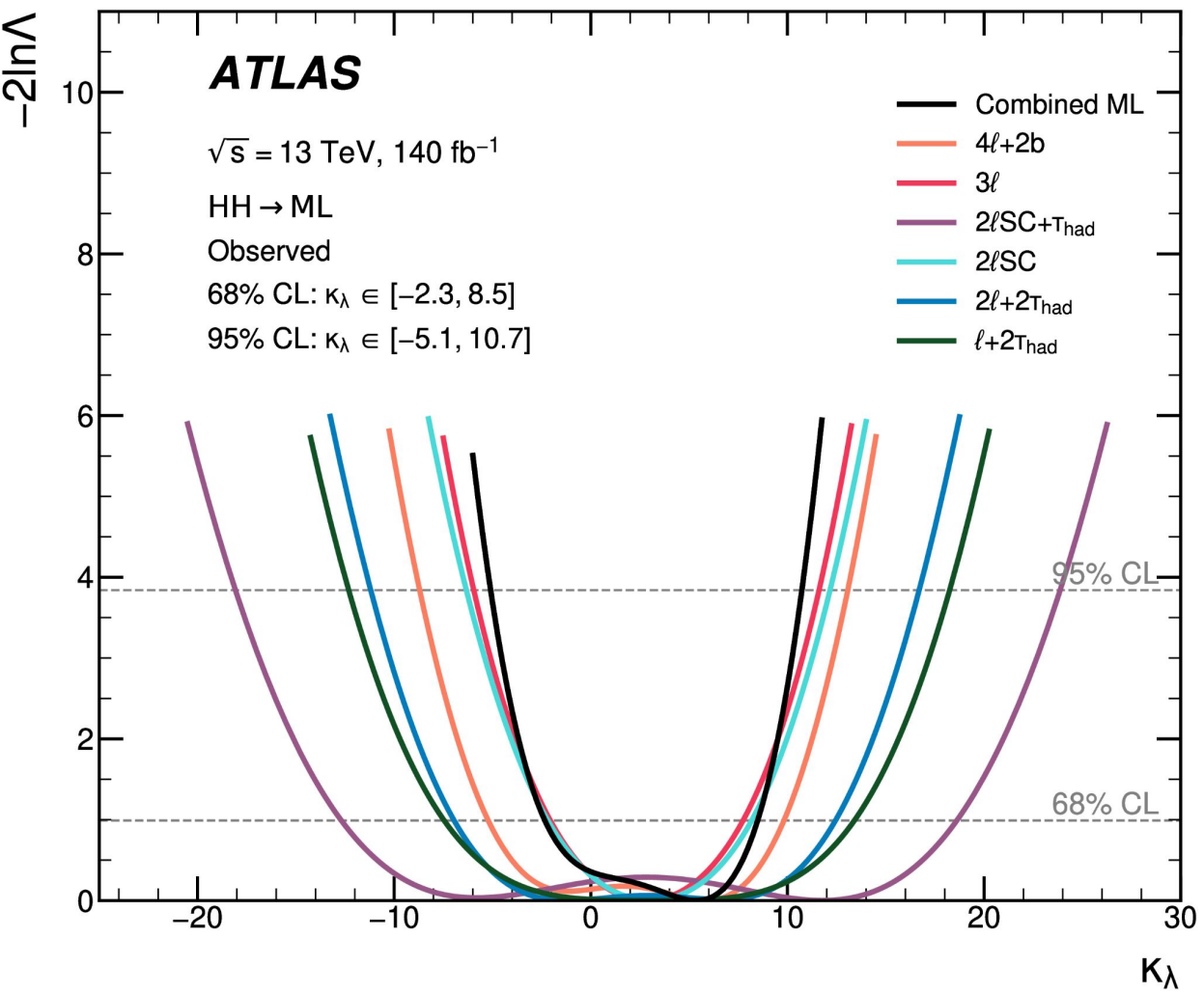

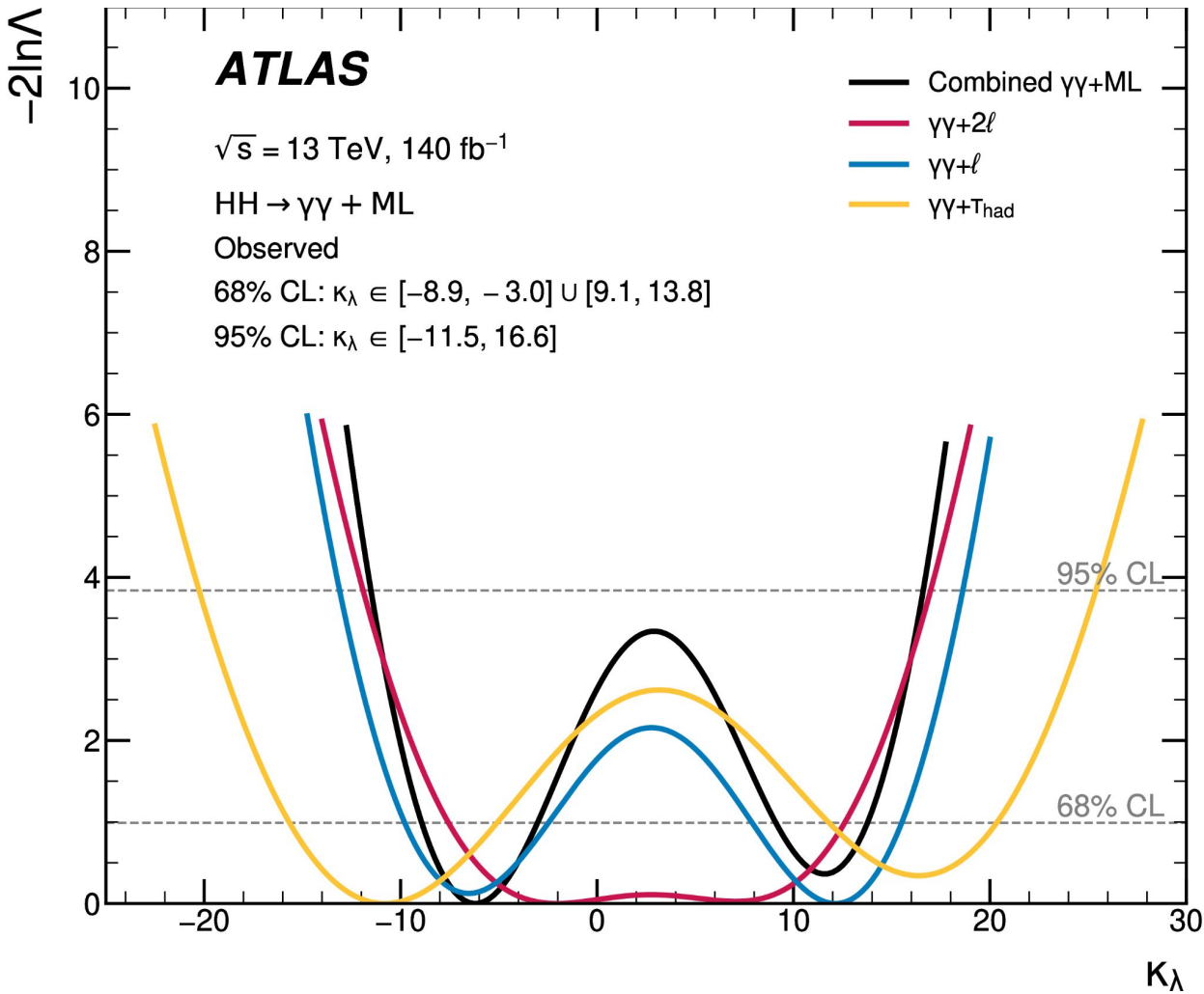

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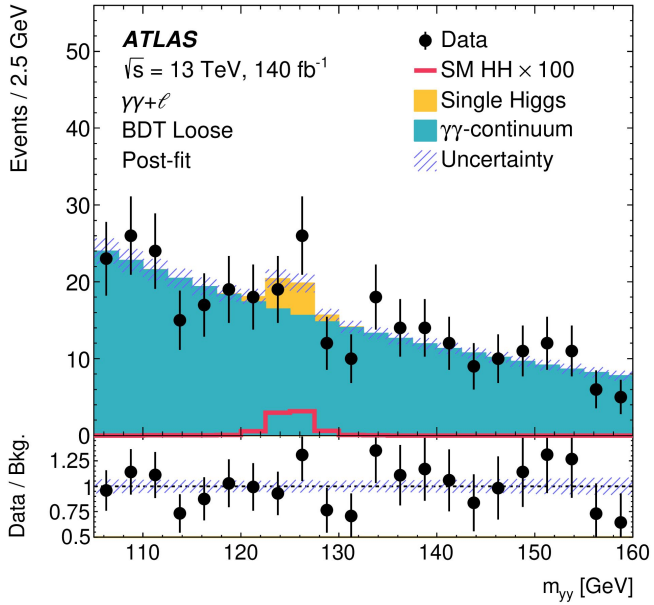
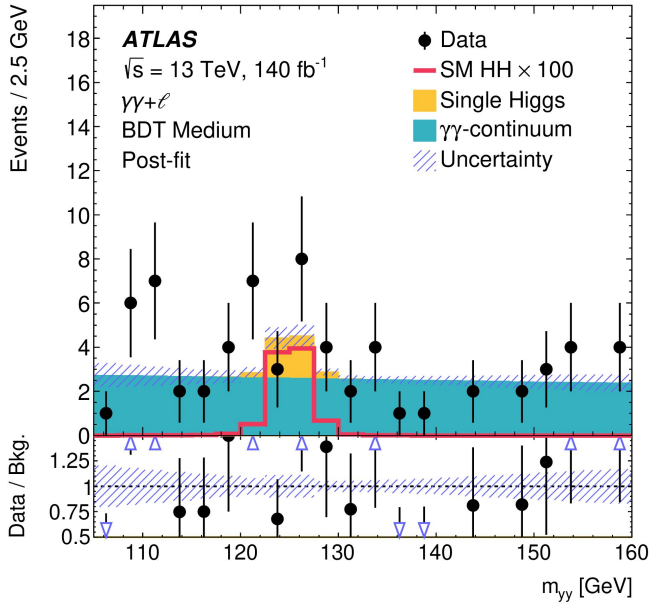
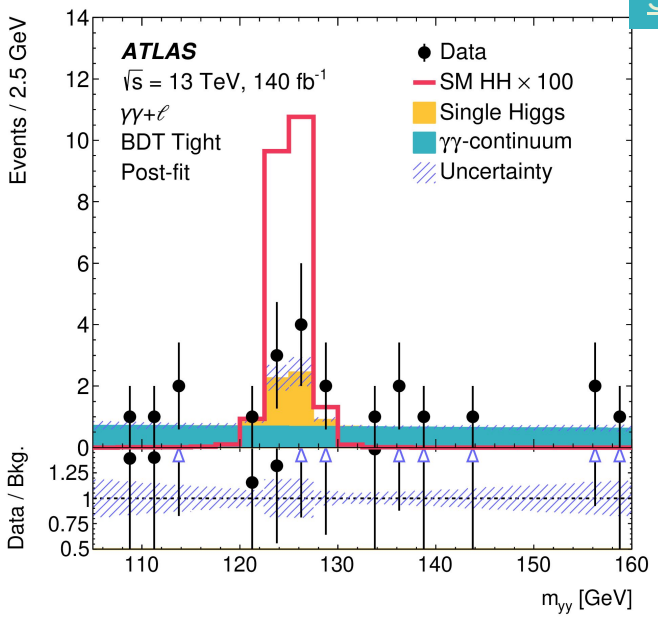
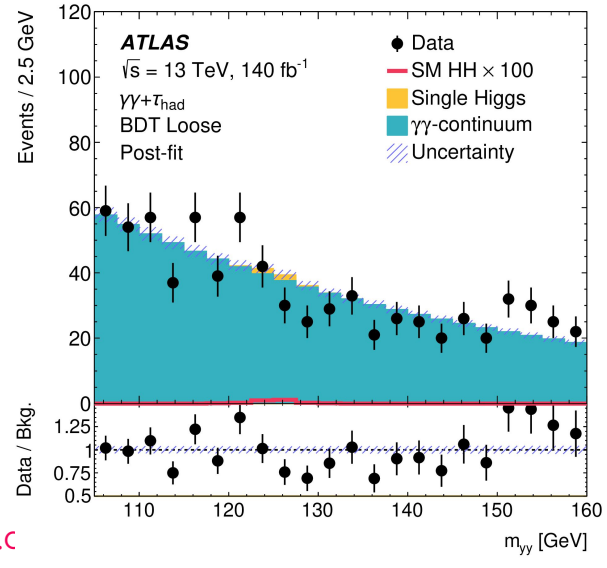
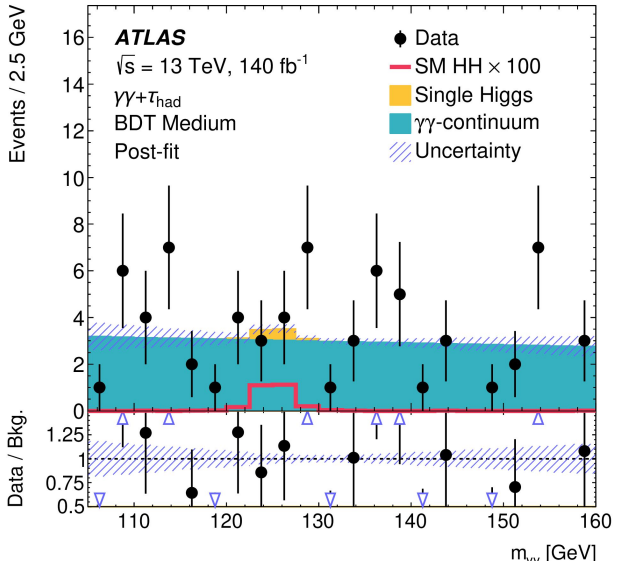
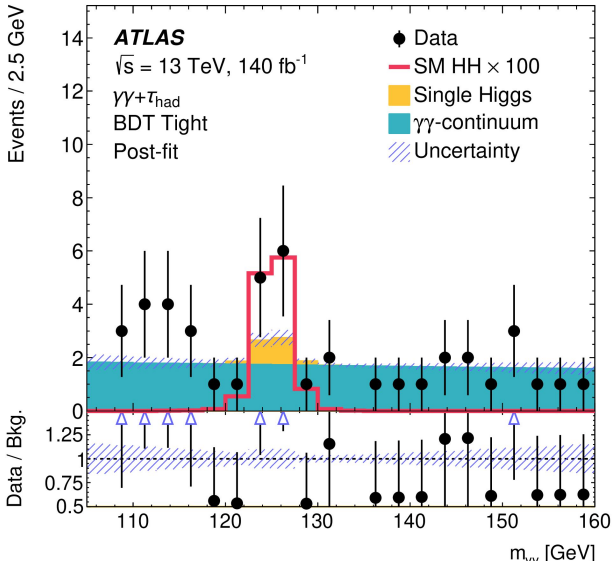






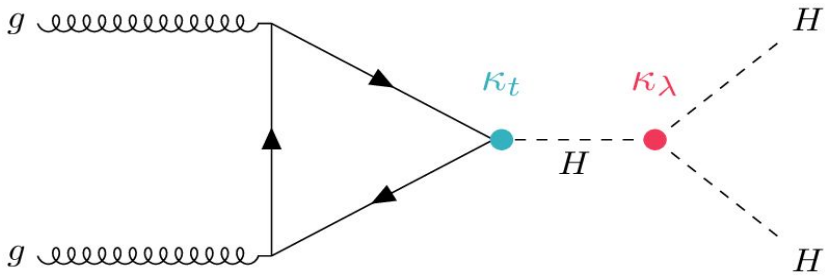


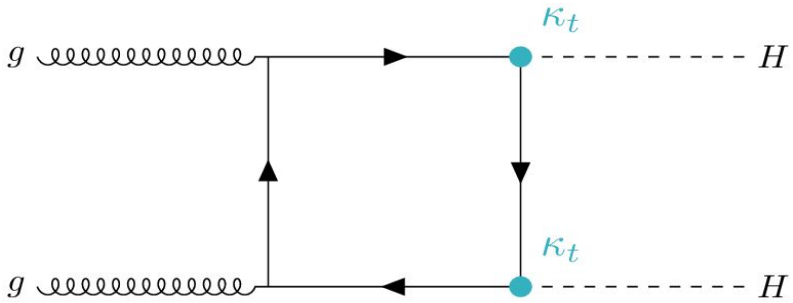




Non-resonant HH production

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

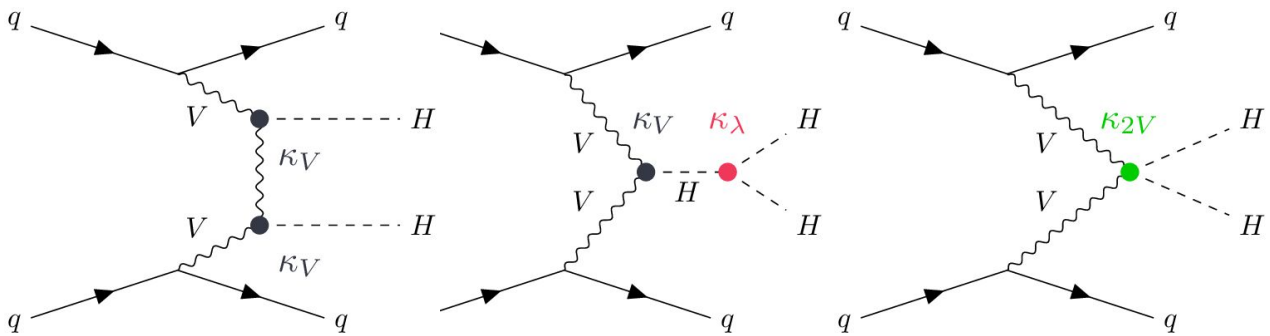




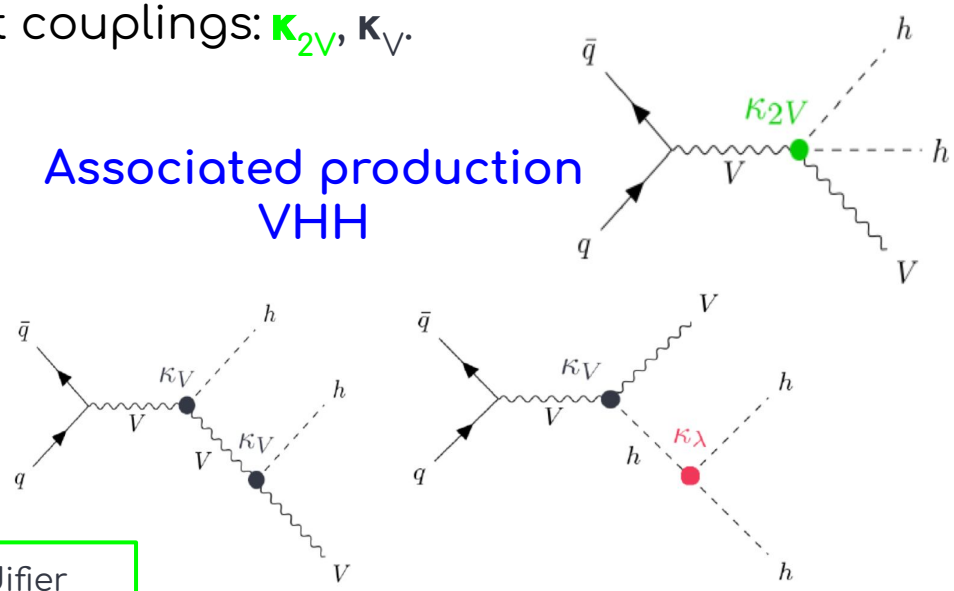
gluon fusion (ggF) is the main production mechanism.

Other production mechanisms also allow us to probe different couplings: κ_{2V}, κ_V.

Vector boson fusion



Associated production VHH



VVH coupling modifier
SM predicts $\kappa_V = 1$

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

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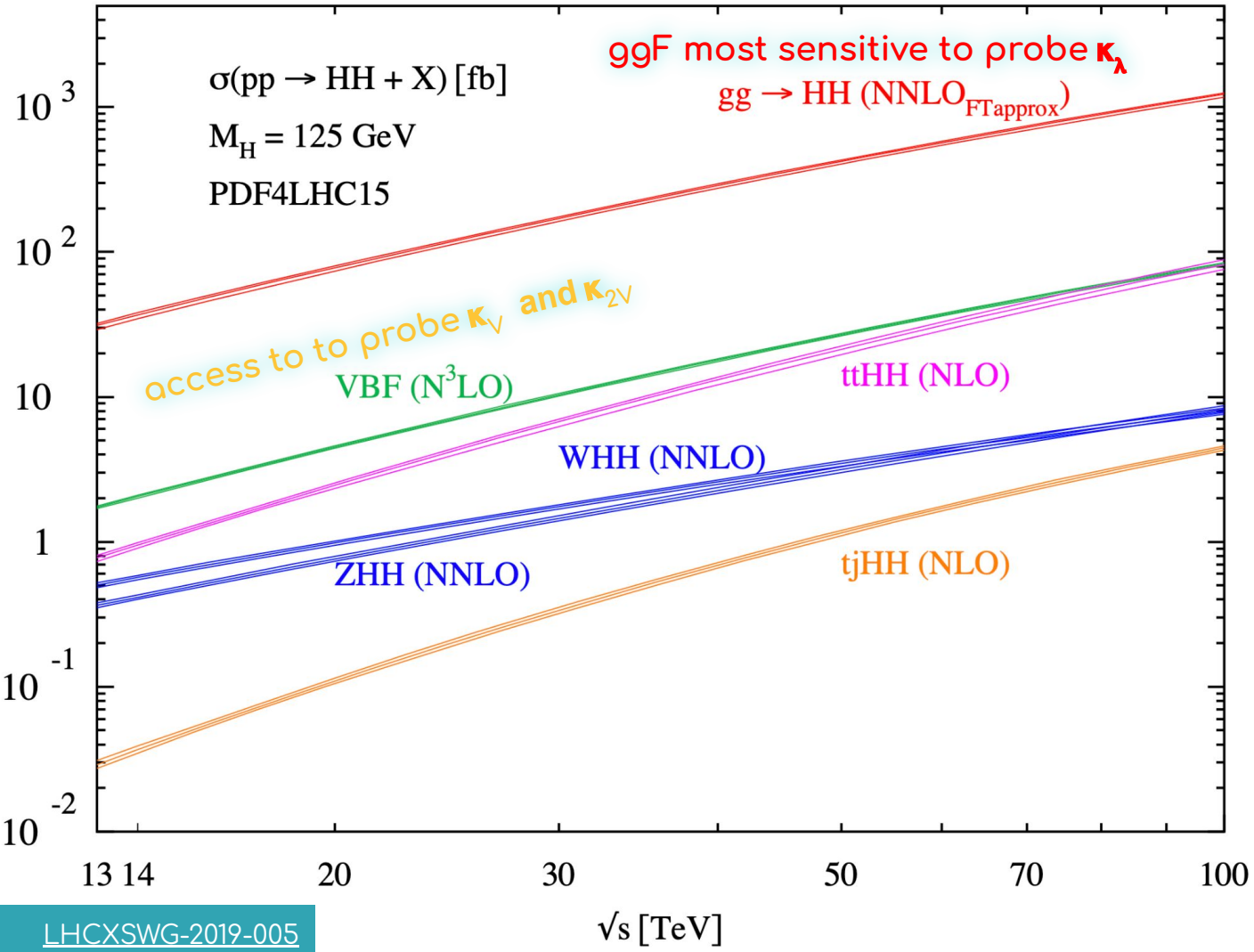
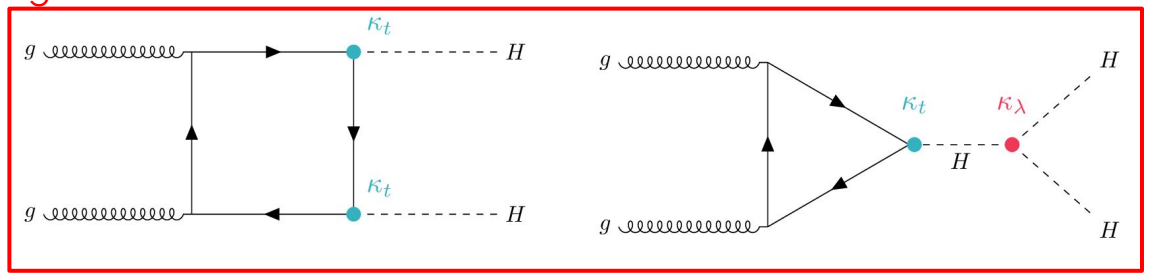
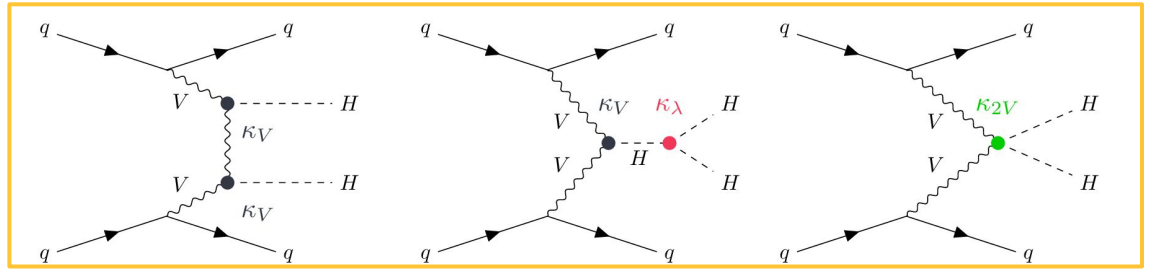
Higgs boson pair production



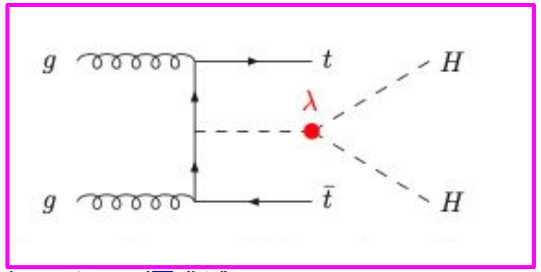
gluon fusion



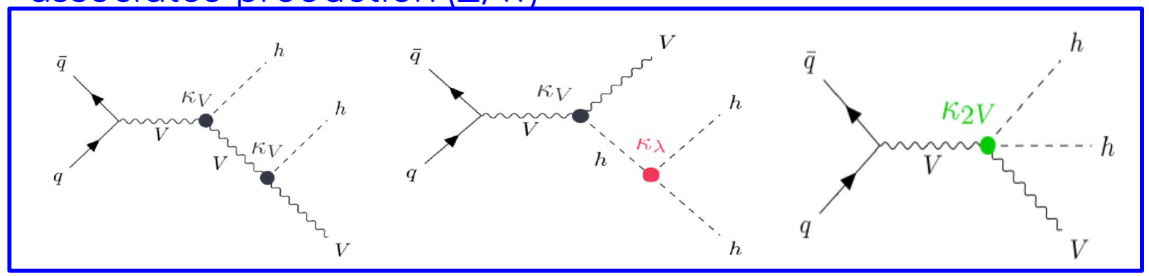
vector boson fusion



associated production (ttbar)



associated production (Z/W)



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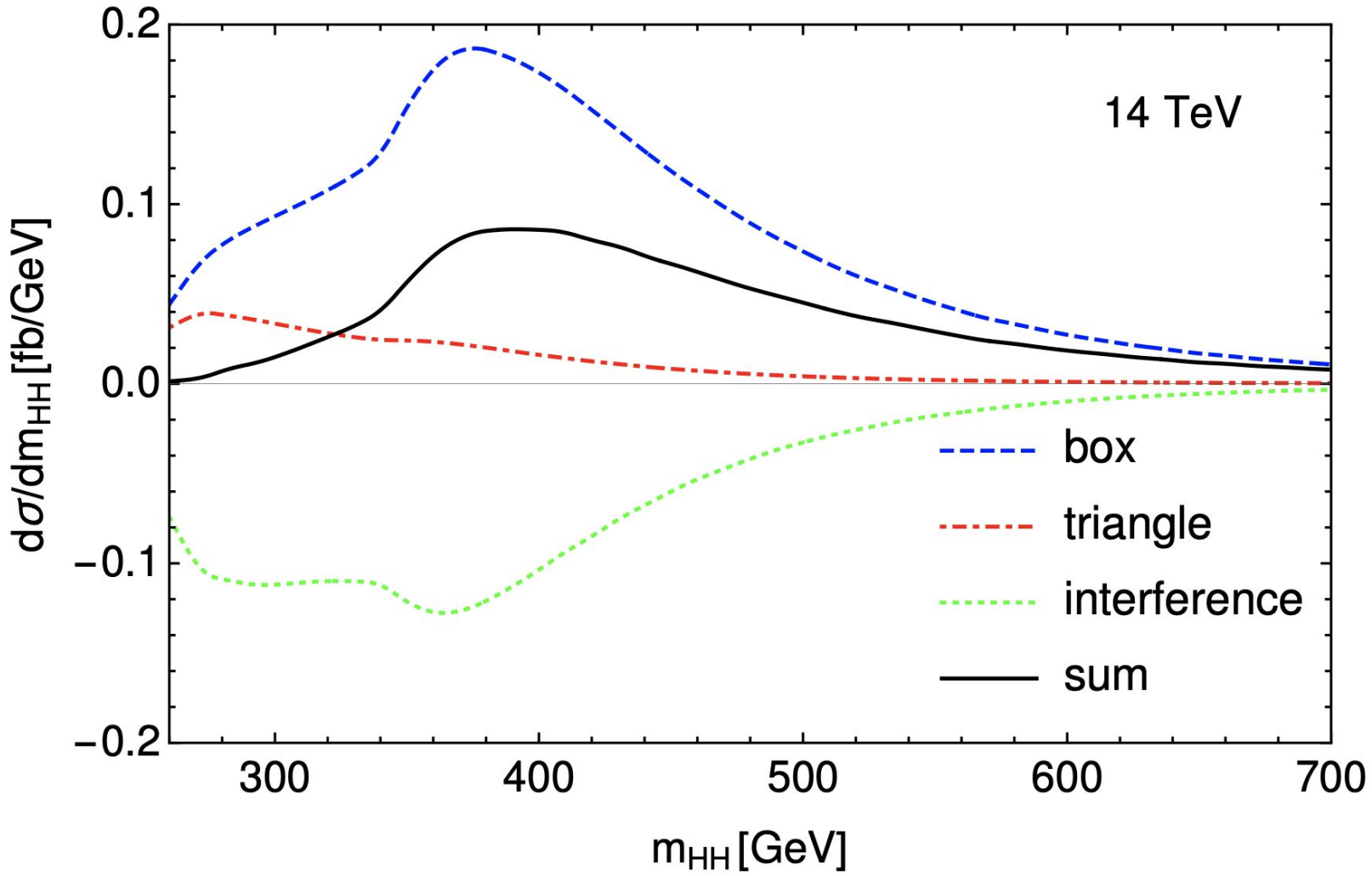
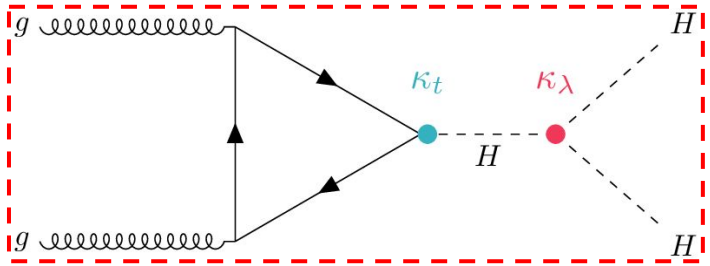
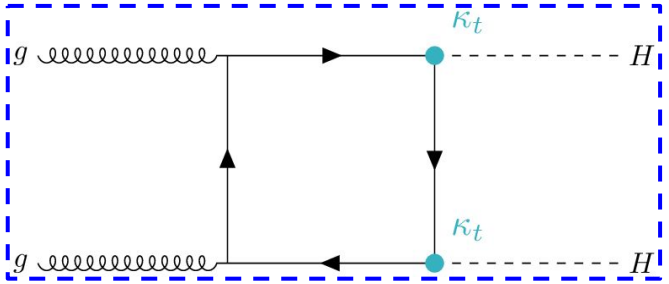
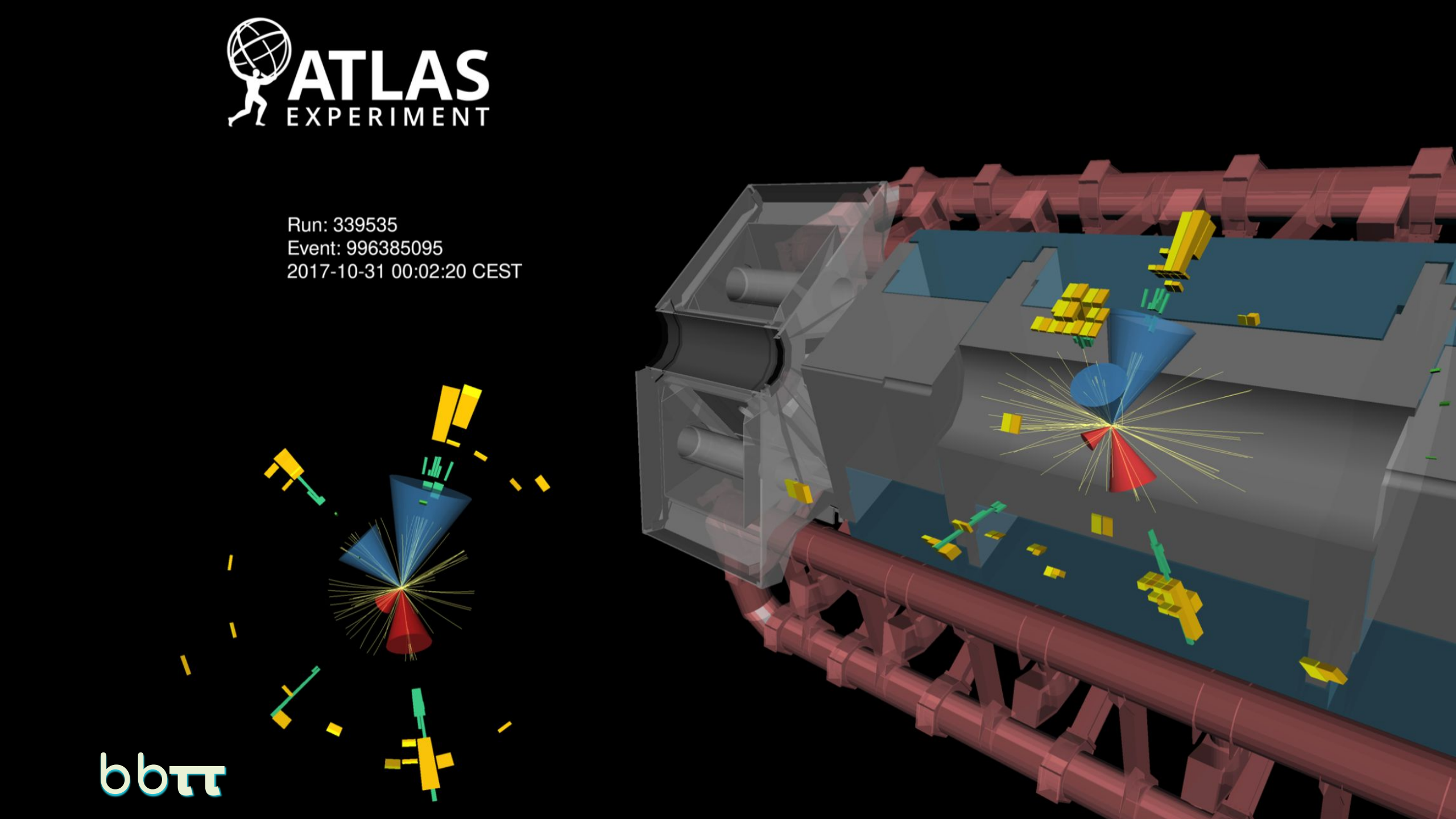
ggF production



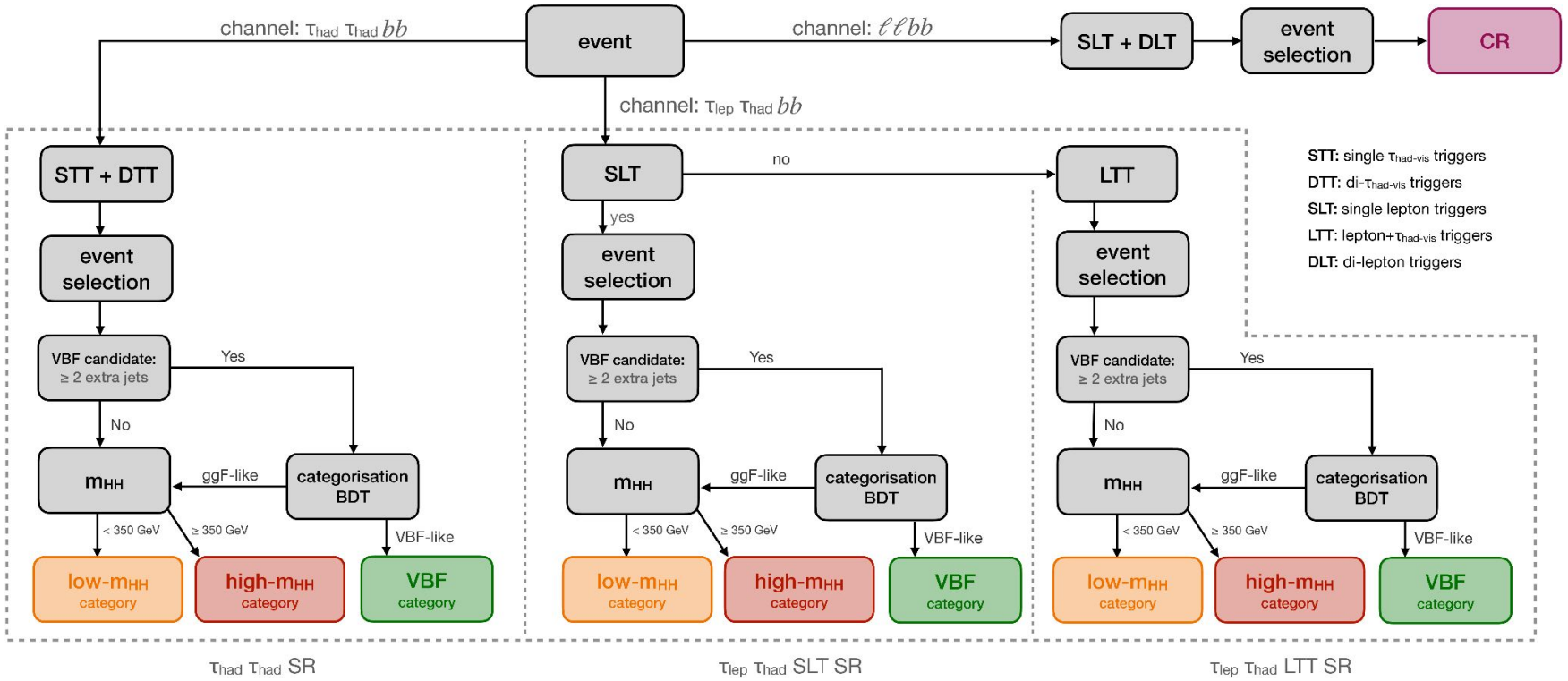





ATLAS
EXPERIMENT
Run: 339535
Event: 996385095
2017-10-31 00:02:20 CEST
bbττ

bbττ

Select 2 b-tagged PFlow jets and 2 OS 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 (SLT+DLT) triggers,
- $H\rightarrow\tau_{had}\tau_{had}$: combination of single-tau (STT) and di-tau triggers.

background discrimination

- BDT training to separate VBF vs ggF
- BDT in different low/high m_{HH} categories.

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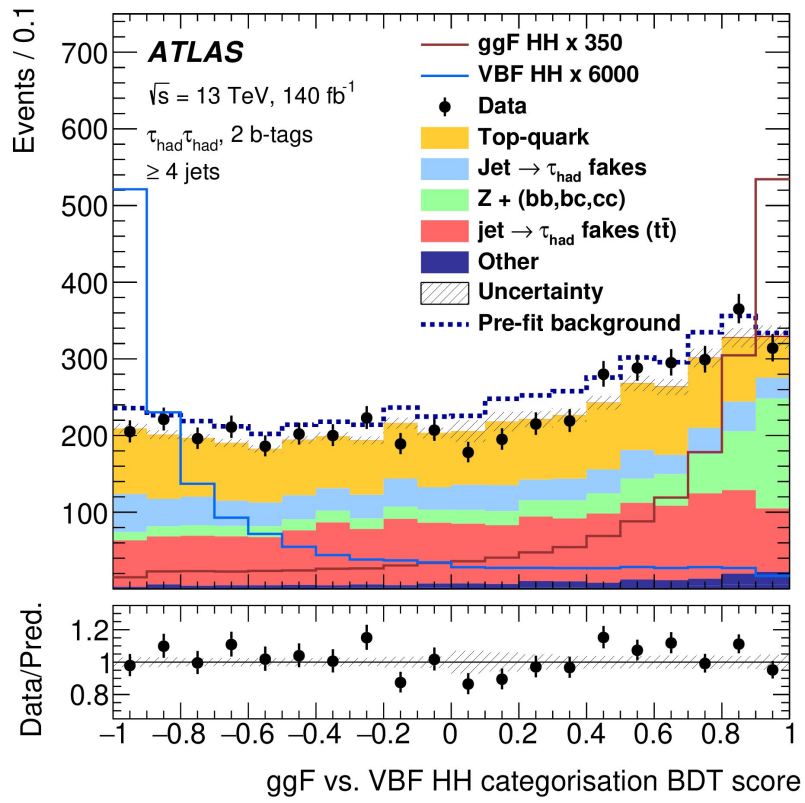
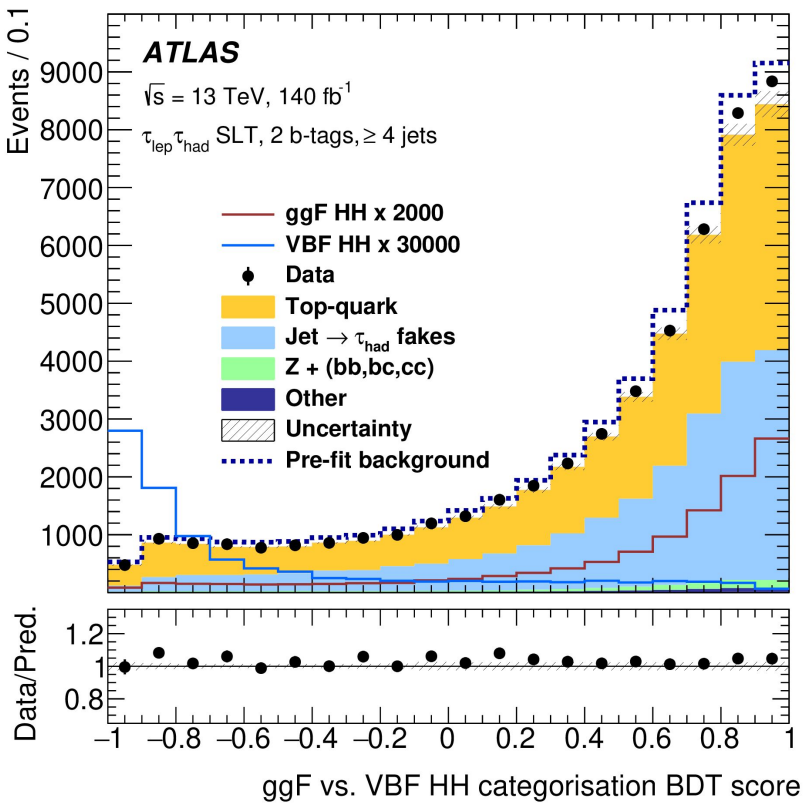
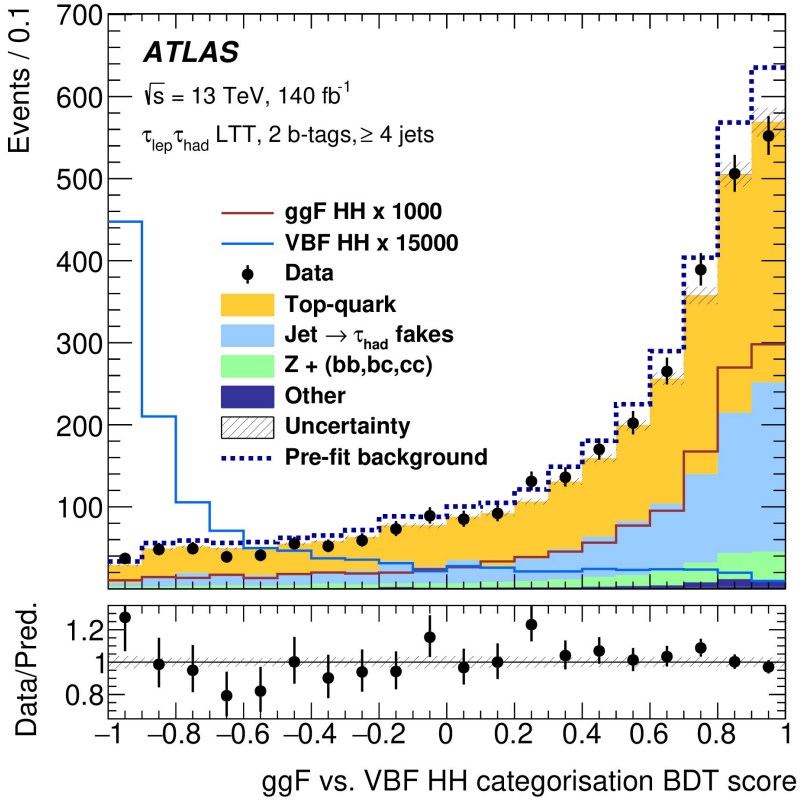
bbττ







BDT training to separate VBF vs ggF in each category

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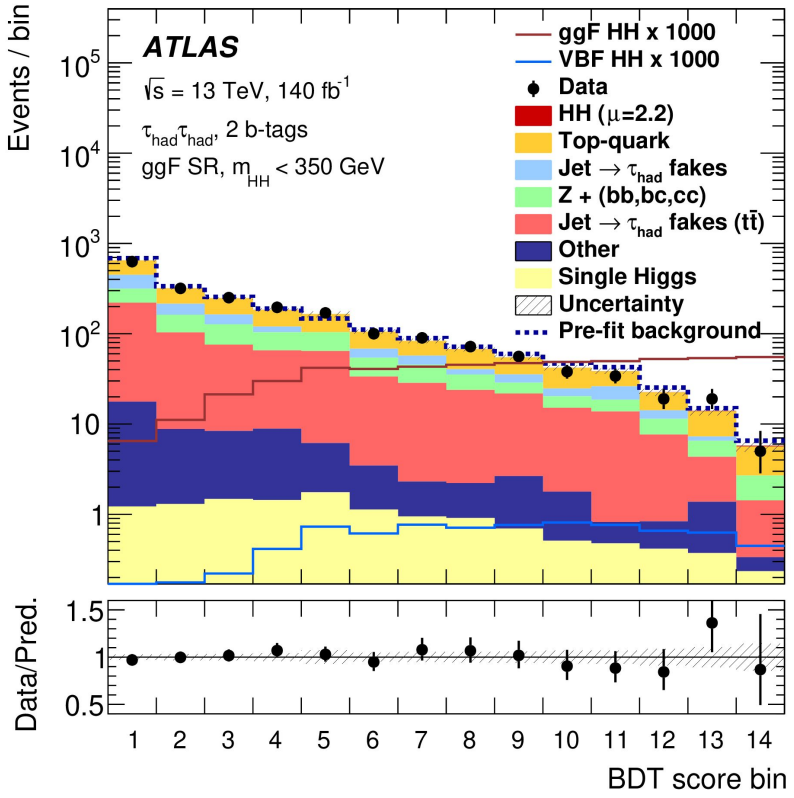
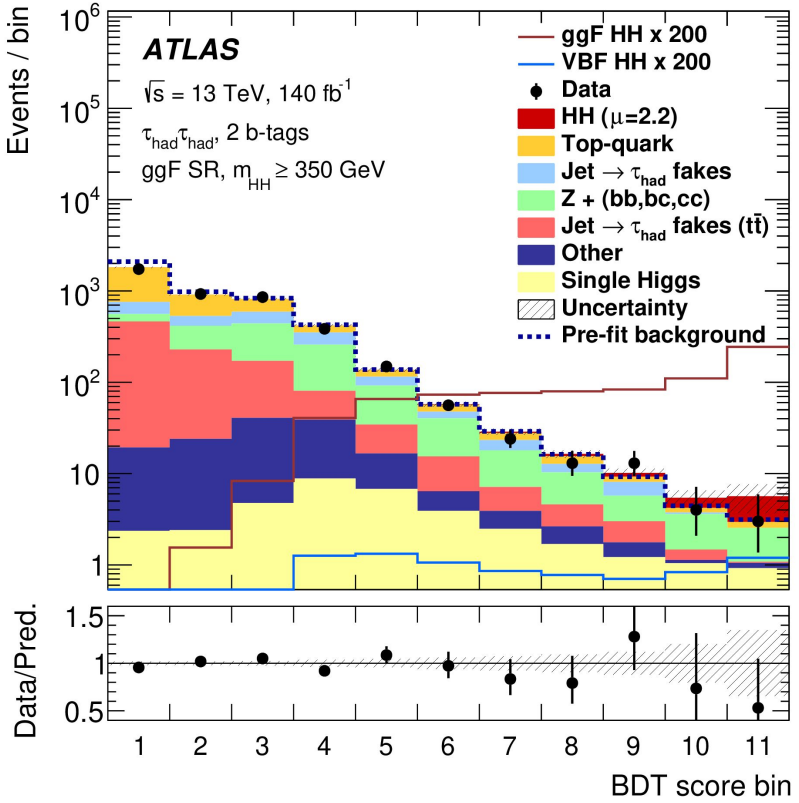
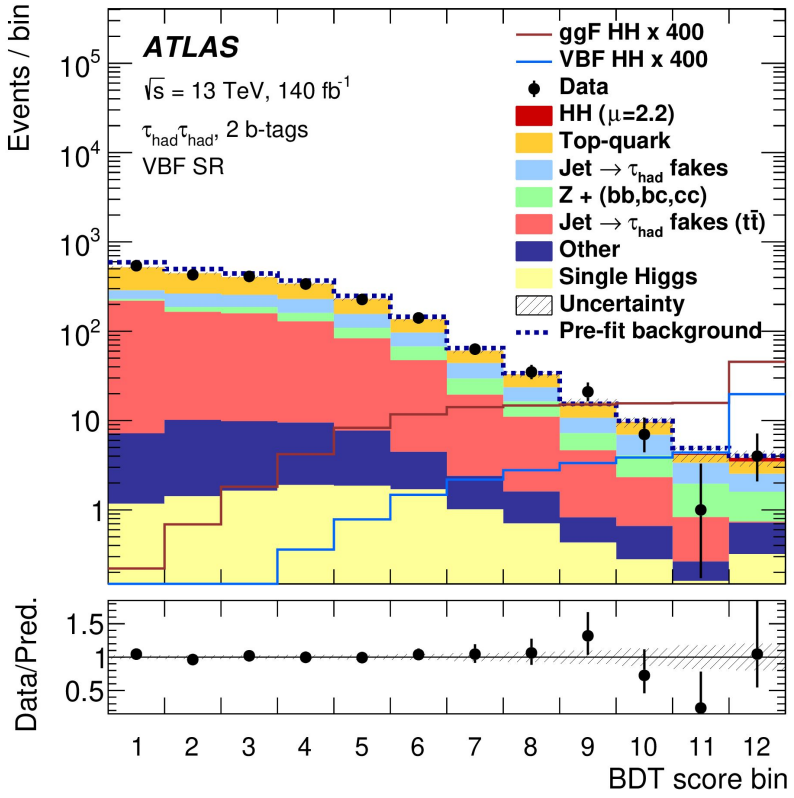
bbττ







$H \rightarrow \tau_{had}\tau_{had}$

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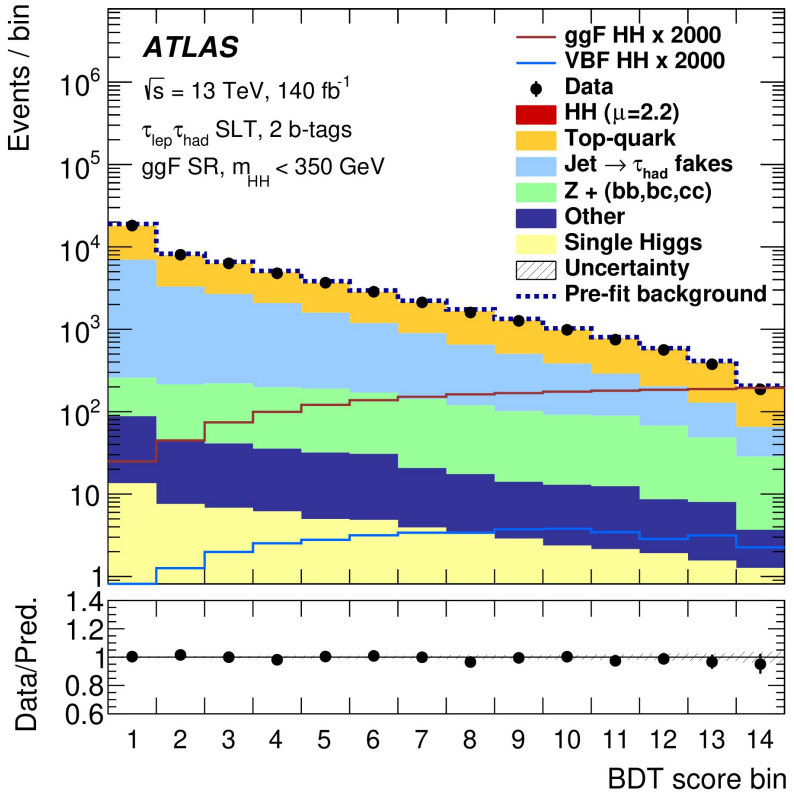
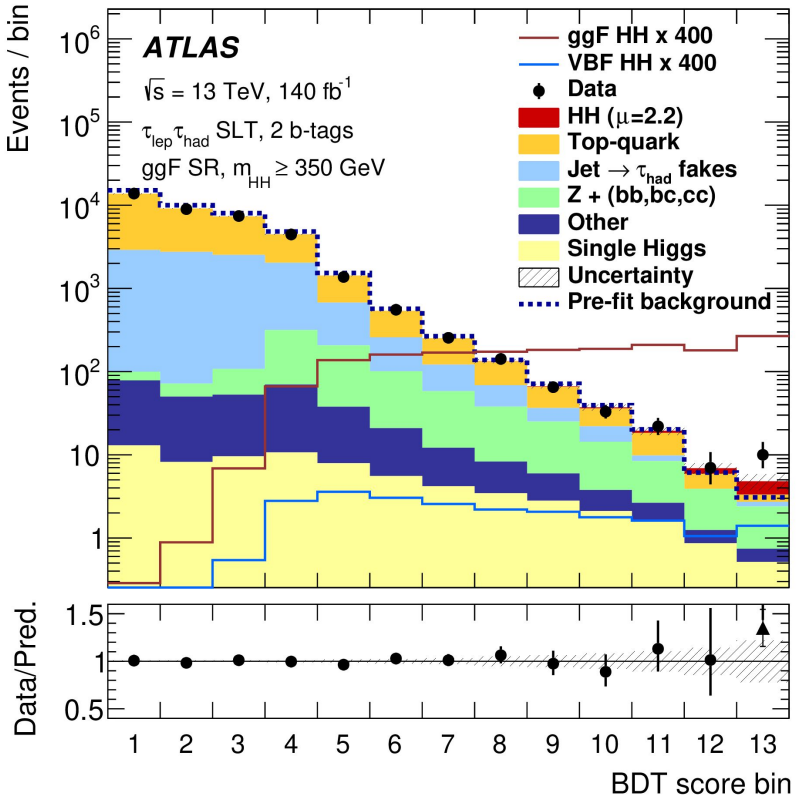
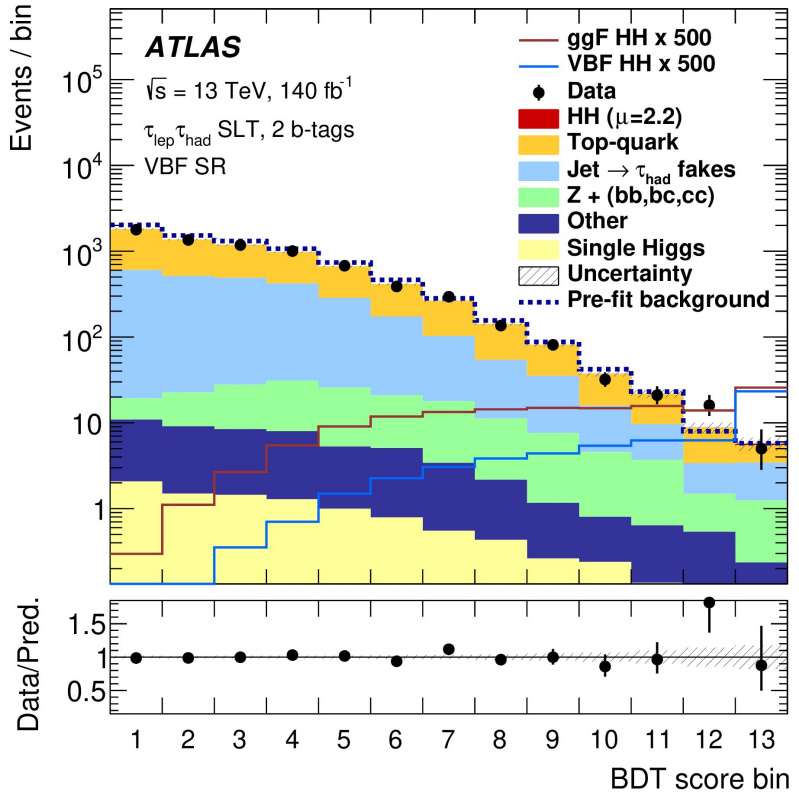
bbττ







H→$\tau_{had}\tau_{lep}$ SLT

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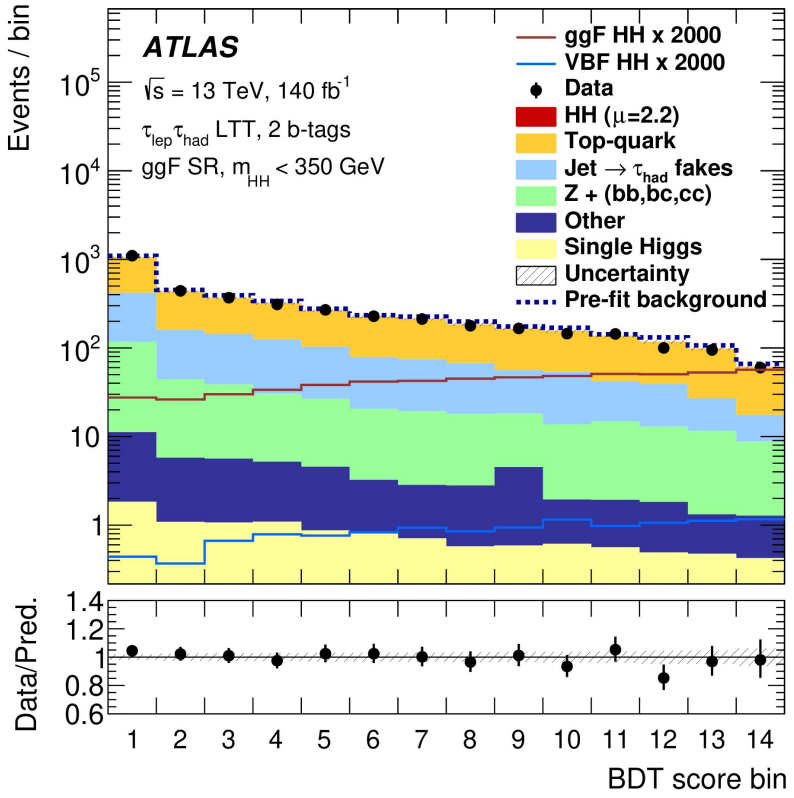
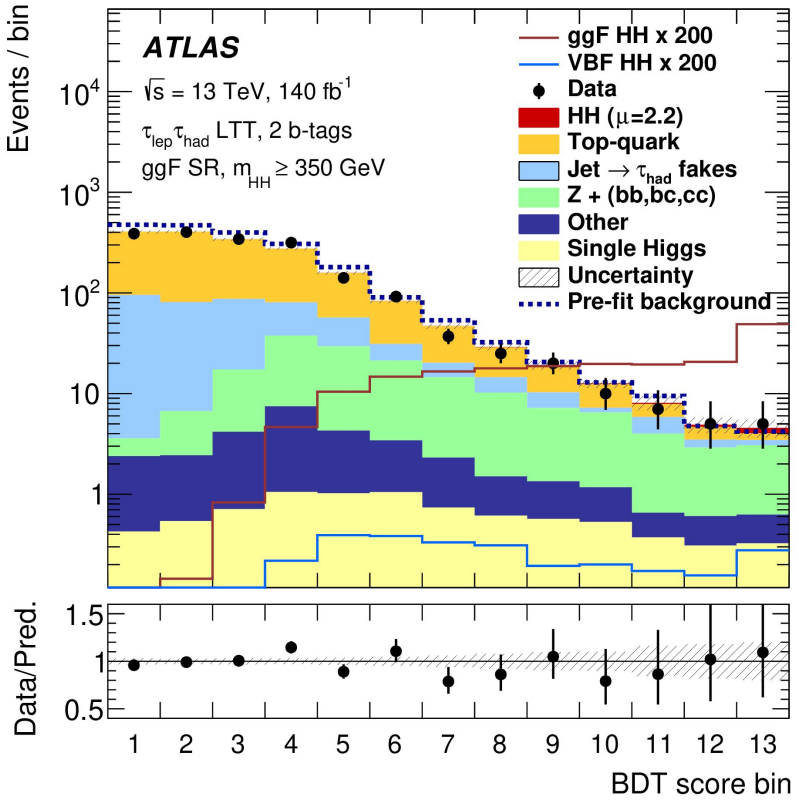
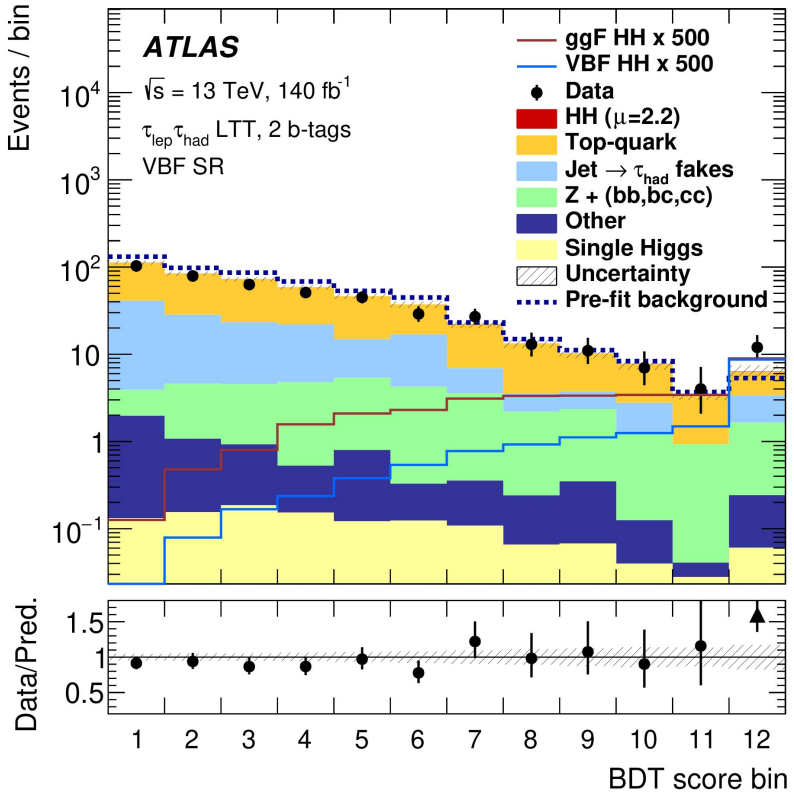
bbττ

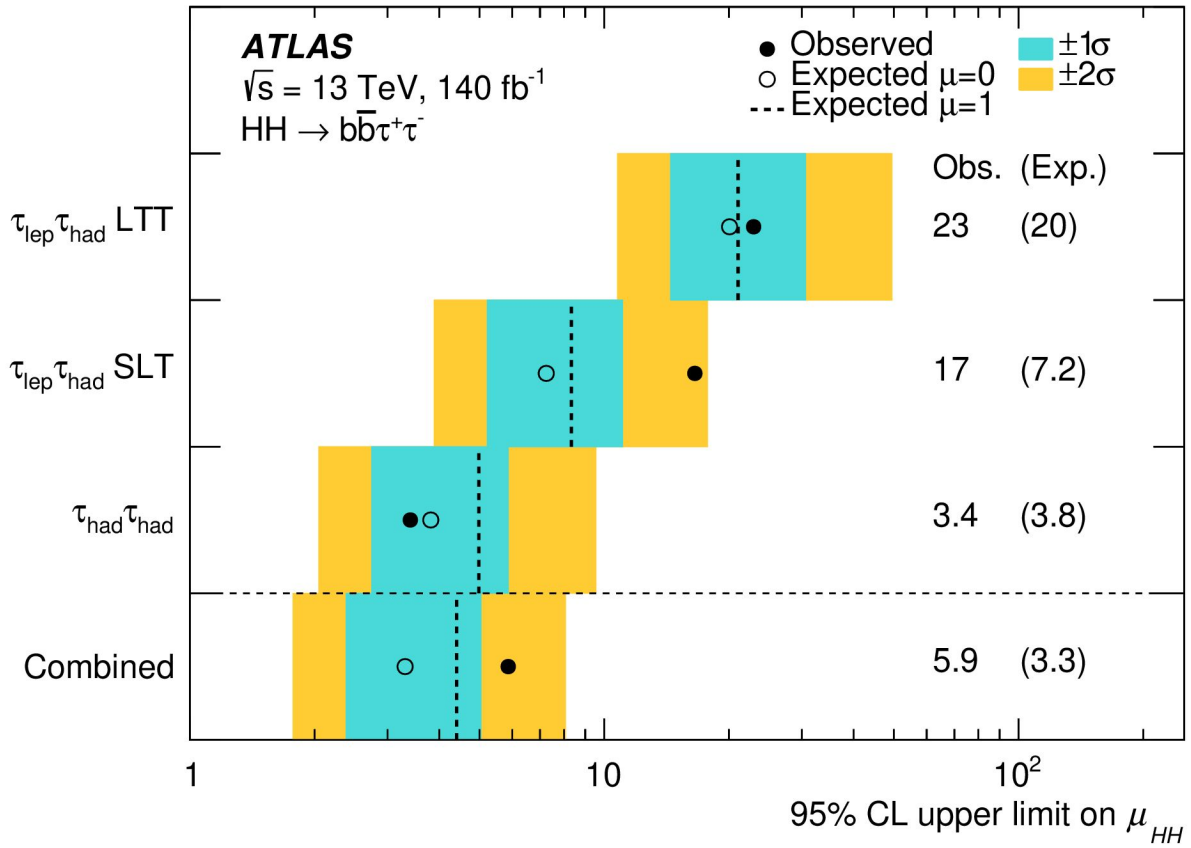


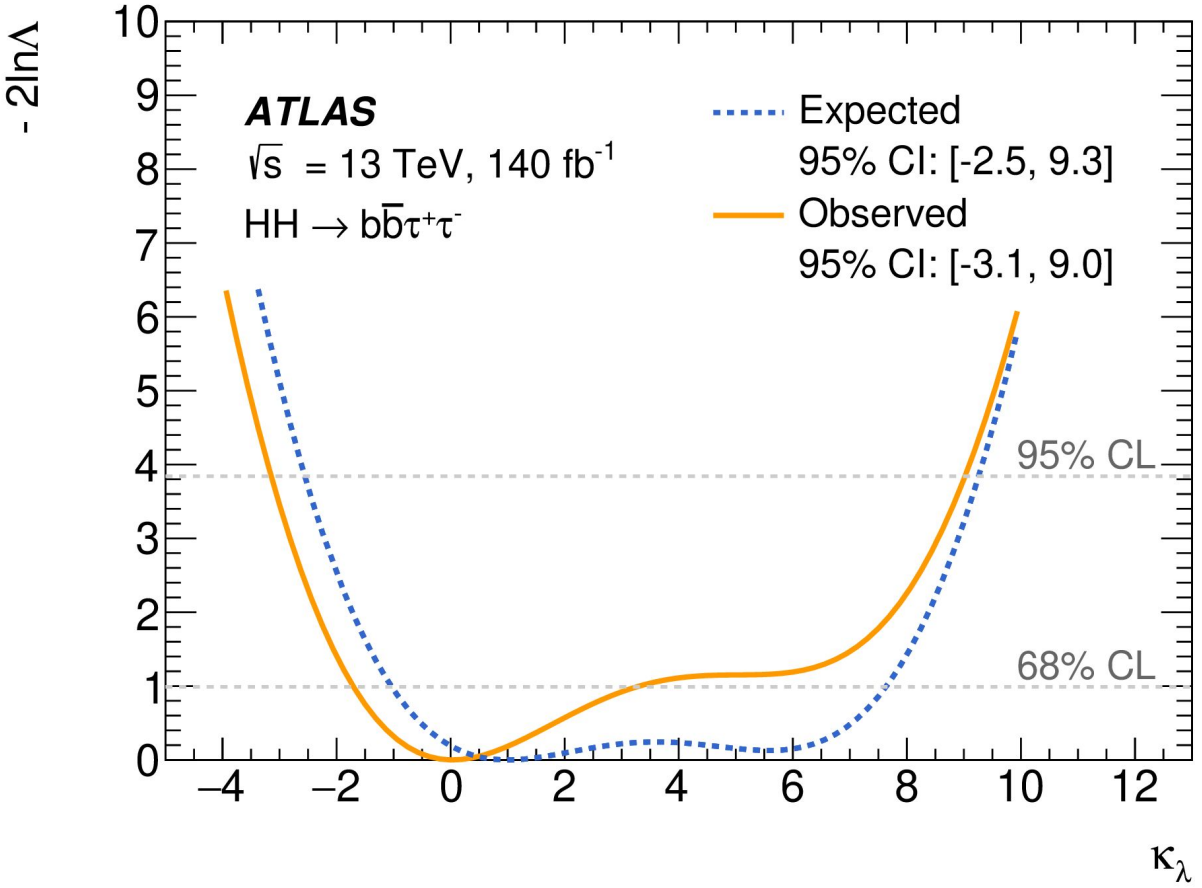




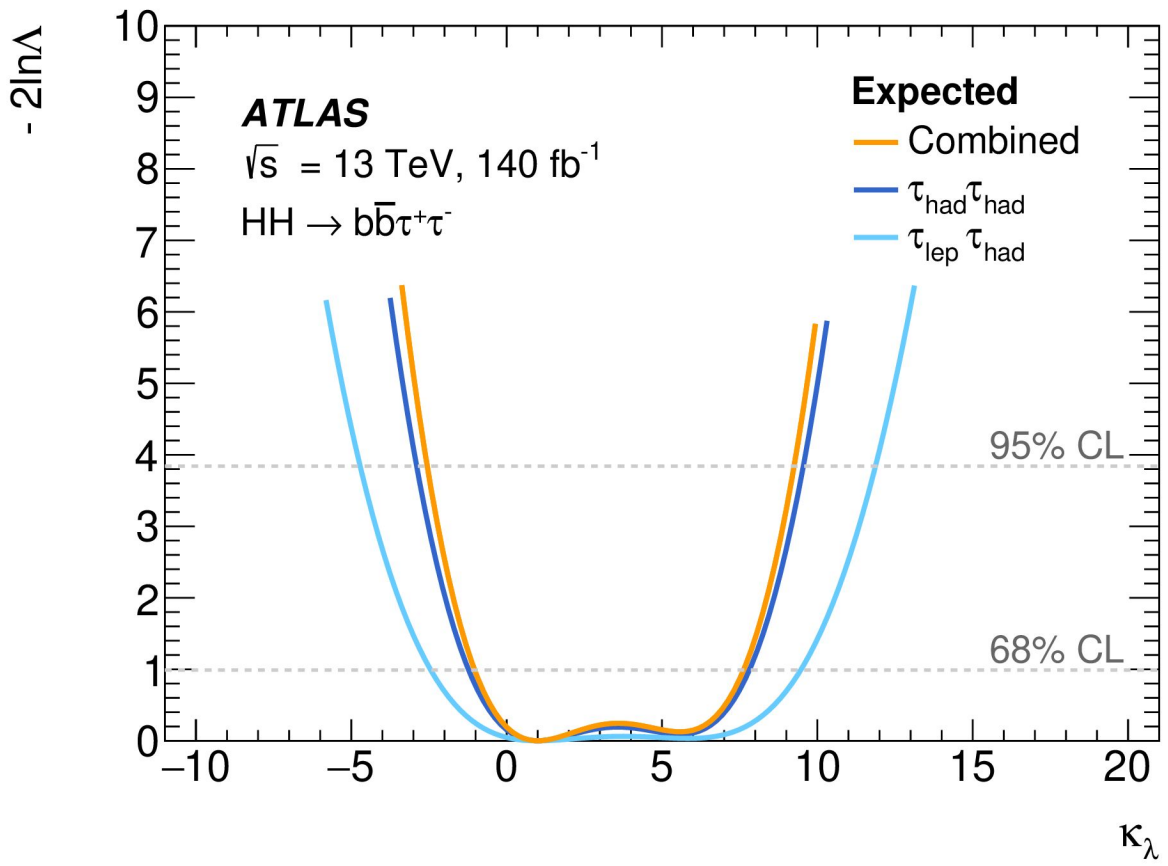
H→$\tau_{had}\tau_{lep}$ LLT

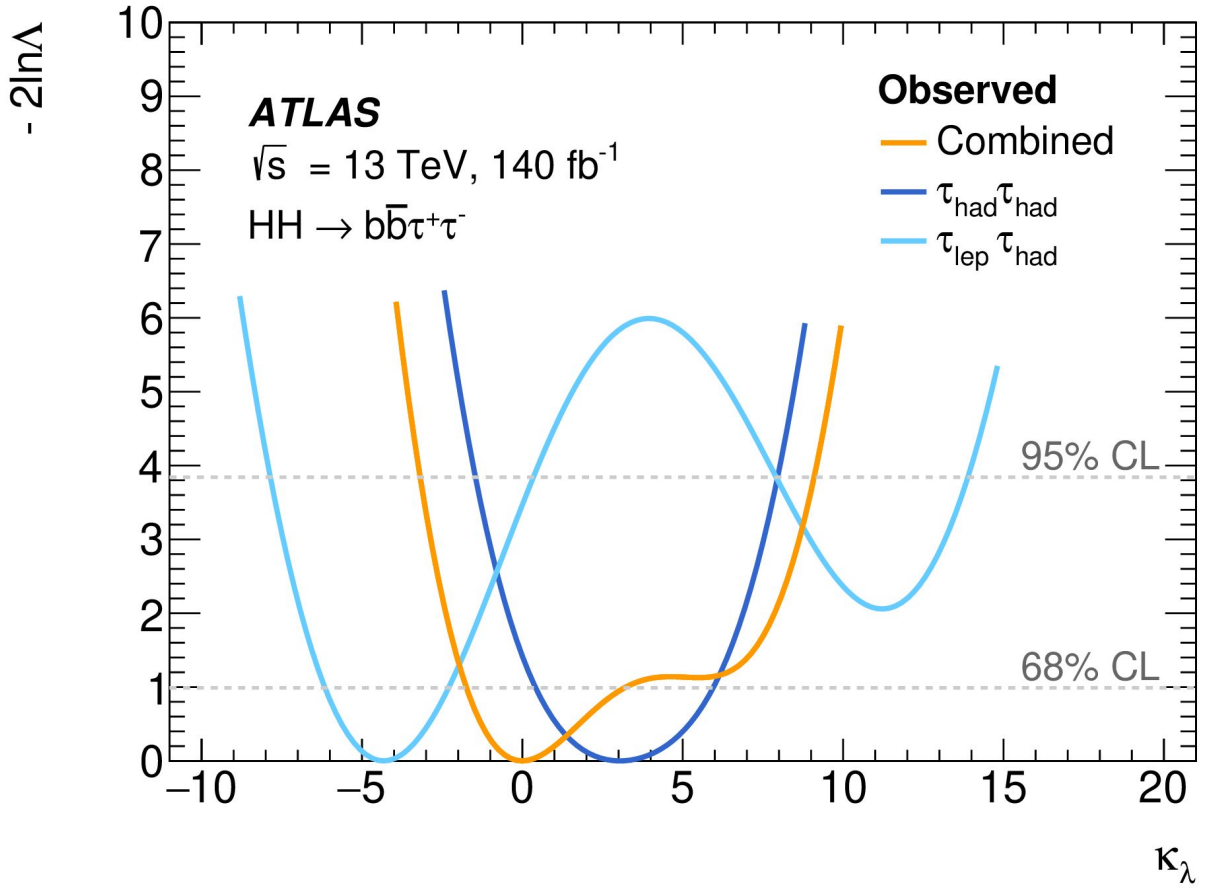
bbττ


ATLAS
√s = 13 TeV, 140 fb-1
HH → bb̄τ+τ-
Observed
Expected μ=0
Expected μ=1
±1σ
±2σ
Obs. (Exp.)
τlepτhad LTT
23 (20)
τlepτhad SLT
17 (7.2)
τhadτhad
3.4 (3.8)
Combined
5.9 (3.3)
1
10
10²
95% CL upper limit on μHH

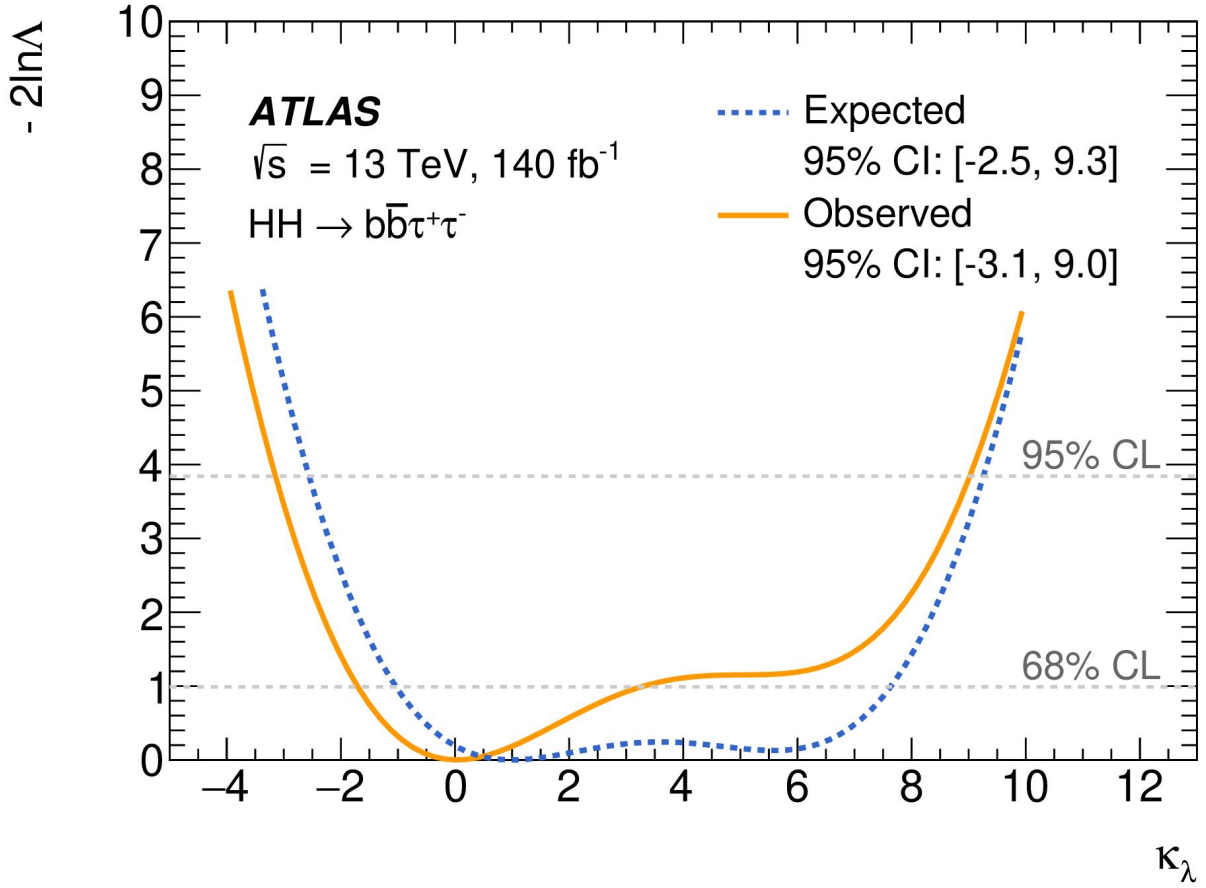

- 2lnΛ
ATLAS
√s = 13 TeV, 140 fb-1
HH → bb̄τ+τ-
Expected
95% CI: [-2.5, 9.3]
Observed
95% CI: [-3.1, 9.0]
95% CL
68% CL
κλ

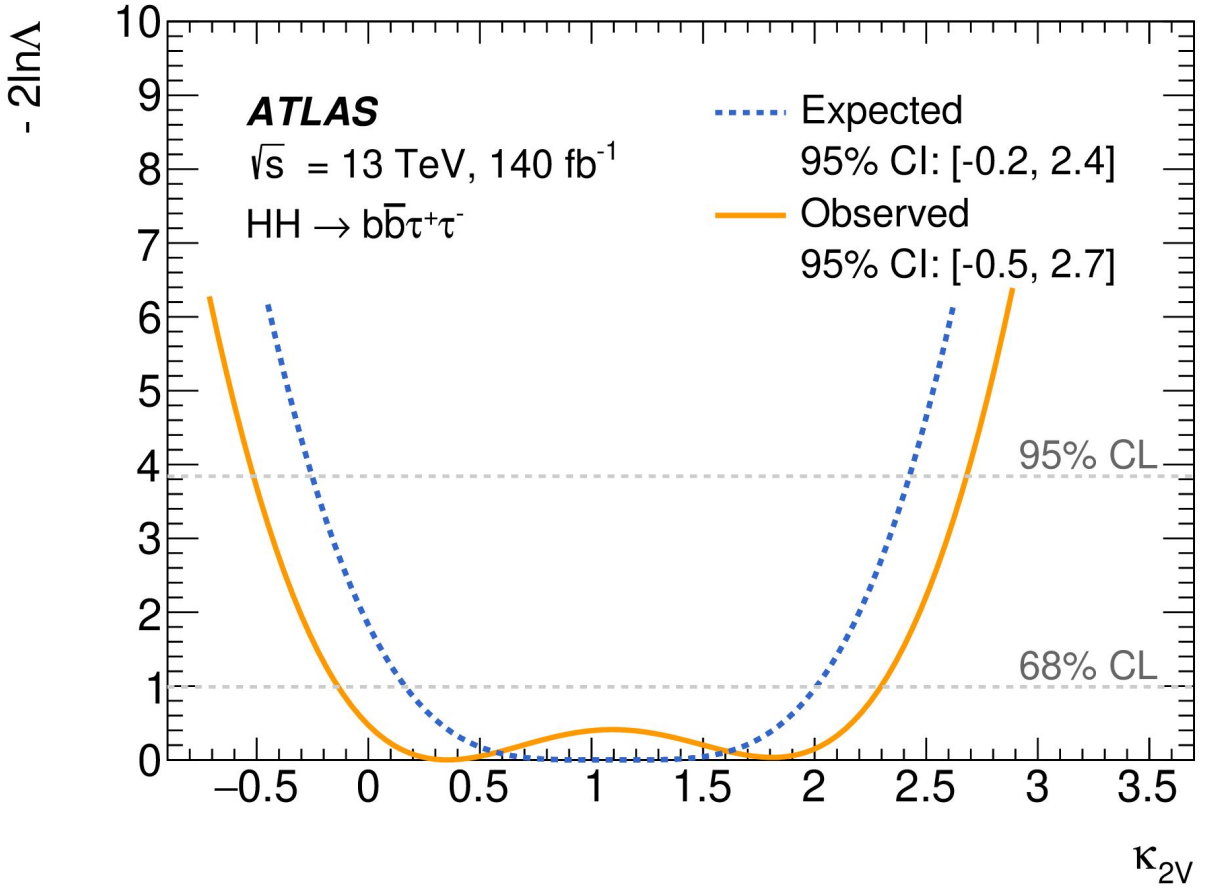
bbττ

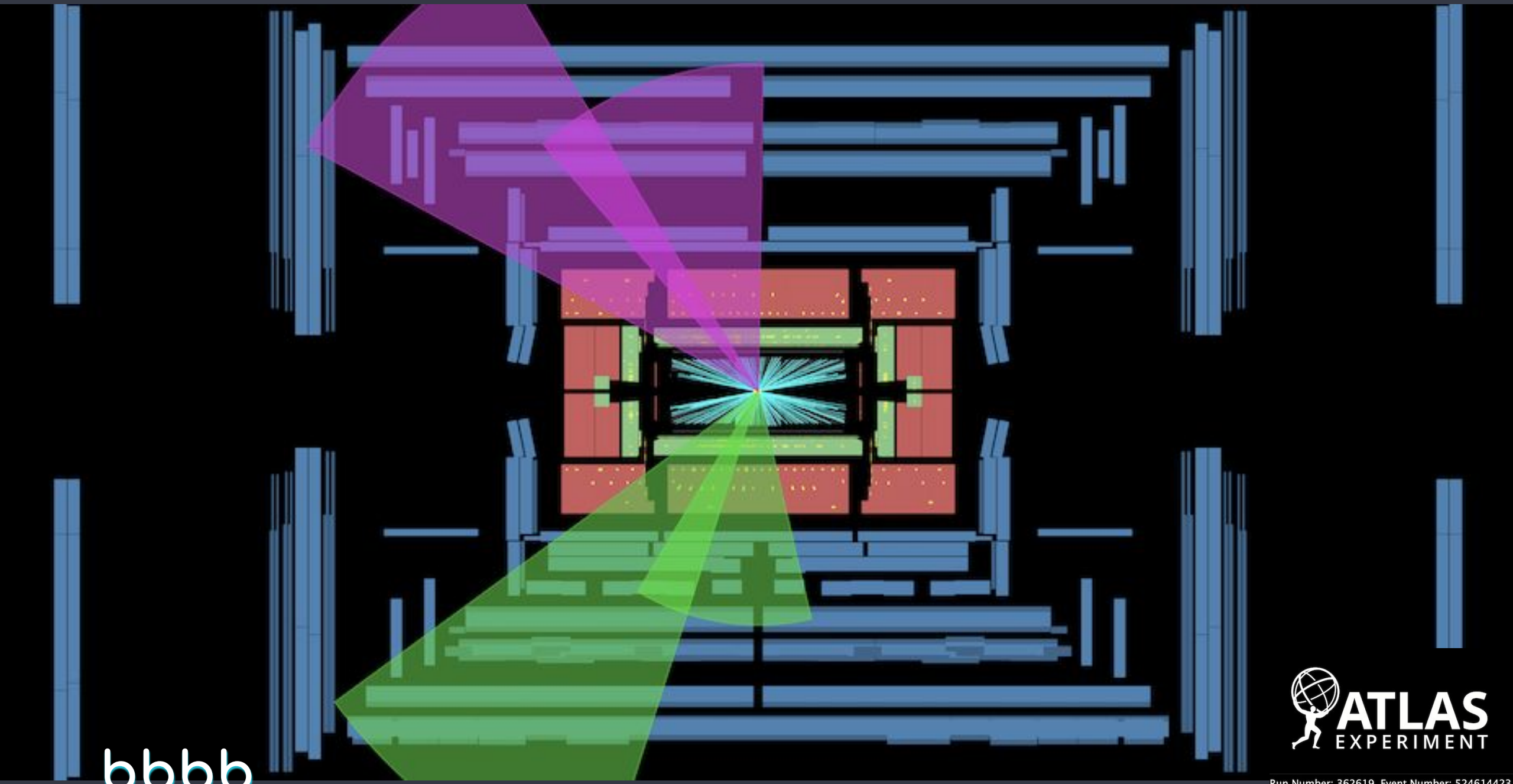

ATLAS
√s = 13 TeV, 140 fb-1
HH → bb̄τ+τ-
Expected
Combined
τhadτhad
τlep τhad
95% CL
68% CL
- 2lnΛ
κλ


ATLAS
√s = 13 TeV, 140 fb-1
HH → bb̄τ+τ-
Observed
Combined
τhadτhad
τlep τhad
95% CL
68% CL
- 2lnΛ
κλ

bbττ

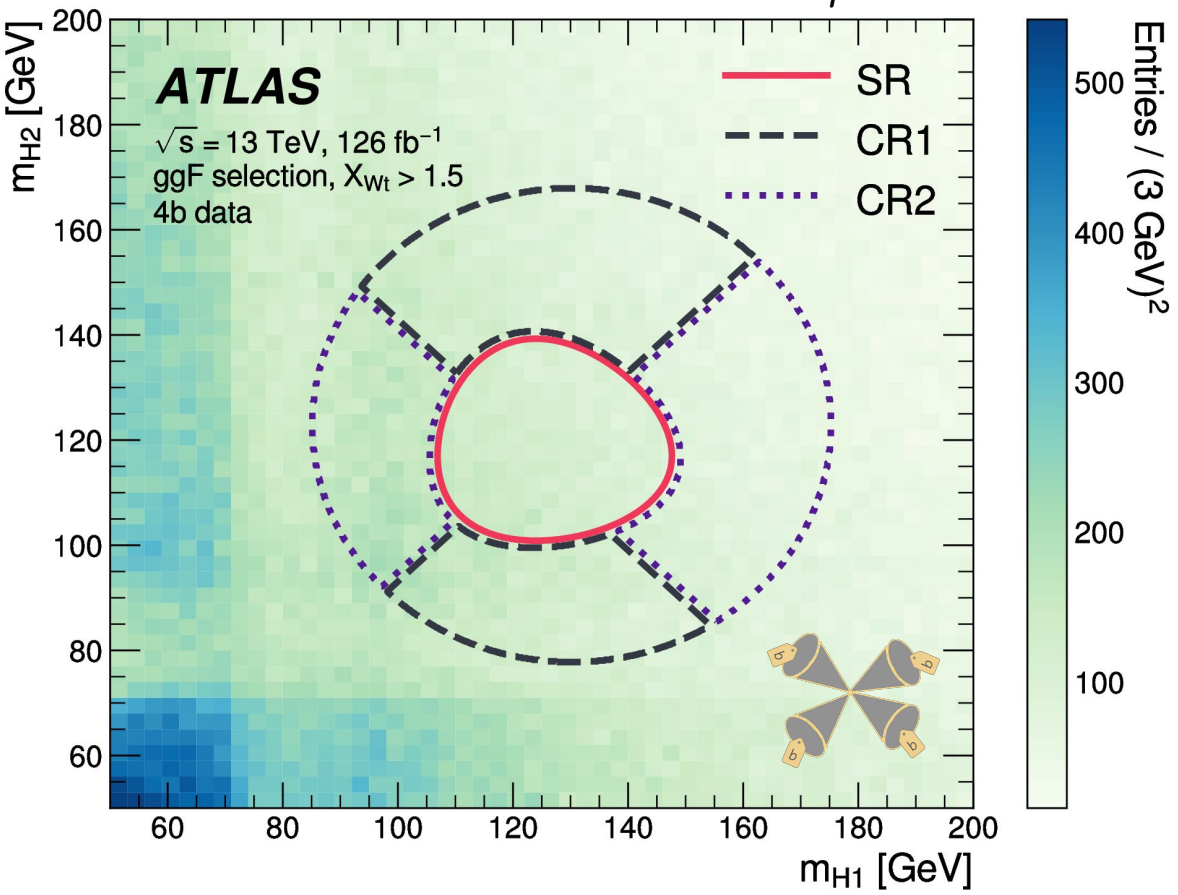

ATLAS
√s = 13 TeV, 140 fb-1
HH → bb̄τ+τ-
Expected
95% CI: [-2.5, 9.3]
Observed
95% CI: [-3.1, 9.0]
95% CL
68% CL
- 2lnΛ
κλ


ATLAS
√s = 13 TeV, 140 fb-1
HH → bb̄τ+τ-
Expected
95% CI: [-0.2, 2.4]
Observed
95% CI: [-0.5, 2.7]
95% CL
68% CL
- 2lnΛ
κ2V


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.

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

X_{HH}: SR cut.

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

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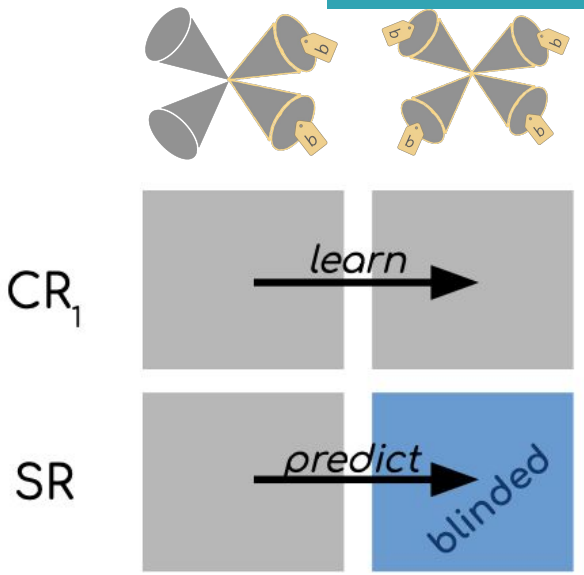

data-driven bkg estimation

- 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

Define different categories to improve analysis sensitivity.

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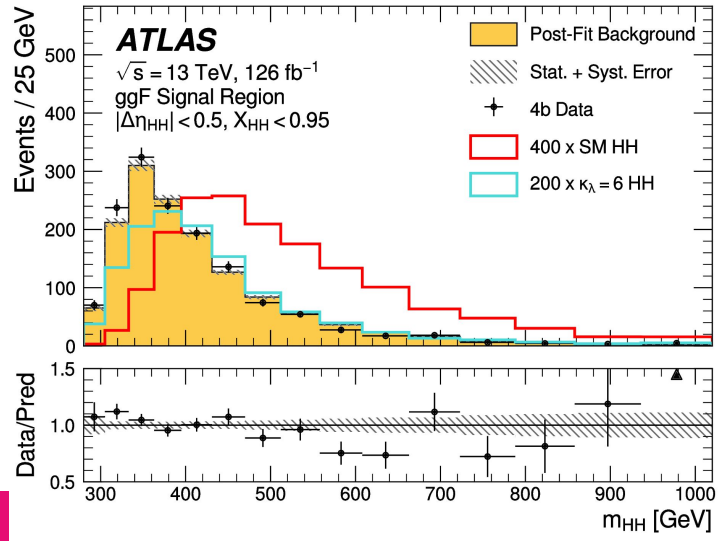
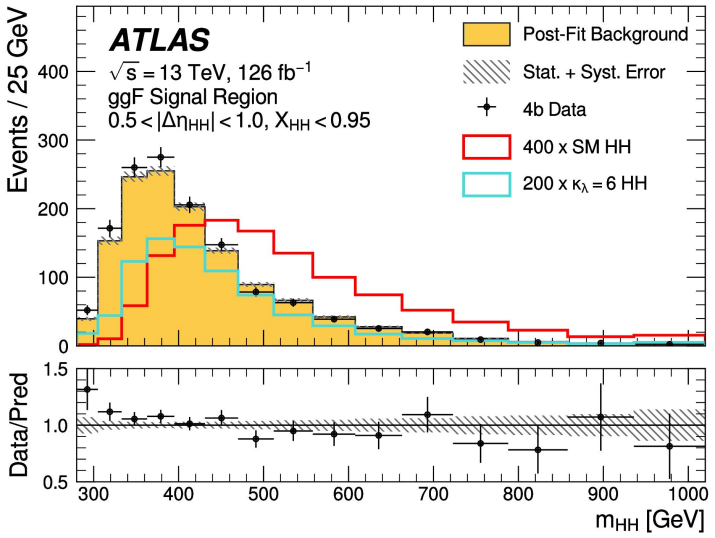
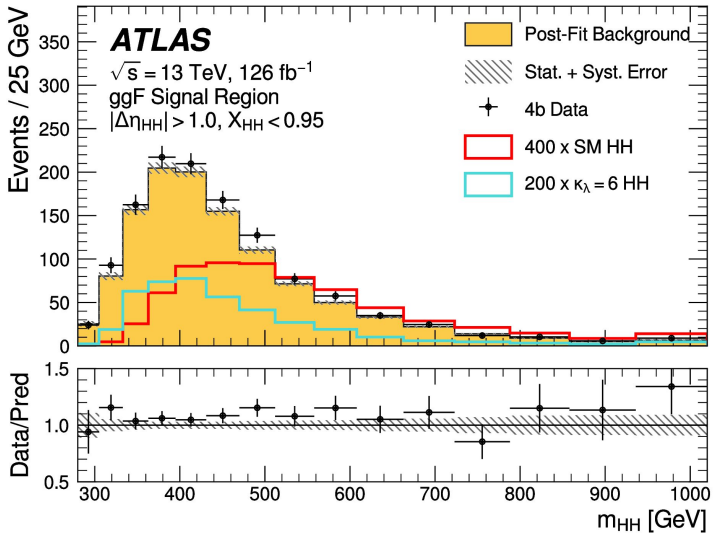
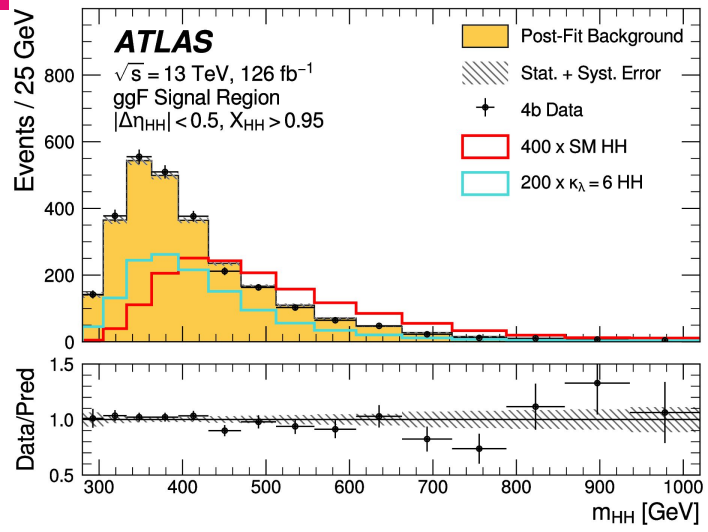
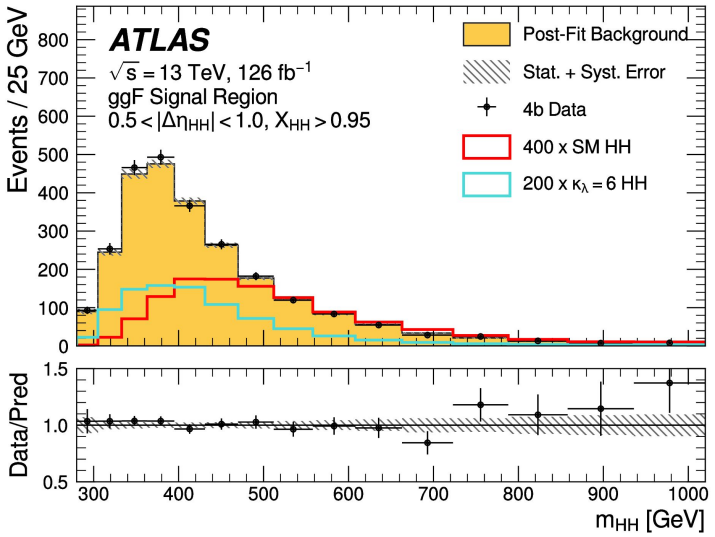
ggF selection

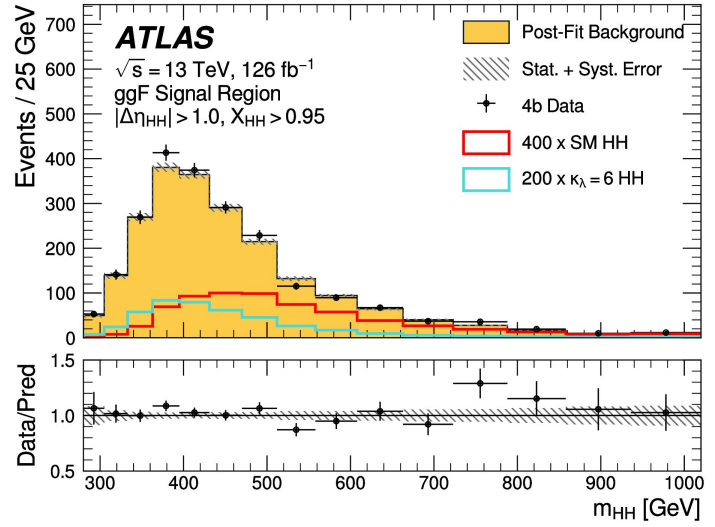












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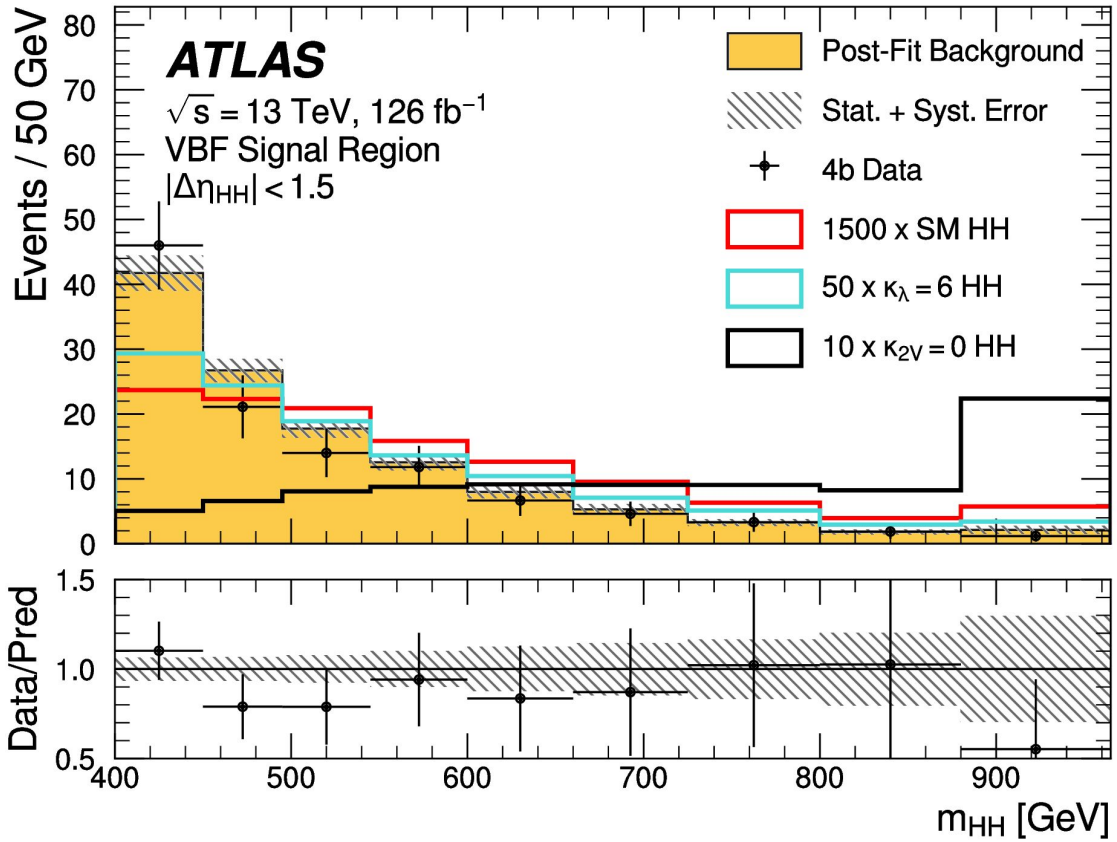
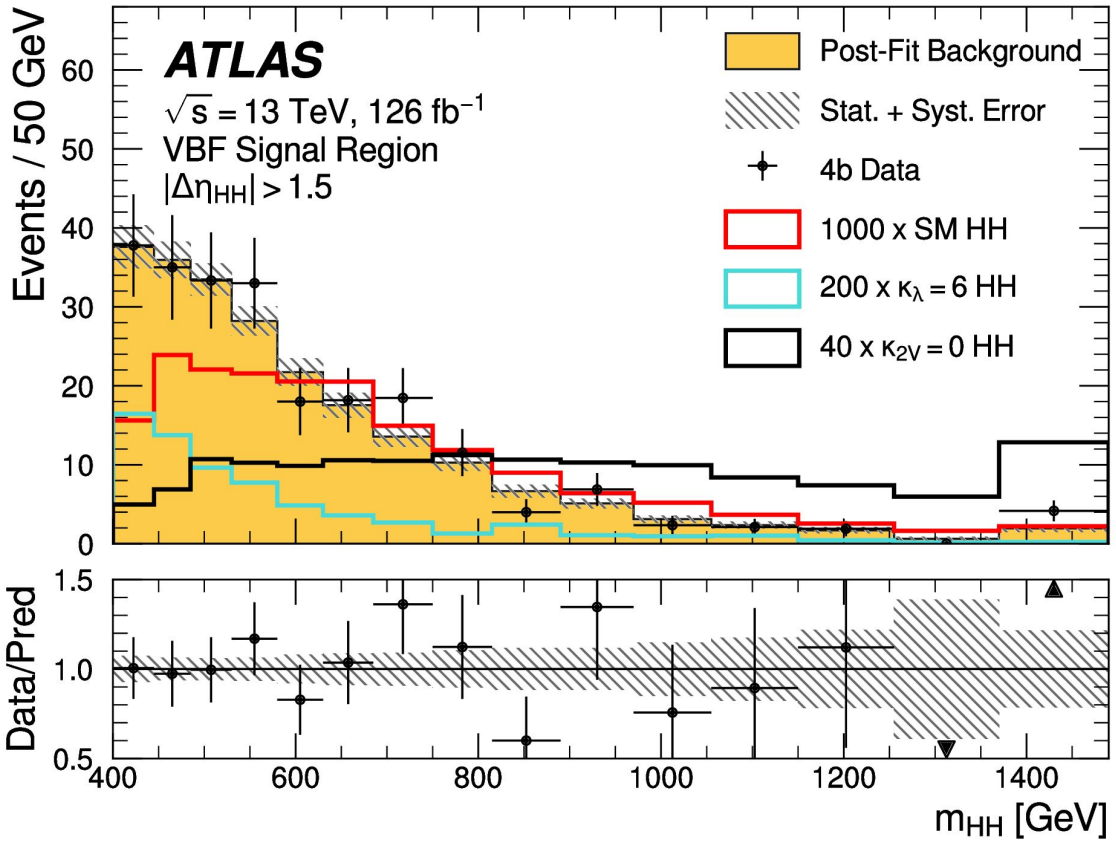
bbbb

Define different categories to improve analysis sensitivity.

[Phys. Rev. D 108 (2023) 052003]

VBF selection





bbbb

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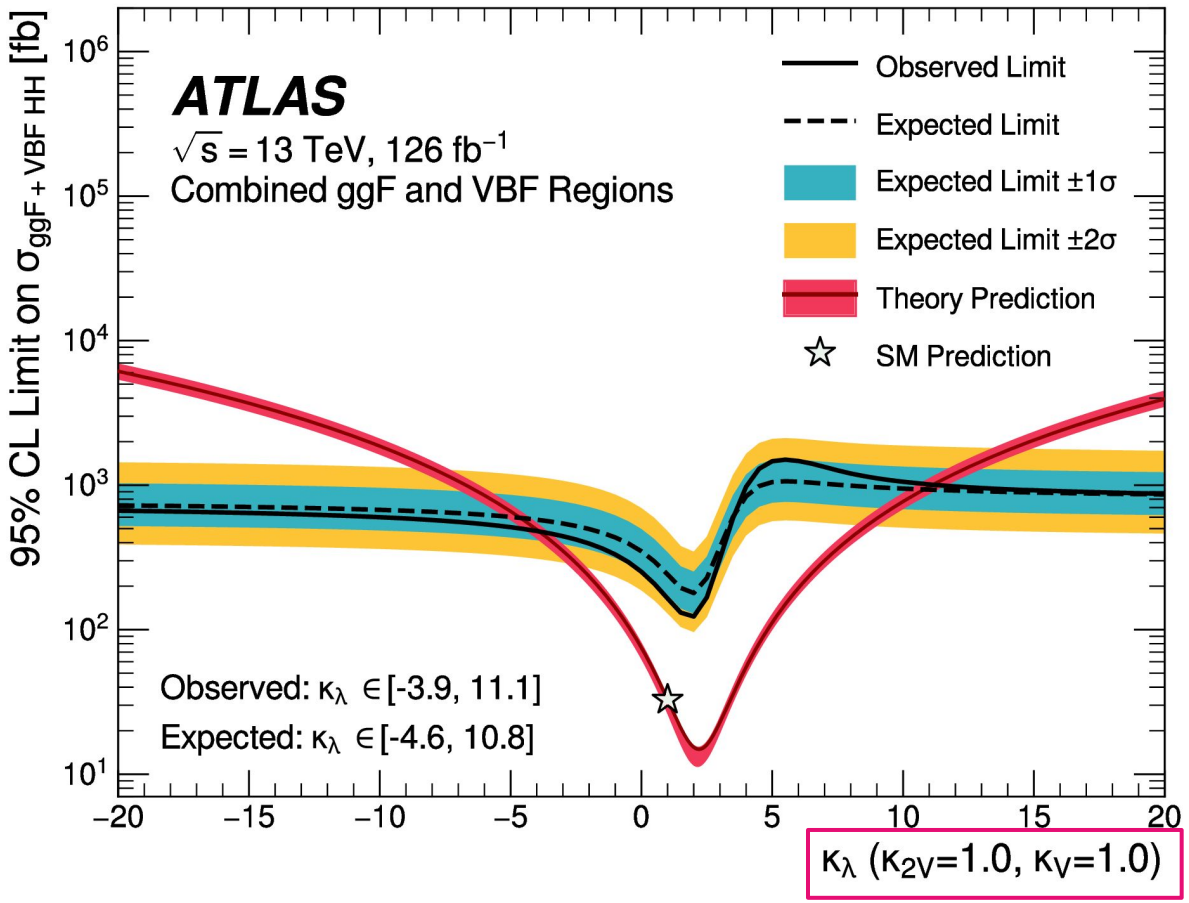
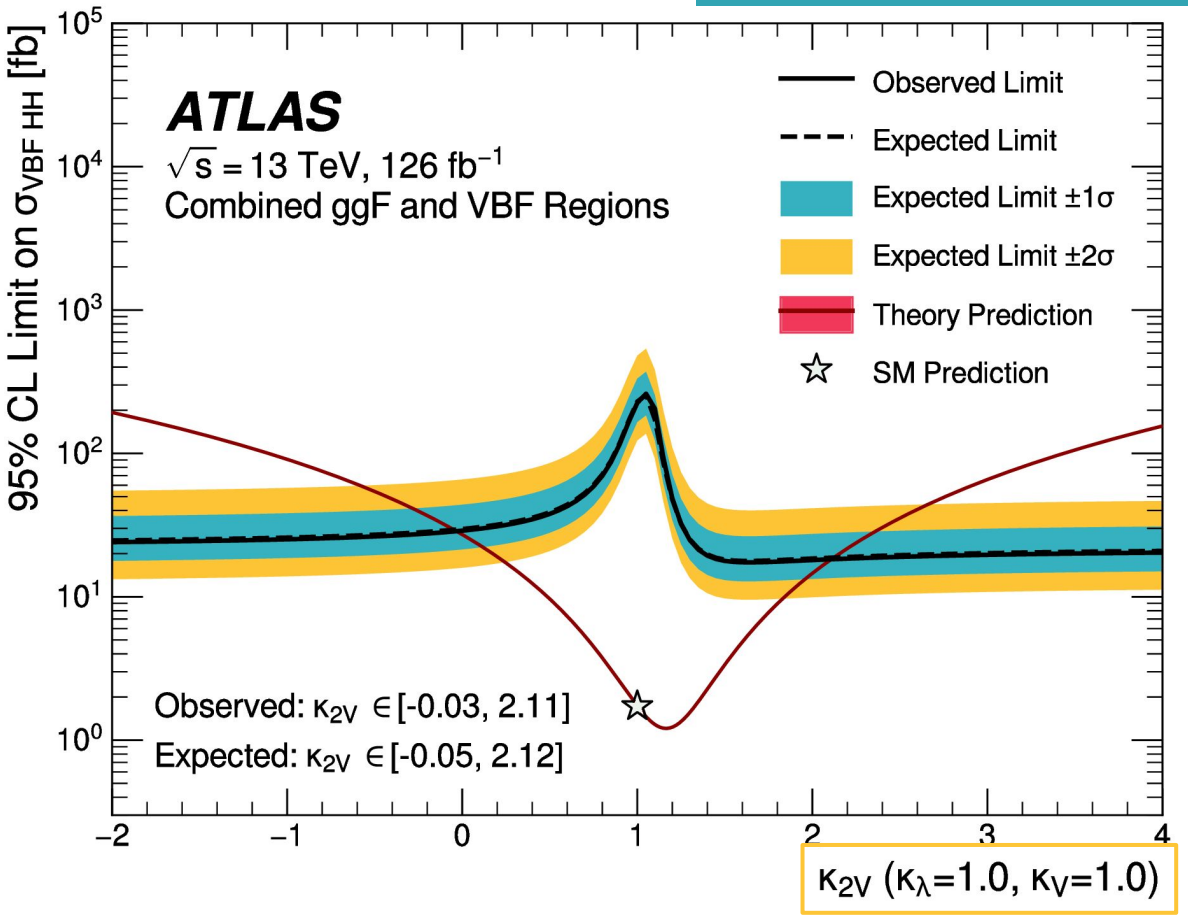


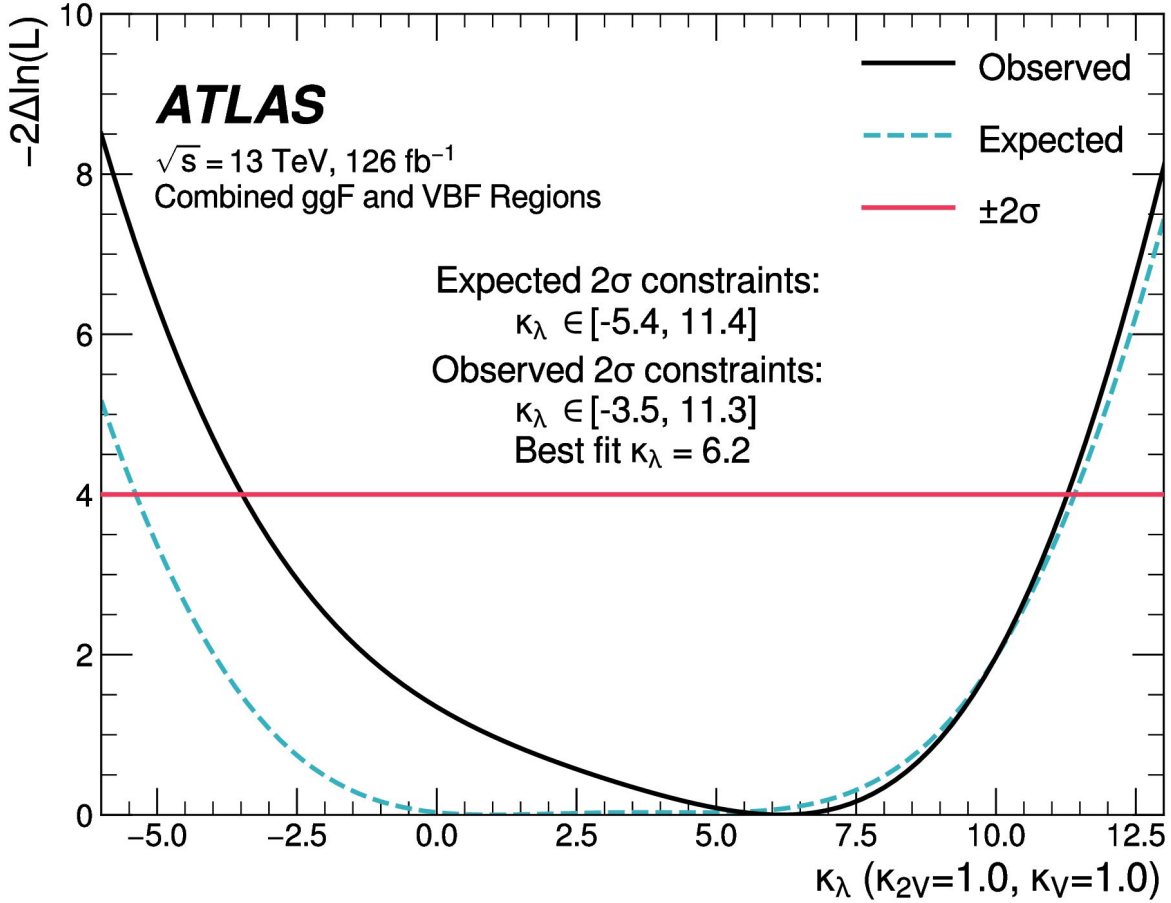


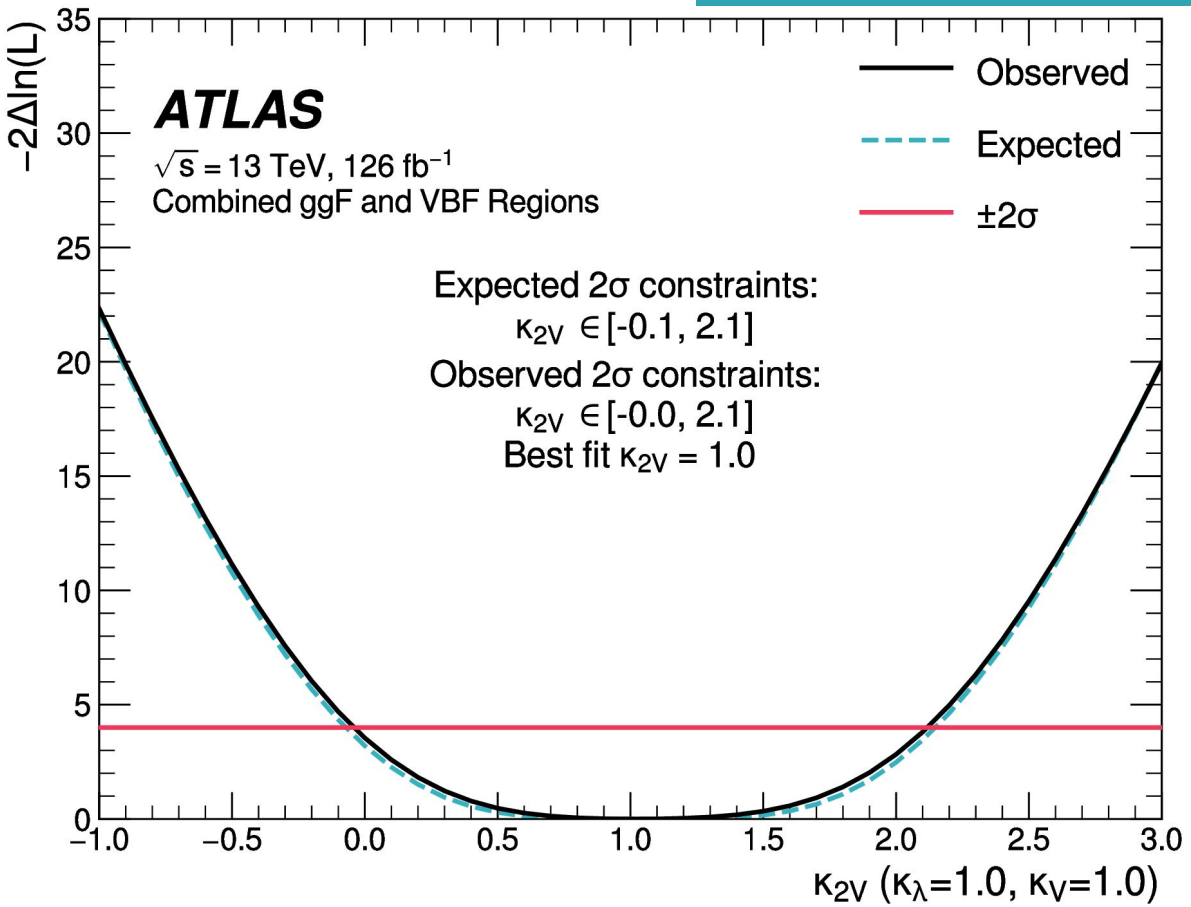
No evidence for a HH(bbbb) signal is found.

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.

bbbb

Phys. Rev. D 108 (2023) 052003





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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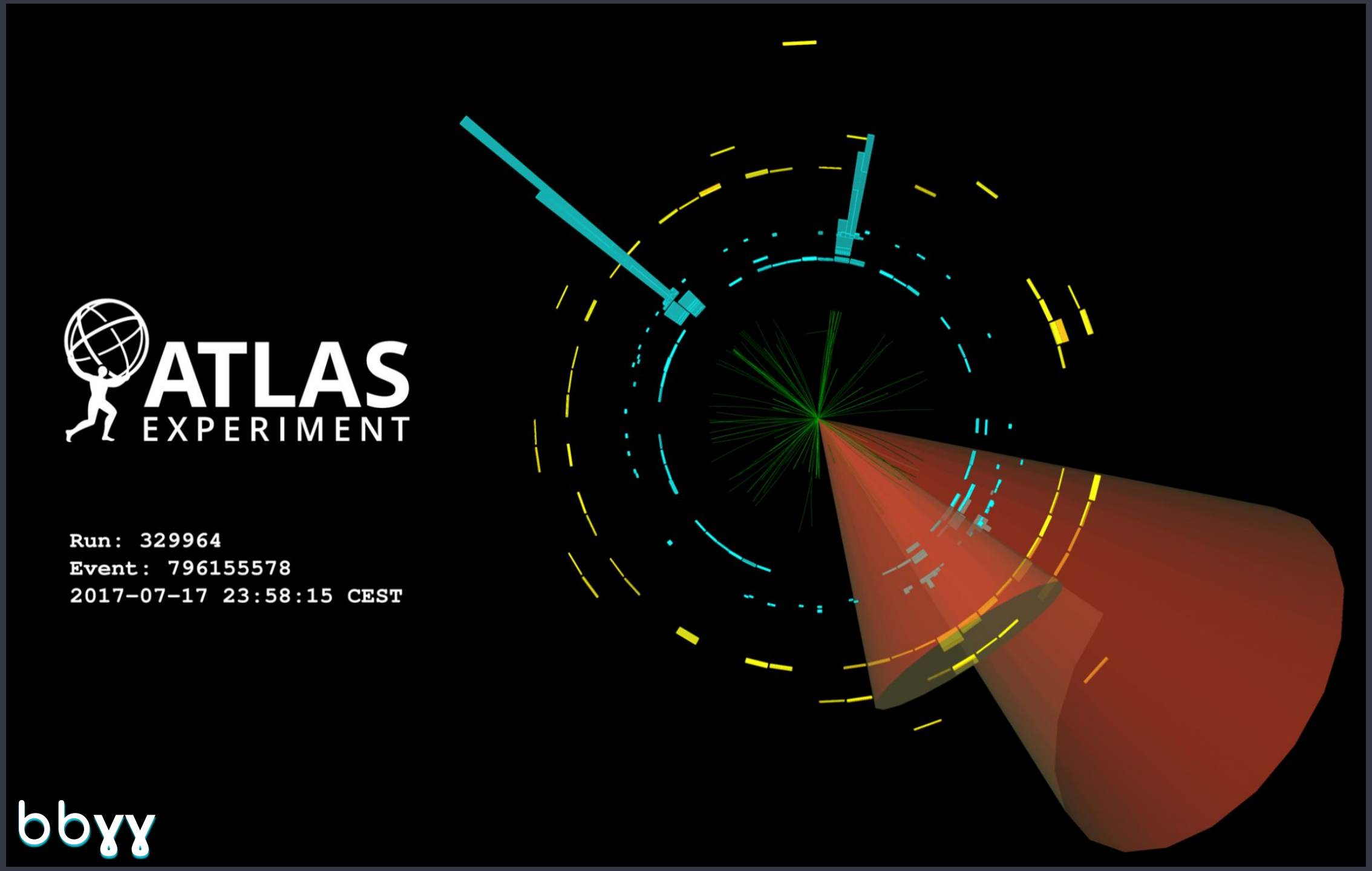
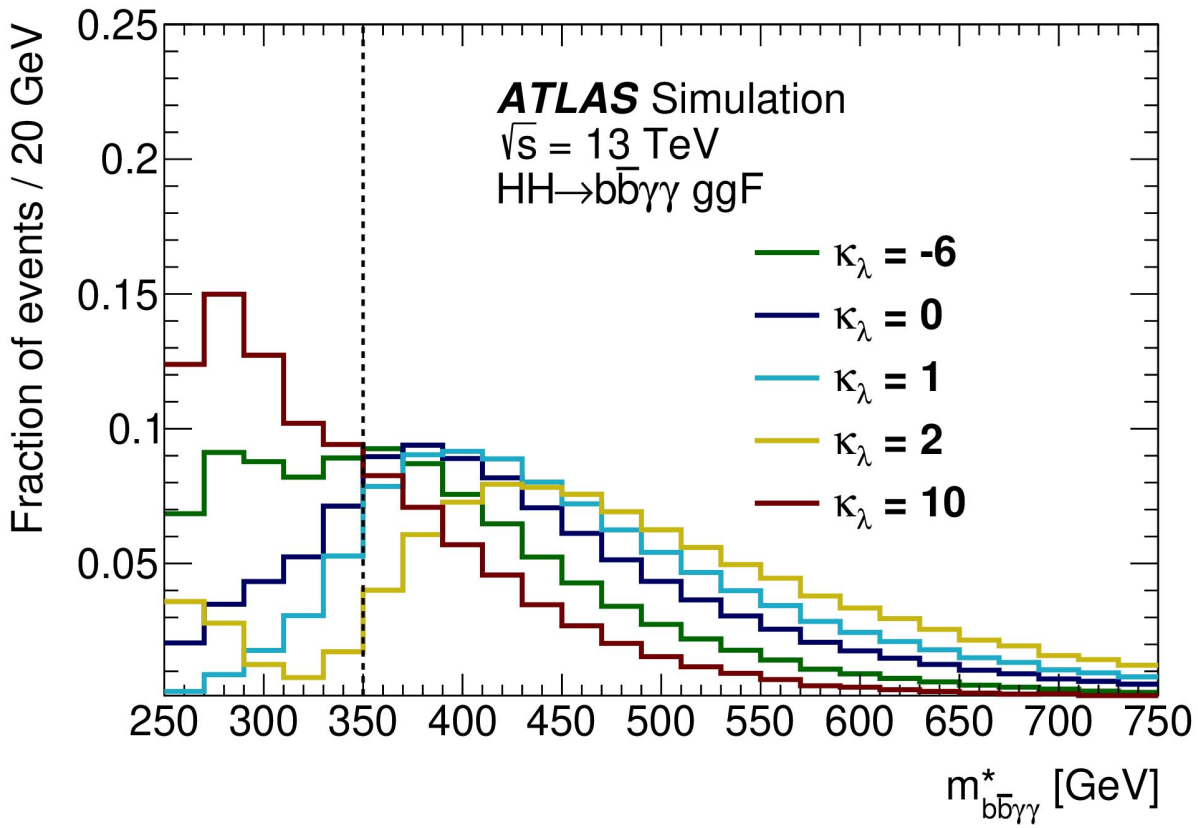
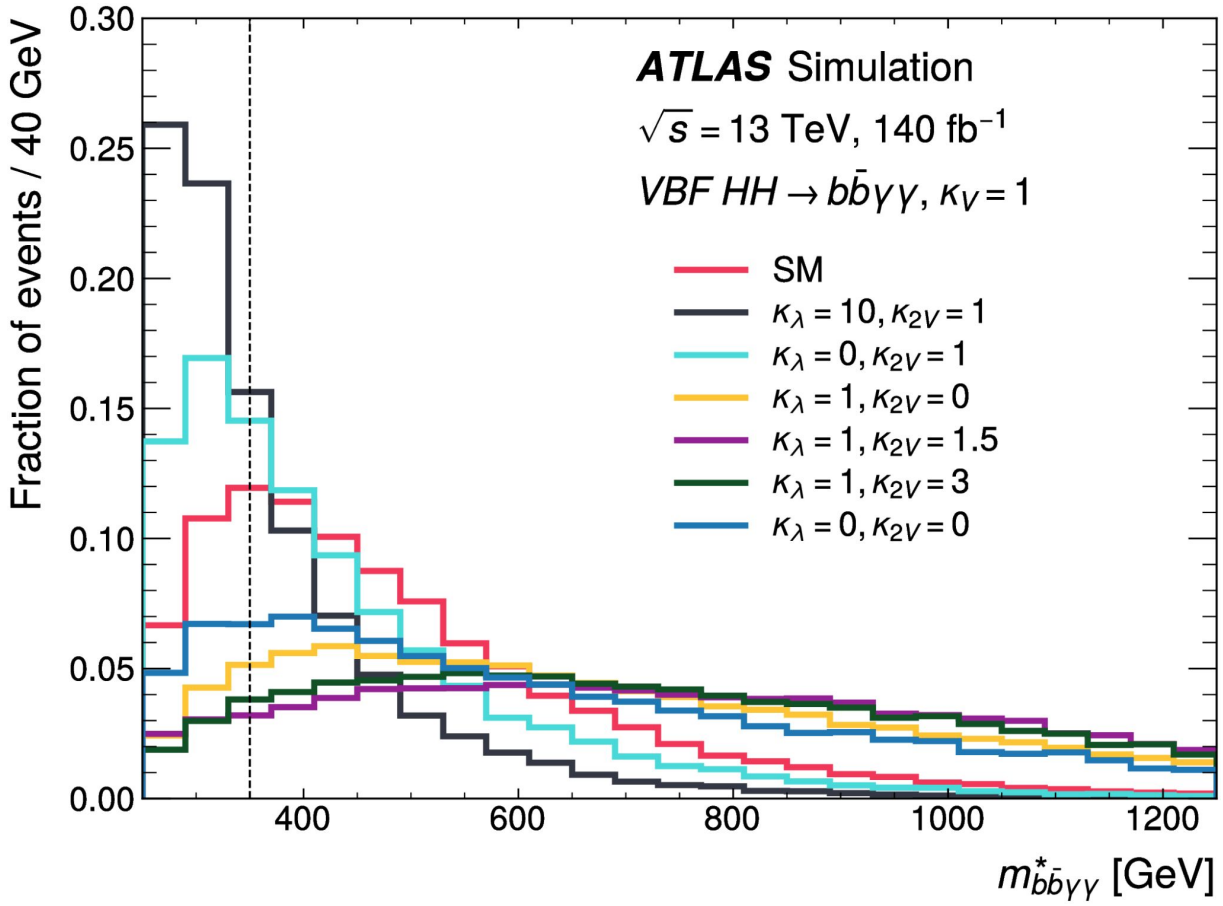

ATLAS
EXPERIMENT
Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST
bbγγ

bbγγ

JHEP 01 (2024) 066

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

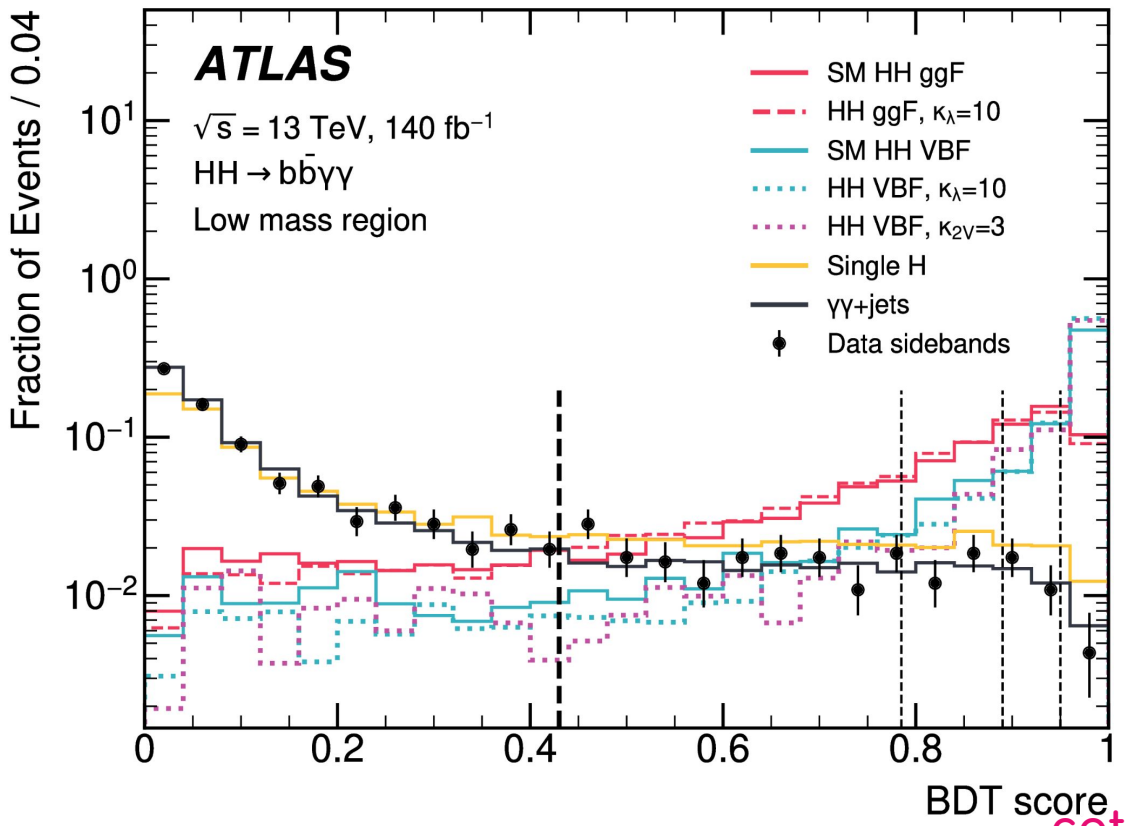


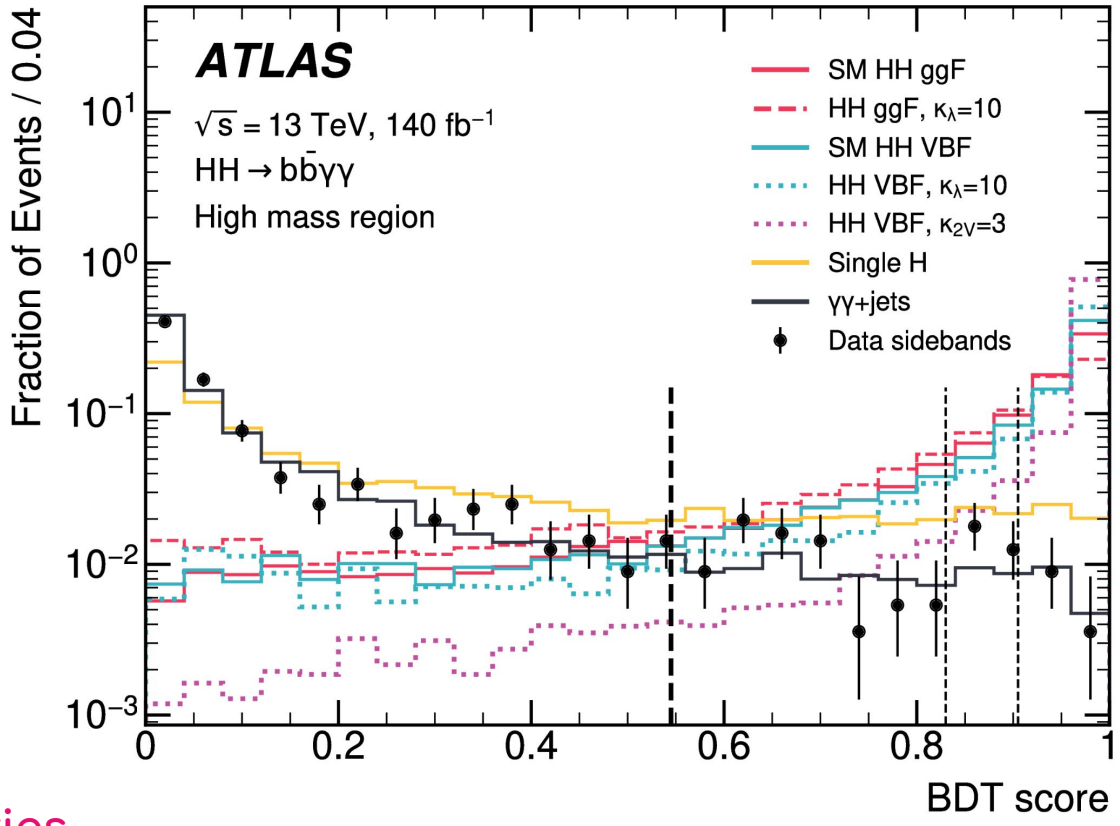


bbγγ

JHEP 01 (2024) 066

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





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 **further BDT categories**.

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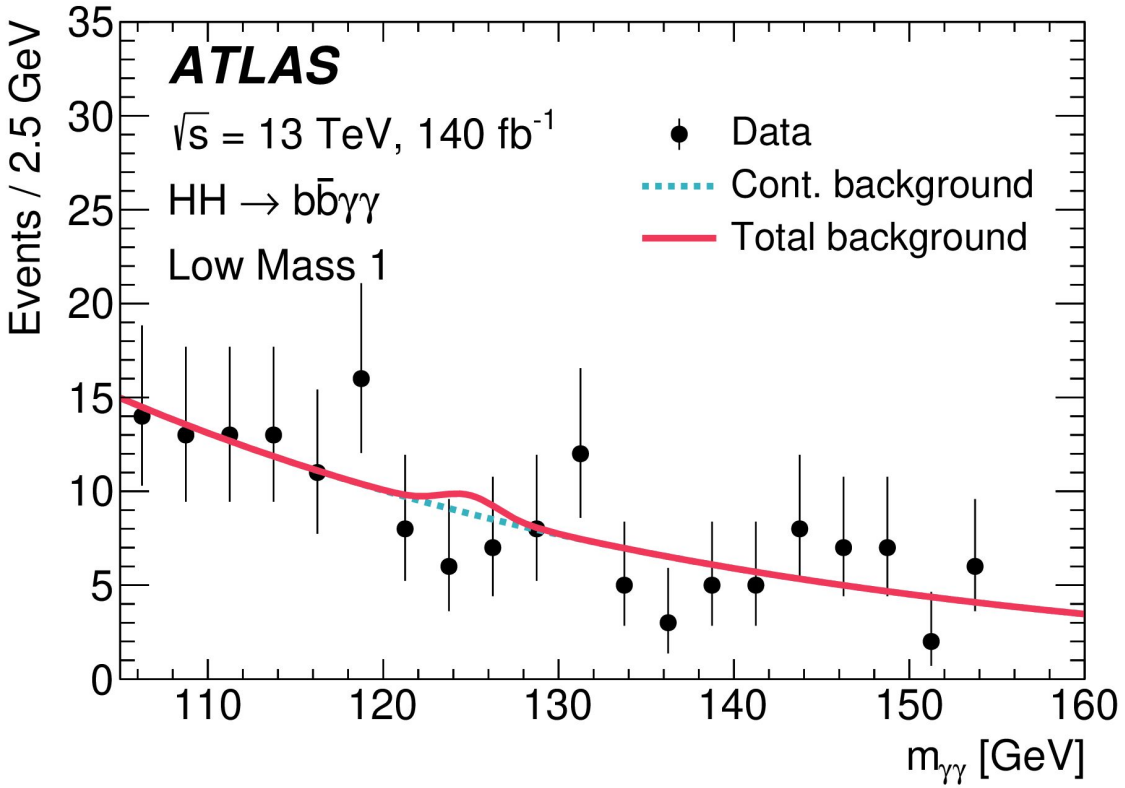
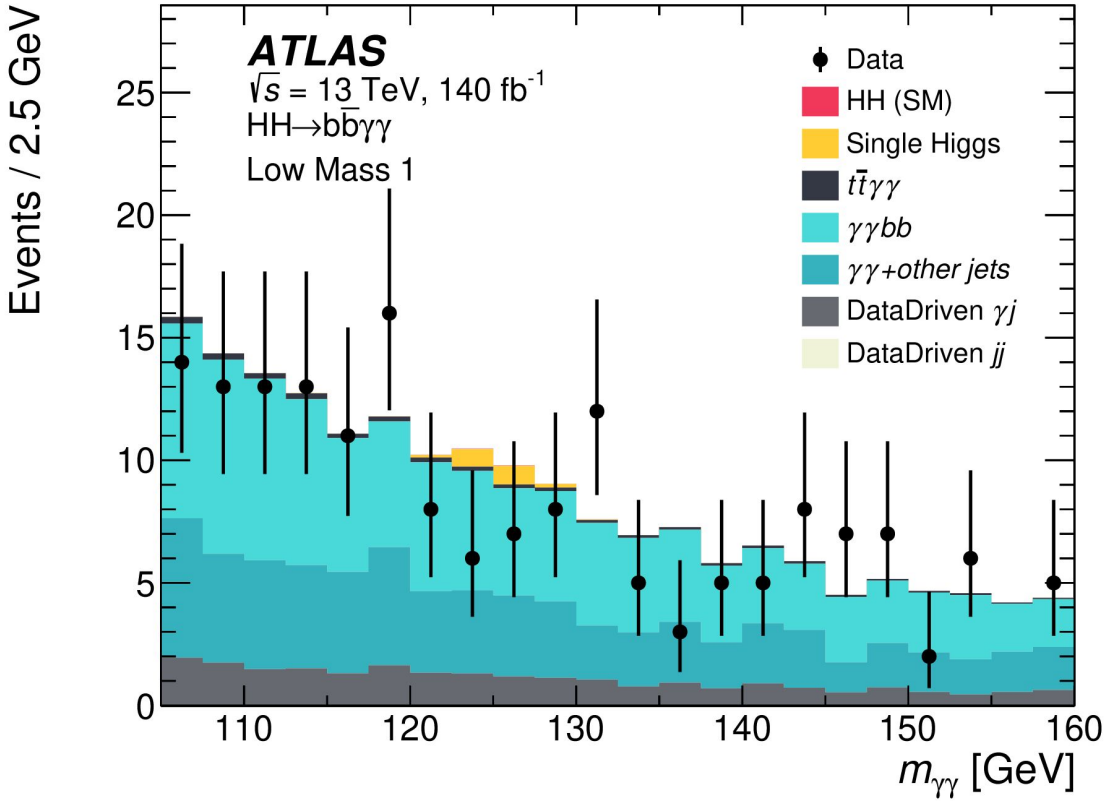
bbγγ

Ref

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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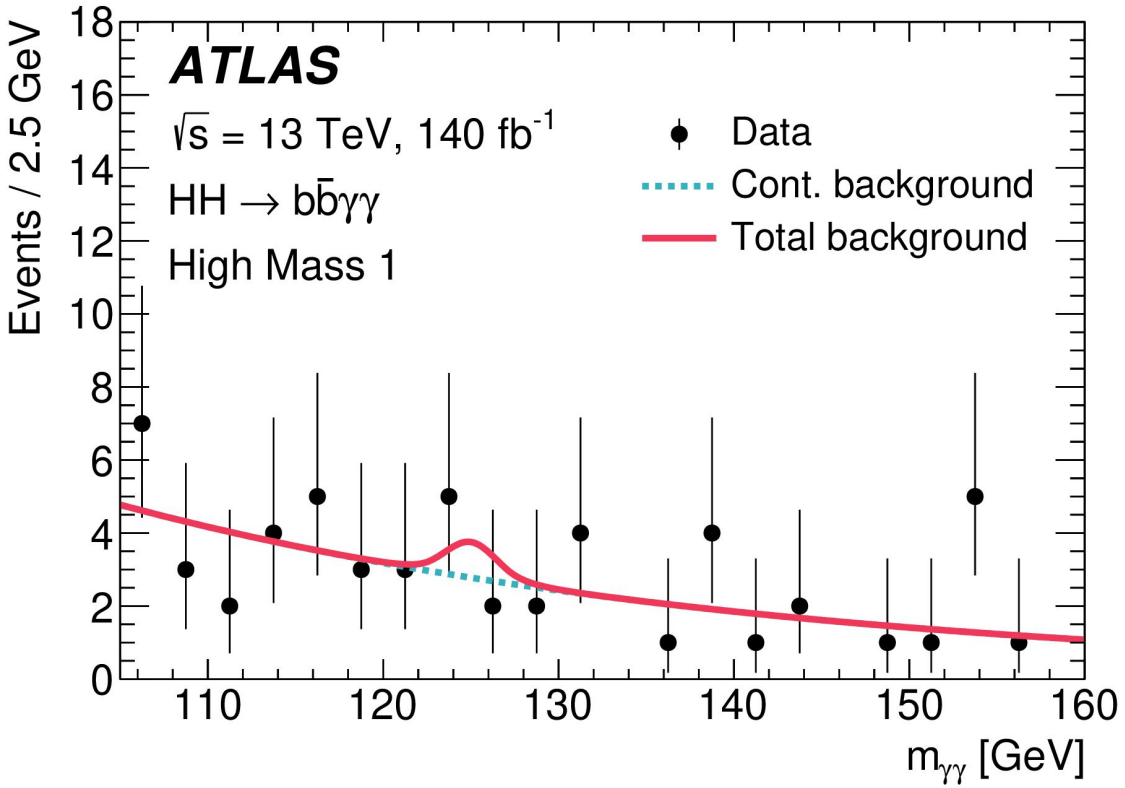
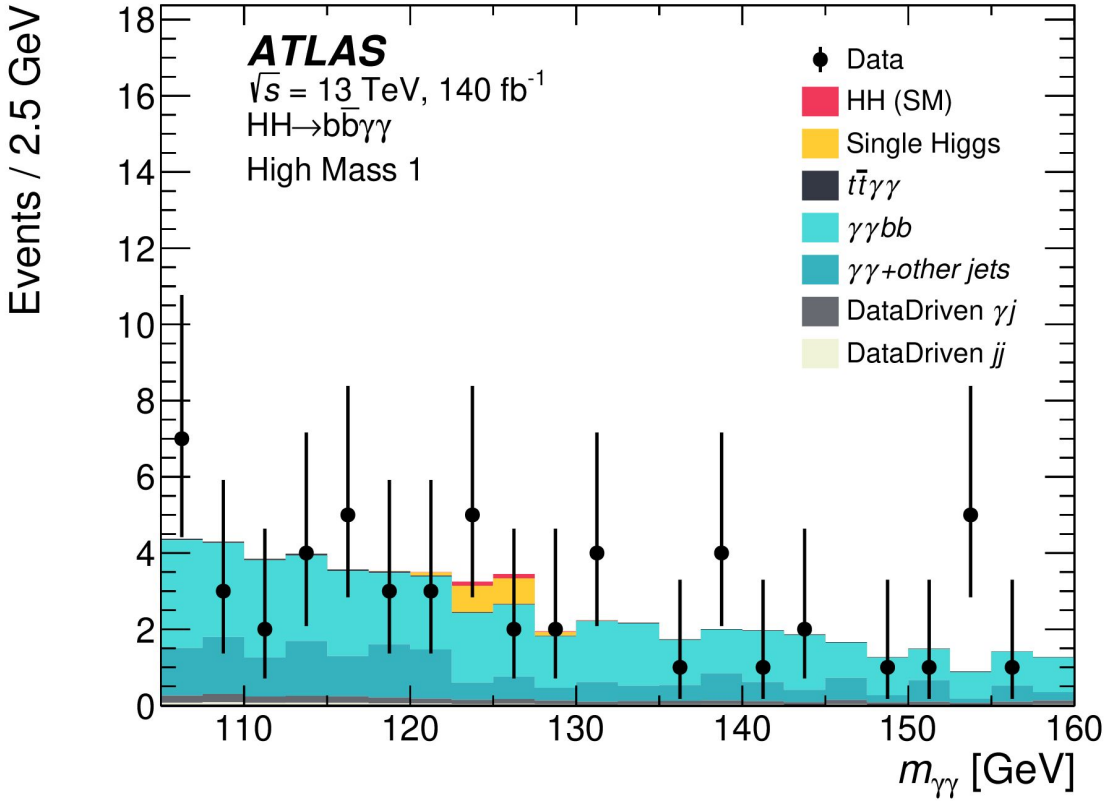
bbγγ

Ref

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



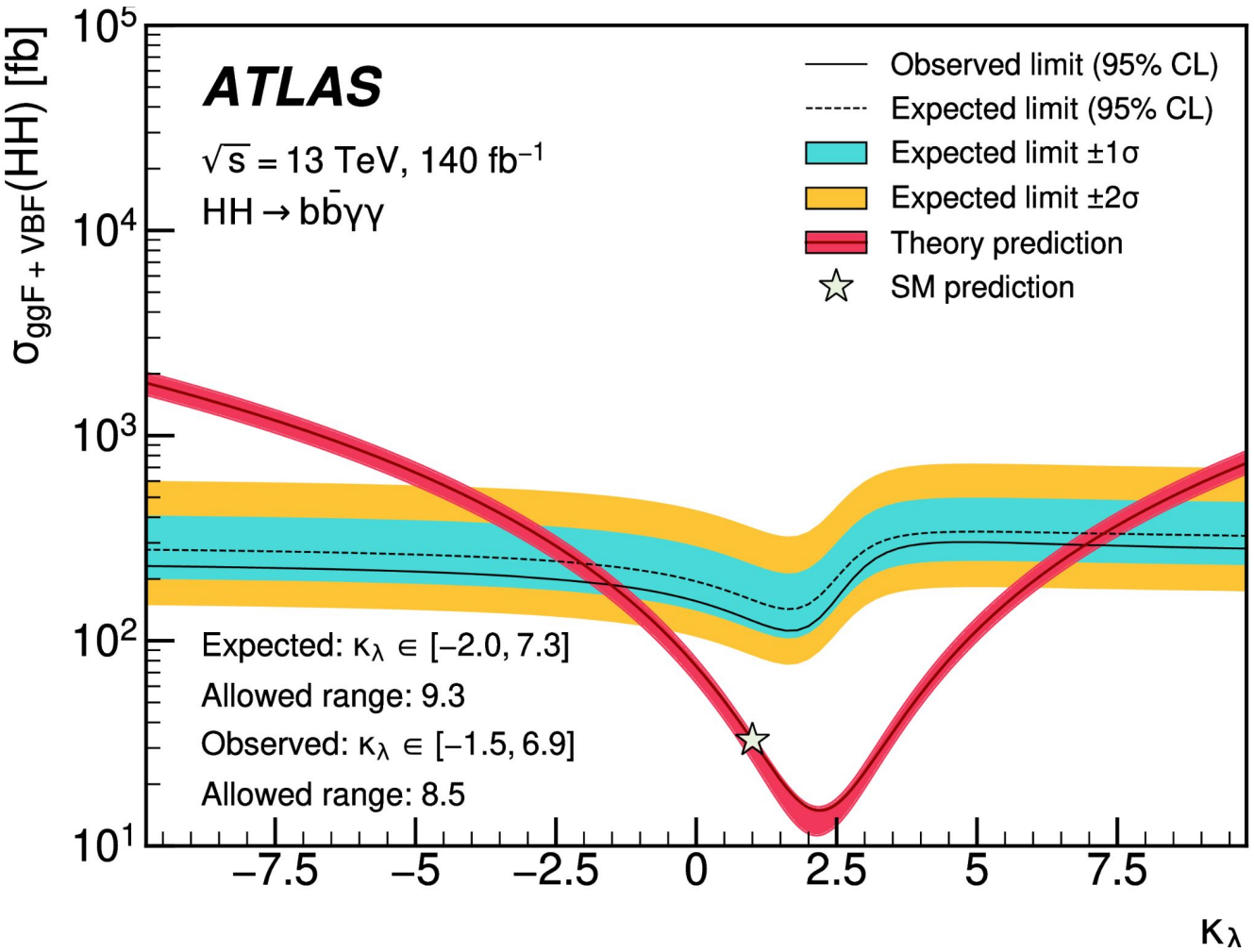


data-driven bkg estimation

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

bbγγ

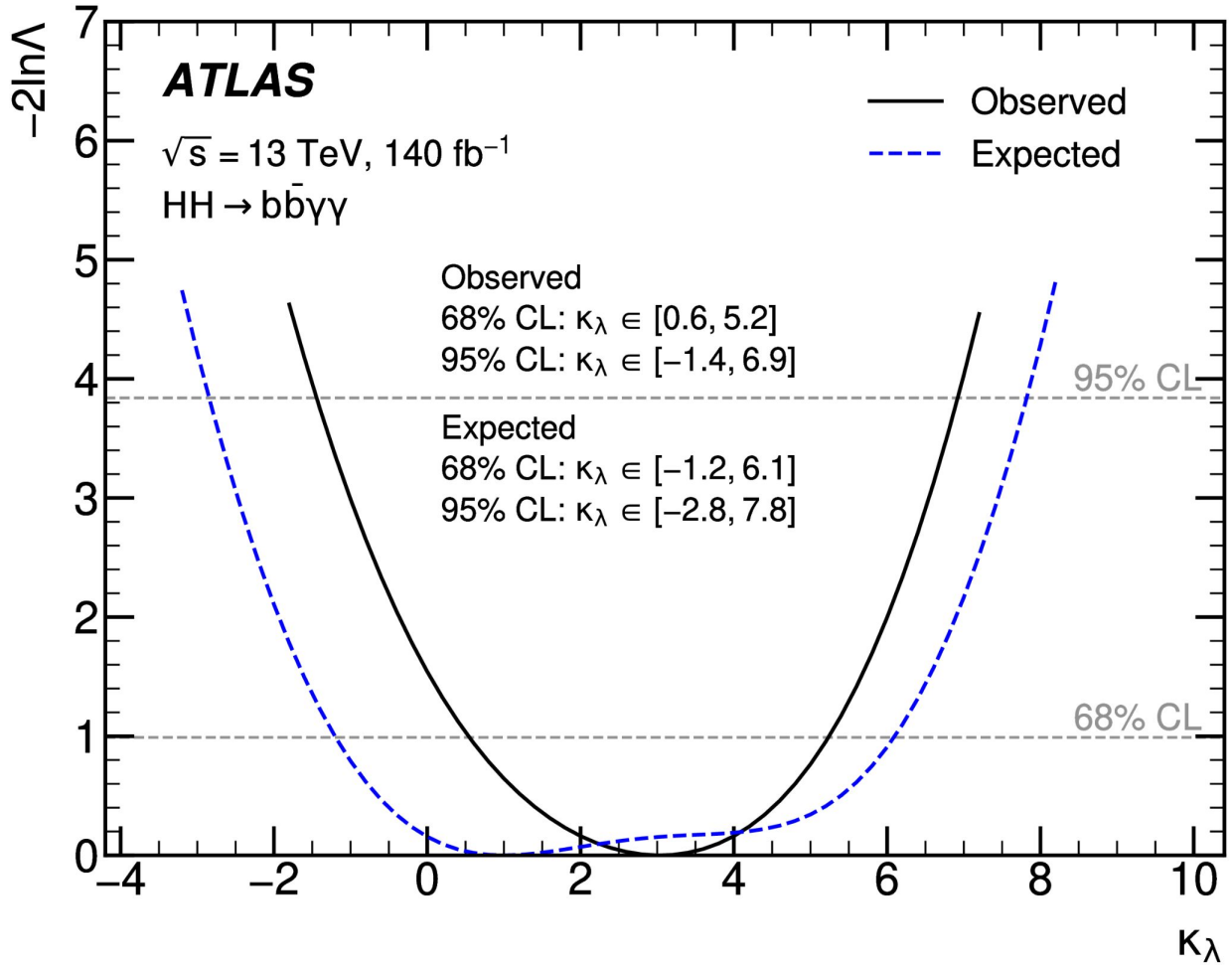
Ref

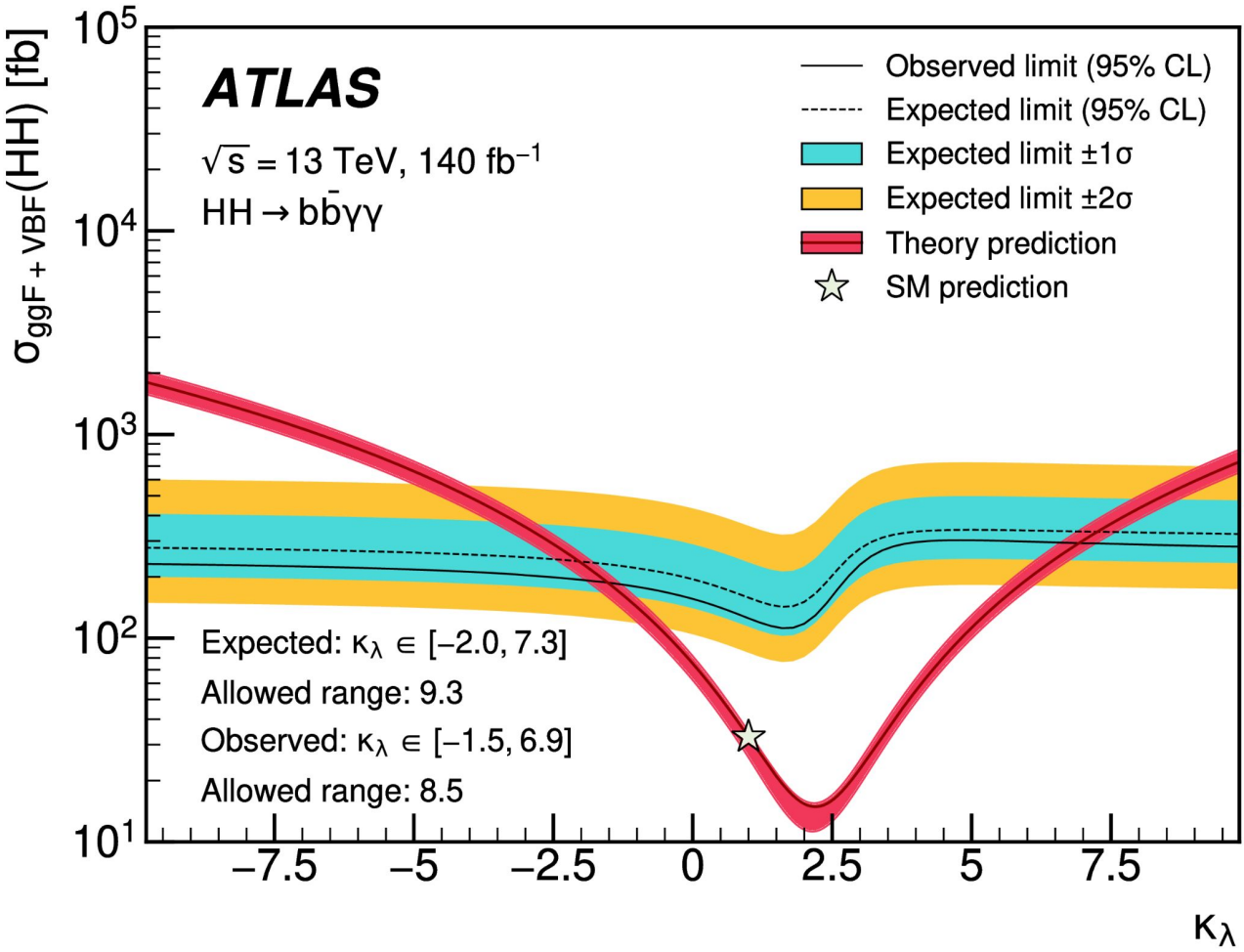


- Analysis dominated by statistical uncertainties.
- No evidence for a HH(bbγγ) signal is found.
- Observed (expected) limit on the cross section for ggF+VBF production is set to 4.2 (5.7) times the SM predicted cross section at 95% CL.

bbγγ

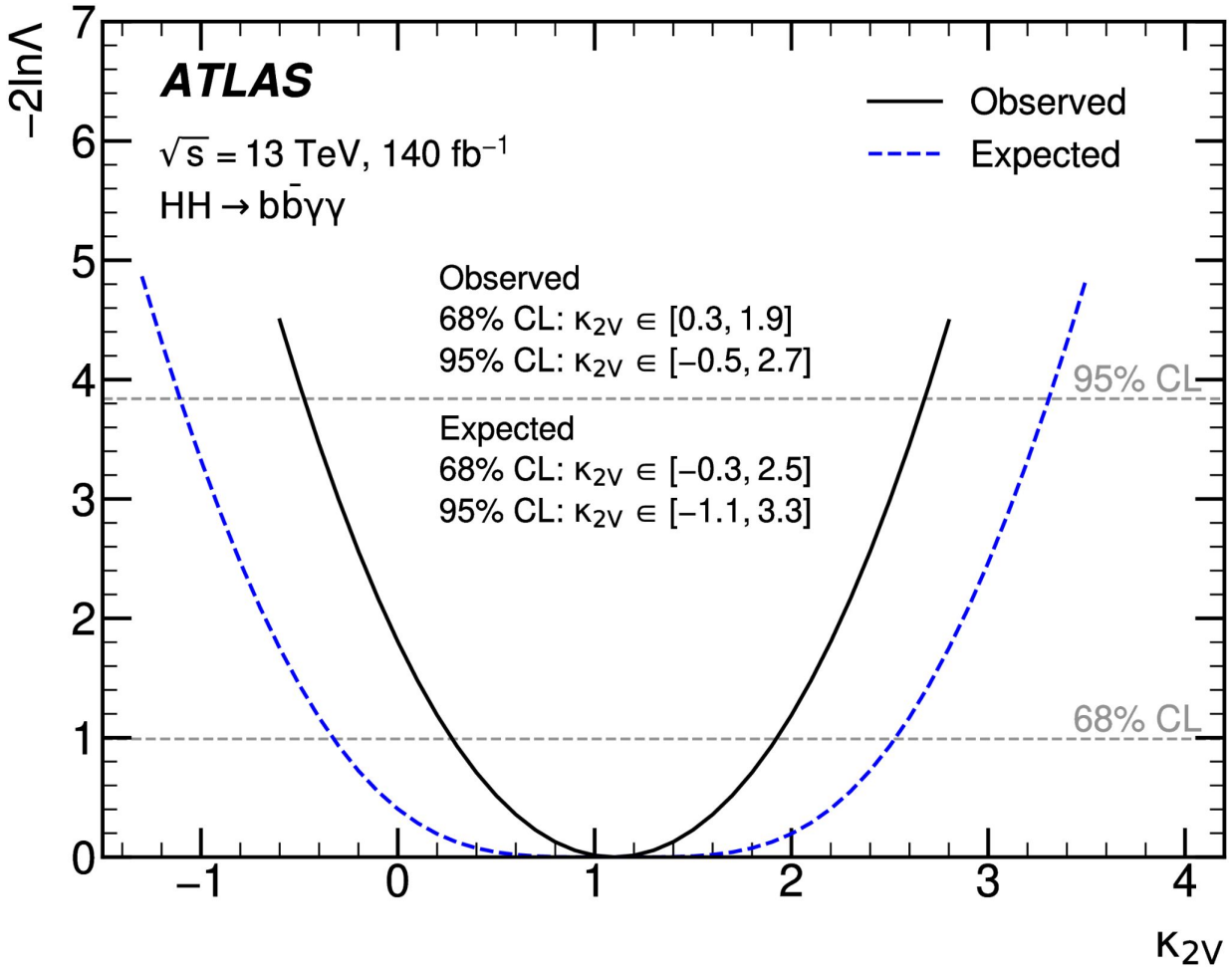
Ref

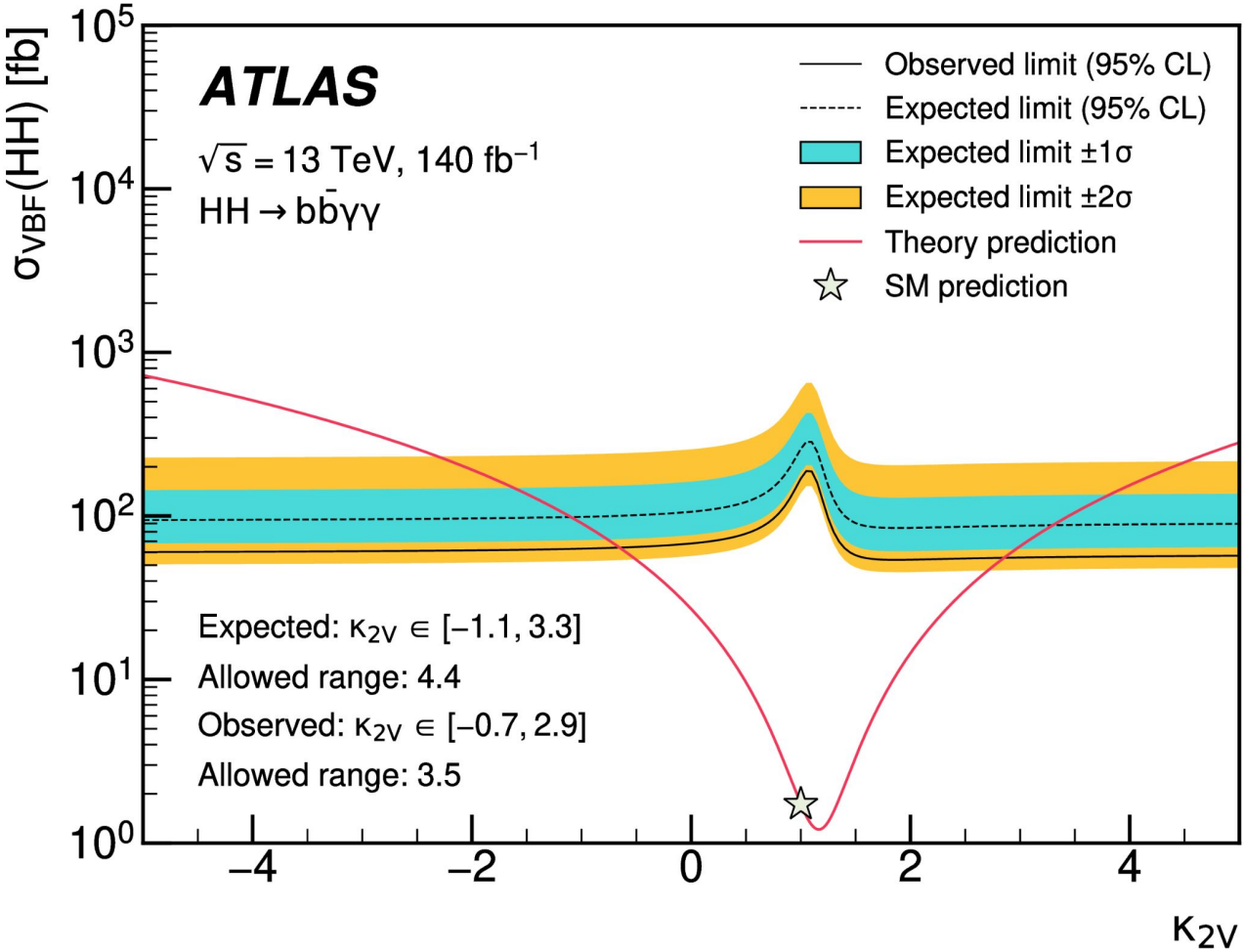

ATLAS
√s = 13 TeV, 140 fb⁻¹
HH → bb̄γγ
Observed
Expected
Observed
68% CL: κλ ∈ [0.6, 5.2]
95% CL: κλ ∈ [−1.4, 6.9]
Expected
68% CL: κλ ∈ [−1.2, 6.1]
95% CL: κλ ∈ [−2.8, 7.8]
95% CL
68% CL
−2lnΛ
κλ


ATLAS
√s = 13 TeV, 140 fb⁻¹
HH → bb̄γγ
Observed limit (95% CL)
Expected limit (95% CL)
Expected limit ±1σ
Expected limit ±2σ
Theory prediction
SM prediction
Expected: κλ ∈ [−2.0, 7.3]
Allowed range: 9.3
Observed: κλ ∈ [−1.5, 6.9]
Allowed range: 8.5
σggF + VBF(HH) [fb]
κλ

bbγγ

Ref


ATLAS
√s = 13 TeV, 140 fb⁻¹
HH → bb̄γγ
Observed
Expected
Observed
68% CL: κ2V ∈ [0.3, 1.9]
95% CL: κ2V ∈ [−0.5, 2.7]
Expected
68% CL: κ2V ∈ [−0.3, 2.5]
95% CL: κ2V ∈ [−1.1, 3.3]
95% CL
68% CL
−2lnΛ
κ2V


ATLAS
√s = 13 TeV, 140 fb⁻¹
HH → bb̄γγ
Observed limit (95% CL)
Expected limit (95% CL)
Expected limit ±1σ
Expected limit ±2σ
Theory prediction
SM prediction
Expected: κ2V ∈ [−1.1, 3.3]
Allowed range: 4.4
Observed: κ2V ∈ [−0.7, 2.9]
Allowed range: 3.5
σVBF(HH) [fb]
κ2V