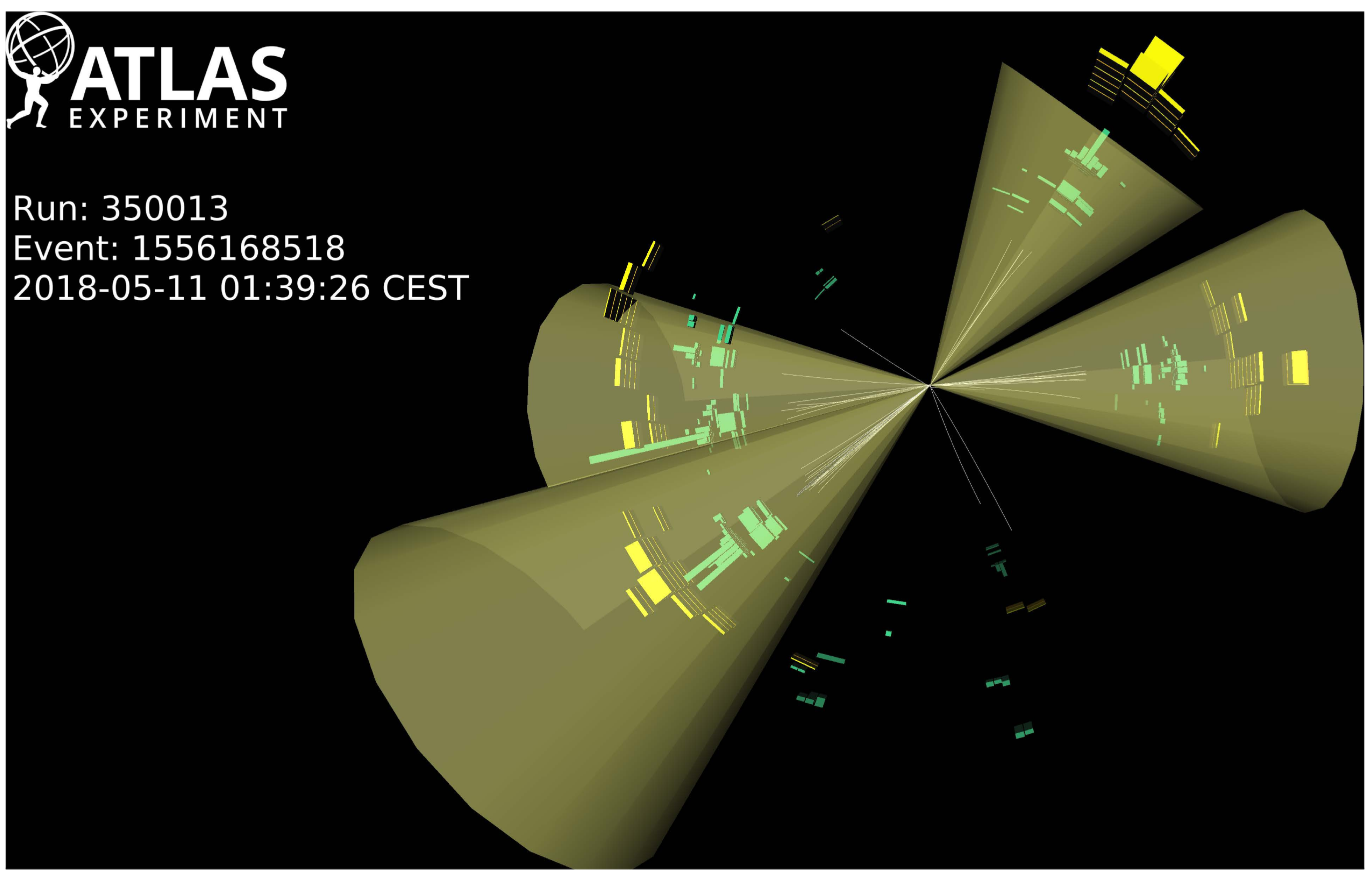
HH→4b searches in ATLAS



Rui Zhang

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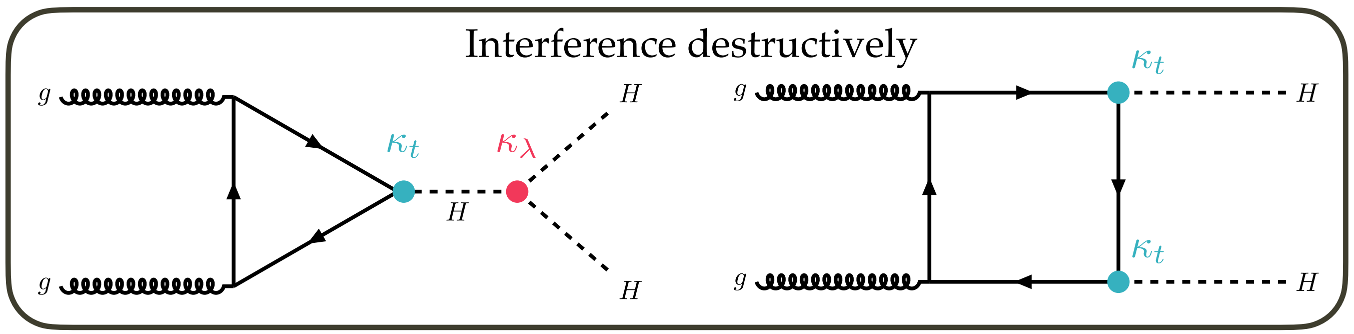
Higgs Potential Conference (Beijing)

26 July 2022

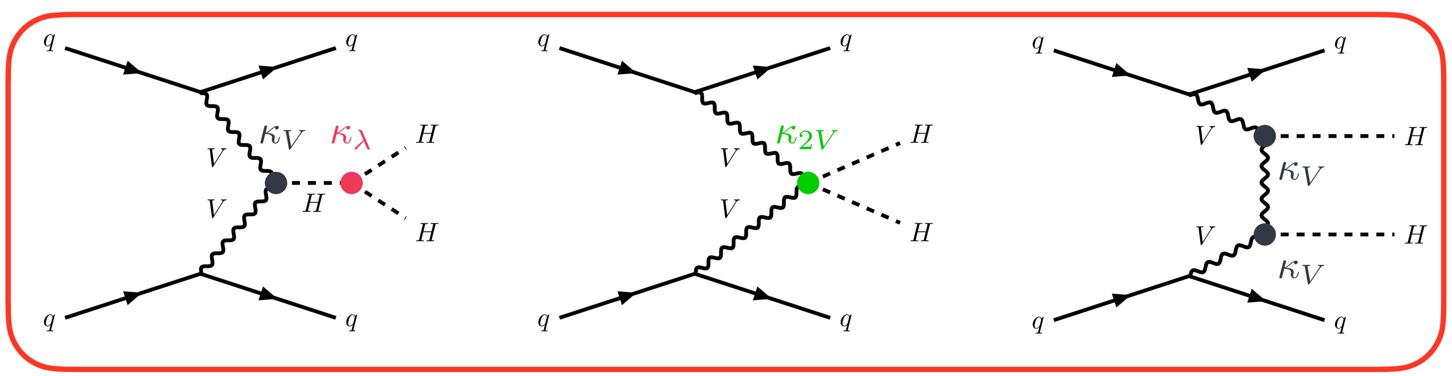
HH production and decay at LHC

σ_{HH} @ 13 TeV ~ 30 fb
(1000x **smaller** than single H)

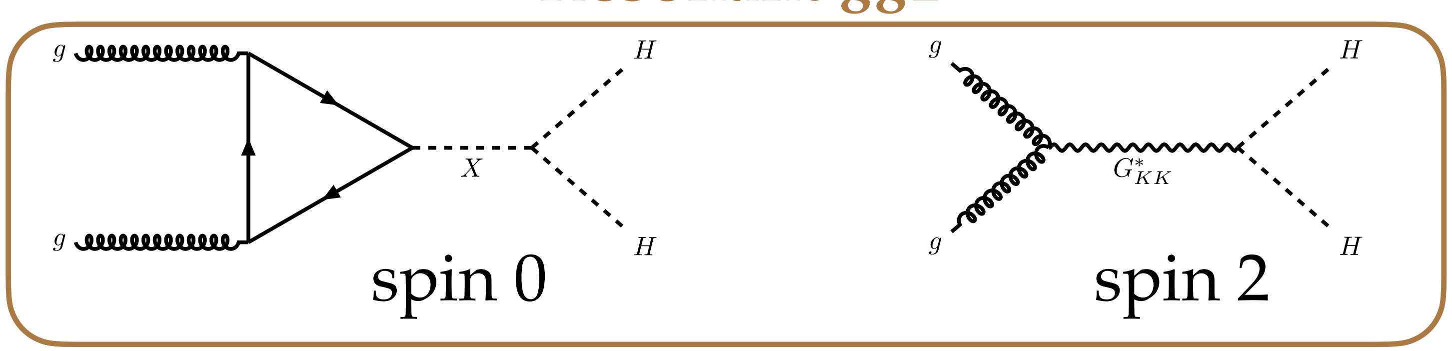
Non-resonant σ^{ggF} = 31.05 fb



Non-resonant σ^{VBF} = 1.73 fb



Resonant *ggF*



Large branching ratio

Clean final state

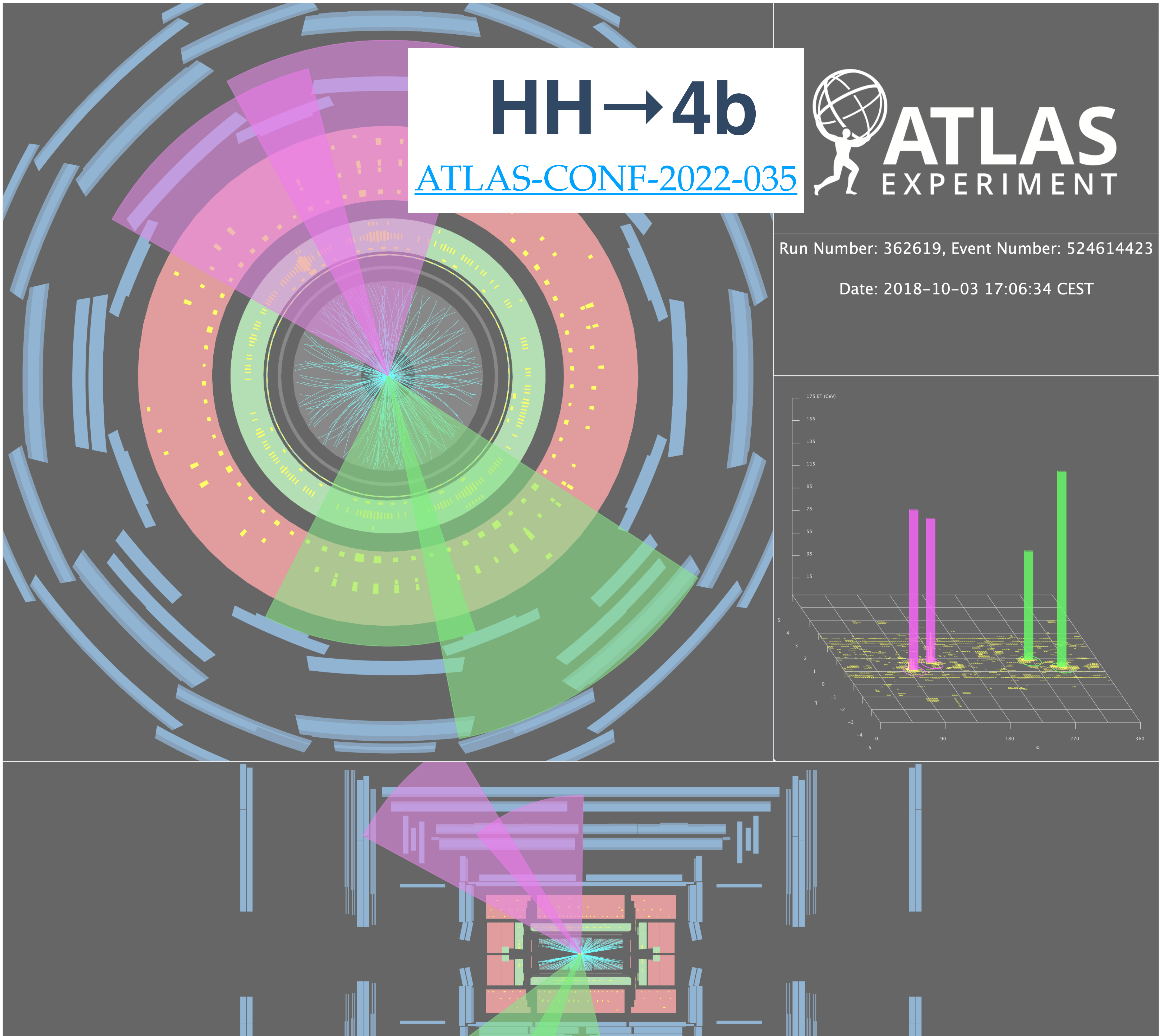
	bb	WW	ττ	ZZ	γγ
bb	34 %				
WW	25 %	4.6 %			
ττ	7.3 %	2.7 %	0.39 %		
ZZ	3.1 %	1.1 %	0.33 %	0.069 %	
γγ	0.26 %	0.10 %	0.028 %	0.012 %	0.0005 %

Combination of various final states fundamental for observation!

New physics can manifest as deviations in σ_{HH}

HH→4b

ATLAS-CONF-2022-035



The HH→4b channel

Largest HH rate ~ 1.5K SM events produced in Run 2 (140 fb^{-1})

But searching for signal events is challenged by the large production of multi-jet bkg events (QCD multijet 90–95%, top quarks (5–10%)

Experimental challenges:

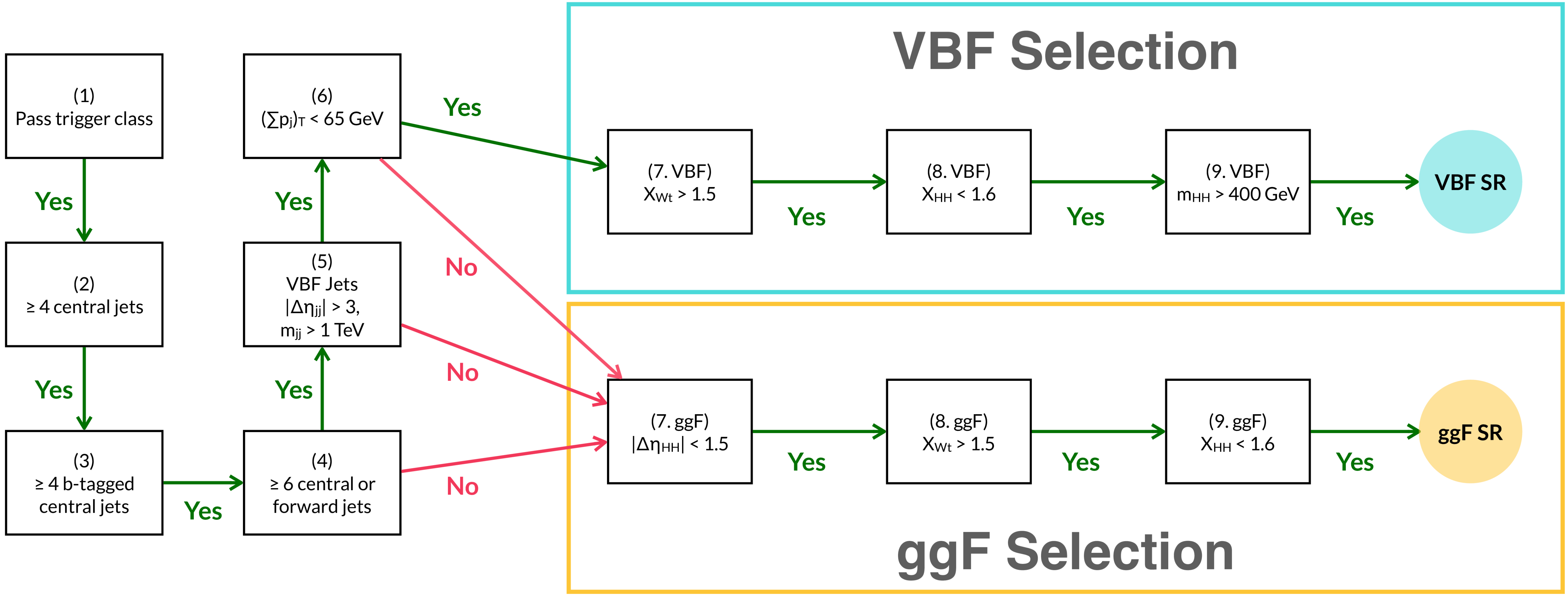
- Online trigger algorithms are complex
  - Depends on Level 1 (L1) seed, High level trigger (HLT) tracking, jet reconstruction/calibration, b-tagging, etc
  - Constrained by L1 rate, HLT CPU limit & output rate
  - Consistency with offline algorithms (e.g. offline b-tagging)
- b quark jet or H jet identification w.r.t large u/s/d/c/g jet bkg
- Higgs boson reconstruction affected by
  - Large jet combinatorics
  - Missing energy from neutrinos in semi-leptonic B decays
  - Jet constituents from Initial/Final state radiation & Pile-up
- Precise model and rejection of multijet bkg are crucial

Event selection — kinematics

Central jets:
pT > 40 GeV
$|\eta| < 2.5$

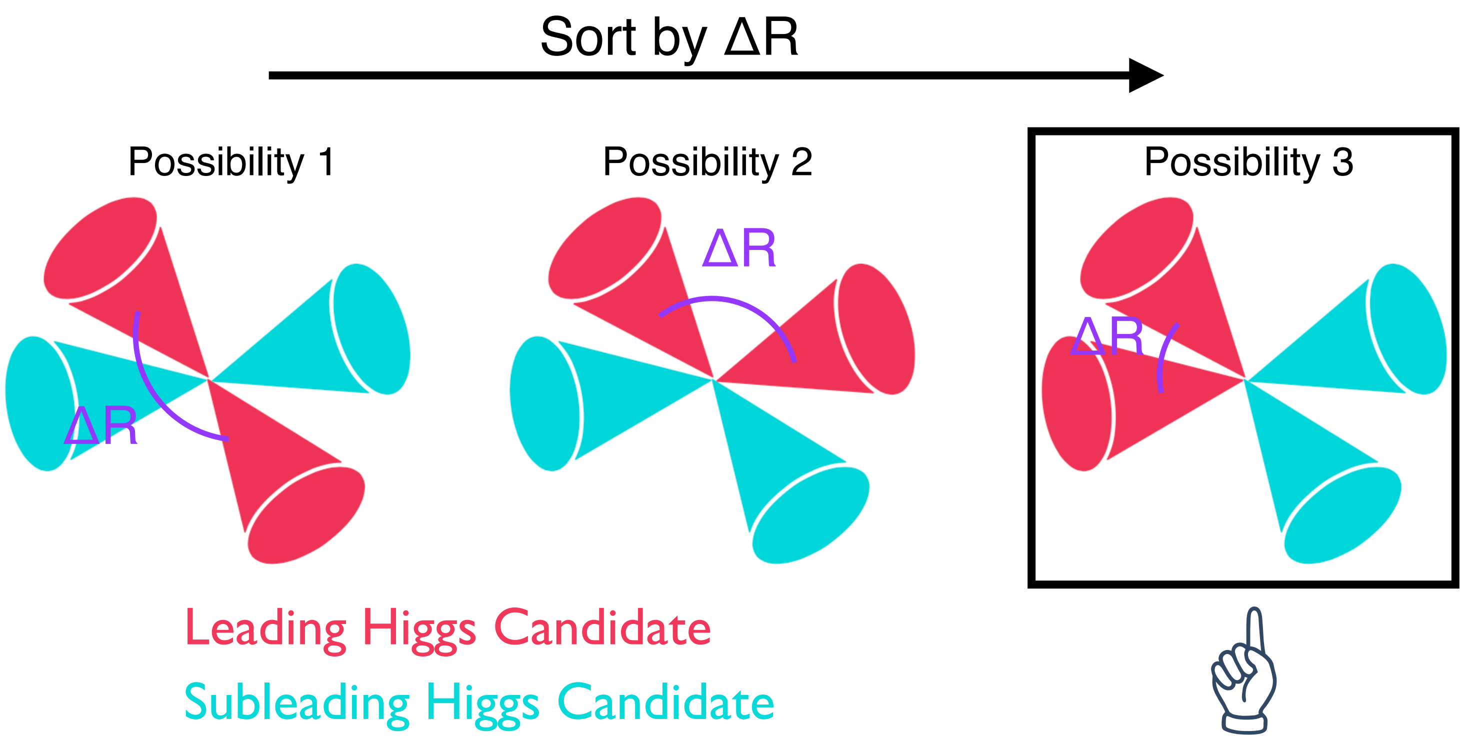
Forward jets:
pT > 30 GeV
$|\eta| > 2.5$

VBF jets:
Pair of non b-tagged jets,
in central+forward selection, with highest m_{jj}

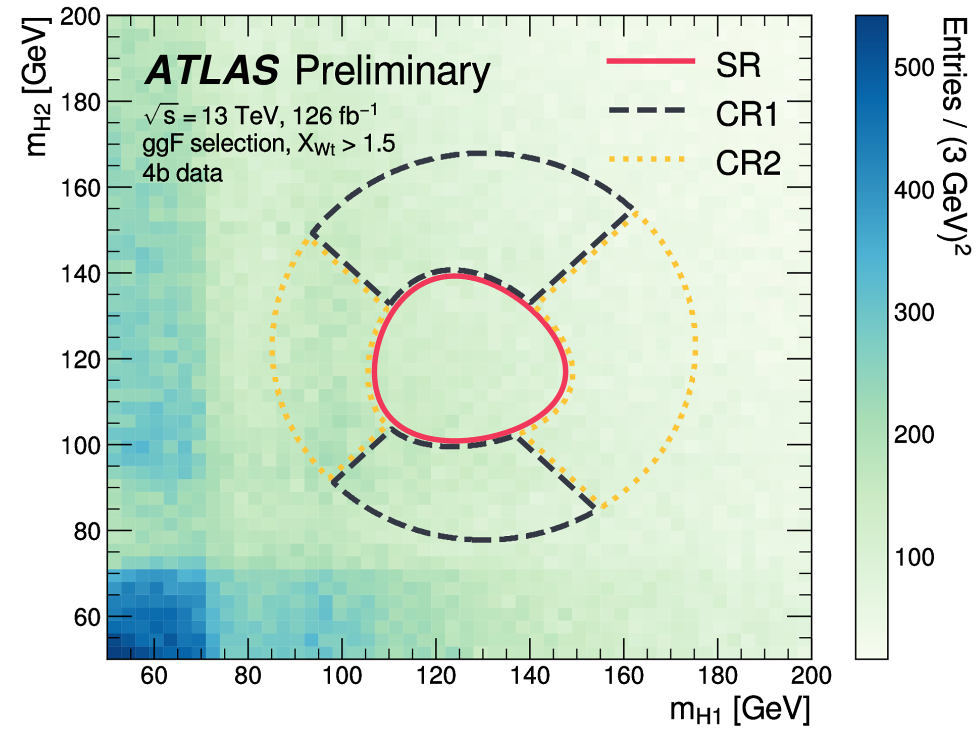


Also keep 2b data for bkg estimation.

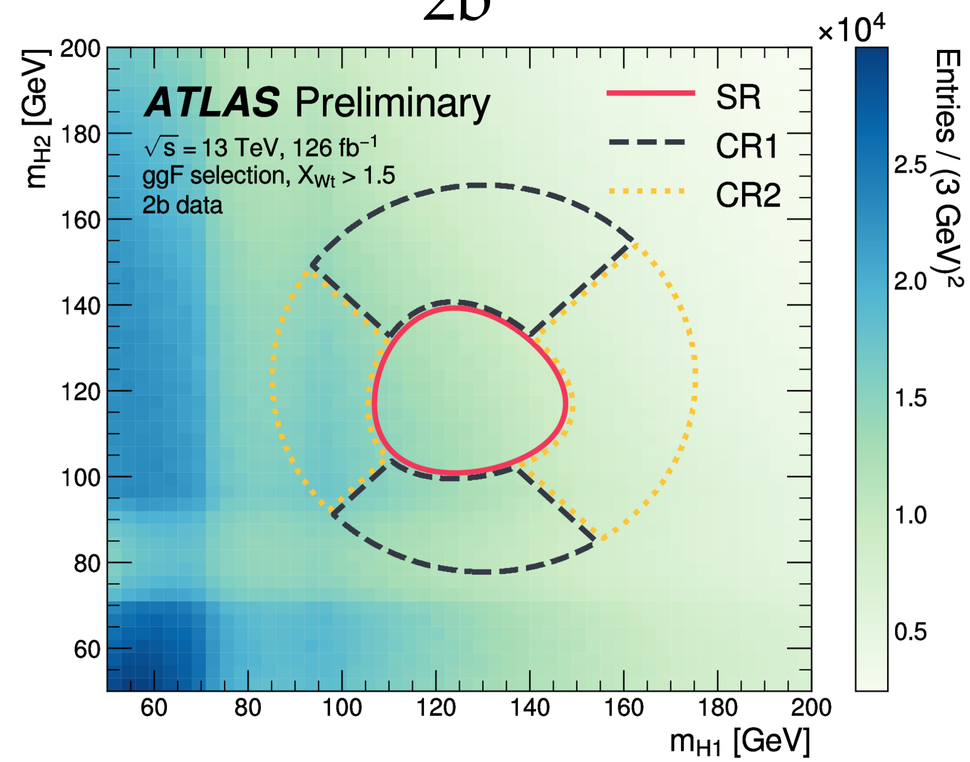
Event selection — pairing



4b



2b

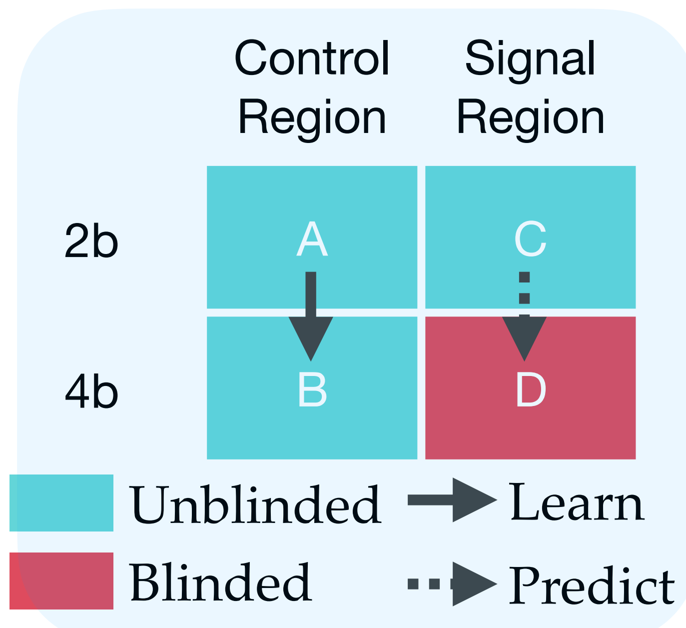


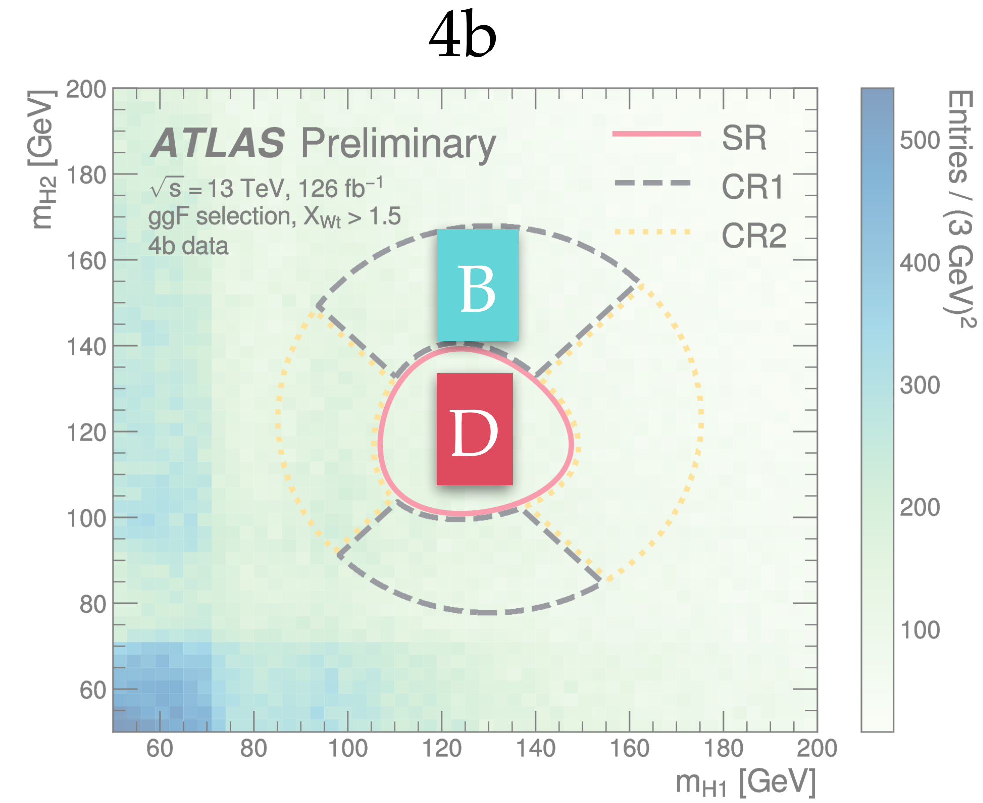
- Choose pairing that minimises ΔR between jets in the leading Higgs candidate (H_1)
- No mass information used to avoid sculpting the H_1-H_2 mass plane
- This is different from the one in the resonant search (see later)

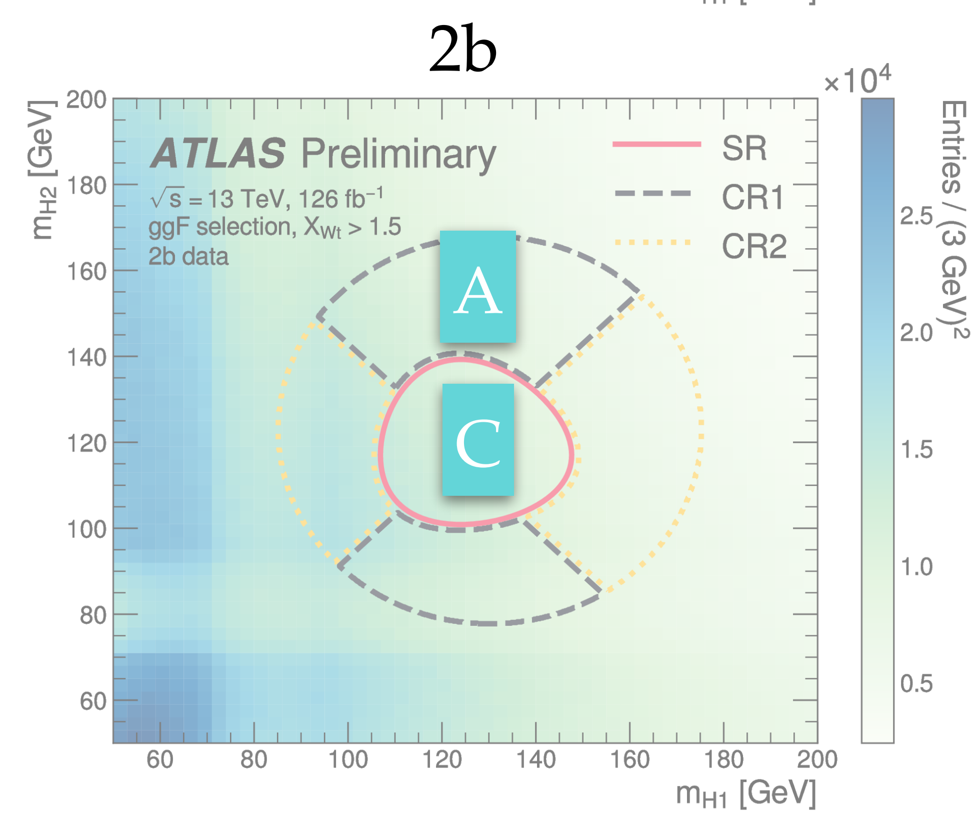
Strips ~80 GeV due to X_{Wt} cut

Background estimation

- 2b events can be reweighted to 4b (kinematically similar)
  - $w(\vec{x}) = \dfrac{p_{4b}(\vec{x})}{p_{2b}(\vec{x})}$

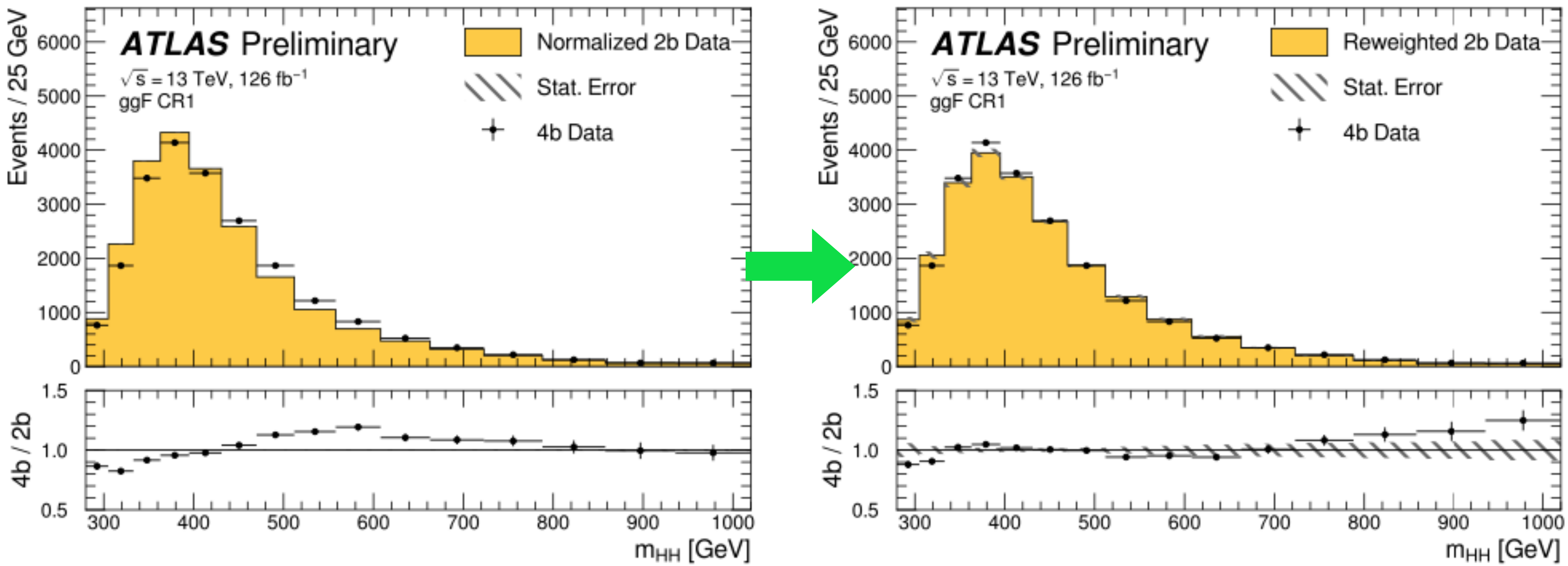






- A neural network is adopted to learn $w(\vec{x})$

Background estimation performance

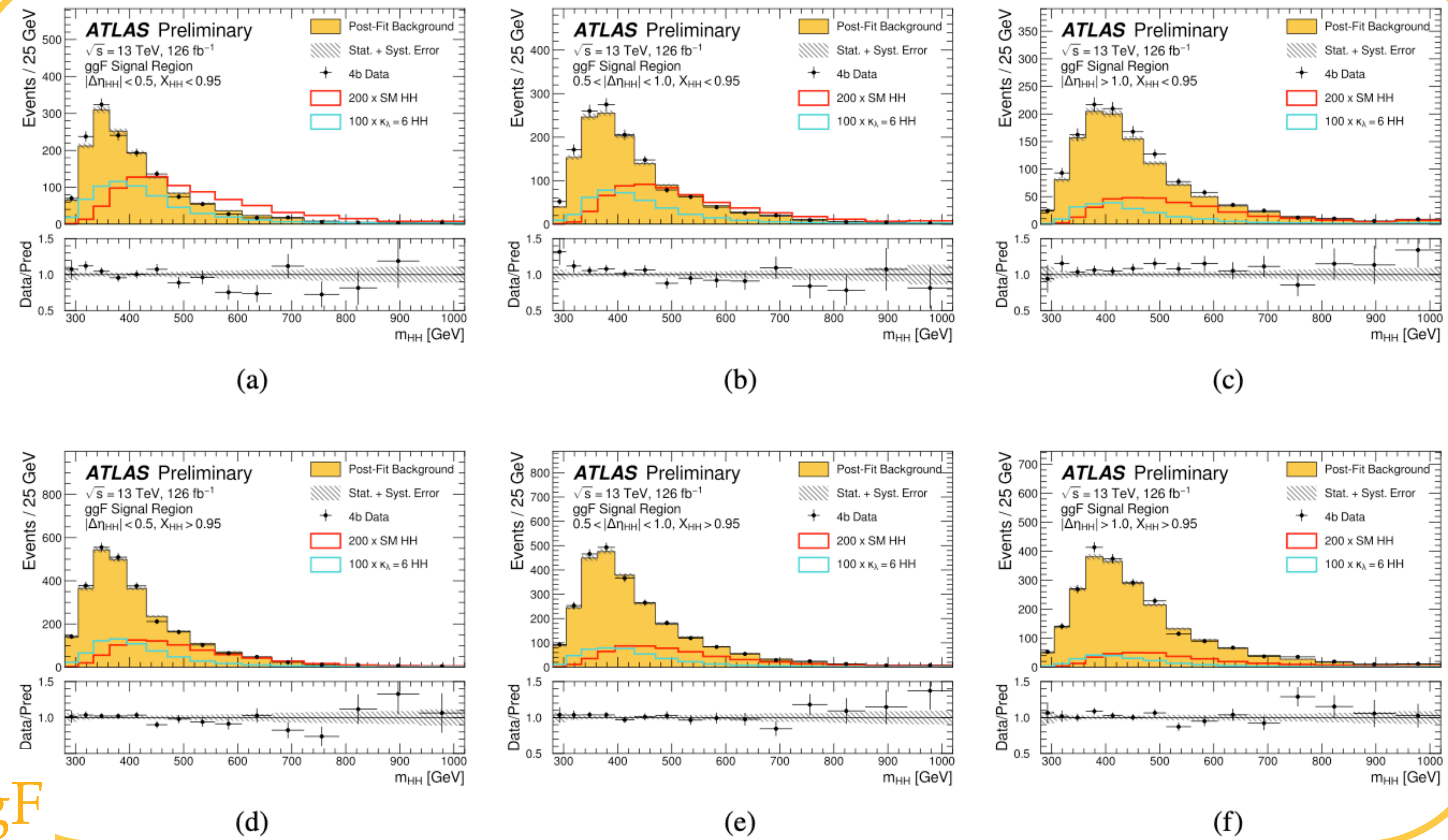


Reweighting improves the agreement with 4b events significantly.

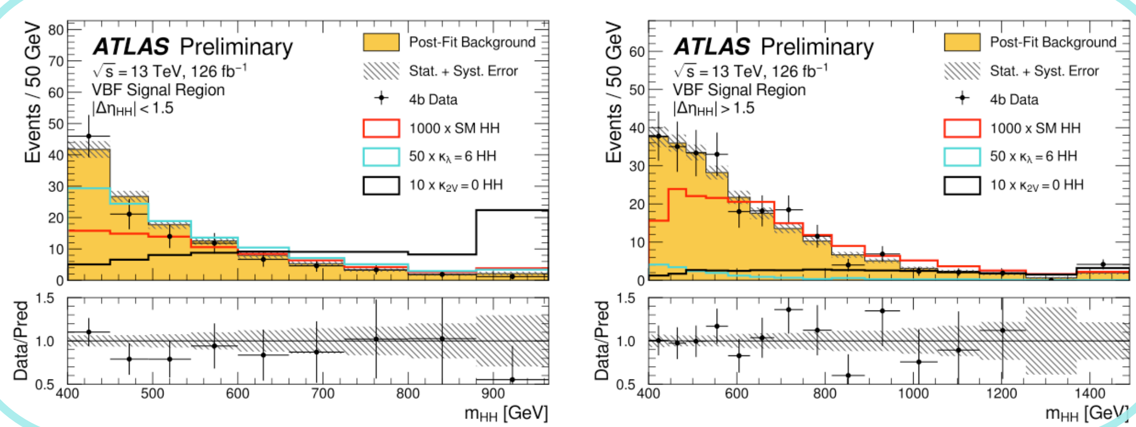
Categorisation

Events are categorised in 6 categories in ggF and 2 categories in VBF.

ggF signal region
$\lvert\Delta\eta_{HH}\rvert < 0.5$, $X_{HH} < 0.95$
$\lvert\Delta\eta_{HH}\rvert < 0.5$, $X_{HH} > 0.95$
$0.5 < \lvert\Delta\eta_{HH}\rvert < 1.0$, $X_{HH} < 0.95$
$0.5 < \lvert\Delta\eta_{HH}\rvert < 1.0$, $X_{HH} > 0.95$
$\lvert\Delta\eta_{HH}\rvert > 1.0$, $X_{HH} < 0.95$
$\lvert\Delta\eta_{HH}\rvert > 1.0$, $X_{HH} > 0.95$
VBF signal region
$\lvert\Delta\eta_{HH}\rvert < 1.5$
$\lvert\Delta\eta_{HH}\rvert > 1.5$



ggF

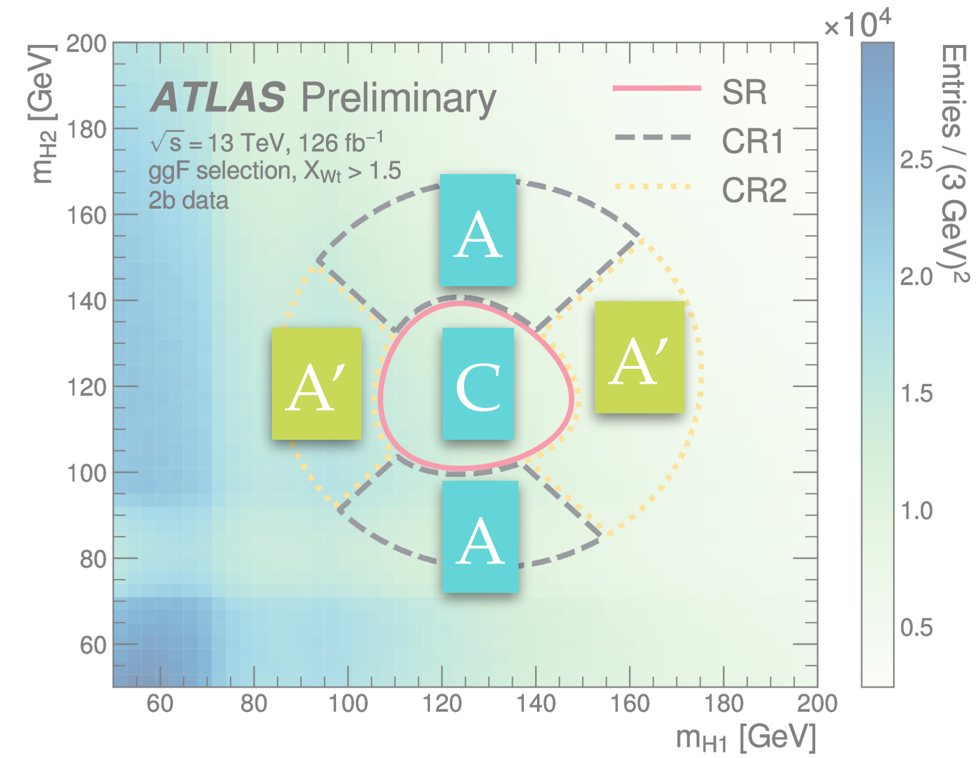


VBF

Categorisation improves S/B in certain categories, therefore improves sensitivity.

Systematic uncertainties

- The major uncertainties are bkg estimation uncertainty
  - Statistical: 2b statistics + DNN variation under bootstrapped deep ensembles (100 trainings)

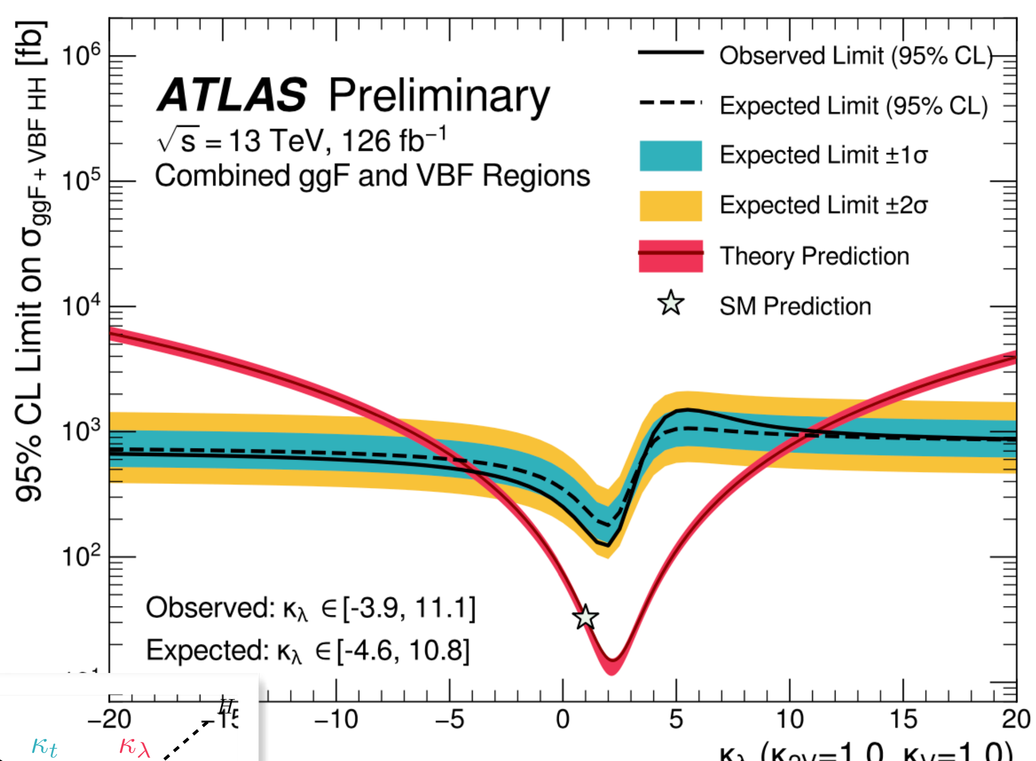


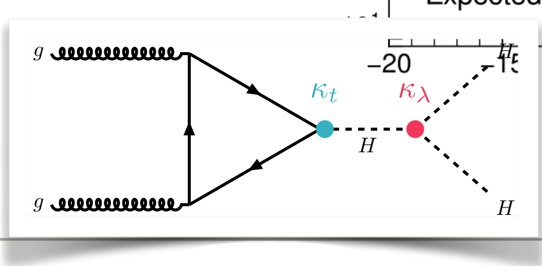
  - Alternative vs nominal estimate (A vs A′)
  - 3b1f region non-closure
  - Normalisation uncertainty from 2b/4b CR
- Signal MC is affected by standard JES, JER, Flavour tagging, luminosity, pileup, modelling, …

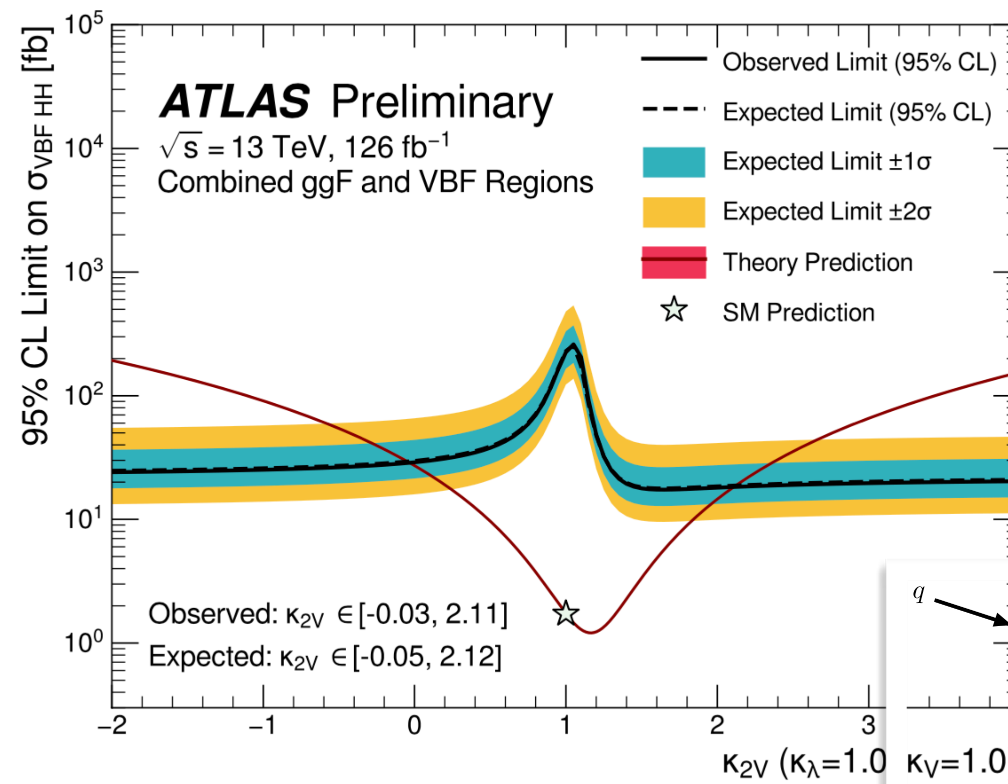
Results

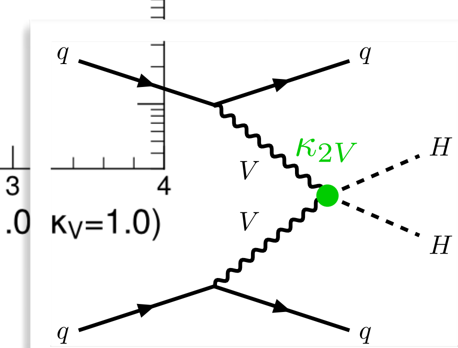
	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
$\sigma_{ggF}/\sigma_{ggF}^{SM}$	5.5	4.4	5.9	8.2	12.4	19.6
$\sigma_{VBF}/\sigma_{VBF}^{SM}$	130.5	71.6	96.1	133.4	192.9	279.3
$\sigma_{ggF+VBF}/\sigma_{ggF+VBF}^{SM}$	5.4	4.3	5.8	8.1	12.2	19.1

- 3x improvement wrt previous ggF result (11.1(20.7) x SM)
- 4x improvement wrt previous VBF results (840(550) x SM)



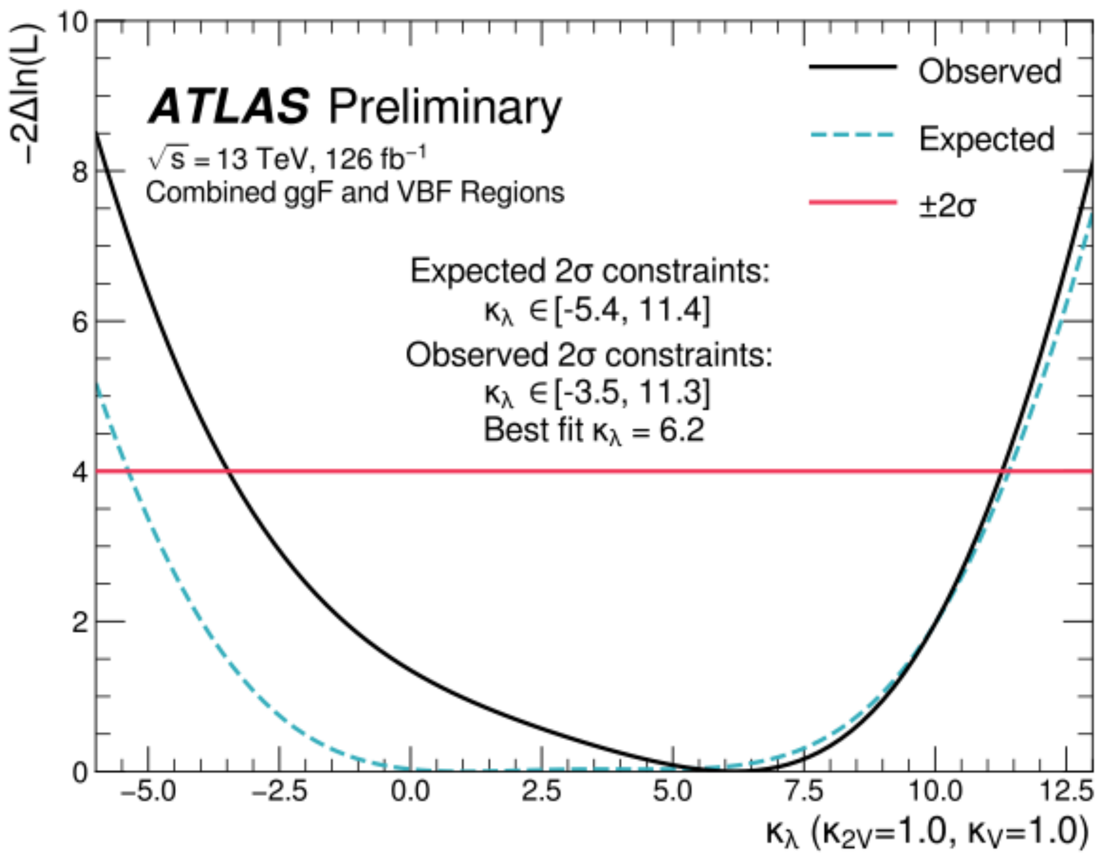


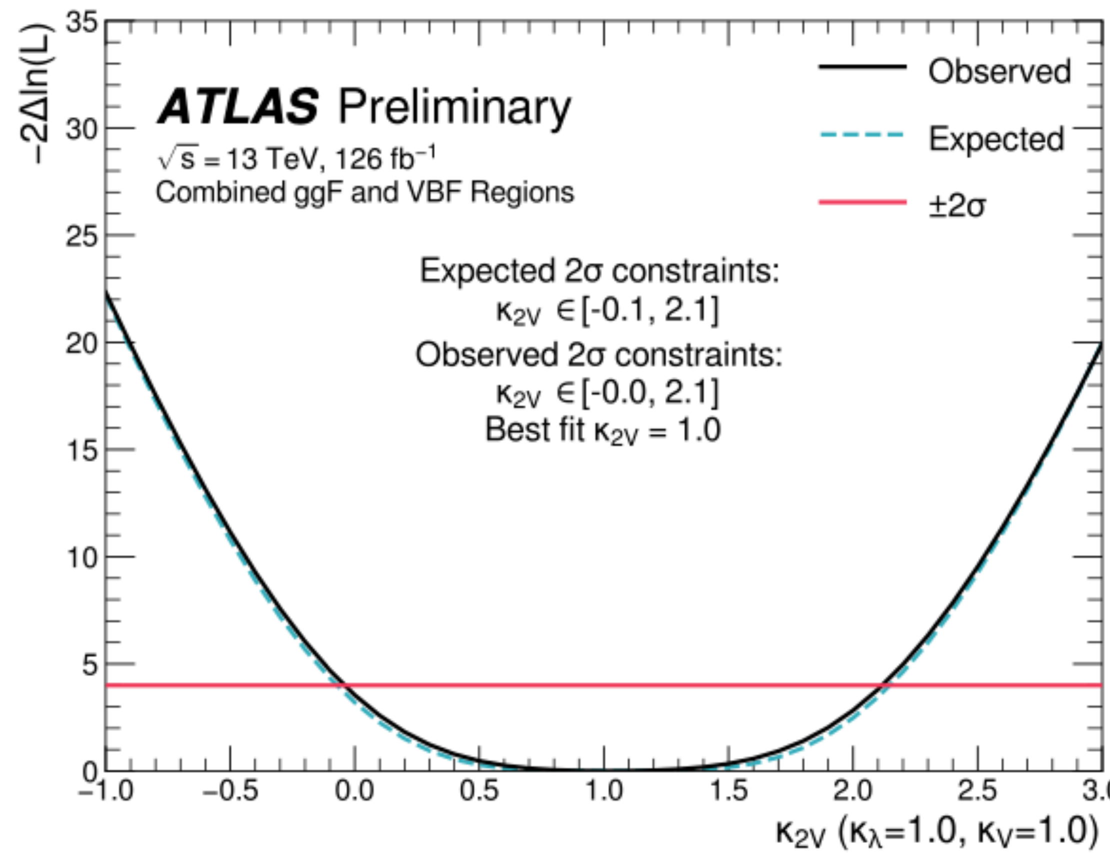




Results — likelihood scan

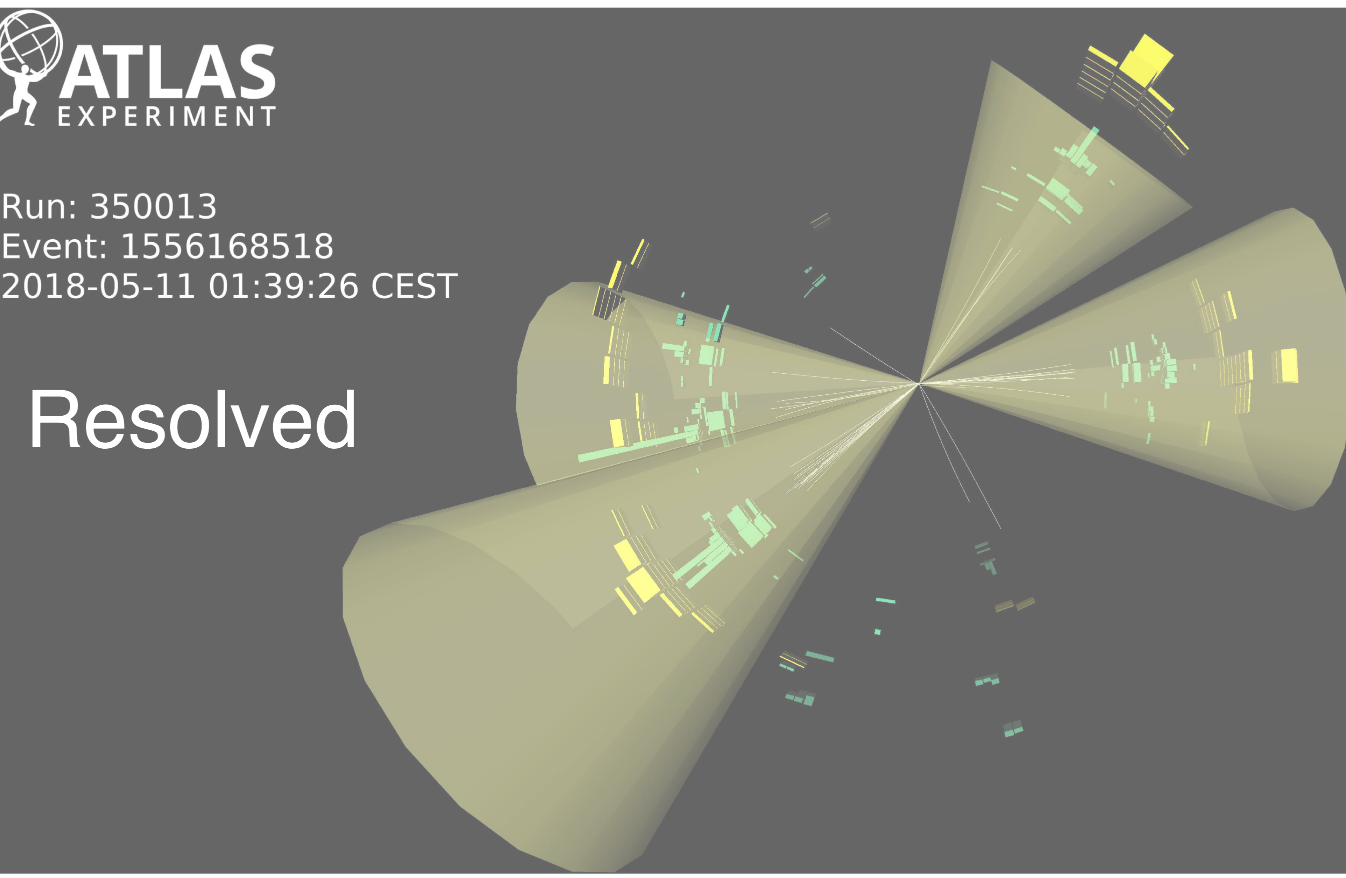
- Cross section scan provides information for signal strength under each κ assumption against SM background
- Another hypothesis test against different couplings values
  - Observed: test which κ value is most compatible to data
  - Expected: test $\kappa \neq 1$ against $\kappa = 1$

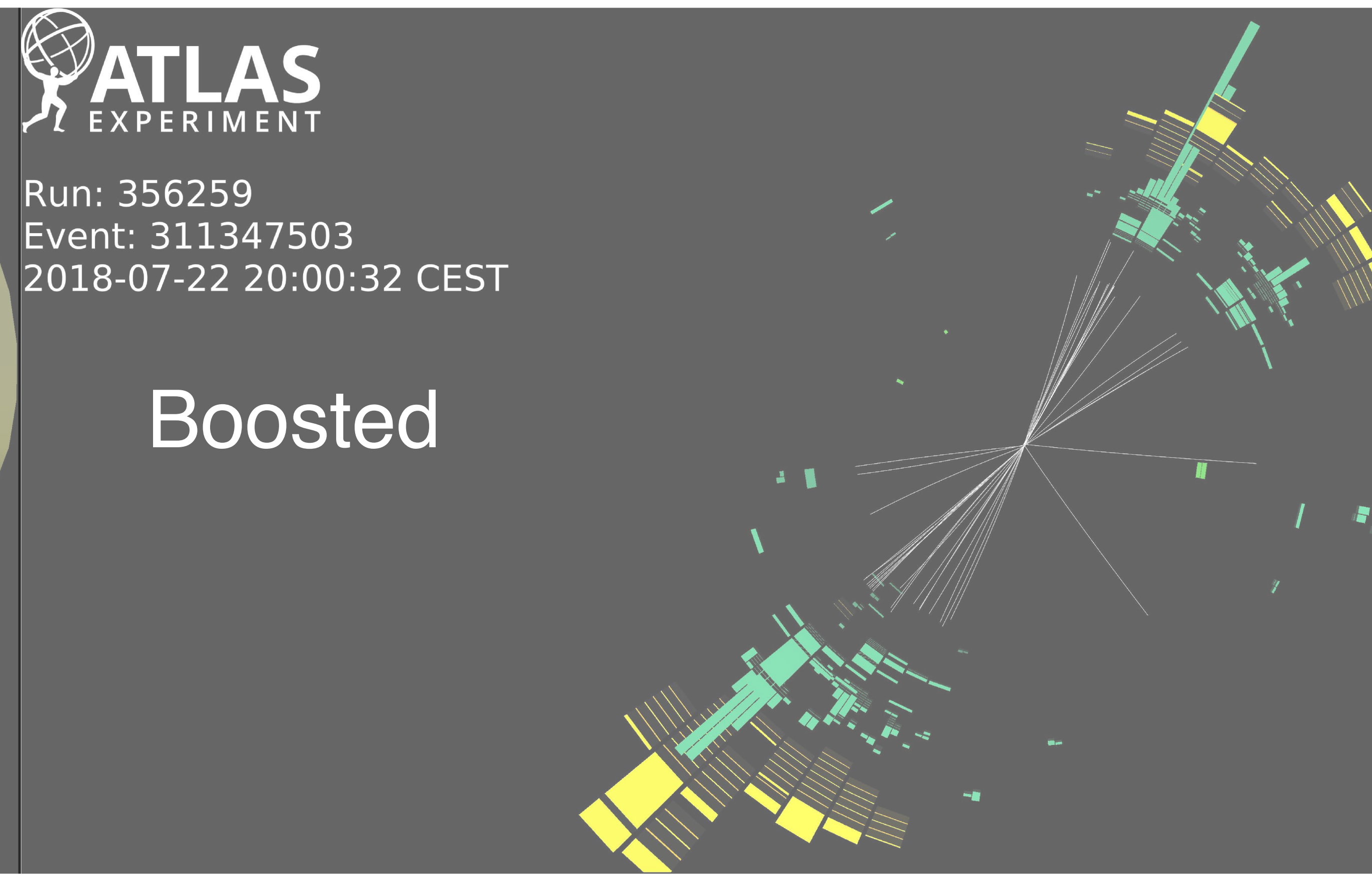




HH→4b resonant search

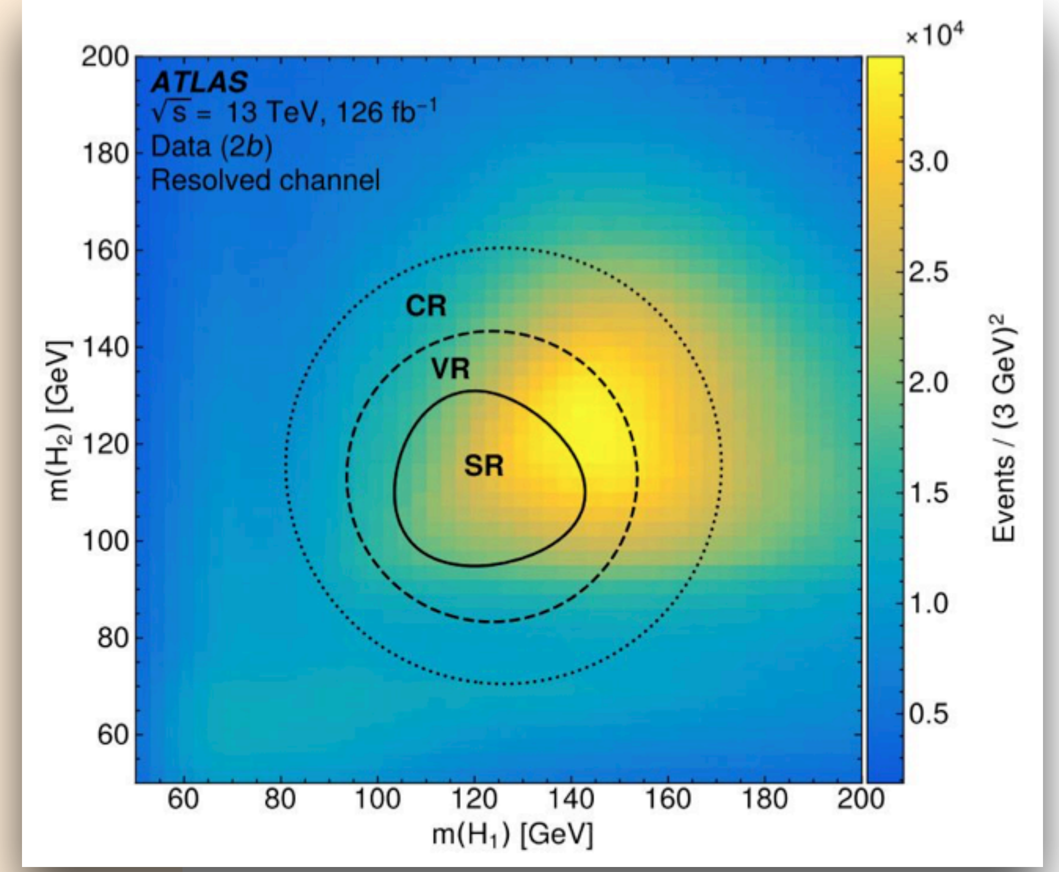
Phys. Rev. D 105, 092002





Resolved channel

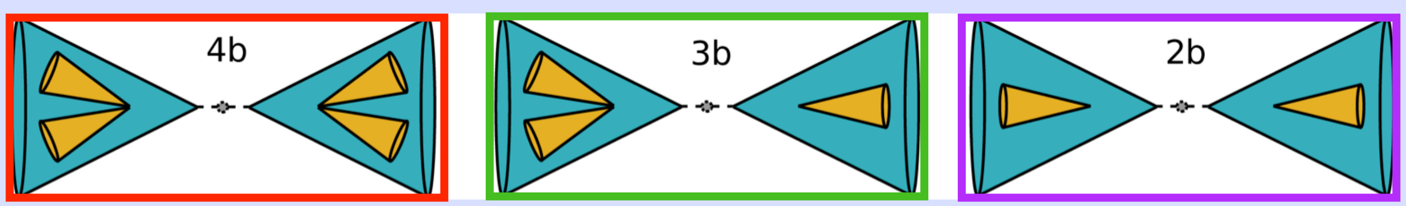
- Target up to 1.5 TeV resonance decay to two Higgs
- Event selection similar to the non-resonant analysis
- Pairing: BDT pairing
  - Parametrised to m_{HH}
  - Better efficiency at low m_{HH}
- Background estimation
  - Similar to the non-resonant analysis
- Final observable: corrected m_{HH}
  - m_{HH} obtained by scaling Higgs candidate four-vectors to match m_H=125 GeV



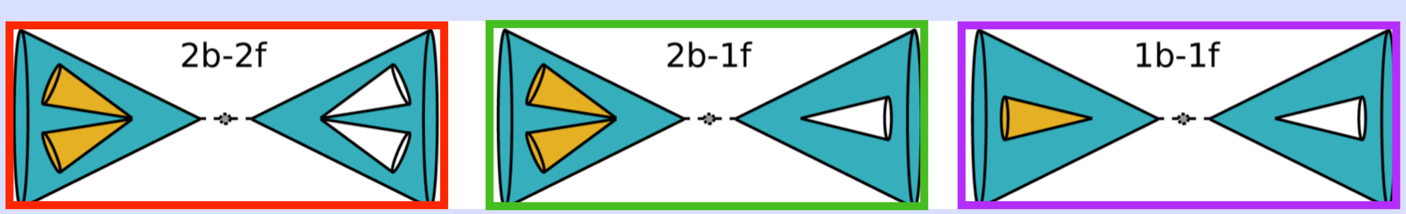
Boosted channel

Discriminant

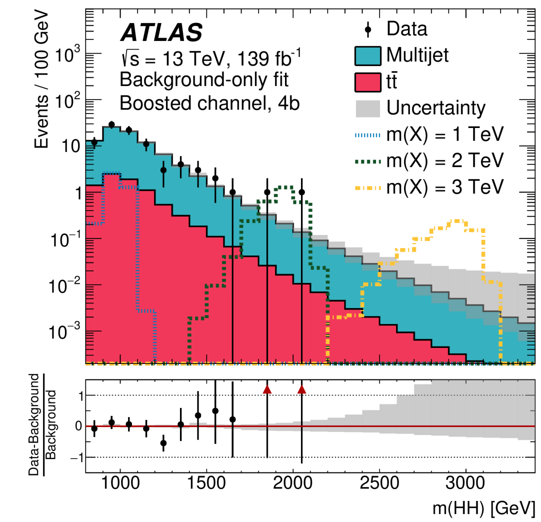
- Target up to 5.0 TeV resonance decay to two Higgs
- Event selection
  - ≥ 2 large-R jets $p_T > 250$ GeV, $|\eta| < 2$
  - m(H) > 50 GeV
  - $|\Delta\eta_{HH}| < 1.3$
  - Resolved events veto
  - Categorised to 2/3/4 b-track-jet

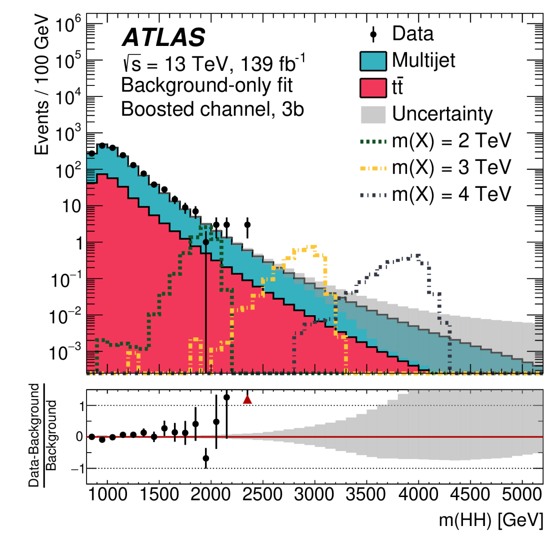


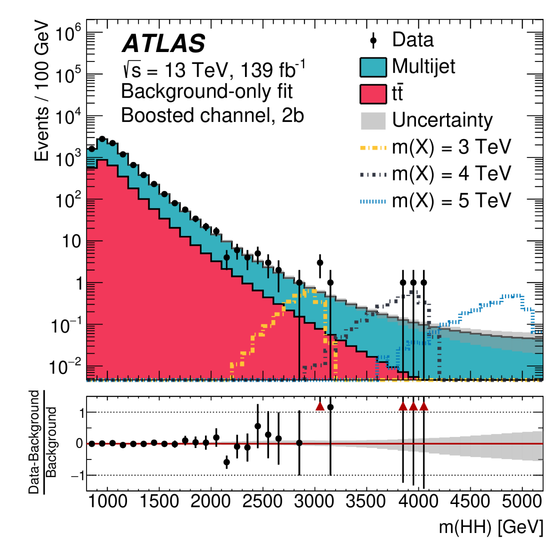
- Background estimation: data-driven QCD estimation, MC based $t\bar{t}$ (next slide)
  - Use of low-tag regions



- Final observable: m_{HH}

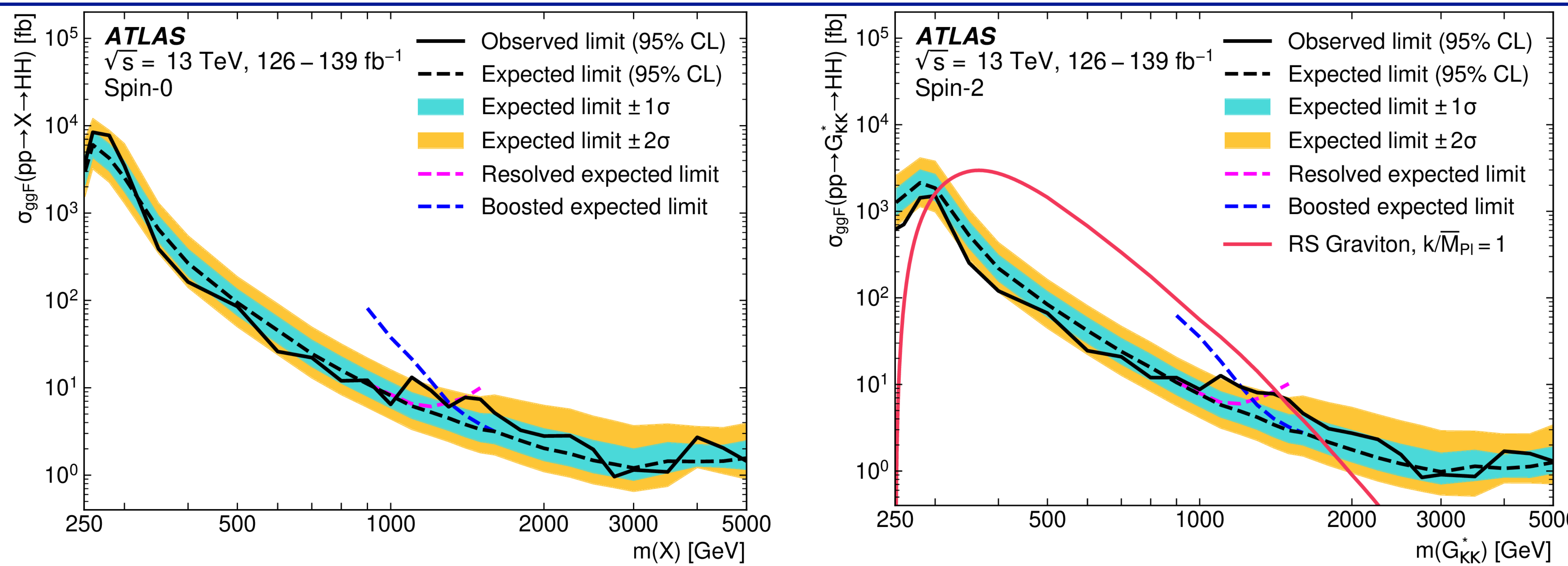






HH→$b\bar{b}b\bar{b}$ resonant results

- Likelihood fit on (corrected) m_{HH} distributions
- Constrained on narrow spin-0 and spin-2 graviton cross sections
- 5x improvement wrt previous result
  - B-tagging and correction, background estimation, BDT-pairing



Largest excess at 1.1 TeV, local (global) significance of 2.6 σ (1.0 σ)

Summary

- Di-Higgs searches in the 4b final states is presented
  - Used ATLAS full Run 2 data
  - Non-resonant signature targeting a search and constraint of Higgs self-coupling κ_λ and HHVV coupling κ_{2V}
  - Resonant searches combine resolved and boosted signatures to probe a wider range of mass
- Areas for potential improvements to explore (my personal take)
  - More efficient event triggers
  - More accurate paring algorithms
  - More robust background estimation
  - More powerful background suppression
  - …
- Will continue searches with Run 3 data. Stay tuned!

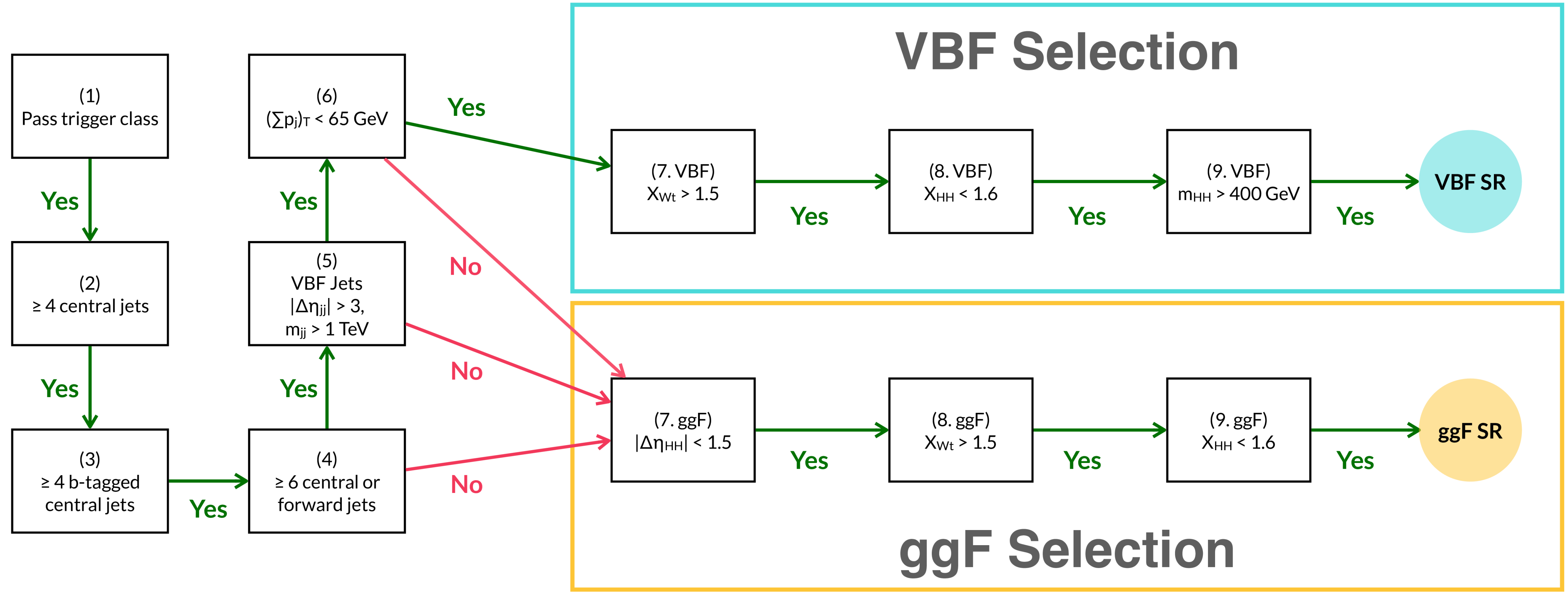
Backup

Event selection — kinematics

Central jets:
pT > 40 GeV
$|\eta| < 2.5$

Forward jets:
pT > 30 GeV
$|\eta| > 2.5$

VBF jets:
Pair of non b-tagged jets,
in central+forward selection, with highest m_{jj}



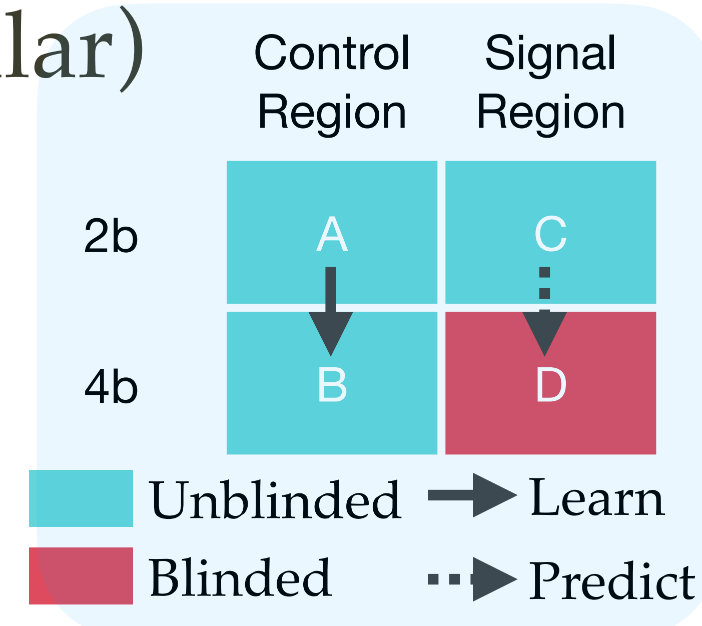
- ≥ 4 b-tagged jets (ε=77%)
- $|\Delta\eta_{HH}| < 1.5$
- Top-quark veto, $X_{Wt} = \sqrt{\left(\frac{m_W - 80.4\text{GeV}}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5\text{GeV}}{0.1 m_t}\right)^2} > 1.5$

- ≥ 6 jets, ≥ 4 b-jets, $(\sum p_j)_T < 65$ GeV
- $|\Delta\eta_{VBFjets}| > 3$, $m_{VBFjets} > 1$TeV
- $|\Delta\eta_{HH}| < 1.5$, Top-quark veto
- $m_{HH} > 400$ GeV

Also keep 2b data for bkg estimation.

Background estimation

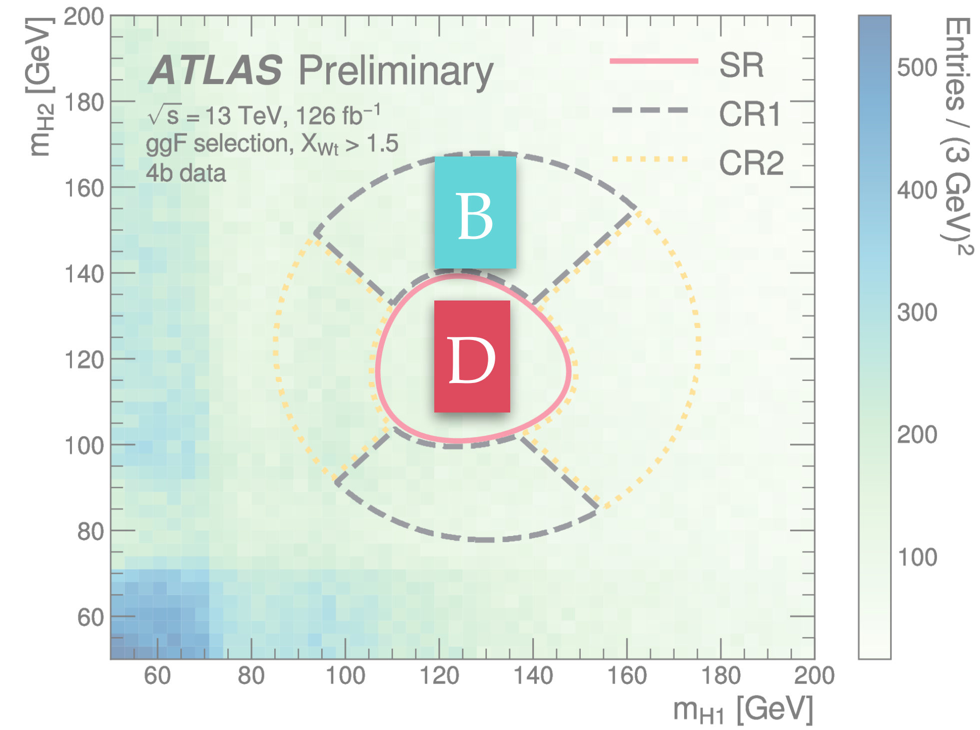
- 2b events can be reweighted to 4b (kinematically similar)
  - $w(\overrightarrow{x}) = \dfrac{p_{4b}(\overrightarrow{x})}{p_{2b}(\overrightarrow{x})}$



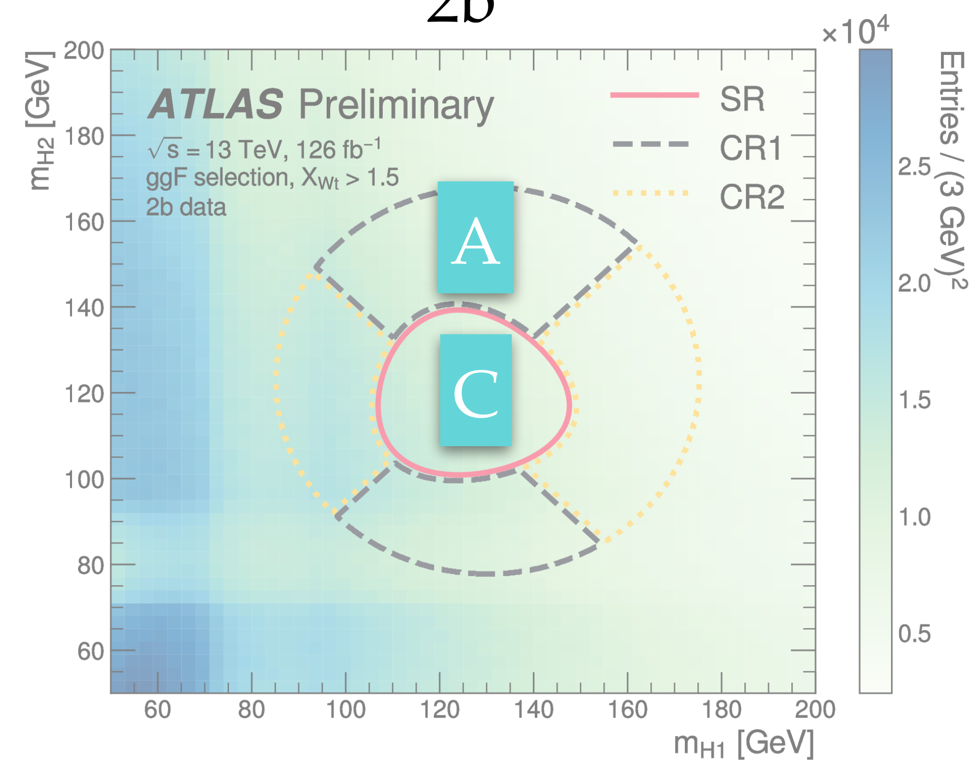
- A neural network is adopted to learn $w(\overrightarrow{x})$
  - To take the desired form of $\dfrac{p_{4b}(\overrightarrow{x})}{p_{2b}(\overrightarrow{x})}$, construct a loss function which satisfies $\arg\min_{R} \mathcal{L}(R(x)) = \dfrac{p_{4b}(x)}{p_{2b}(x)}$
  - Such loss exists, e.g.

$$\mathcal{L}(R(x)) = \mathbb{E}_{x\sim p_{2b}}[\sqrt{R(x)}] + \mathbb{E}_{x\sim p_{4b}}[\frac{1}{\sqrt{R(x)}}]$$

4b



2b



Background estimation inputs

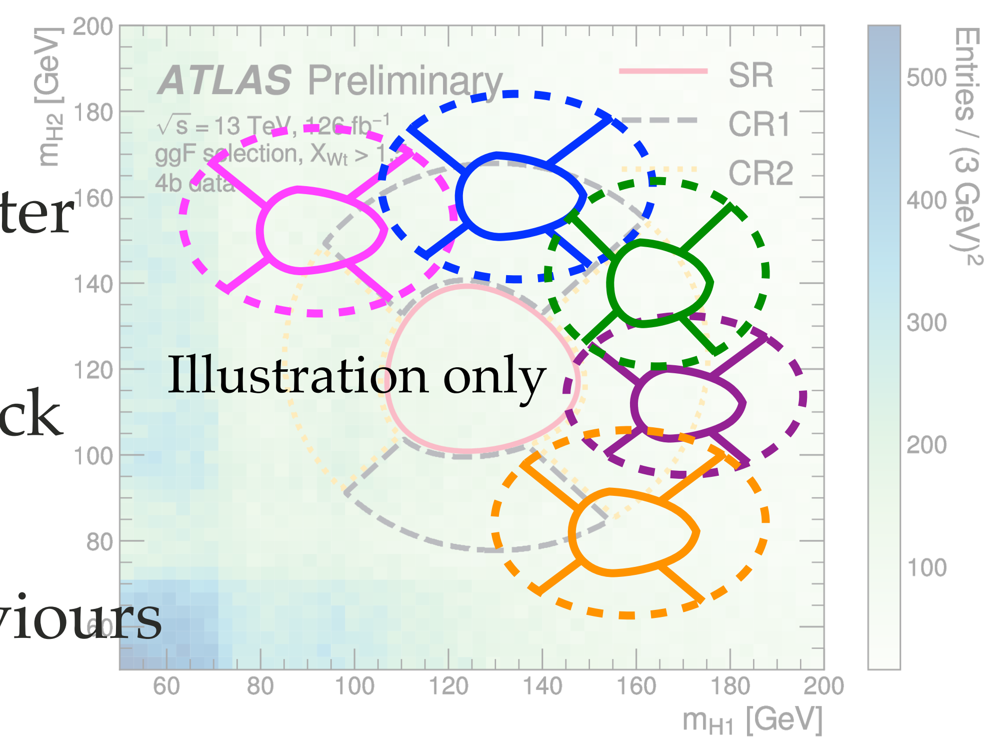
ggF	VBF
1. $\log(p_T)$ of the 2^{nd} leading Higgs boson candidate jet	1. Maximum di-jet mass out of the possible pairings of the four Higgs boson candidate jets
2. $\log(p_T)$ of the 4^{th} leading Higgs boson candidate jet	2. Minimum di-jet mass out of the possible pairings of the four Higgs boson candidate jets
3. $\log(\Delta R)$ between the closest two Higgs boson candidate jets	3. Energy of the leading Higgs boson candidate
4. $\log(\Delta R)$ between the other two Higgs boson candidate jets	4. Energy of the subleading Higgs boson candidate
5. Average absolute η value of the Higgs boson candidate jets	5. Second smallest ΔR between the jets in the leading Higgs boson candidate (out of the three possible pairings for the leading Higgs candidate)
6. $\log(p_T)$ of the di-Higgs system	6. Average absolute η value of Higgs boson candidate jets
7. ΔR between the two Higgs boson candidates	7. $\log(X_{Wt})$
8. $\Delta\phi$ between jets in the leading Higgs boson candidate	8. Trigger class index as one-hot encoder
9. $\Delta\phi$ between jets in the subleading Higgs boson candidate	9. Year index as one-hot encoder (for years inclusive training)
10. $\log(X_{Wt})$	
11. Number of jets in the event	
12. Trigger class index as one-hot encoder	

Background estimation validation

- Comprehensive validations are conducted

Control Data Sample	Definition	Usage
Control Region (CR)	Events with $X_{HH} > 1.6$ and within the circle defined by: $\sqrt{\left(m_{H1} - 1.05 \cdot 124\,\text{GeV}\right)^2 + \left(m_{H2} - 1.05 \cdot 117\,\text{GeV}\right)^2} = 45\,\text{GeV}$	Background estimation (ggF and VBF)
$2b$	Remove the ≥ 4 b-tagged central jets selection and require exactly 2 b-tagged central jets plus two additional untagged central jets	Background estimation (ggF and VBF)
$3b1f$	Remove the ≥ 4 b-tagged central jets selection and require exactly 3 b-tagged central jets plus one central jet failing a looser b-tagging requirement	Background estimation validation (ggF and VBF), additional background modeling uncertainty (ggF only)
Reverse $\lvert\Delta\eta_{HH}\rvert$	Remove the $\lvert\Delta\eta_{HH}\rvert < 1.5$ selection and require $\lvert\Delta\eta_{HH}\rvert > 1.5$	Background estimation validation (ggF only)
Shifted region	Shift the center of the SR in the m_{H1}-m_{H2} plane to avoid overlap with the nominal SR	Background estimation validation (ggF only)

- In particular:
  - Reversed $\lvert\Delta\eta_{HH}\rvert$ region to check nuisance parameter pulls
  - 3b1f, one jet fails a looser b-tagging criterion, to check residual of systematics coverage
  - Multiple shifted regions to check higher level behaviours



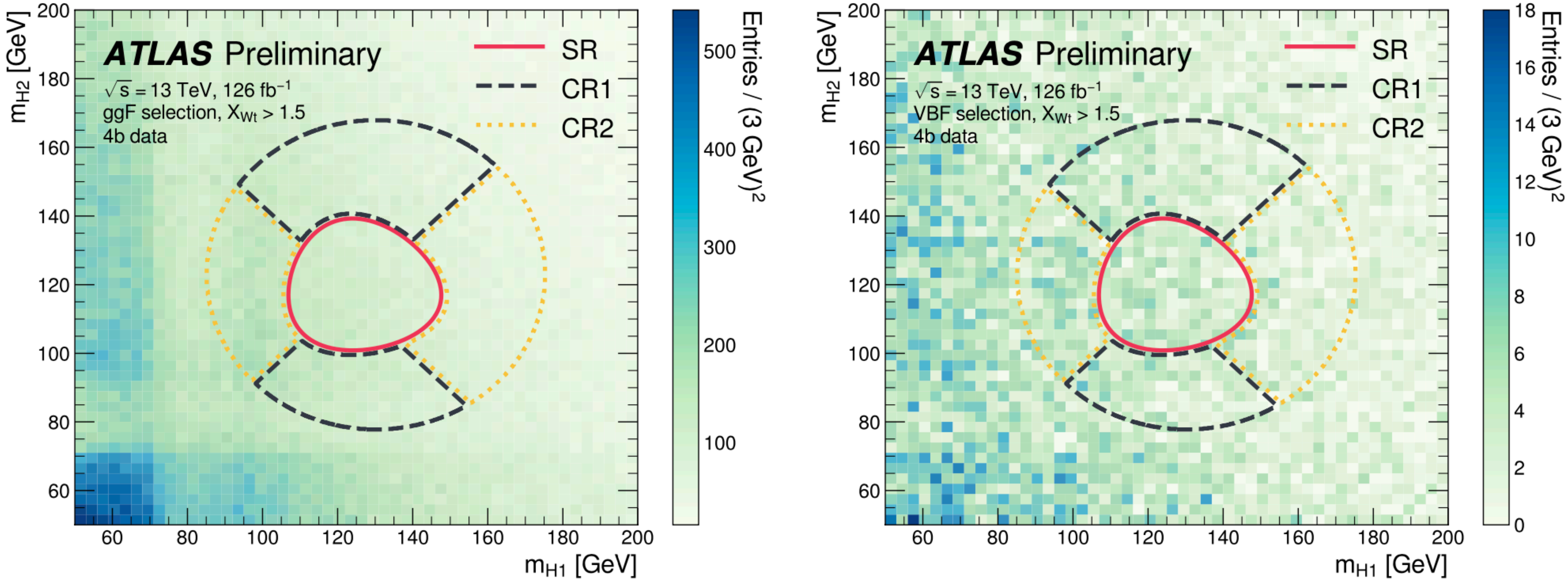
4b non-resonant cutflow

	Data	ggF Signal		VBF Signal	
		SM	$\kappa_\lambda = 10$	SM	$\kappa_{2V} = 0$
Common preselection					
Preselection	5.70×10^8	526.6	7337.7	22.3	626.1
Trigger class	2.49×10^8	381.8	5279.1	16.1	405.2
ggF selection					
Fail VBF selection	2.46×10^8	376.6	5198.0	13.9	334.4
At least 4 b-tagged central jets	1.89×10^6	86.0	1001.7	1.9	65.2
$\lvert\Delta\eta_{HH}\rvert < 1.5$	1.03×10^6	71.9	850.6	0.9	46.4
$X_{Wt} > 1.5$	7.51×10^5	60.4	569.0	0.7	43.1
$X_{HH} < 1.6$ (ggF signal region)	1.62×10^4	29.1	182.7	0.2	23.0
VBF selection					
Pass VBF selection	3.30×10^6	5.2	81.1	2.2	70.7
At least 4 b-tagged central jets	2.71×10^4	1.1	15.3	0.7	27.6
$X_{Wt} > 1.5$	2.18×10^4	1.0	11.2	0.7	26.5
$X_{HH} < 1.6$	5.02×10^2	0.5	3.1	0.3	17.3
$m_{HH} > 400$ GeV (VBF signal region)	3.57×10^2	0.4	1.8	0.3	16.4

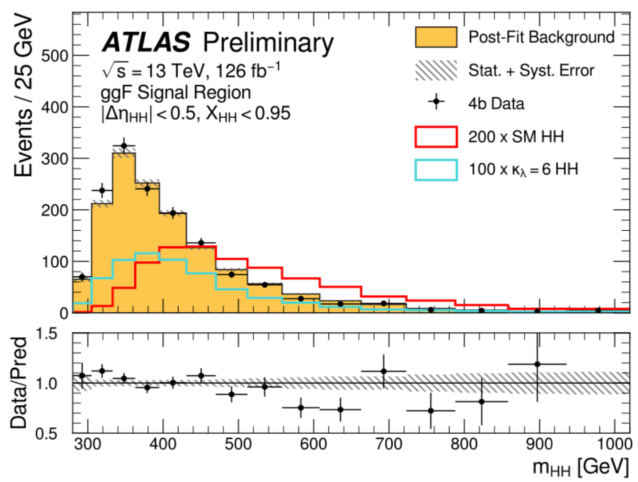
4b resonant yields table

$m(X)$ [GeV]	Corrected $m(HH)$ range [GeV]	Data	Background model	Spin-0 signal model
260	[250, 321]	18554	18300 ± 110	503 ± 43
500	[464, 536]	2827	2866 ± 22	105.4 ± 5.7
800	[750, 850]	358	366.2 ± 7.3	37.7 ± 1.7
1200	[1079, 1250]	68	52.6 ± 1.7	11.71 ± 0.62

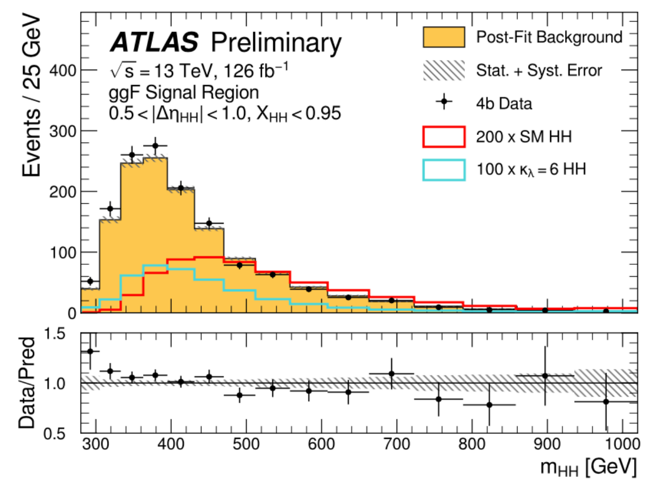
4b non-resonant mass plane



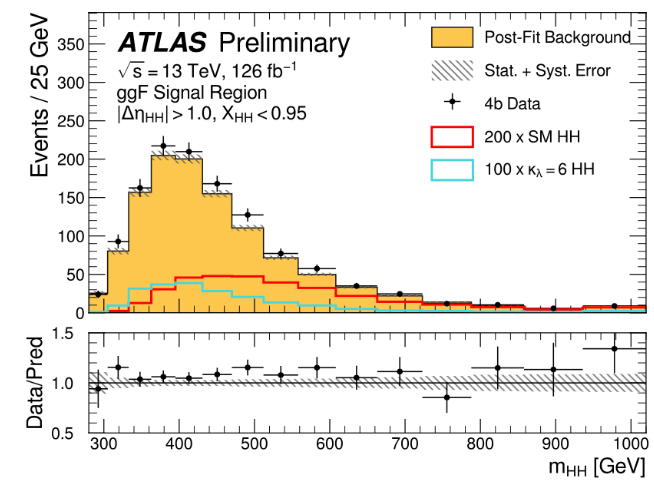
4b non-resonant discriminants



(a)



(b)



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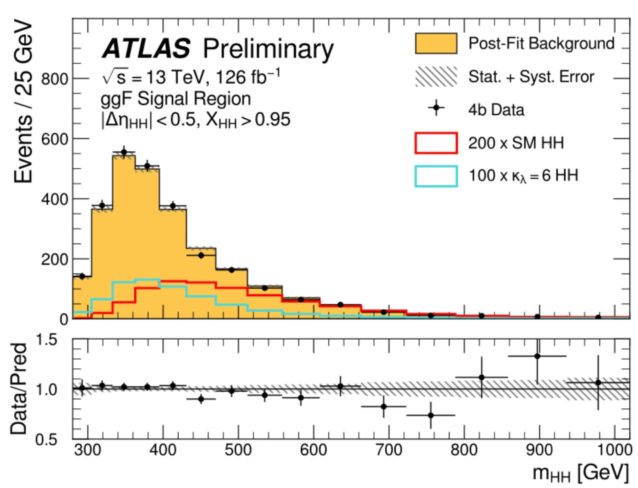
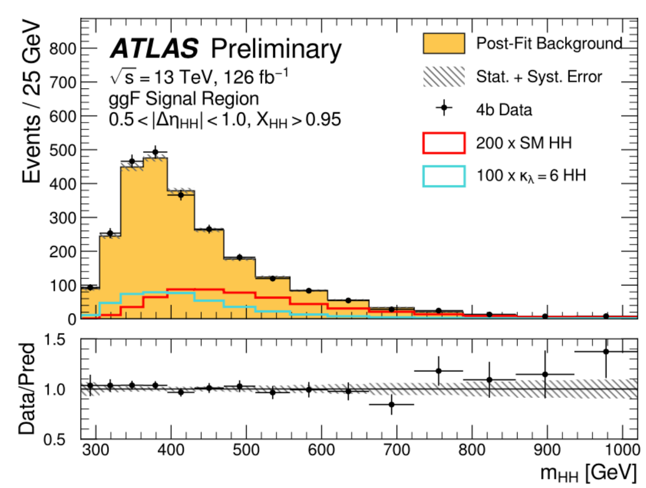


(d)



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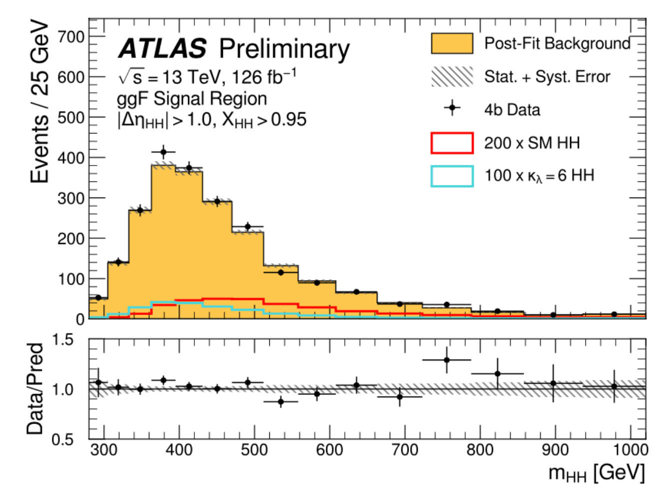

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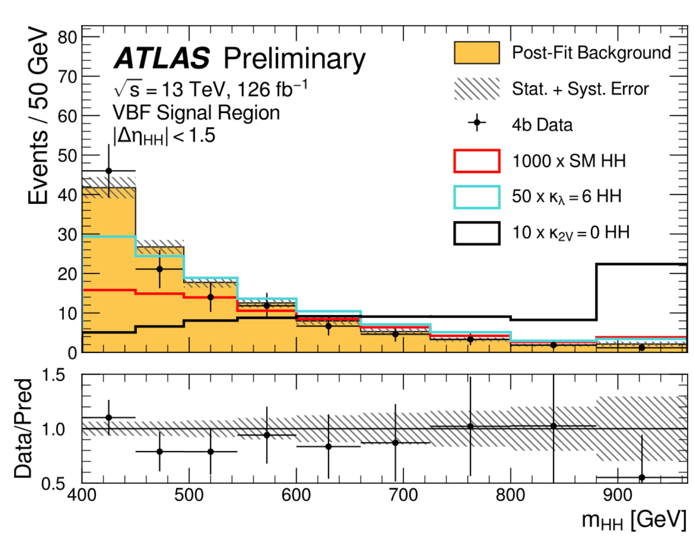
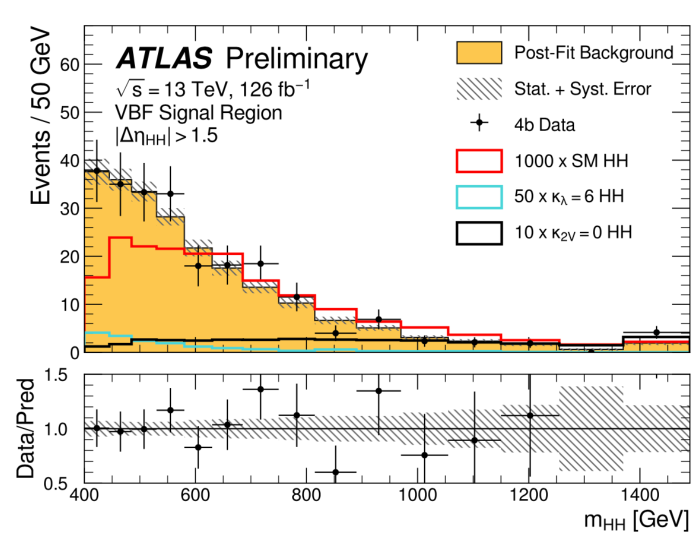


(a)



(b)

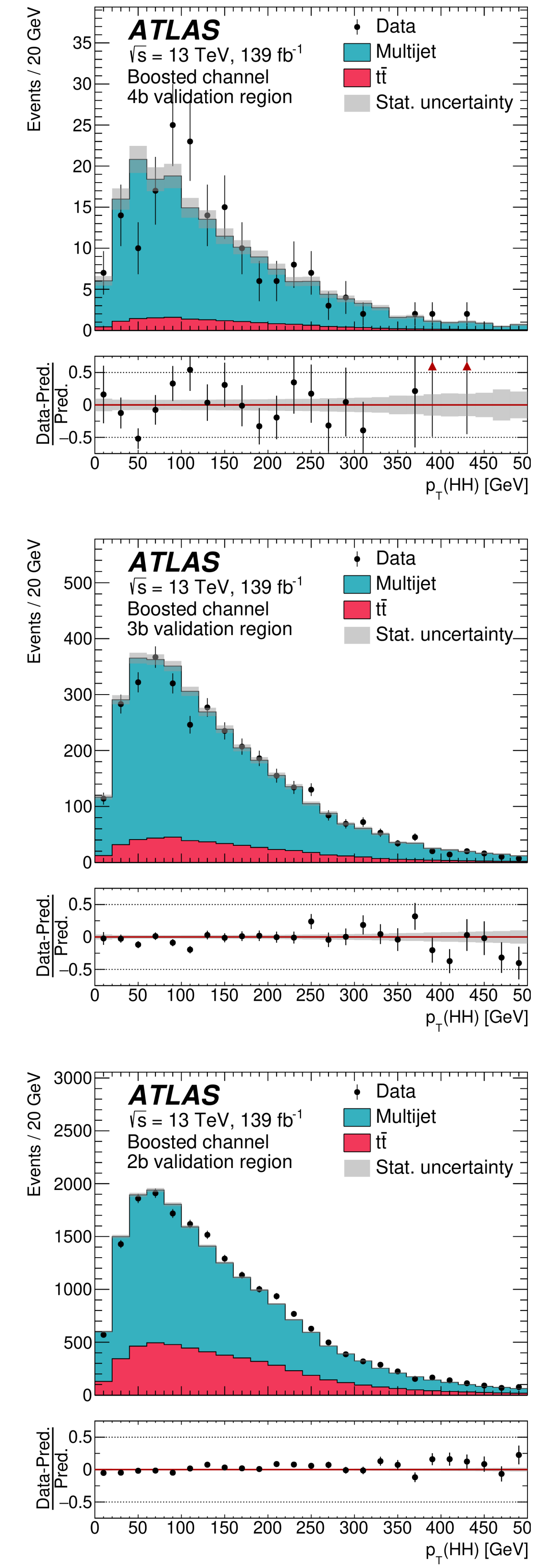
Background estimation

Agreement in VR after bkg estimation

- Major bkg: 10%(4b), 15%(3b), 30%(2b) $t\bar{t}$, QCD
- Normalisation
  - Simultaneous fit to H_1 mass distributions in CR between high tag and low-tag (totally 6 param.)

$$N^{\mathrm{hi}}_{i,\mathrm{data}} = \mu^{n_b}_{\mathrm{QCD}}(N^{\mathrm{lo}}_{i,\mathrm{data}} - N^{\mathrm{lo}}_{i,t\bar{t}}) + \alpha^{n_b}_{t\bar{t}} N^{\mathrm{hi}}_{i,t\bar{t}}$$

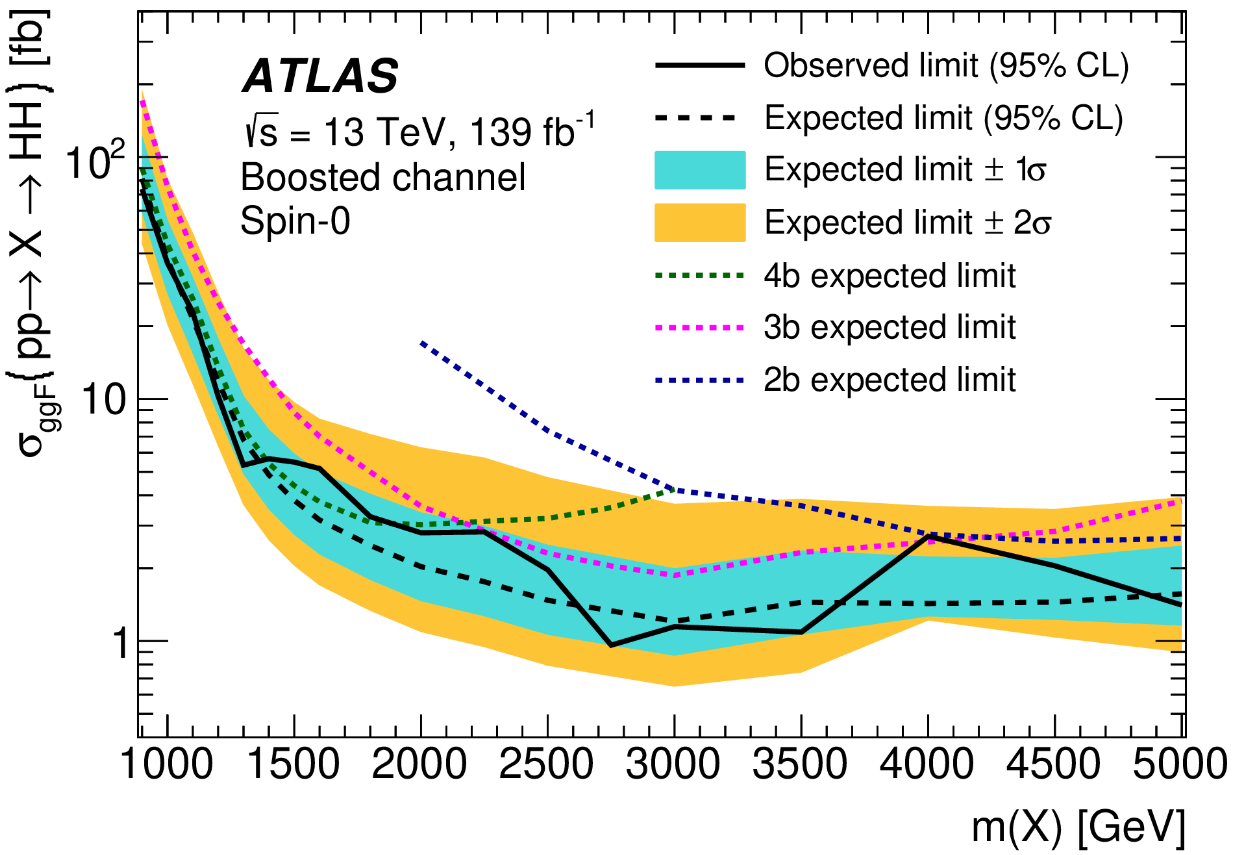
  - Syst: Choice of CR, extrapolation to SR, fit uncertainty
- Shape
  - Reweight untag into tagged Higgs candidate by fitting ratios of jet quantities
  - Apply smoothing on m_{HH} for $m_{HH} > 1200$ GeV to reduce statistical fluctuations for QCD and $t\bar{t}$ separately in each region
  - Syst: fit uncertainty, fit function and range choice, residual in VR, non-closure from MC

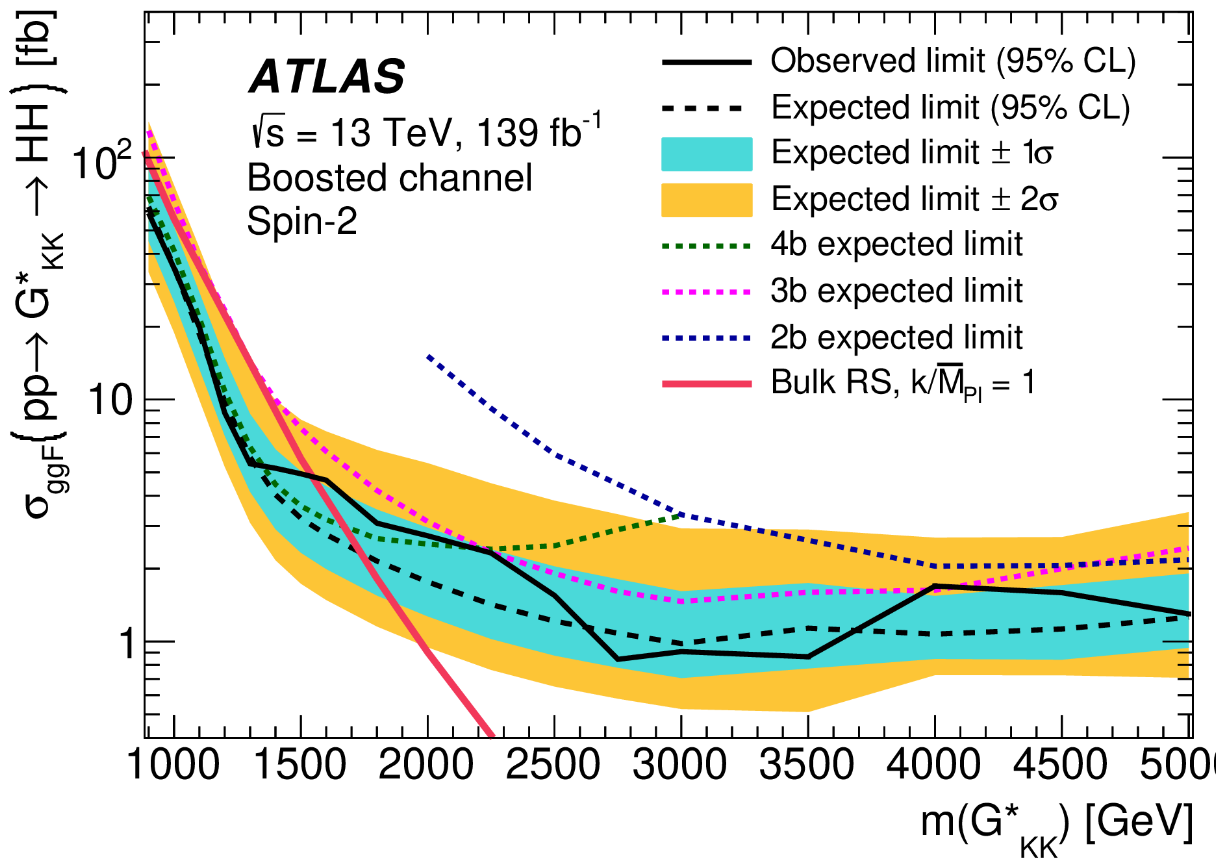


Boosted results

Spin-0

Spin-0





4b sensitive at low m_X

2b sensitive at high m_X

3b sensitive in full range