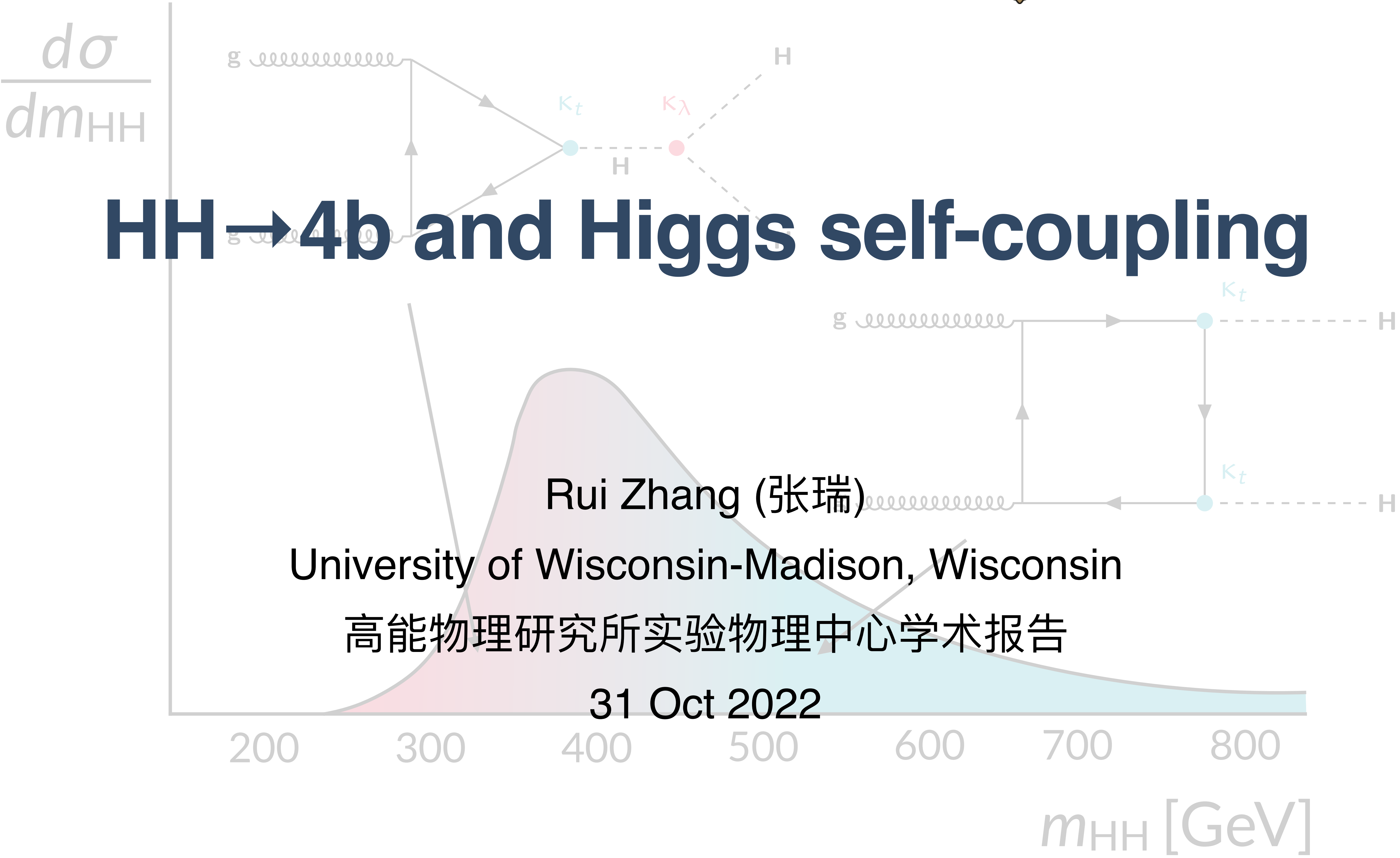

HH→4b and Higgs self-coupling

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University of Wisconsin-Madison, Wisconsin

高能物理研究所实验物理中心学术报告

31 Oct 2022

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The international journal of science / 7 July 2022

nature

HIGGS AT 10

Probing the properties of the most elusive particle in physics

Coronavirus Did vaccine mandates help or hinder the fight against COVID?

Cleaning up How to pull the plug on coal-fired power plants

Sea of plenty Ocean microbiome reveals wealth of biosynthetic pathways

Image: CERN

nature @Nature · Jul 4

"Out of all elementary particles, the Higgs boson holds the record for the longest time between its prediction and discovery"

Today @NaturePhysics is celebrating 10 years of Higgs – a particle which was discovered a whopping 48 years after its prediction

nature.com

Higgs Higgs hooray

Nature Physics - We celebrate the ten-year anniversary of the discovery of the Higgs boson — a whopping 48 years after its prediction.

Physics Today @PhysicsToday · Jul 4

Ten years ago today, @ATLASexperiment @CMSExperiment physicists gathered at @CERN to announce the discovery of what Physics Today described then as the "#Higgs particle, or something much like it." #Higgs10

physicstoday.scitation.org

The Higgs boson discovery, 10 years later

Authors reflect on the historic achievement a decade ago and examine the current state of particle physics.

Max Planck Society @maxplanckpress · Jun 21

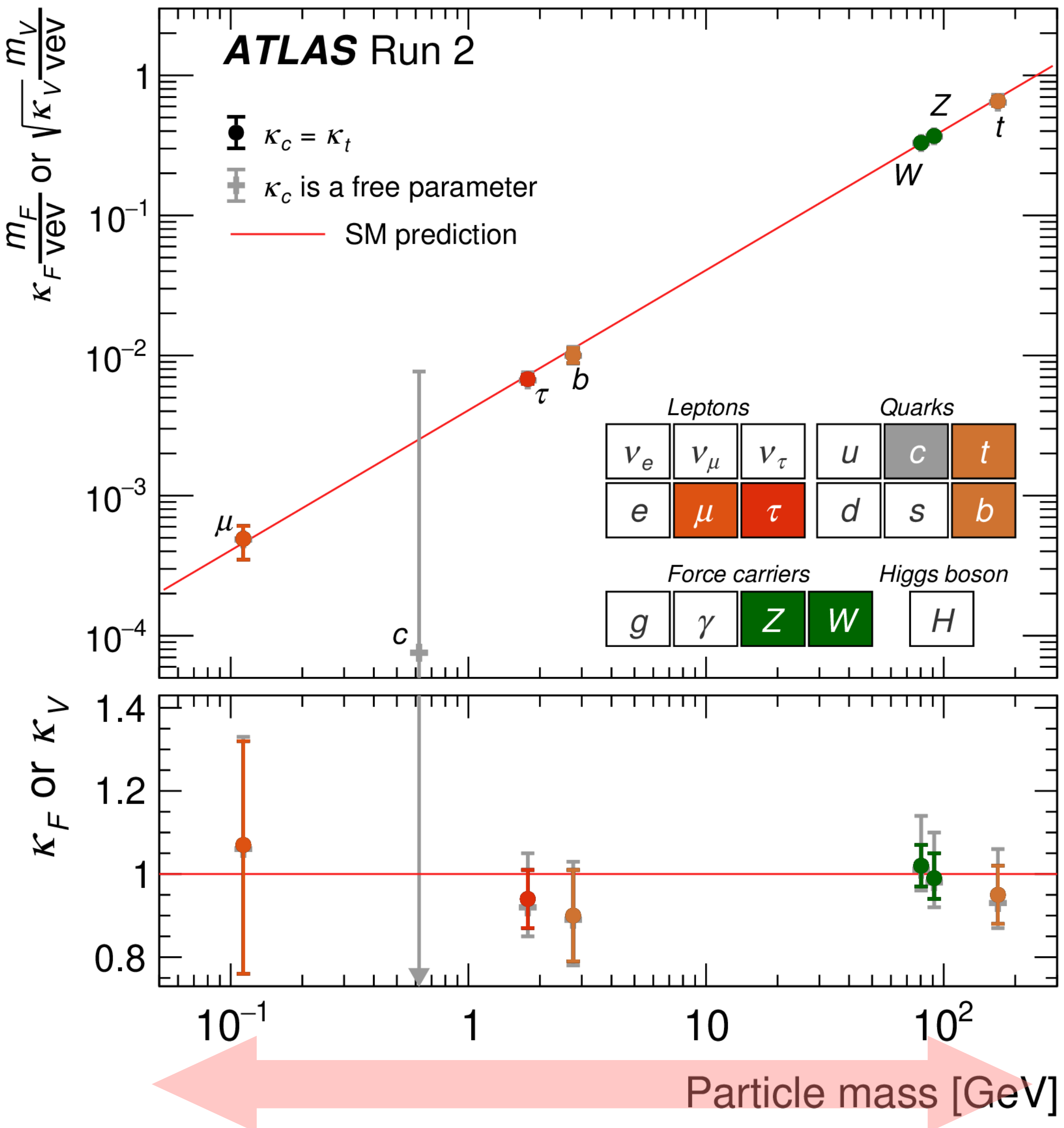
Higgs, Higgs, Hooray! On July 4, 2012, @CERN announced the discovery of the #Higgsboson. The Max Planck Institute for Physics is celebrating the 10th birthday in #Munich. You are welcome to join in! 🎉 mpp.mpg.de/en/higgs-10 #Higgs10 #particlephysics

3 53 230

Why is the Higgs boson *still* interesting?

What we’ve learnt since Higgs discovery?

- All main **production modes** (ggF, VBF, VH, ttH+tH) established at **> 5σ**
- Couplings to **gauge bosons** and **3rd gen.** charged fermions all **observed**
- Couplings to **2nd gen.** charged fermions: **3σ** evidence for H→μμ; first constraints on H→cc
- **Mass** measured to **~ 0.1%**
- $\mathbf{J^{CP} = 0^{++}}$ (large number of alternative hypotheses excluded at > 99.9% C.L.)
- … …
- Tremendous advances in our understanding of the Higgs boson since its discovery in 2012



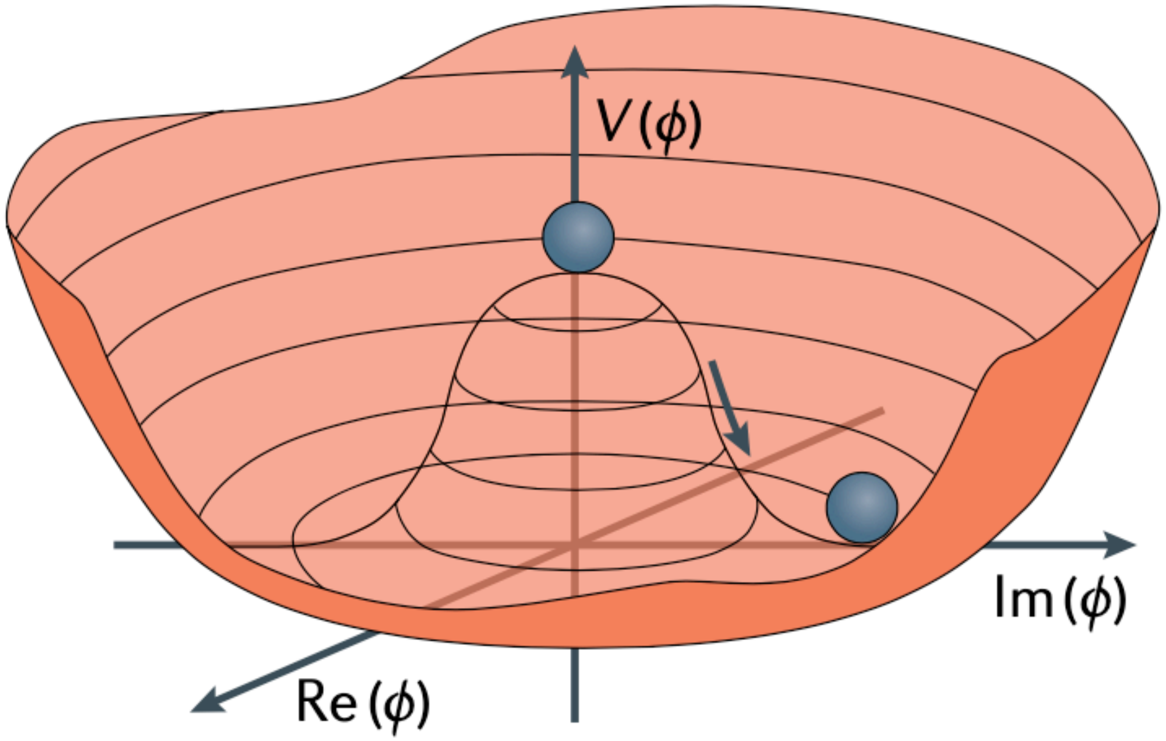
3 orders of magnitude

… primarily, discovery of the Higgs particle is a **direct evidence** of the existence of a ubiquitous **Higgs field**.

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

When $\mu^2 < 0$ the potential has a minimum at:

$$|\phi|_{\text{min}} = \sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{\nu}{\sqrt{2}}, \nu = 246 \text{ GeV}$$



This is one form of the potential, is this the form taken by nature?

- SM cannot be a complete description of nature
  - Origin of neutrino masses
  - Origin of mass hierarchy?
  - Origin of baryonic asymmetry?
- Theories explaining (part) above questions require modification of the shape form

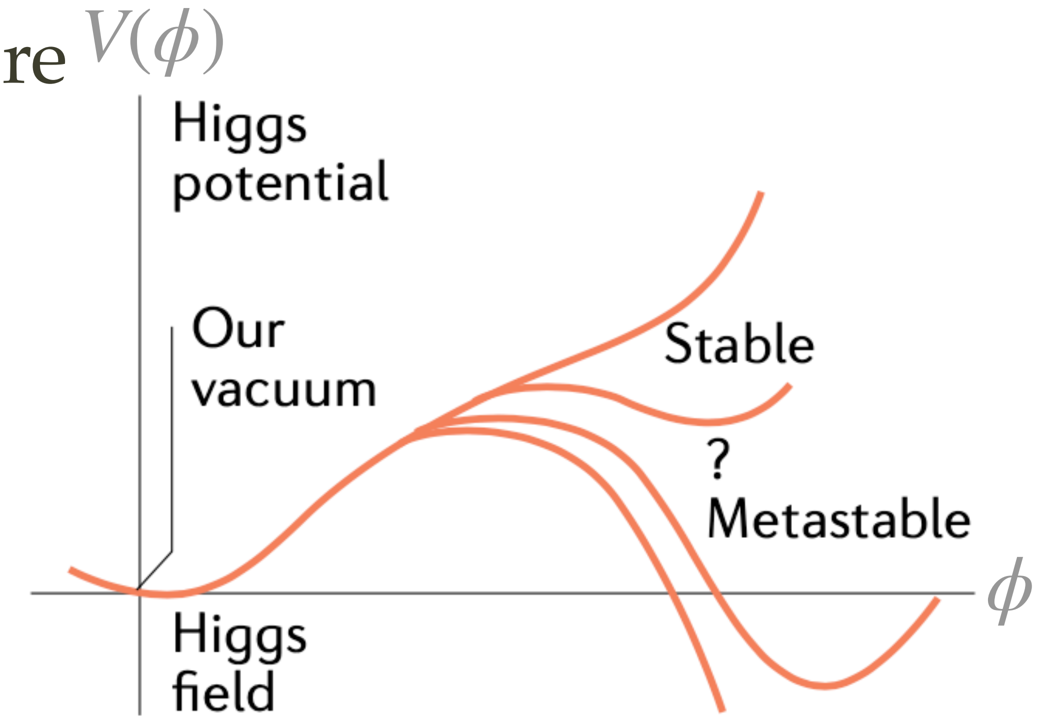
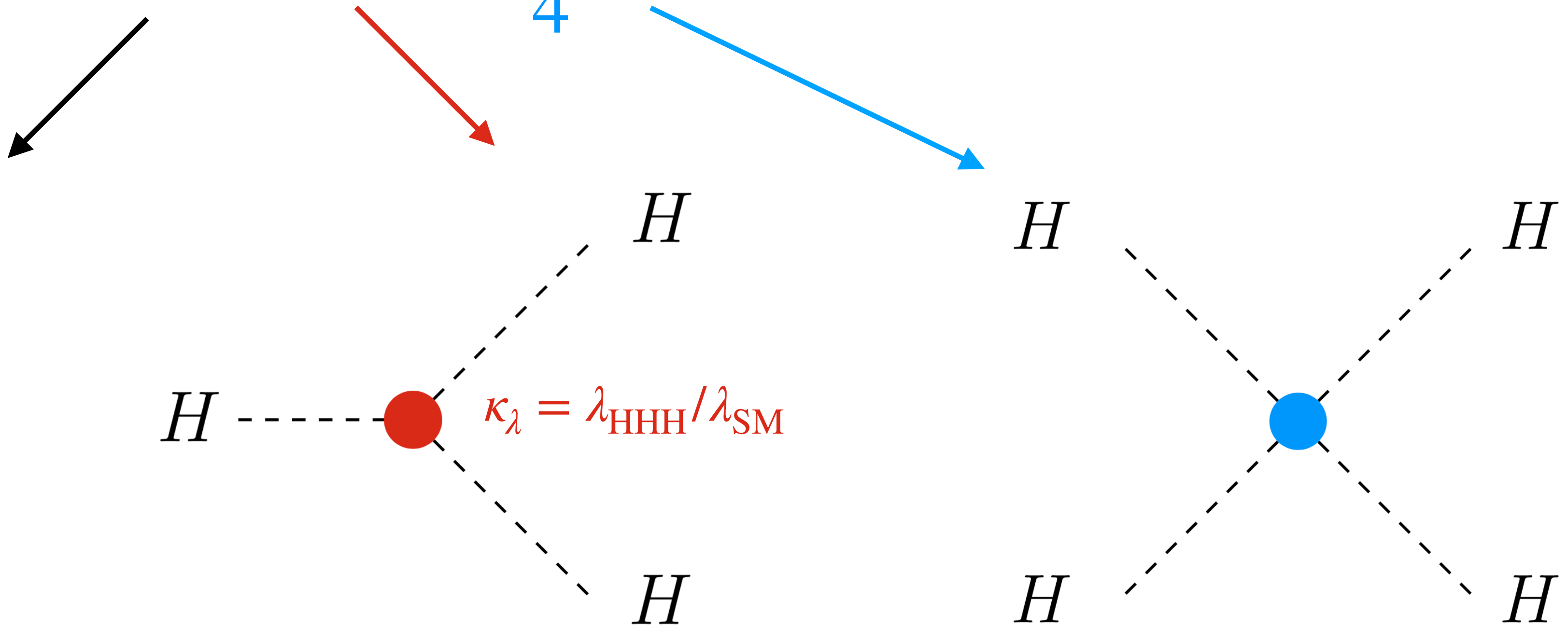


Image credit: Nature Reviews Physics 3.9 (2021)

Higgs self-coupling

- Direct exploring the potential at each Higgs field value ϕ is not possible.

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \supset \lambda\nu^2h^2 + \lambda\nu h^3 + \frac{\lambda}{4}h^4$$

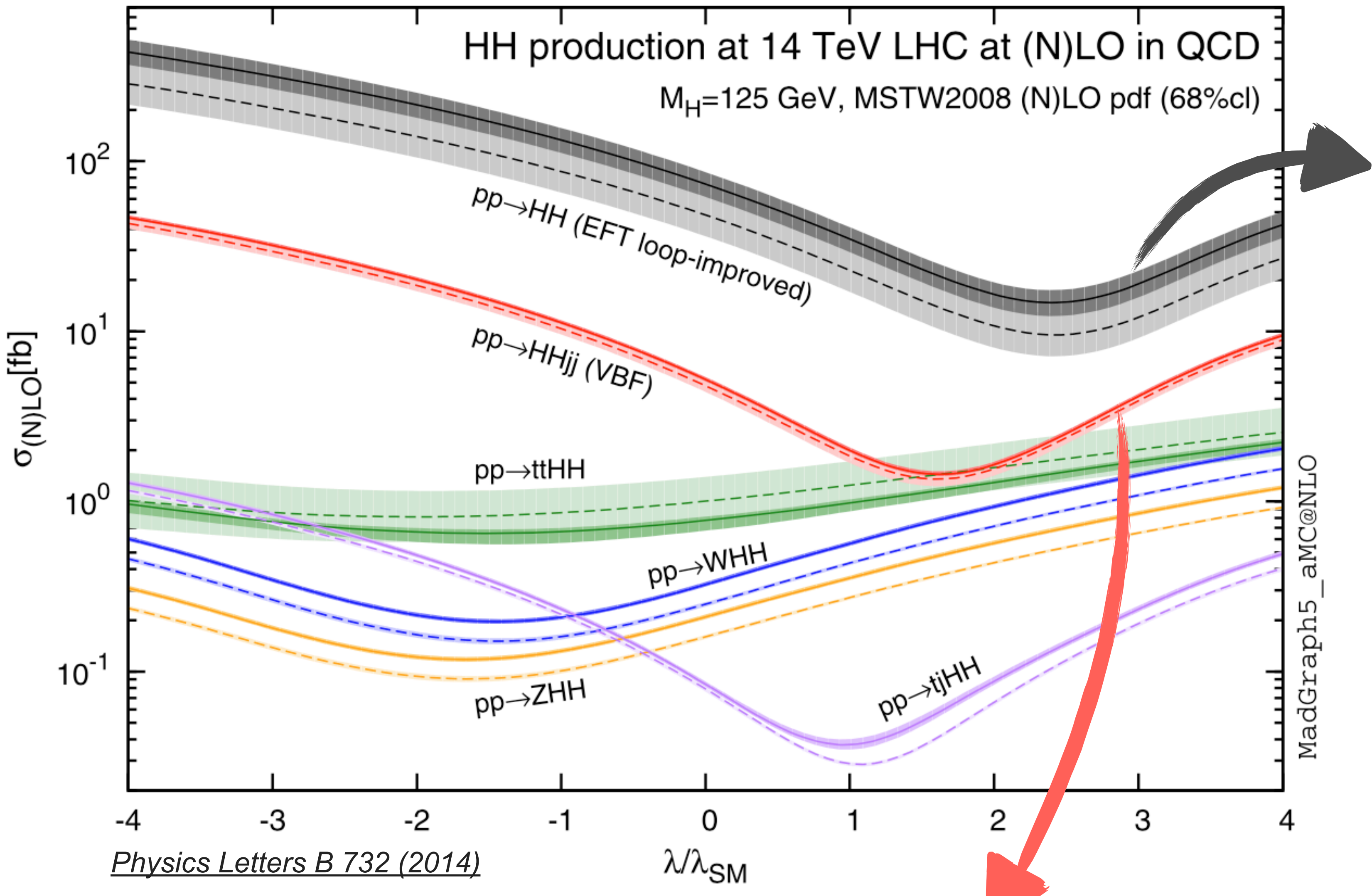


Mass term

Processes of Higgs Boson split into two or three can shed light.

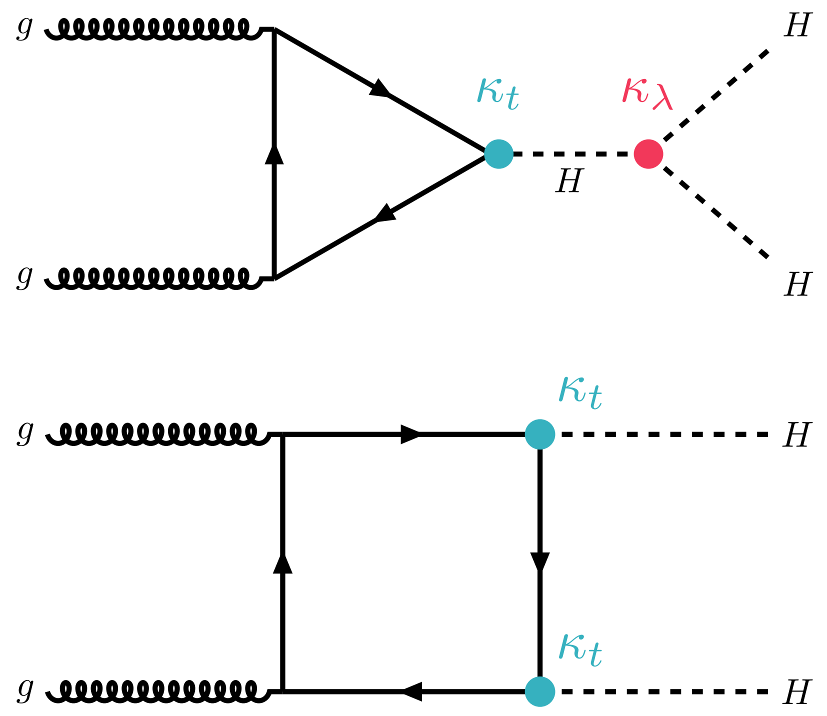
Probing the Higgs-self coupling is a key towards pinning down the exact shape of the potential.

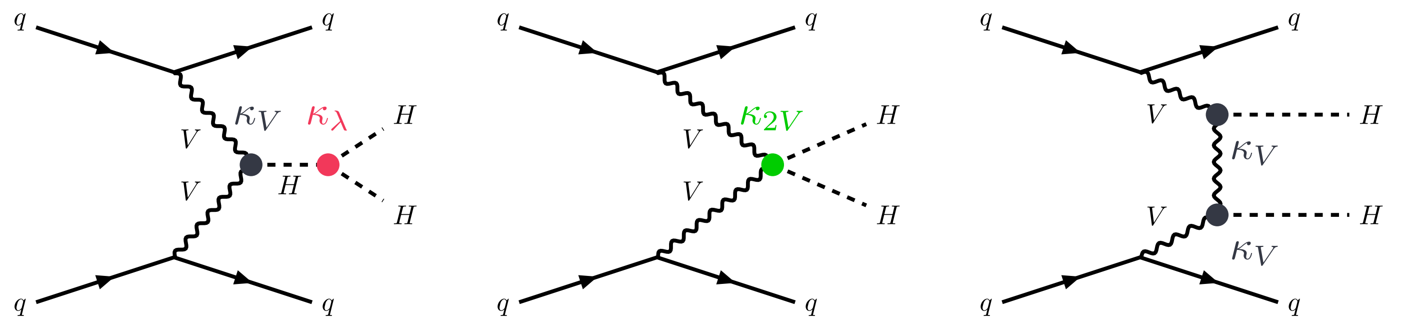
HH production at LHC



Physics Letters B 732 (2014)

Gluon-gluon Fusion production (ggF)





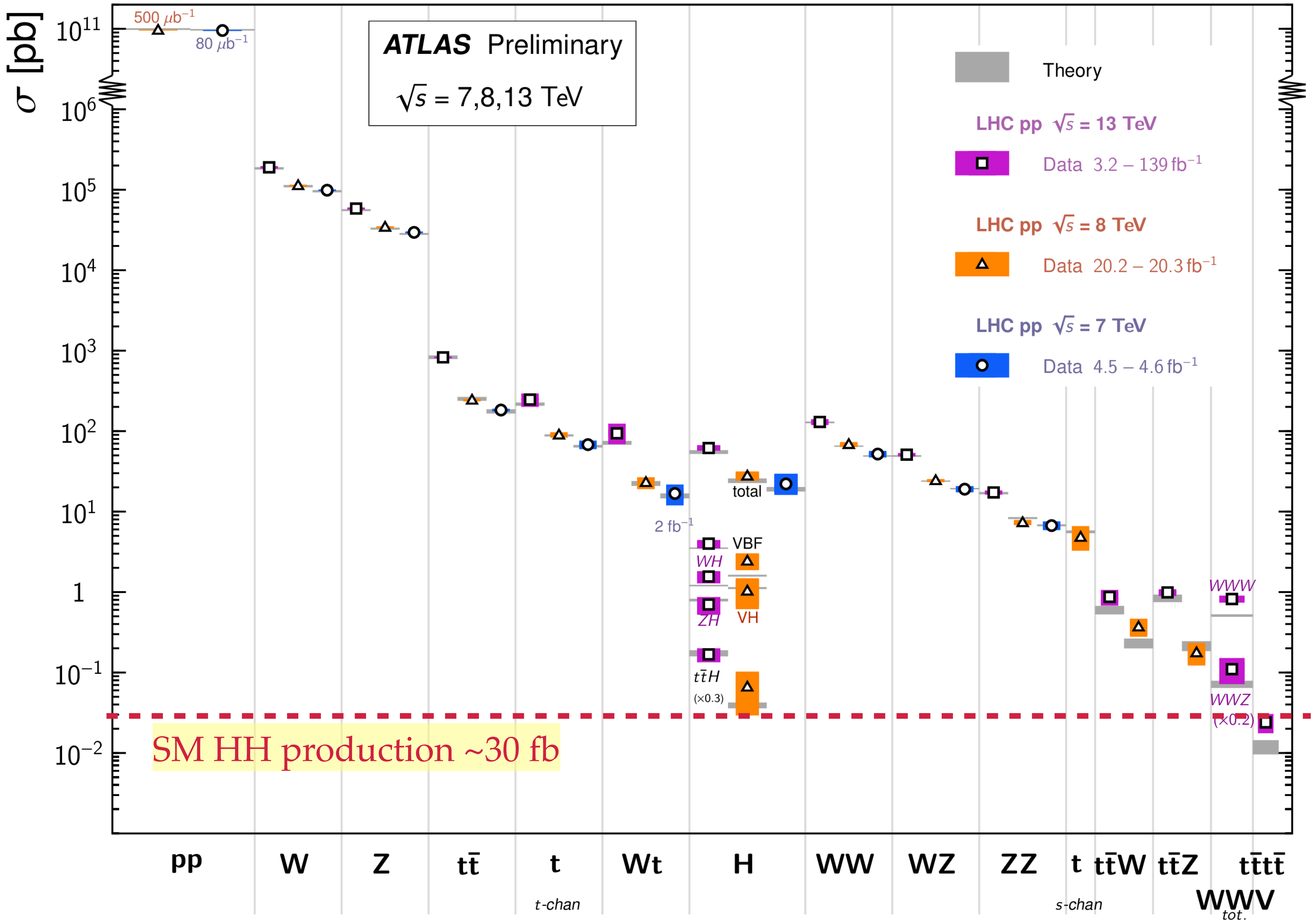
Vector Boson Fusion production (VBF)

SM σ_{HH} @ 13 TeV ~ 30 fb

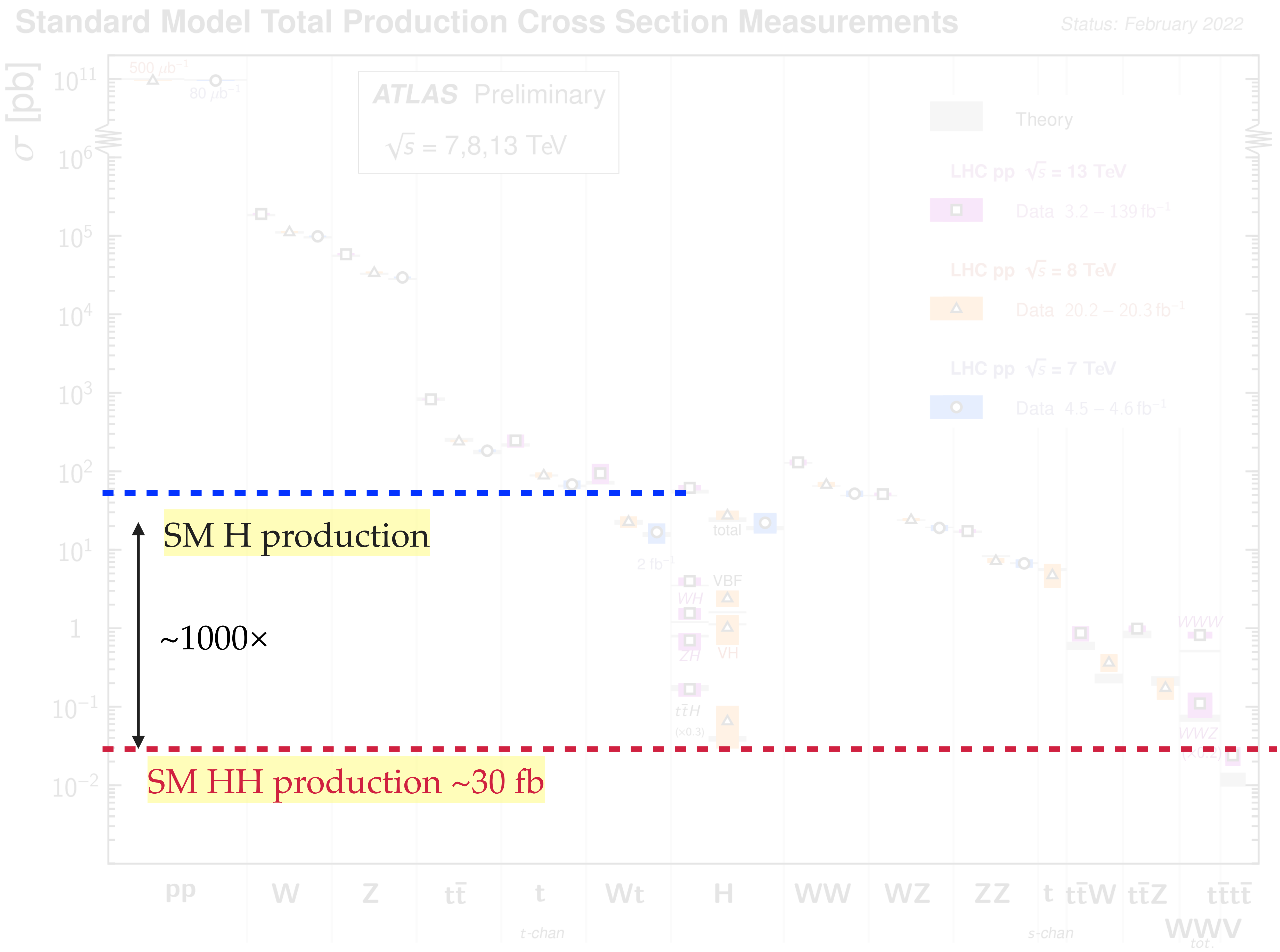
New physics can manifest itself as deviations in σ_{HH} through a **resonance** decay

Standard Model Total Production Cross Section Measurements

Status: February 2022



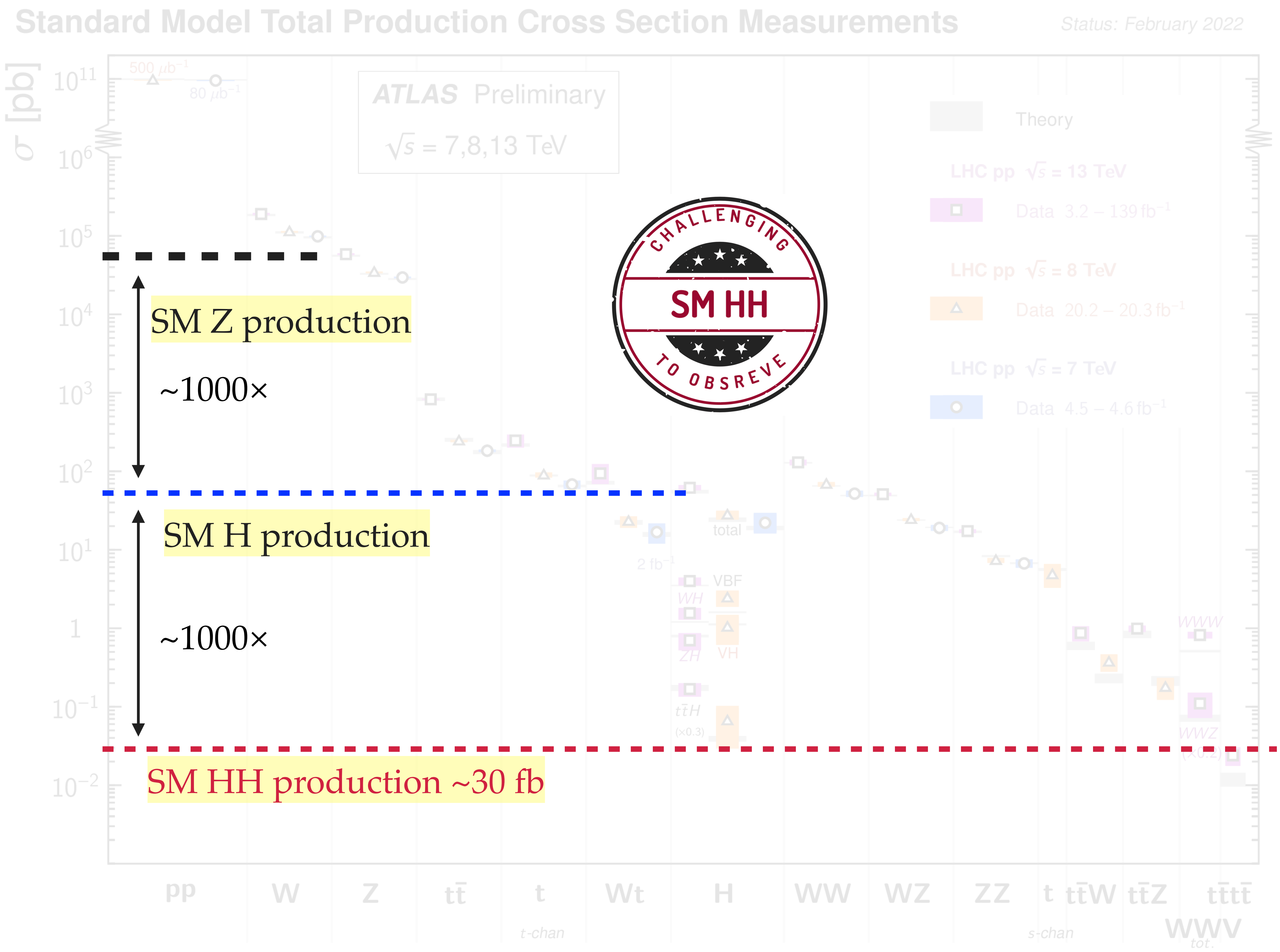
SM HH production ~30 fb



SM H production

~1000×

SM HH production ~30 fb



SM Z production

~1000×

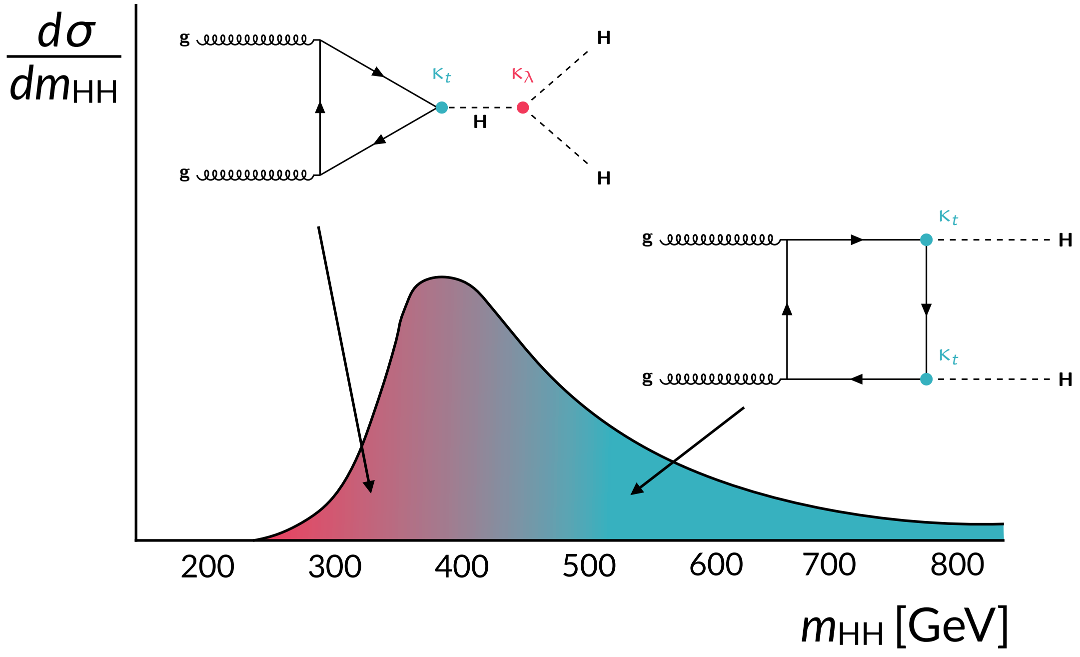
SM H production

~1000×

SM HH production ~30 fb

CHALLENGING
SM HH
TO OBSREVE

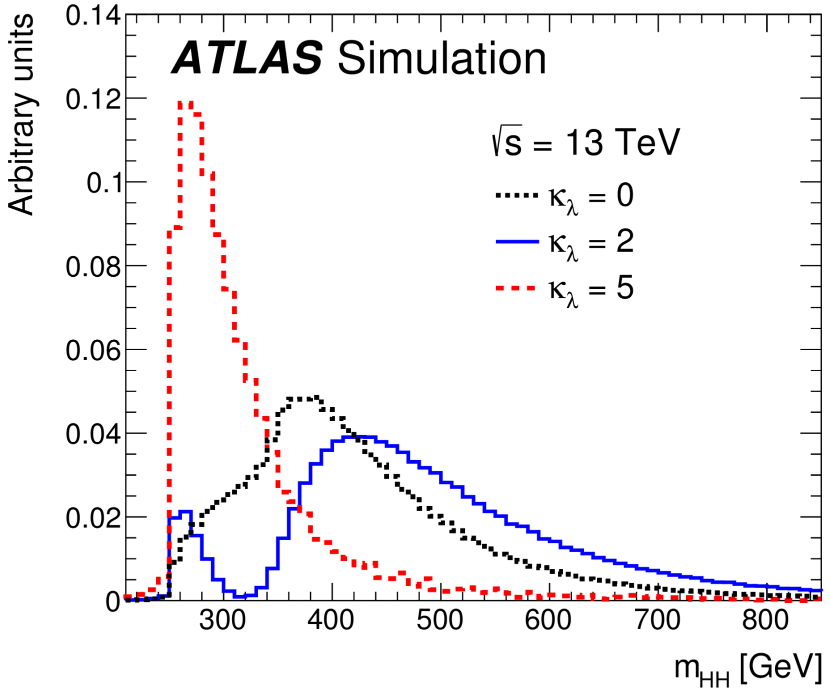
Why is it small?

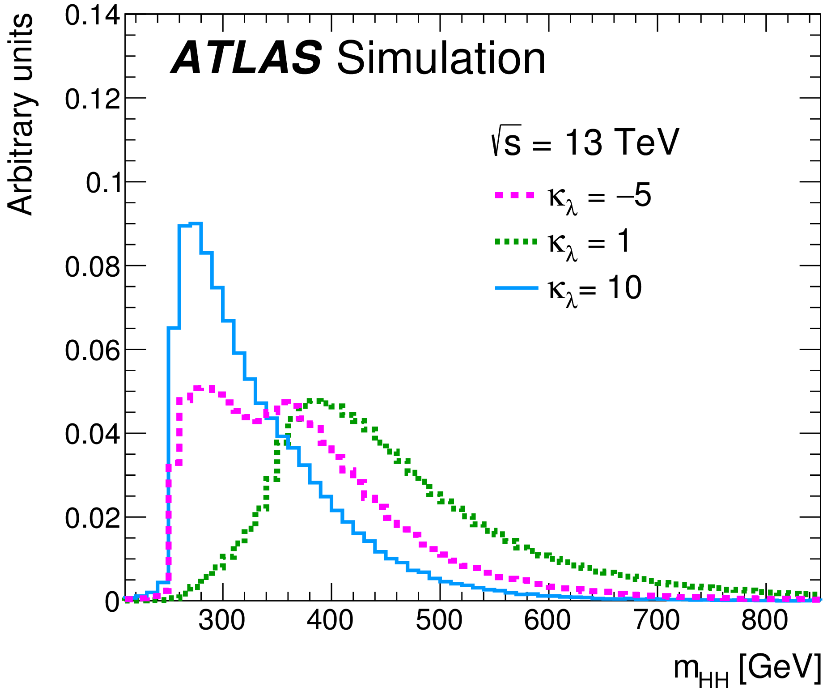


- Destructive interference of the triangle and box amplitude

And even worse …

- m_{HH} shape differs a lot
  - Remember we want to understand κ_λ



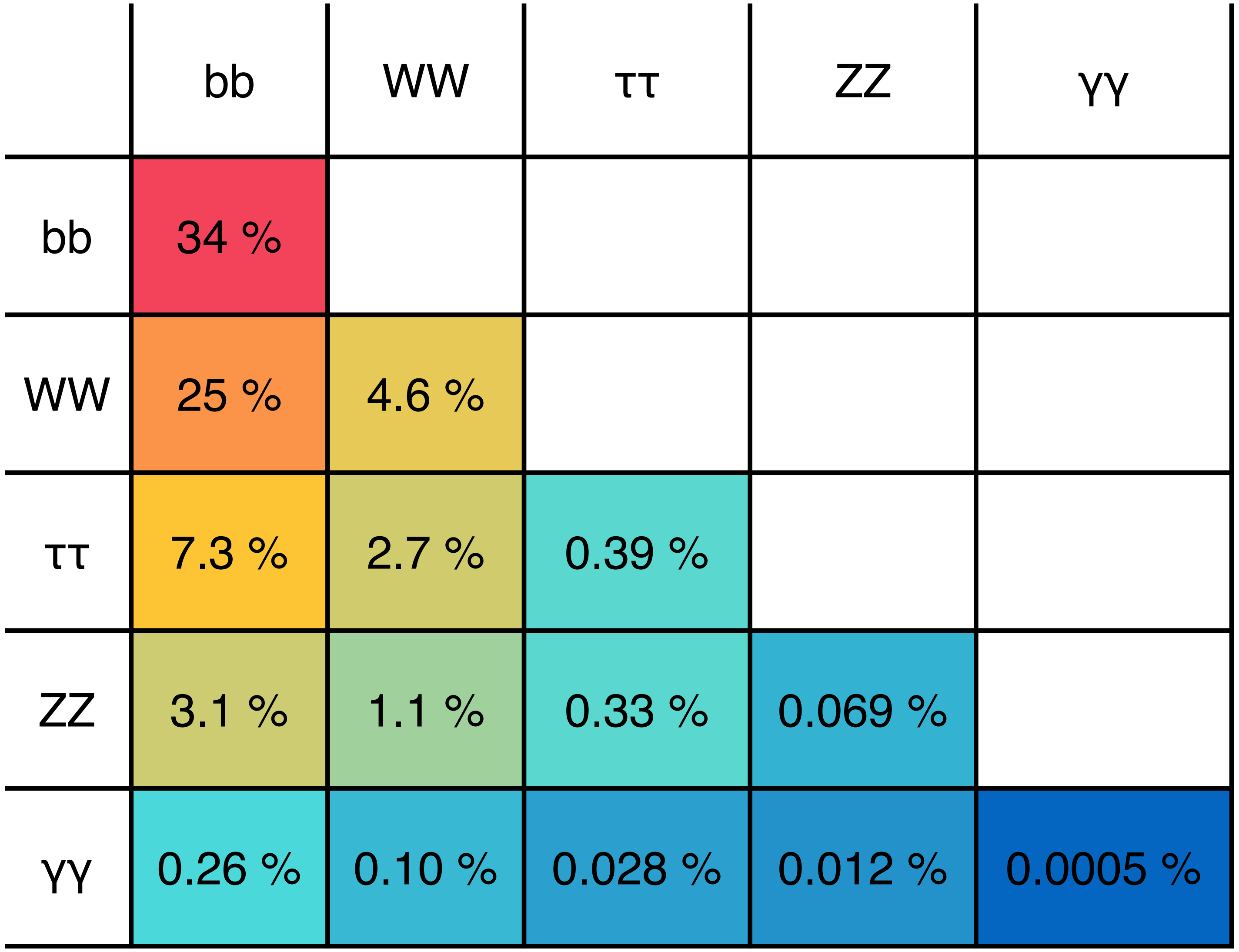


- $\kappa_\lambda = 2.4$ maximum destructive effect ~ 350 GeV
- Very soft kinematics for large κ_λ

HH decay channels

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 %

- No golden channel
- bbbb:
  - The most abundant final state
  - Challenge from large multi-jet background.
- Combination is fundamental for observation!
- New physics can manifest as deviations in σ_{HH}

CERN-EP-2022-235

Non-resonant HH→4b

Largest rate ~ 1.5K in Run 2
Searching is challenged by the large background events from multi-jet
(QCD multi-jet 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
  - Consistency with offline b-tagging
- Flavour tagging is crucial
- Higgs boson reconstruction affected by
  - 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

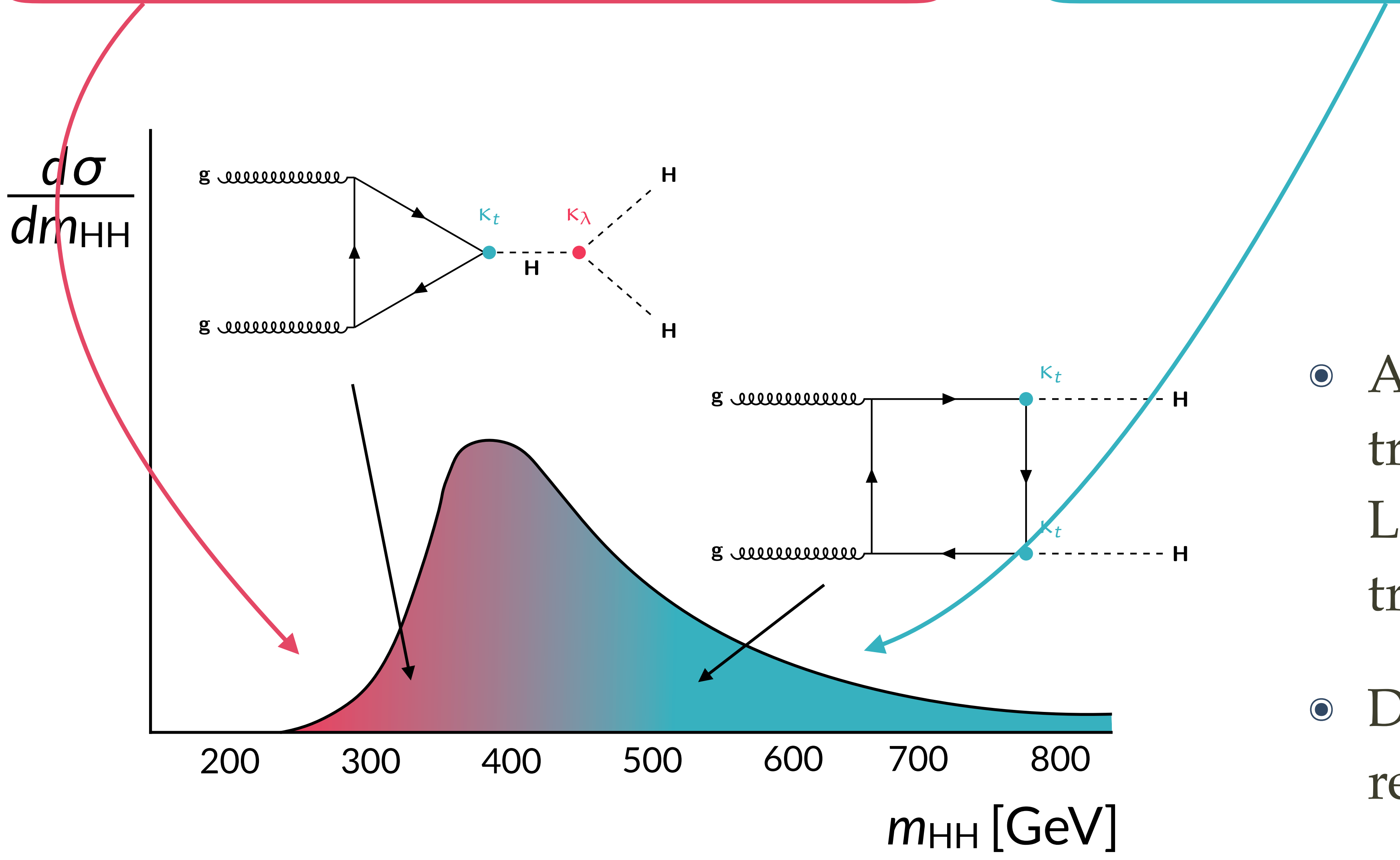
Trigger

“2b2j” trigger

- 2 b jets (35 GeV) + 2 extra jets (35 GeV)
- Important for low m_{HH} events

“2b1j” trigger

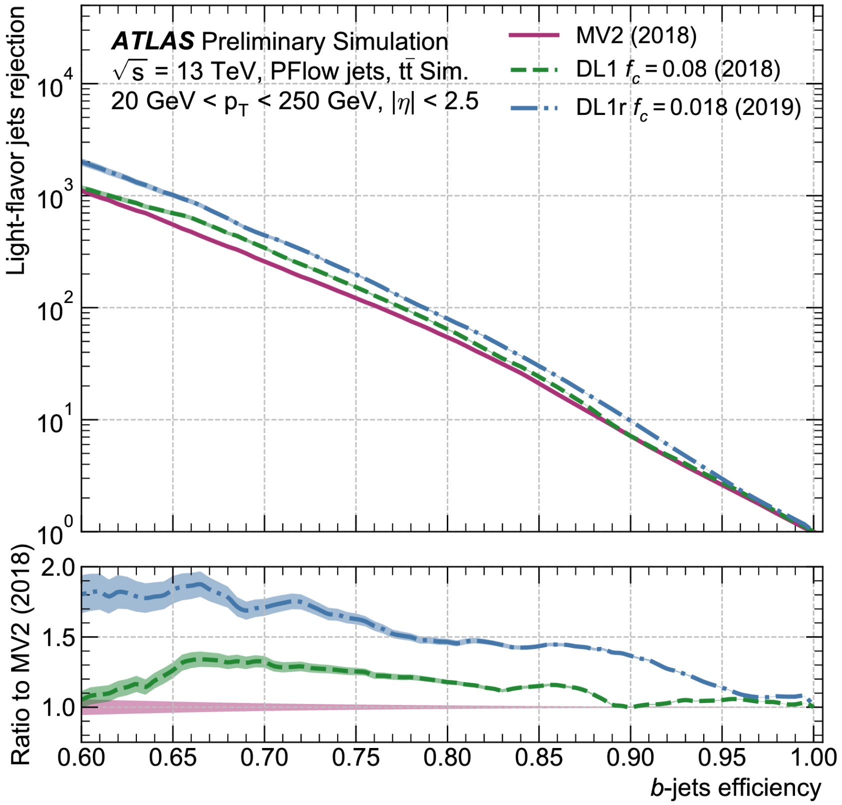
- 2 b jets (55 GeV) + 1 extra jets (100-150 GeV)
- Important for high m_{HH} events



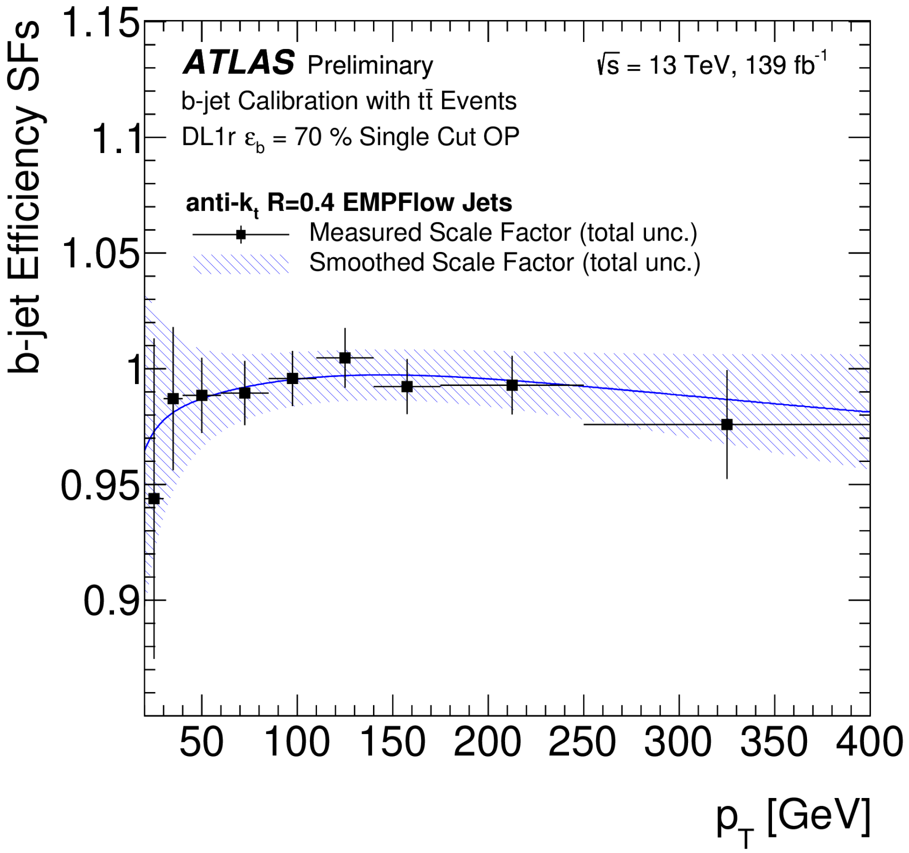
- Analysis operating on trigger turn-on both of Level 1 and High level triggers
- Dedicated calibrations required for both levels

Flavour tagging

DL1r performance



DL1r calibration



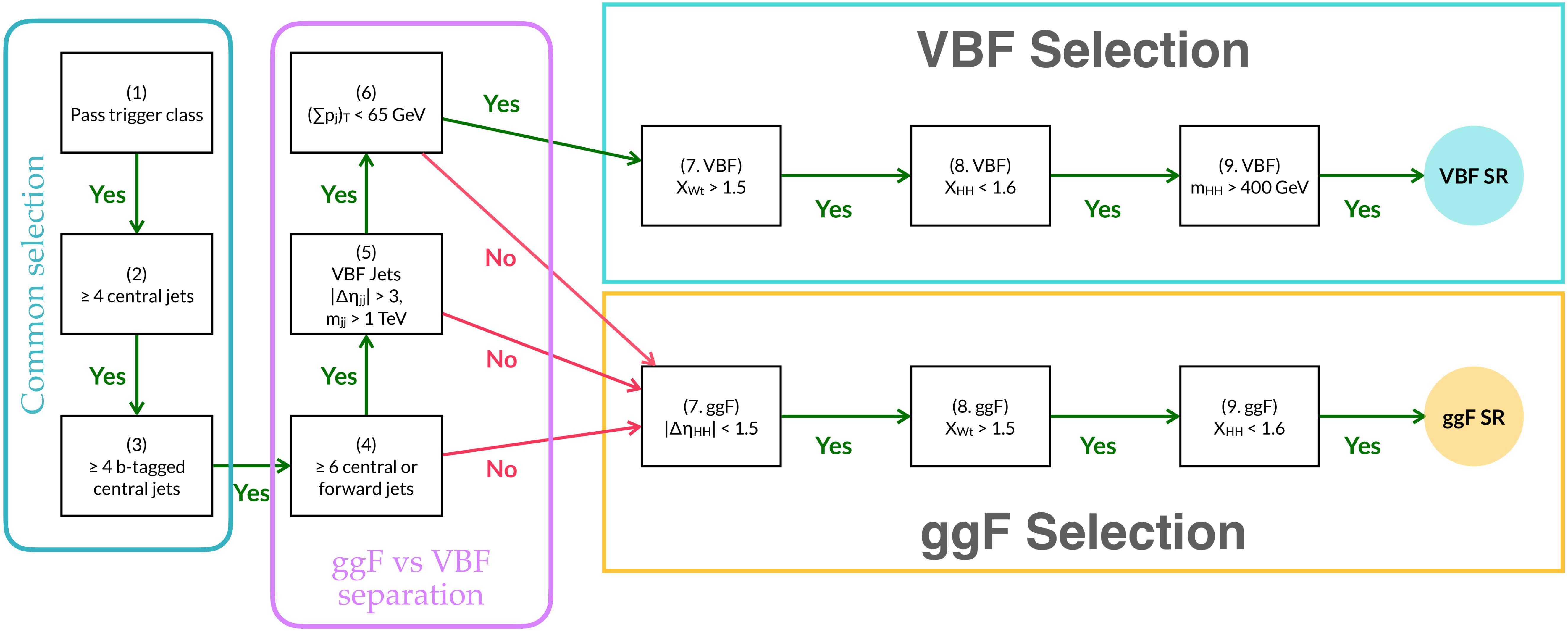
- Using DL1r tagger: Deep neural network plus recurrent neural network
  - Allowed for 10% looser b-jet efficiency working points maintaining same background rejection with respect to previous analysis
  - One of the largest sources of improvements for all ATLAS HH analyses!

Event selection — kinematics

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

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

VBF jets:
Pair of untagged central or forward jets with highest m_{jj}



(1) Pass trigger class

(2) ≥ 4 central jets

(3) ≥ 4 b-tagged central jets

(4) ≥ 6 central or forward jets

(5) VBF Jets $|\Delta\eta_{jj}| > 3$, $m_{jj} > 1$ TeV

(6) $(\sum p_j)_T < 65$ GeV

(7. VBF) $X_{Wt} > 1.5$

(8. VBF) $X_{HH} < 1.6$

(9. VBF) $m_{HH} > 400$ GeV

(7. ggF) $|\Delta\eta_{HH}| < 1.5$

(8. ggF) $X_{Wt} > 1.5$

(9. ggF) $X_{HH} < 1.6$

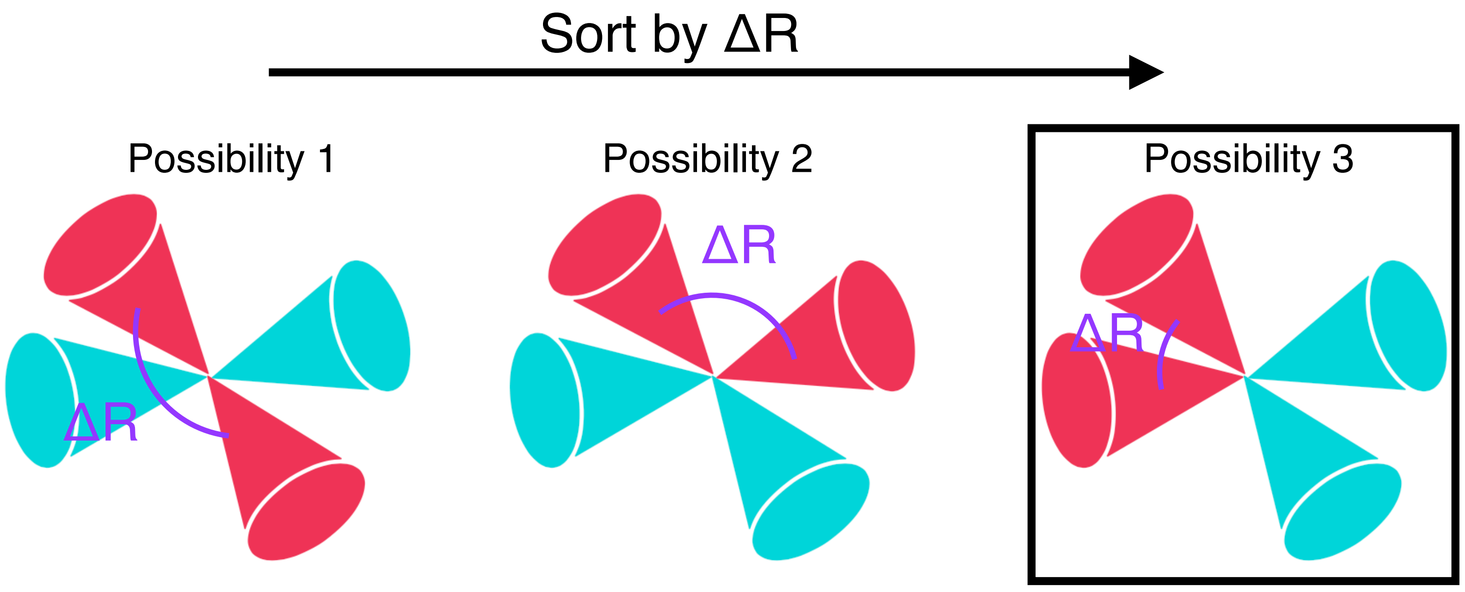
$$X_{Wt} = \sqrt{\left(\frac{m_W - 80.4\text{GeV}}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5\text{GeV}}{0.1 m_t}\right)^2} > 1.5$$

Top-quark veto cut

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

Signal region definition cut

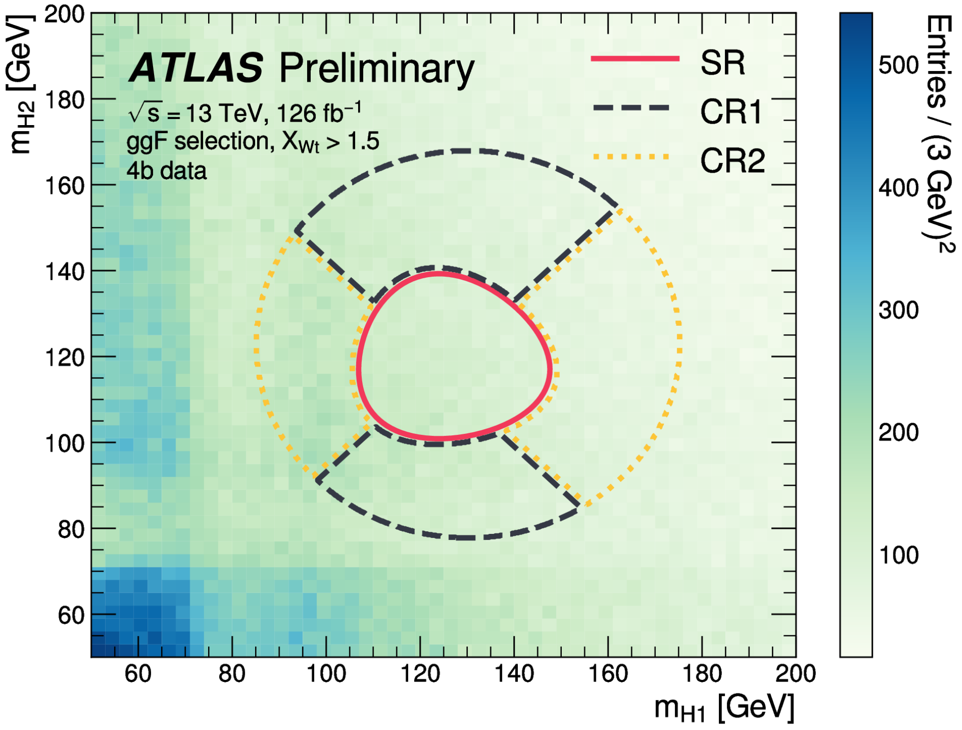
Event selection — pairing



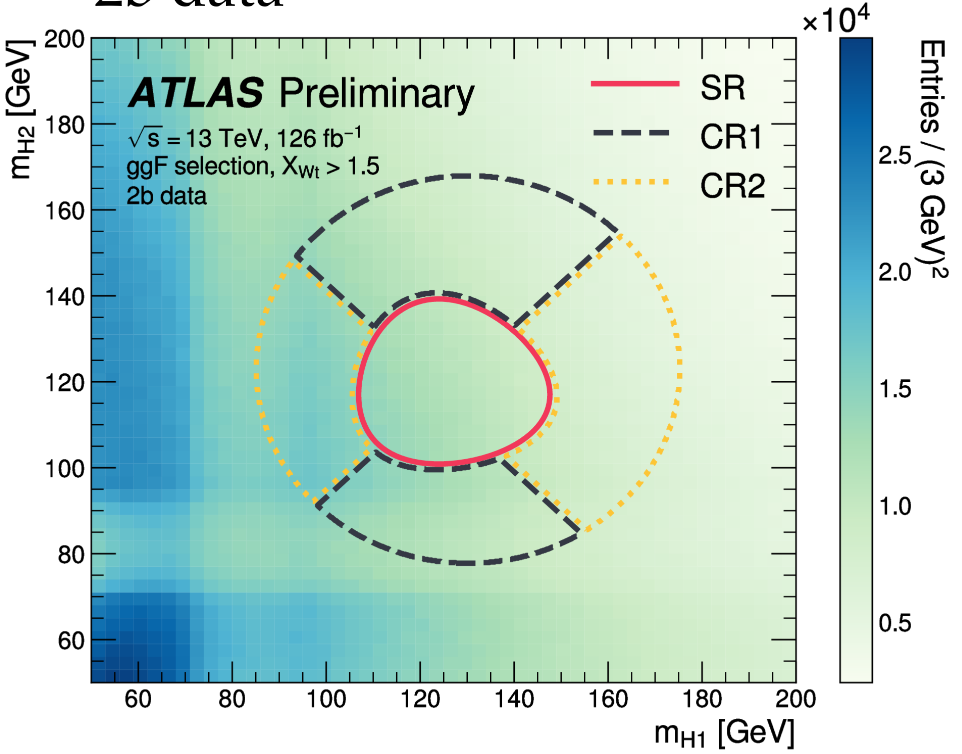
Leading Higgs Candidate

Subleading Higgs Candidate

4b data



2b data



Strips ~80 GeV due to X_{Wt} cut

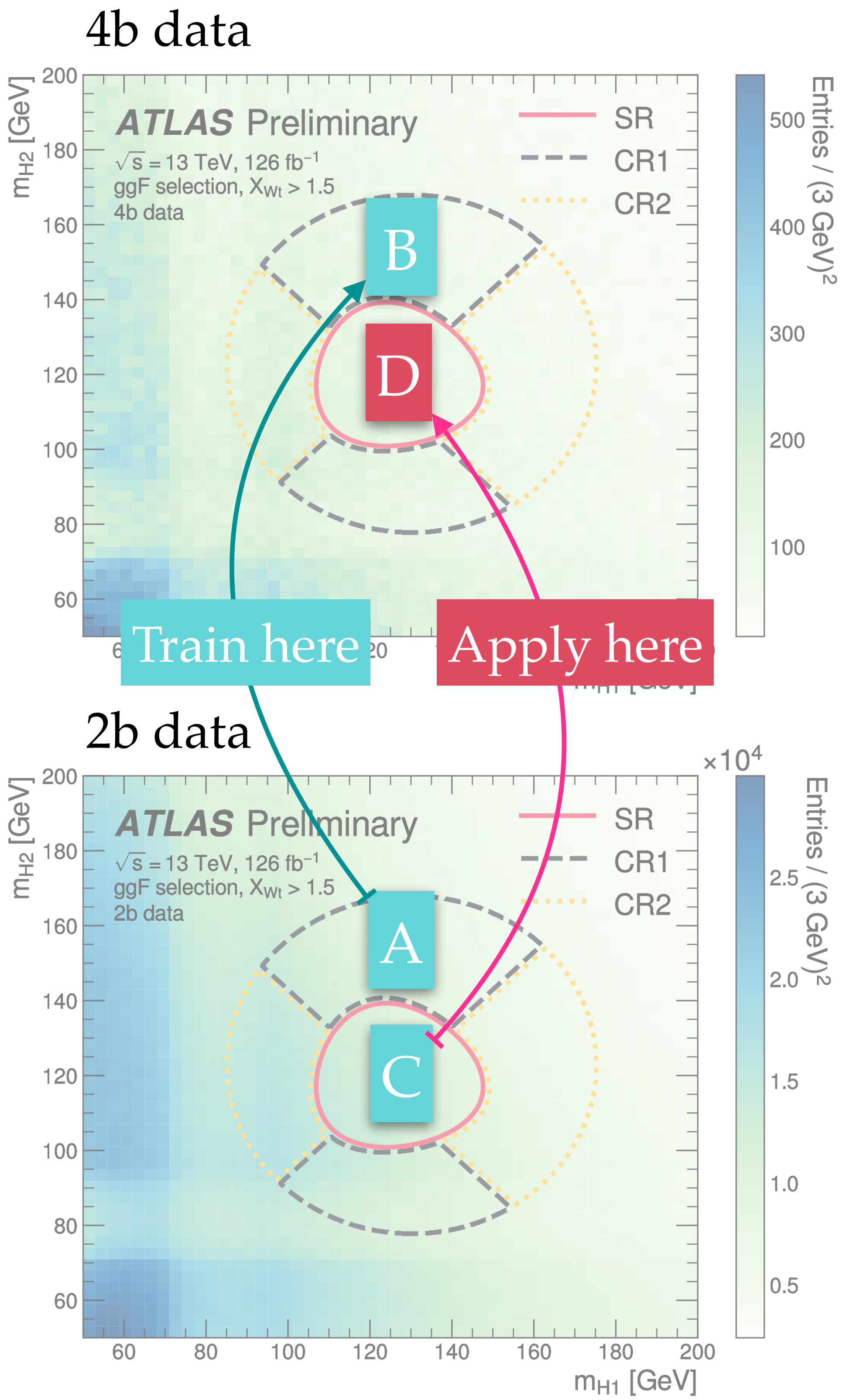
- Choose pairing that minimises ΔR between jets in the leading Higgs candidate (H_1)
- No mass information used to avoid sculpting the H_1-H_2 mass plane
- This is different from the one in the resonant search (see later)

Background estimation

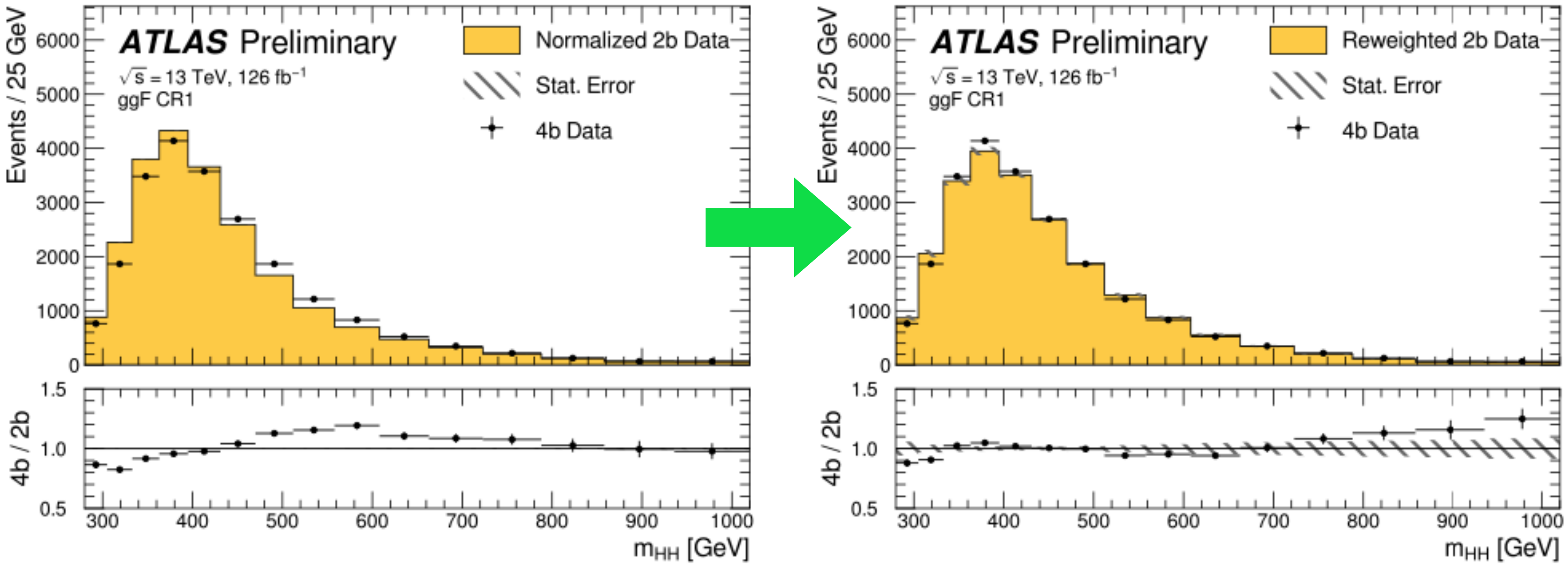
- $$\text{Data}[D](x) = \boxed{\begin{array}{c}\dfrac{\text{Data}[B](x)}{\text{Data}[A](x)} \\ R(x)\end{array}} \times \text{Data}[C](x)$$
  - 2b events can be reweighted to 4b (kinematically similar)
- A neural network is adopted to learn $R(x)$
  - Found better performance with NNs than with other methods (iterative reweighting, BDTs) specially modelling steeply falling / peaking distributions
  - Construct following loss function

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

such that $\underset{R}{\arg\min}\, \mathcal{L}(R(x)) = \dfrac{p_{4b}(x)}{p_{2b}(x)}$

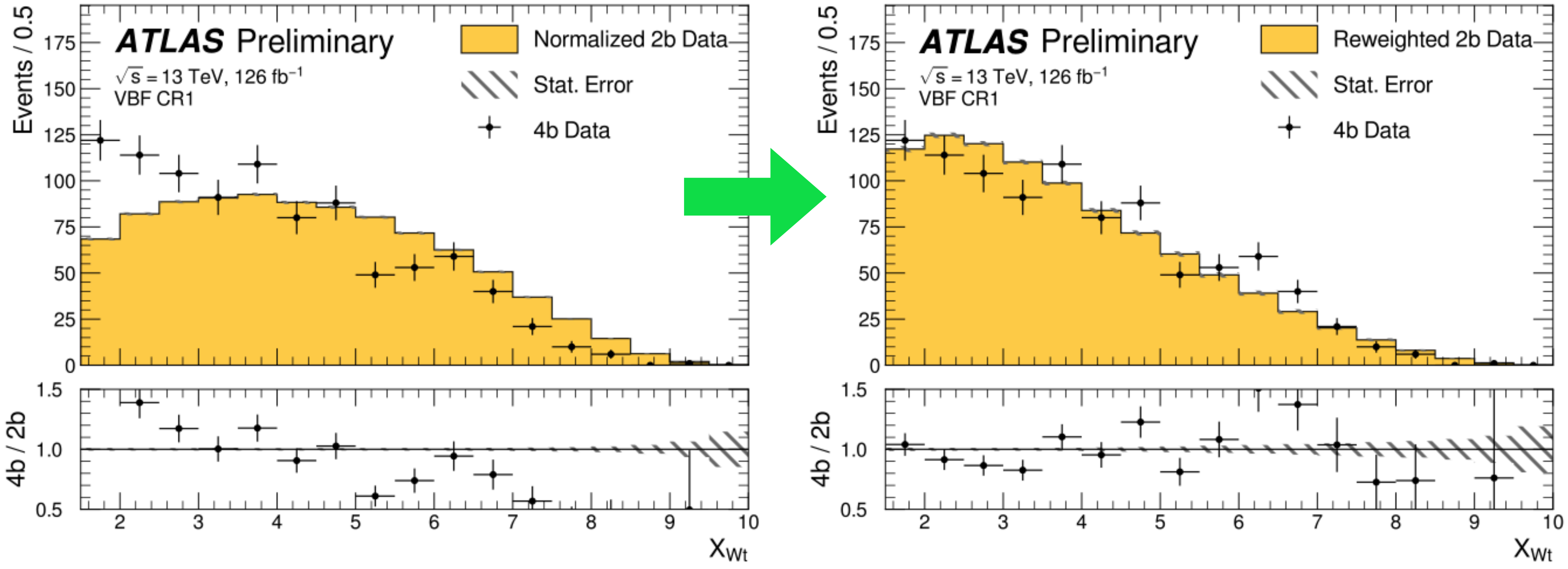


Background estimation performance



☜ m_{HH} in control region in ggF selection before and after reweighting.

X_{Wt} in control region in VBF selection before and after reweighting. ☞



Reweighting improves the agreement with 4b events significantly.

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 $|\Delta\eta_{HH}|$ 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

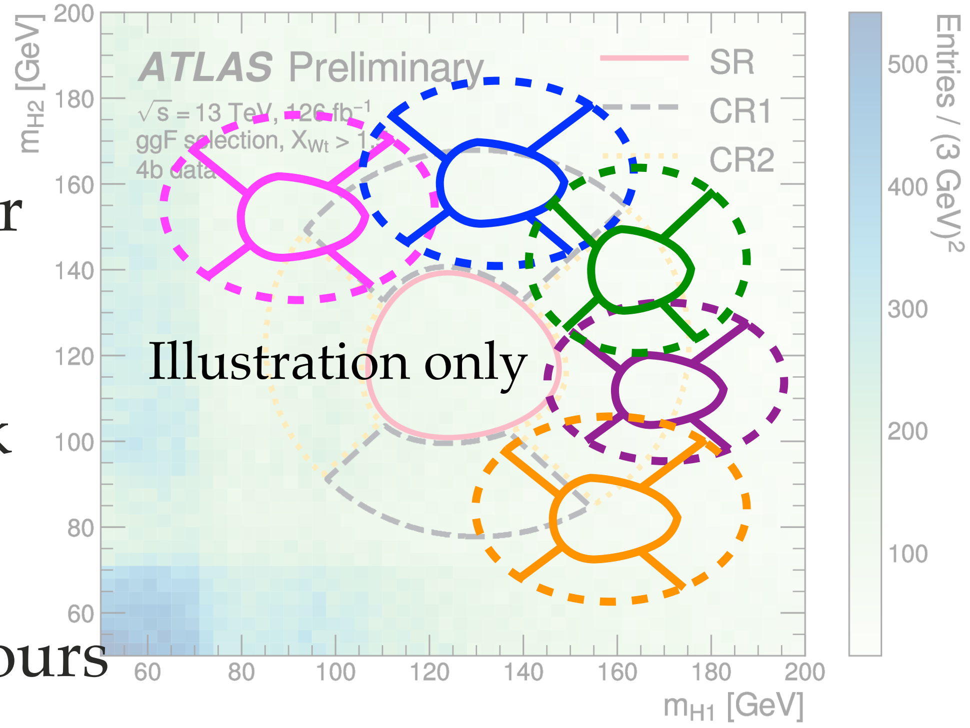
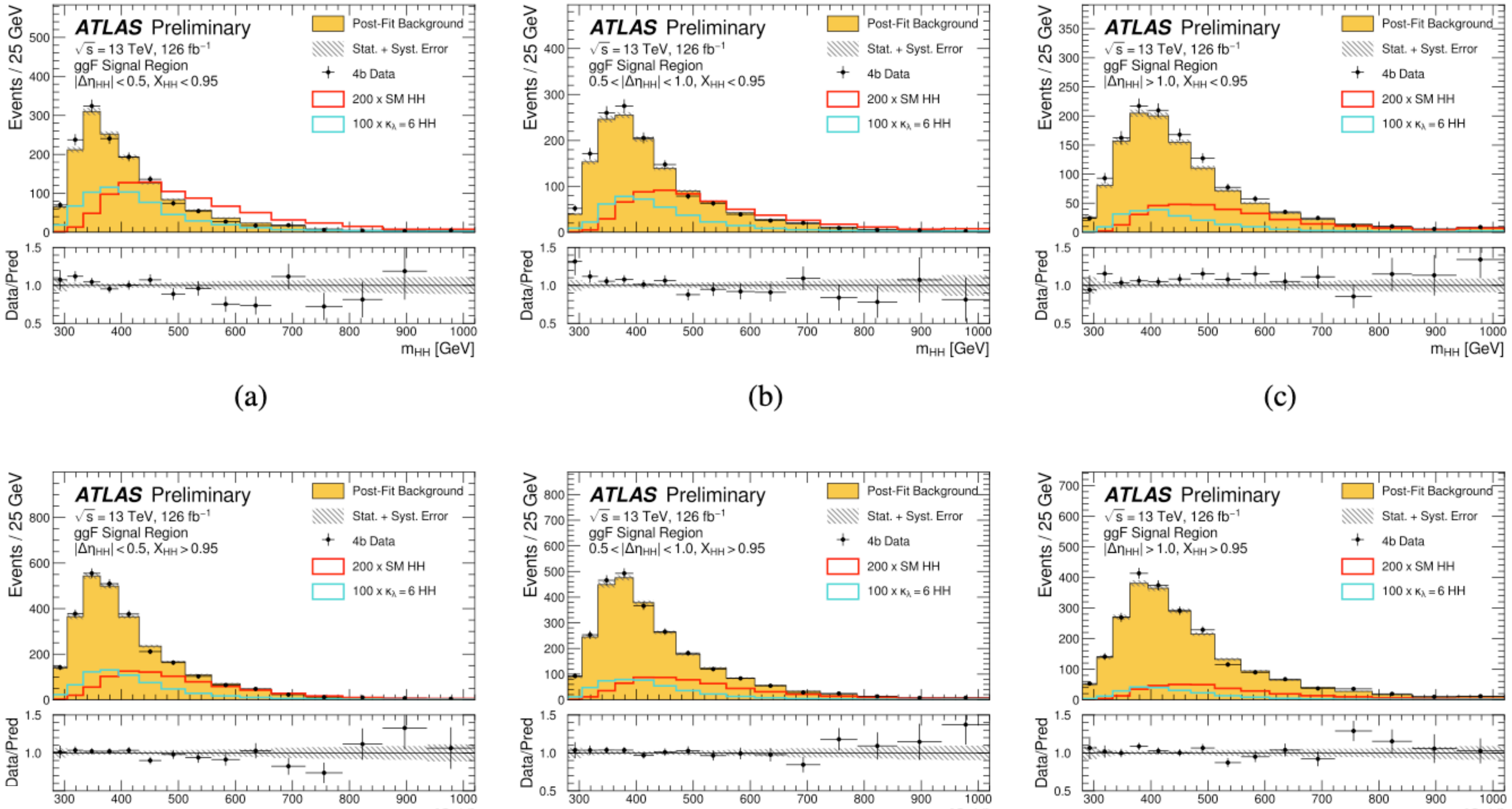


Illustration only

Categorisation

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

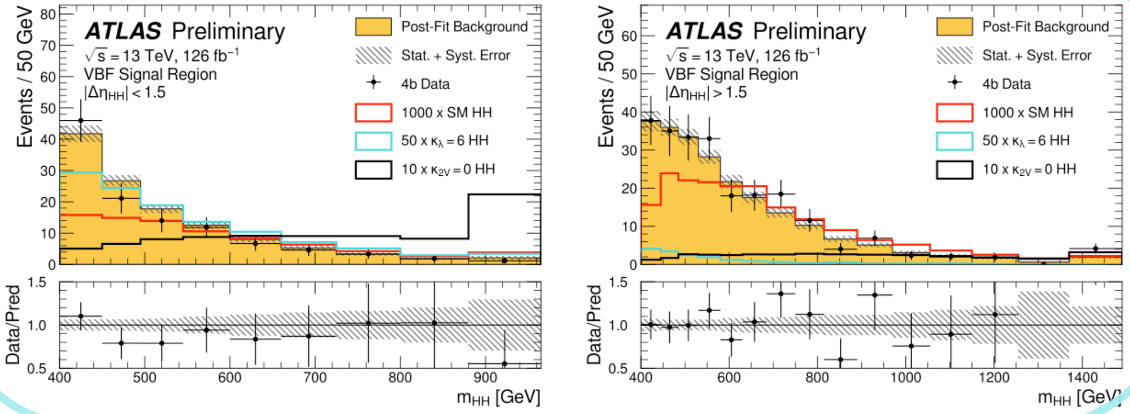
ggF signal region
$\lvert\Delta\eta_{HH}\rvert < 0.5,\ X_{HH} < 0.95$
$\lvert\Delta\eta_{HH}\rvert < 0.5,\ X_{HH} > 0.95$
$0.5 < \lvert\Delta\eta_{HH}\rvert < 1.0,\ X_{HH} < 0.95$
$0.5 < \lvert\Delta\eta_{HH}\rvert < 1.0,\ X_{HH} > 0.95$
$\lvert\Delta\eta_{HH}\rvert > 1.0,\ X_{HH} < 0.95$
$\lvert\Delta\eta_{HH}\rvert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



(a) (b) (c)

(d) (e) (f)

ggF

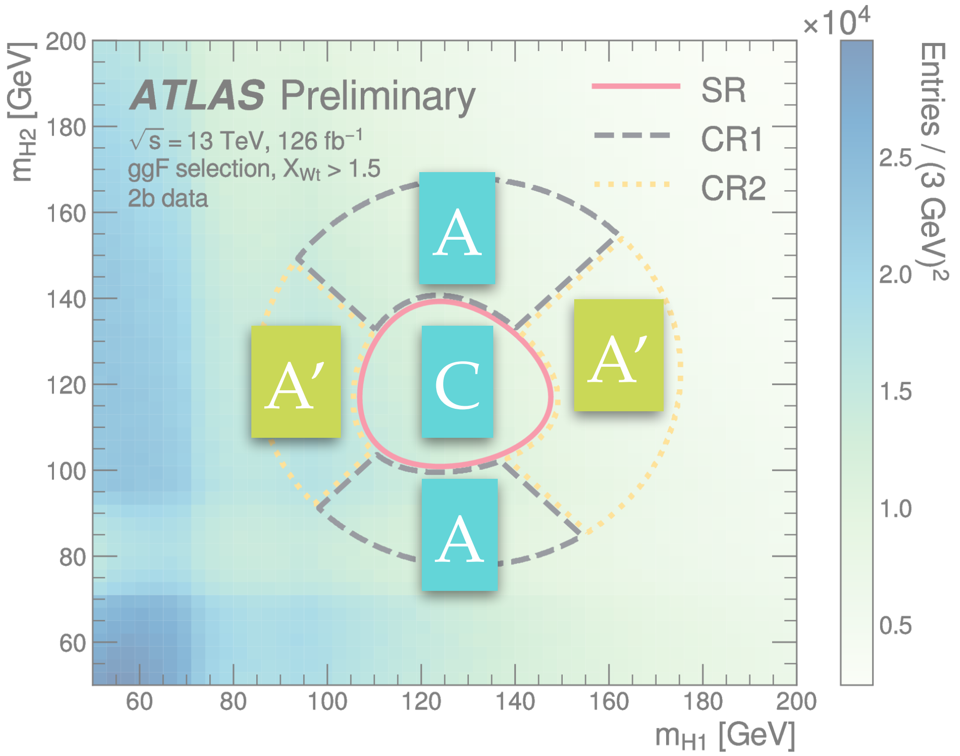


VBF

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 jet energy scale, jet energy resolution, flavour tagging, luminosity, pileup, modelling, …

Results

Results compatible with SM

- No significant deviations found

SM cross-section limit at 5.4 (8.1) x SM observed (expected)

Constraints on κ_λ

[-3.9, 11.1] from CLs limits at 95% CL

[-3.5, 11.3] from profile likelihood scan at 2σ

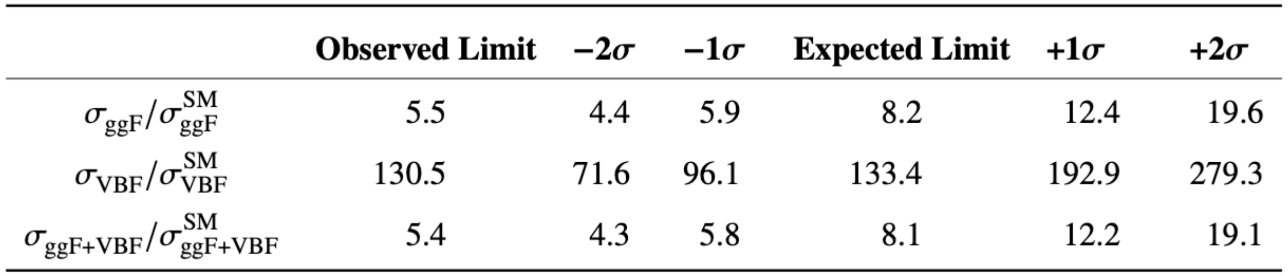
Constraints on κ_{2V}

[-0.03, 2.11] from CLS limits at 95% CL

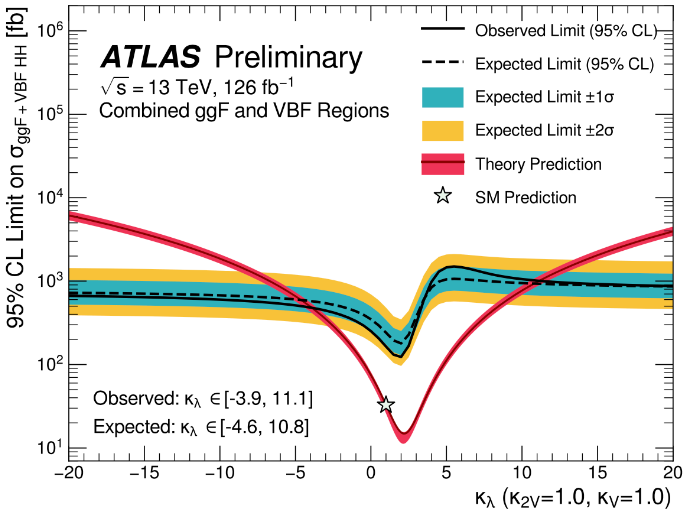
[0, 2.1] from profile likelihood scan at 2σ

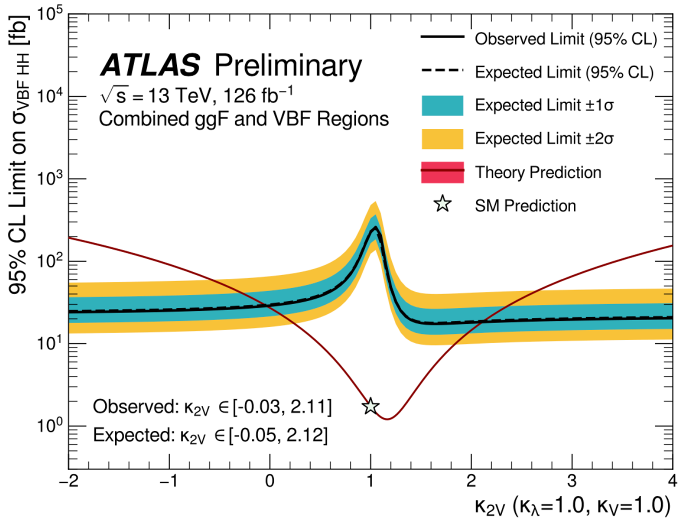
Significant improvements w.r.t 36 fb^{-1} ggF and previous 127 fb^{-1} VBF results!

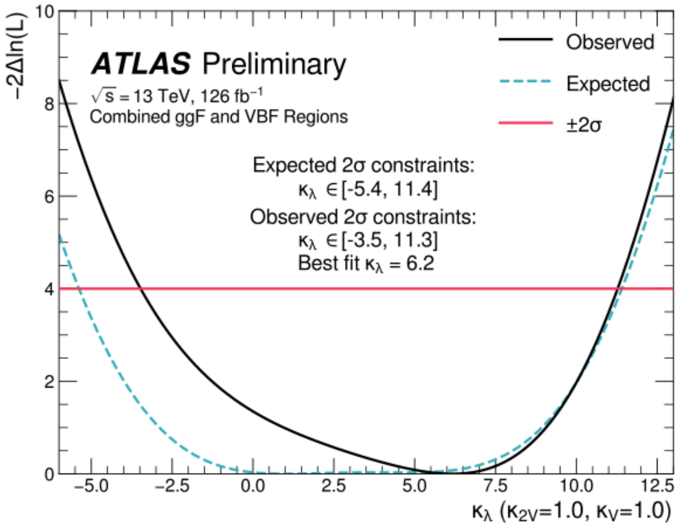
- Signal categorisation
- More precise background estimate
- More performant b-tagging

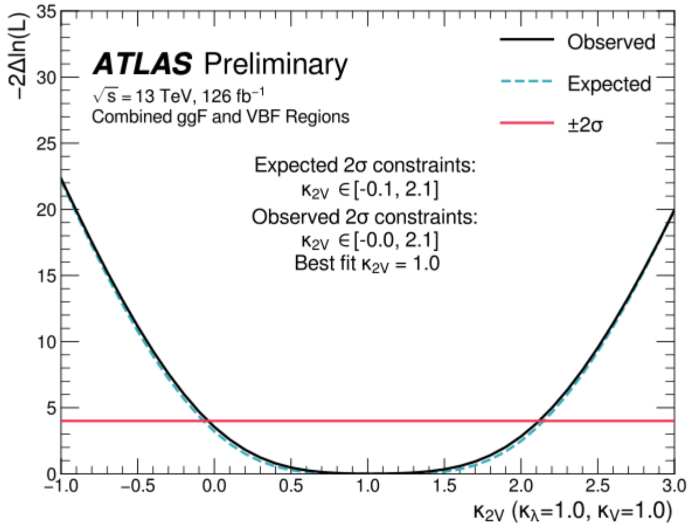


	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
$\sigma_{\text{ggF}}/\sigma_{\text{ggF}}^{\text{SM}}$	5.5	4.4	5.9	8.2	12.4	19.6
$\sigma_{\text{VBF}}/\sigma_{\text{VBF}}^{\text{SM}}$	130.5	71.6	96.1	133.4	192.9	279.3
$\sigma_{\text{ggF+VBF}}/\sigma_{\text{ggF+VBF}}^{\text{SM}}$	5.4	4.3	5.8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





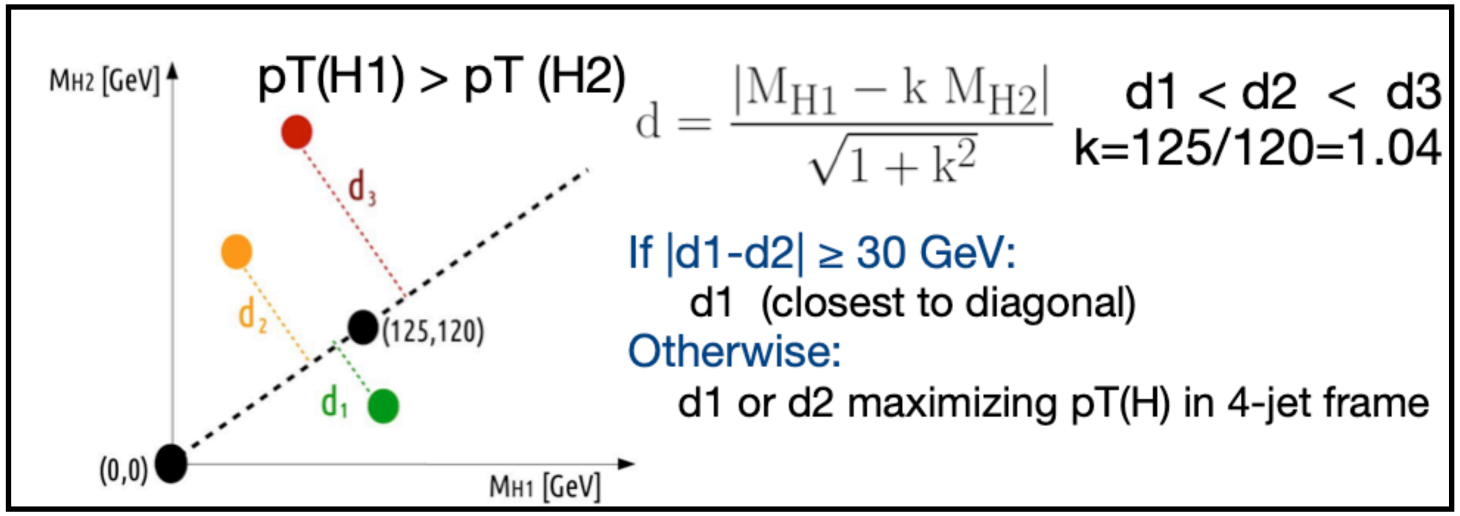




Comparing with CMS 4b results

Obs (Exp)	ATLAS	CMS (resolved)	CMS (boosted)
SM signal strength	5.4 (8.1)	3.9 (7.8)	9.9 (5.1)
$\kappa\lambda$	[-3.5,11.3] ([-5.4,11.4])	[-2.3, 9.4] ([-5.0,12.0])	[-9.9,16.9] ([-5.1,12.2])
κ**2V**	[0, 2.1] ([-0.1,2.1])	[-0.1, 2.2] ([-0.4,2.5])	[0.6,1.4] ([0.7,1.4])

- A few key differences between ATLAS and CMS (resolved)
  - Pairing:



$$d = \frac{|M_{H1} - k\ M_{H2}|}{\sqrt{1+k^2}}$$

d1 < d2 < d3

k=125/120=1.04

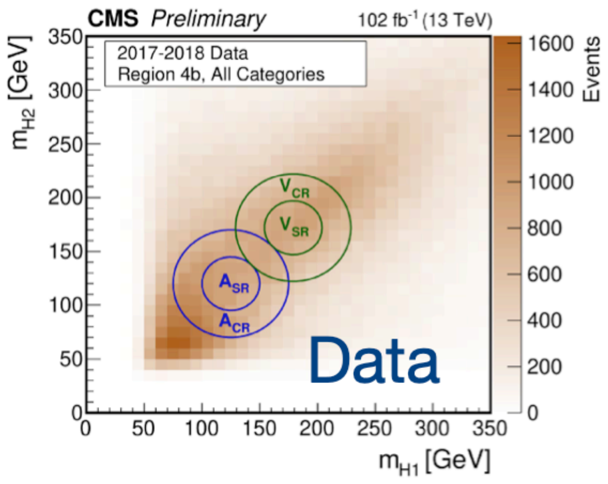
If |d1-d2| ≥ 30 GeV:

d1 (closest to diagonal)

Otherwise:

d1 or d2 maximizing pT(H) in 4-jet frame

- Validation region



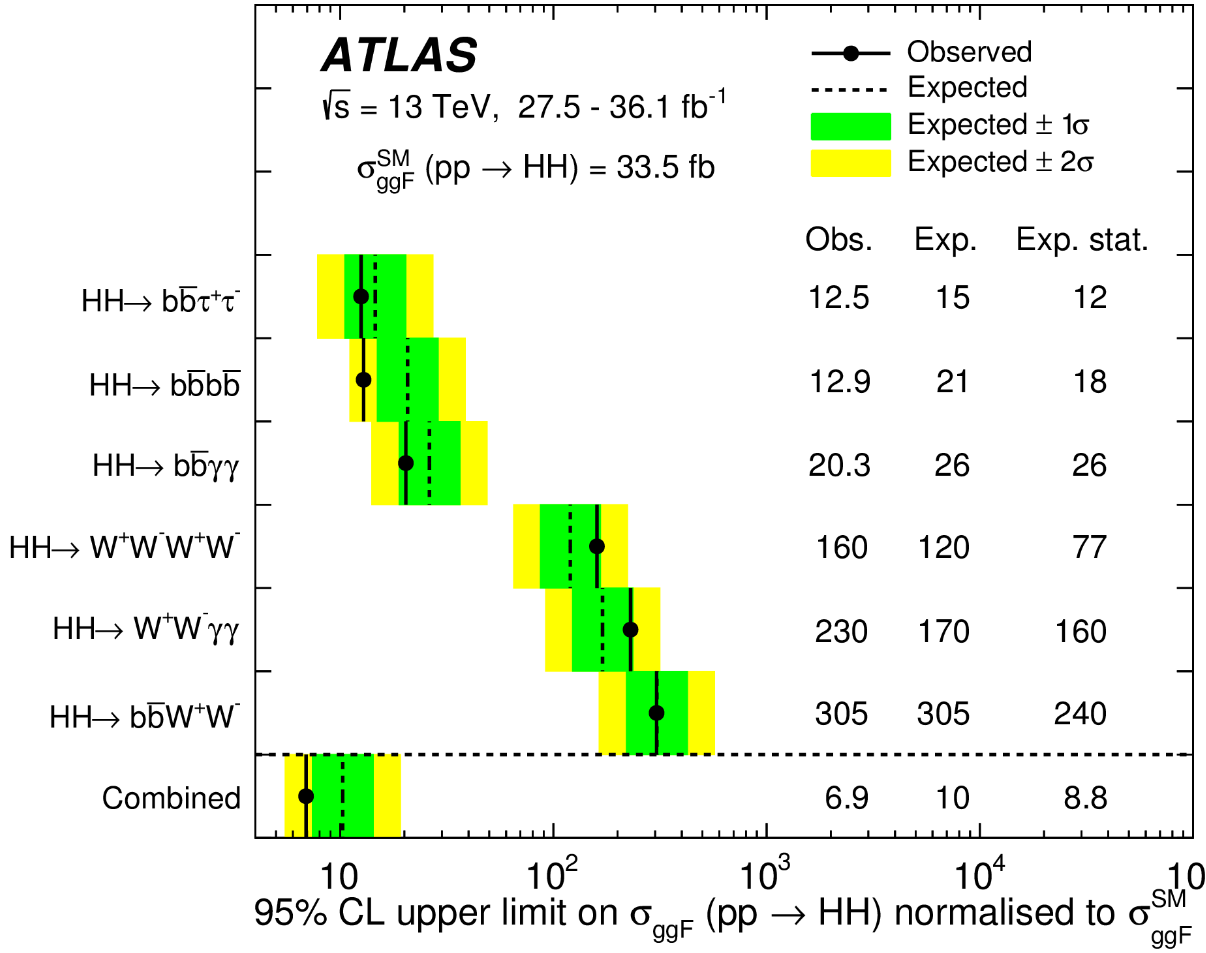
  - 3b instead of 2b for background estimation

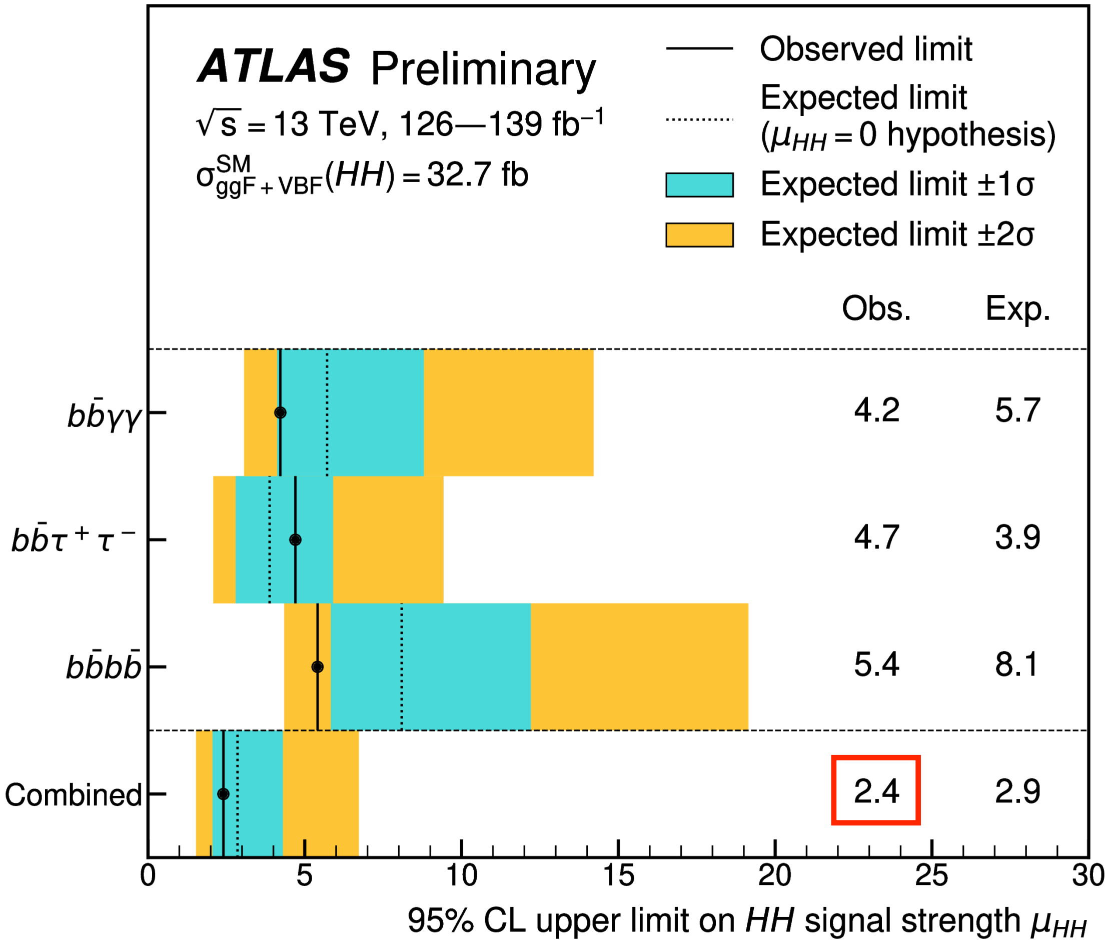
HH combination

ATLAS-CONF-2021-052
ATLAS-CONF-2022-050

- Top 3 HH decay channels are combined to reach the best sensitivity
  - **3x improvement** w.r.t. six channel combination results at 36 fb^{-1}
  - 2x comes from luminosity increase, rest from improved analysis techniques

PRB 800 (2020) 135103

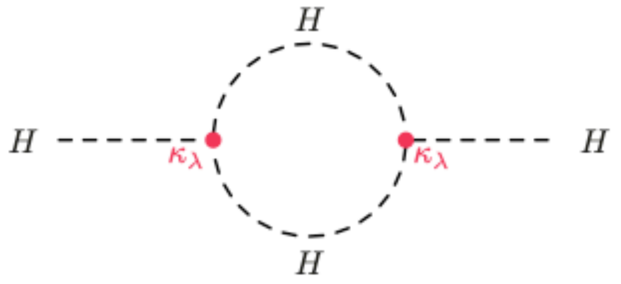




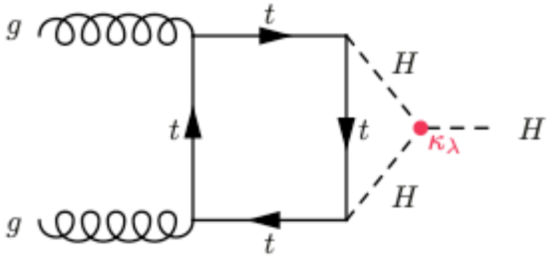
Probing self-coupling

- HH is ideal to study κ_λ, κ_{2V} but not powerful to constrain κ_t, κ_V, κ_b, κ_τ
- Combining HH + H could simultaneously constrain above parameters
  - Higher order corrections are required; HH is sensitive to κ_t through H decays, while single H is sensitive to κ_λ via electro-weak corrections

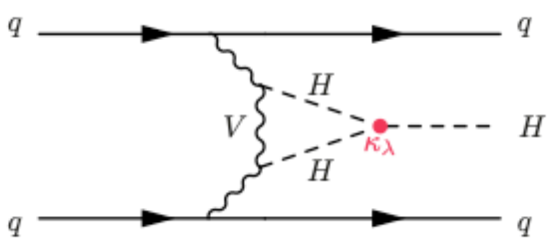
Higgs self-energy



Production



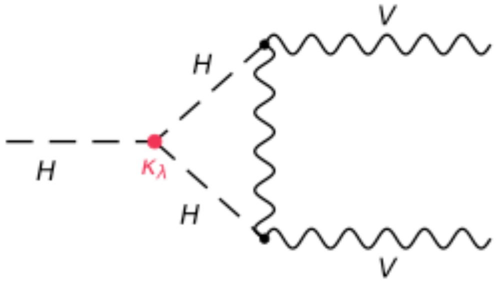
ggF



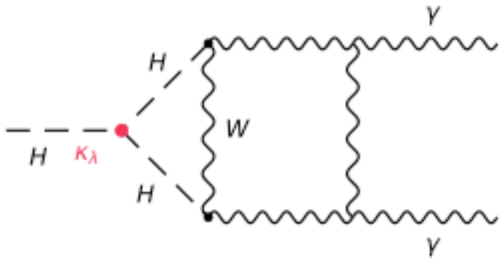
VBF

These corrections affect the **inclusive** cross-sections, Higgs-boson **branching fractions** and differential **distributions**.

Decay



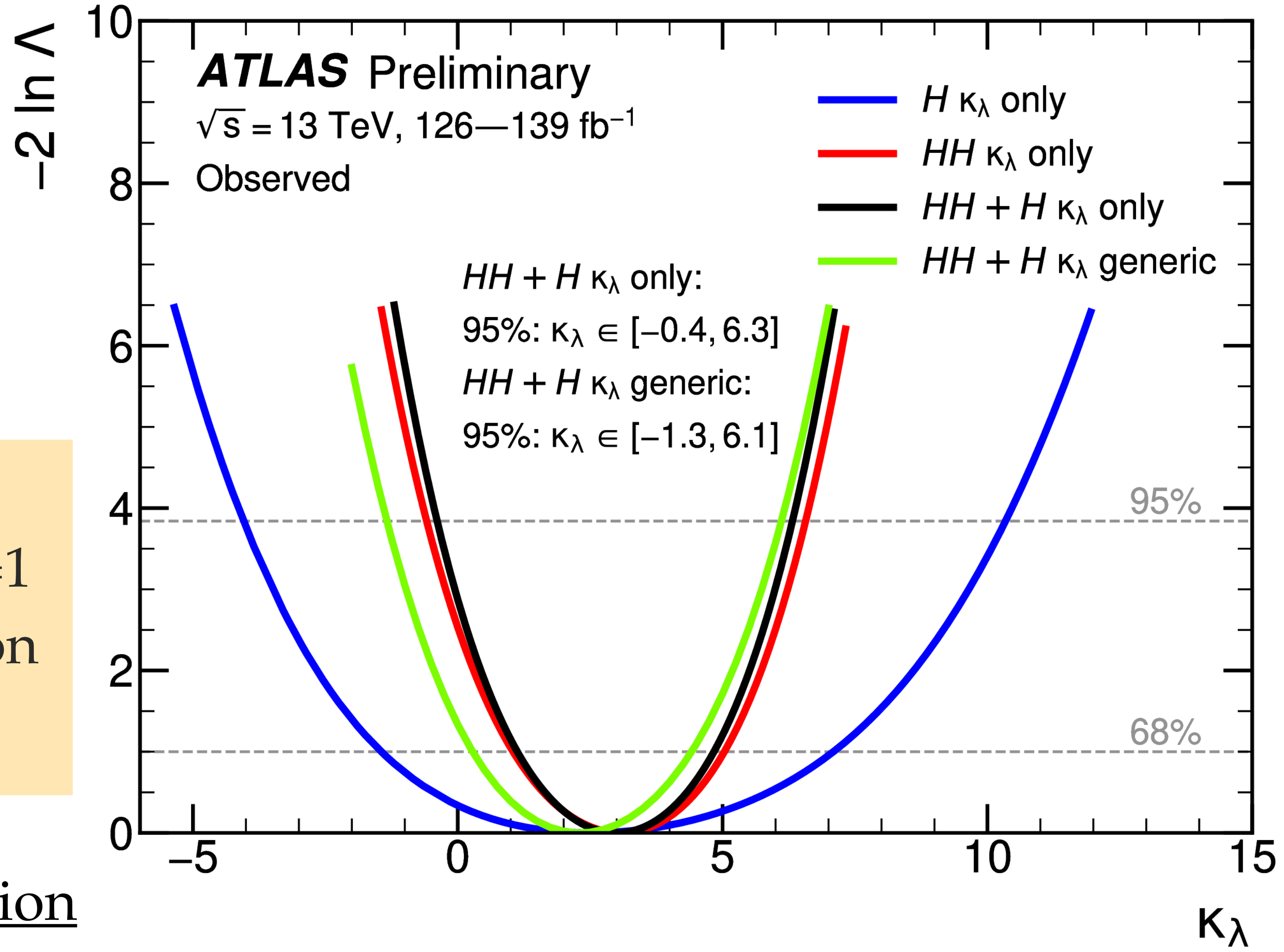
$H \to VV$



$H \to \gamma\gamma$

Self-coupling constrains

- Run 2 bb$\gamma\gamma$, bb$\tau\tau$, 4b are combined with Run 2 $\gamma\gamma$, 4l, $\tau\tau$, WW, bb
  - In addition to κ_λ, the coupling modifiers κ_t, κ_V (κ_t, κ_V, κ_b, κ_τ) are considered in double (single) Higgs processes
  - The **overlap** between/within HH and H analyses is **negligible** or has minor impact on results
  - **Uncertainties** across channels are **correlated** when relevant



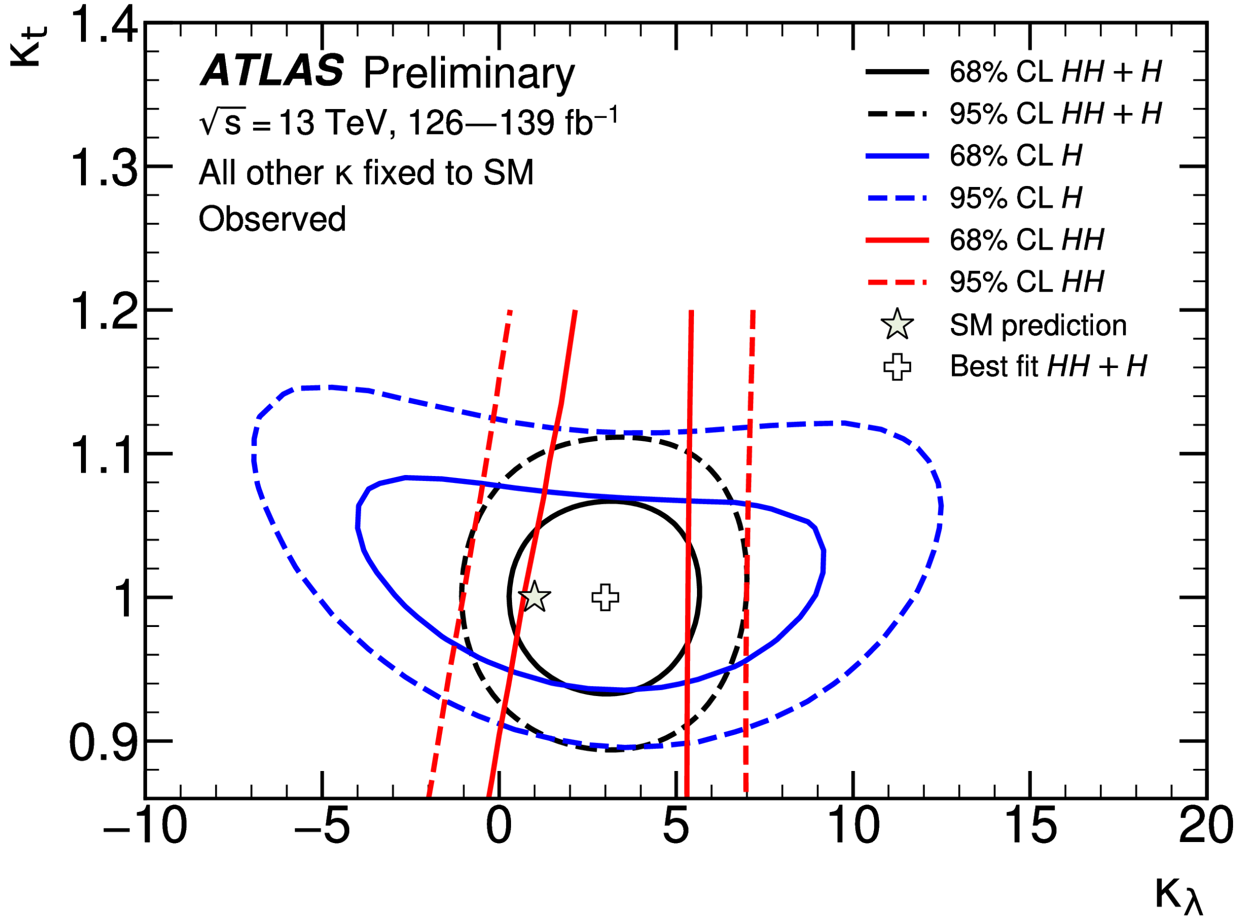
  - Constraints on κ_λ
    [-0.4, 6.3] if assume other κ=1
    [-1.3, 6.1] if no assumption on other κ

[-2.3, 10.3] in 2019 combination

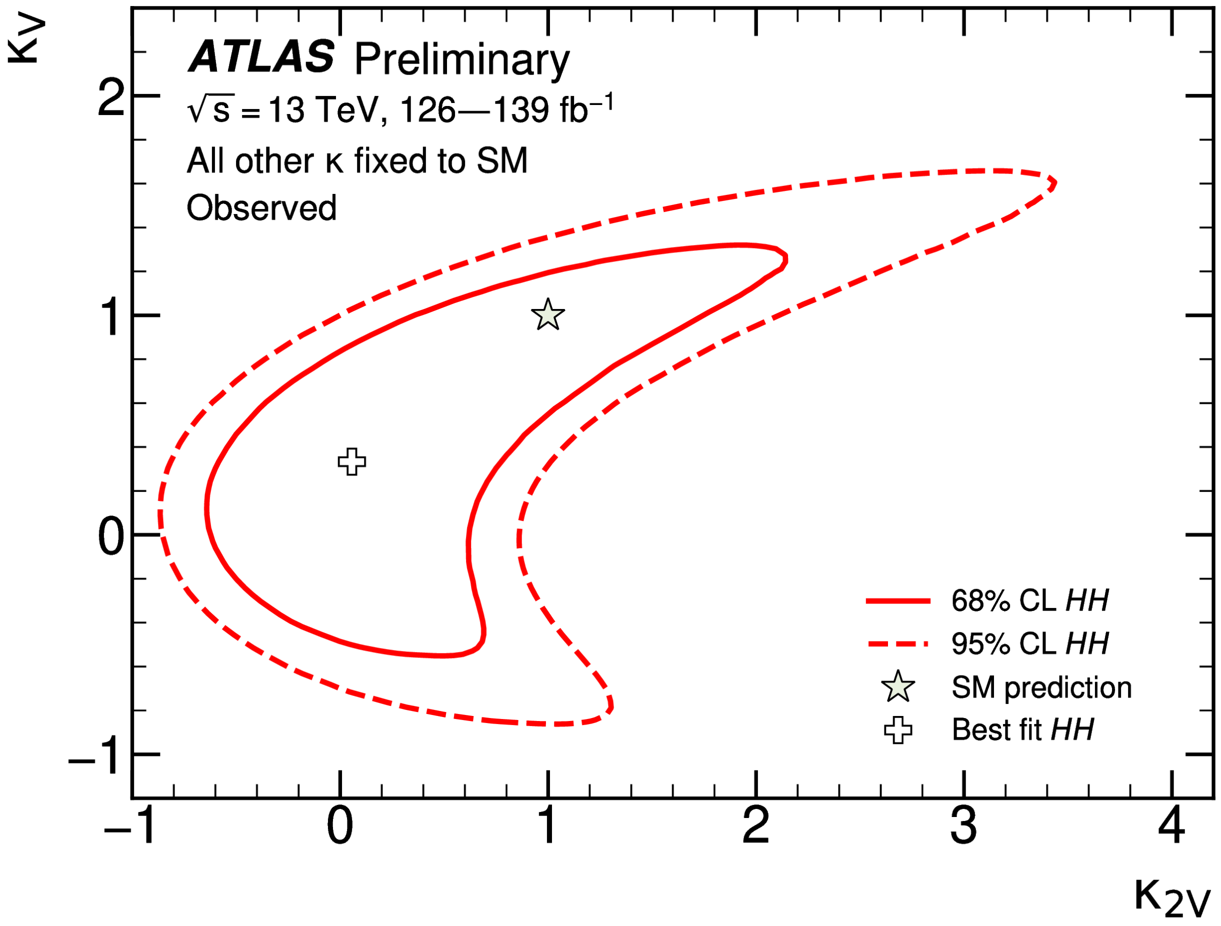
2D contours

- Interesting κ pairs are also probed

κ_λ, κ_t



κ_V, κ_{2V}

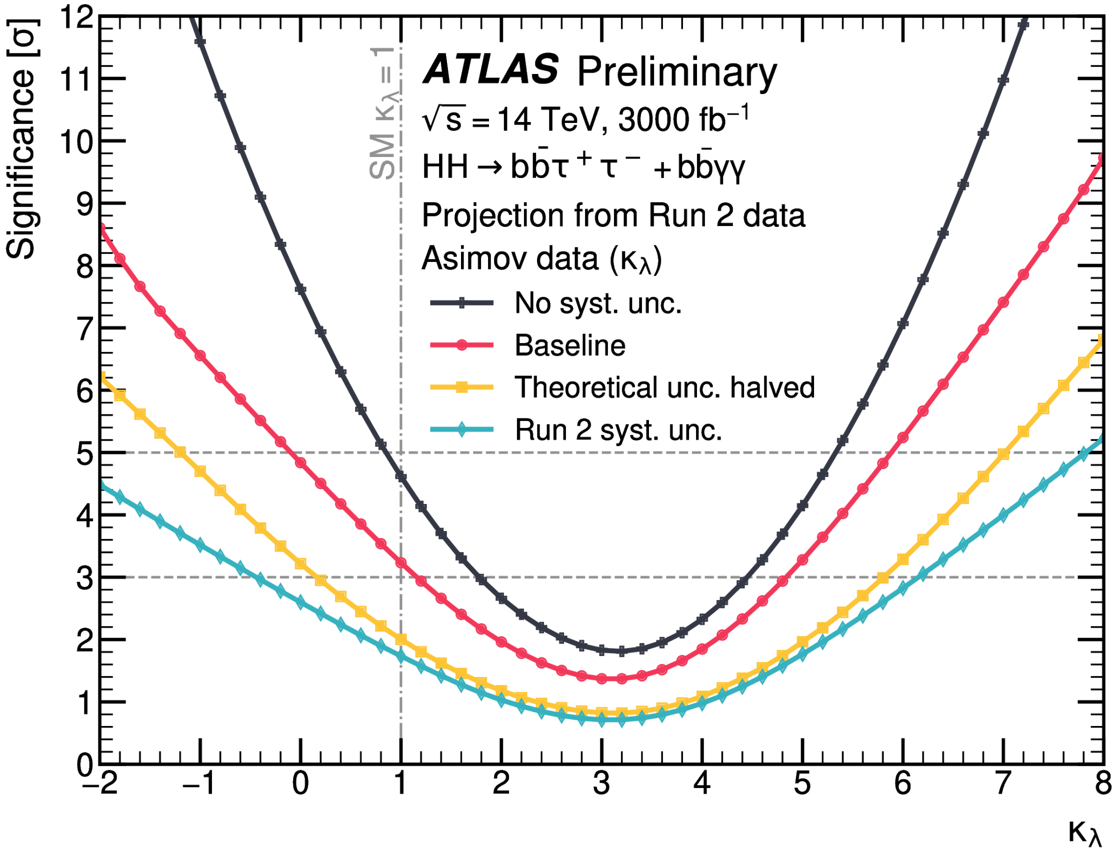


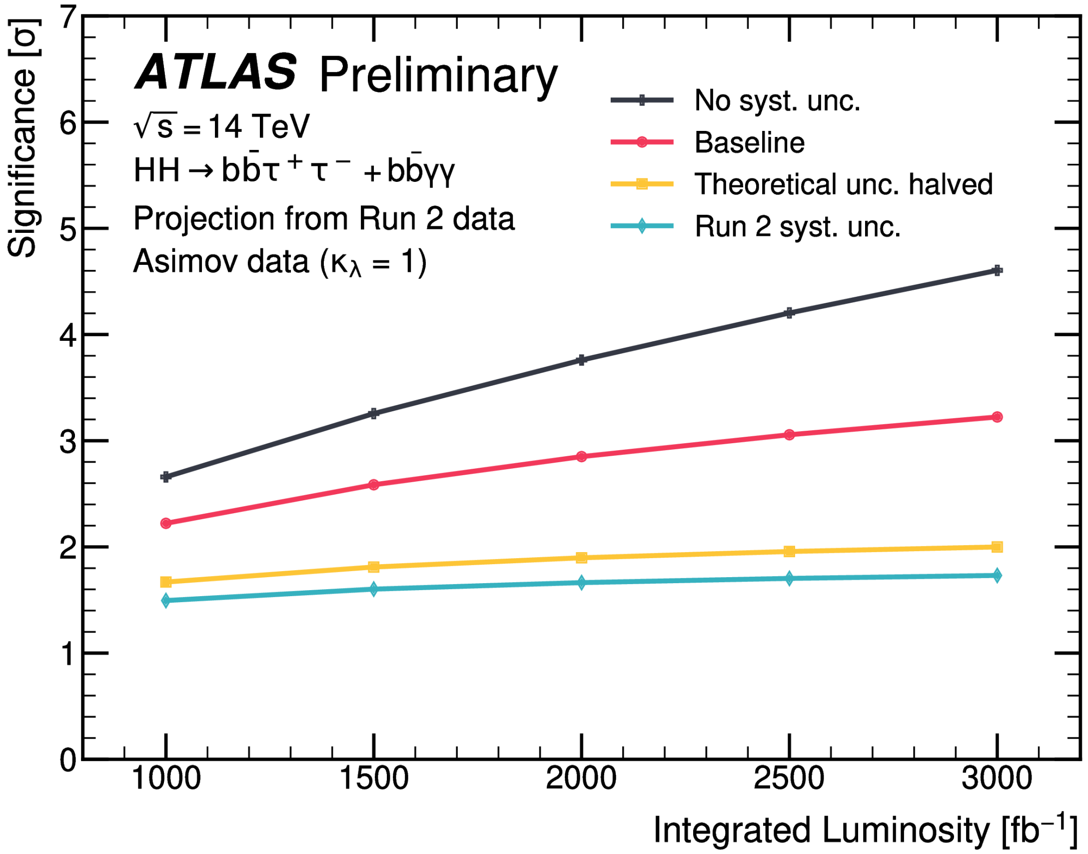
Other results

HL-LHC projection

ATL-PHYS-PUB-2022-001
ATL-PHYS-PUB-2021-044
ATL-PHYS-PUB-2022-005

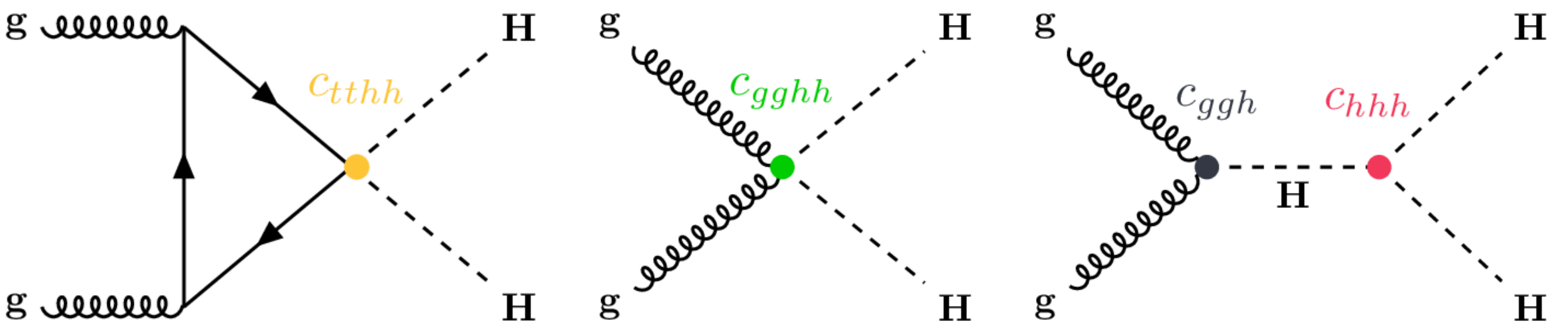
- Full Run 2 ATLAS bbγγ and bbττ and their combination projected at HL-LHC
- Probed assumptions on the systematic uncertainties in four scenarios
  - Baseline: halved theoretical uncertainties + scaled Run 2 systematic uncertainties
  - New triggers, increased pile-up level, and detector upgrades effects not considered
- HH observation with baseline or without systematic uncertainties: 3.2σ or 4.6σ
- κ_λ 1σ CL interval [0.5, 1.6] (baseline) or [0.6, 1.5] (w/o syst) from -2Δln(L) scans



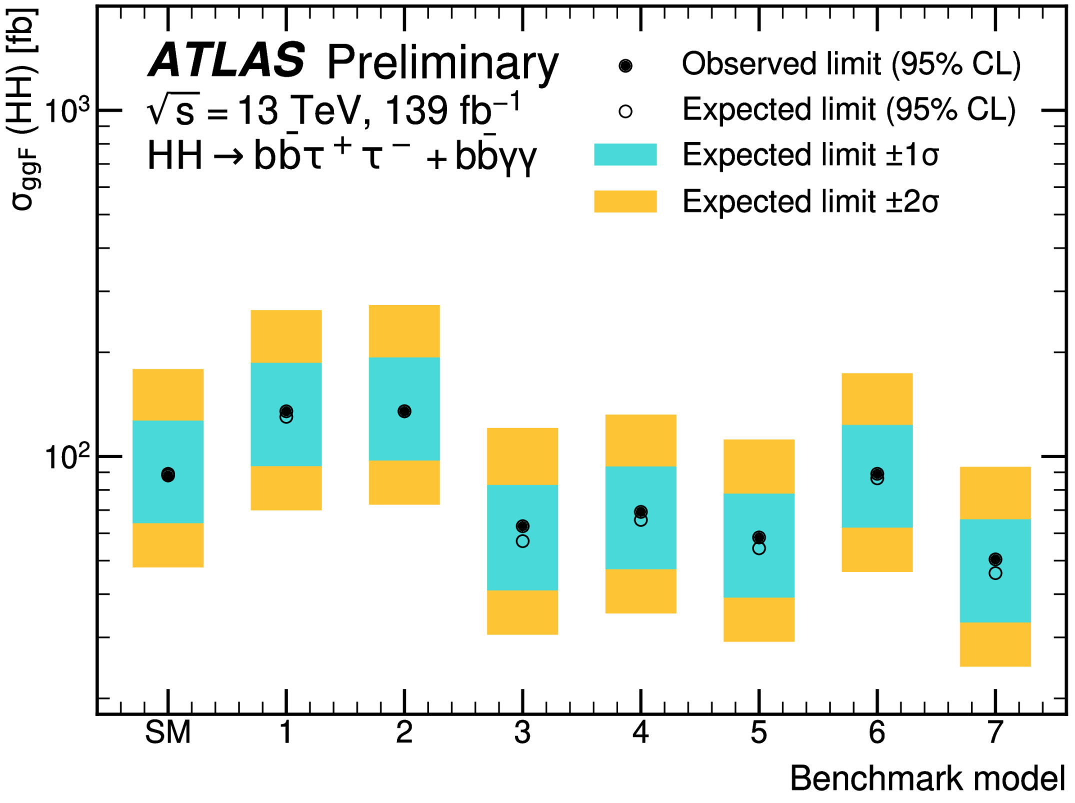


EFT interpretation

ATL-PHYS-PUB-2022-019



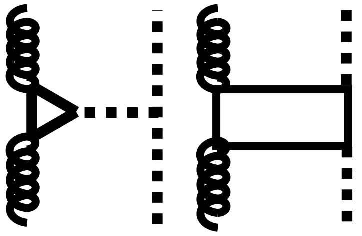
- bbγγ and bbττ HEFT interpretation and their combination
- Upper limits are set for the benchmark models and on cgghh and ctthh Wilson coefficients



	$b\bar{b}\gamma\gamma$		$b\bar{b}\tau^+\tau^-$		Combination	
Wilson coefficient	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
c_{gghh}	$[-0.4, 0.5]$	$[-0.5, 0.7]$	$[-0.4, 0.4]$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	$[-0.3, 0.3]$
c_{tthh}	$[-0.3, 0.8]$	$[-0.4, 0.9]$	$[-0.3, 0.7]$	$[-0.2, 0.6]$	$[-0.2, 0.6]$	$[-0.2, 0.6]$

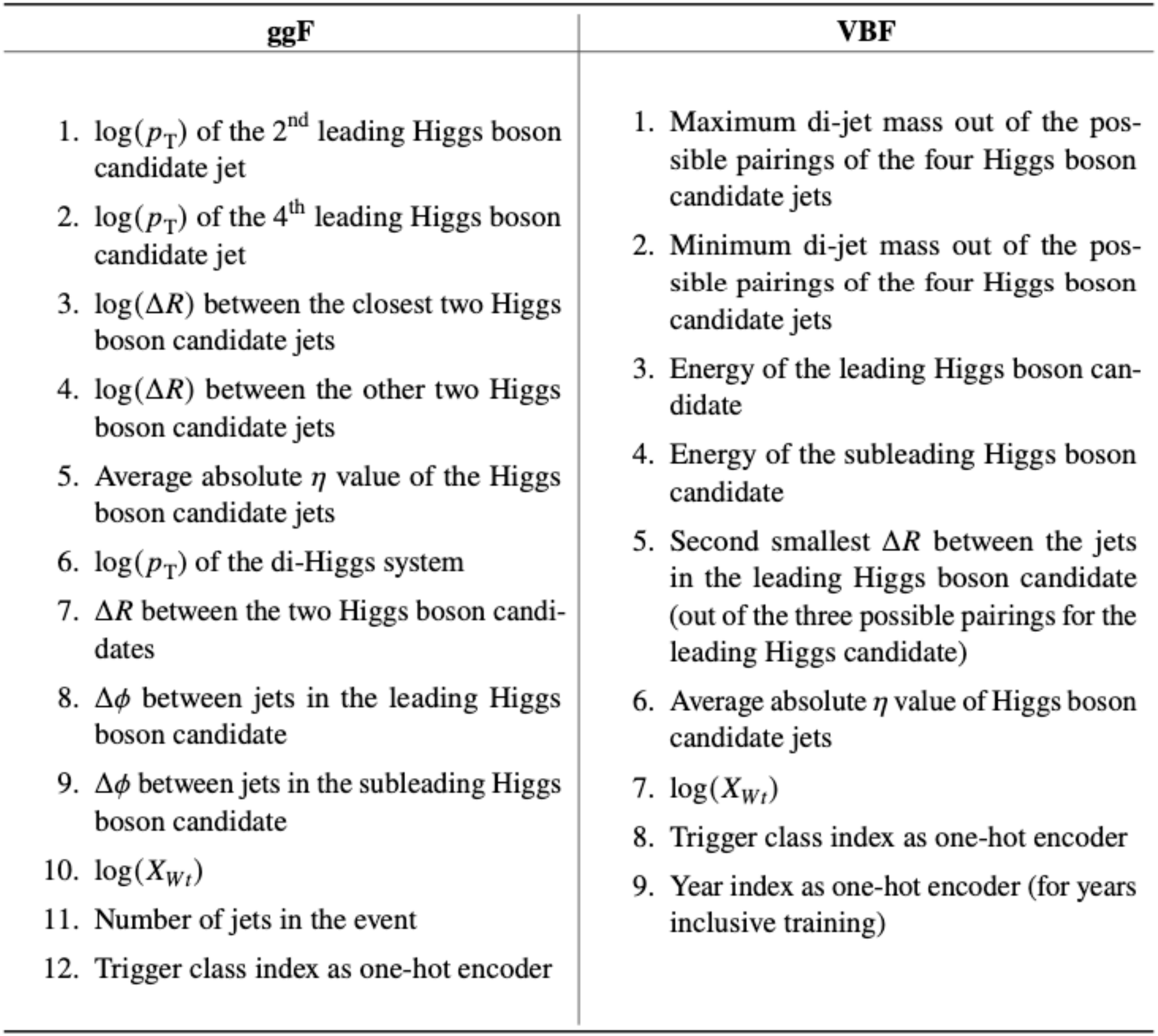
Summary

- Di-Higgs search and measurement is an important LHC topic to understand the exact form of Higgs potential.
- Various analyses targeting final states have done and are ongoing at ATLAS; a combine of them will give the best sensitivity.
  - Benefit from ATLAS combined performance improvements in Jets, b-tagging, etc.
  - 4b channel being the dominant channel remains challenging and will be crucial to help go beyond to HHH→6b.
- Projection to HL-LHC from current full Run 2 results predicts 3σ at ATLAS, promising to reach 5σ together with CMS.

Tank you!

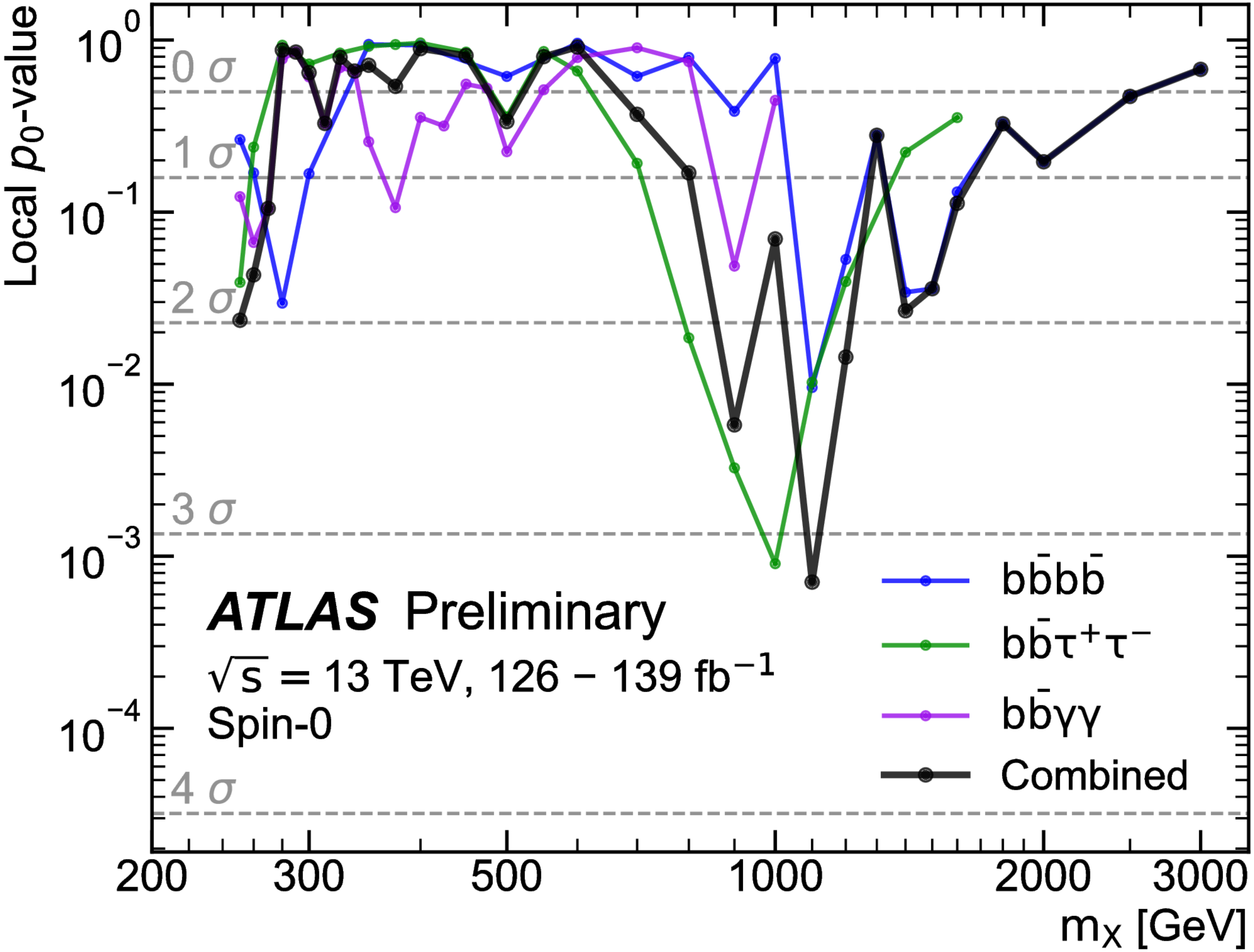
Backup

Background estimation inputs

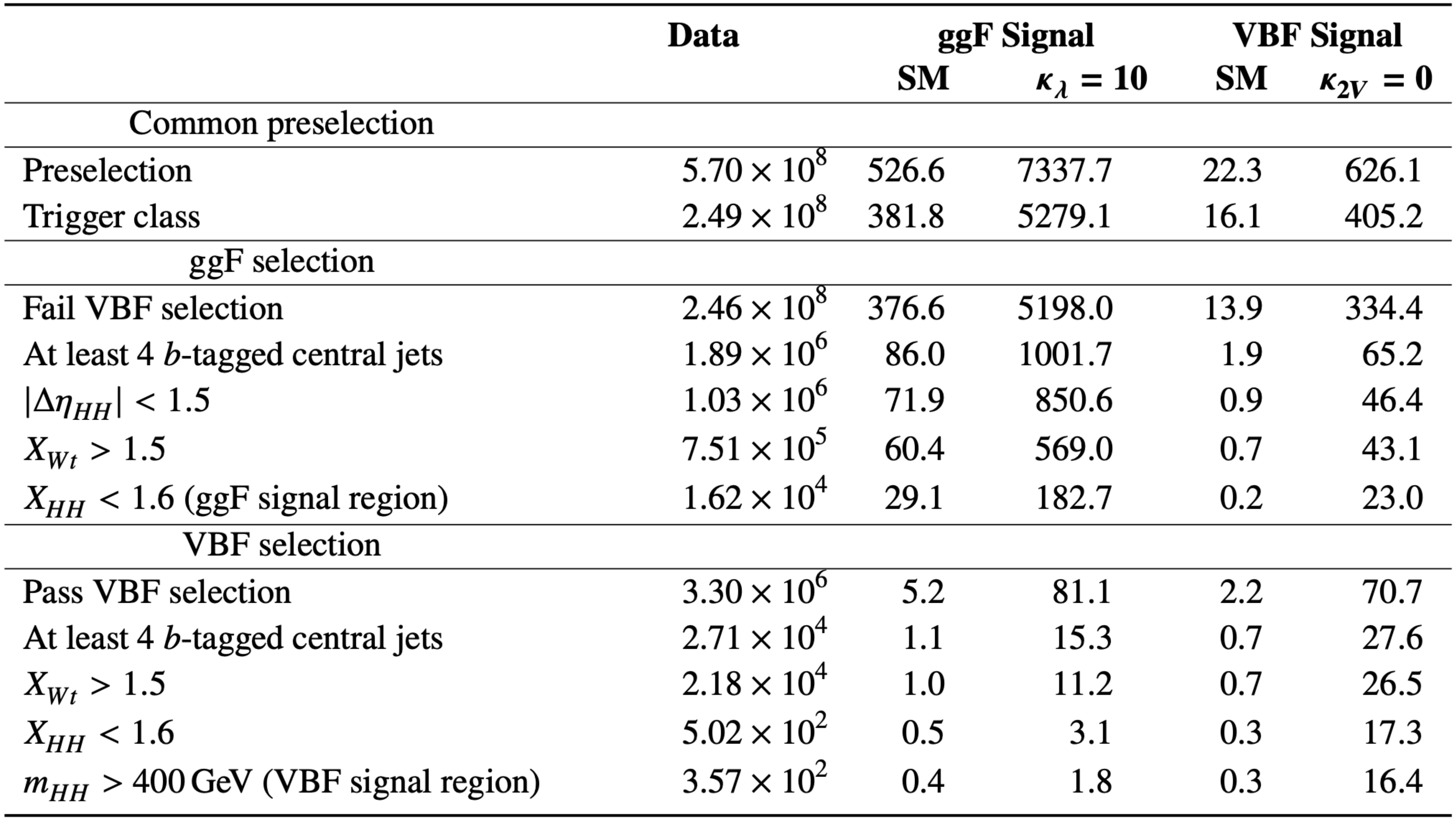


ggF	VBF
1. $\log(p_{\mathrm{T}})$ of the 2nd leading Higgs boson candidate jet 2. $\log(p_{\mathrm{T}})$ of the 4th leading Higgs boson candidate jet 3. $\log(\Delta R)$ between the closest two Higgs boson candidate jets 4. $\log(\Delta R)$ between the other two Higgs boson candidate jets 5. Average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

Resonant combined search

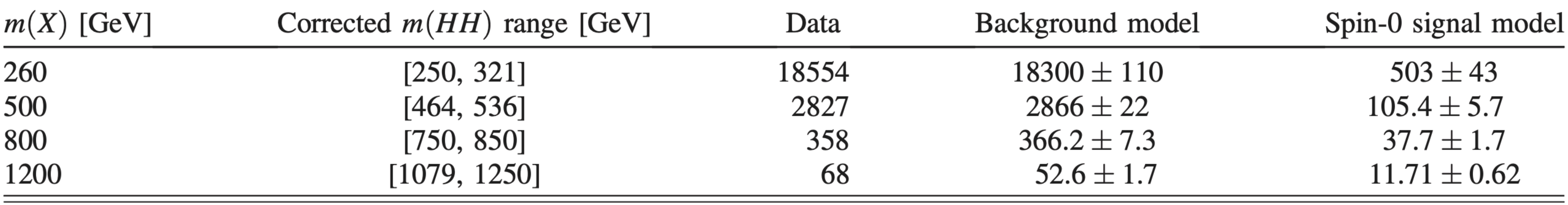


4b non-resonant cutflow



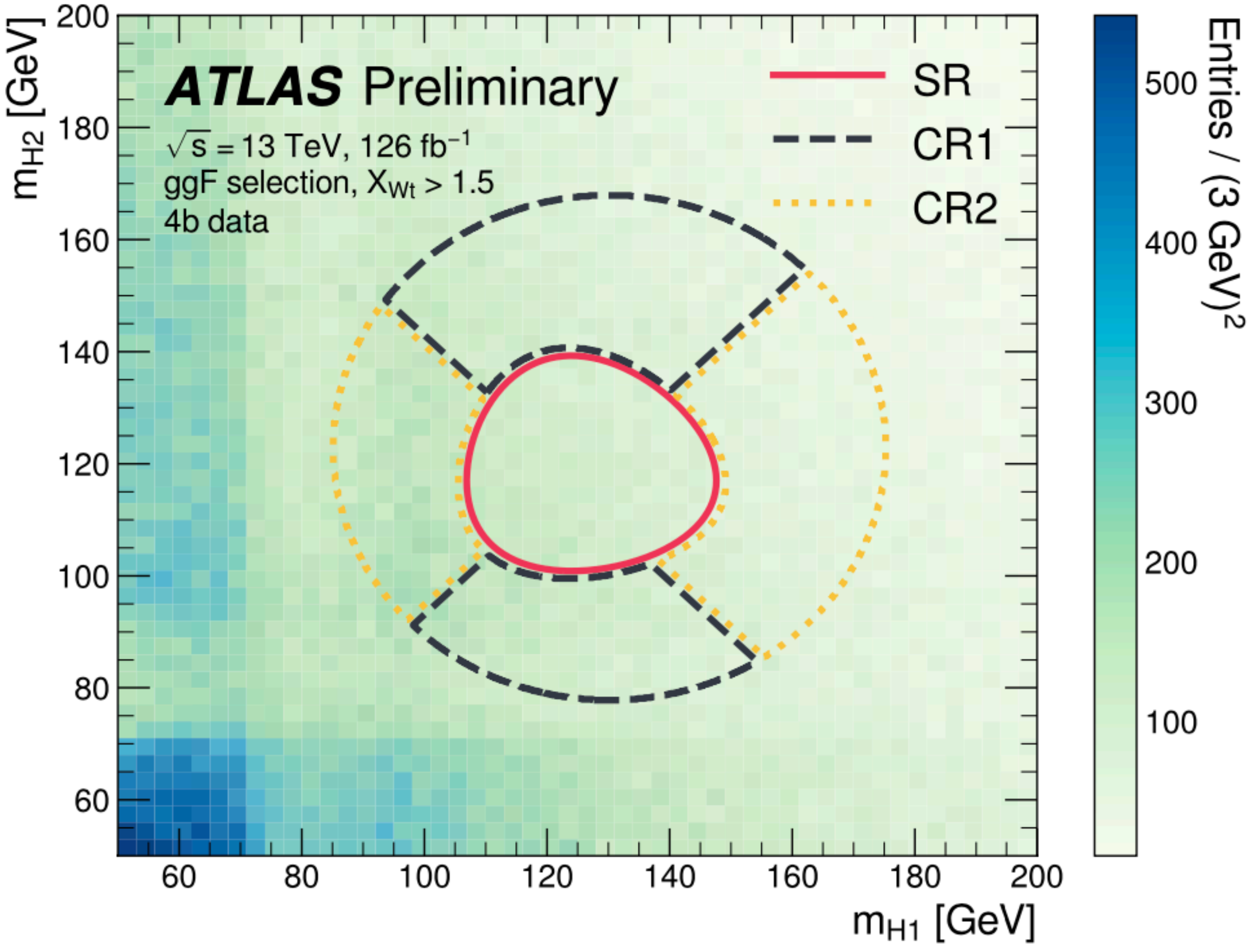
	Data	ggF Signal		VBF Signal	
		SM	$\kappa_\lambda = 10$	**SM**	$\kappa_{2V} = 0$
Common preselection					
Preselection	5.70×10^8	526.6	7337.7	22.3	626.1
Trigger class	2.49×10^8	381.8	5279.1	16.1	405.2
ggF selection					
Fail VBF selection	2.46×10^8	376.6	5198.0	13.9	334.4
At least 4 *b*-tagged central 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

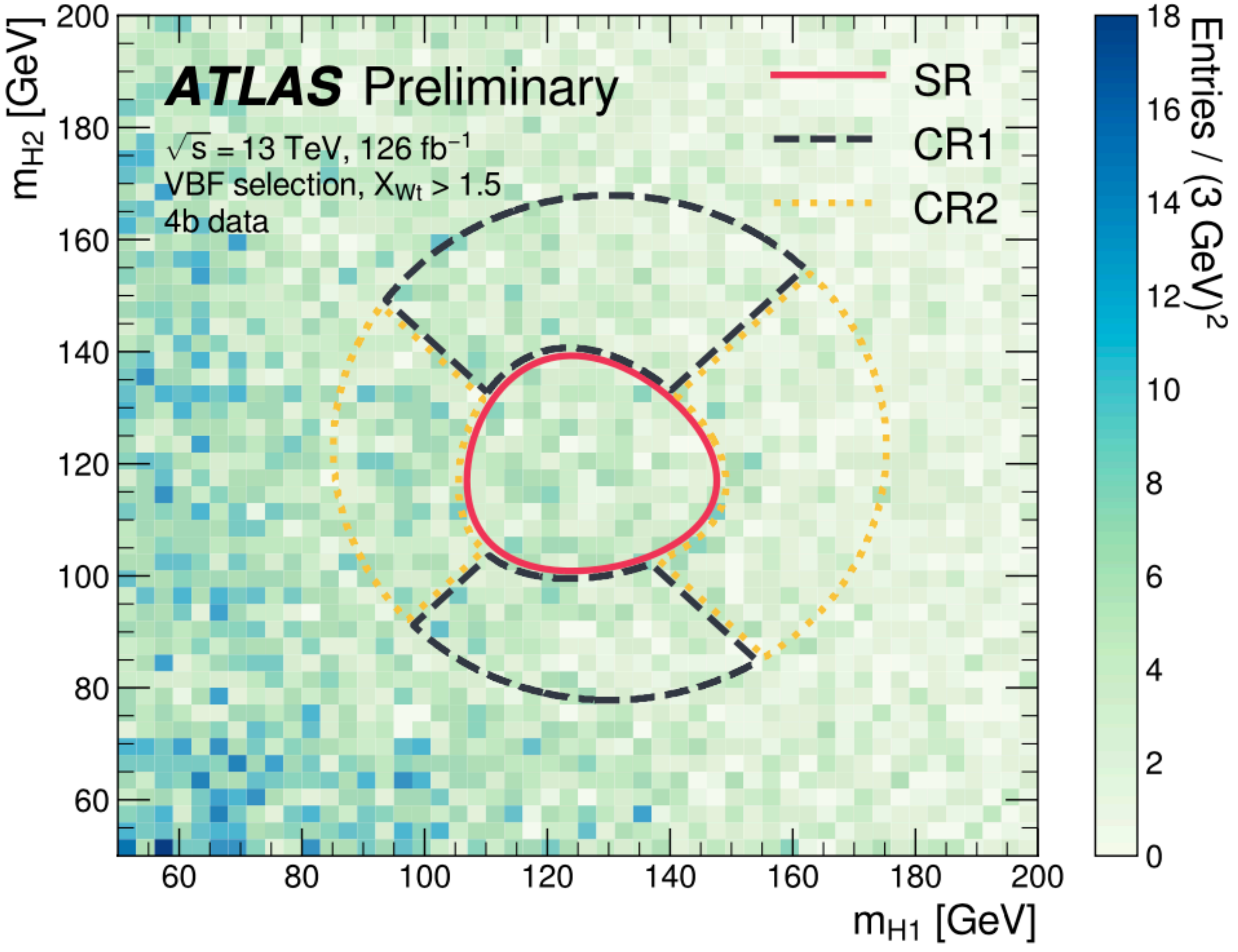
4b resonant yields table



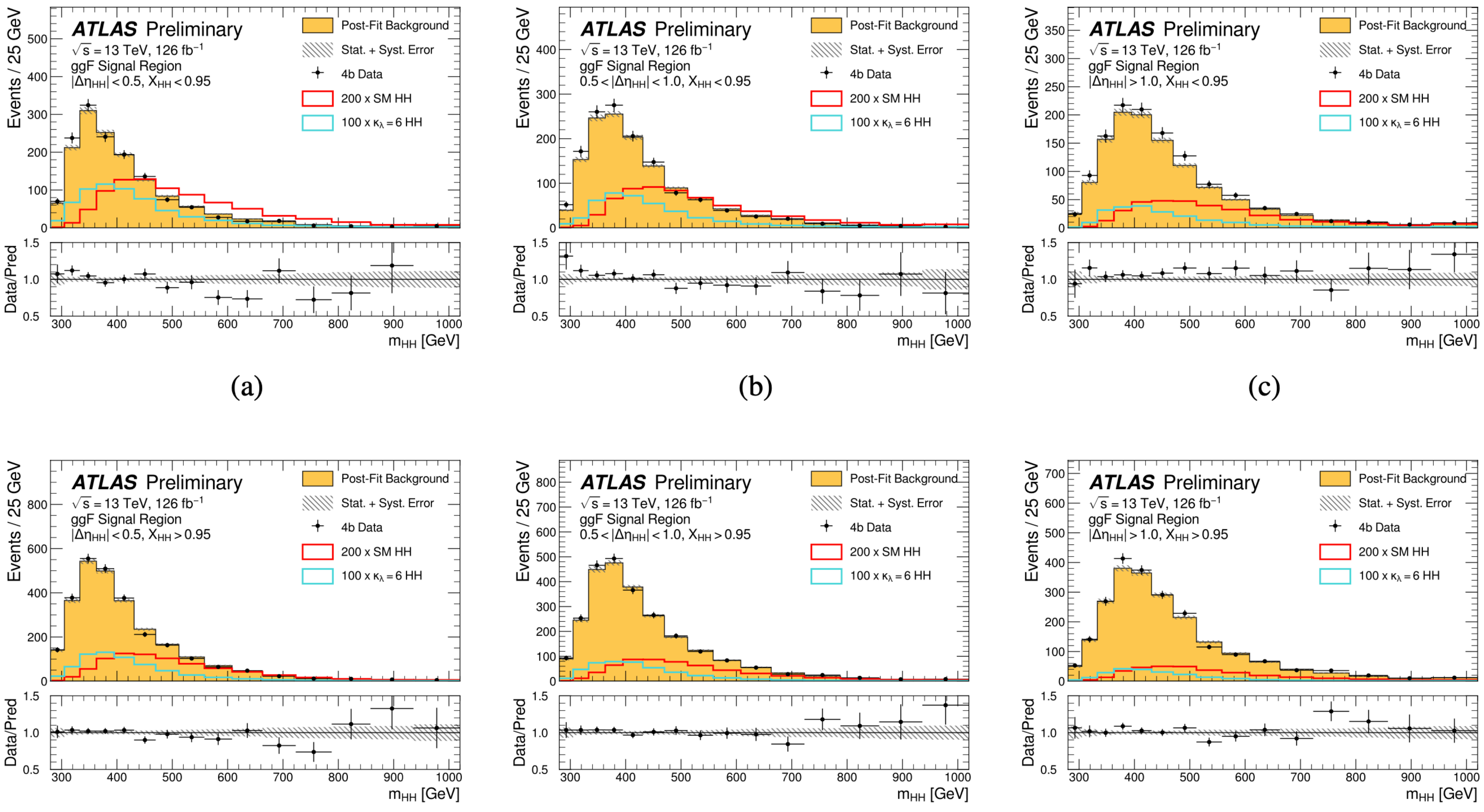
$m(X)$ [GeV]	Corrected $m(HH)$ range [GeV]	Data	Background model	Spin-0 signal model
260	[250, 321]	18554	18300 ± 110	503 ± 43
500	[464, 536]	2827	2866 ± 22	105.4 ± 5.7
800	[750, 850]	358	366.2 ± 7.3	37.7 ± 1.7
1200	[1079, 1250]	68	52.6 ± 1.7	11.71 ± 0.62

4b non-resonant mass plane



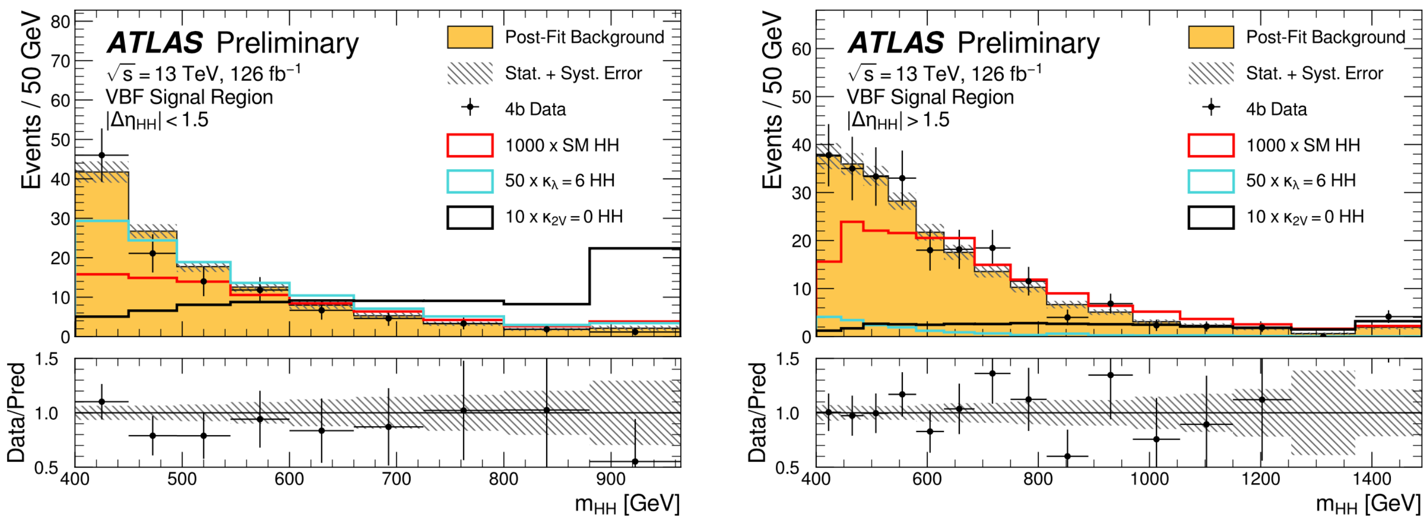


4b non-resonant discriminants



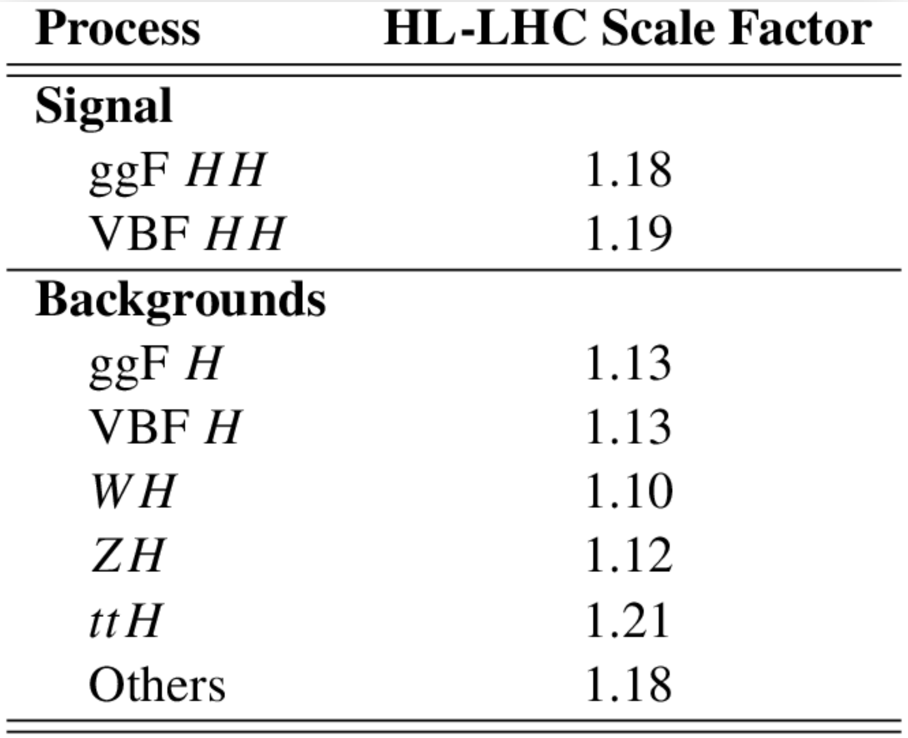
(a) (b) (c)

(d) (e) (f)

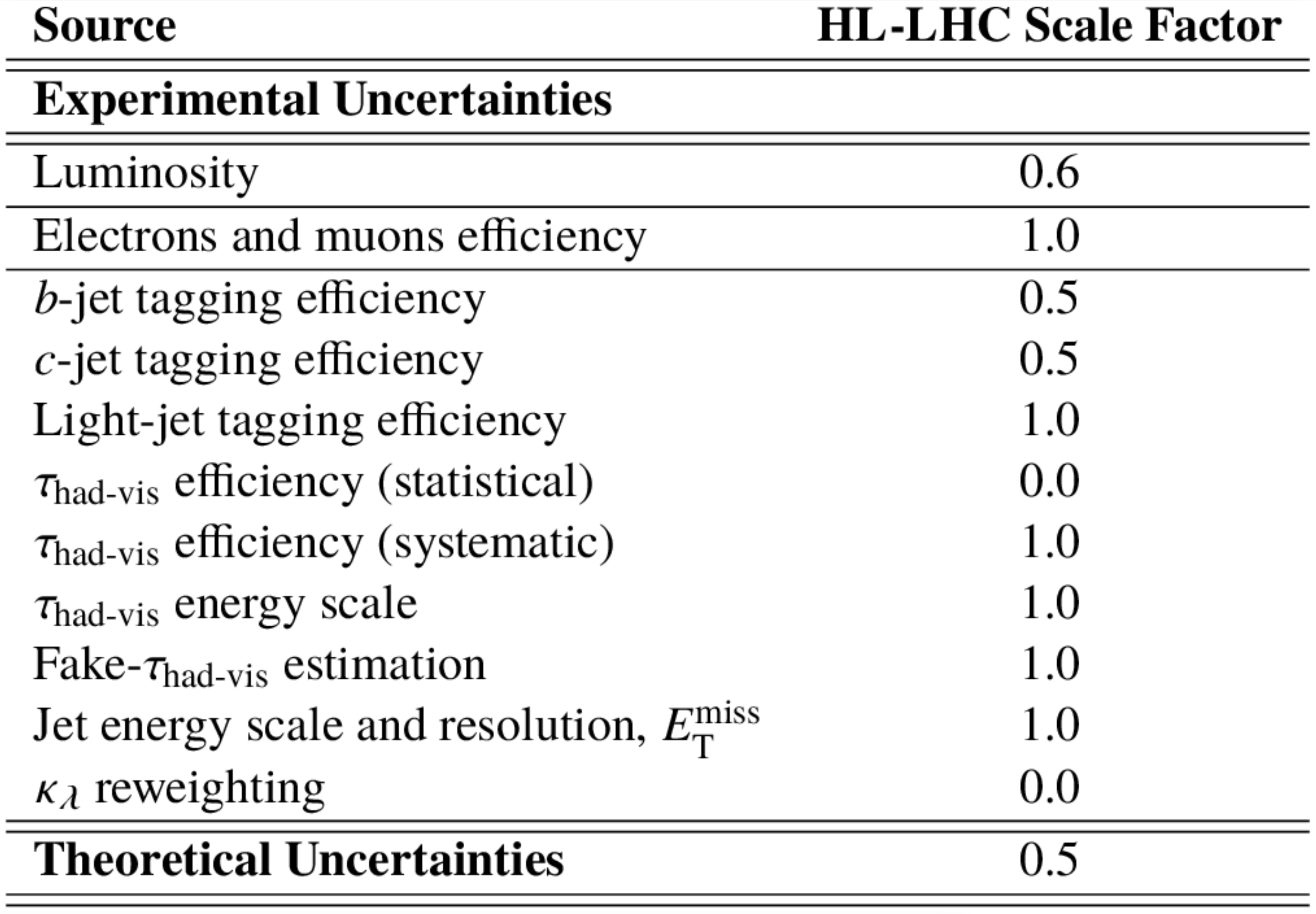


(a) (b)

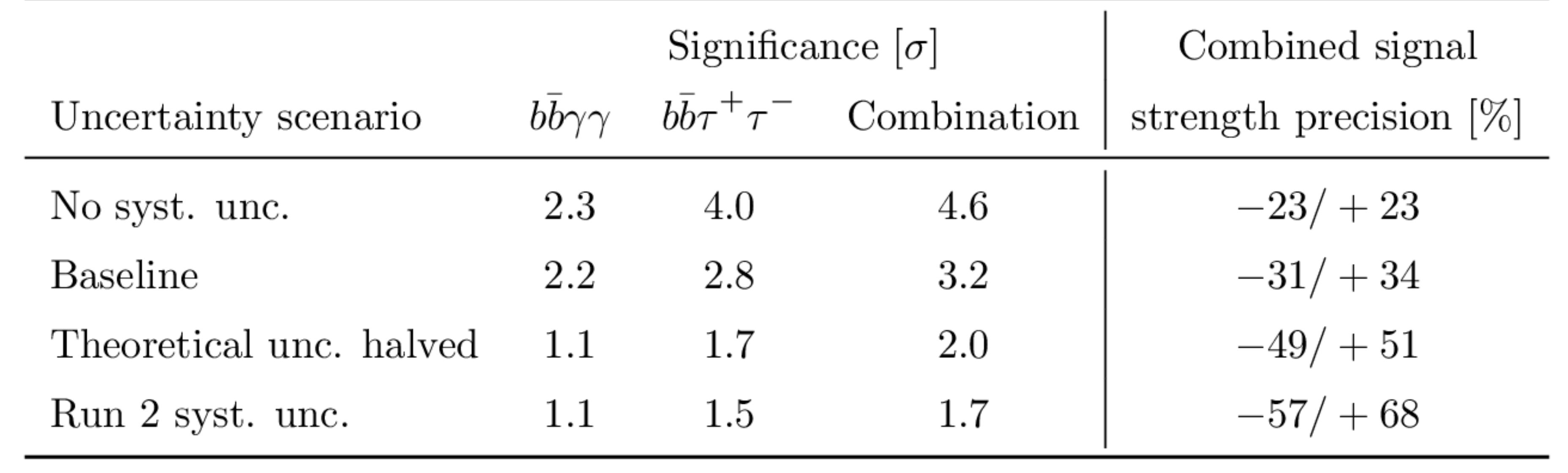
HL-LHC baseline scenario



Process	HL-LHC Scale Factor
Signal	
ggF HH	1.18
VBF HH	1.19
Backgrounds	
ggF H	1.13
VBF H	1.13
WH	1.10
ZH	1.12
ttH	1.21
Others	1.18

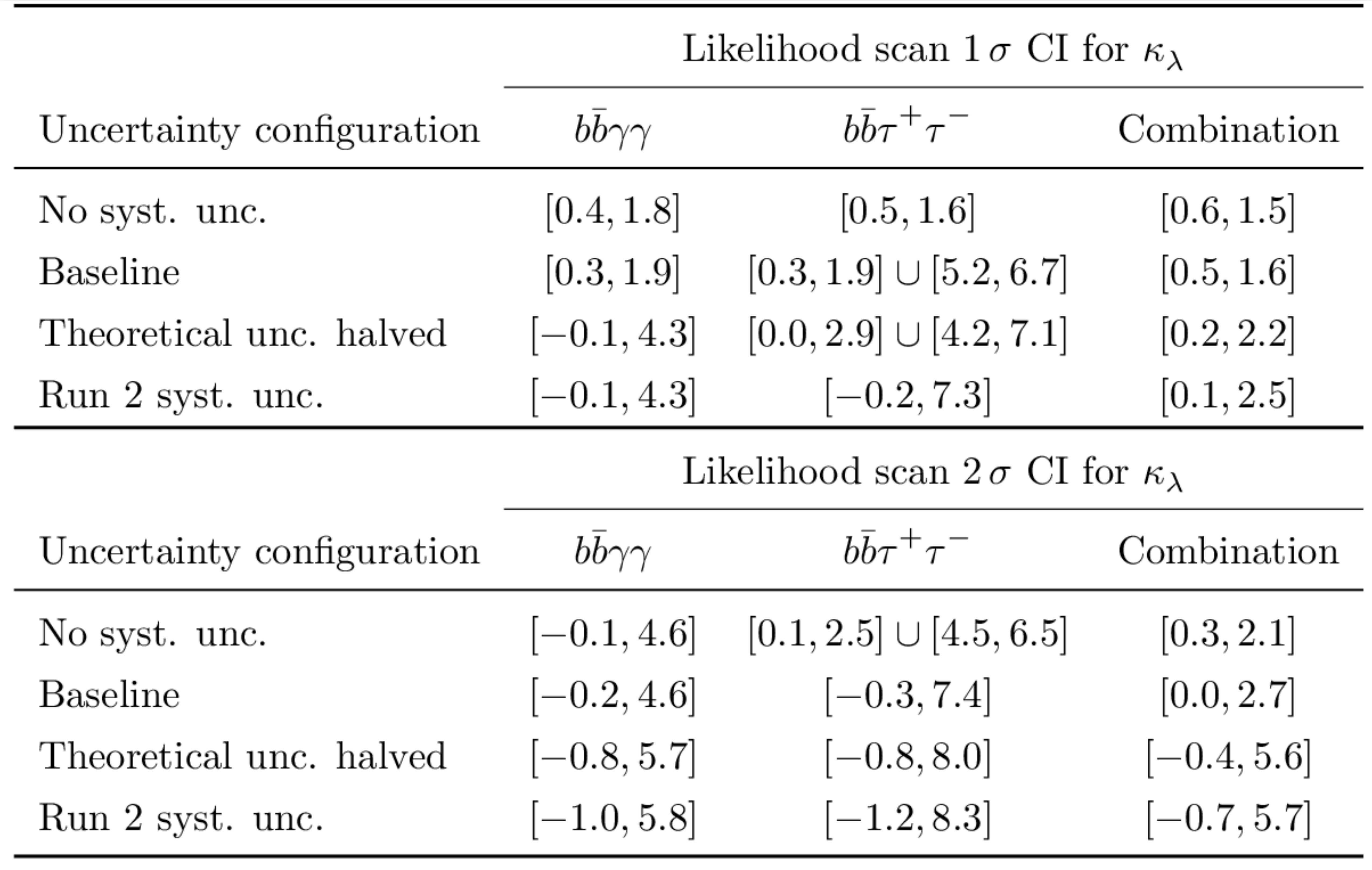


Source	HL-LHC Scale Factor
Experimental Uncertainties	
Luminosity	0.6
Electrons and muons efficiency	1.0
b-jet tagging efficiency	0.5
c-jet tagging efficiency	0.5
Light-jet tagging efficiency	1.0
$\tau_{\text{had-vis}}$ efficiency (statistical)	0.0
$\tau_{\text{had-vis}}$ efficiency (systematic)	1.0
$\tau_{\text{had-vis}}$ energy scale	1.0
Fake-$\tau_{\text{had-vis}}$ estimation	1.0
Jet energy scale and resolution, $E_{\text{T}}^{\text{miss}}$	1.0
κ_{λ} reweighting	0.0
Theoretical Uncertainties	0.5



	Significance $[\sigma]$			Combined signal
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination	strength precision [%]
No syst. unc.	2.3	4.0	4.6	$-23/+23$
Baseline	2.2	2.8	3.2	$-31/+34$
Theoretical unc. halved	1.1	1.7	2.0	$-49/+51$
Run 2 syst. unc.	1.1	1.5	1.7	$-57/+68$

HL-LHC self-coupling

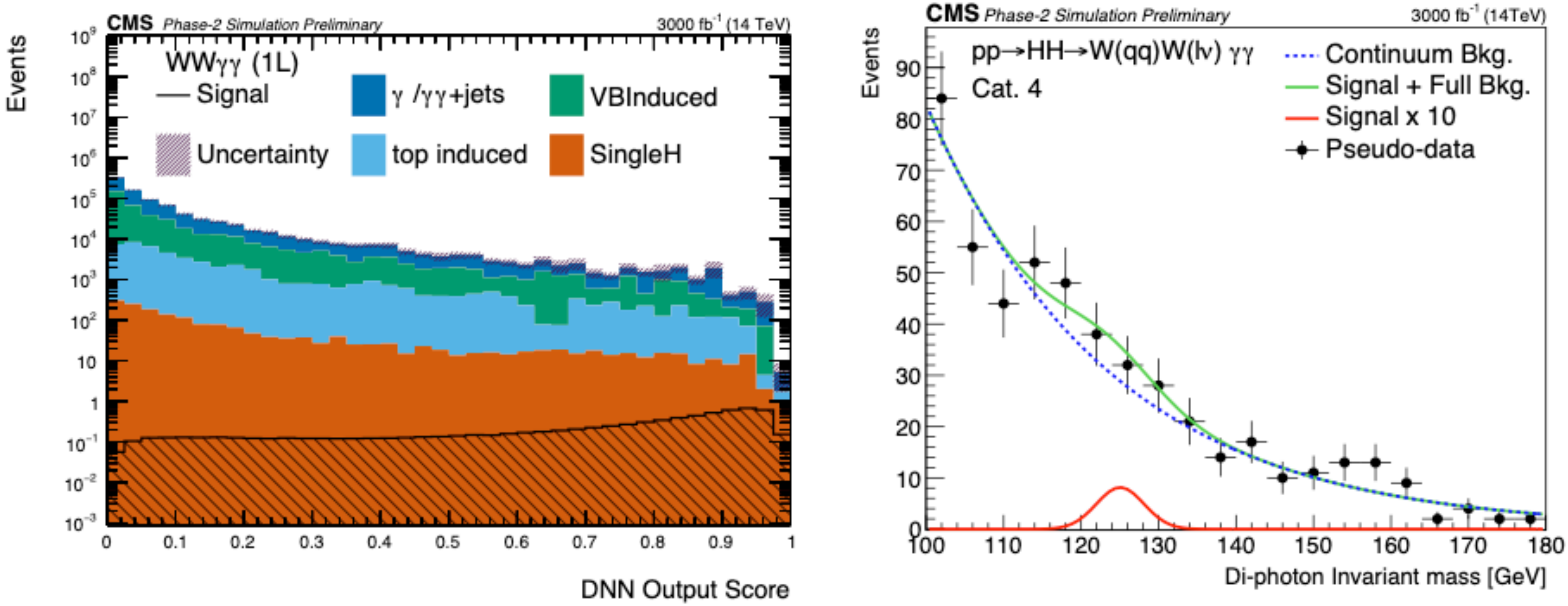


	Likelihood scan $1\,\sigma$ CI for κ_λ		
Uncertainty configuration	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination
No syst. unc.	$[0.4, 1.8]$	$[0.5, 1.6]$	$[0.6, 1.5]$
Baseline	$[0.3, 1.9]$	$[0.3, 1.9] \cup [5.2, 6.7]$	$[0.5, 1.6]$
Theoretical unc. halved	$[-0.1, 4.3]$	$[0.0, 2.9] \cup [4.2, 7.1]$	$[0.2, 2.2]$
Run 2 syst. unc.	$[-0.1, 4.3]$	$[-0.2, 7.3]$	$[0.1, 2.5]$

	Likelihood scan $2\,\sigma$ CI for κ_λ		
Uncertainty configuration	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination
No syst. unc.	$[-0.1, 4.6]$	$[0.1, 2.5] \cup [4.5, 6.5]$	$[0.3, 2.1]$
Baseline	$[-0.2, 4.6]$	$[-0.3, 7.4]$	$[0.0, 2.7]$
Theoretical unc. halved	$[-0.8, 5.7]$	$[-0.8, 8.0]$	$[-0.4, 5.6]$
Run 2 syst. unc.	$[-1.0, 5.8]$	$[-1.2, 8.3]$	$[-0.7, 5.7]$

Snowmass new decay mode HH→WWγγ,ττγγ

FTR-21-003



- Analysis using Delphes CMS HL-LHC simulation samples
- First study of HL-LHC projection of HH→WWγγ,ττγγ
- Signal extraction: 1D fit in $m_{\gamma\gamma}$
- Presence of leptons and photons, DNN helps reducing background

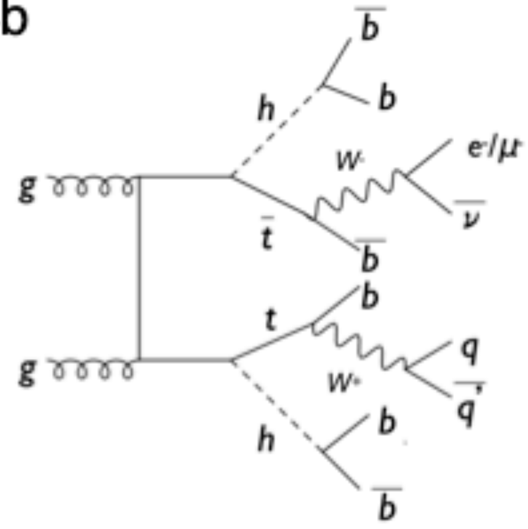
Lu Nan, Higgs Pair 2022

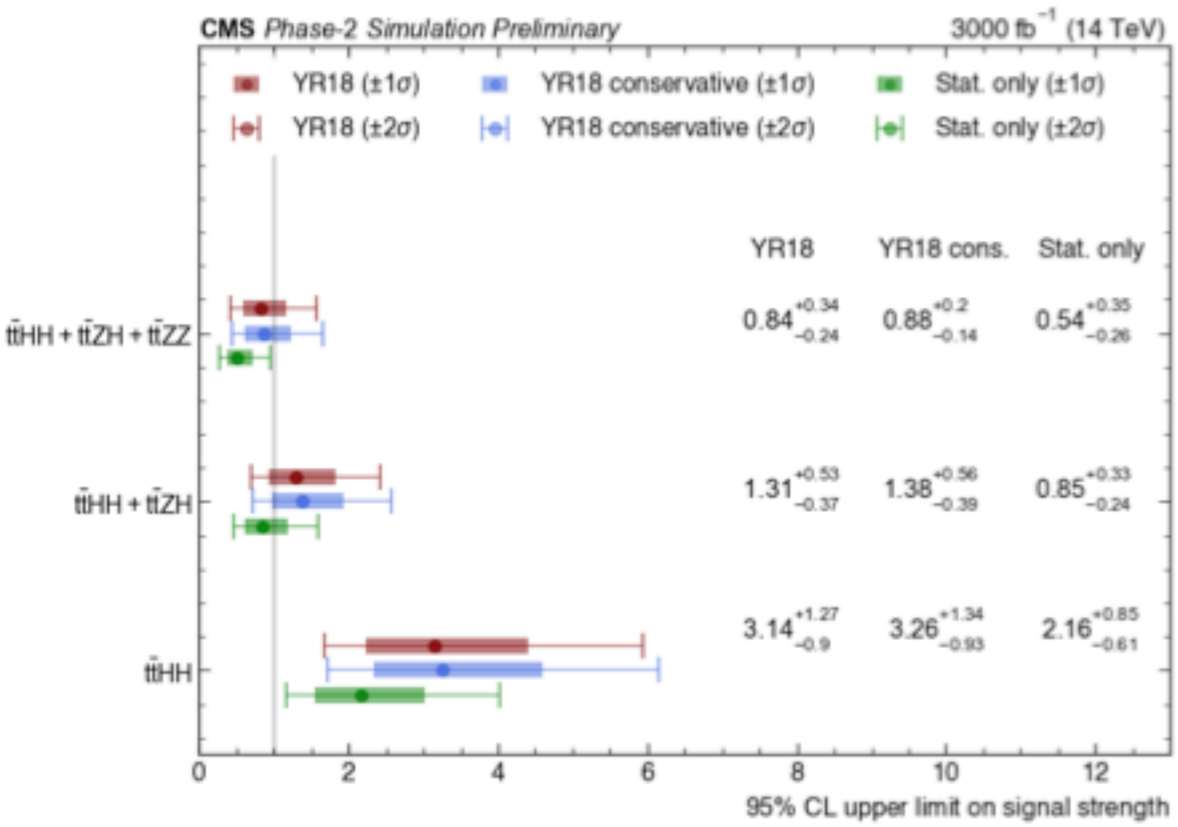
Snowmass new production mode ttHH

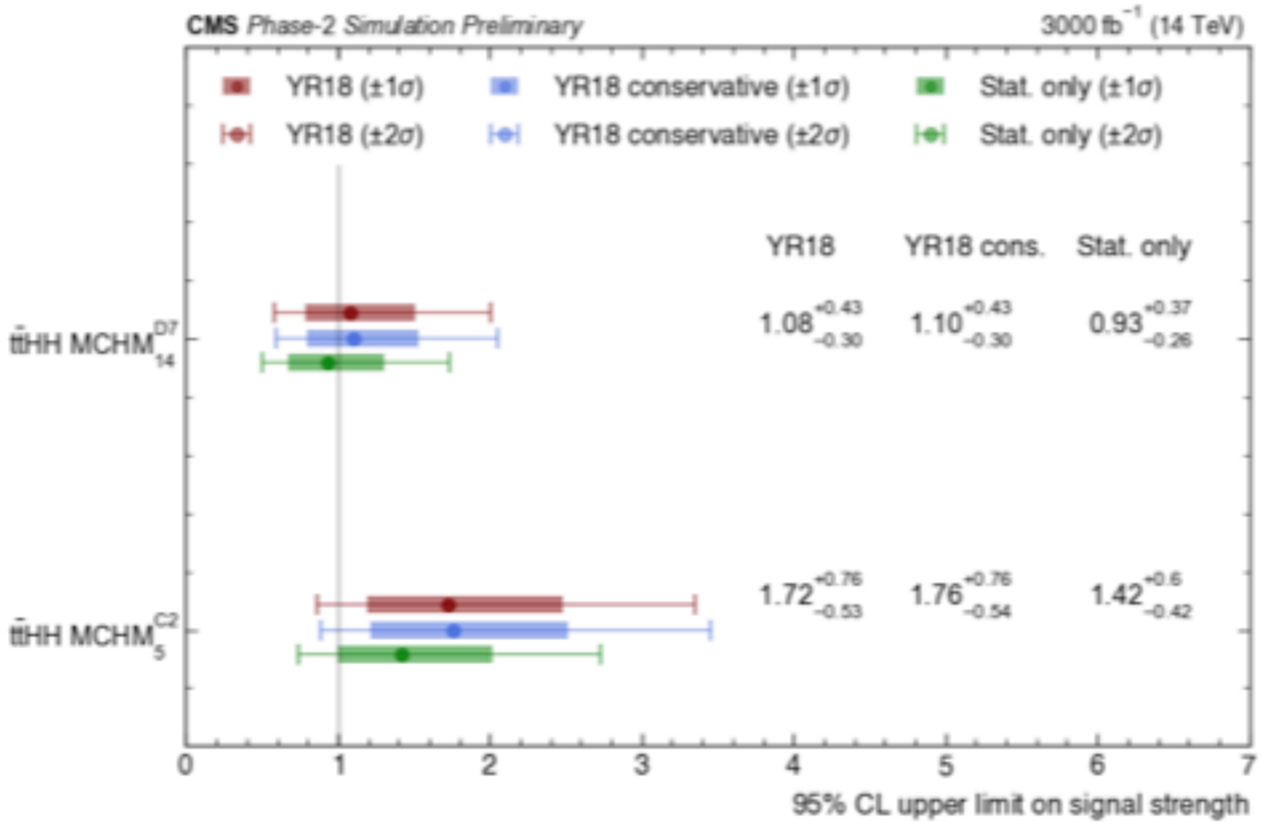
CMS-PAS-FTR-21-010

- ttHH can provide
  - complimentary constraint on κ_λ
  - sensitivity to BSM models such as Minimal Composite Higgs Model (MCHM)
- Expected upper limit σ(ttHH) < 3.14 x SM

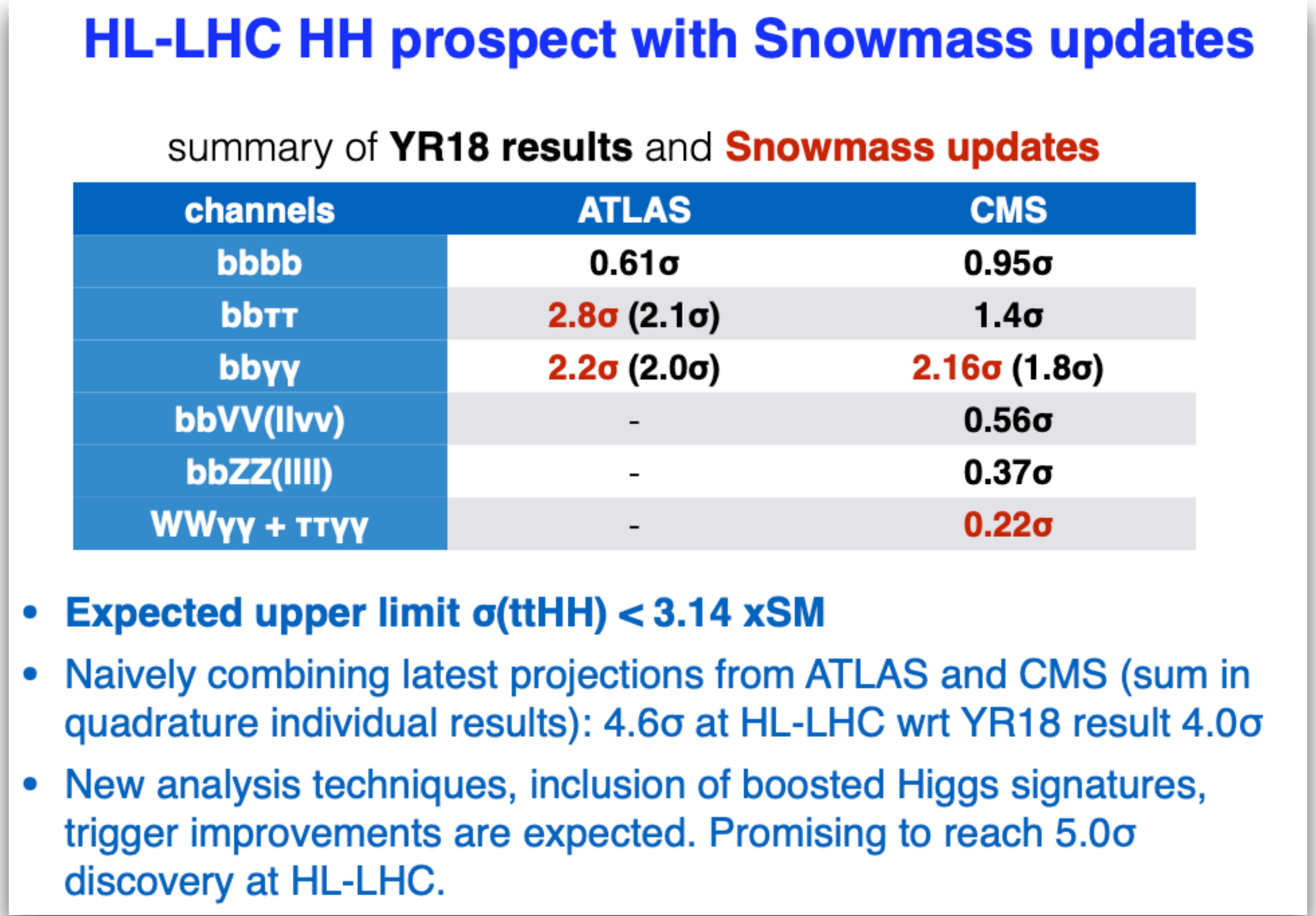
- semileptonic decay of top-antitop pai
- HH→4b







Lu Nan, Higgs Pair 2022



HL-LHC HH prospect with Snowmass updates

summary of **YR18 results** and **Snowmass updates**

channels	ATLAS	CMS
bbbb	0.61σ	0.95σ
bbττ	2.8σ (2.1σ)	1.4σ
bbγγ	2.2σ (2.0σ)	2.16σ (1.8σ)
bbVV(llνν)	-	0.56σ
bbZZ(llll)	-	0.37σ
WWγγ + ττγγ	-	0.22σ

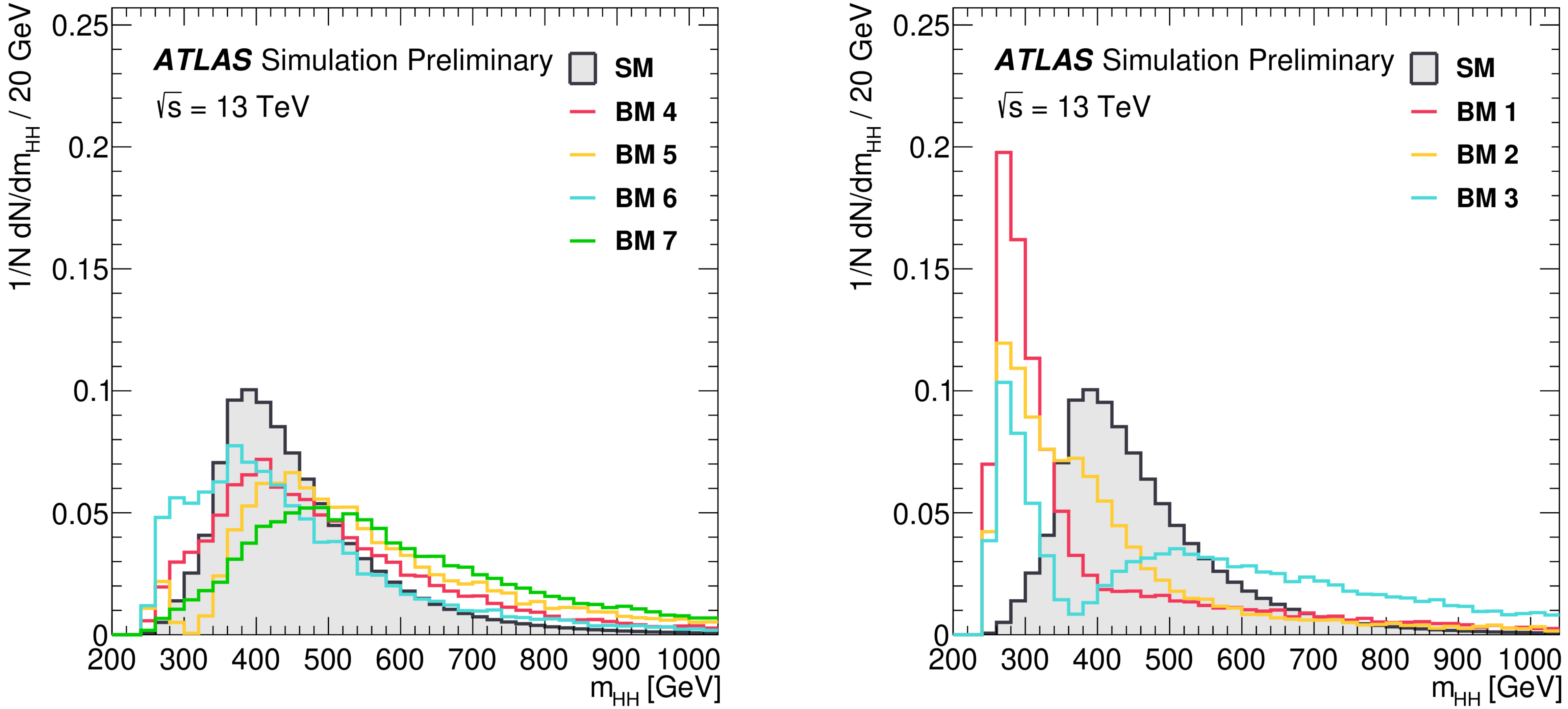
- **Expected upper limit σ(ttHH) < 3.14 xSM**
- Naively combining latest projections from ATLAS and CMS (sum in quadrature individual results): 4.6σ at HL-LHC wrt YR18 result 4.0σ
- New analysis techniques, inclusion of boosted Higgs signatures, trigger improvements are expected. Promising to reach 5.0σ discovery at HL-LHC.

Lu Nan, Higgs Pair 2022

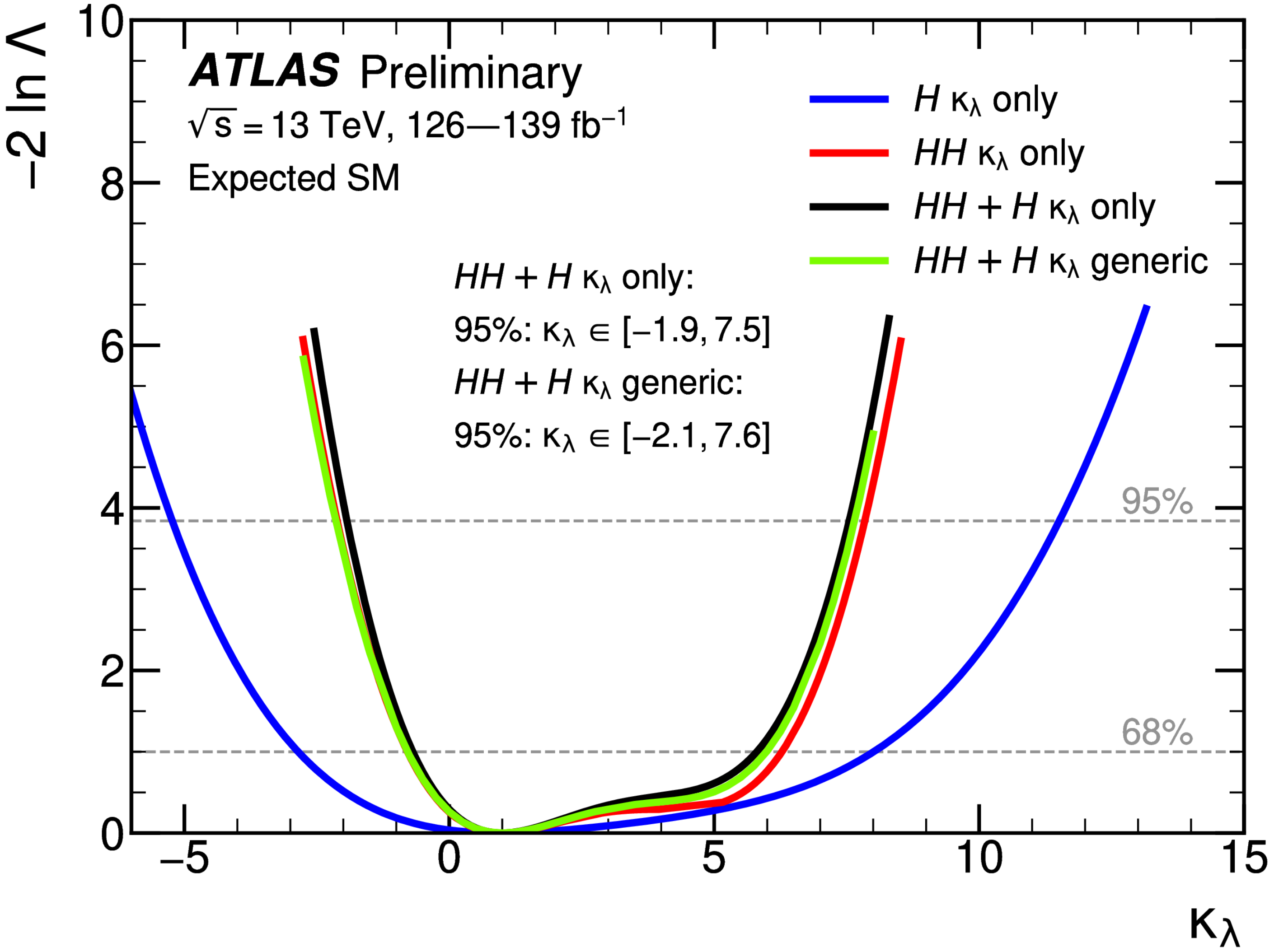
HEFT benchmark definitions

- A cluster analysis is used to define groups of different HEFT models according to their impact on the shape of the m_{HH} distribution

Benchmark model	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
BM 1	3.94	0.94	1/2	1/3	−1/3
BM 2	6.84	0.61	0.0	−1/3	1/3
BM 3	2.21	1.05	1/2	1/2	−1/3
BM 4	2.79	0.61	−1/2	1/6	1/3
BM 5	3.95	1.17	1/6	−1/2	−1/3
BM 6	5.68	0.83	−1/2	1/3	1/3
BM 7	−0.10	0.94	1/6	−1/6	1

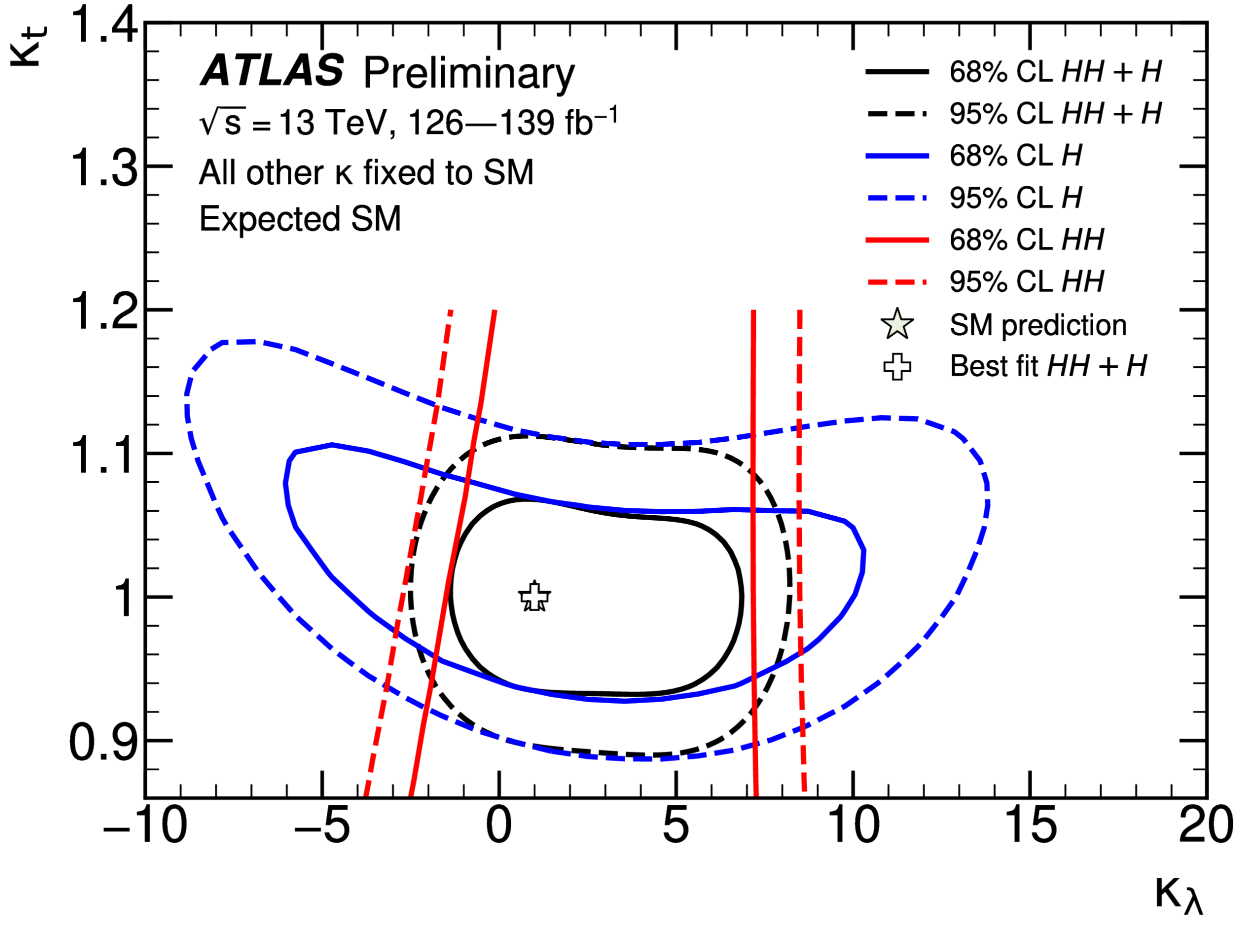


Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

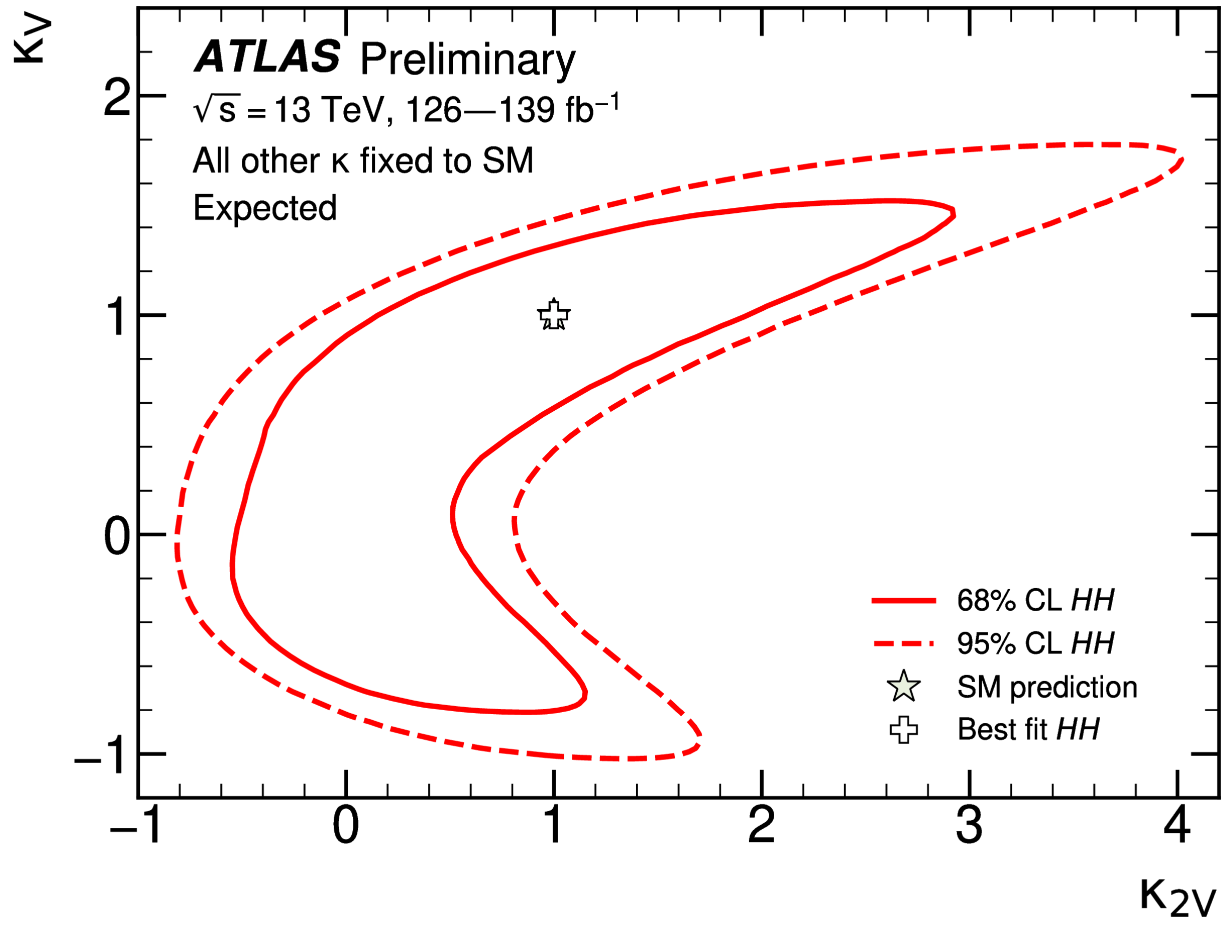


2D contours

- Interesting κ pairs are also probed



κ_λ, κ_t



κ_V, κ_{2V}