Searching for **Higgs Boson Pairs** in the **bbττ** Final State with the **ATLAS** Experiment with **Run 2 and beyond**

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Higgs Hunting 2024

NEW

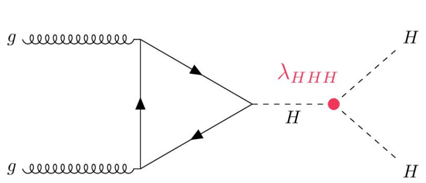
based on [ATL-PHYS-PUB-2024-016]
and [Phys. Rev. D 110 (2024) 032012]

bbττ

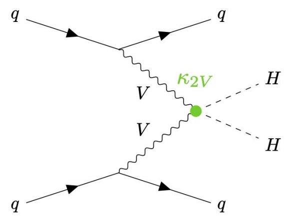
Legacy Run 2 HH→bbττ

bb$\tau\tau$: relatively large BR (~7.3%) & di-τ: multijet rejection

Re-analyse Run 2 and focus on non-resonant HH production



Higgs boson self-coupling (κ_λ)



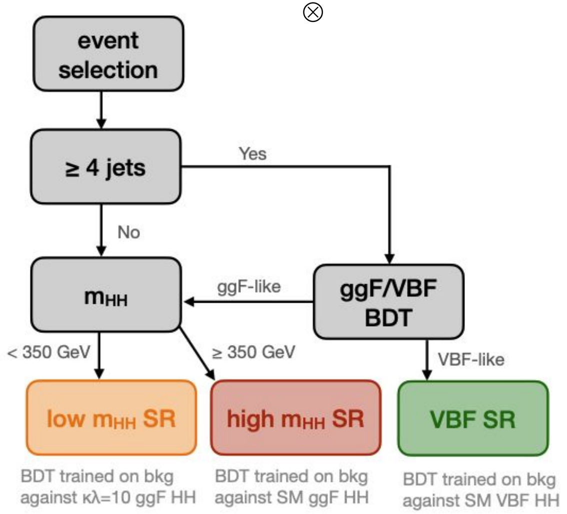
VVHH coupling (κ_{2V})

New:
- finer event categorisation for better κ_λ and κ_{2V} constraints
- improved MVA discriminants
- improved modelling, incl. new samples
- EFT interpretation

τ-decay specific triggers

$\tau_{had}\tau_{had}$ $\tau_{lep}\tau_{had}$ (SLT) $\tau_{lep}\tau_{had}$ (LTT)

⊗



targets κ_λ targets κ_{2V}

⊕ 1 CR

[Phys. Rev. D 110 (2024) 032012]

Legacy Run 2 Results

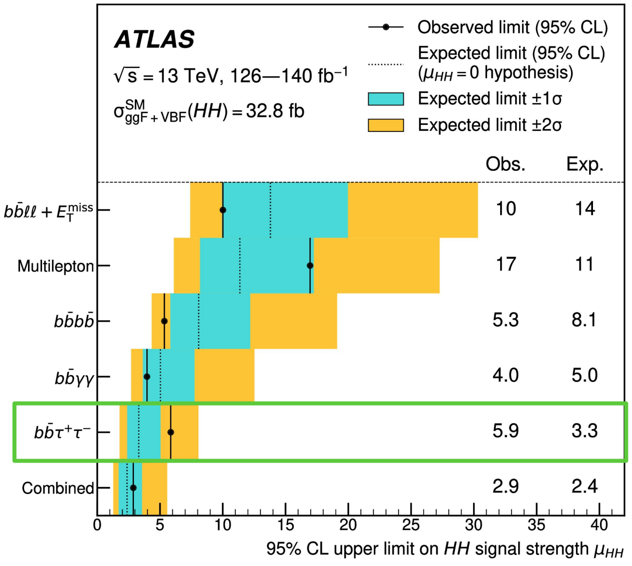
No significant excess observed above SM prediction.

Obs. (Exp.) limits at 95% CL: **μ_{HH} < 5.9 (3.3) x SM**

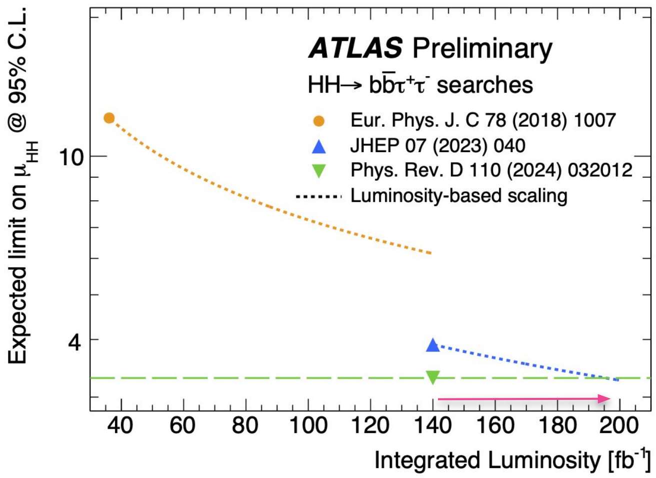
First simultaneous constraint of **ggF** and **VBF** HH production! μ_{ggF} < 5.9 (3.4) x SM
μ_{VBF} < 93 (72) x SM

Improved κ_λ and κ_{2V} constraints: $\kappa_\lambda \in$ [-3.1, 9.0] ([-2.5, 9.3])
$\kappa_{2V} \in$ [-0.5, 2.7] ([-0.2, 2.4])

ATLAS HH combination



[Phys. Rev. D 133 (2024) 101801]



Exp. limit improves by **-15%** wrt previous Run 2 analysis
Improvements are equivalent to …
☞ … 30% more data *or*
☞ … a new analysis < 6x SM

Results are statistically limited!
☞ **many of the analysis improvements will show full potential at HL-LHC!**

HL-LHC Extrapolation [ATL-PHYS-PUB-2024-016]

ATLAS EXPERIMENT

Crystal-balling impact of HL-LHC **luminosity** & **collision energy**

Consider **6 uncertainty scenarios + algorithmic improvements**

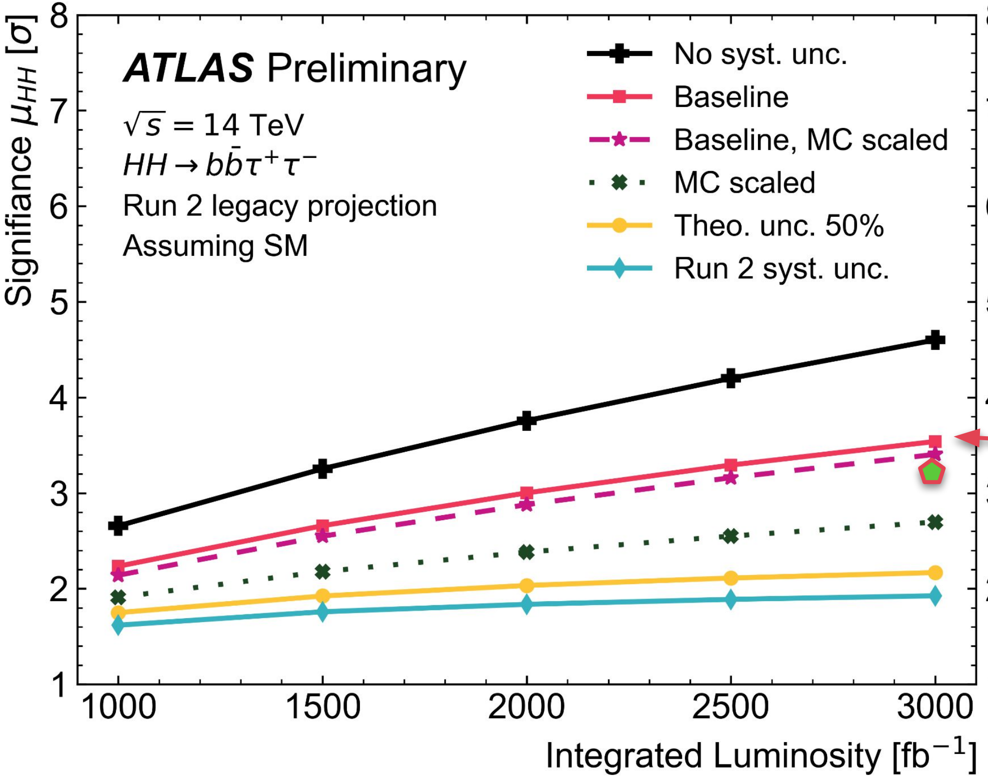
"Run 2 Systs"	keep all uncertainties as they are
"Theo. unc. halved"	half all theory signal and background unc.
"MC lumi scaled"	scale MC stat. uncertainty with √(L'/L)
"Baseline"	Snowmass recommendations for expected HL-LHC ATLAS performance, no MC stat. uncertainty
"Baseline + MC lumi scaled"	baseline, but scale MC stat. unc. with √(L'/L)
"No syst. unc"	no systematic uncertainties, no MC stat. unc. (only floating norms in the fit)

- ✓ **Luminosity**
- ✓ **Collision energy**
- ✓ **Combined performance**
- ✓ **Theory**
- ✓ **Monte Carlo**
- ✓ **Detector performance** [simplified]
- ✓ **Analysis techniques**

[How? scale final discriminant from Run 2 to HL-LHC, conservative estimate]

Will we observe SM-like HH production?

Significance assuming **SM** pp→HH



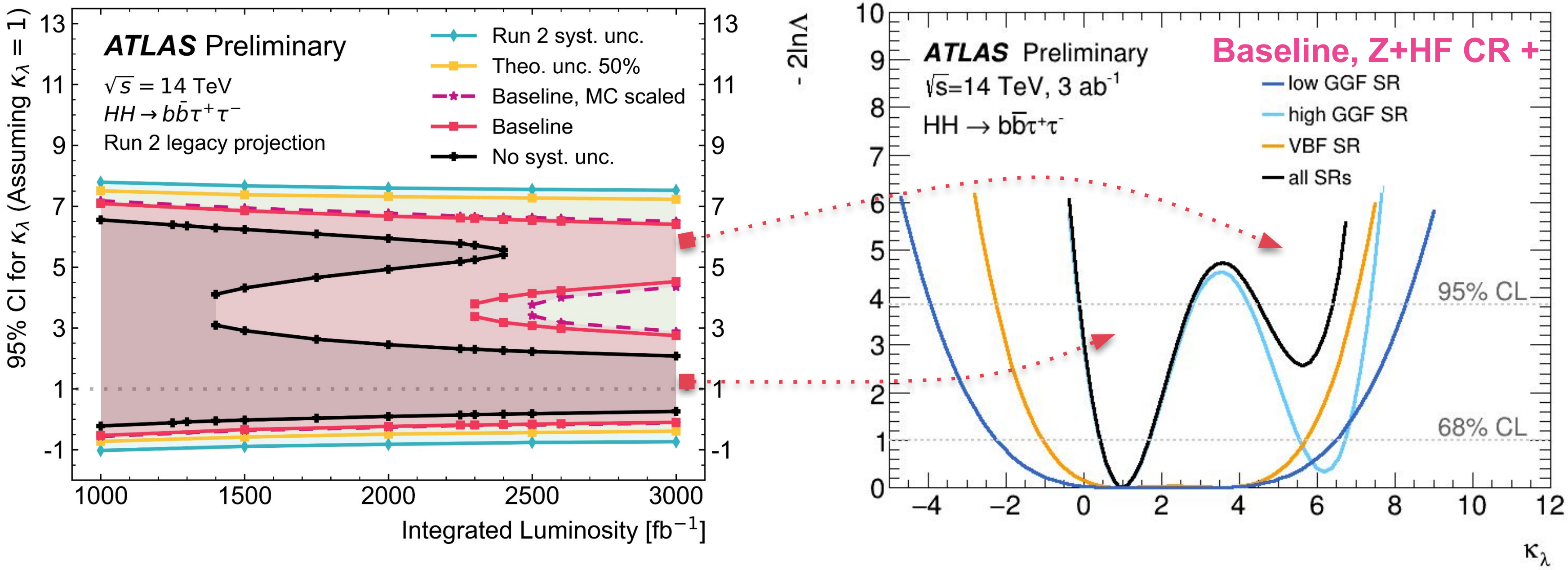
Δμ ≈ 30%

Observation of SM-like HH production is in reach with 3000 fb^{-1} with bb$\tau\tau$!

Legacy bb$\boldsymbol{\tau\tau}$ projection reaches very similar performance as the previous combination (ATL-PHYS-PUB-2022-053) of first Run 2 bbbb, bb$\gamma\gamma$ and bb$\tau\tau$!

How well will we know κ_λ - if SM-like universe ?

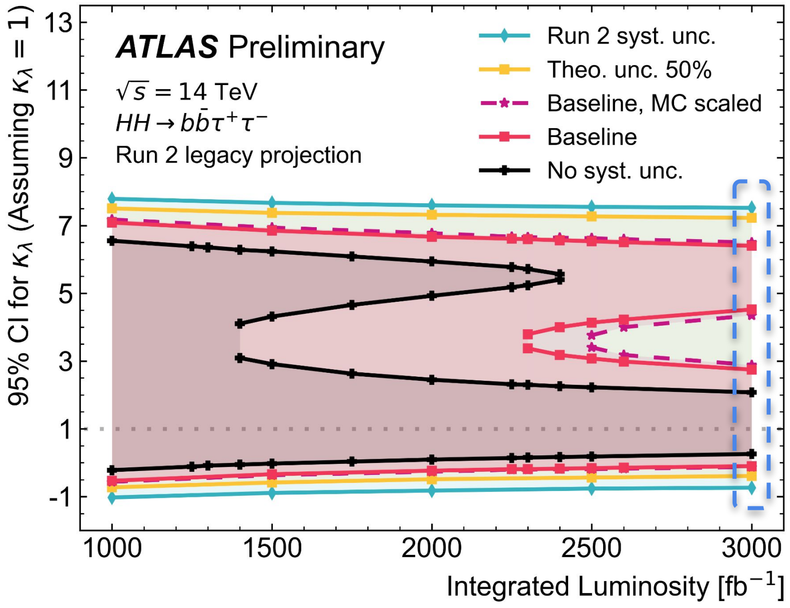
95% CI for κ_λ (assuming **SM**) … constraint from new SRs!



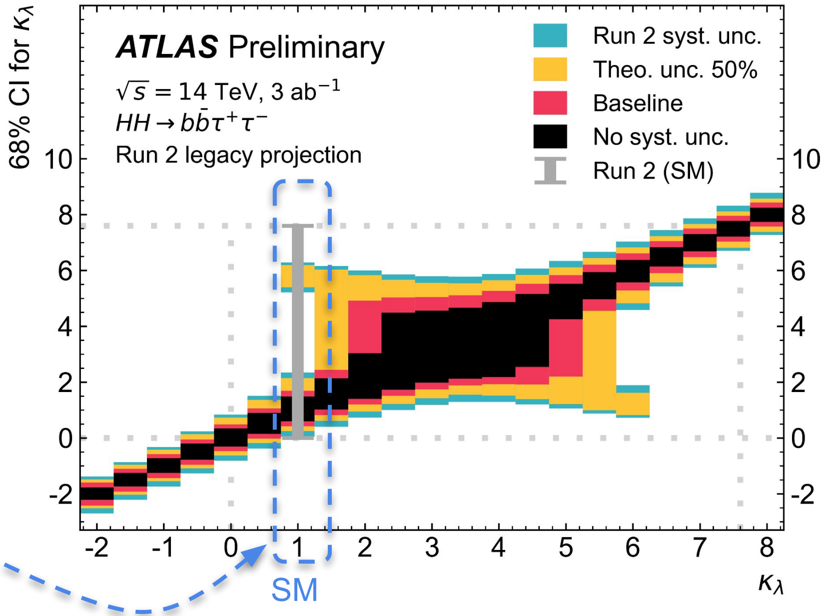
Low GGF and VBF signal regions allow **resolving κ_λ degeneracy** ($\sigma(\sim\kappa^2)$) with ca. 2500 fb^{-1} for most optimistic scenario.

How well will we know κ_λ - if non-SM-like universe ?

95% CI for κ_λ (assuming **SM**)



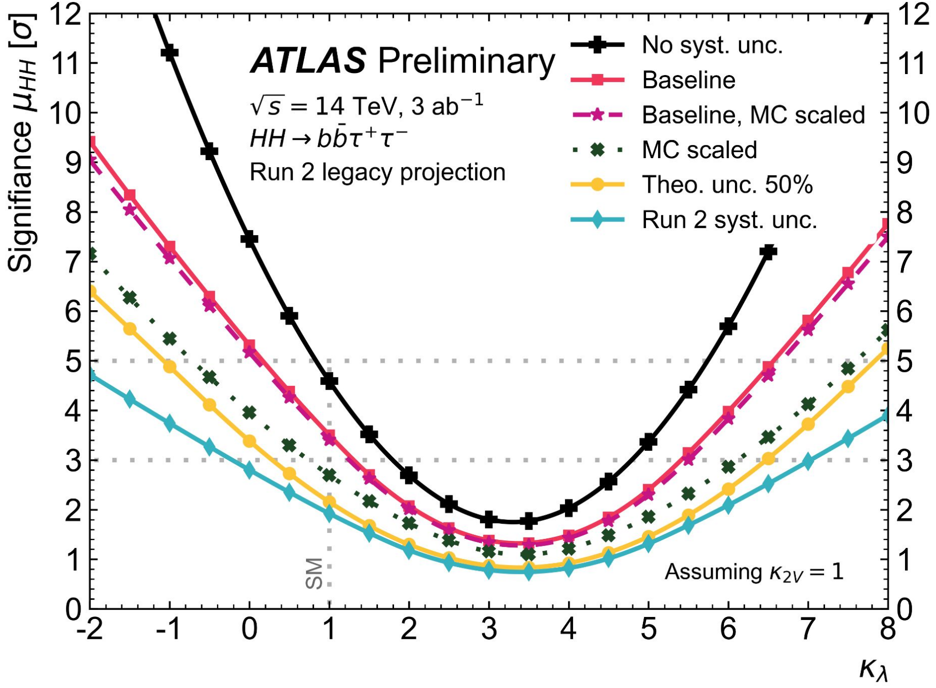
68% CI for κ_λ at **3000 fb^{-1}** varying κ_λ



Our knowledge of κ_λ very much will depend on the universe's implementation!

Will we observe HH production?

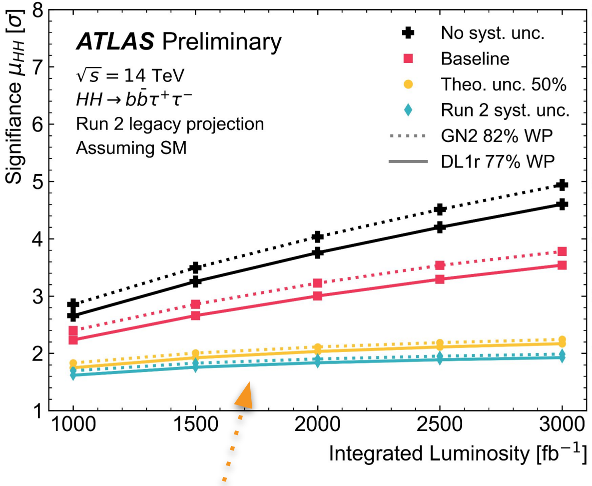
HH significance varying κ_λ



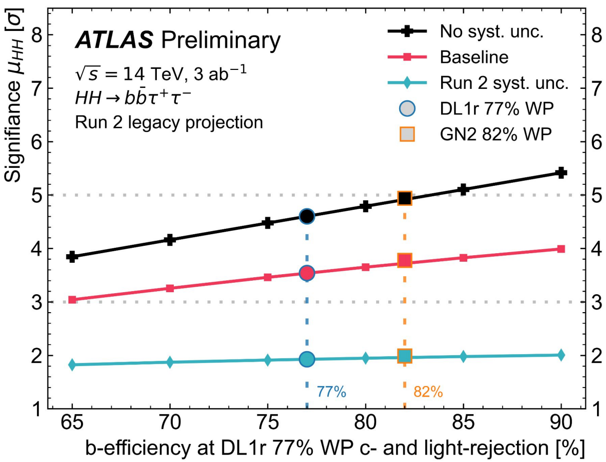
We will observe small and very large HHH couplings, but significantly reduced sensitivity around $\kappa_\lambda \approx 3.5 \pm 1$

Improving … b-tagging … τ-tagging

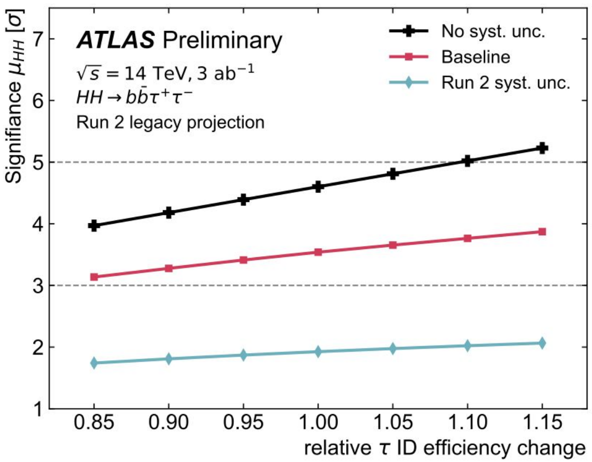
GN2 (GNN) vs DL1r (DNN)



b-efficiency beyond GN2



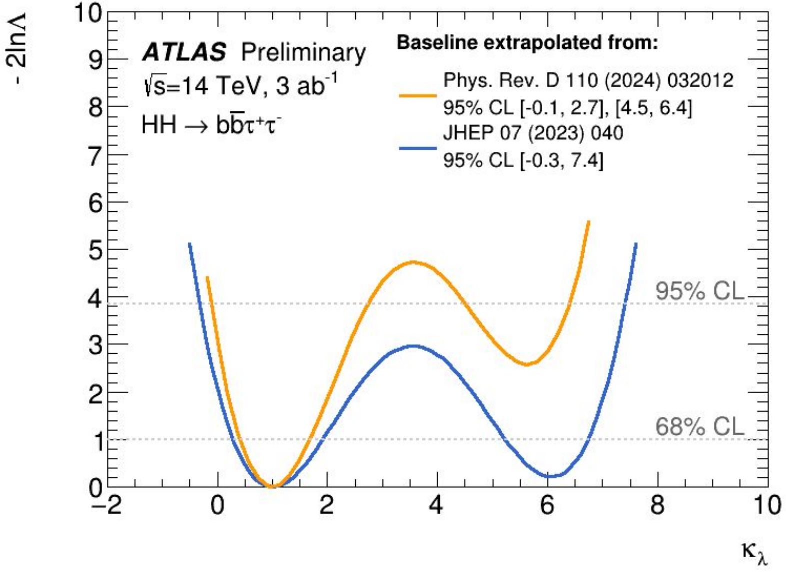
relative τ-ID efficiency



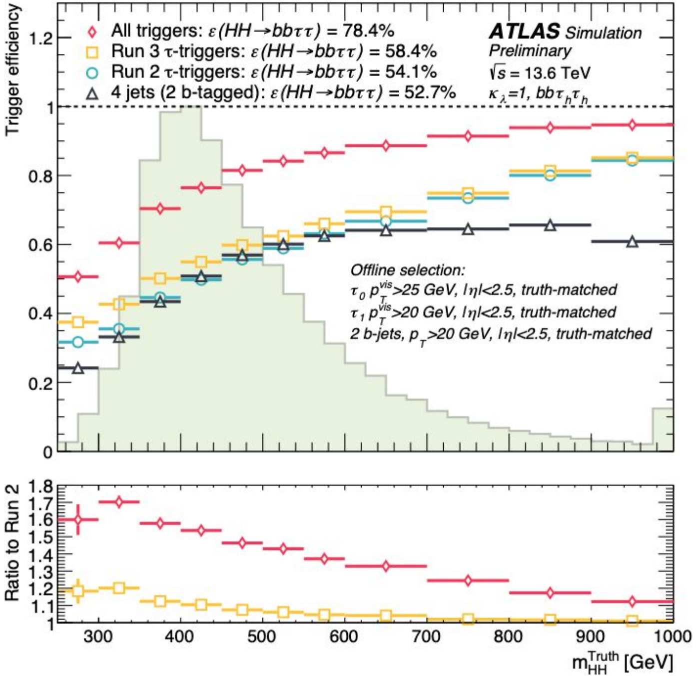
GN2's 82% working point (available today!) will bring us close to *observation* in the most optimistic scenario.

Improvements in the identification of hadronic signatures would greatly benefit the analysis! ☞ how high can we go?

Exciting times ahead!



Improvements in the Legacy Run 2 analysis half the projected uncertainty in κ_λ wrt previous extrapolations



[ATL-COM-DAQ-2023-100-a.]

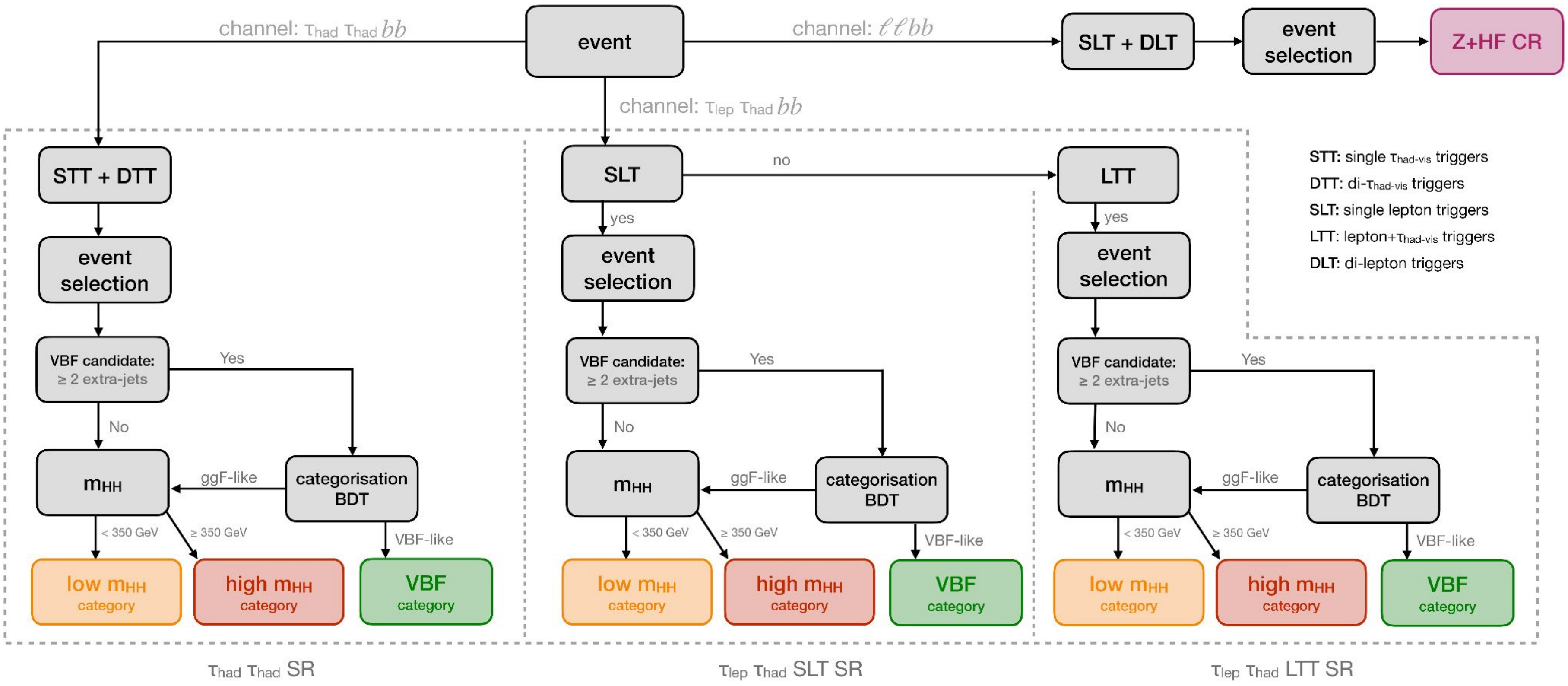
Expect improvements from refined trigger, too!

☞ Observation gets within realistic reach!

[ATL-PHYS-PUB-2024-016] NEW

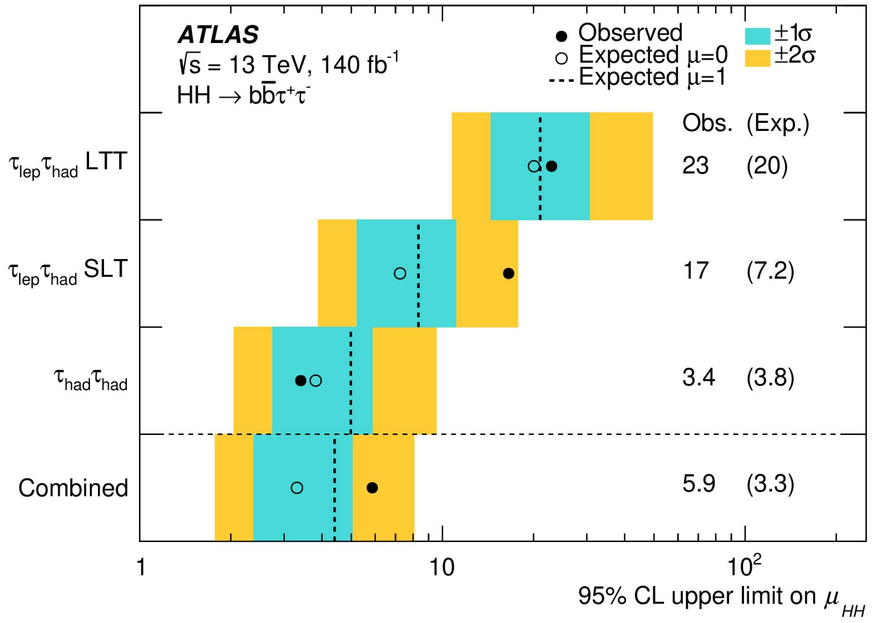
Backup

Legacy Run 2 Signal regions



[Phys. Rev. D 110 (2024) 032012]

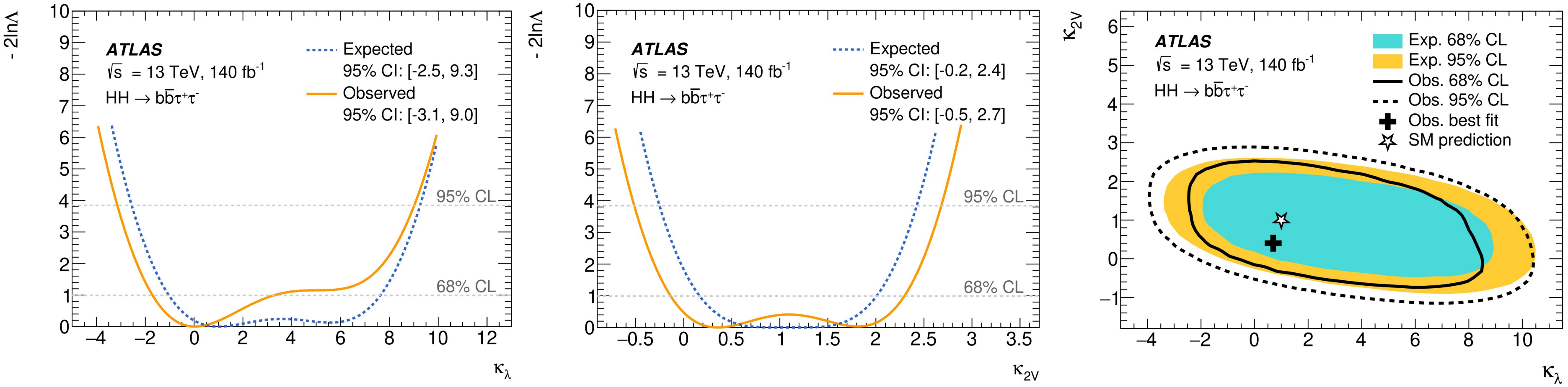
Legacy Run 2 Result



		μ_{HH}	μ_{ggF}	μ_{VBF}	μ_{ggF} (μ_{VBF}=1)	μ_{VBF} (μ_{ggF}=1)
$\tau_{had}\tau_{had}$	observed	3.4	3.6	87	3.5	80
	expected	3.8	3.9	102	3.9	99
$\tau_{lep}\tau_{had}$ SLT	observed	17	17	136	17	158
	expected	7.2	7.4	129	7.4	127
$\tau_{lep}\tau_{had}$ LTT	observed	23	18	765	22	733
	expected	20	21	359	20	350
Combined	observed	5.9	5.8	91	5.9	93
	expected	$3.3^{+1.7}_{-0.9}$	$3.4^{+1.8}_{-1.0}$	73^{+32}_{-21}	$3.4^{+1.8}_{-0.9}$	72^{+32}_{-20}

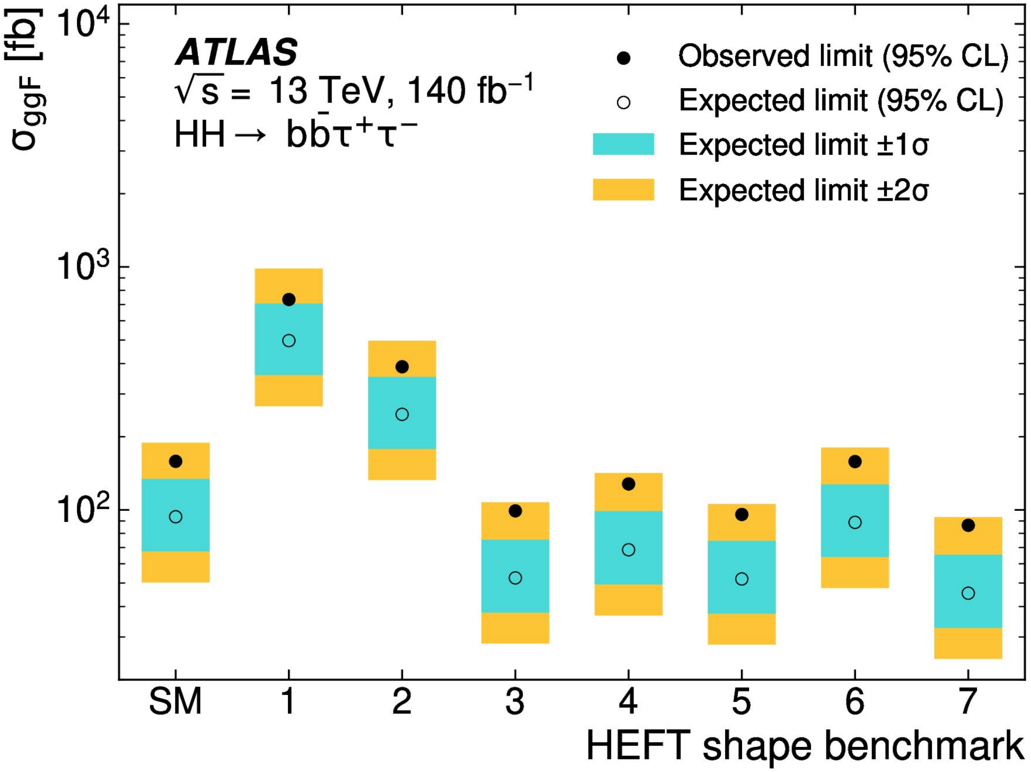
[Phys. Rev. D 110 (2024) 032012]

Legacy Run 2 Result



[Phys. Rev. D 110 (2024) 032012]

Run 2 Legacy EFT interpretation



[Phys. Rev. D 110 (2024) 032012]

Post fit distribution

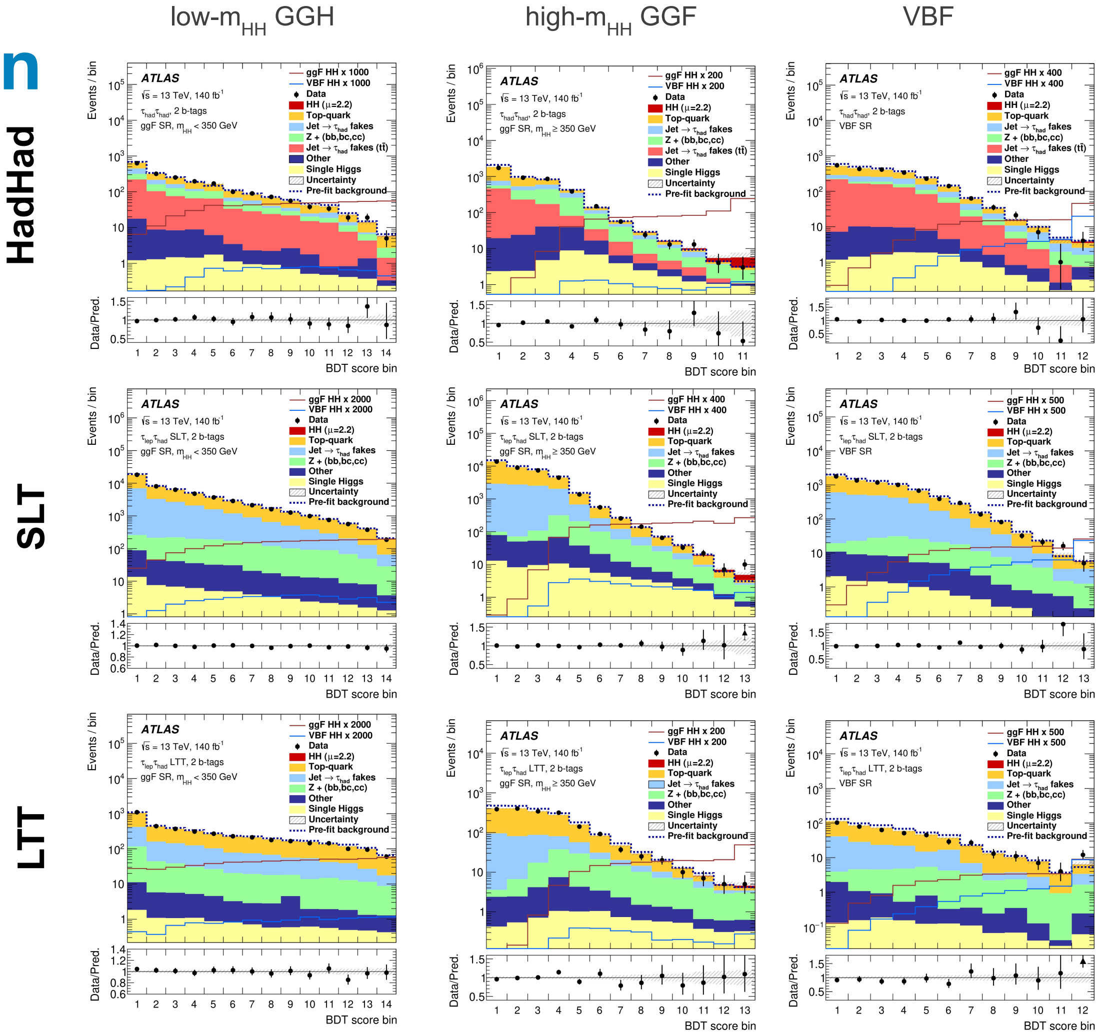
Main backgrounds:

HadHad top (single-t, ttbar), QCD fake τ_{had}, Z+heavy flavor jets, ttbar fake τ_{had}, single Higgs, …

SLT
LTT top (single-t, ttbar), fake τ_{had}, Z+heavy flavor jets, single Higgs, …

Backgrounds are estimated from MC except fake τ_{had}

BDT score binning:
maximize expected sensitivity while minimising MC statistical uncertainty (Trafo 60 algorithm)



[Phys. Rev. D 110 (2024) 032012]

Projection Scalings

Luminosity

Scale MC to HL- LHC L_{int} testing values from $1ab^{-1}$ to $3ab^{-1}$

This assumes that the Phase-II ATLAS detector will be as performant as the current one

The BDT histogram binning is not changed by this scaling → very conservative approach [next slide]

Collision energy

$\sqrt{s}$ → 14 TeV increases σ(process)

σ(process, 14 TeV) = A x σ(process, 13 TeV)

Process	Scale factor
Signals	
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

Residual scale factors

Run 2 found the Z+heavy flavour norm to significantly deviate from unity
→ scale with 1.3 before building (pre-fit) Asimov

The remaining normalisations are taken from MC

Binning

Trafo 60

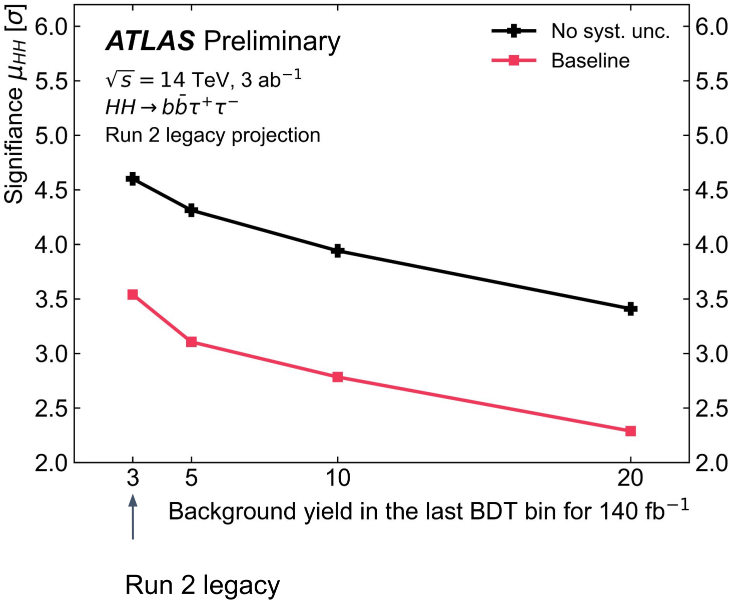
Scale MC to HL- LHC L_{int} testing values from 1 ab^{-1} to 3 ab^{-1}

The BDT histogram binning is not changed by this scaling → very **conservative** approach

Since we cannot estimate how much better we would be with more aggressive binning at 3 ab^{-1} we can estimate **how much worse we would be with a more conservative binning at 140fb^{-1}**

This clearly demonstrates that **all our extrapolations are very conservative**
→ the binning matters a lot

With the current extrapolation,
the last BDT bin has O(100) events at 3 ab^{-1} …



Uncertainty scaling for Baseline

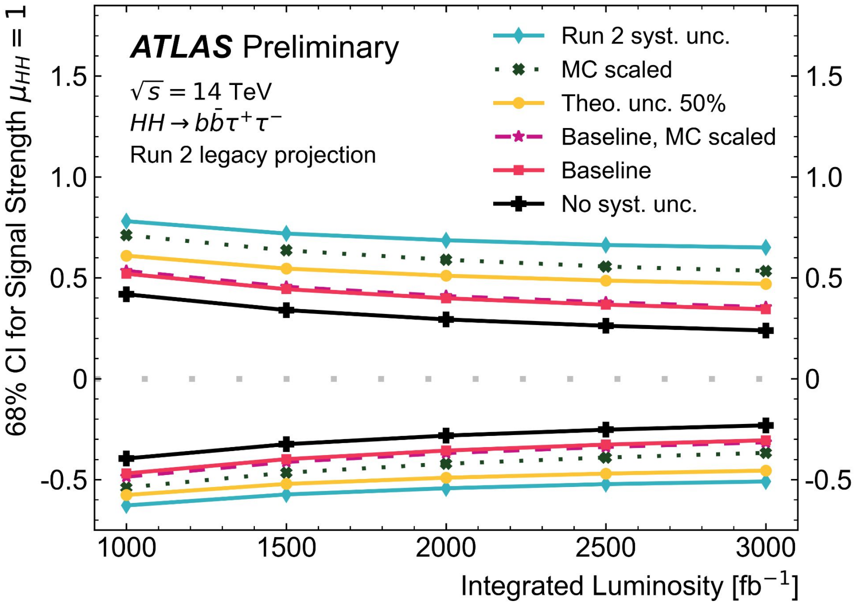
Source	Scale factor
Experimental uncertainties	
Luminosity	1.0
Electrons and muons efficiency	1.0
b-jet b-tagging efficiency	0.5
c-jet b-tagging efficiency	0.5
Light-jet b-tagging efficiency	1.0
τ_{had} efficiency (statistical)	0.0
τ_{had} efficiency (systematic)	1.0
τ_{had} energy scale	1.0
Fake-τ_{had} estimation (statistical)	0.0
Fake-τ_{had} estimation (systematic)	0.5
Jet energy scale and resolution, $E_{\text{T}}^{\text{miss}}$	1.0
Theoretical uncertainties	0.5
MC statistical uncertainties	0.0

→ Run 2 lumi. unc is better than the HL-LHC expectation, thus not scaled here [pragmatically it does not matter]

Otherwise this is following the latest recommendations that were also used for Snowmass 2022 [TWiki]

What will be limiting us?

Uncertainty on **SM** pp→HH signal strength



3000 fb^{-1}

Source of uncertainty	Baseline $\Delta\mu_{HH}$		Run 2 Syst. $\Delta\mu_{HH}$	
Total	+0.35	-0.31	+0.65	-0.51
Statistical	+0.24	-0.23	+0.24	-0.23
↪ Data stat only	+0.24	-0.23	+0.24	-0.23
↪ Floating normalisations	+0.02	-0.02	+0.04	-0.02
Systematic	+0.25	-0.20	+0.61	-0.46
Experimental uncertainties				
Electrons and muons	< 0.01		< 0.01	
τ-leptons	+0.03	-0.03	+0.06	-0.05
Jets	+0.06	-0.06	+0.06	-0.07
b-tagging	+0.02	-0.02	+0.04	-0.03
E_T^{miss}	+0.03	-0.02	+0.04	-0.02
Pile-up	+0.01	-0.01	+0.01	-0.01
Luminosity	+0.02	-0.01	+0.02	-0.01
Theoretical and modelling uncertainties				
Signal	+0.12	-0.05	+0.39	-0.07
Backgrounds	+0.19	-0.17	+0.37	-0.30
↪ Single Higgs	+0.17	-0.15	+0.34	-0.27
↪ Z + jets	+0.06	-0.05	+0.10	-0.09
↪ W + jets	< 0.01		< 0.01	
↪ $t\bar{t}$	+0.02	-0.02	+0.03	-0.02
↪ Single top quark	+0.01	-0.01	+0.03	-0.04
↪ Diboson	< 0.01		< 0.01	
↪ Jet → τ_{had} fakes	+0.05	-0.05	+0.09	-0.08
MC statistical	< 0.01		+0.38	-0.36

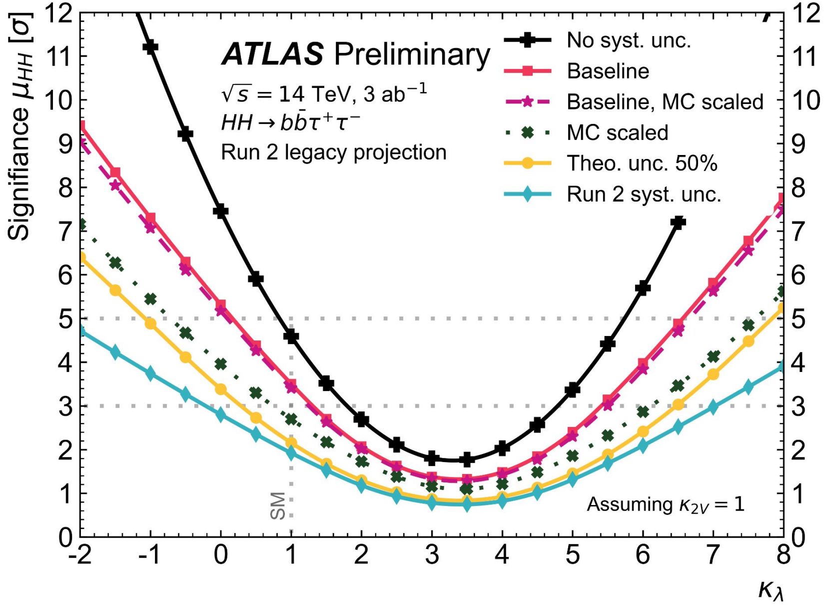
Δsyst ~ Δstat

jets, τ, E_T^{miss}

signal & bkg modelling

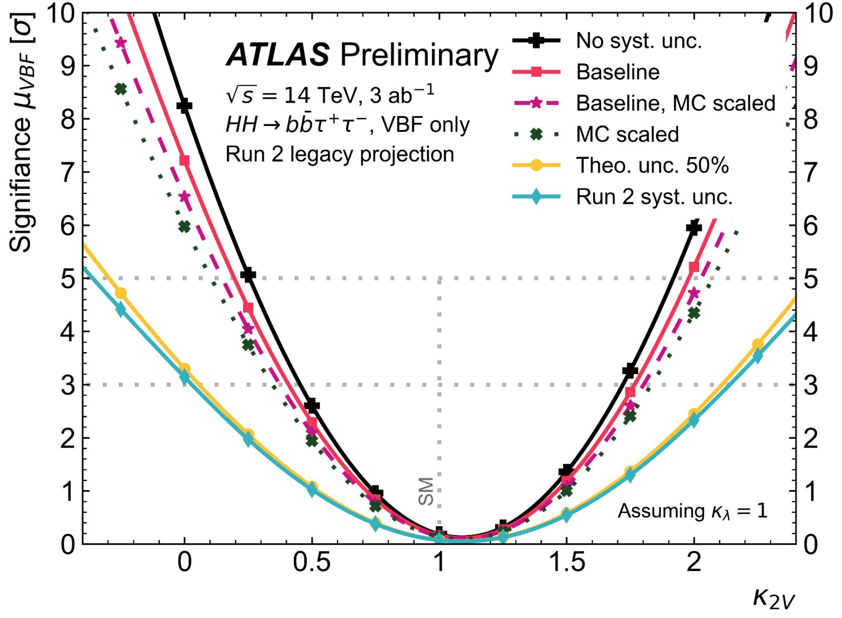
Will we observe HH production?

HH (ggF + VBF) significance varying κ_λ



We will observe small and very large HHH couplings, but significantly reduced sensitivity around $\kappa_\lambda \approx 3.5 \pm 1$

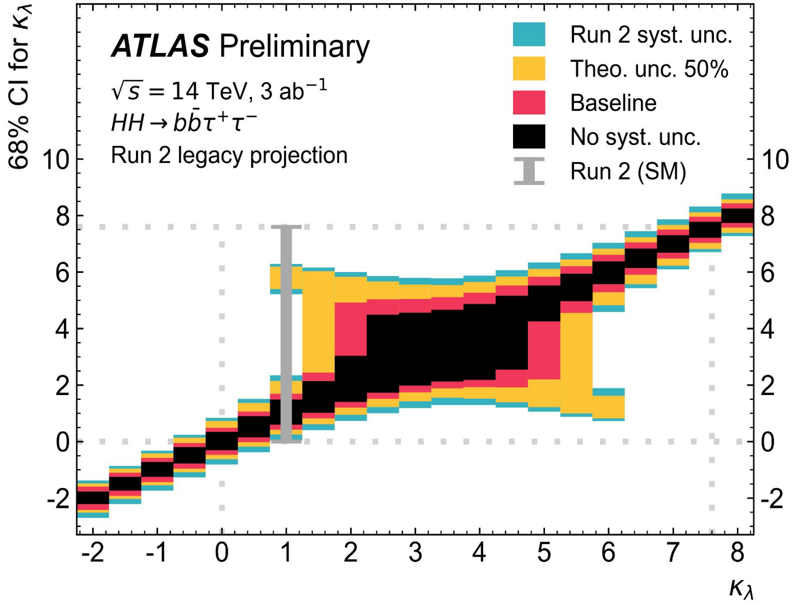
VBF HH significance varying κ_{2V}



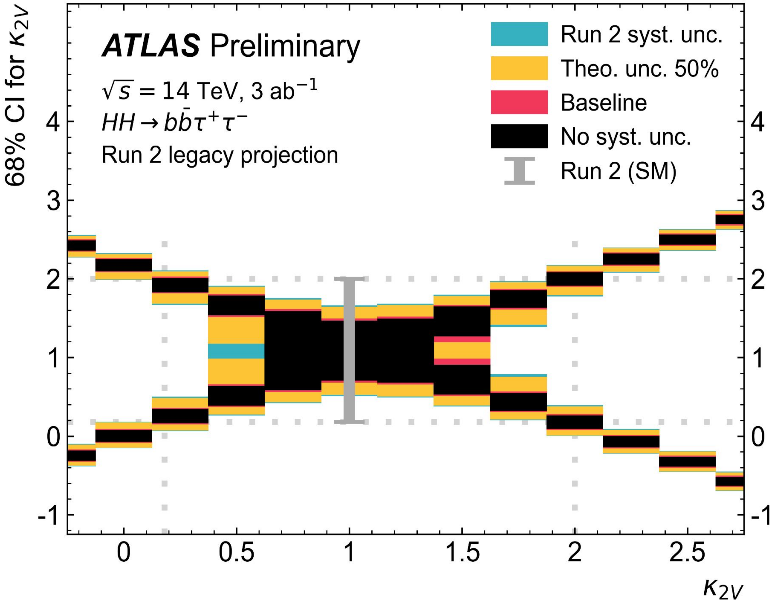
HH VBF production will likely not be observed even at HL-LHC (if SM-like universe)

Uncertainty on κ as a function of κ

HHH coupling modifier κ_λ

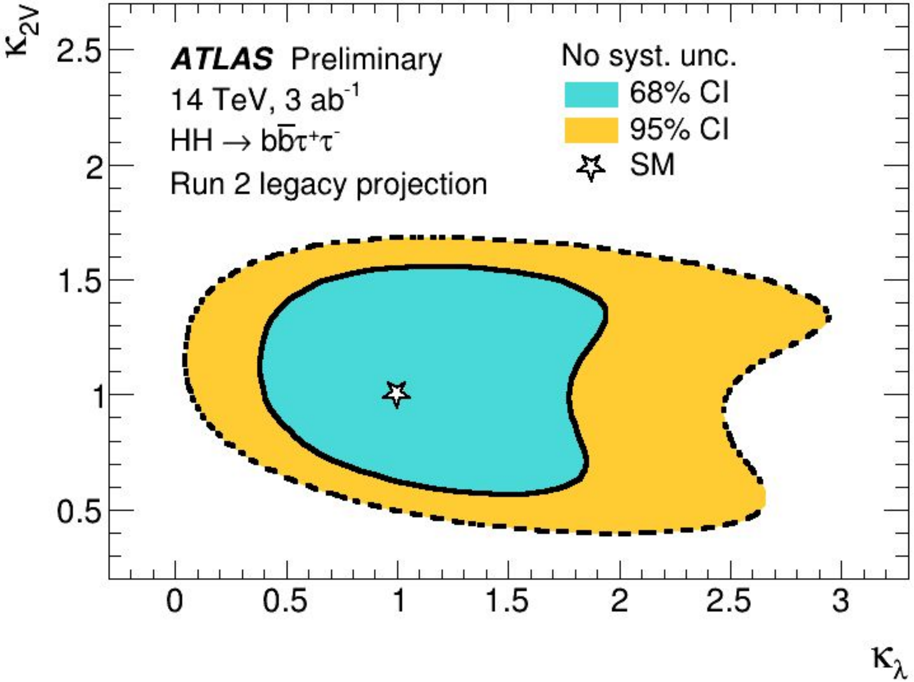


VVHH coupling modifier κ_{2V}



How precise could we measure the self-couplings if Nature realized a certain value of κ_λ or κ_{2V}?

2D likelihood scan of κ_λ vs κ_{2V}



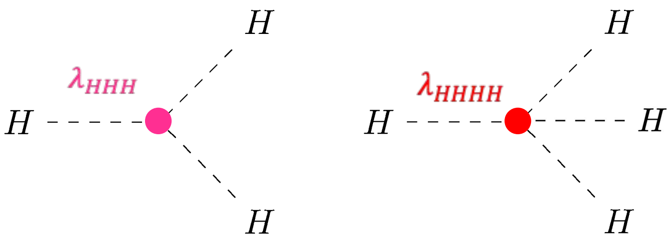
Expected 2D confidence intervals for κ_λ and κ_{2V} at 68% and 95% CL at 3 ab^{-1} in the extrapolation scenario without systematic uncertainties

The Higgs potential and Di-Higgs searches

Standard Model Higgs Potential

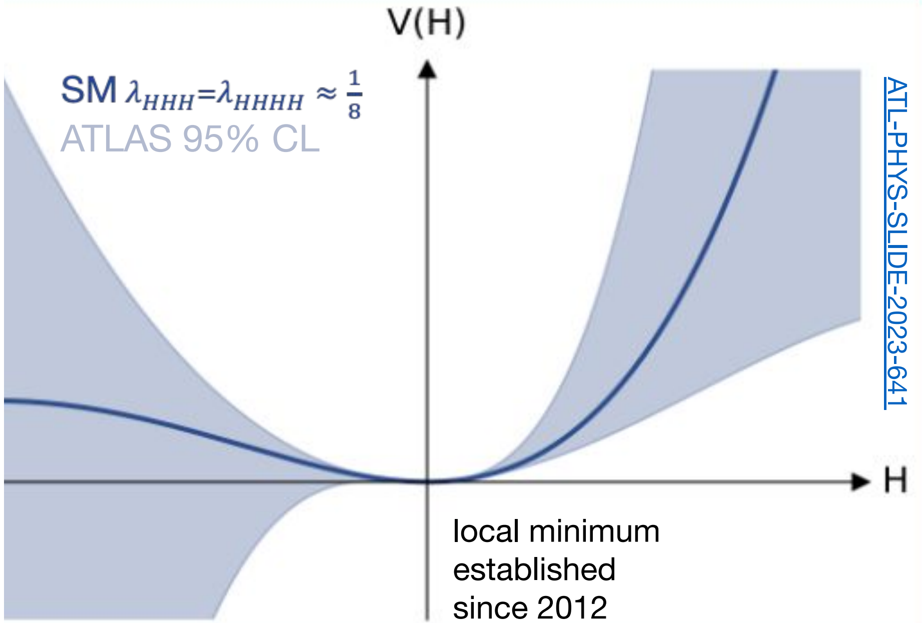
Higgs boson mass

$$V_{SM,EWSB} = \frac{1}{2} m_h^2 h^2 + \lambda_{HHH} v\, h^3 + \lambda_{HHHH} h^4$$



Higgs boson self-interaction strength λ

Potential's shape & origin are experimentally very loosely unconstrained



ATL-PHYS-SLIDE-2023-641

measure HH to probe coupling modifier $\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$