ATLAS EXPERIMENT

Search and Prospects for Non-Resonant Higgs Boson Pair Production in the $bb\tau\tau$ Final State in the ATLAS Experiment

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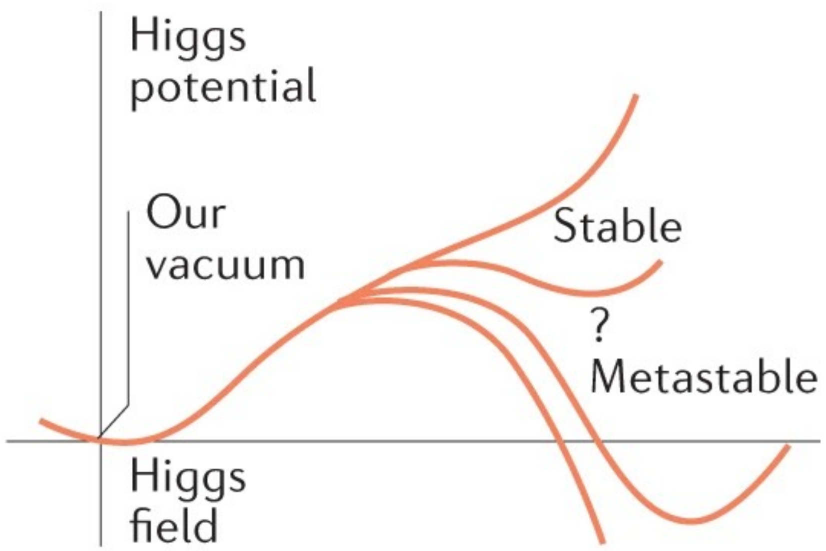
Higgs potential and Di-Higgs searches

Higgs potential : $$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

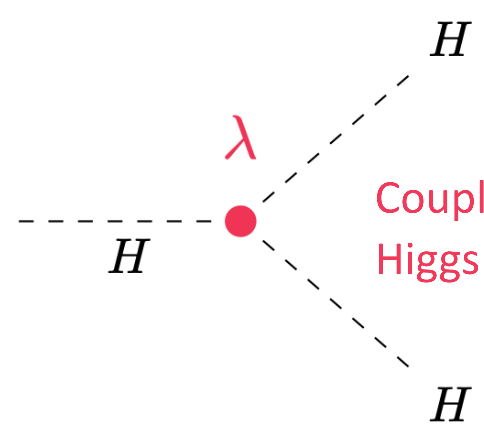
$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \cdots$$

After symmetry breaking : $$V = V_0 + \frac{1}{2}m_H^2 h^2 + \frac{m_H^2}{2v^2} v h^3 + \ldots$$

Nature..R.Physics 3,608-624 (2021)



in SM $$\lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2}$$



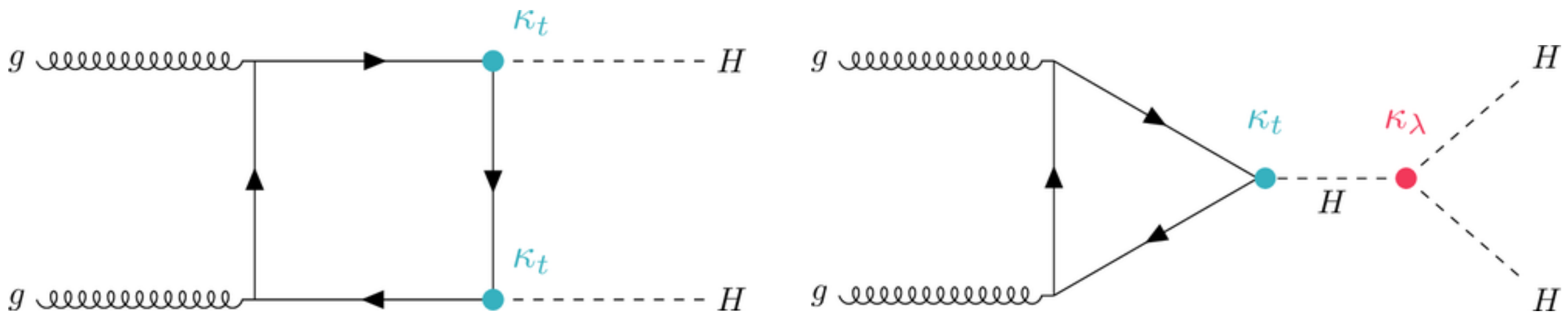
Coupling strength of the Higgs boson self-interaction

Existence of BSM physics can alter the shape of V(ϕ) and modify λ significantly

→ Measure HH production to probe coupling modifier
Coupling deviation expressed as ratio wrt to the SM prediction : $\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$

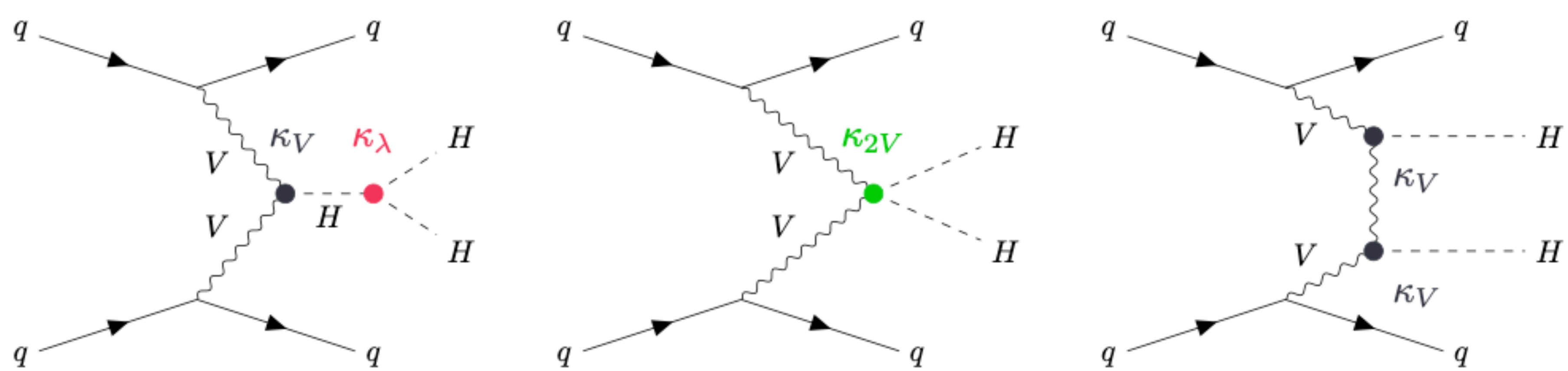
Di-Higgs production mode

gluon-gluon Fusion (ggF) 90%, 31.02 fb @ 13TeV



Depends on the trilinear coupling modifier κ_λ

Vector Boson Fusion (VBF) 4.5 %, 1.72 fb @ 13 TeV



Sensitive to VVHH coupling and the corresponding κ_{2V} coupling modifier

ATLAS HH search

	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%

Explore a mixture of different Higgs decay channels to maximize the sensitivity

[bbbb]
[bbττ]
[bbγγ]

[bbll + ETmiss]
[Multilepton]

Analyses orthogonal by design

Combining HH searches is necessary since they are statistically limited

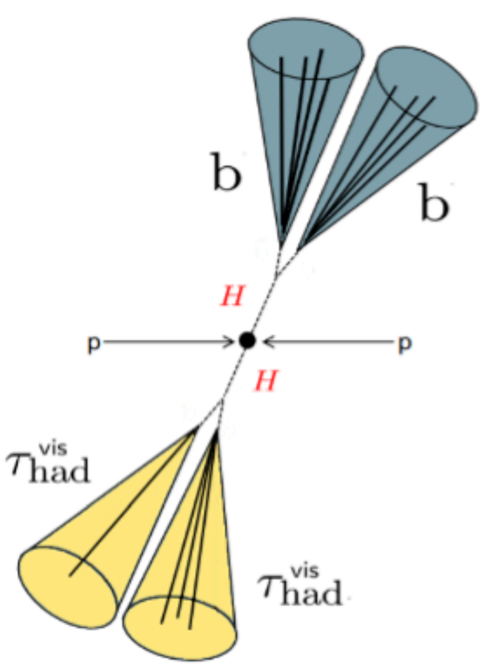
bbττ decay channel

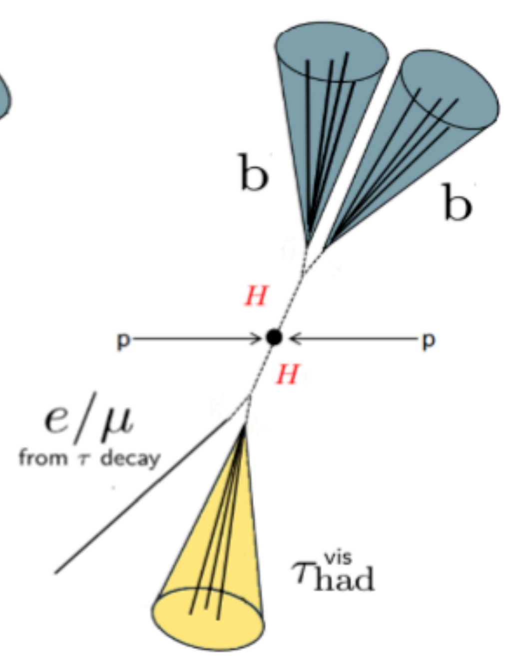
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

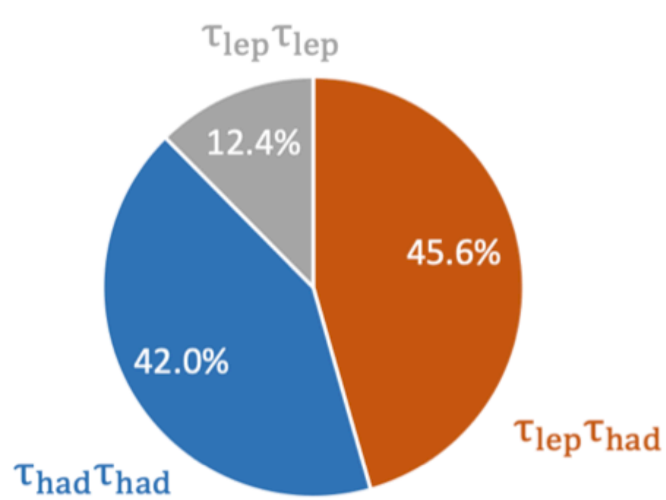
bbττ is one of the golden channels

di-b : relatively large BR

di-τ : Clean signal







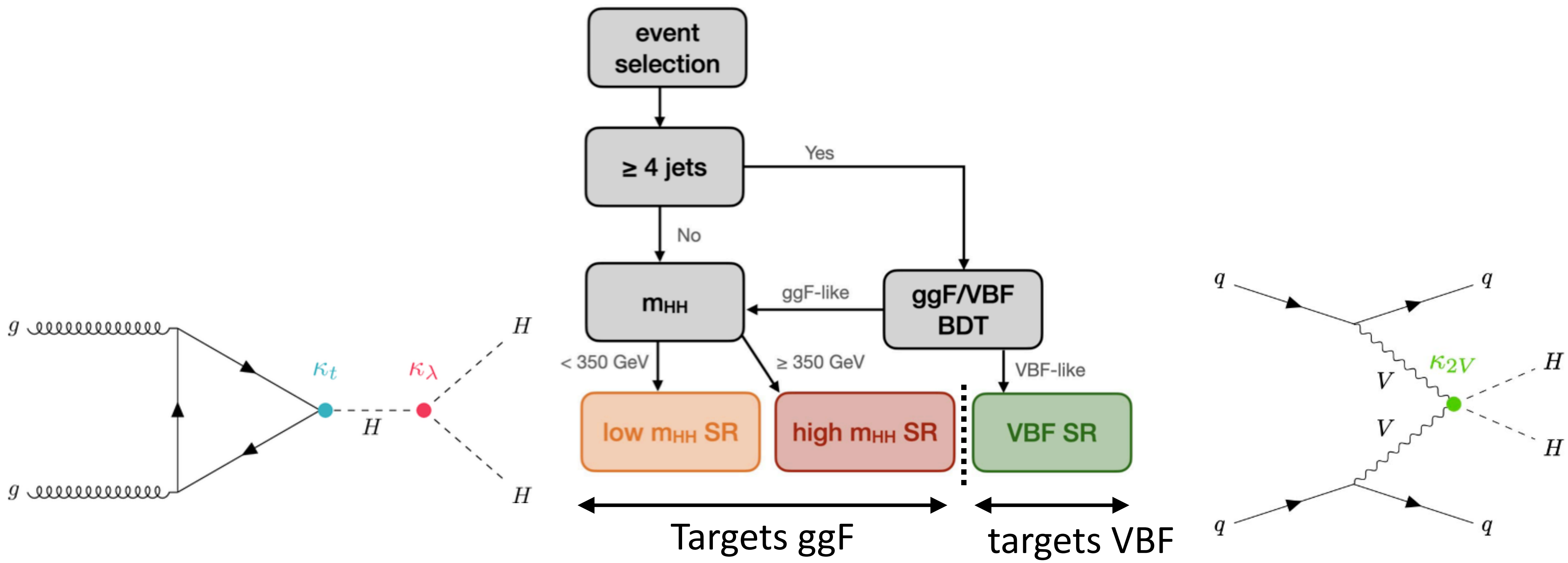
2 decay channels :

- HadHad
  (fully hadronic) channel
- LepHad
  (semi leptonic) channel

Legacy Run2 HH->bbττ analysis

Phys. Rev. D 110 (2024) 032012

- Re-analyzed LHC Run2 data with 140 fb^{-1} datasets
- Signal regions split into 3 categories based on the channel/trigger ($\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$ (SingleLeptonTrigger), $\tau_{lep}\tau_{had}$ (LeptonTauTrigger))
- In each category, further categorization is applied to target different production modes

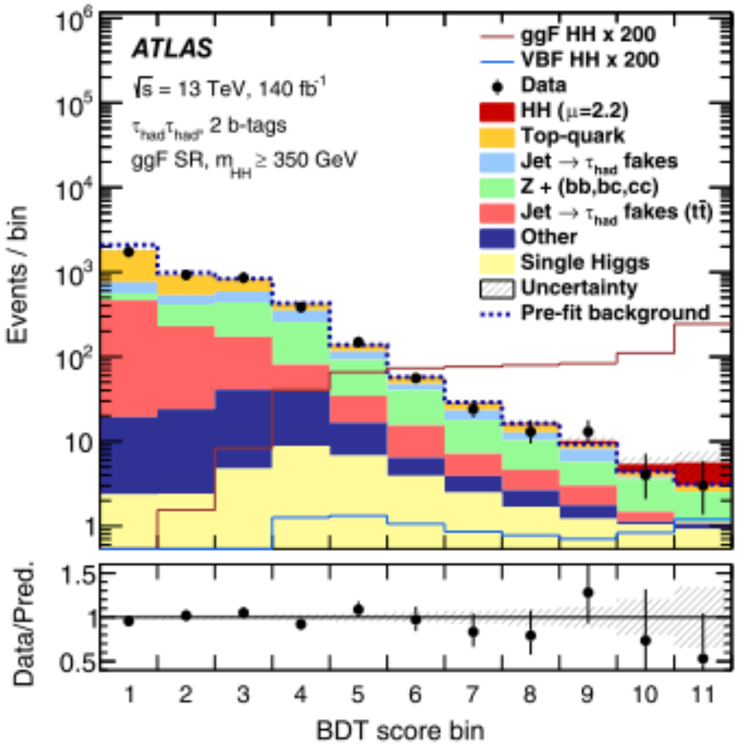


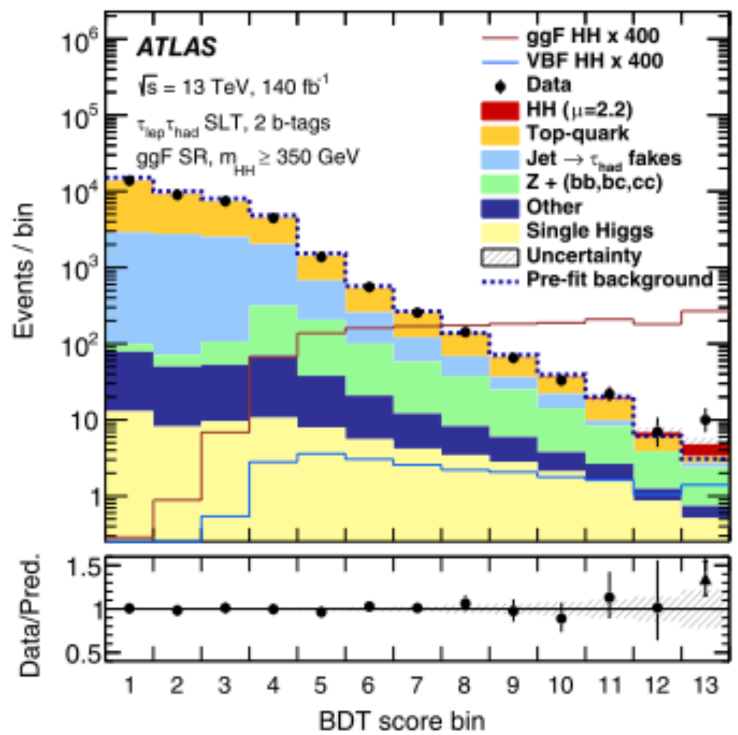
Split ggF SR for better sensitivity to κ_λ

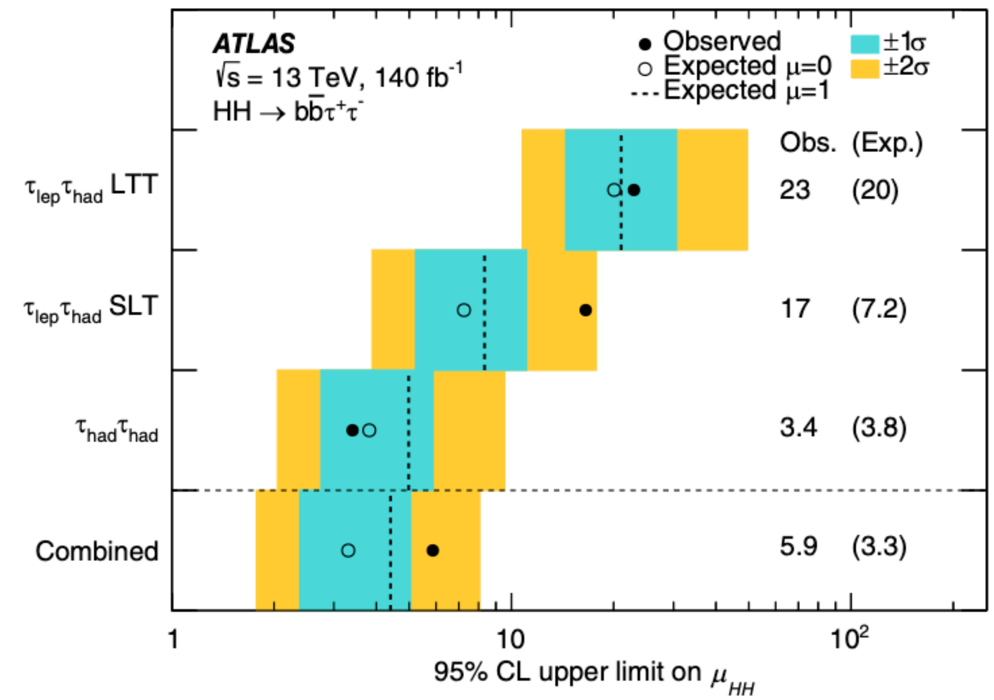
- Trained BDTs in ordered to separate the signal from the background
- Fitted BDT discriminiants in all SRs and control regions for signal strength μ_{HH}
- A fit to simultaneously extract μ_{ggF} and μ_{VBF} was also performed

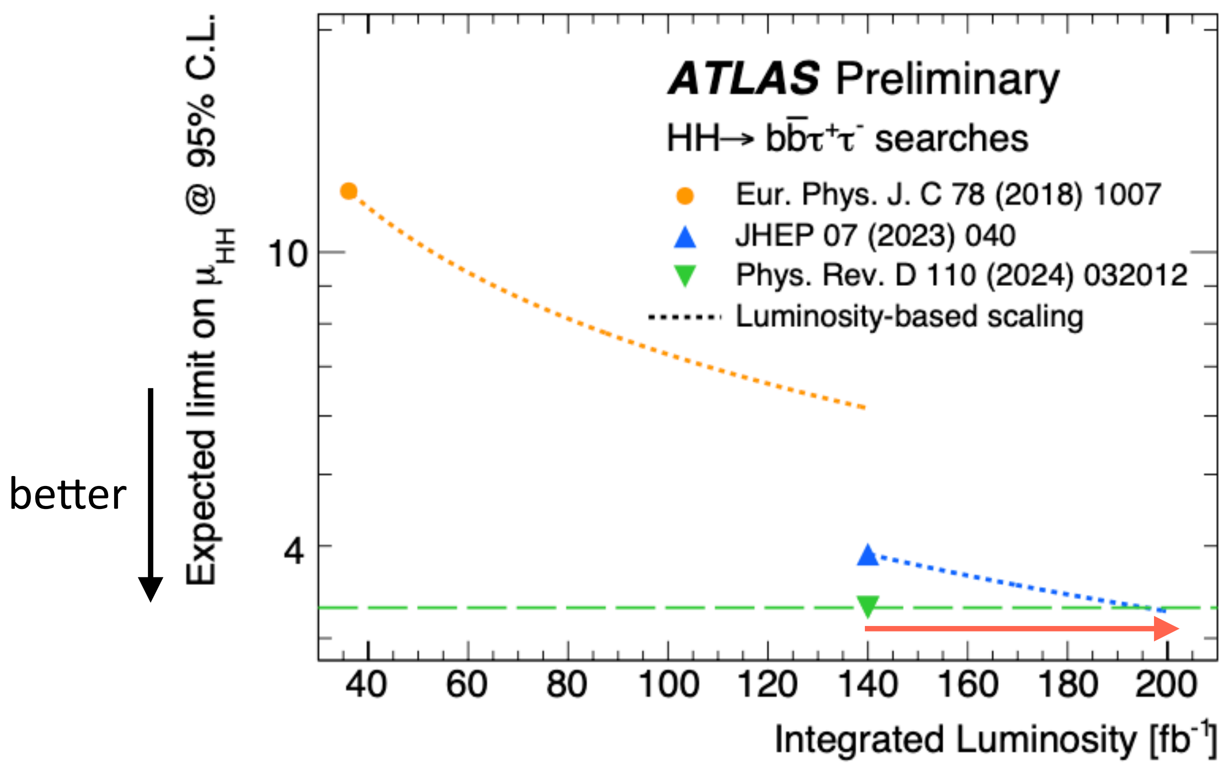
Legacy Run2 HH->bbττ analysis results

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









No significant excess above SM prediction

Obs. (Exp.) 95% CL :

$\mu_{\rm HH}$ < 5.9 (3.3) × SM

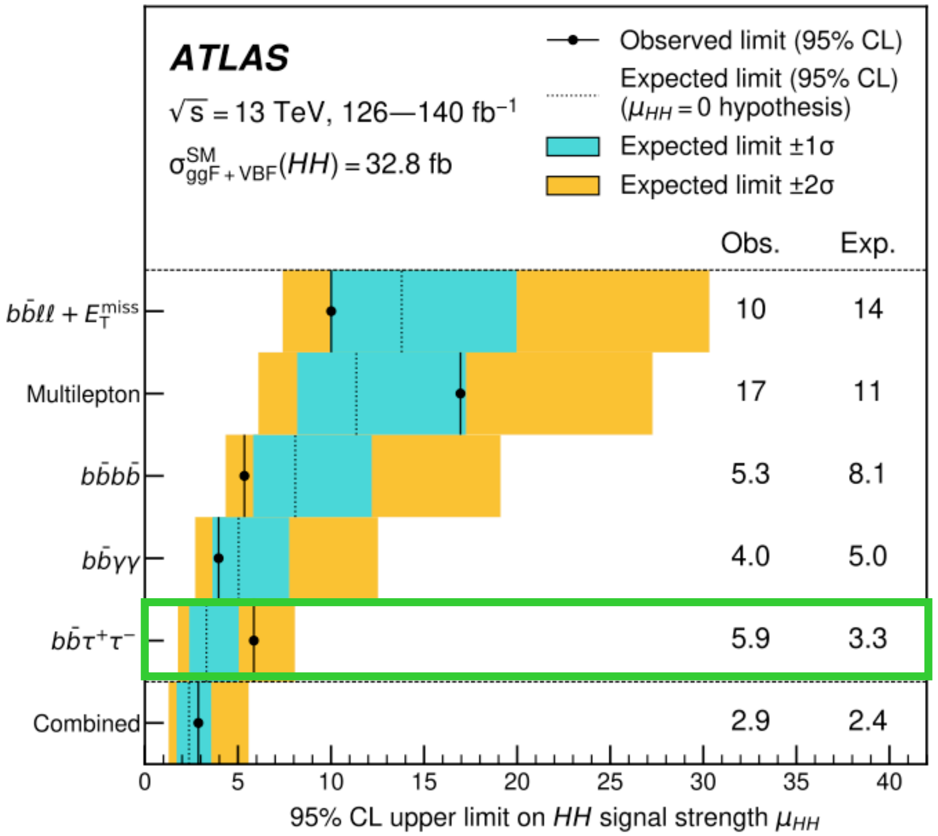
$-3.1 < \kappa_\lambda < 9.0$ ($-2.5 < \kappa_\lambda < 9.3$)

$-0.5 < \kappa_{2V} < 2.4$ ($-0.2 < \kappa_{2V} < 2.4$)

- Exp. limit improves by **15%** wrt previous Run 2 analysis
  = equal improvement to have +30% data
- Results are statistically limited

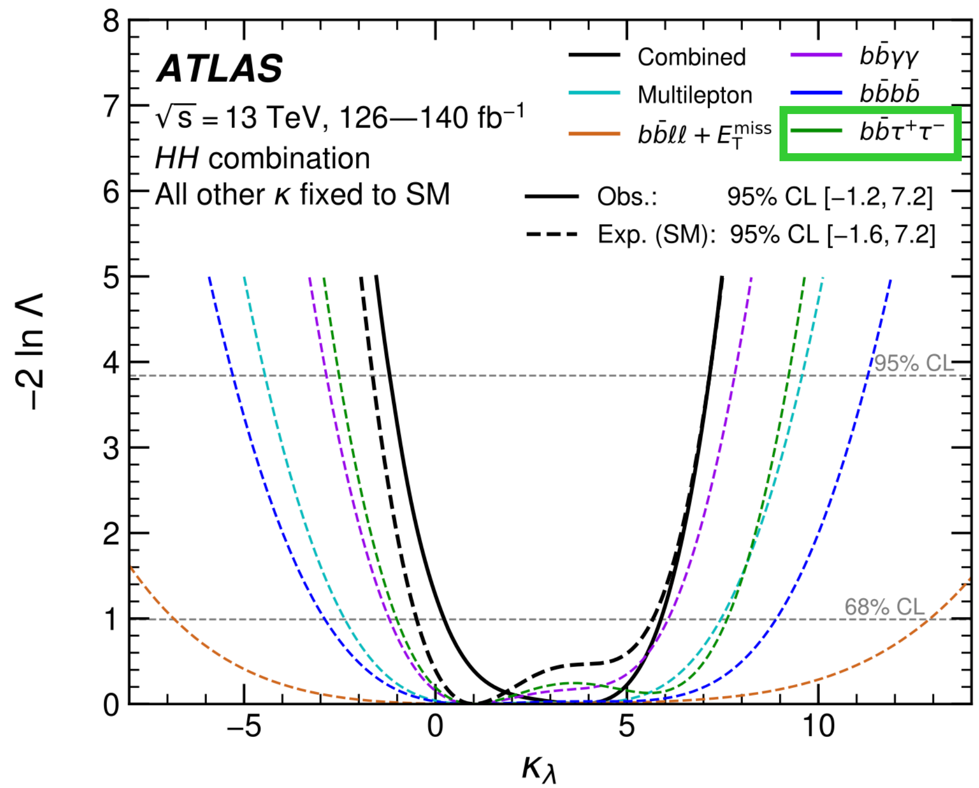
bbττ in Run2 combination studies

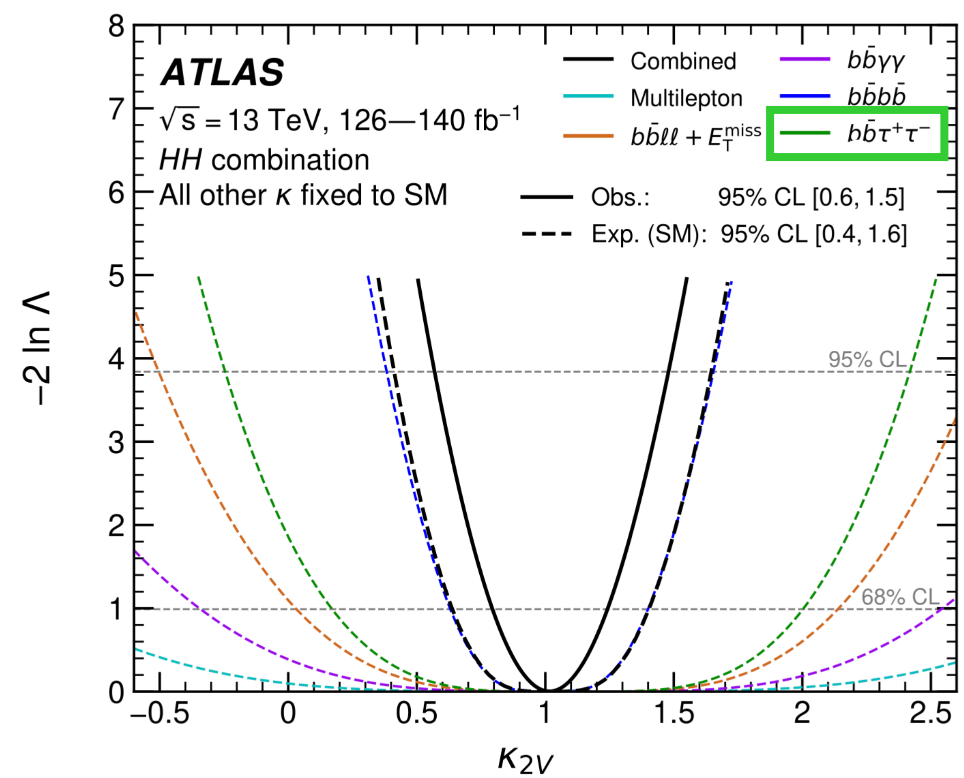
[PhysRevLett.133 (2024) 101801]



bbττ channel gives the best expected sensitivity in Run2 combination study

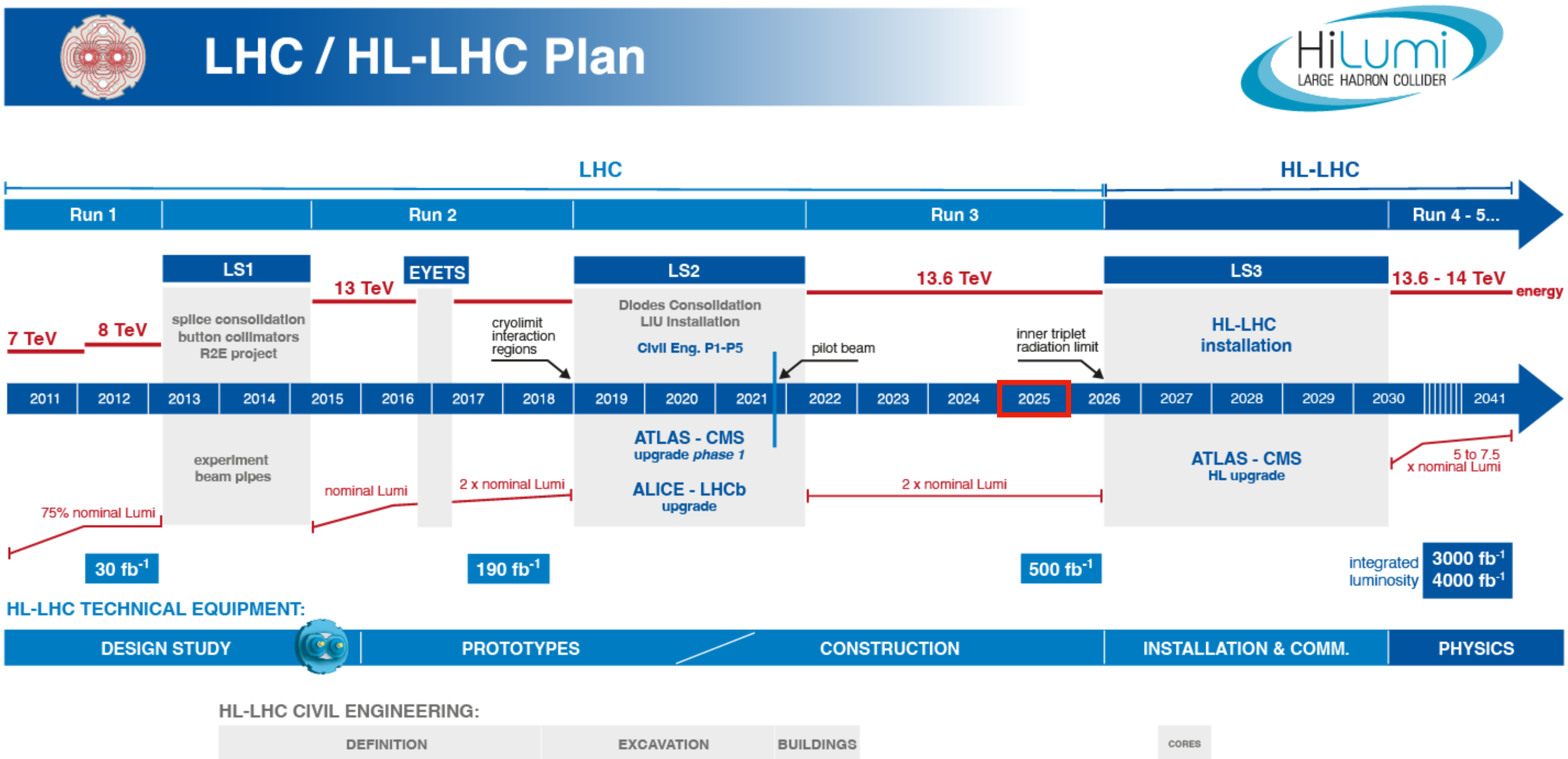
2nd contribution for constraining κ_λ and κ_{2V}





High Luminosity-LHC

LHC/ HL-LHC Plan (last update January 2025)



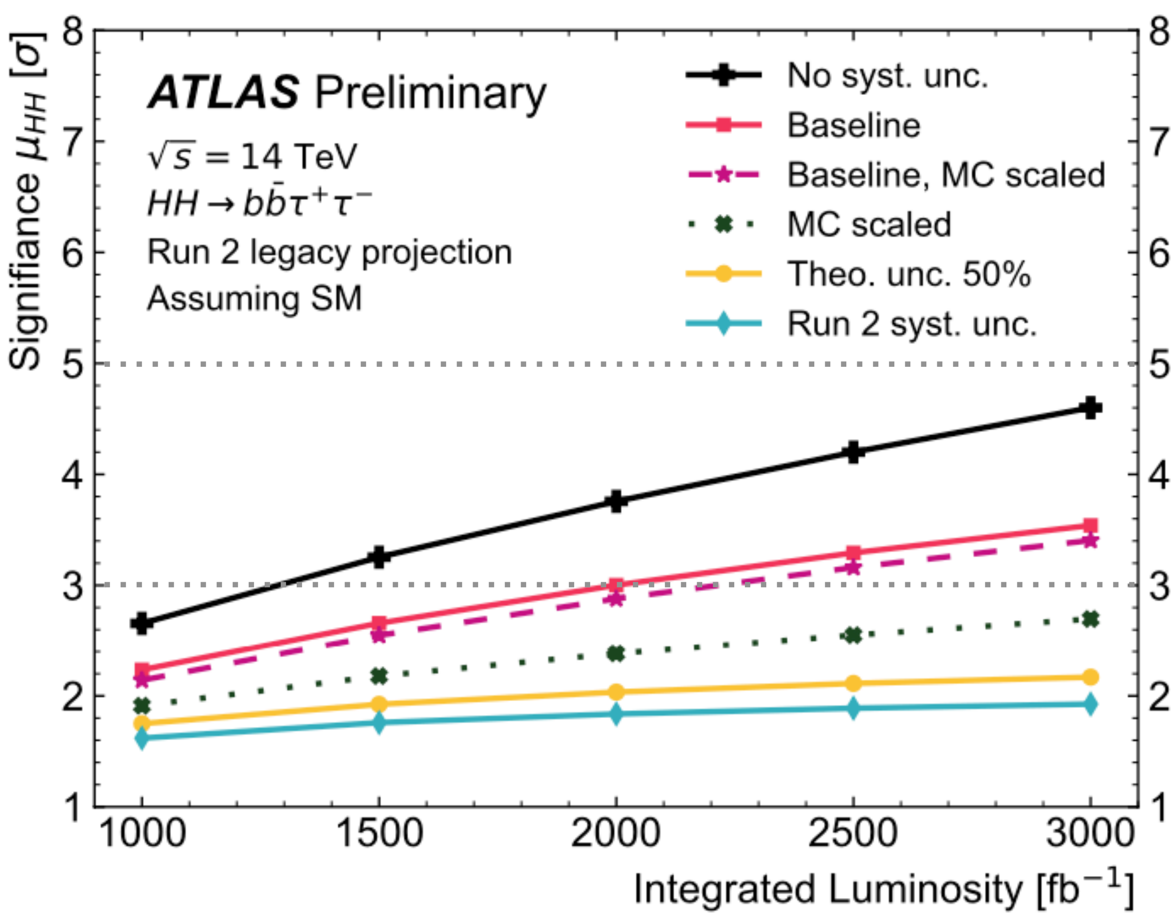
- The HL-LHC aims at collecting at least 3000 fb^{-1} of 14 TeV pp collisions

Extrapolation towards HL-LHC

[ATL-PHYS-PUB-2024-016]

Expected sensitivity of the Run 2 Legacy analysis extrapolated to the HL-LHC dataset (140 → 1000 ~ 3000 fb^{-1}, 13 → 14 TeV) by scaling signal and background yields

Run 2 syst. unc.	All uncertainties kept at their Run2 values
Theo. unc. 50%	Half all theory sig & bkg uncertainties
MC scaled	MC stat. uncertainty is scaled by √(L/L')
Baseline	Recommendation for expected HL-LHC performance, no MC stat.
Baseline, MC scaled	Baseline, scaled MC stat. by √(L/L')
No syst. unc.	All uncertainties removed

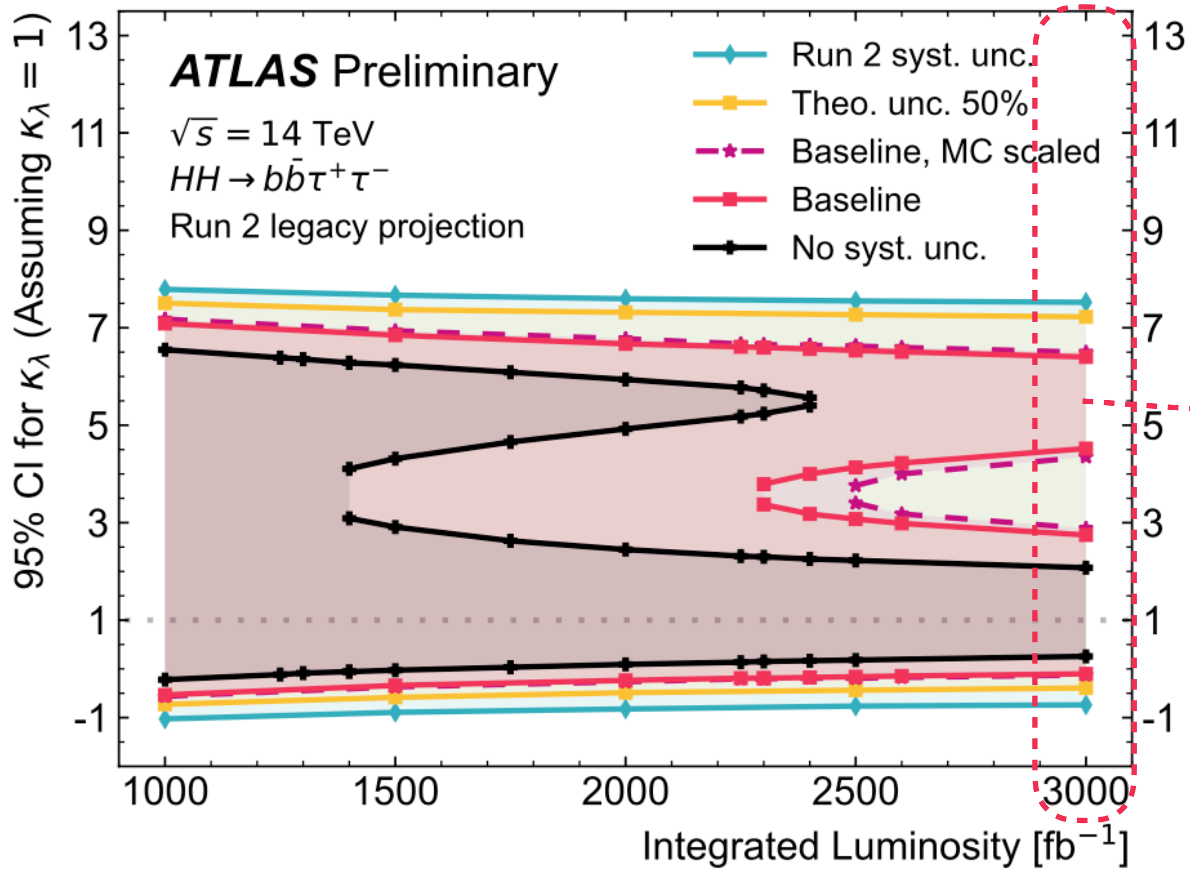


- Evidence for HH production is in reach with 3000 fb^{-1} with only bbττ
- In Baseline scenario expect 3.5 σ excess Statistical and systematic uncertainties are of the same size

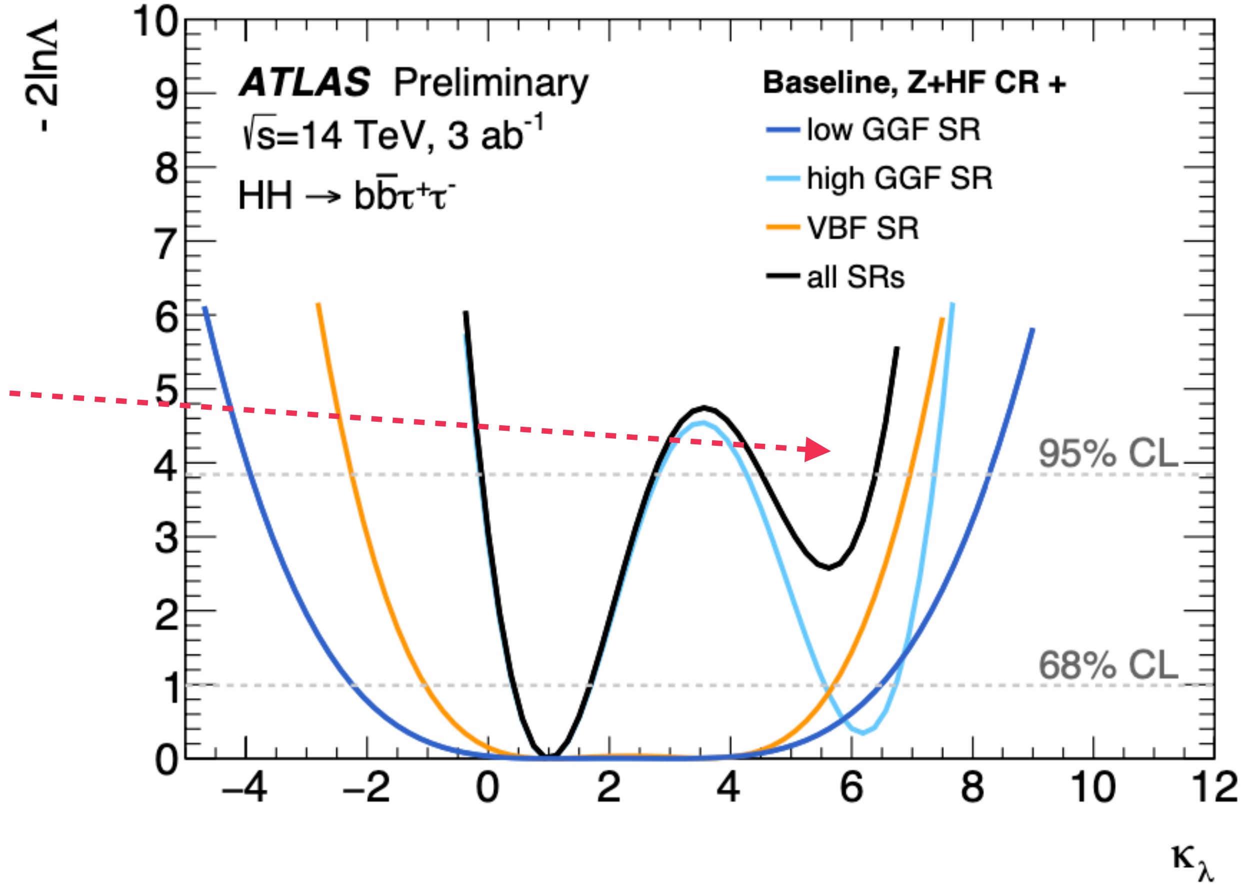
Extrapolation of the constraining κλ

[ATL-PHYS-PUB-2024-016]

- 95% CI for κ_λ assuming SM (κ_λ = 1)



Baseline



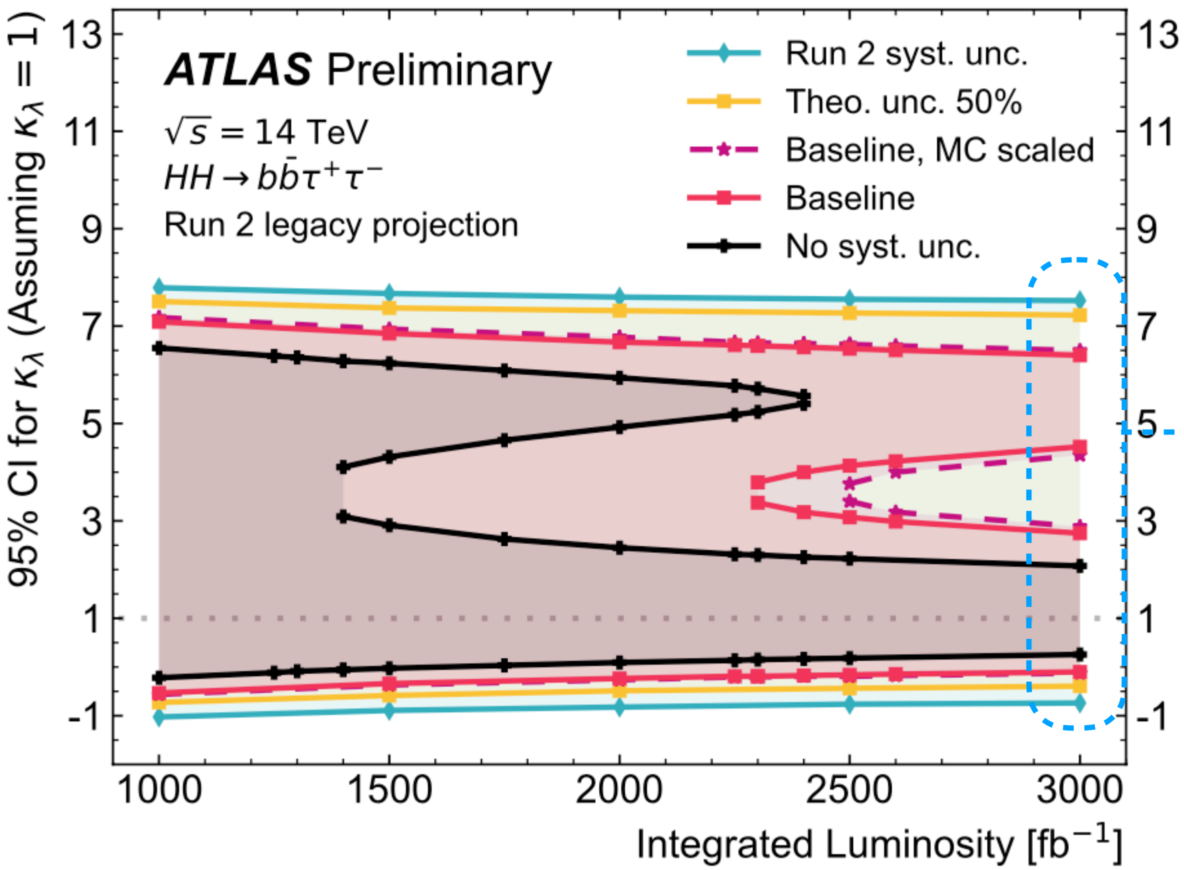
- The new ggF low-mHH and VBF signal regions partially resolve the likelihood degeneracy as a function of κ_λ

  In Baseline The 2nd minimum can be distinguished clearly
  In No syst. It can be excluded ~@ 2500 fb^{-1}

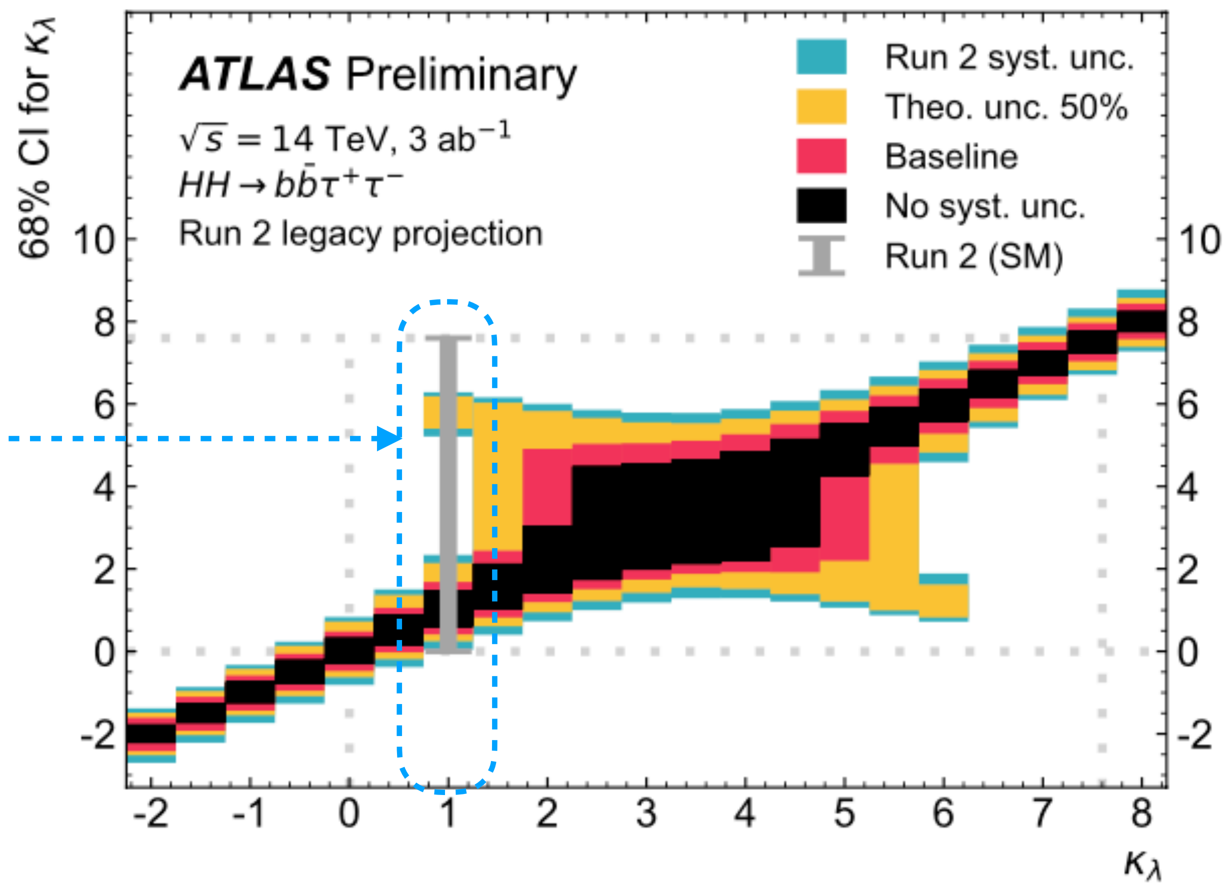
Non-SM scenario

[ATL-PHYS-PUB-2024-016]

- 95% CI for κ_λ assuming SM



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

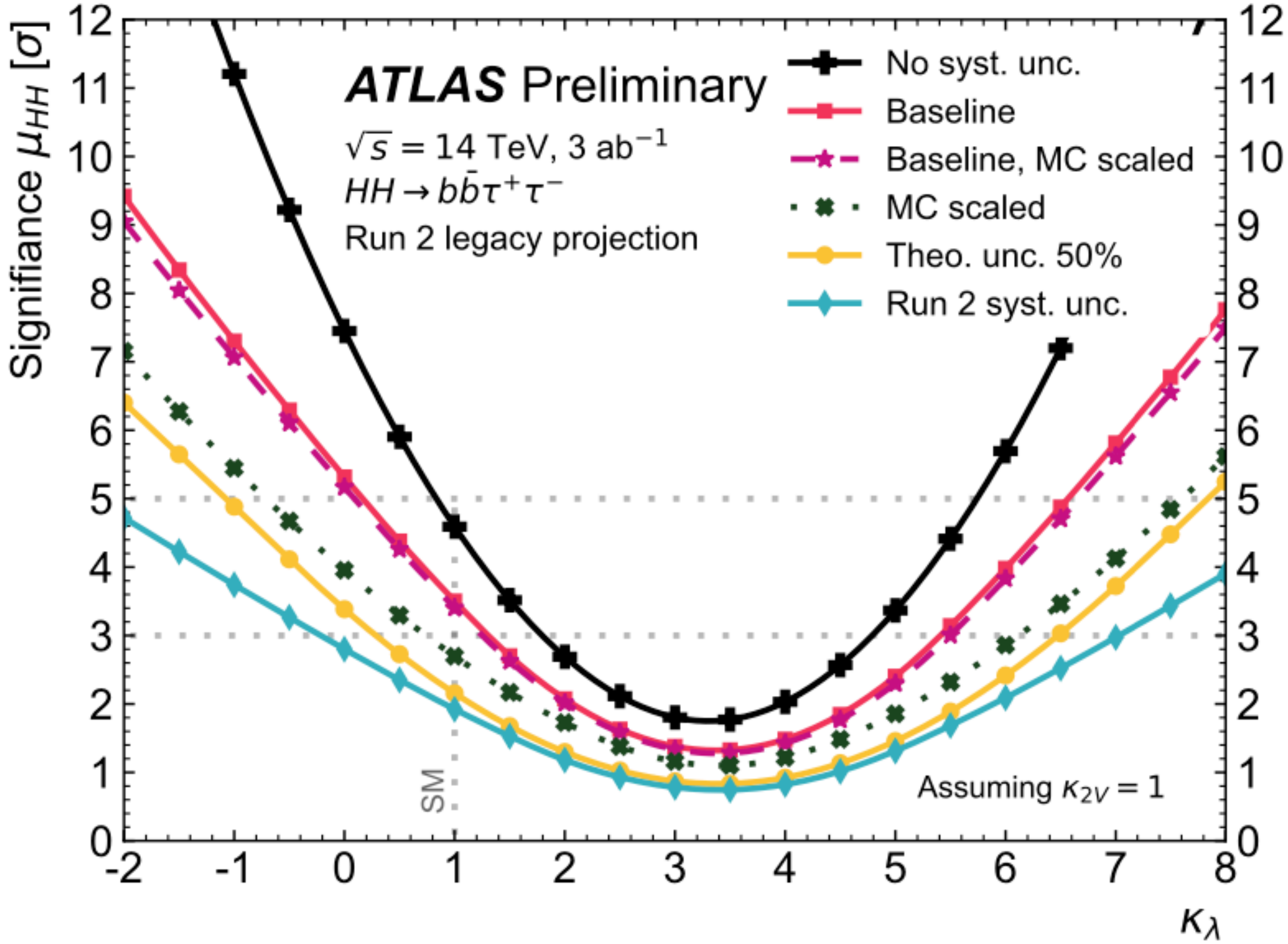


- How much we can constrain largely depends on true κ_λ value

Possibility of observing BSM κ_λ

[ATL-PHYS-PUB-2024-016]

- Expected significance of observing HH, assuming various κ_λ @ 3000 fb^{-1}



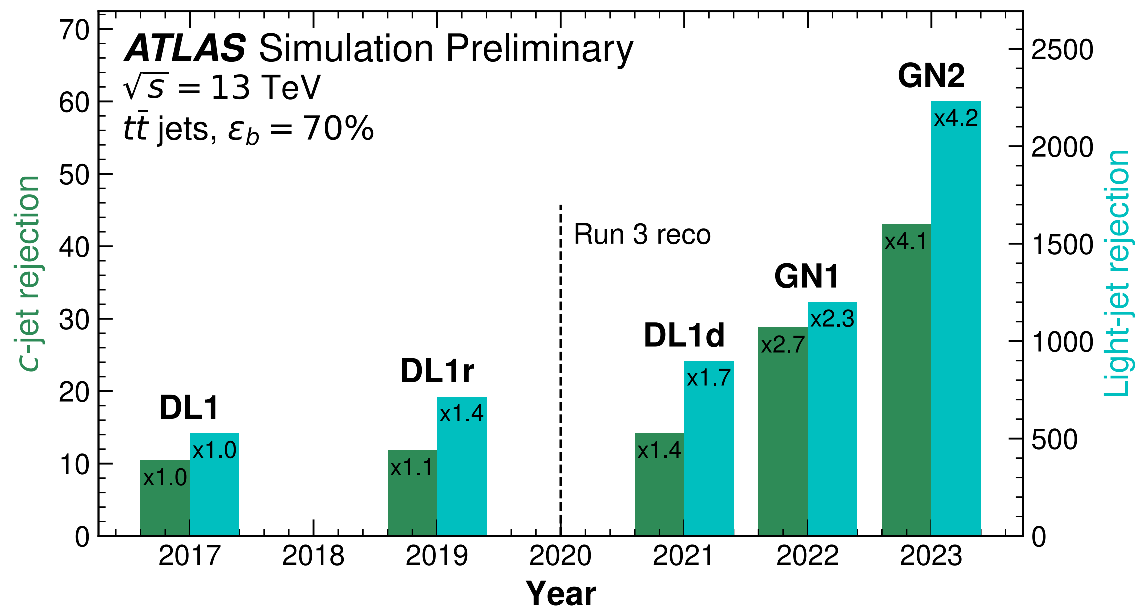
- Small and very large κ_λ can be observed but significantly reduced sensitivity around $\kappa_\lambda \approx 3.5 \pm 1$

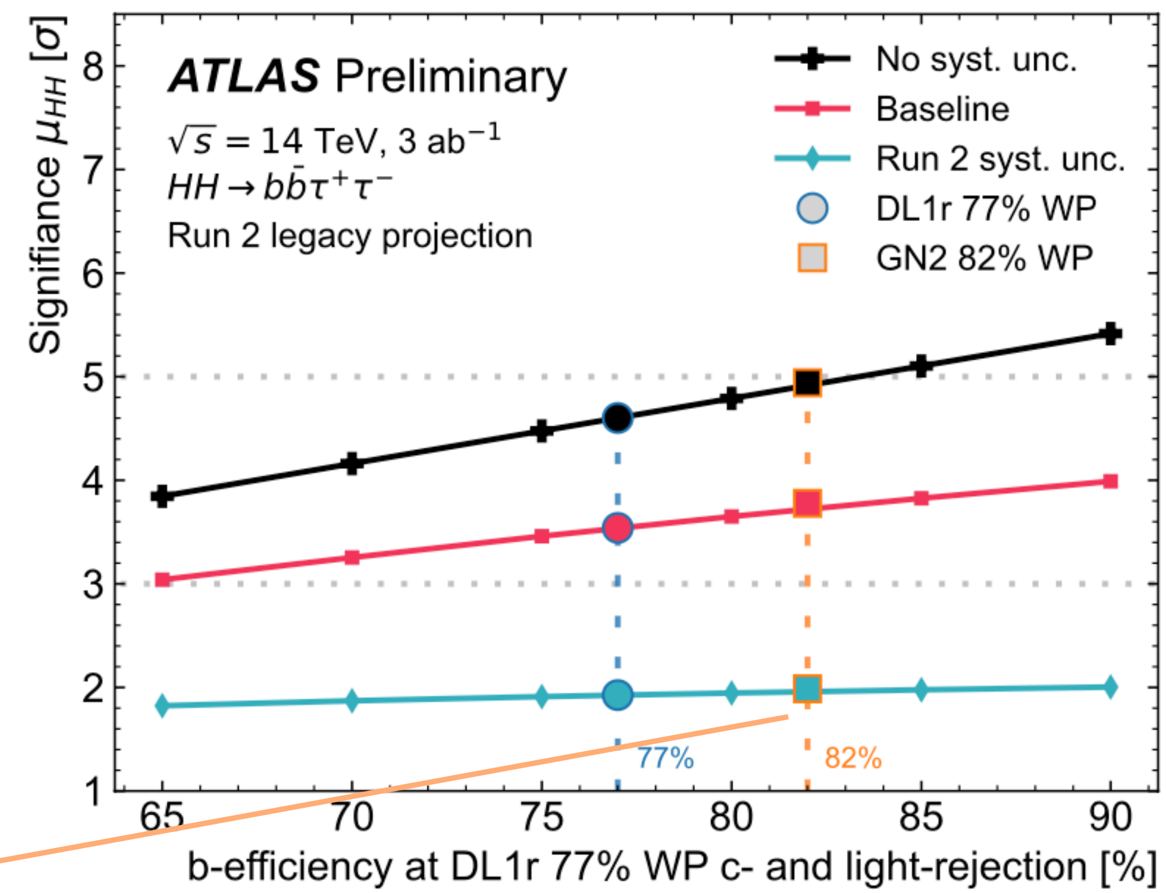
Hadronic-identification improvements

[ATL-PHYS-PUB-2024-016]

- The sensitivity can be improved based on the improvements of the algorithms used in the analysis

ATLAS-FTAG-2023-01

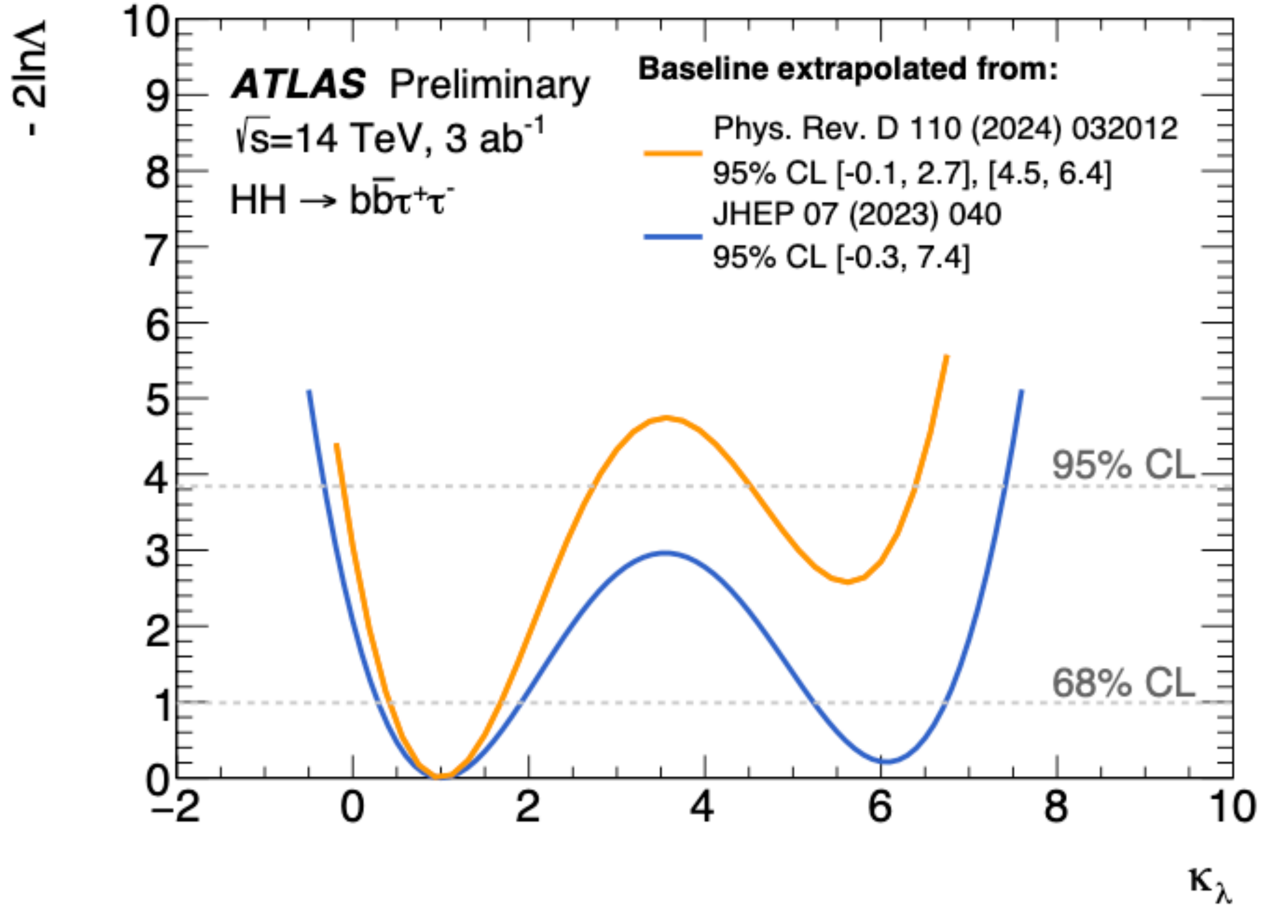




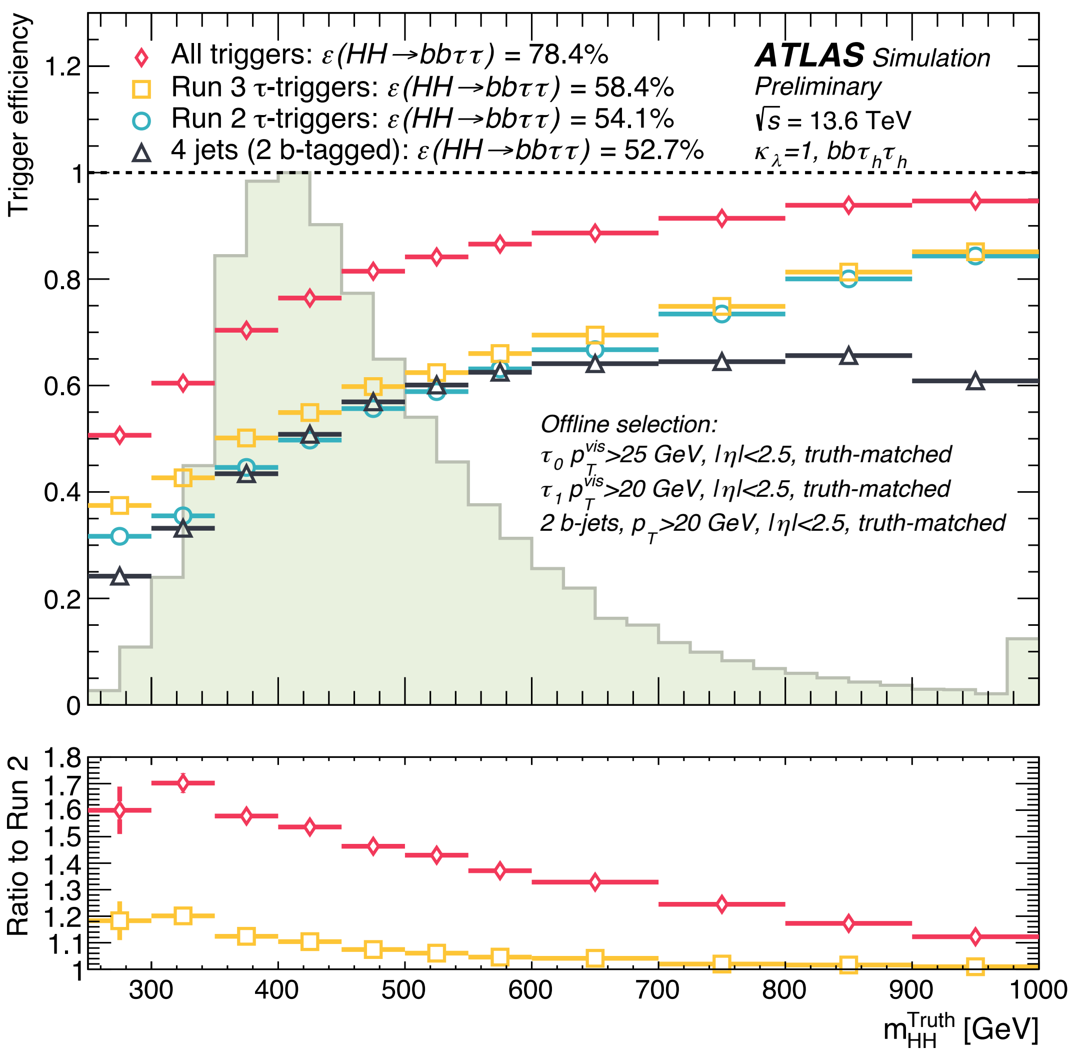
- GN2 82% WP (now available) in Baseline scenario gains O(10%) improvement
  6-7% improvement in efficiency per b-jet → ~0.3 σ sensitivity gain
- Improvement of the hadronic signature tagging greatly benefits us.
  Tau-tagging is also being studied

Comparison to the earlier extrapolation and new triggers

[ATL-PHYS-PUB-2024-016]



[TauTriggerPubResults]

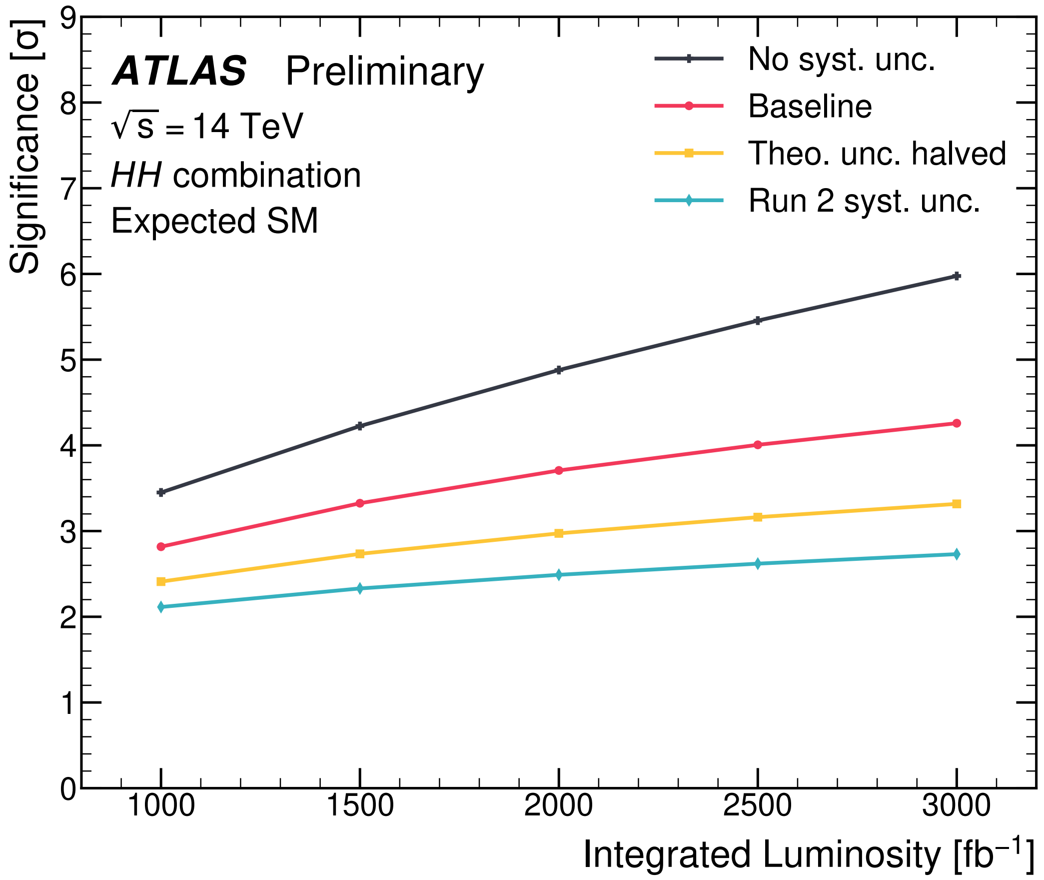


- In the same Baseline scenario, the extrapolation from the Legacy Run2 analysis halved the uncertainty in κ_λ wrt the extrapolations from the earlier Run2 analysis
  → Improvement by the analysis

- Also expect improvement from the triggers in Run3
  (not included in the extrapolation)

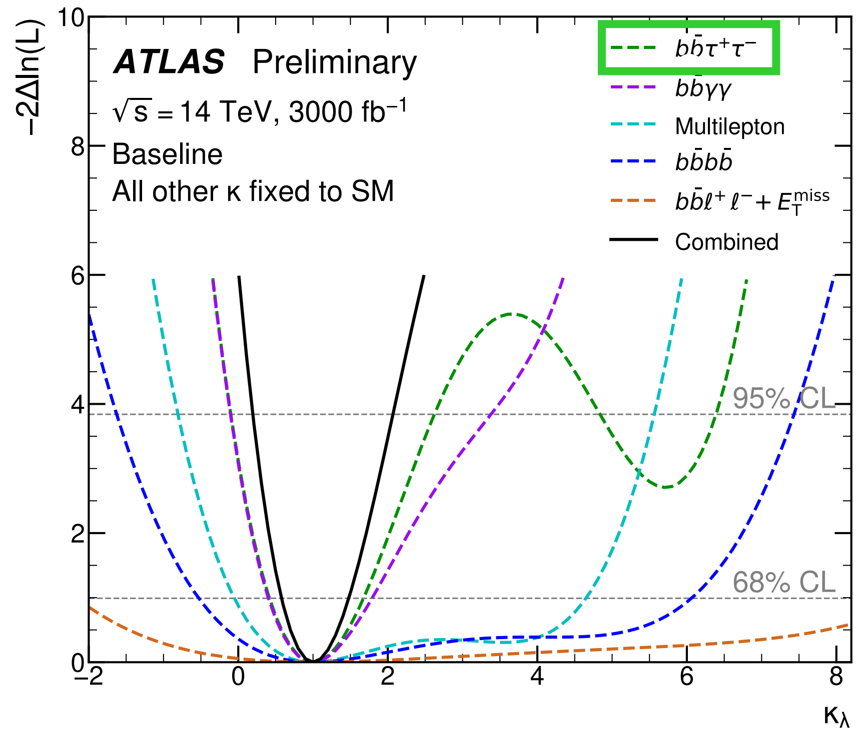
HH combination extrapolation

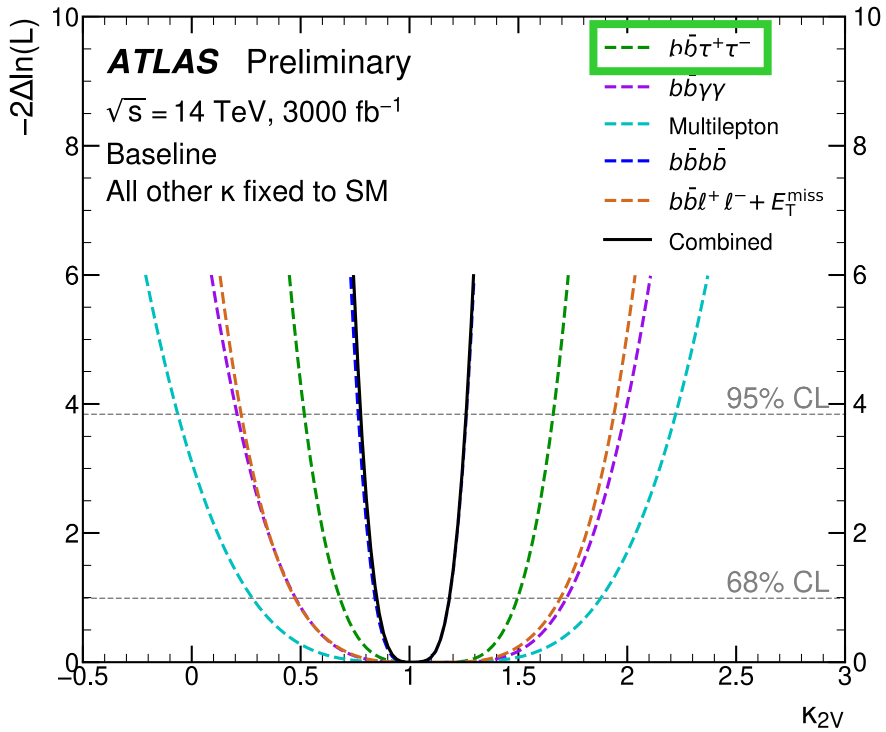
[ATL-PHYS-PUB-2025-006]



Extrapolation with the combination of the 5 Run2 analyses

- In Baseline scenario expect 4.3 σ excess





Summary

- ATLAS HH searches are ongoing to prove the Higgs potential shape
  The Run2 bbττ analysis showed no excess but provided the strongest HH constraints so far

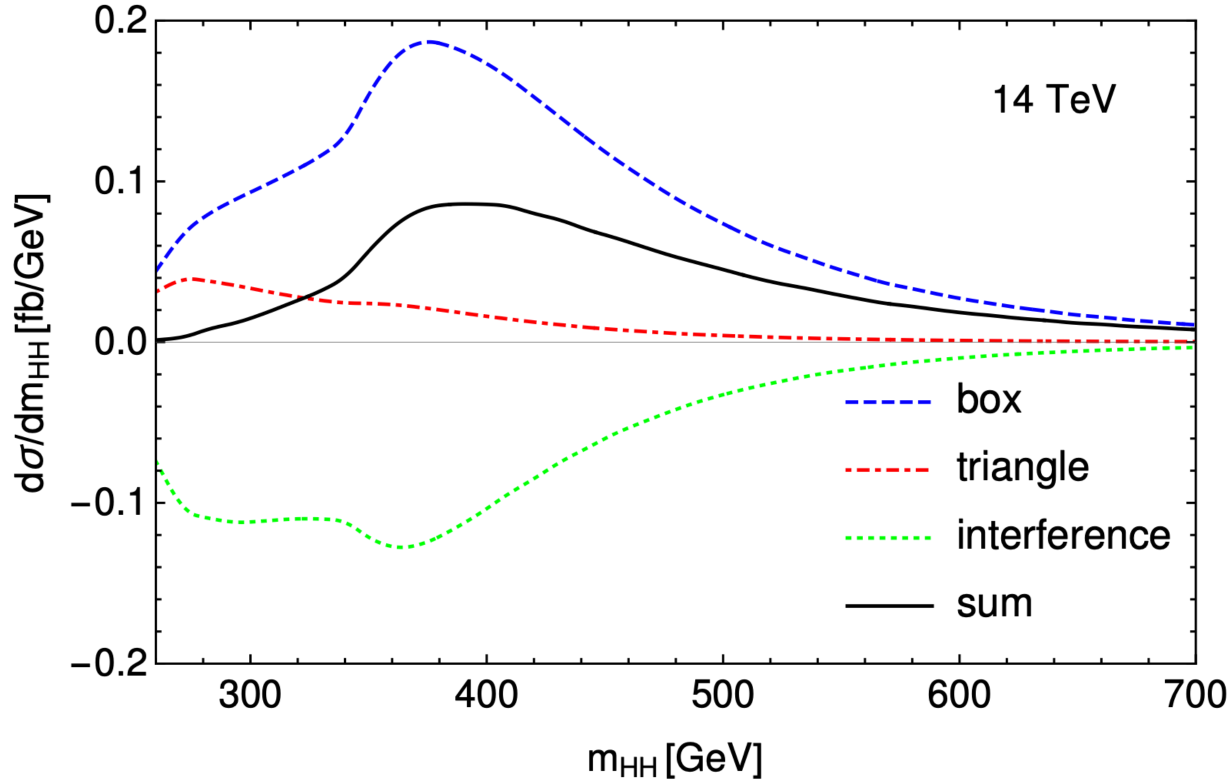
- HL-LHC projection studies are carried out based on the Run2 analyses
  Observation of the SM-like HH production is in reach at the HL-LHC

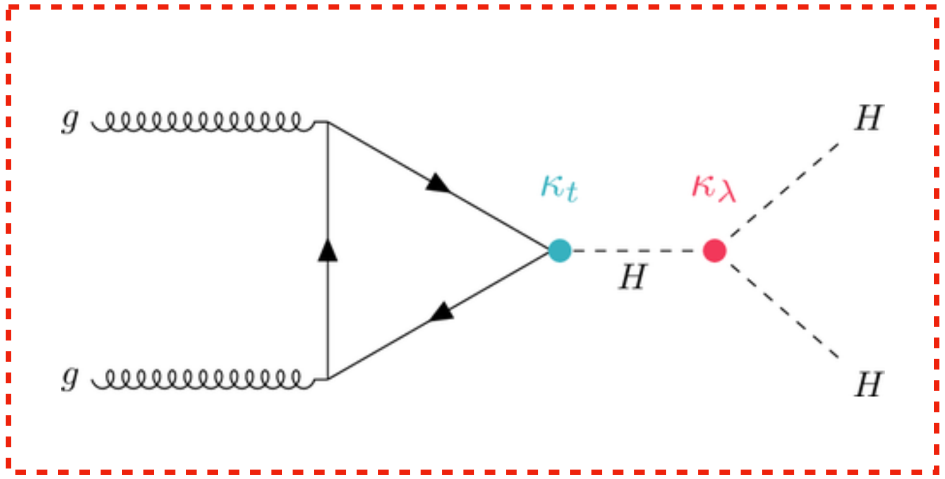
- The extrapolation strategy here does not take into account expected improvements in new triggers, better object reconstruction/ID, novel analysis strategy
  → This study is likely conservative and we can expect more from the HL-LHC dataset

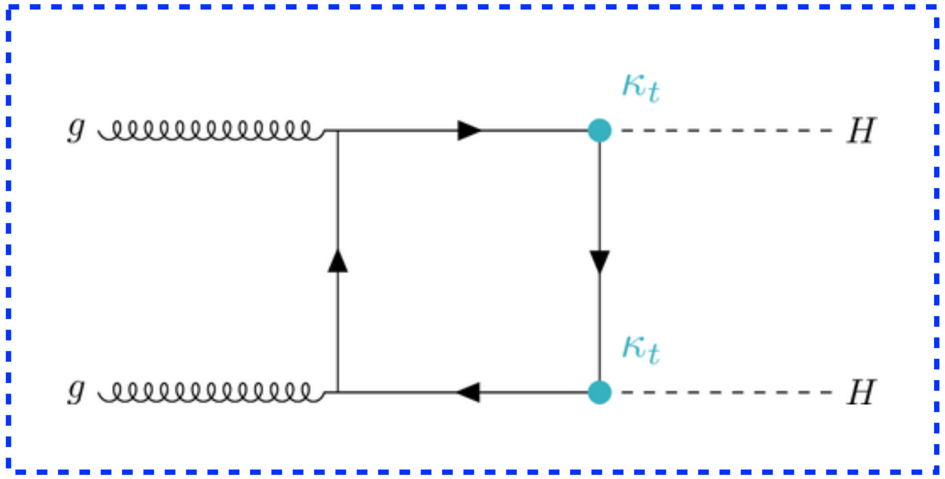
Backup

ggF HH production

LHCHXSWG-2019-005







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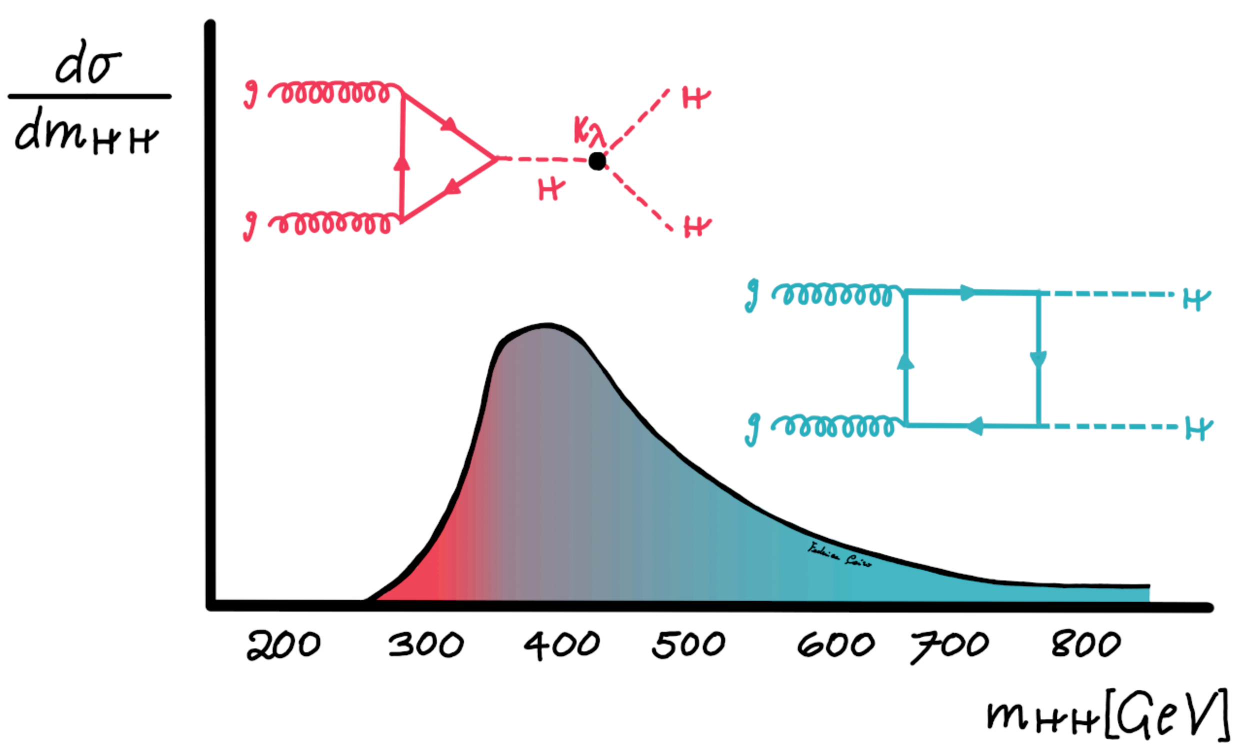
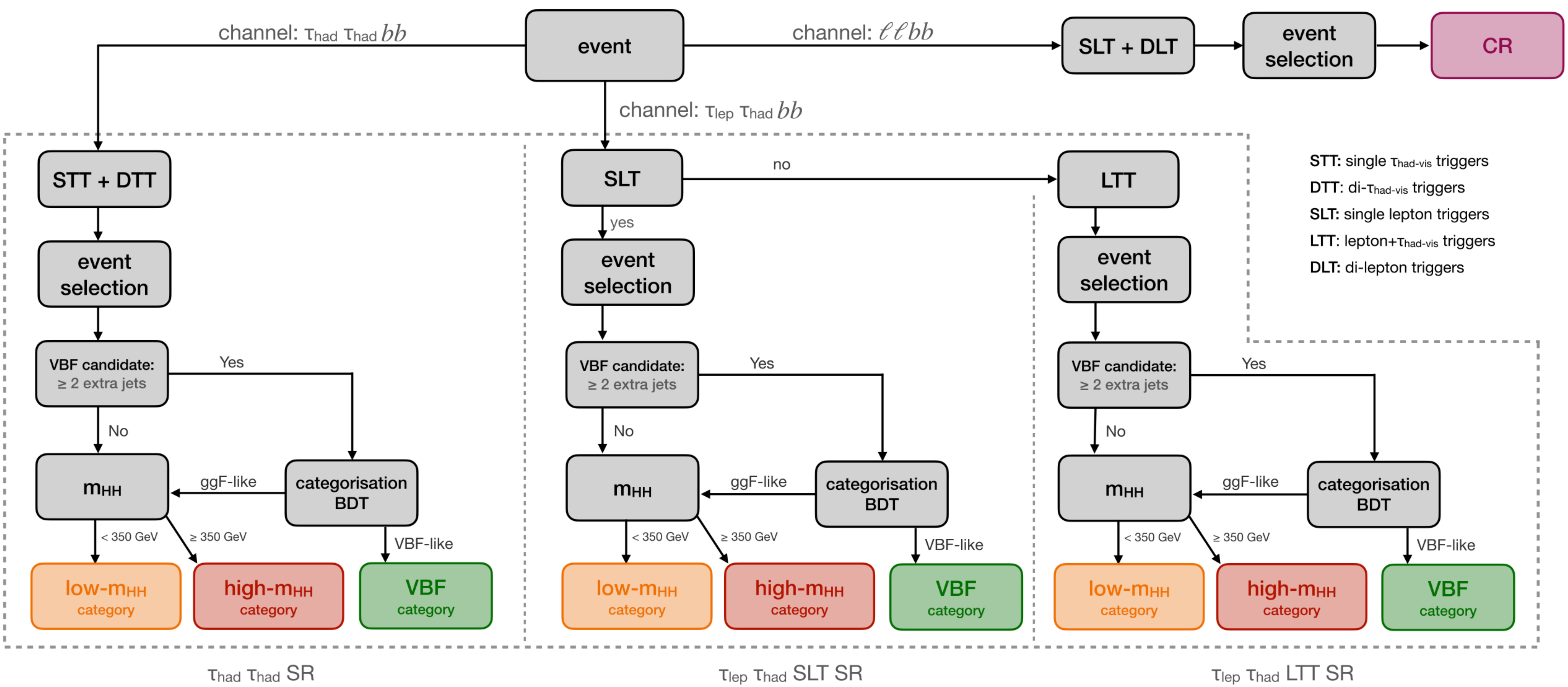


Run2 legacy analysis event categorization

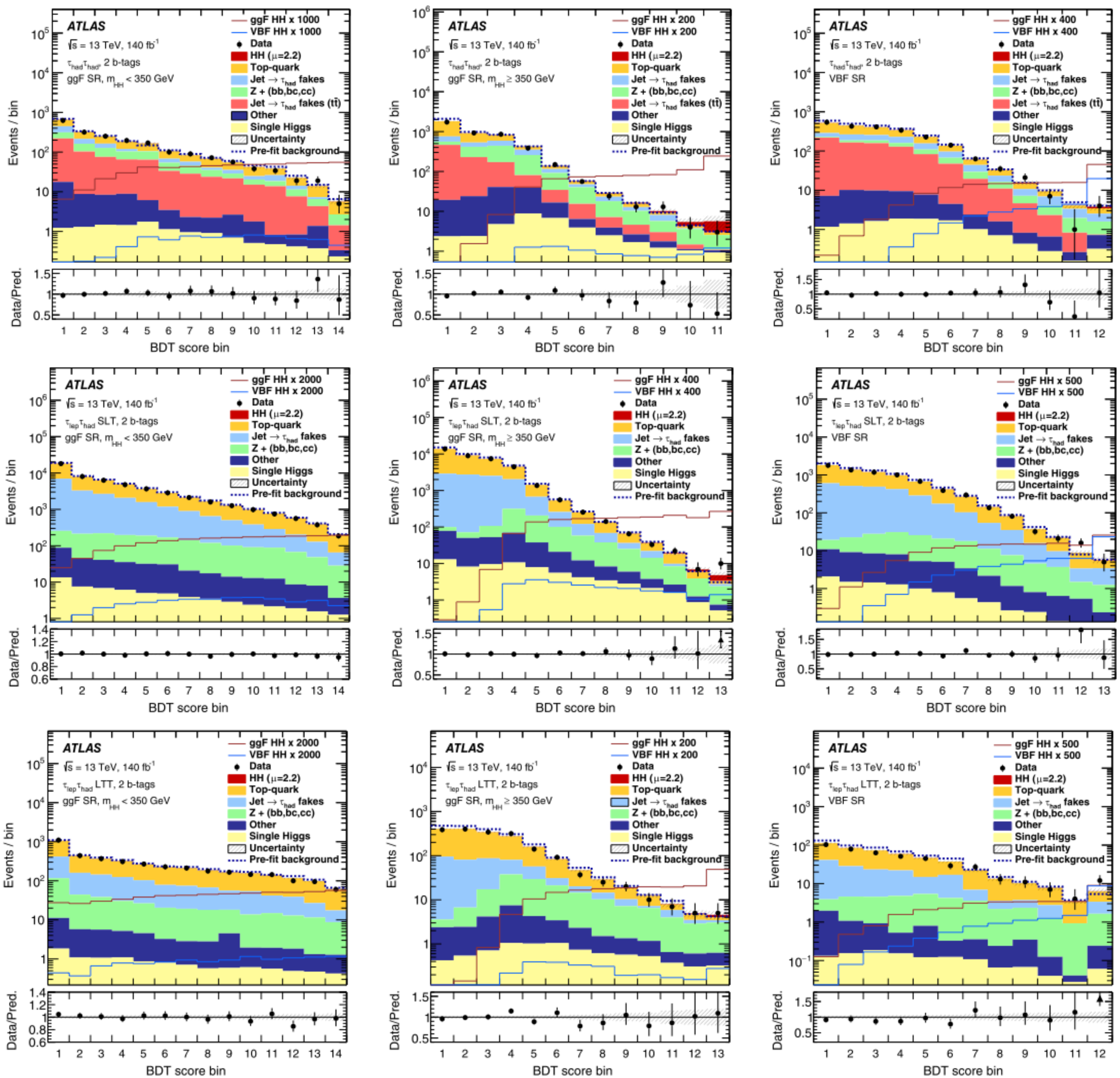
[Phys. Rev. D 110 (2024) 032012]

- Updates wrt last round:
  - New event categorization
  - MVA discriminants improved
  - Improvement in modeling, with new samples



Run2 legacy analysis post-fit plots

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

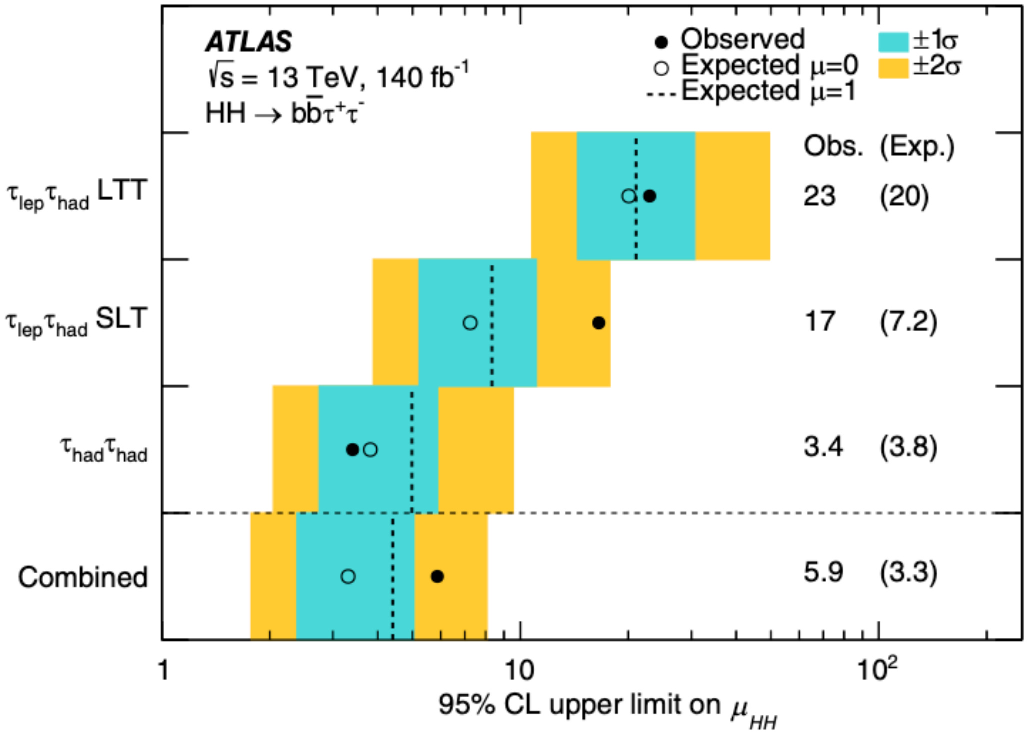


- Main bkgs
  - ttbar, Z + HF; rely on MC simulations
  - Fake-τ backgrounds ; data-driven techniques
- BDT inputs

Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{jj}^{VBF}	✓	✓	✓
$\Delta\eta_{jj}^{VBF}$	✓	✓	✓
VBF $\eta_0 \times \eta_1$	✓	✓	
$\Delta\phi_{jj}^{VBF}$	✓		
ΔR_{jj}^{VBF}		✓	✓
$\Delta R_{\tau\tau}$	✓		
m_{HH}	✓		
f_2^a	✓		
C^a		✓	✓
m_{Eff}^a		✓	✓
f_0^c		✓	
f_0^a			✓
h_3^a			✓

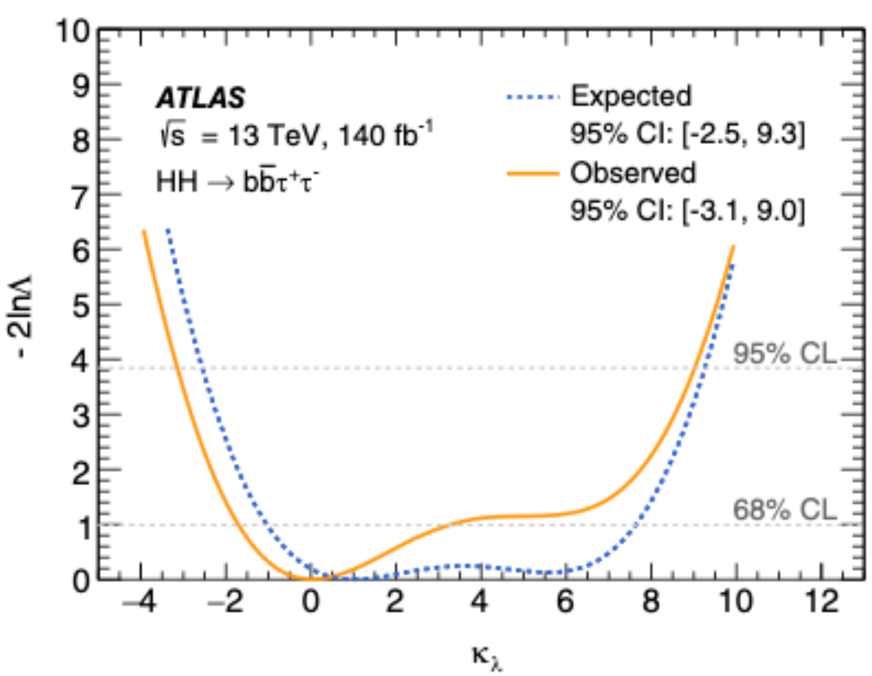
Run2 legacy analysis results

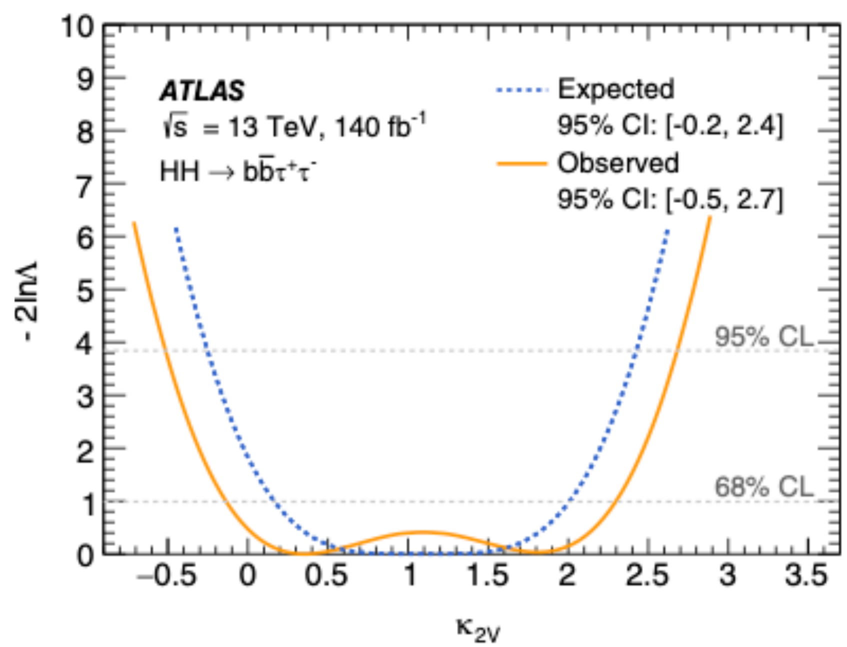
[Phys. Rev. D 110 (2024) 032012]

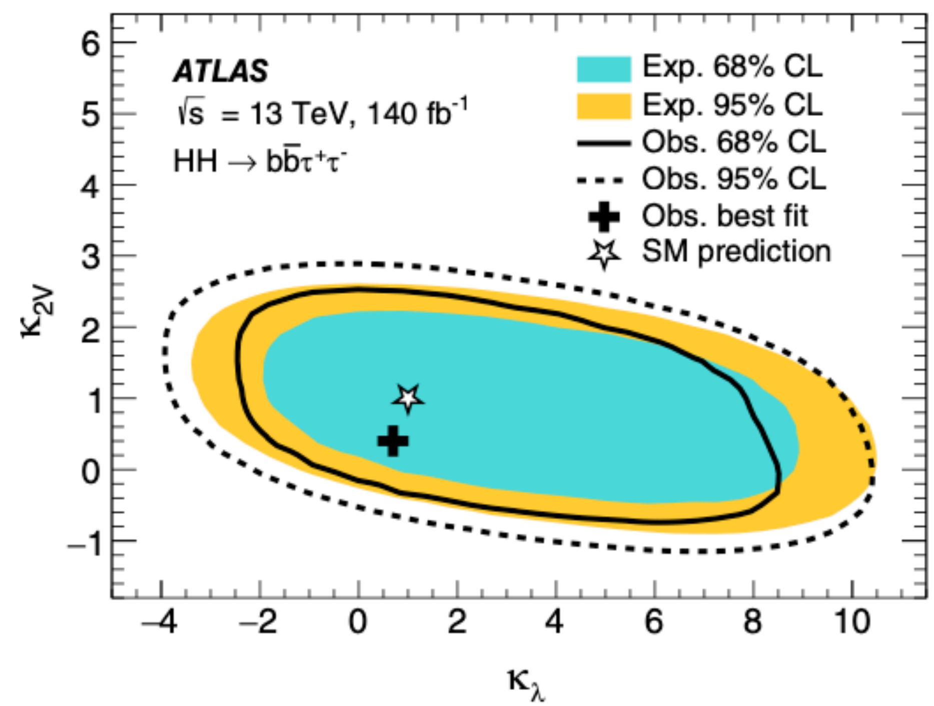


95% CL upper limits

		μ_{HH}	μ_{ggF}	μ_{VBF}	μ_{ggF} ($\mu_{VBF}=1$)	μ_{VBF} ($\mu_{ggF}=1$)
$\tau_{had}\tau_{had}$	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}



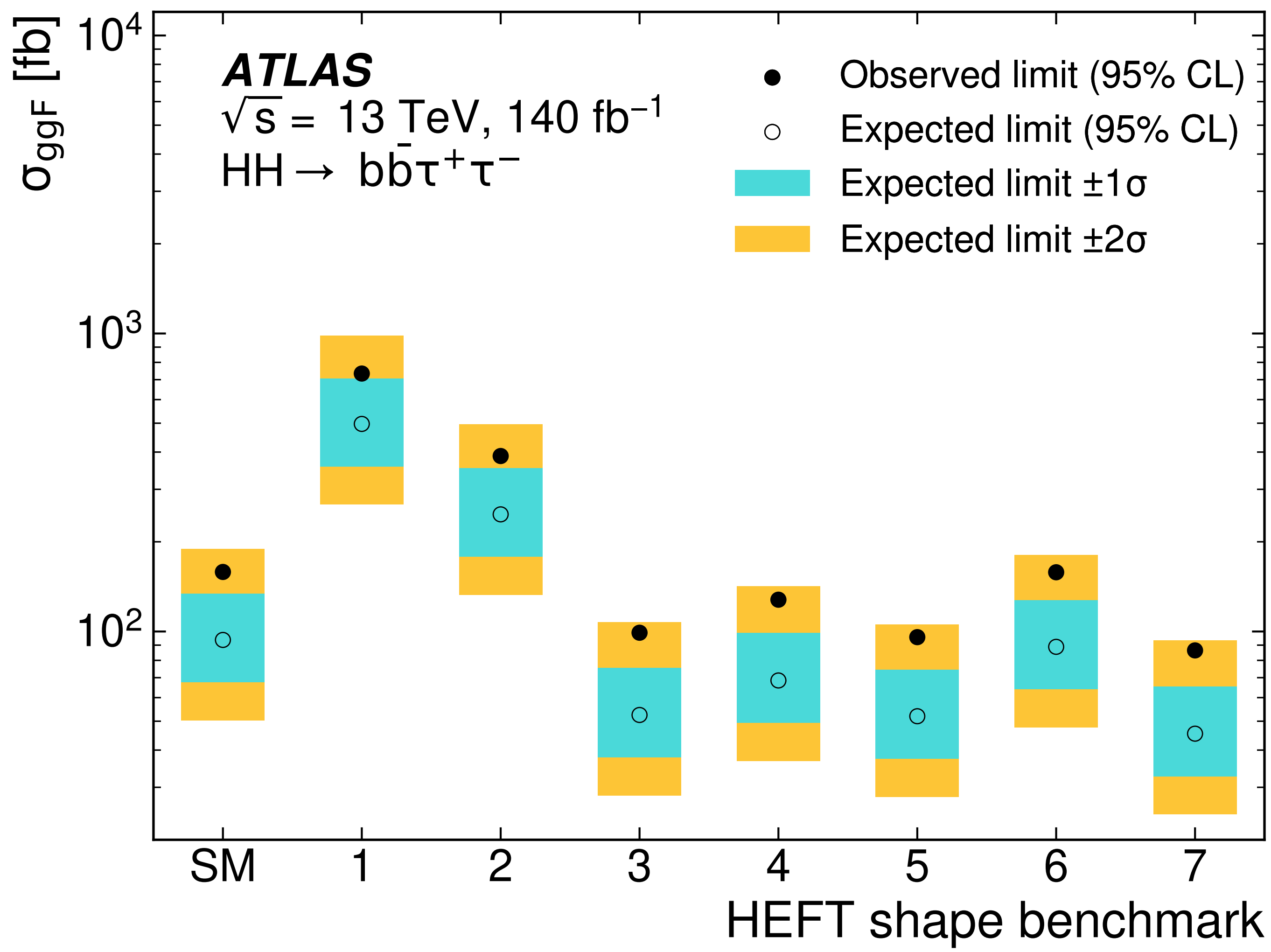




Run2 legacy analysis EFT interpretation

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

- Interpretation of the results into Higgs effective field theory (HEFT)



Extrapolation procedure to HL-LHC

[ATL-PHYS-PUB-2024-016]

Scale the final BDT discriminant for all κ signals and backgrounds

- **For Luminosity**
  Apply scale factor of L'/L (L' : 1000 ~ 3000 fb^{-1}, L : 140 fb^{-1})
  Assumes the performance of the upgraded ATLAS detector will perform as current
- Apply scale factor to fix the Z+HF normalization deviation between MC and data
- **For Collision Energy**
  Apply process dependent scale factor to take the cross-section change of
  $\sqrt{s}$ = 13 TeV to $\sqrt{s}$ = 14 TeV into account

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

Extrapolation procedure to HL-LHC

[ATL-PHYS-PUB-2024-016]

- **Binning**
  Binning has not been changed from Run2 → conservative extrapolation

- **For systematics uncerterties**
  Apply several scenarios

In Baseline scenario

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

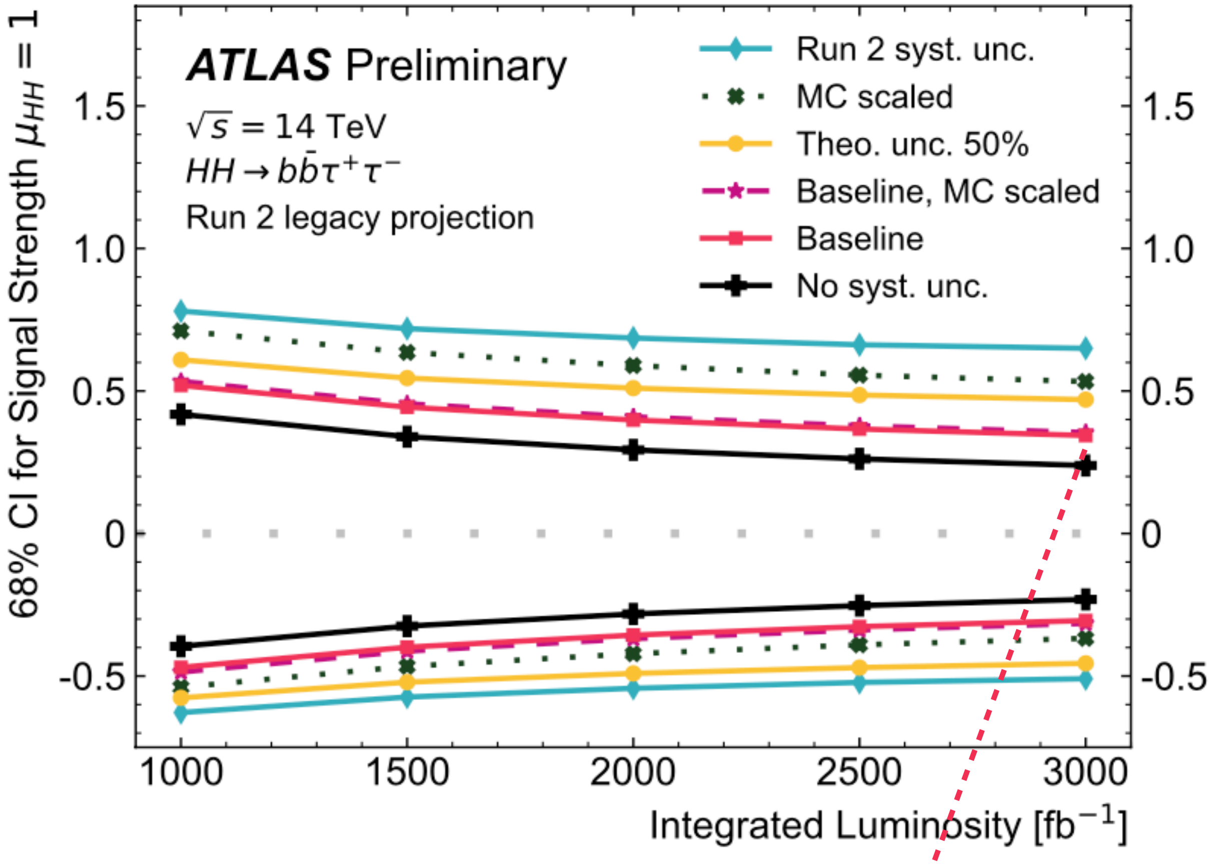
This scenario follows the latest recommendations which were use for Snowmass 2022

Assume lumi. unc. similar to Run2

Theoretical unc. halved

Extrapolated uncertainties on μ_{HH}

[ATL-PHYS-PUB-2024-016]



$\Delta\mu \approx 0.3$

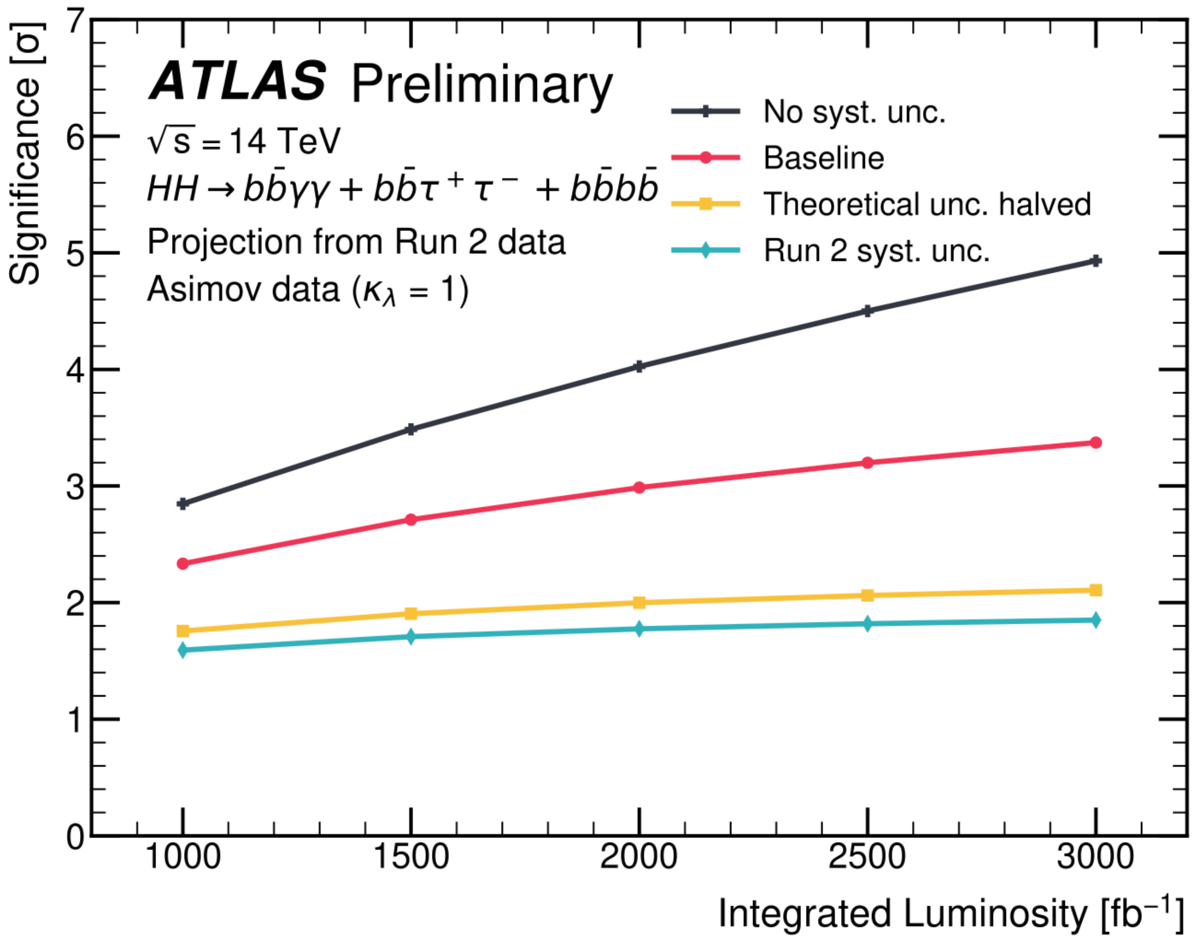
Signal & bkg modelling limits us the most

@ 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 (stat ≈ syst)	+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
$E_{\text{T}}^{\text{miss}}$	+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 boson	+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

The previous extrapolation to the HL-LHC

[ATL-PHYS-PUB-2022-005]



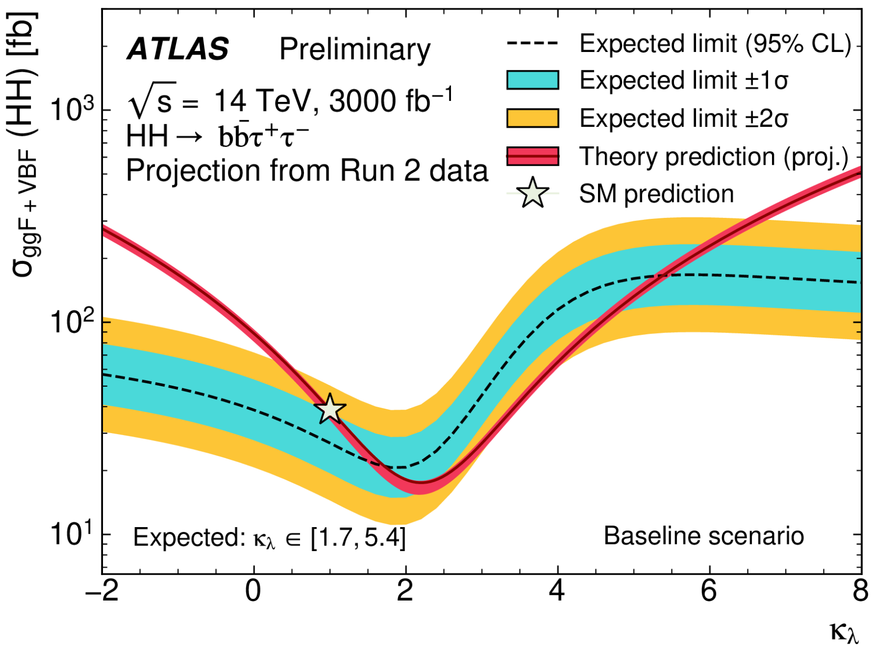
- Extrapolation from the Run2 126-139 fb^{-1}
  Combined bbbb (126 fb^{-1}) + bb$\tau\tau$ (139 fb^{-1} , old) + bb$\gamma\gamma$ (139 fb^{-1}) results

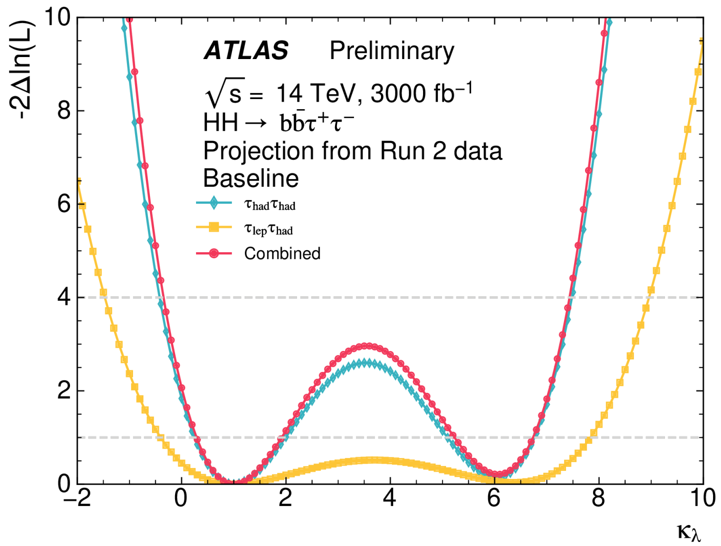
- In Baseline scenario expect 3.4 σ excess

Double minimum of the κ_λ

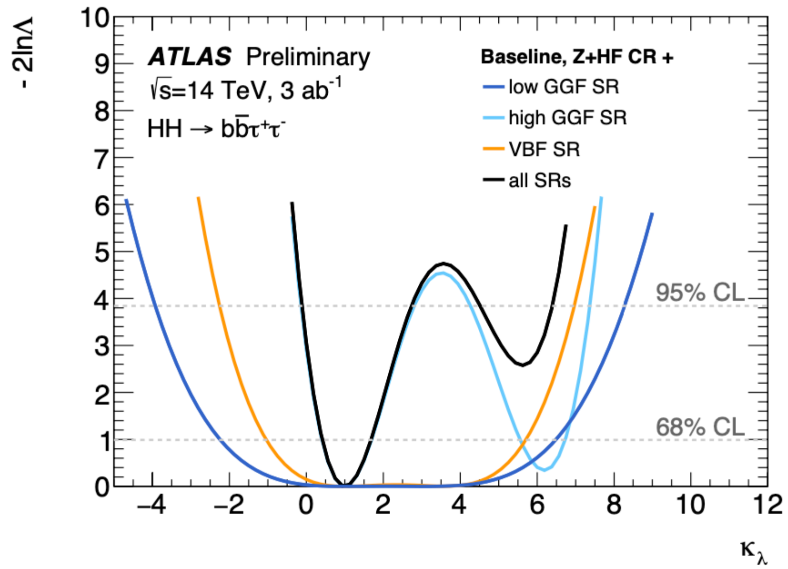
[ATL-PHYS-PUB-2021-044] [Phys. Rev. D 110 (2024) 032012]

[ATL-PHYS-PUB-2021-044]



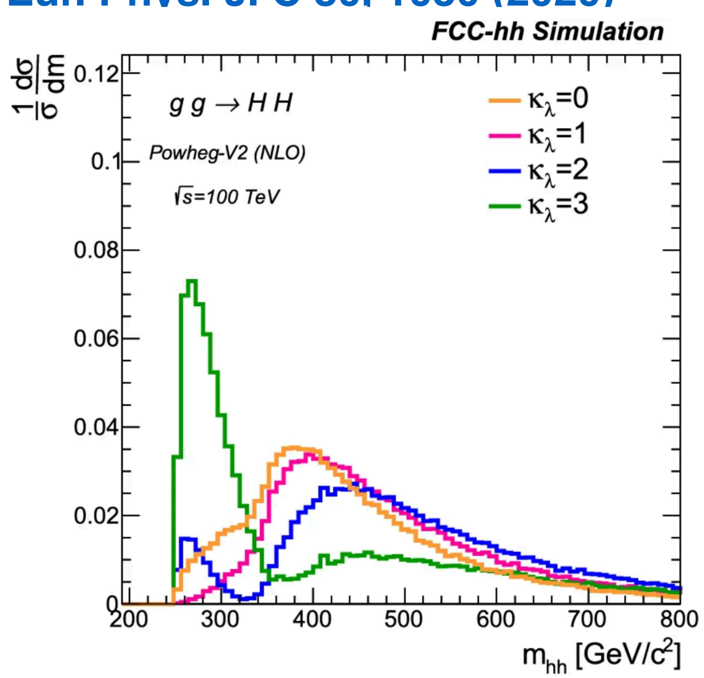


[Phys. Rev. D 110 (2024) 032012]



- There are 2 κ_λ values for a given cross section
- In the extrapolation from the previous Run2 bb$\tau\tau$ analysis there were no low-/high-ggF regions and double minimum of κ_λ was clear

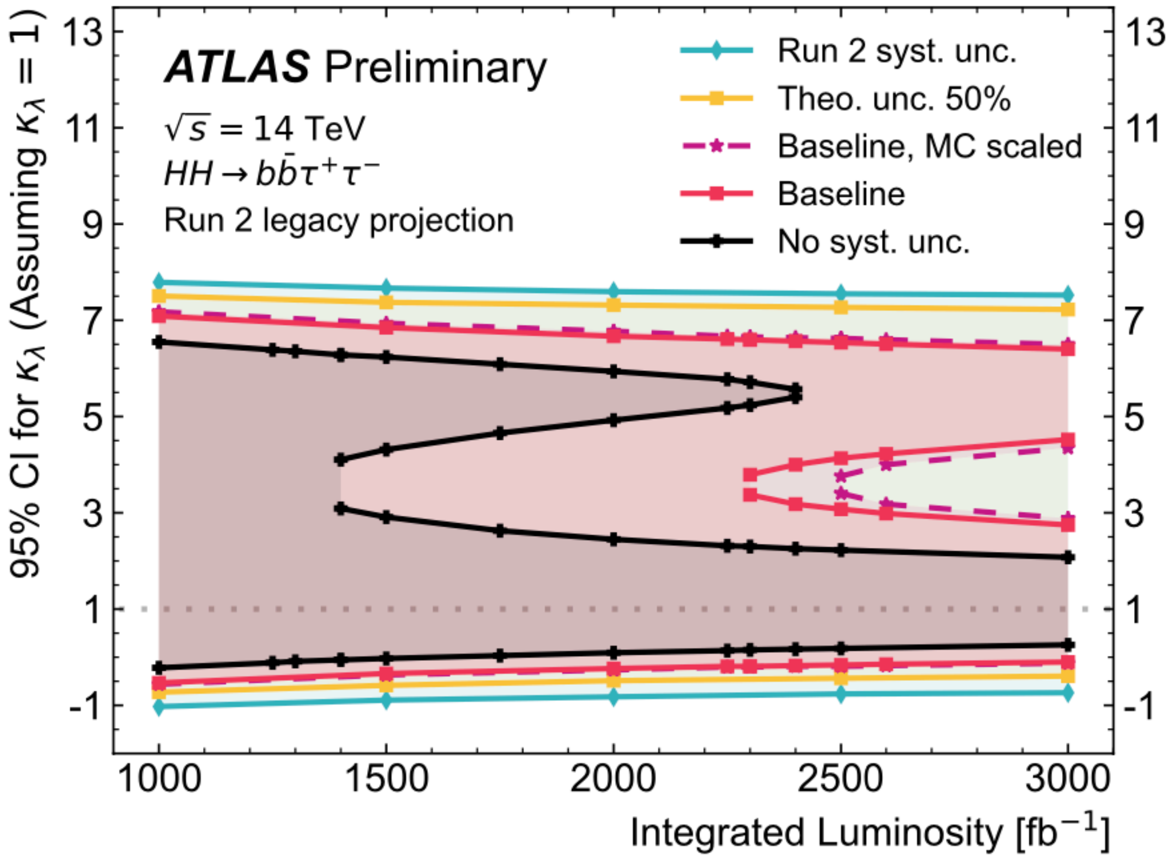
Eur. Phys. J. C 80, 1030 (2020)

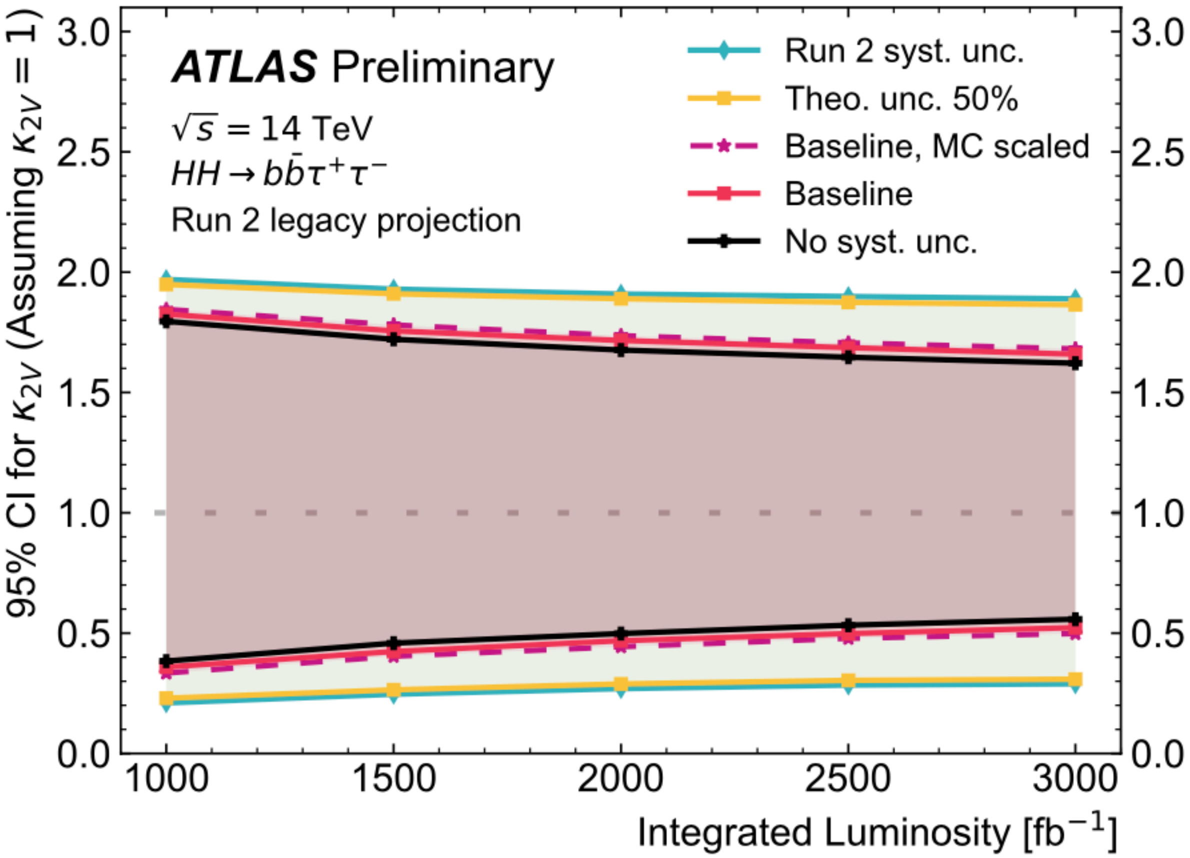


- Adding low-/high-ggF allow to see the feature of the shape of the mHH and help excluding the second minimum

95% CI for κ_λ and κ_{2V}

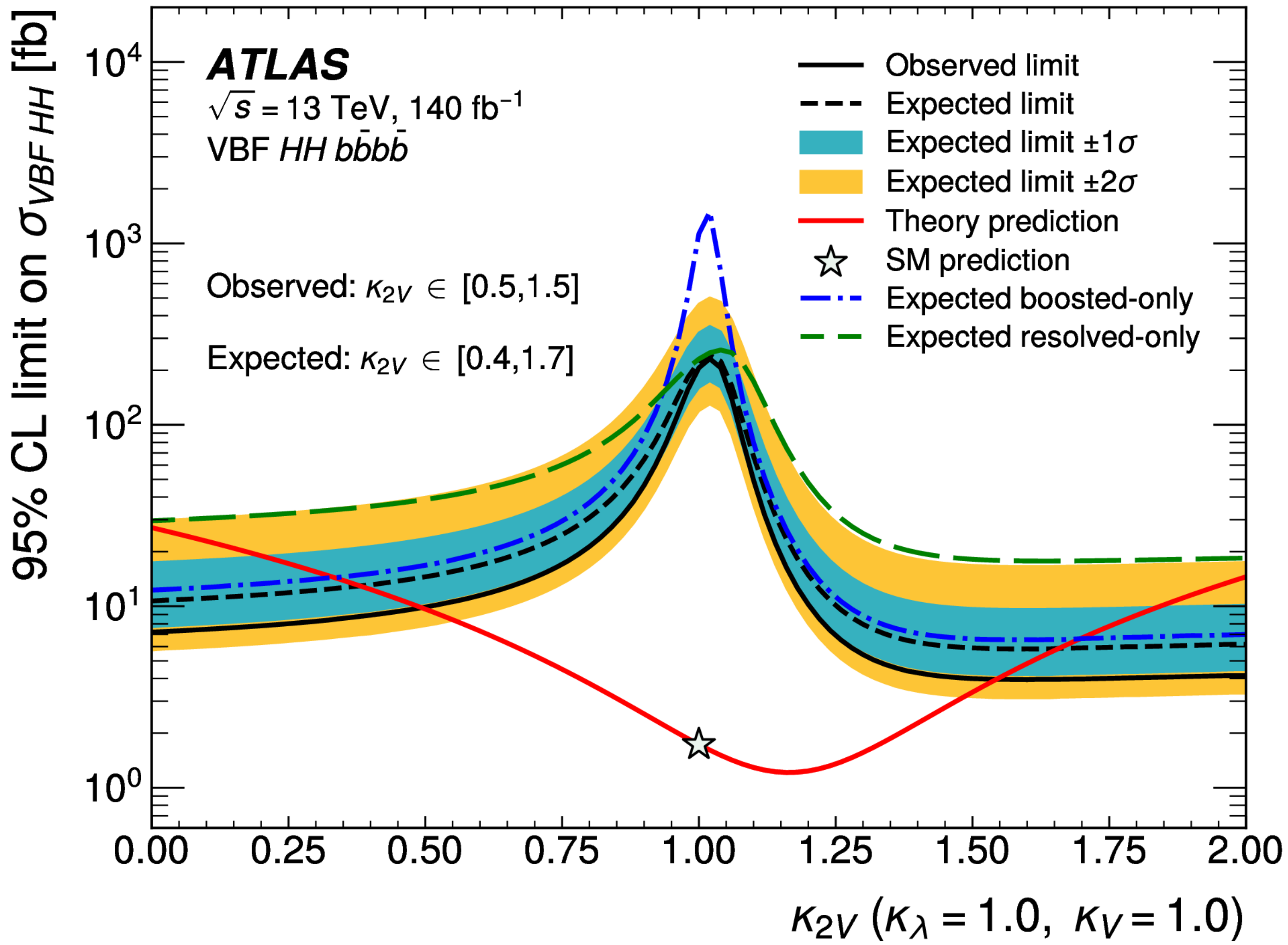
[ATL-PHYS-PUB-2024-016]





Constraining κ_{2V}

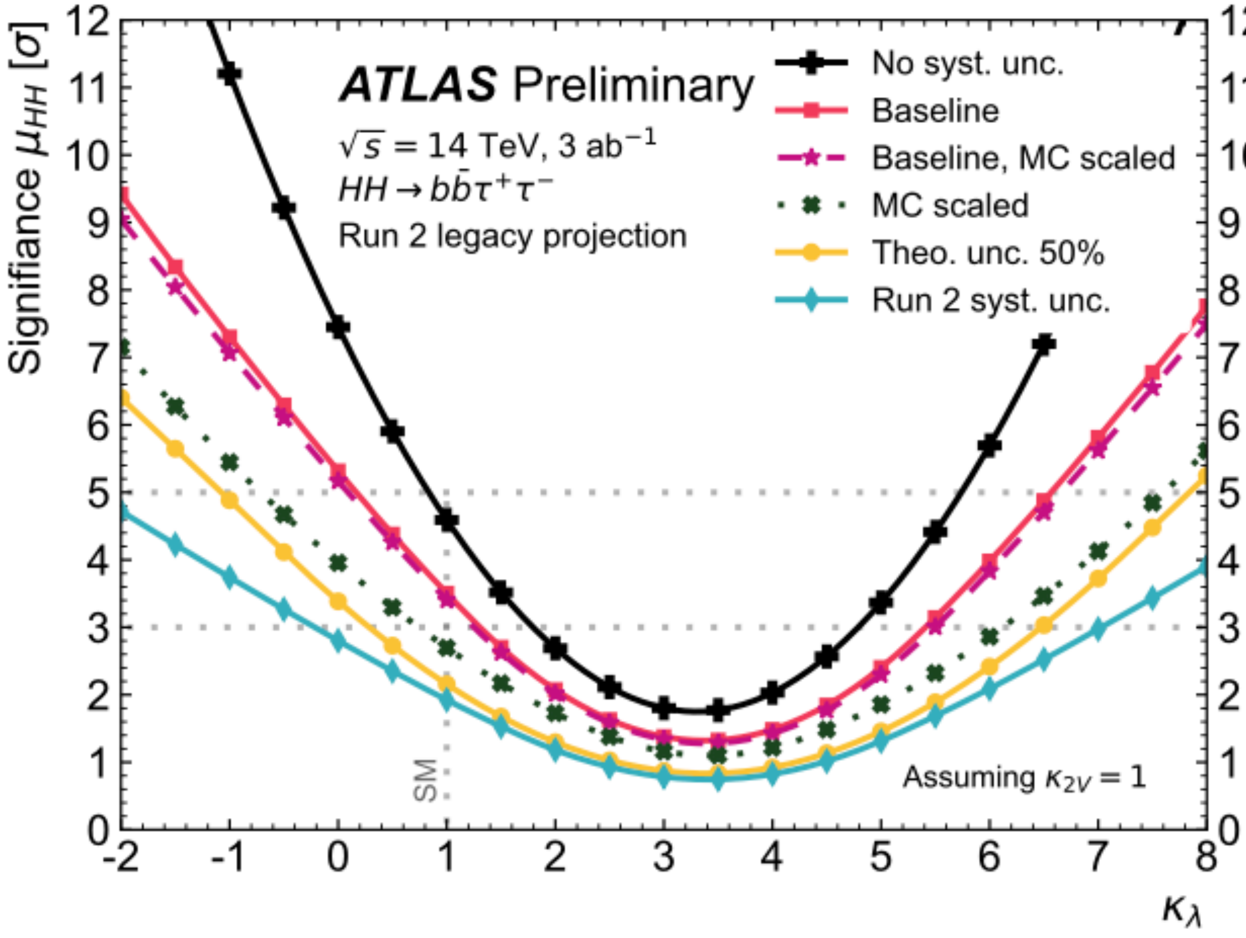
[ATL-PHYS-PUB-2024-016]

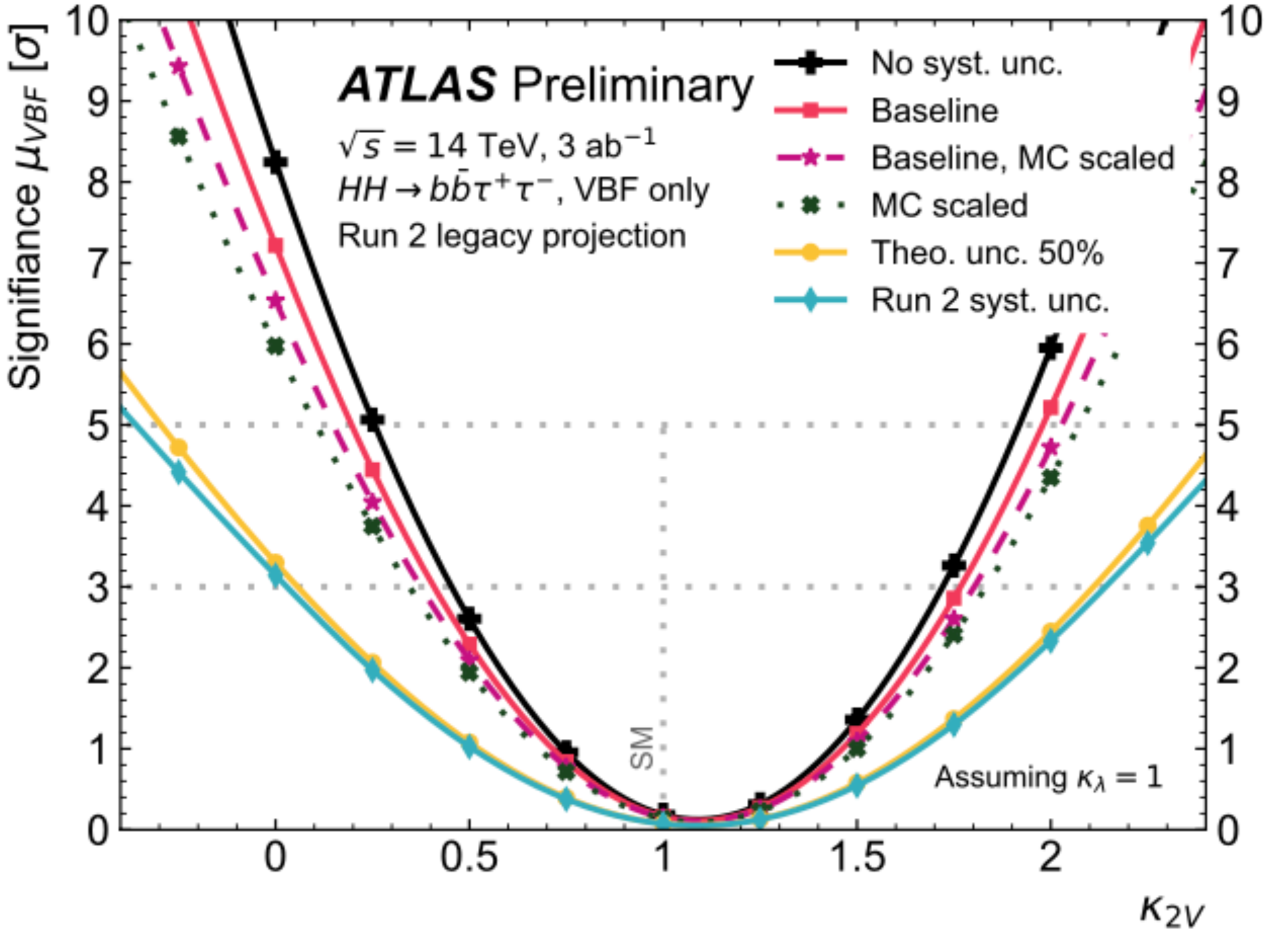


- For constraining κ_{2V} = 1 (SM), Resolved region leads (green) in bbbb channel
  For other κ_{2V} Boosted region leads (blue)
- Now analysis including the Boosted regions are ongoing/evolving in bbbb/bb$\tau\tau$

μ_{HH} significance varying κ values

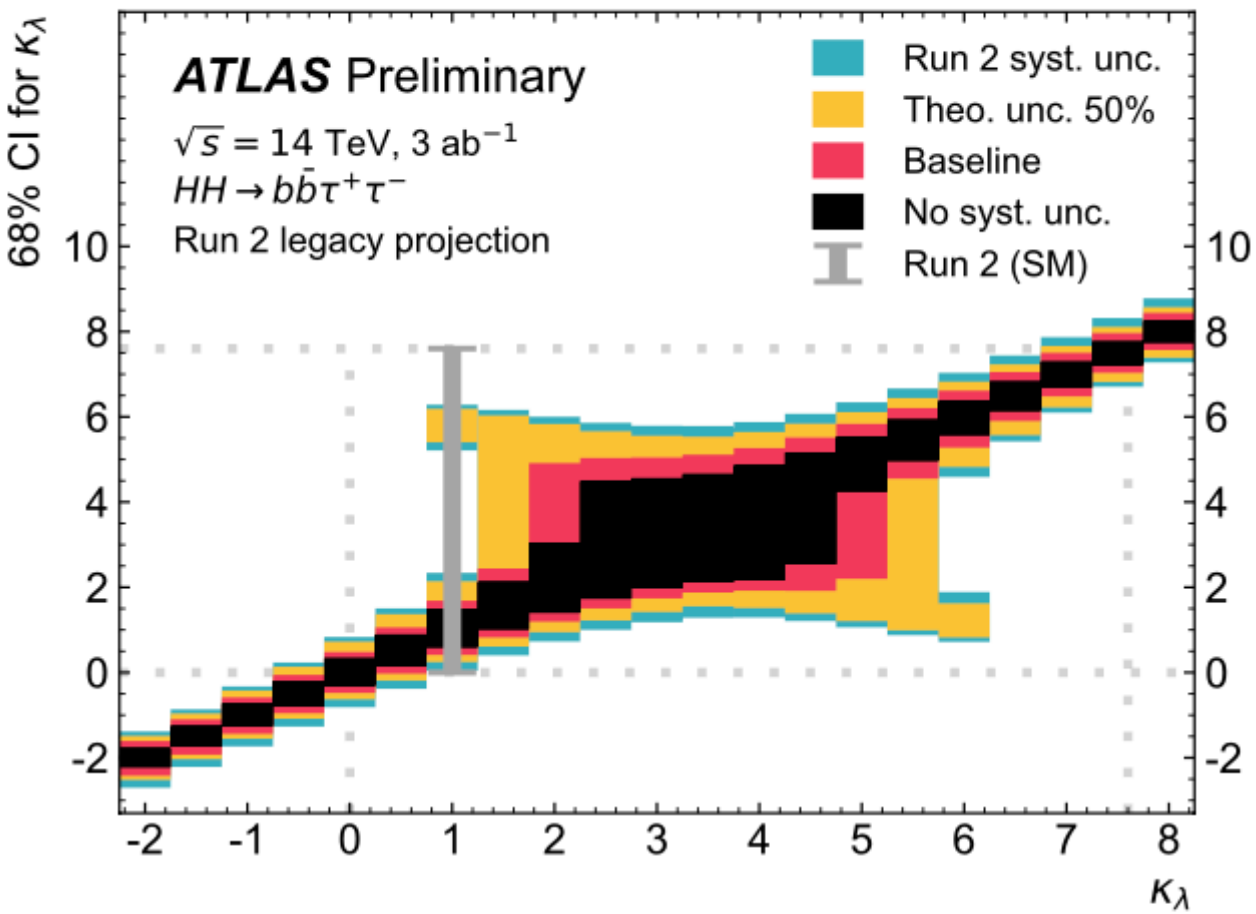
[ATL-PHYS-PUB-2024-016]

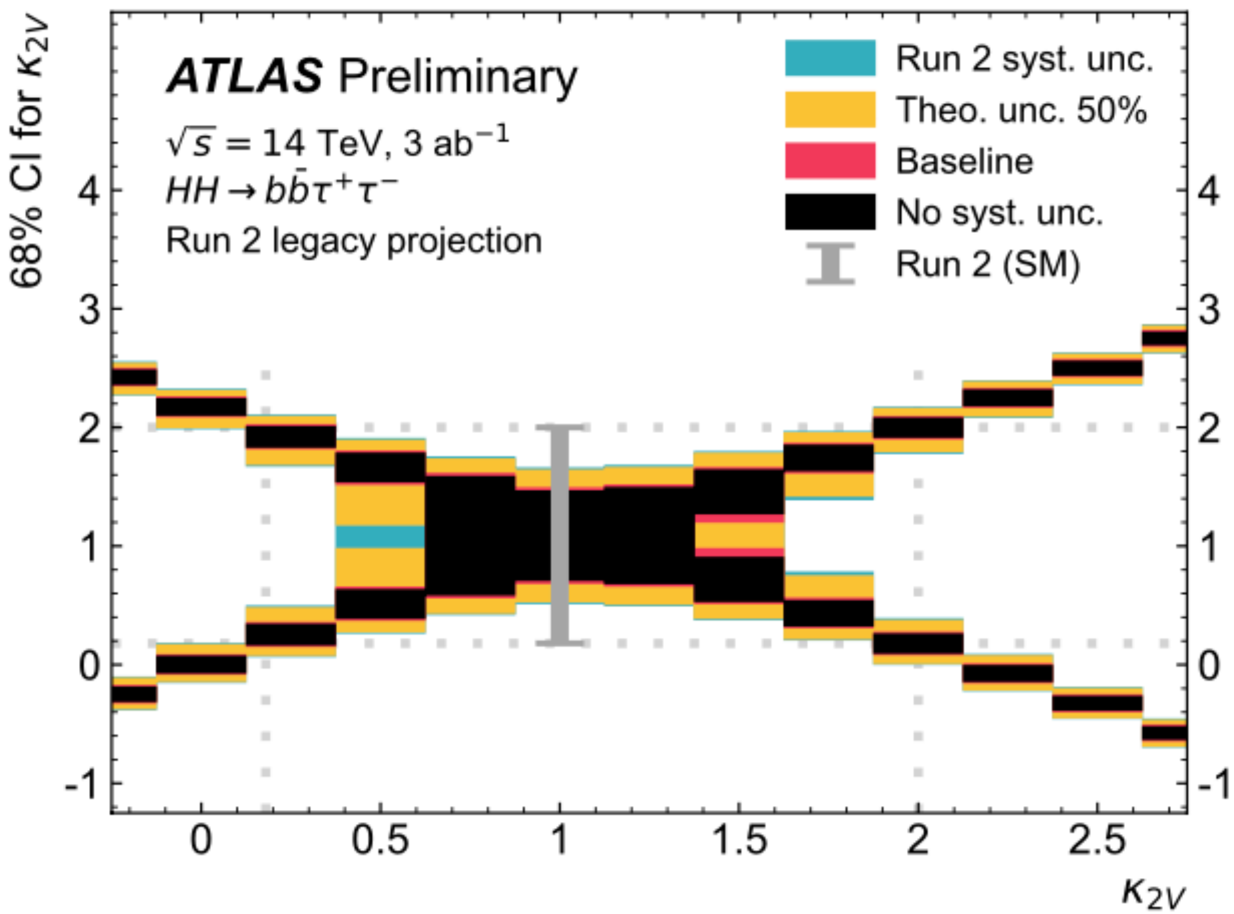




68% CI varying κ values

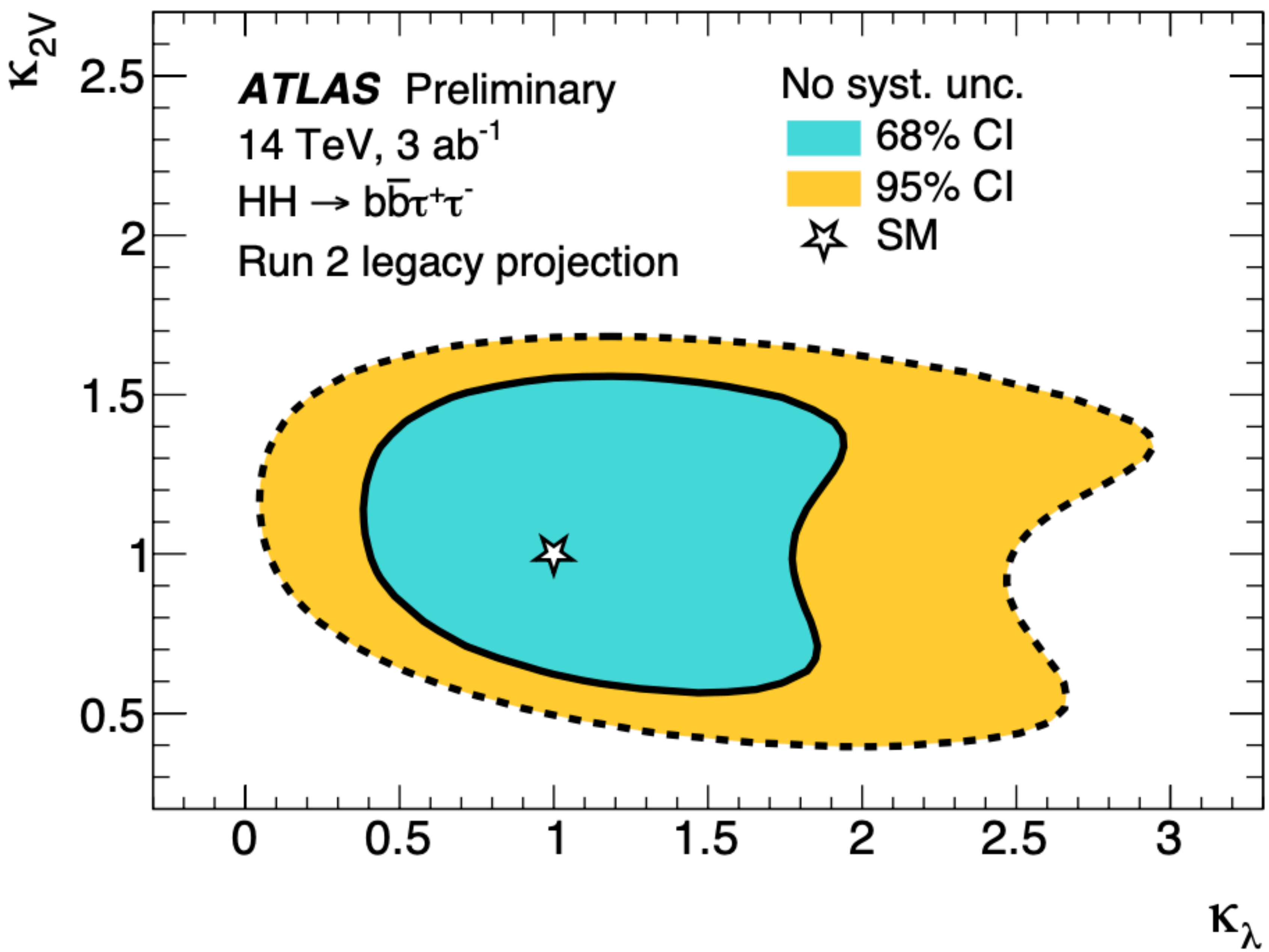
[ATL-PHYS-PUB-2024-016]





2D scan of κ_λ and κ_{2V}

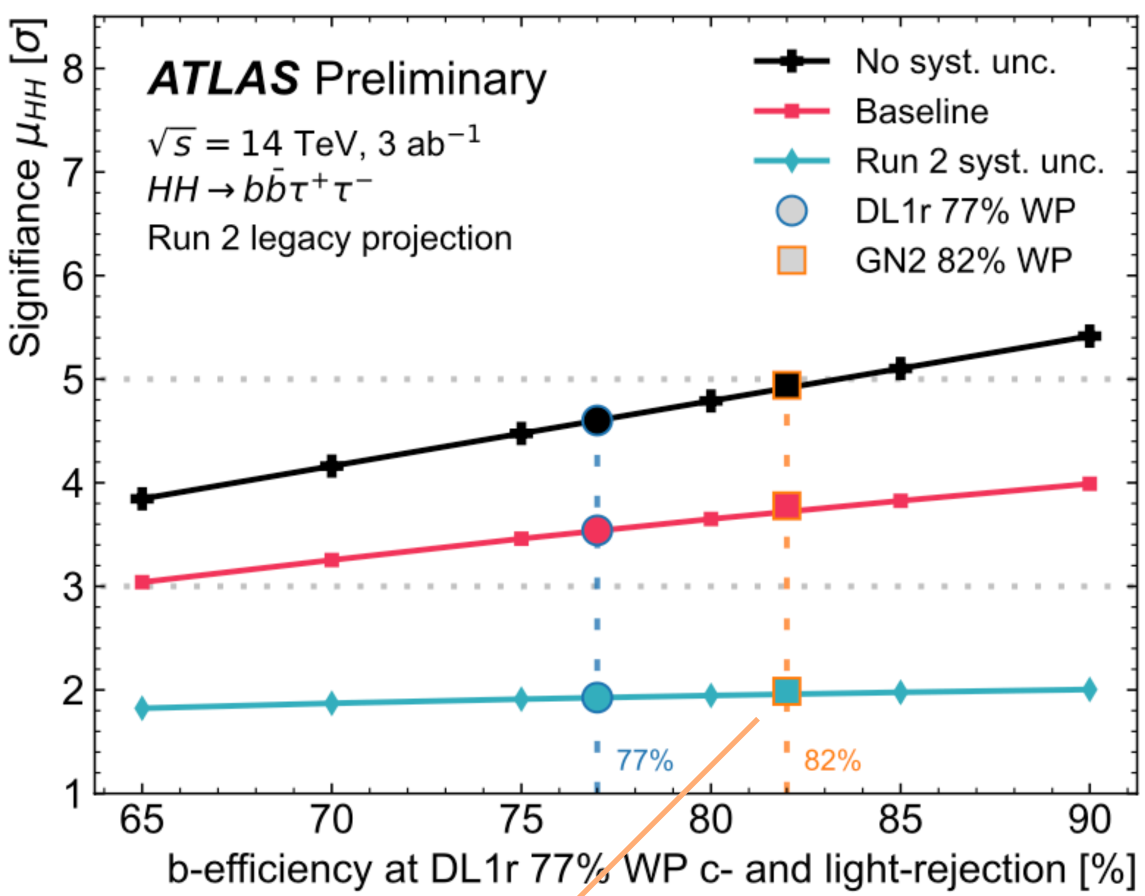
[ATL-PHYS-PUB-2024-016]

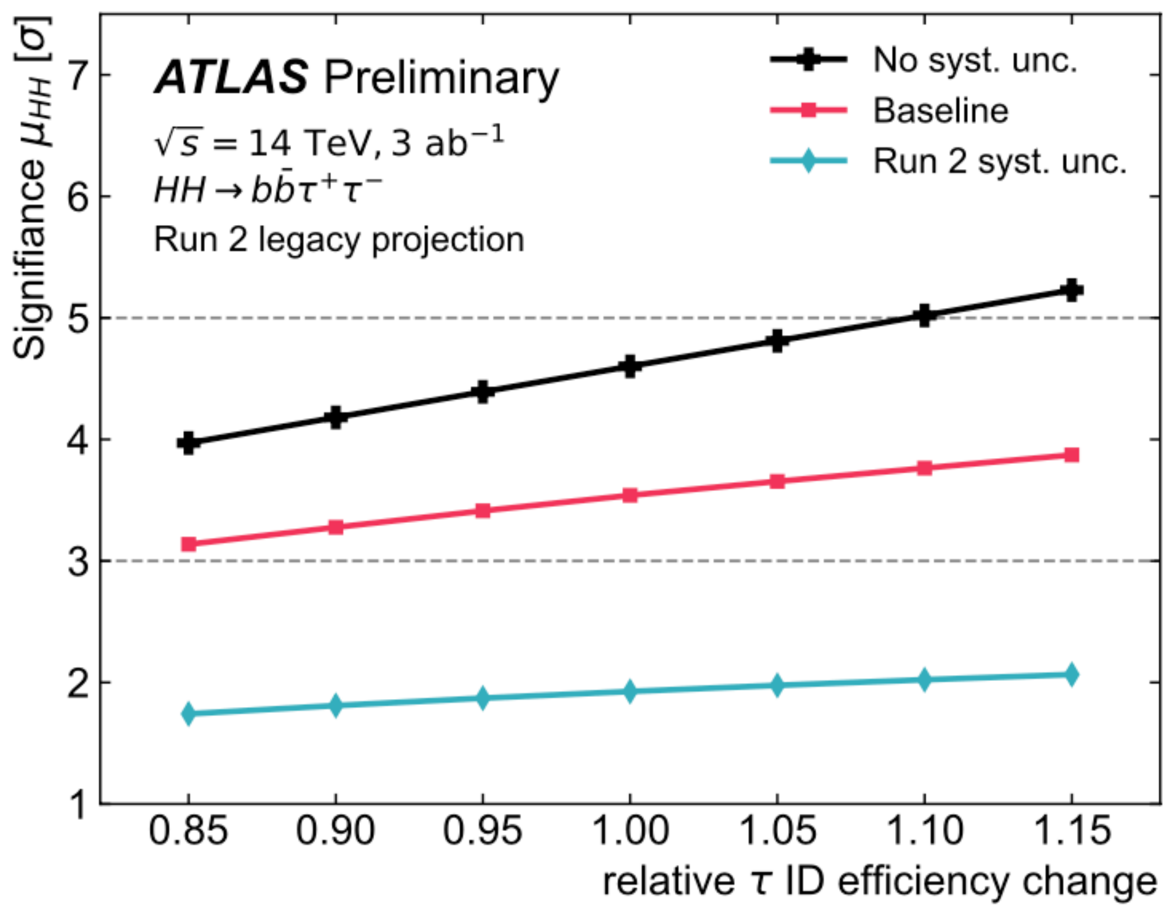


B-tagging and τ-identification improvements

[ATL-PHYS-PUB-2024-016]

- The sensitivity can be improved according to the improvements of the algorithms used in the analysis



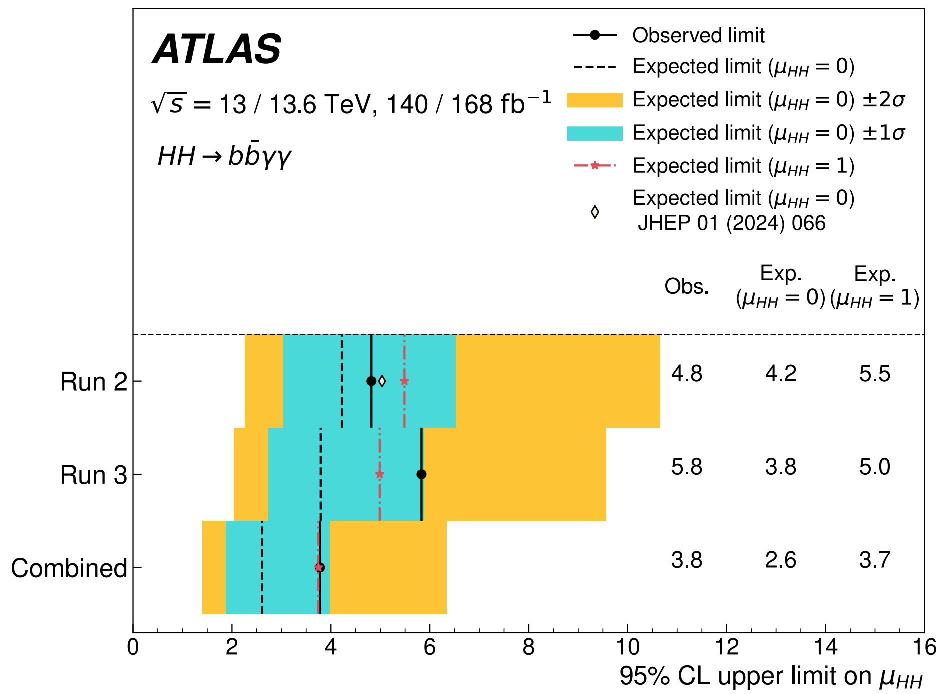


- GN2 82% WP (now available) in Baseline scenario gains O(10%) improvement
  5% improvement in efficiency → ~0.3 σ sensitivity gain
- Improvement of the hadronic signature tagging greatly benefits us

First Run3 analysis : non-resonant HH->bbγγ

[ATLAS-CONF-2025-005]

- First ATLAS analysis with Run2 (140 fb^{-1}) + partial Run3 (2022, 2023 and 2024 : 168fb^{-1}) total data : 308 fb^{-1}



Upper limit (μ_{HH}=0) improved by ~100%

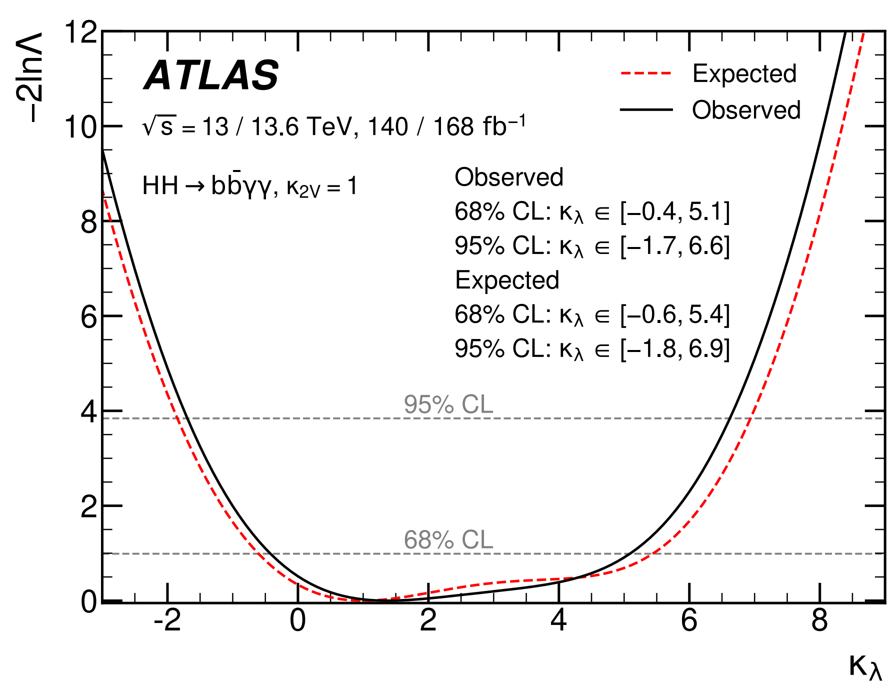
(- 20% from flavour tagging

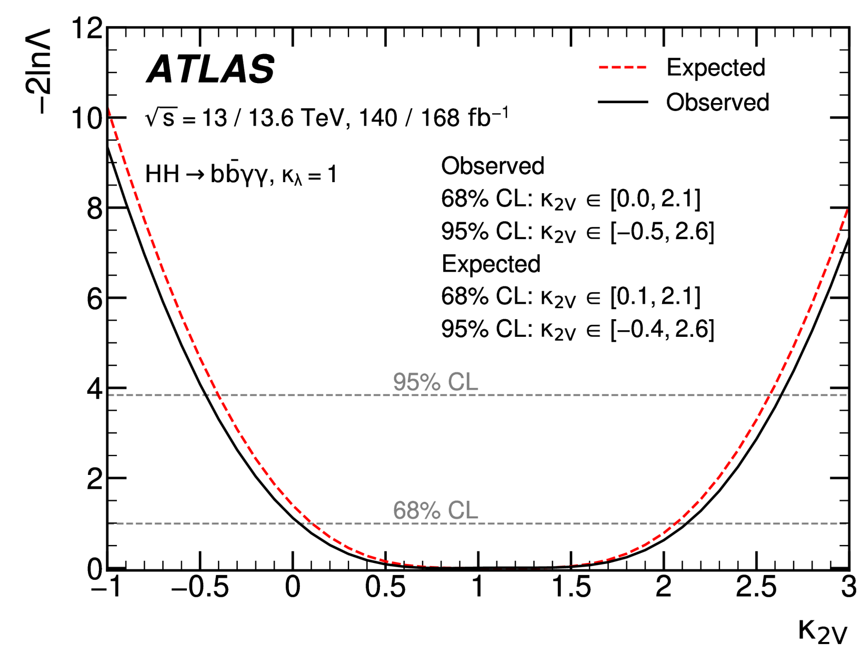
- 5% from mγγ resolution
- 10% from combined Run2, Run3 categories
- 50% from Run3 stats etc..)

Expected SM significance 1σ with the 308 fb^{-1} data

~20% improvement on the expected 95%CL κ_λ

~30% improvement on the expected 95%CL κ_{2V}





Comparison with CMS

PAS-HIG-20-011

Phys. Rev. D 133 (2024) 101801