HH searches in bb$\tau\tau$ final state in the ATLAS experiment, Run 2 to the HL-LHC

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

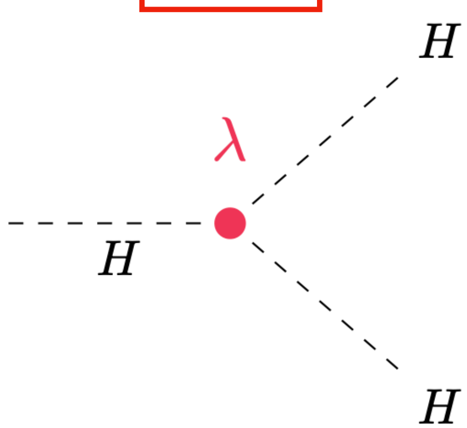
IRN terascale workshop
15.11.24

Minori Fujimoto (CPPM)

Di-Higgs searches

- After symmetry breaking the Higgs potential

$$V(H) = \frac{1}{2}m_H^2 H^2 + \boxed{\lambda v H^3} + \frac{1}{4}\lambda H^4$$



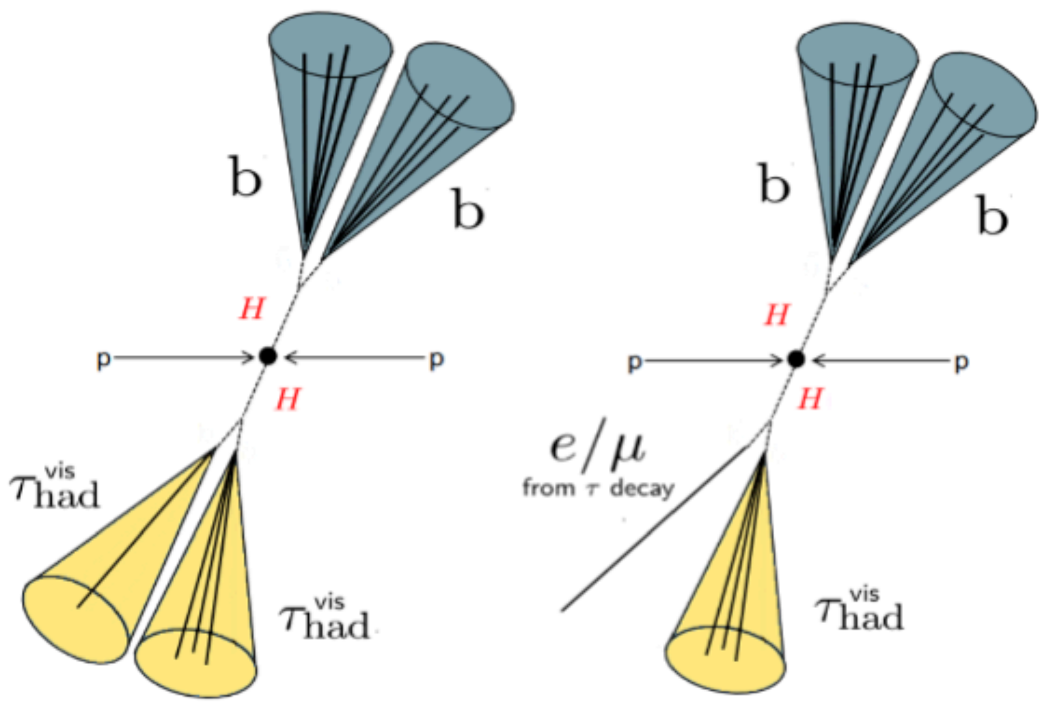
Coupling strength of the Higgs boson self-interaction

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

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

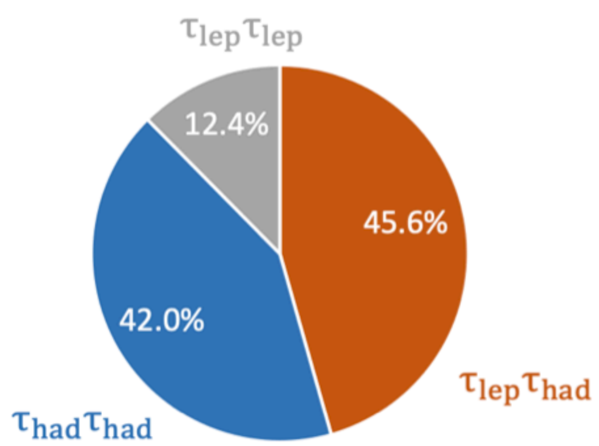
bbττ final state

	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%



- HH exploring a mixture of different Higgs decay channels to increase the sensitivity
  bbττ is one of the main channels : [bbbb, bb$\tau\tau$, bb$\gamma\gamma$]
  There are also [bbll + MET, ($\gamma\gamma$) multi-lepton]

- [bb$\tau\tau$] di-b : relatively large BR & di-τ : Clean signal
  HadHad & LepHad channel

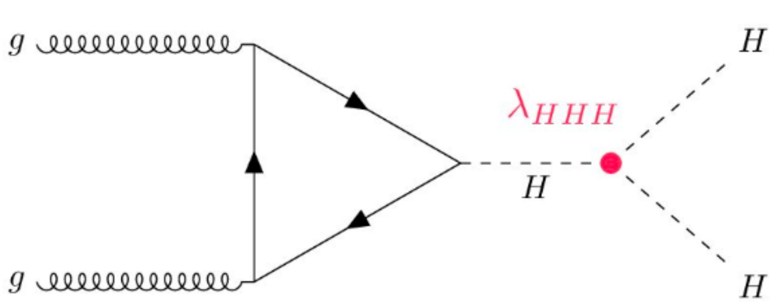


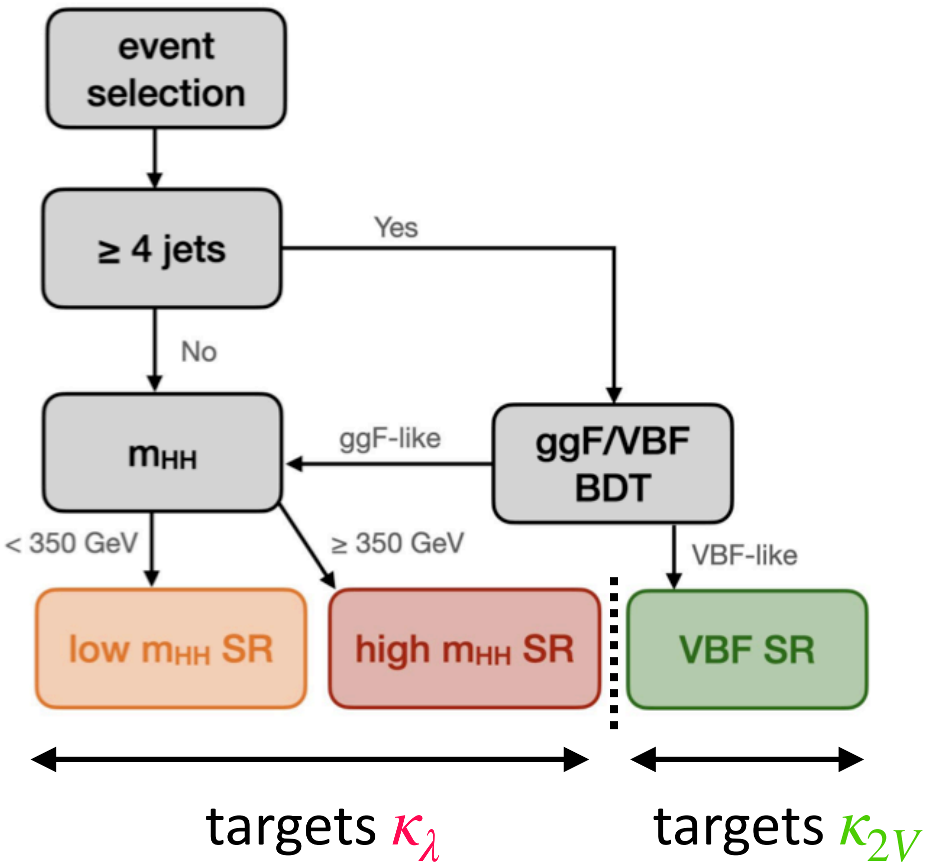
Legacy Run2 HH->bbττ analysis

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

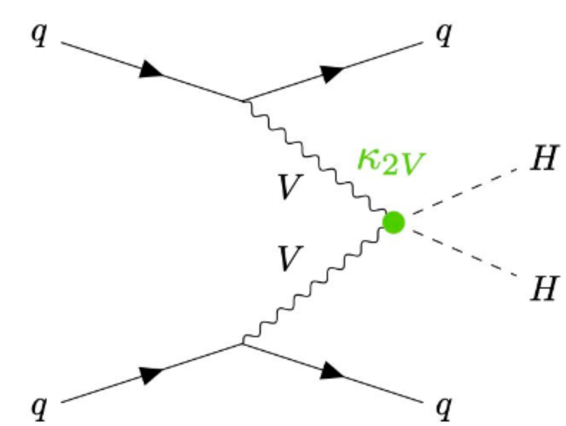
- Re-analyse Run2 with 140 fb^{-1} datasets
- 3 τ-decay specific triggers ($\tau_{\text{had}}\tau_{\text{had}}$, $\tau_{\text{lep}}\tau_{\text{had}}$ (SLT), $\tau_{\text{lep}}\tau_{\text{had}}$ (LTT))
- For each of the triggers new signal categorization targets different production modes

gluon-gluon Fusion





Vector Boson Fusion



- Fitted all signal regions and CRs simultaneously for signal strength μ_{HH}
- μ_{ggF} and μ_{VBF} are also constrained

Legacy Run2 HH->bbττ analysis results

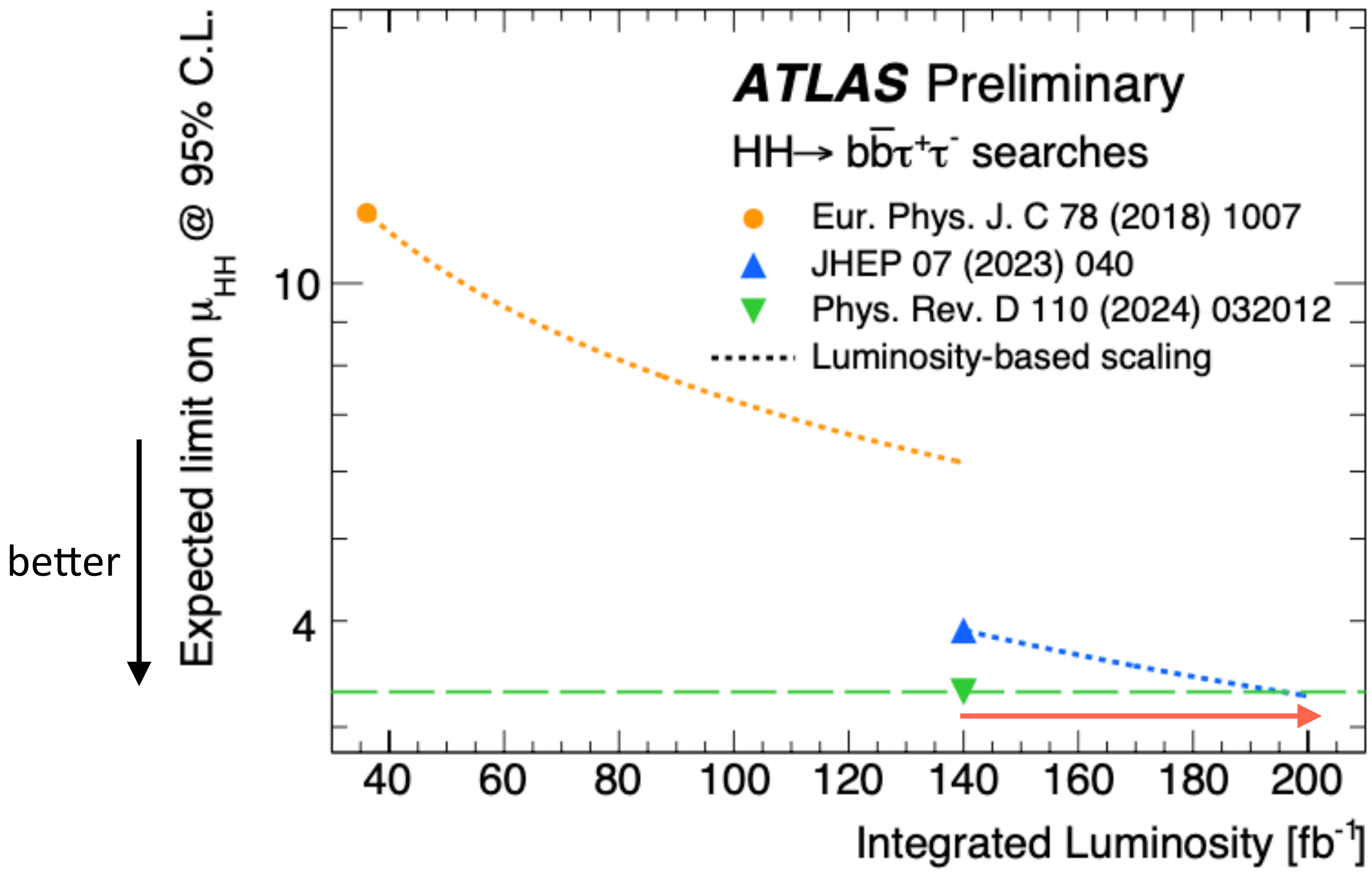
[Phys. Rev. D 110 (2024) 032012]

- No significant excess above SM prediction

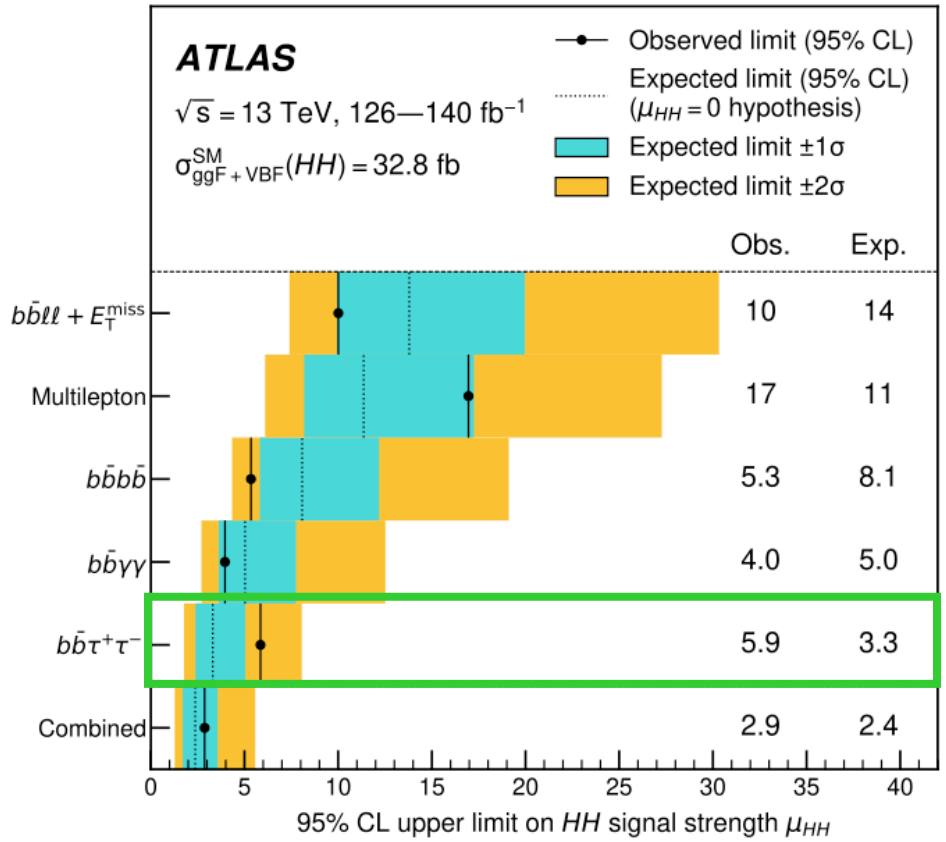
Obs. (Exp.) 95% CL limits μ_{HH} **< 5.9 (3.3)** $\times$ **SM**

-3.1 < κ_λ < 9.0 (-2.5 < κ_λ < 9.3)

-0.5 < κ_{2V} < 2.4 (-0.2 < κ_{2V} < 2.4)



[PhysRevLett.133 (2024) 101801]



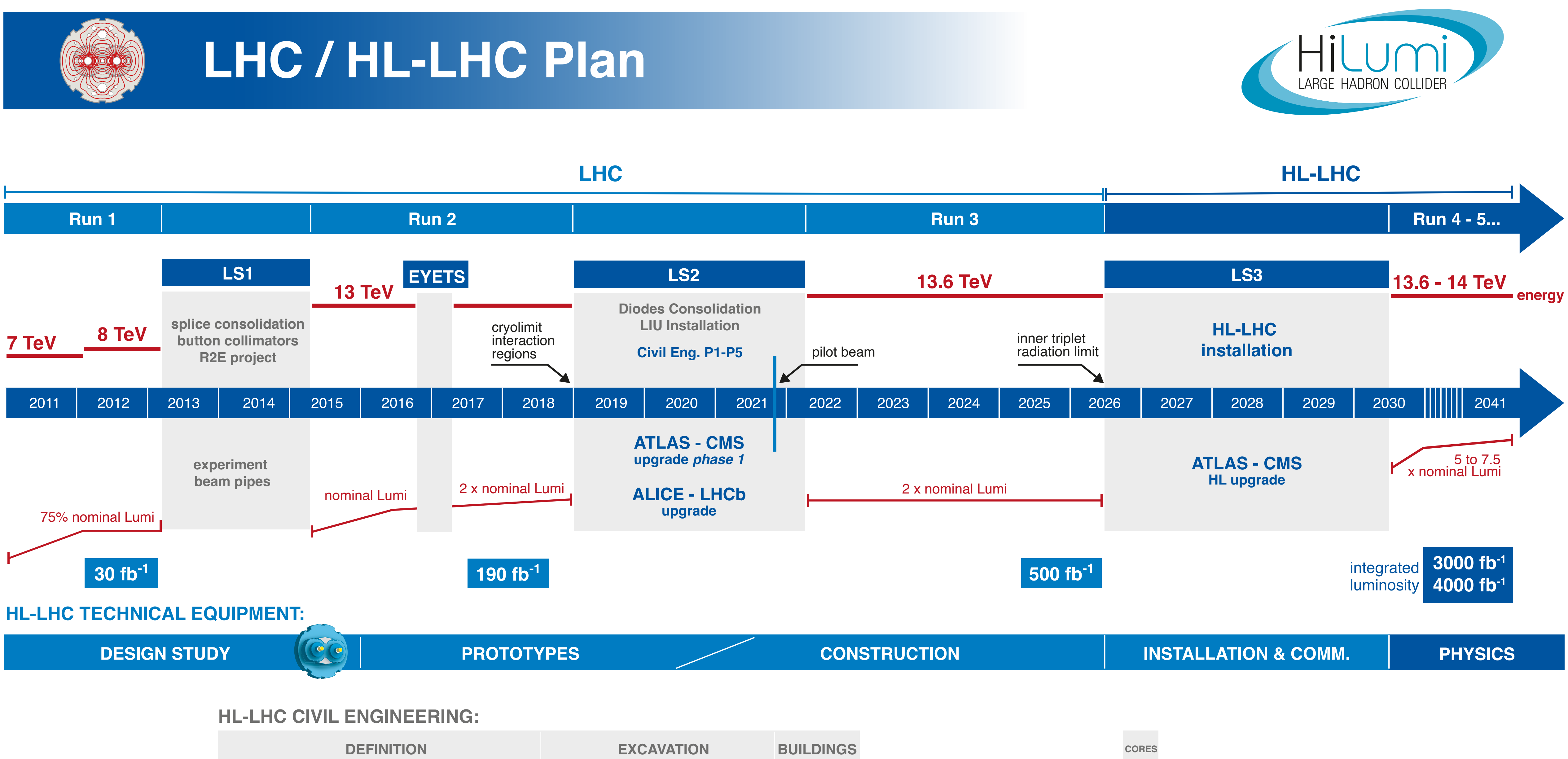
- Exp. limit improves by **15%** wrt previous Run 2 analysis

  This improvement is equivalent to having 30% more data

- Results are statistically limited

High Luminosity-LHC

LHC/ HL-LHC Plan (last update October 2024)



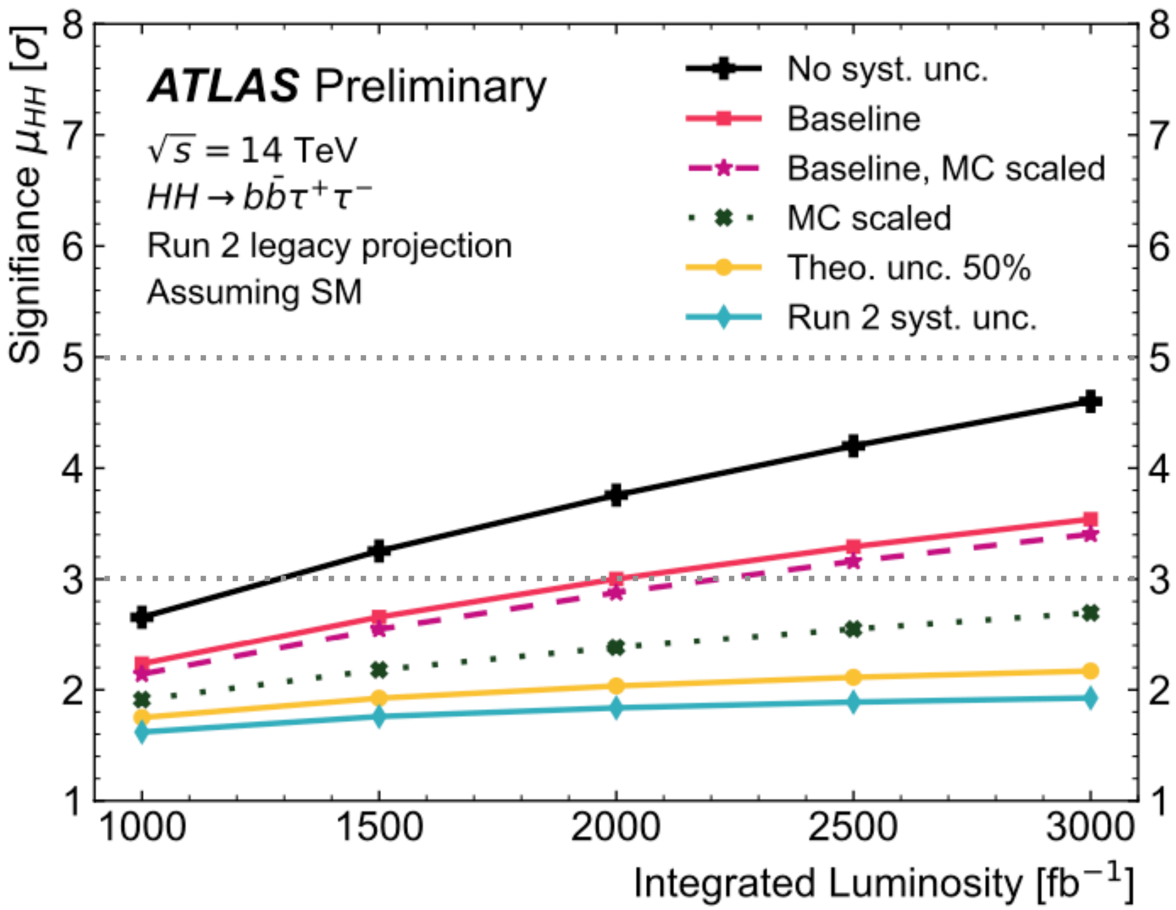
- The HL-LHC aims at collecting at least 3000 fb^{-1} of 14 TeV pp collisions

Extrapolation towards HL-LHC

[ATL-PHYS-PUB-2024-016]

- Based on the Run2 Legacy analysis results, extrapolated for HL-LHC (140 → 1000 ~ 3000 fb^{-1}, 13 → 14 TeV) by scaling the final BDT discriminant

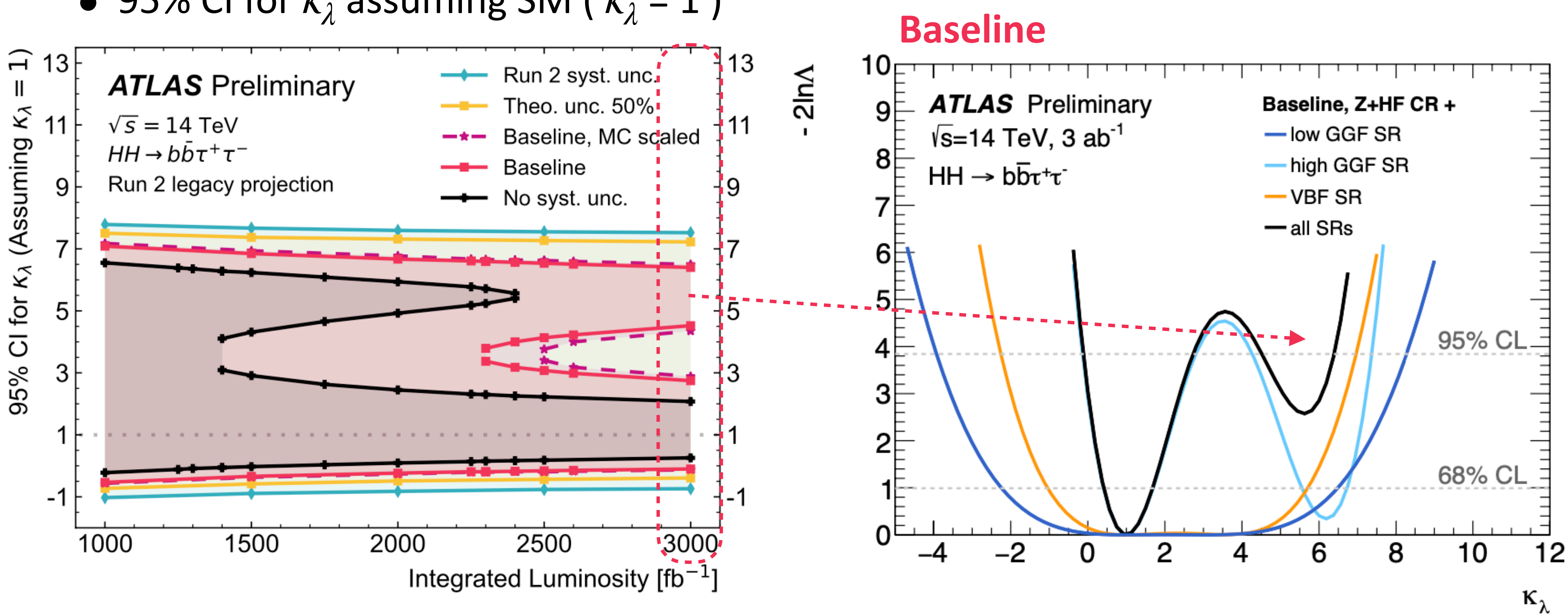
Run 2 syst. unc.	All uncertainties kept at their Run2 values
Theo. unc. 50%	Half all theory sig & bkg uncertainties
MC scaled	MC stat. uncertainty is scaled by √(L/L’)
Baseline	Recommendation for expected HL-LHC performance, no MC stat.
Baseline, MC scaled	Baseline, scaled MC stat. by √(L/L’)
No syst.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



- Observation of HH production is in reach with 3000 fb^{-1} with only bbττ
- In Baseline scenario expect 3.5 σ excess, stat unc. ~ syst unc.

Extrapolation of the constraining κλ

- 95% CI for κ_λ assuming SM ($\kappa_\lambda = 1$)

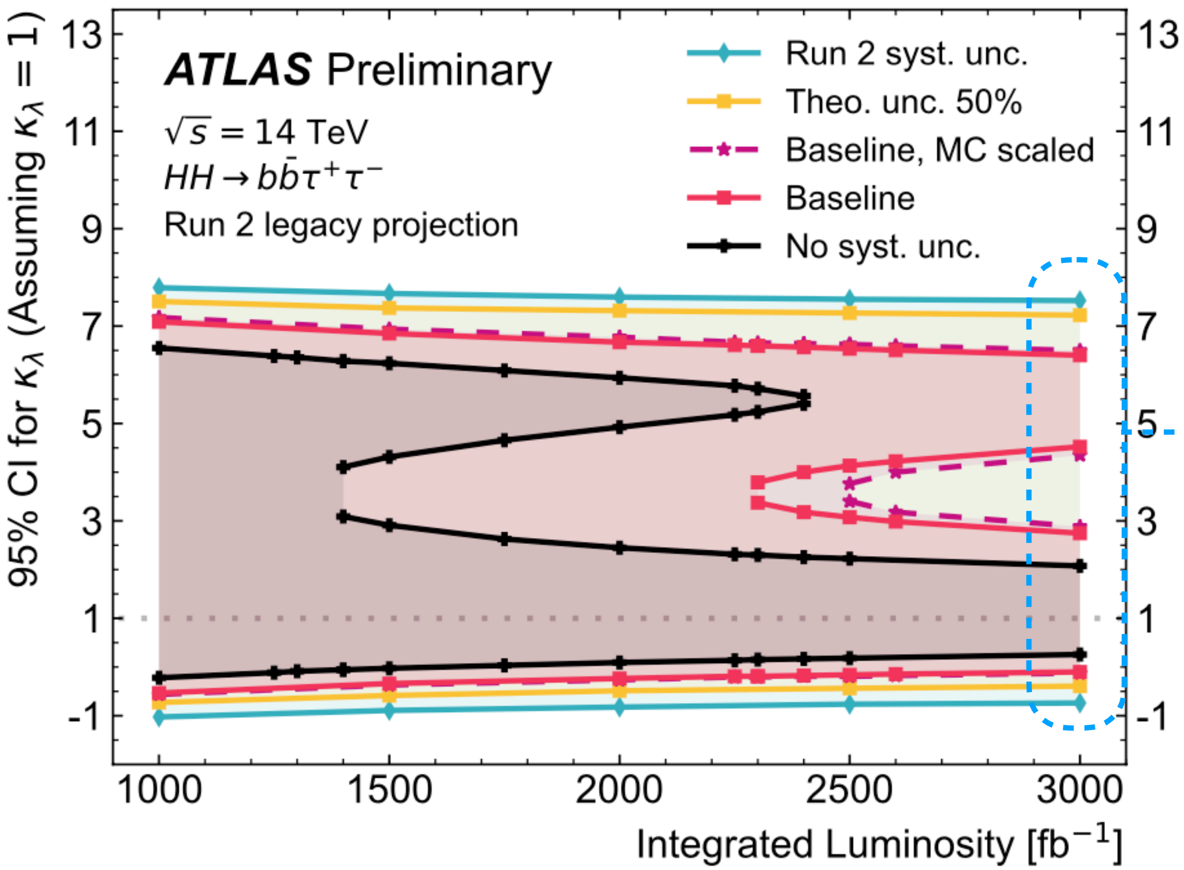


- Constraint from new SRs Low-ggF and VBF signal regions allow resolving the κ_λ degeneracy

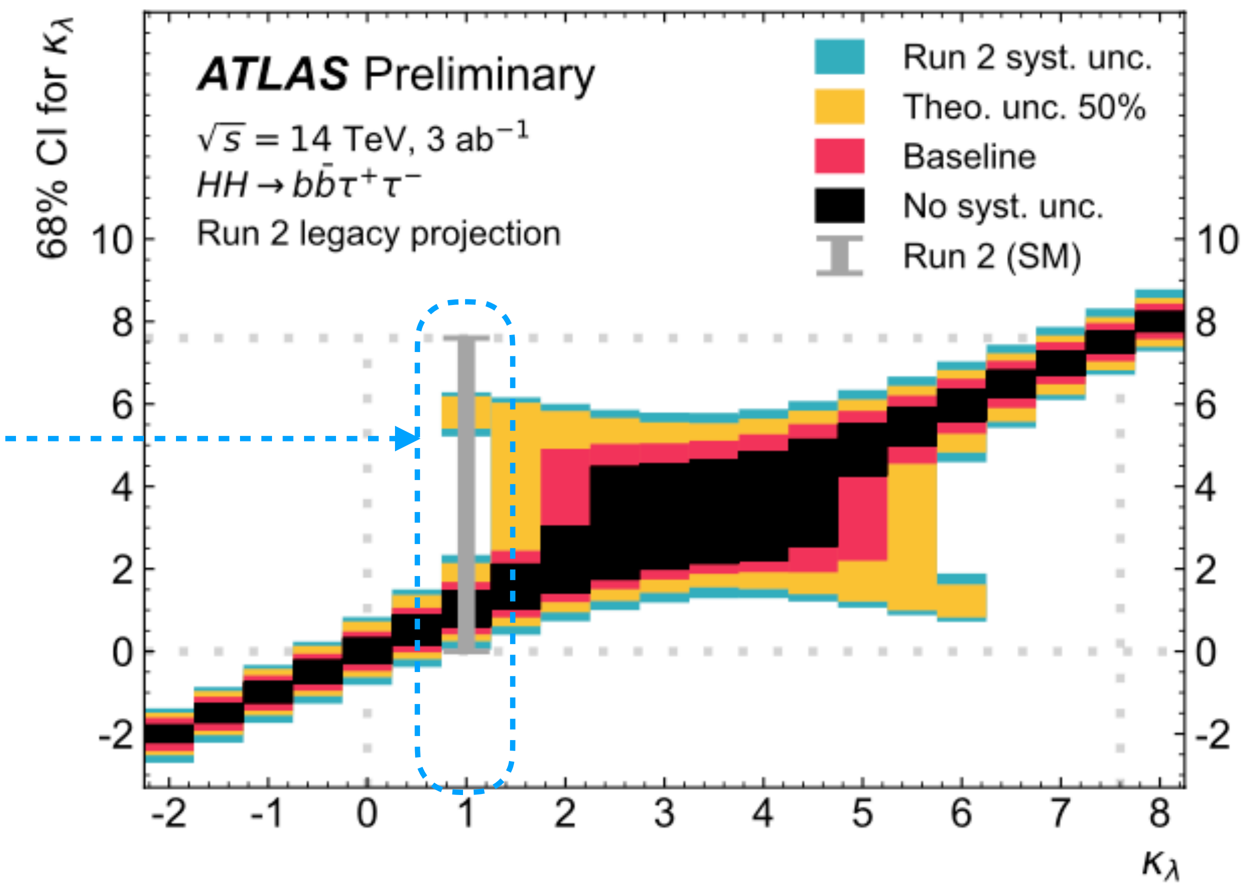
In Baseline The 2nd minimum can be distinguished clearly
In No syst. It can be excluded ~@ 2500 fb^{-1}

Non-SM scenario

- 95% CI for κ_λ assuming SM



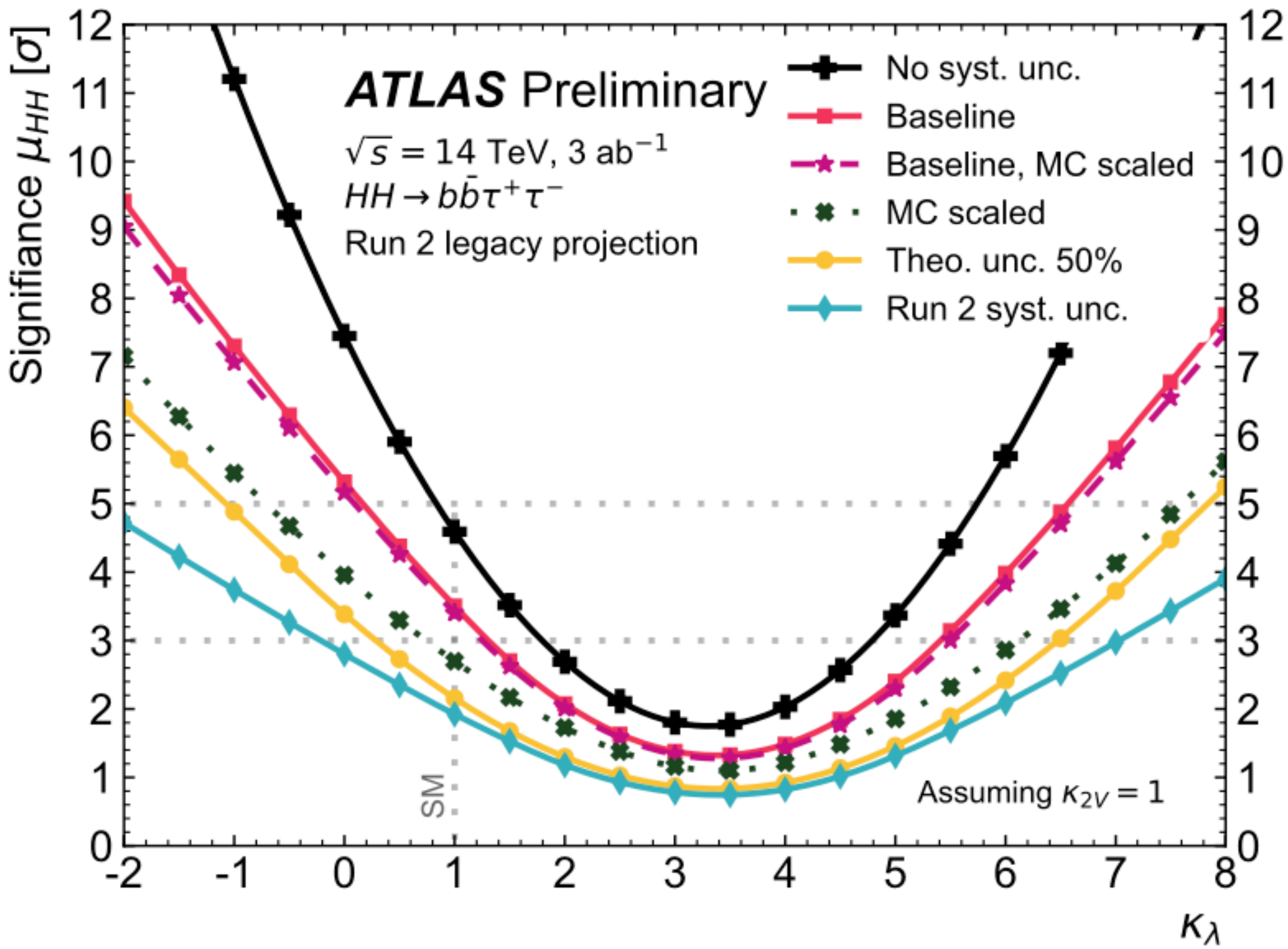
- 68% CI for varying κ_λ @ 3000 fb^{-1}



- How much we can constraint largely depends on κ_λ value

Possibility of observation of the BSM κ_λ

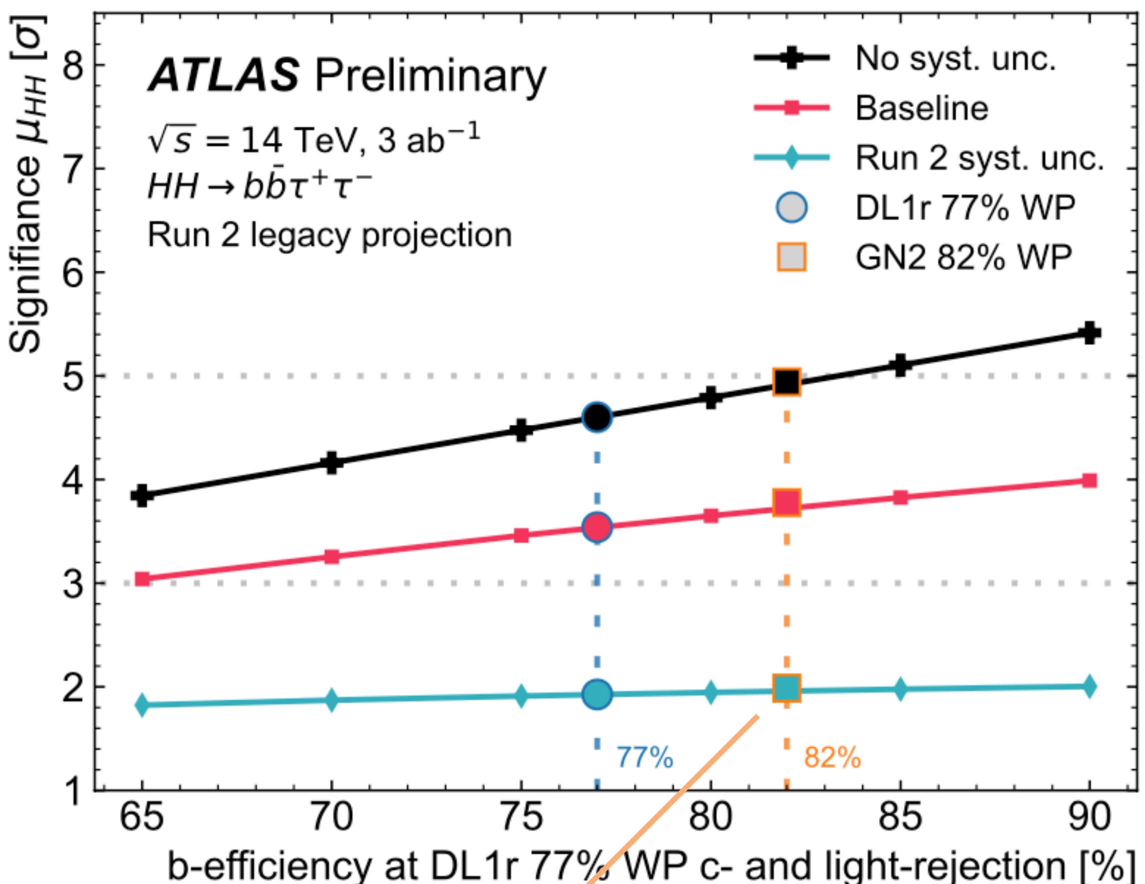
- Significance of HH, when varying κ_λ @ 3000 fb^{-1}

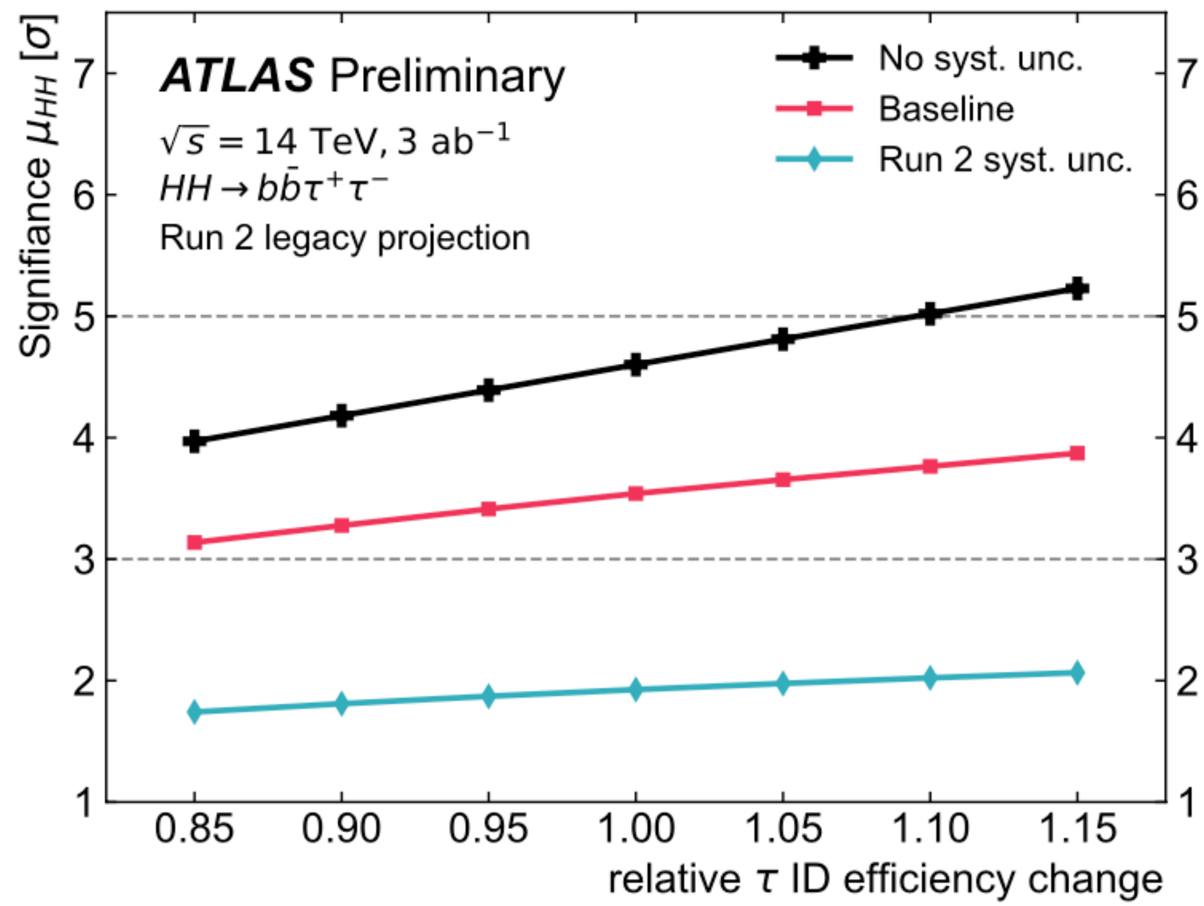


- Small and very large κ_λ can be observed but significantly reduced sensitivity around $\kappa_\lambda \approx 3.5 \pm 1$

B-tagging and τ-identification improvements

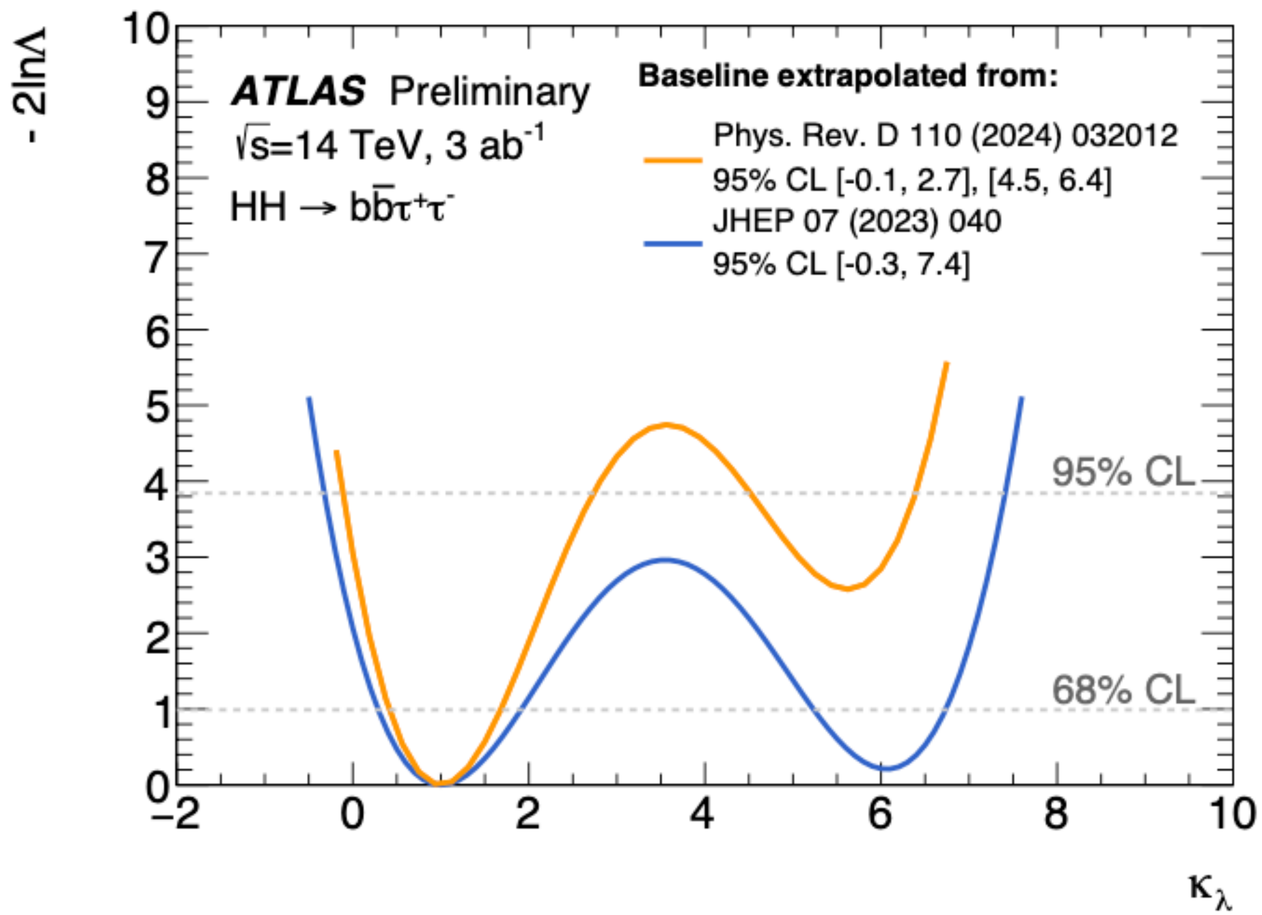
- The sensitivity can be improved according to the improvements of the algorithms used in the analysis





- 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

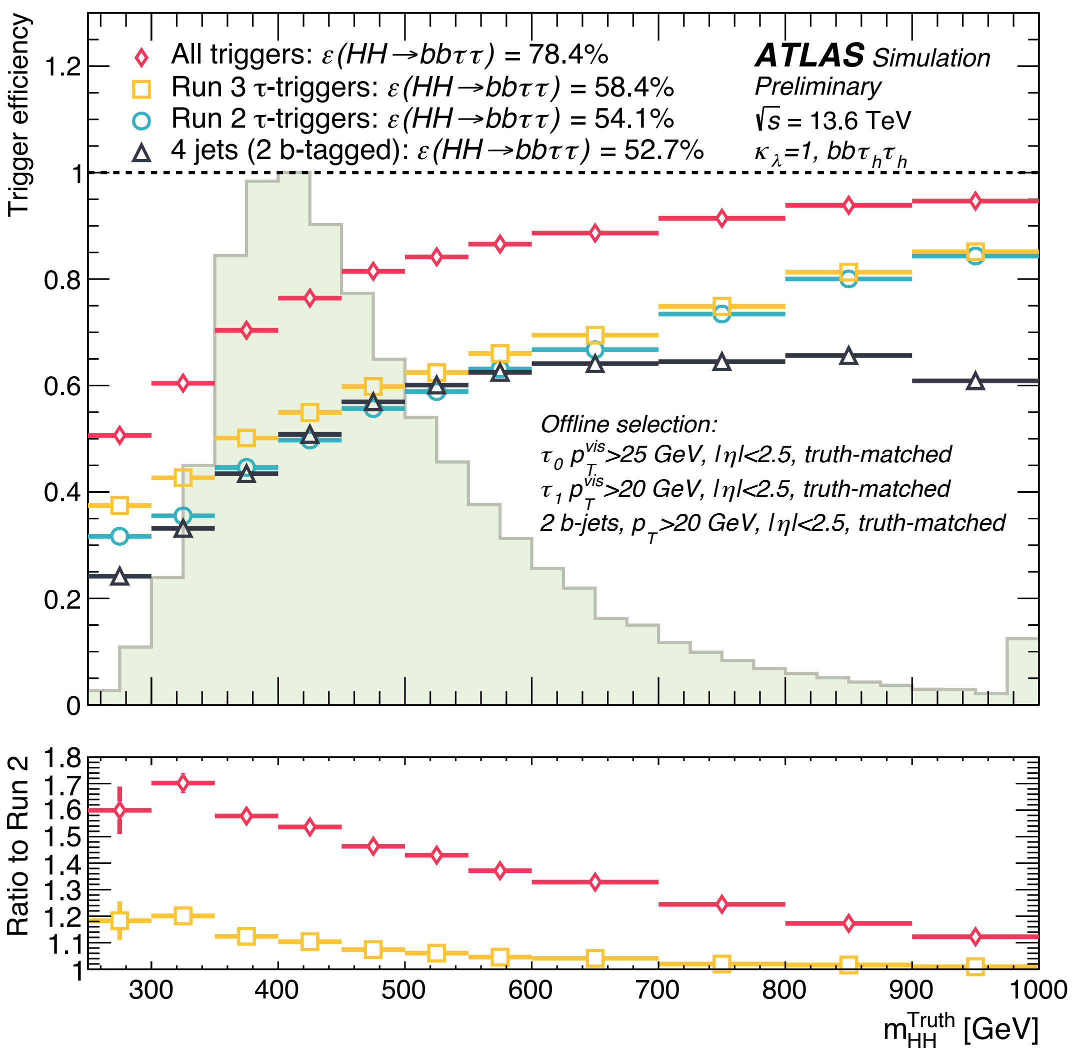
Improvement by the analysis



- In the same Baseline scenario, the extrapolation from the Legacy Run2 analysis half the uncertainty in κ_λ wrt the extrapolations from the earlier Run2 analysis

→ Improvement by the analysis

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



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

Summary

- HL-LHC projection studies are carried out based on the Run2 HH→bb$\tau\tau$ analysis, in various extrapolation scenarios

  - Observation of the SM-like HH production is in reach in HL-LHC
  (In Baseline scenario expect 3.5 σ, in No syst. 4.6 σ)

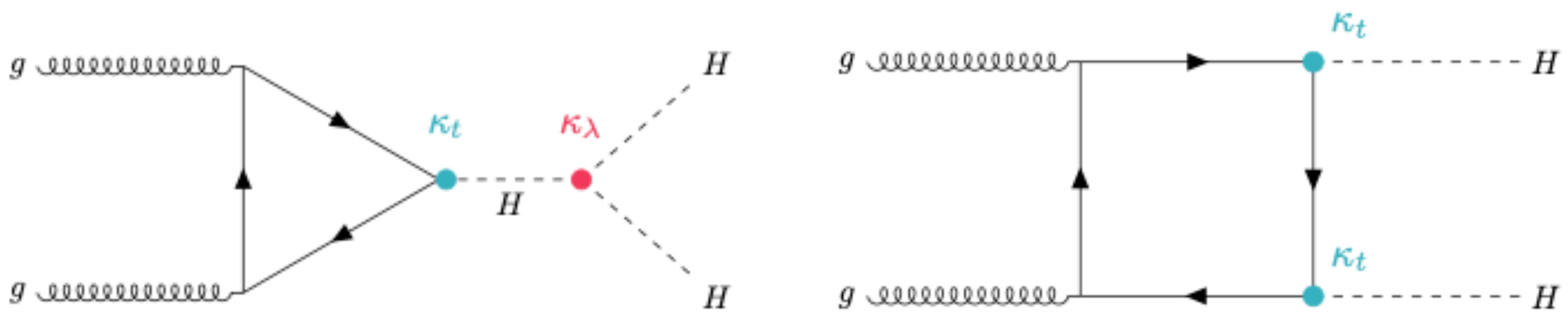
- The extrapolation strategy here does not taken account expected improvements in new triggers, better object reconstruction/ID, novel analysis strategy
  → This study is likely conservative and we can expect more in HL-LHC !

Backup

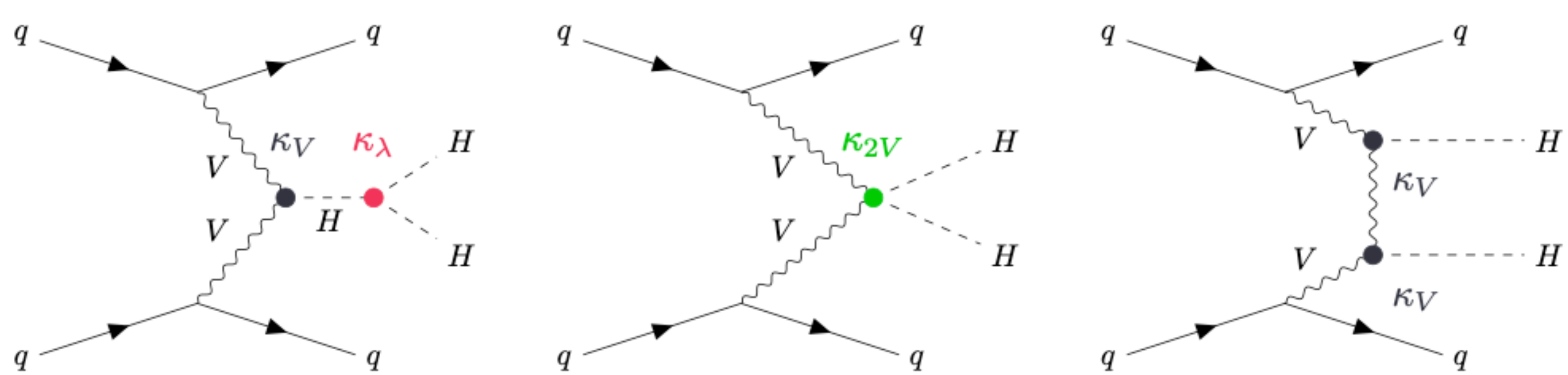
Di-Higgs production mode

- Production mode;

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



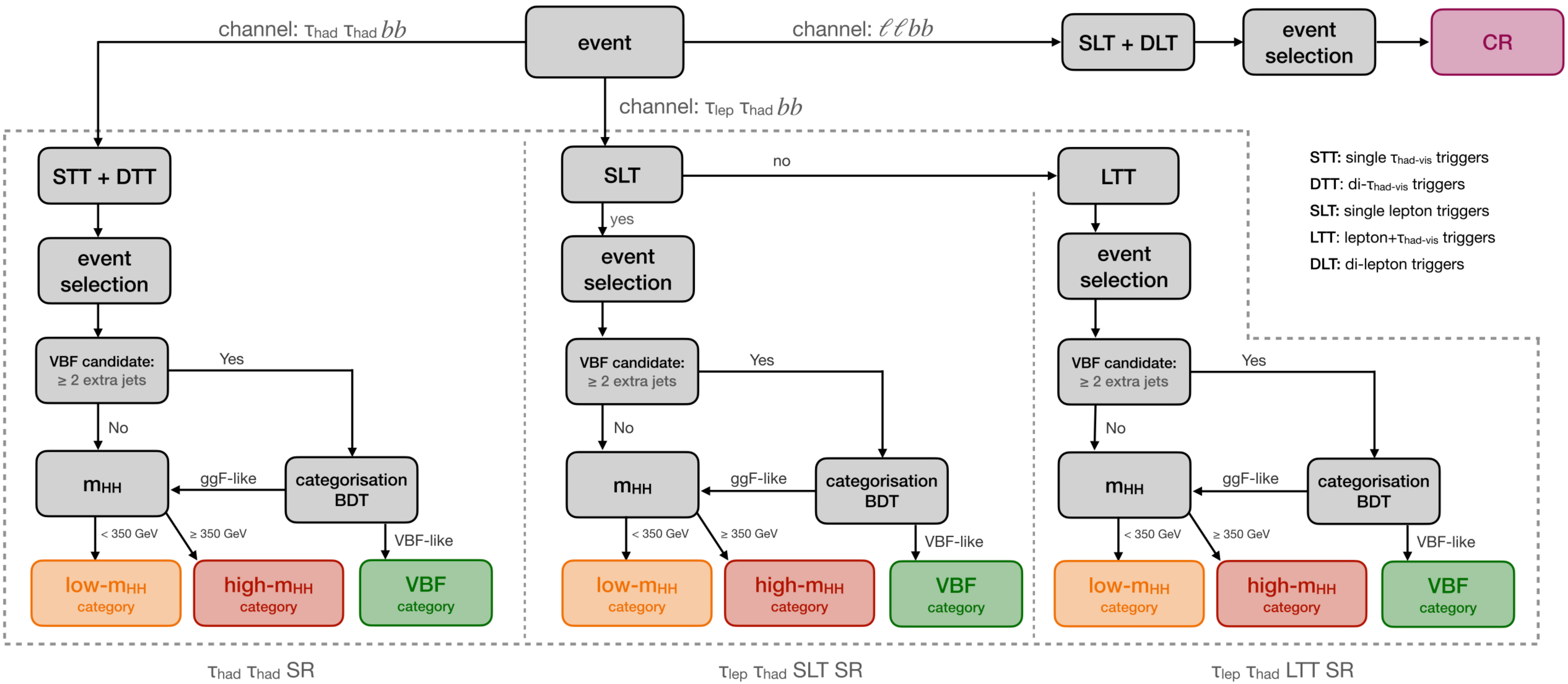
Vector Boson Fusion (VBF) 4.5 %, 1.72 fb @ 13 TeV



Run2 legacy analysis event categorization

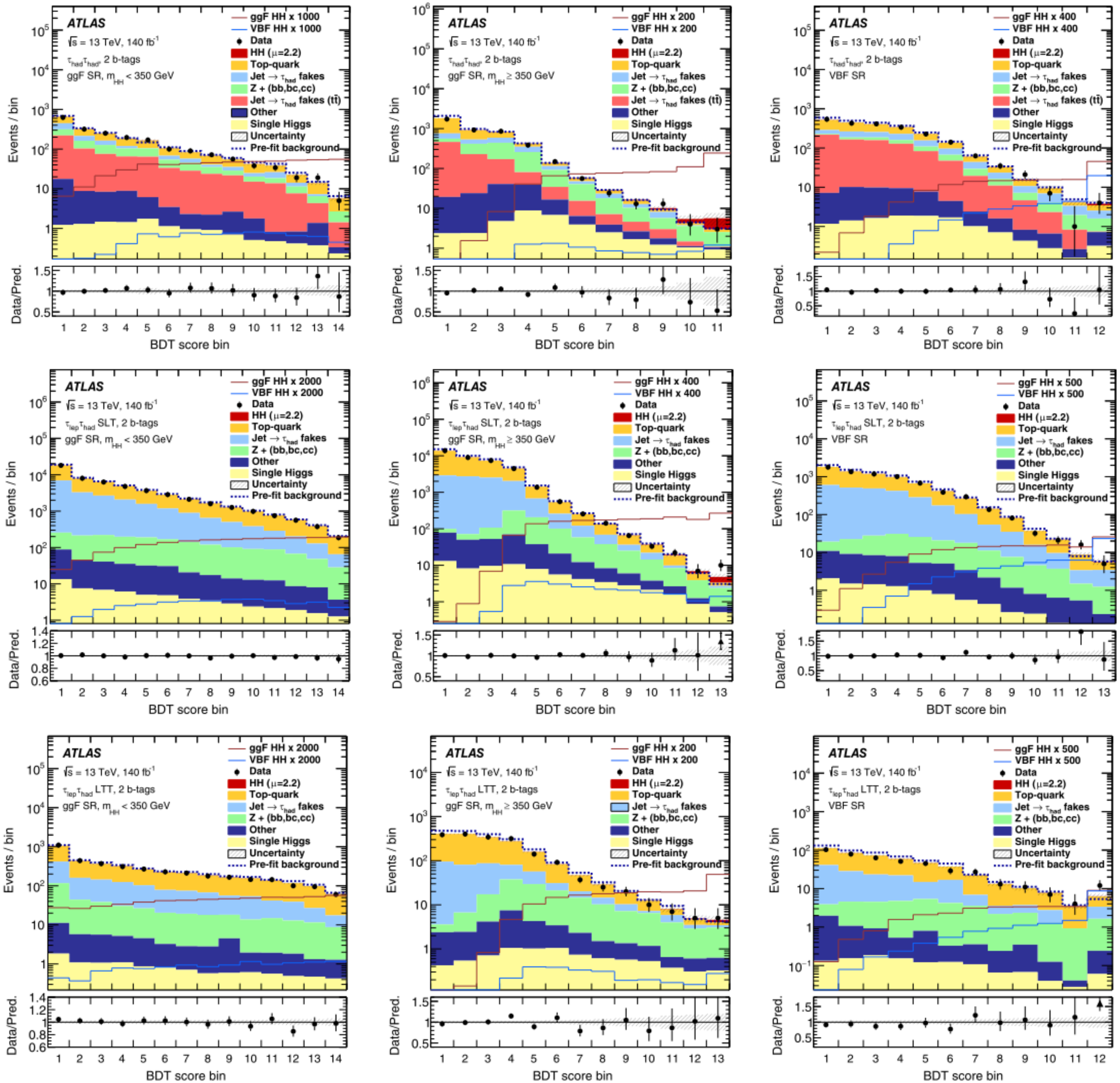
[Phys. Rev. D 110 (2024) 032012]

- 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]

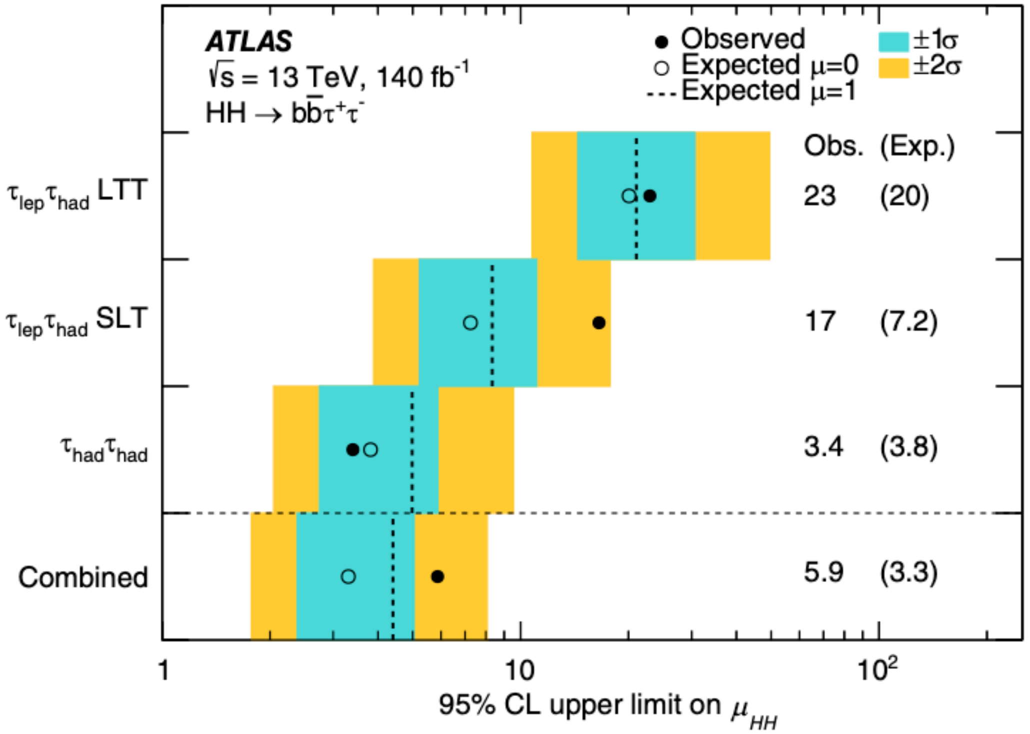


- Main bkgs
  - ttbar, Z + HF;
    rely on MC simulations
  - Fake-τ backgrounds ;
    data-driven techniques
- BDT inputs

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			✓

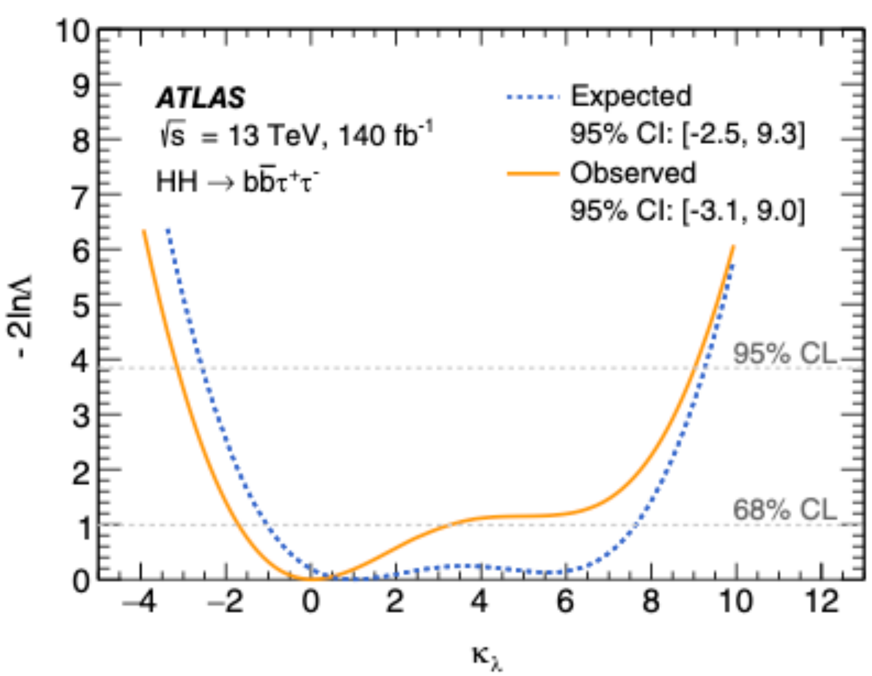
Run2 legacy analysis results

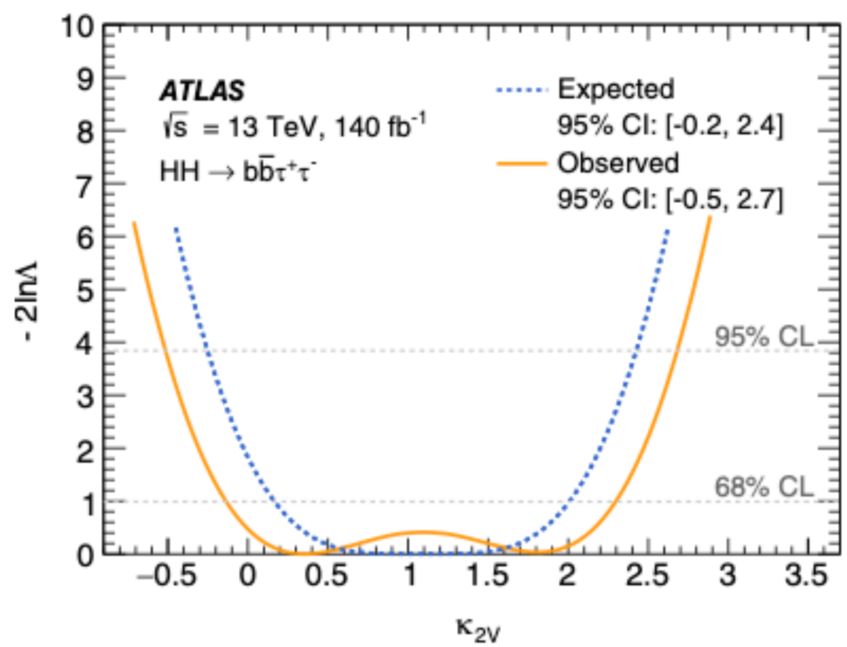
[Phys. Rev. D 110 (2024) 032012]

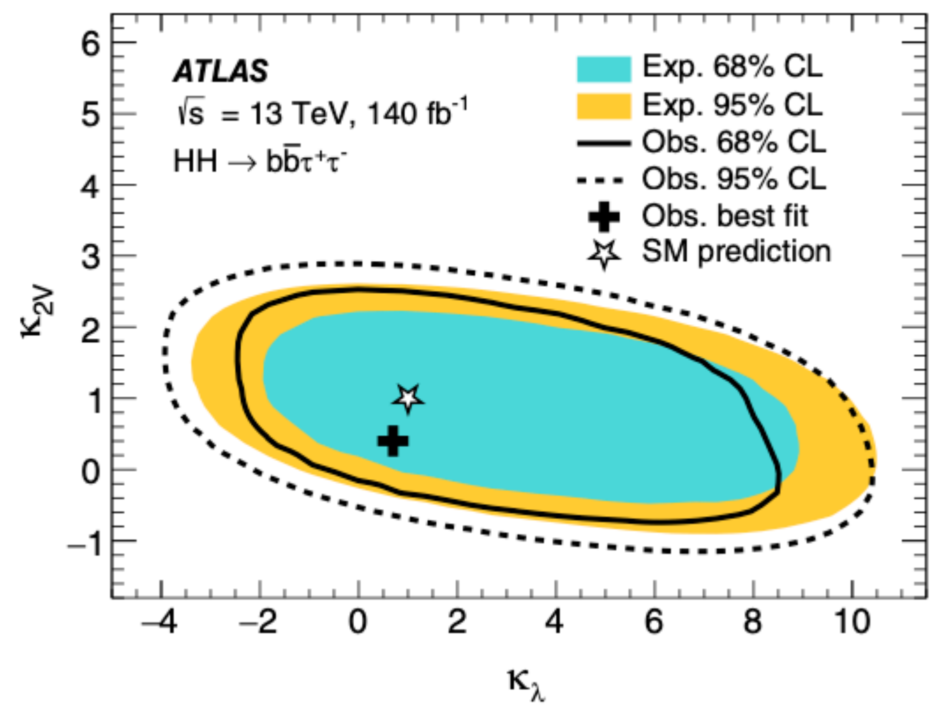


95% CL upper limits

		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}

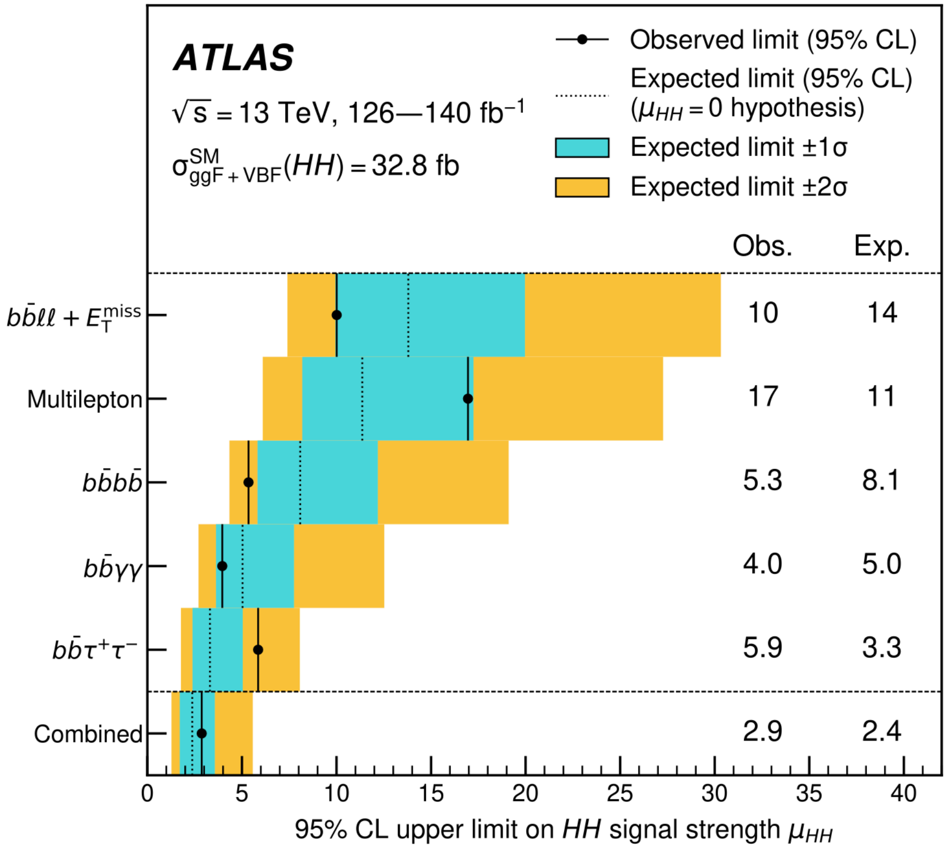






HH Combination studies

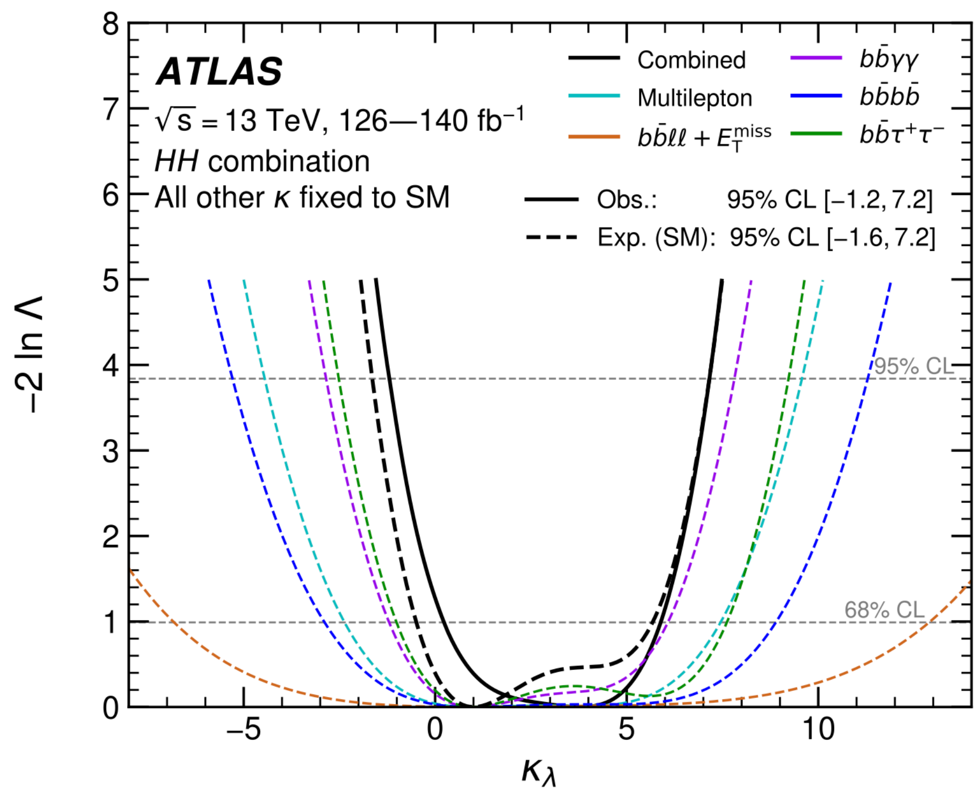
[PhysRevLett.133 (2024) 101801]

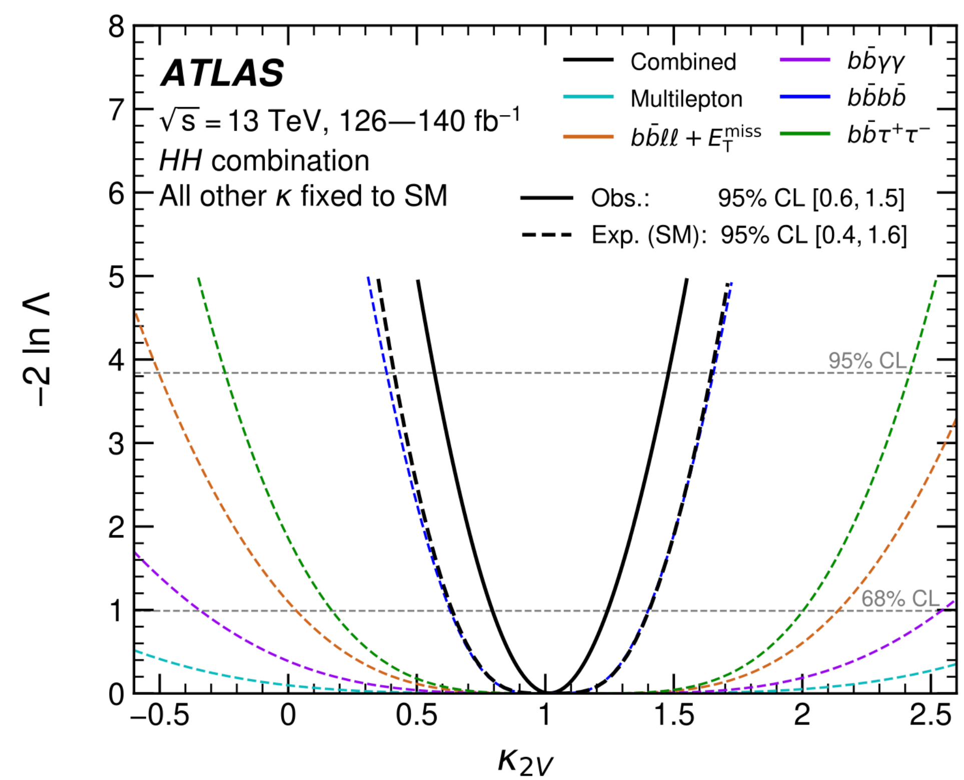


- Updates wrt last combination:
  - Improved results for bb$\tau\tau$, bb$\gamma\gamma$
  - New boosted VBF bbbb
  - New decay modes : multi-leptons and bbll + MET

- Best expected sensitivity to date on μ_{HH}

  Obs. (Exp.) 95% CL limits μ_{HH} < 2.9 (2.4) $\times$ SM





Extrapolation procedure to HL-LHC

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

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

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

- **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

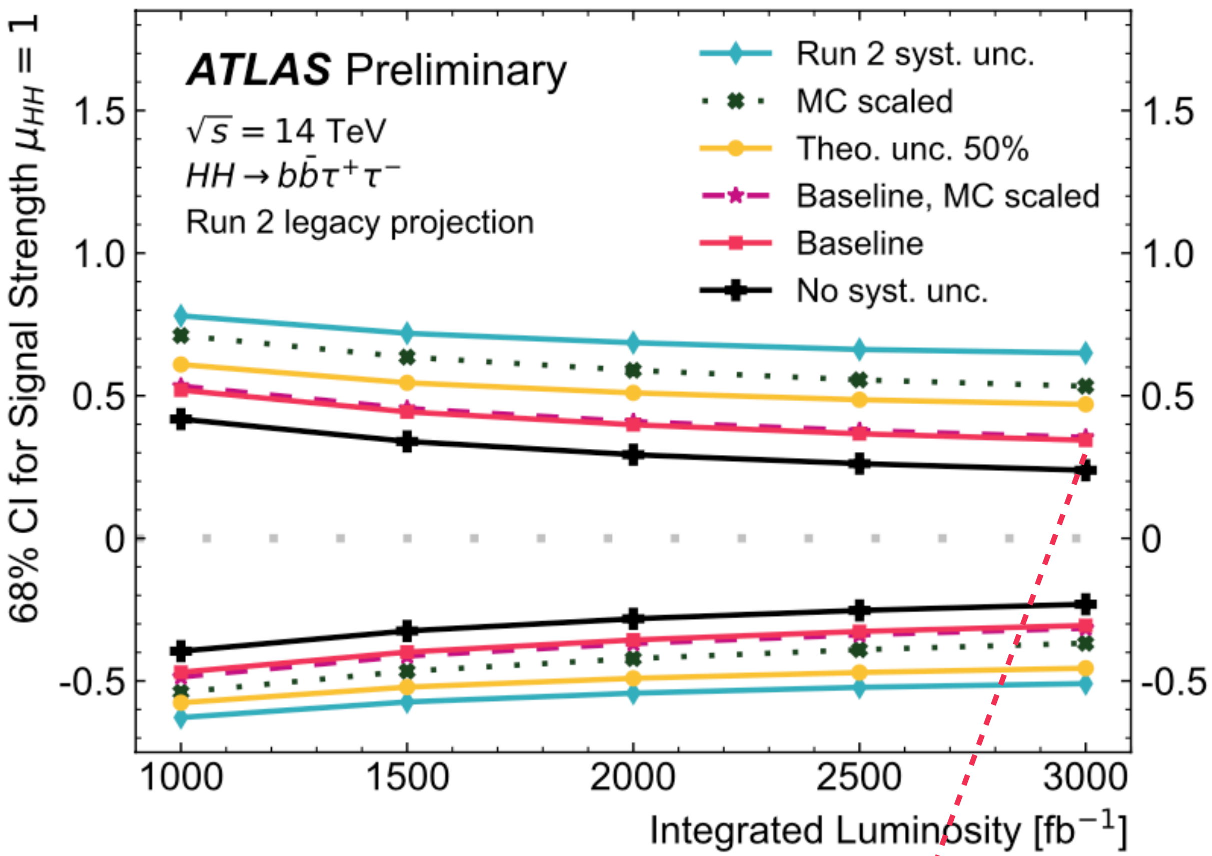
This scenario follows the latest recommendations which were use for Snowmass 2022

Assume lumi. unc. similar to Run2

Theoretical unc. halved

Extrapolated uncertainties on μ_{HH}

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



$\Delta\mu \approx 0.3$

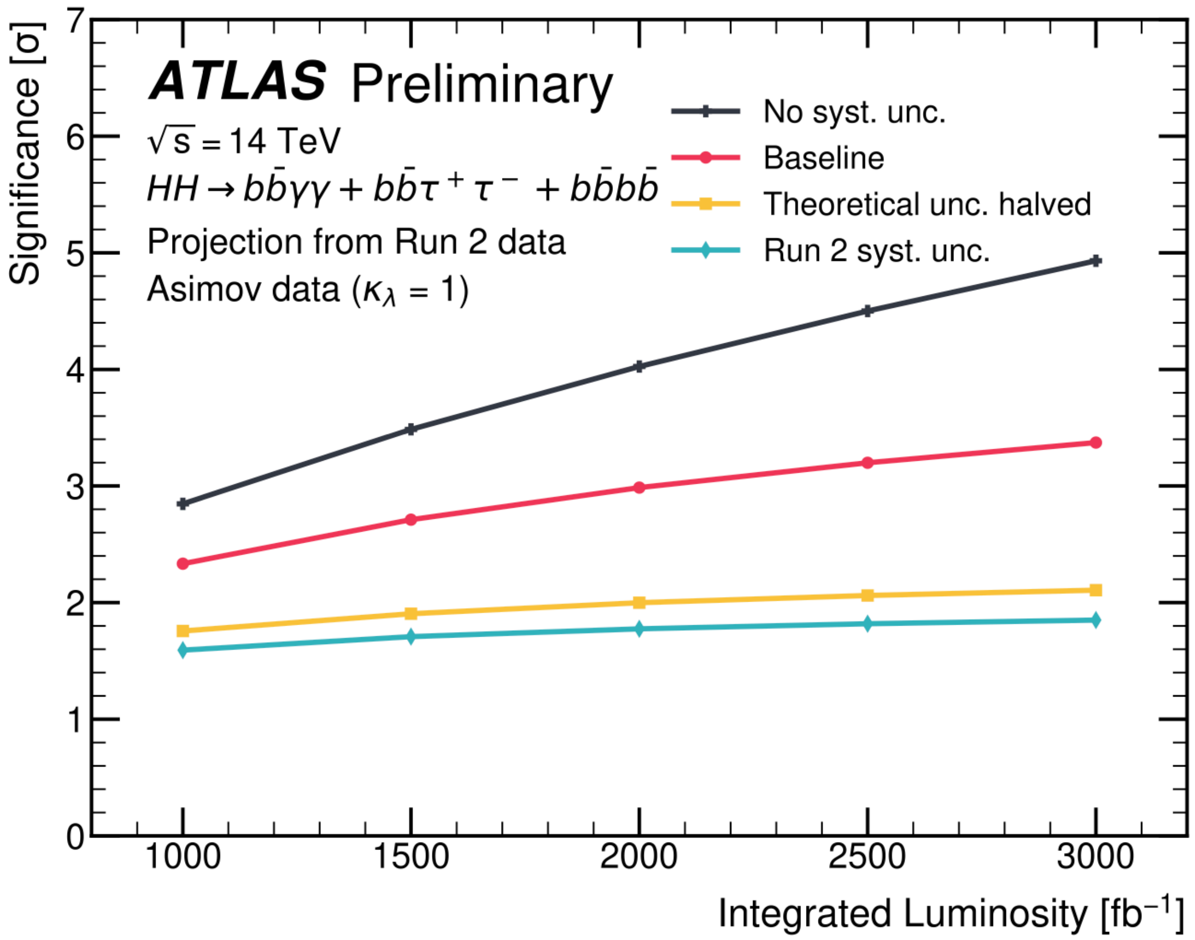
Signal & bkg modelling limits us the most

@ 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_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 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]



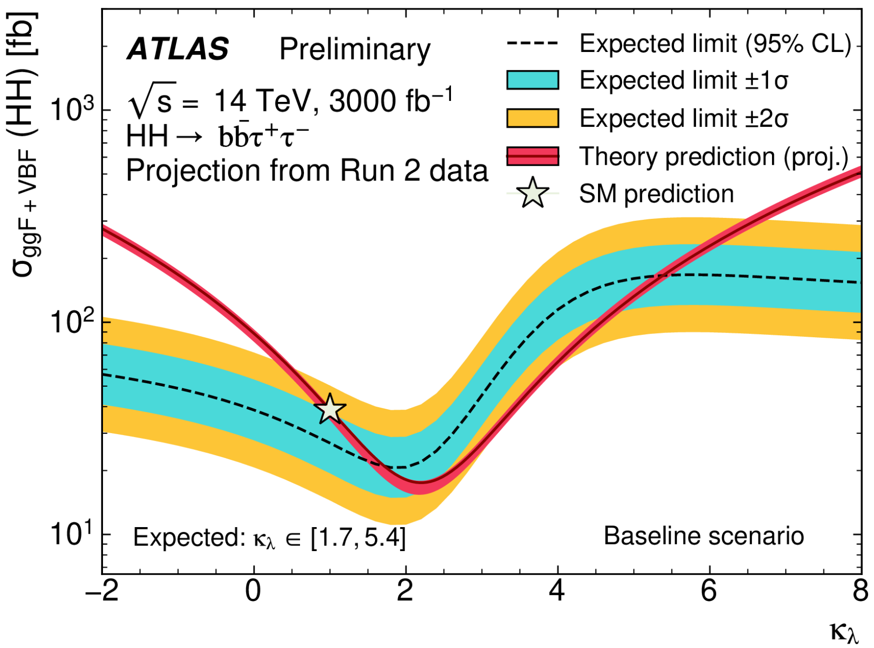
- Extrapolation from the Run2 126-139 fb^{-1}
  Combined bbbb (126 fb^{-1}) + bb$\tau\tau$ (139 fb^{-1}, old) + bb$\gamma\gamma$ (139 fb^{-1}) results

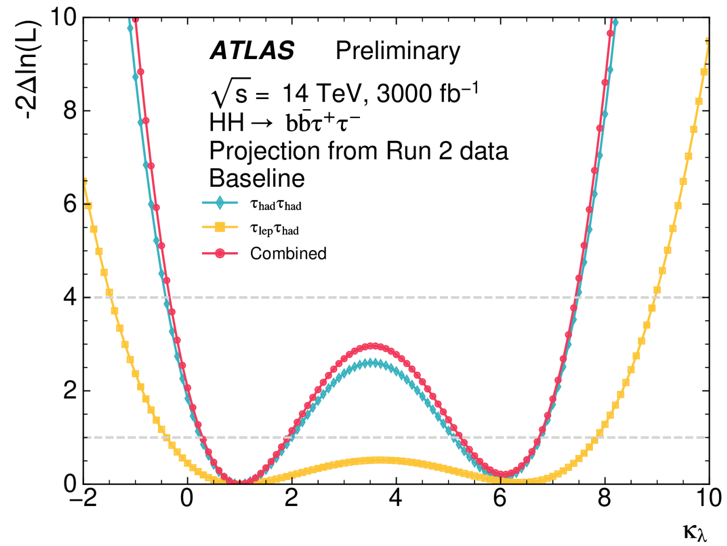
- In Baseline scenario expect 3.4 σ excess

Double minimum of the κ_λ

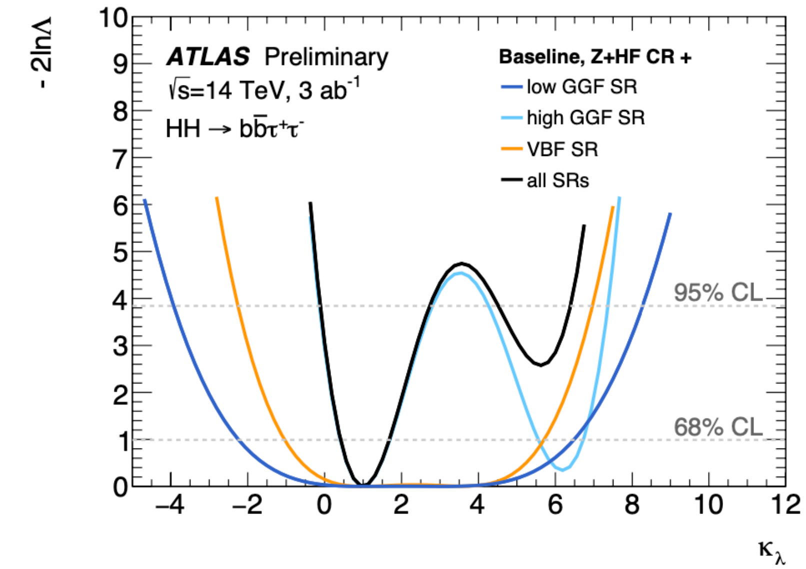
[ATL-PHYS-PUB-2021-044] [Phys. Rev. D 110 (2024) 032012]

[ATL-PHYS-PUB-2021-044]



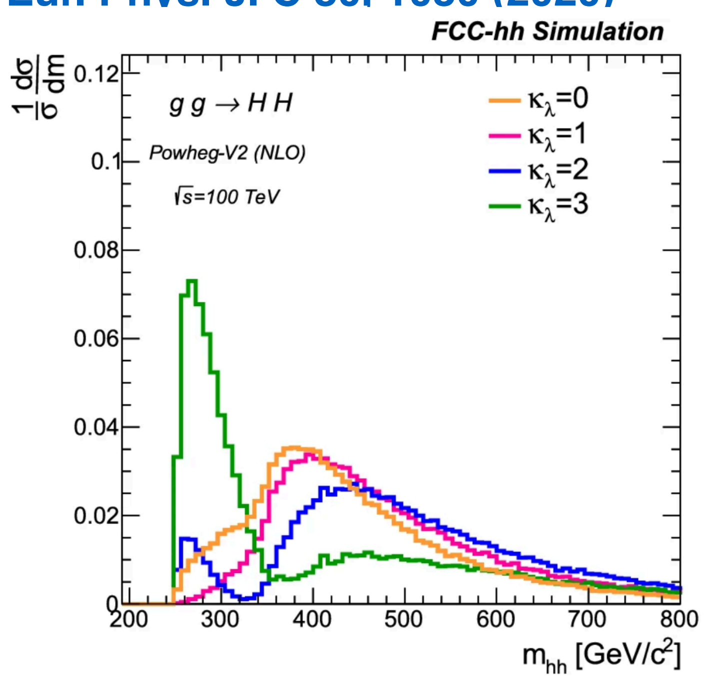


[Phys. Rev. D 110 (2024) 032012]



- 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

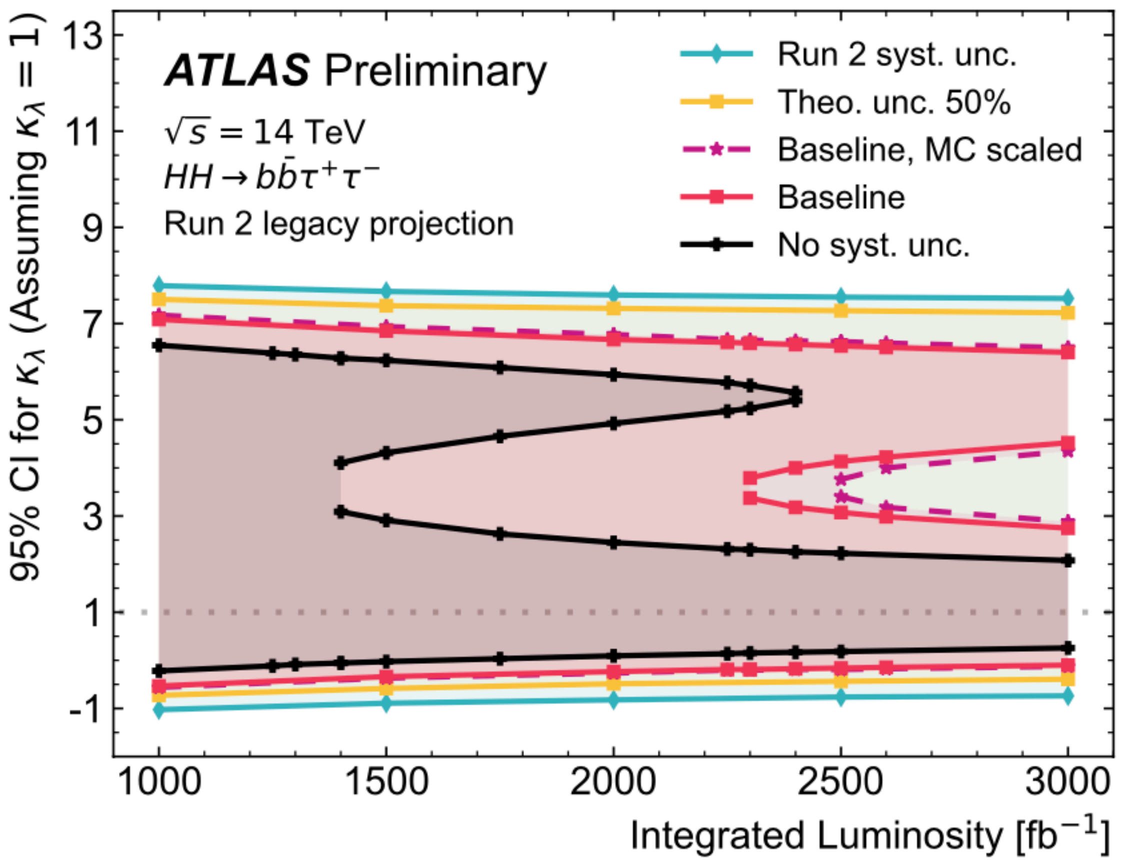
Eur. Phys. J. C 80, 1030 (2020)

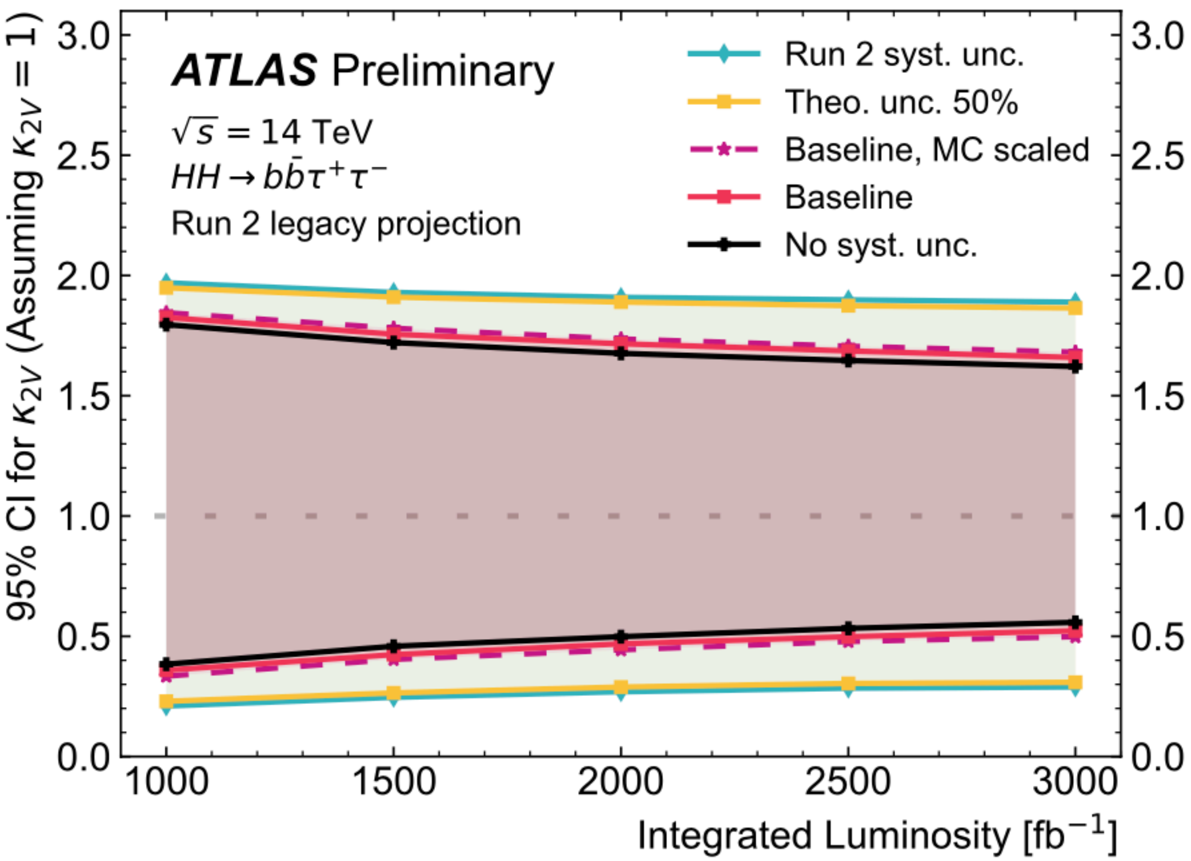


- Adding low-/high-ggF allow to see the feature of the shape of the mHH and help excluding the second minimum

95% CI for κ_λ and κ_{2V}

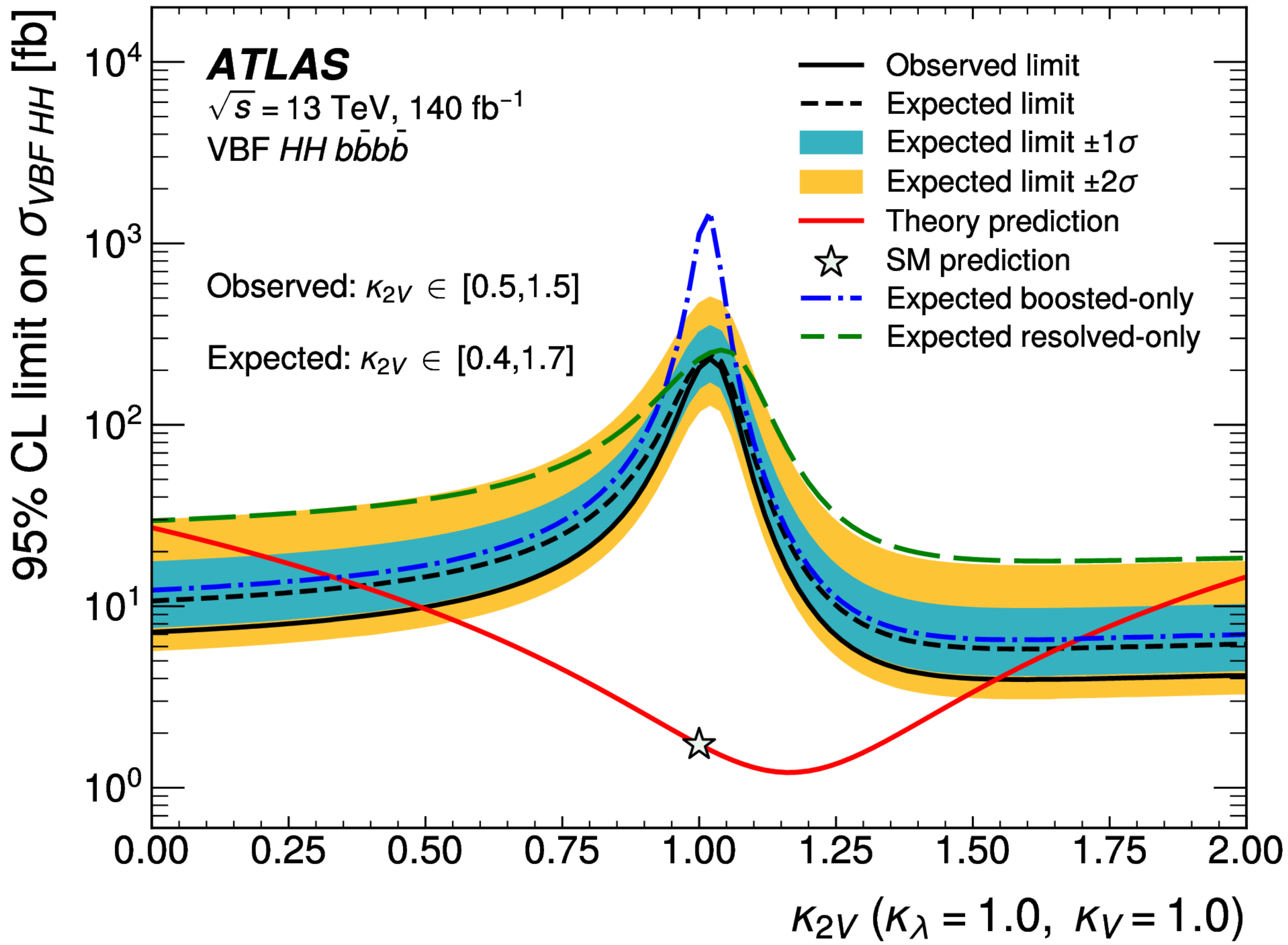
[Phys. Rev. D 110 (2024) 032012]





Constraining κ_{2V}

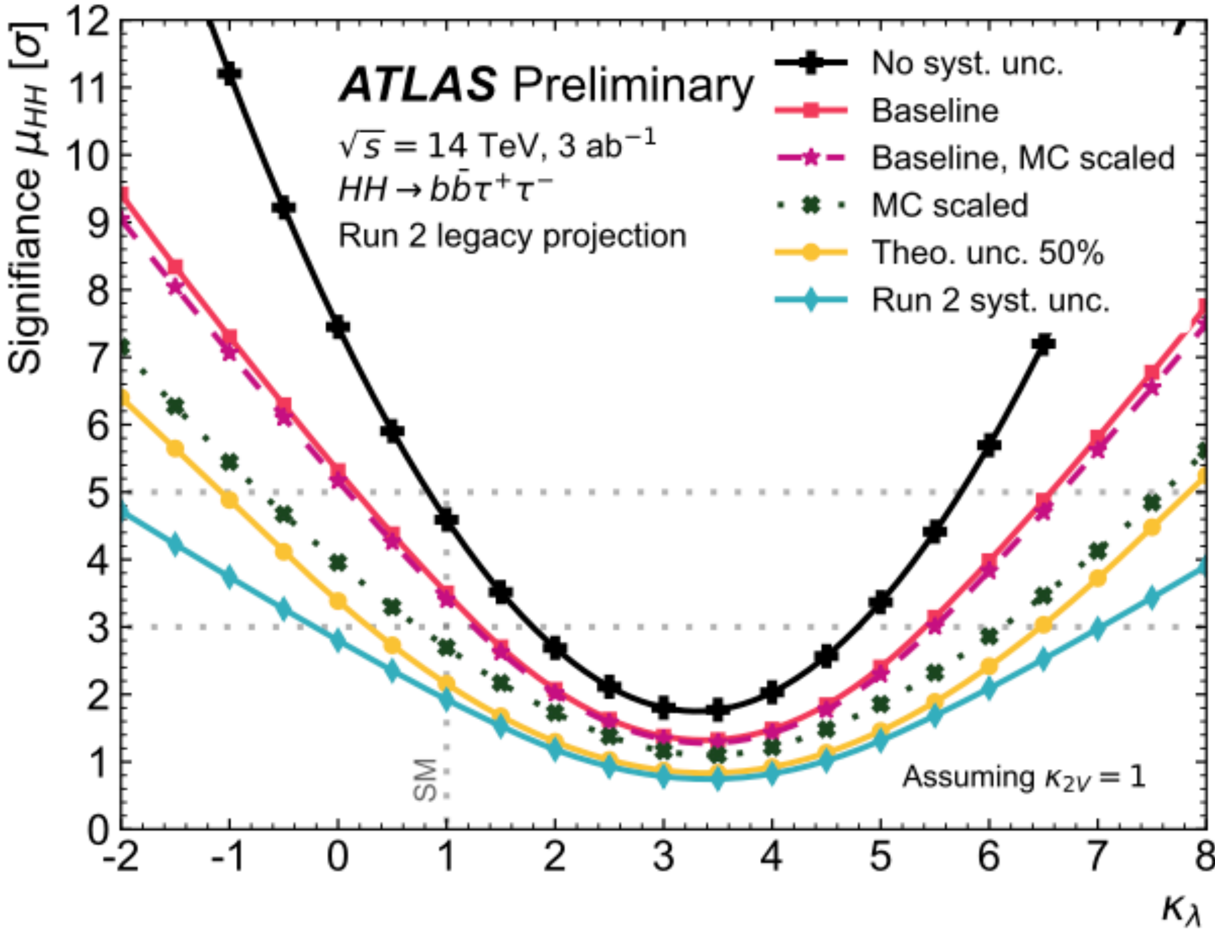
[Phys. Lett. B 858 (2024) 139007]

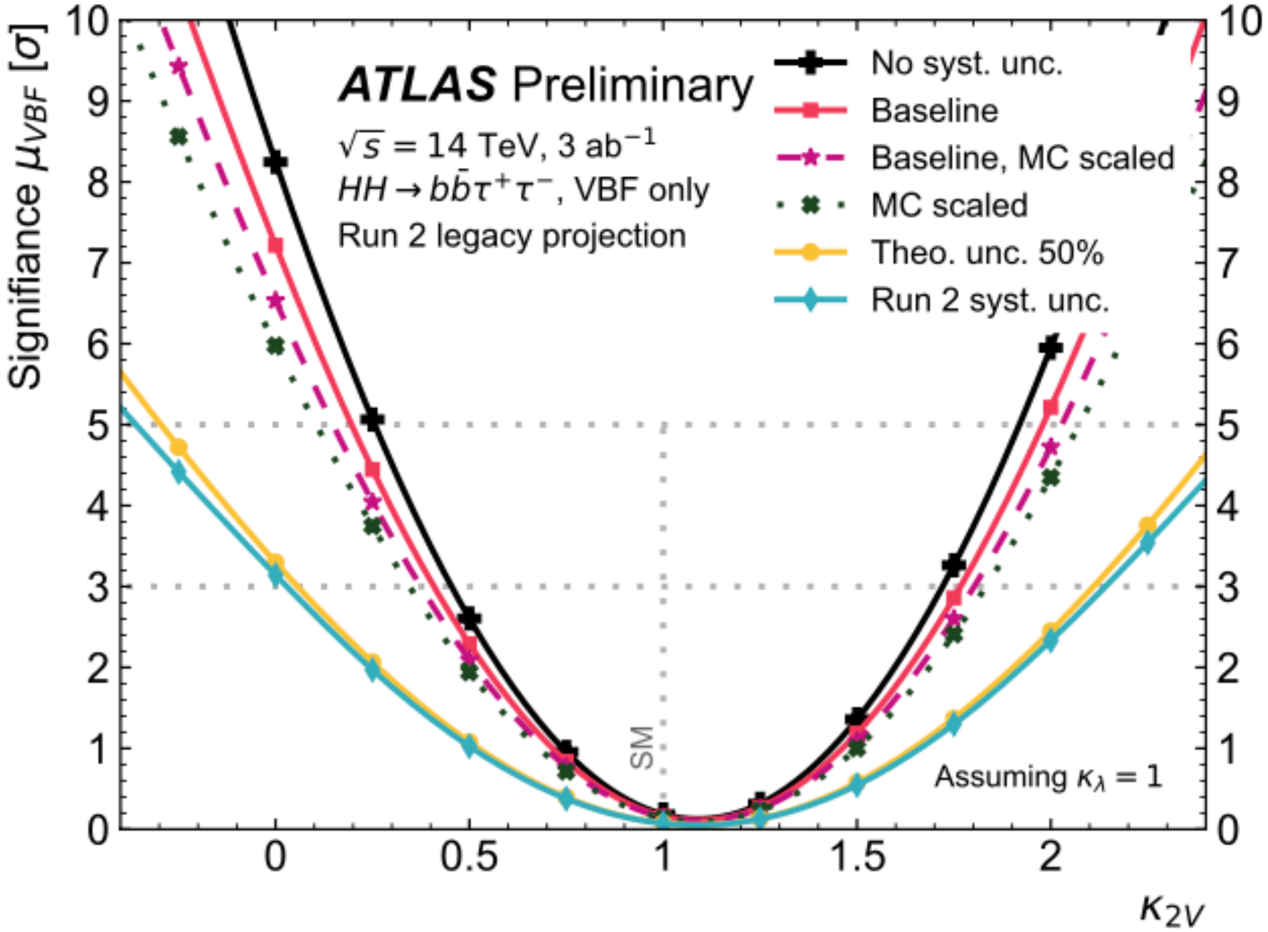


- For constraining κ_{2V} = 1 (SM), Resolved region leads (green) in bbbb channel
  For other κ_{2V} Boosted region leads (blue)
- Now analysis including the Boosted regions are ongoing/evolving
  in bbbb/bb$\tau\tau$

μ_{HH} significance varying κ values

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





68% CI varying κ values

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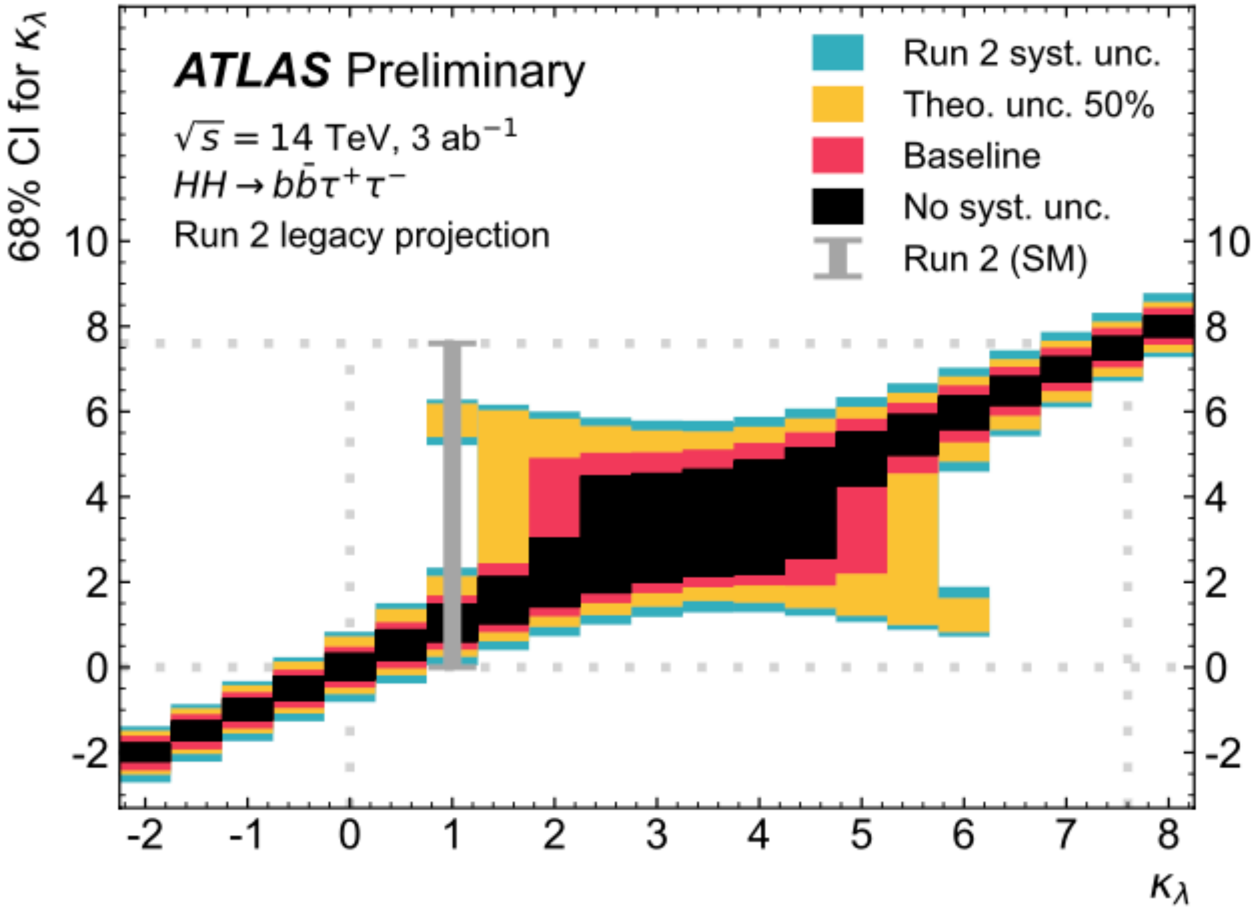

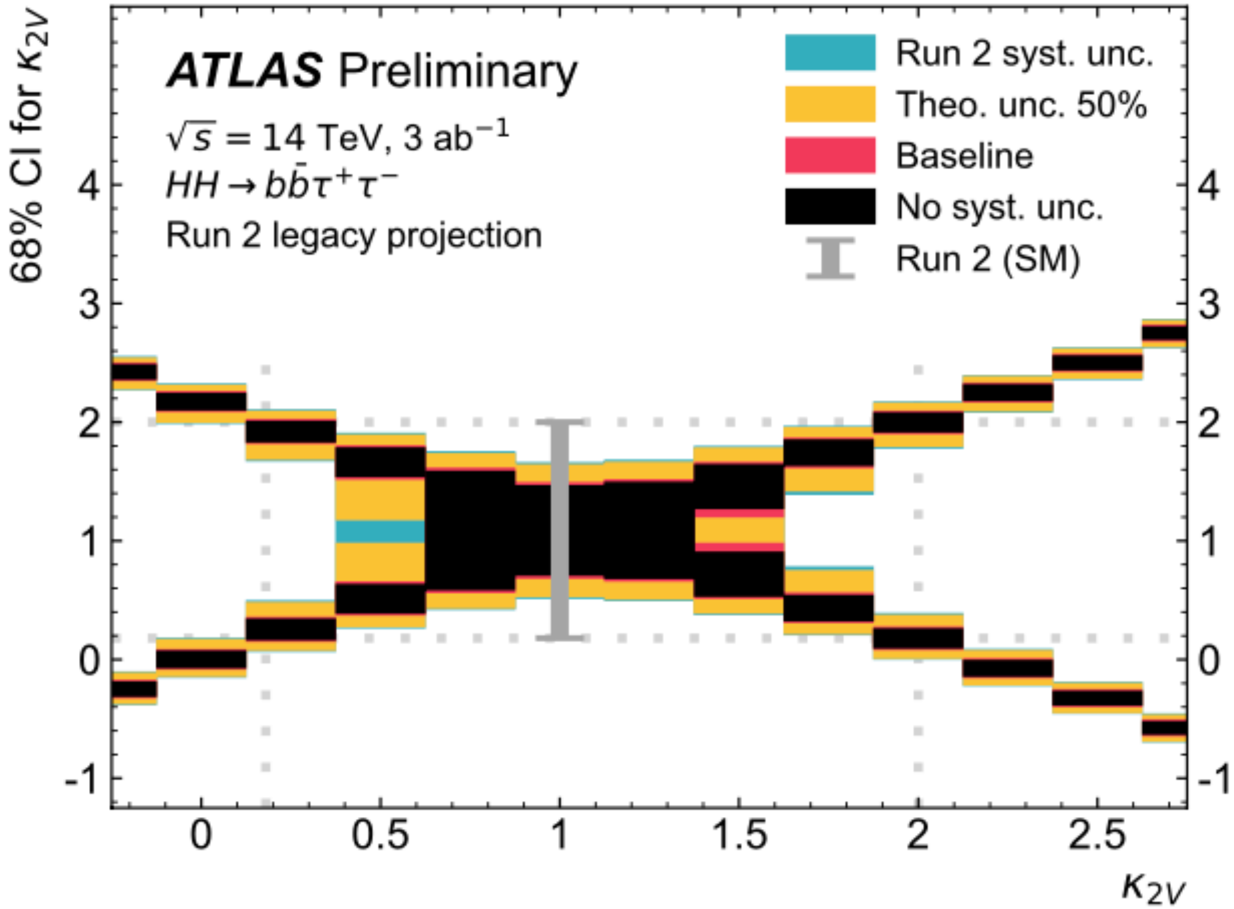

2D scan of κ_λ and κ_{2V}

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