Di-Higgs Recent Highlights and Summary

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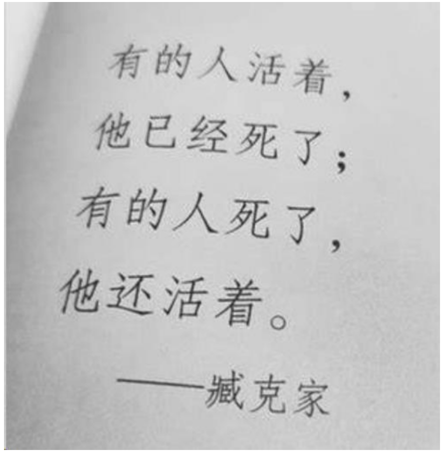
Peter left, but "Higgs" is there..

Statement on the death of Professor Peter Higgs

It has been confirmed that Professor Peter Higgs has died at the age of 94. He passed away peacefully at home on Monday 8 April following a short illness.

Professor Peter Higgs following confirmation of the existence of Higgs Boson particle in 2012.

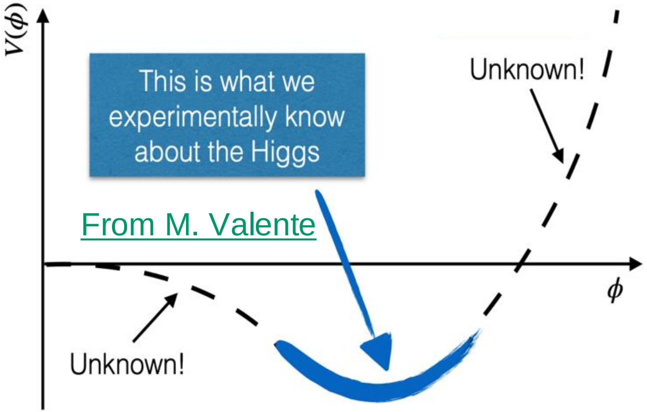
Higgs studies are crucial to be continued…


有的人活着，
他已经死了；
有的人死了，
他还活着。
——臧克家

Many Open Questions about the Higgs

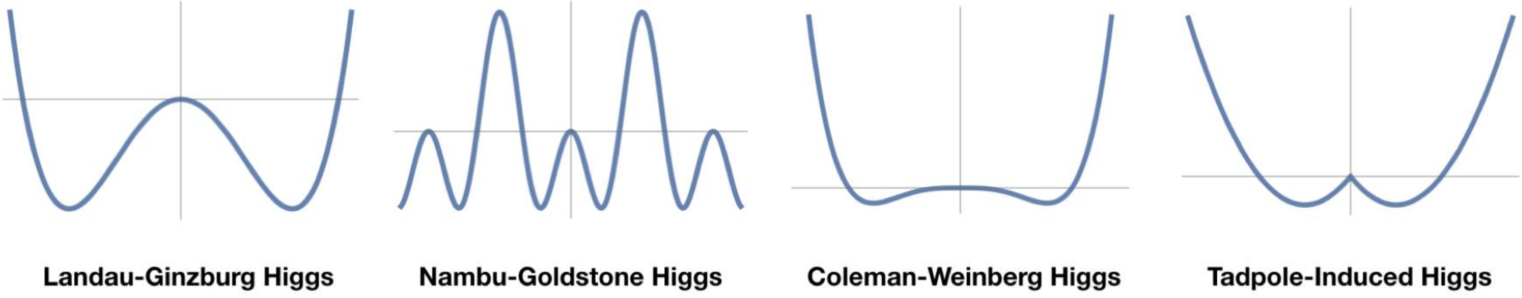
- Are the properties and couplings of the Higgs consistent with the SM prediction? What are its mass, width, rate, etc? } Talk by Kun Liu
- Can we probe the rare Higgs boson decay? Does it decay to any final states not predicted by the SM ?
- Does additional BSM Higgs boson exist? } Talk by Jin Wang
- How to access the structure of the Higgs potential? Is it consistent with SM prediction } What I will cover today
- …

Higgs Potential Not Determined Yet



From M. Valente

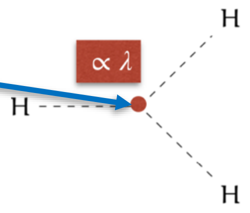
- New physics (e.g. 1st order EW phase transition) can cause a significant deviation from SM prediction
- Measurements of Higgs self-coupling can provide discrimination between different scenarios/models



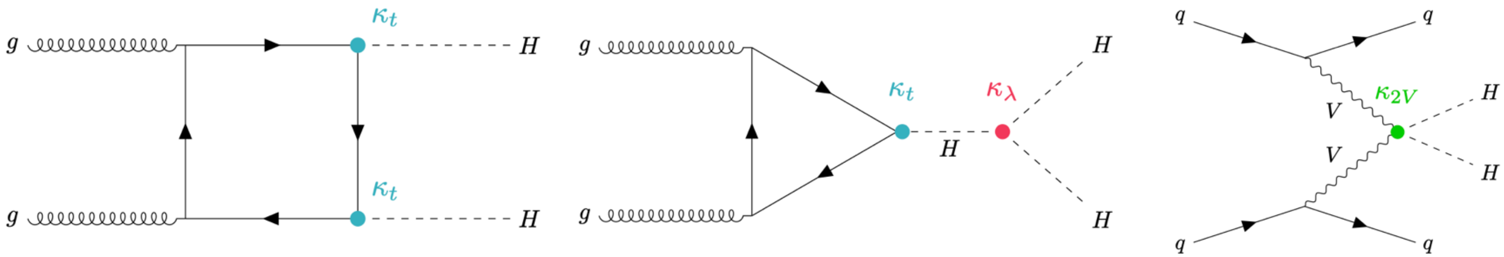
Ref: Phys. Rev. D 101, 075023 (2020)

Higgs Self-coupling and HH Production

- Higgs potential: $V(h) \;=\; \frac{1}{4}\lambda h^4 + \lambda v h^3 + \lambda v^2 h^2$
  - In SM, $\lambda \approx 0.13$ give $m_H \approx 125$ GeV



- HH productions provide directly access to Higgs self-coupling κ_λ ($\lambda_{HHH}/\lambda_{SM}$)
- SM non-resonant HH: σ_{HH}^{ggF} = 31.05 fb, σ_{HH}^{VBF} = 1.72 fb
  - Direct access to κ_λ and Higgs potential
  - VBF: unique process to probe HHVV coupling (κ_{2V})



HH Decay Channels

HH Branching Ratios

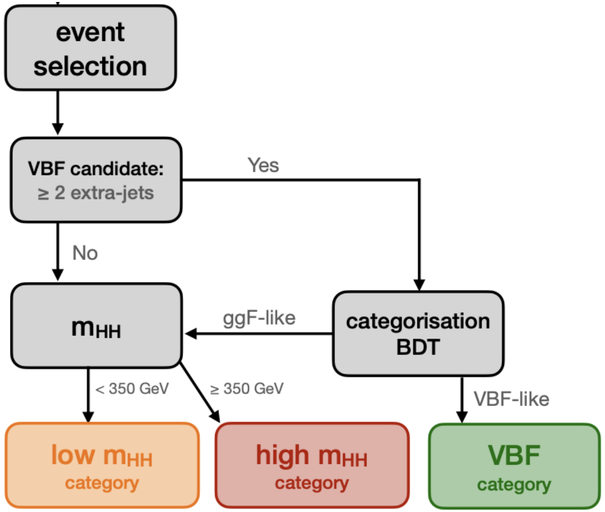
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

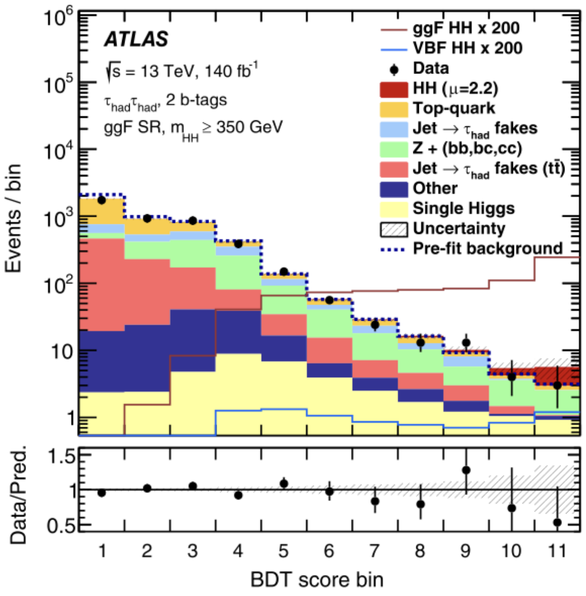
- HH events are rare and precious: ~4k events expected to be produced during Run 2 for each experiment
- H→bb: large BR but suffering from large bkg.
- H→l/τ/γ: efficient bkg. reduction
- Complementarity of various decay channels to utilize the HH events as much as we can

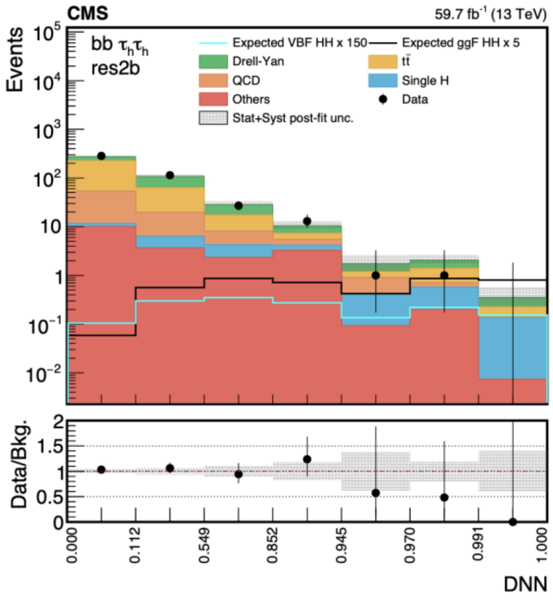
Disclaimer: due to time constraint, will only cover the most sensitive or latest results.

HH→bbττ

- Moderate BR with relatively clean signature; exploiting two channels depending on τ decay: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$
- MVA used to maximize sensitivity to both ggF and VBF modes, used as fitting discriminant

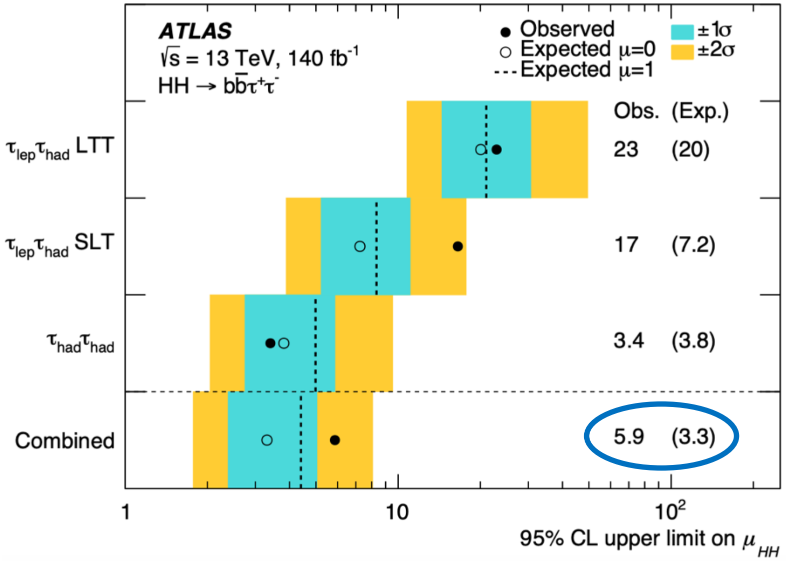




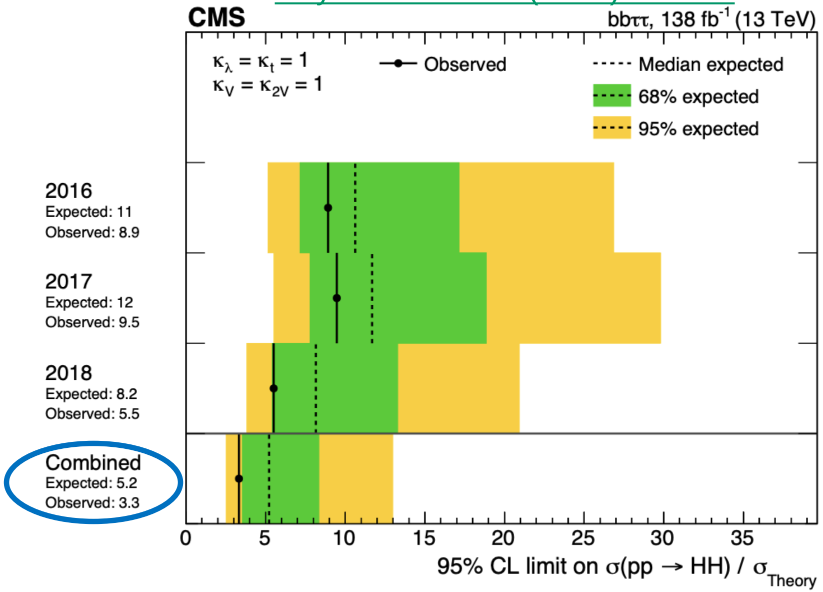


HH→bb$\tau\tau$ Results

Phys. Rev. D 110 (2024) 032012



Phys. Lett. B 842 (2023) 137531



Obs. (exp.) constraints

XS: 5.9 (3.3) × σ_{SM} → best expected XS constraint in single channel

κ_λ: [-3.1, 9.0] ([-2.5, 9.3])

κ_{2V}: [-0.5, 2.7] ([-0.2, 2.4])

Obs. (exp.) constraints

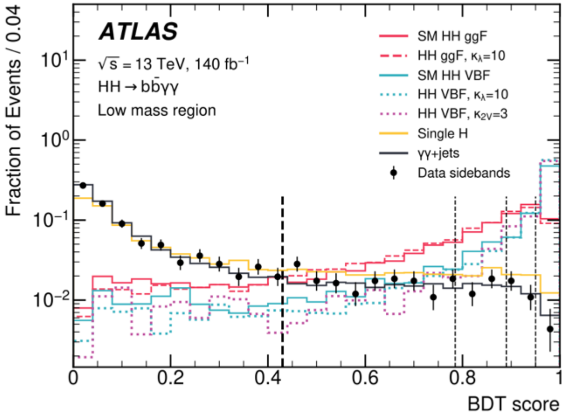
XS: 3.3 (5.2) × σ_{SM}

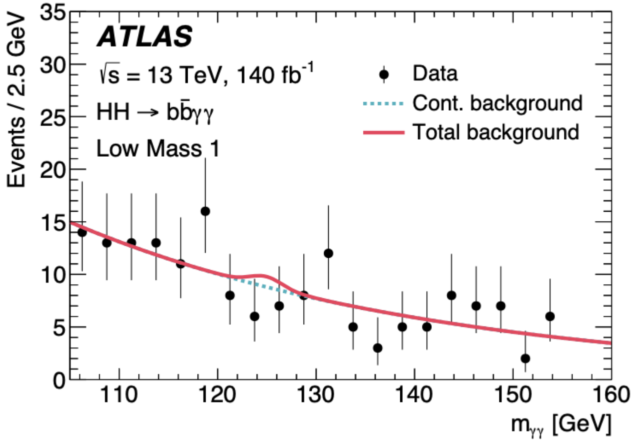
κ_λ: [-1.7, 8.7] ([-2.9, 9.8])

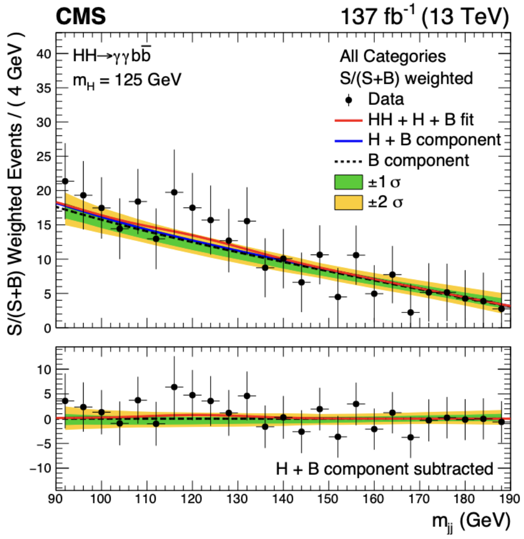
κ_{2V}: [-0.4, 2.6] ([-0.6, 2.8])

HH→bb$\gamma\gamma$

- Low BR, $\gamma\gamma$ provides clean signature and excellent mass resolution
- Di-photon trigger used for both ATLAS and CMS
- Event categorization based on XGBoost BDT and m_{HH}
- ATLAS: fit with $m_{\gamma\gamma}$; CMS: 2D fit with $m_{\gamma\gamma}$ and m_{jj}

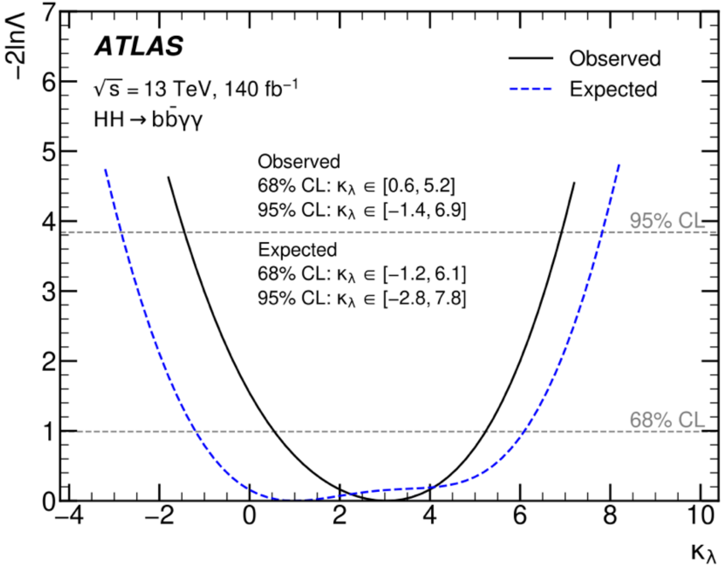






HH→bbγγ Results

JHEP 01 (2024) 066



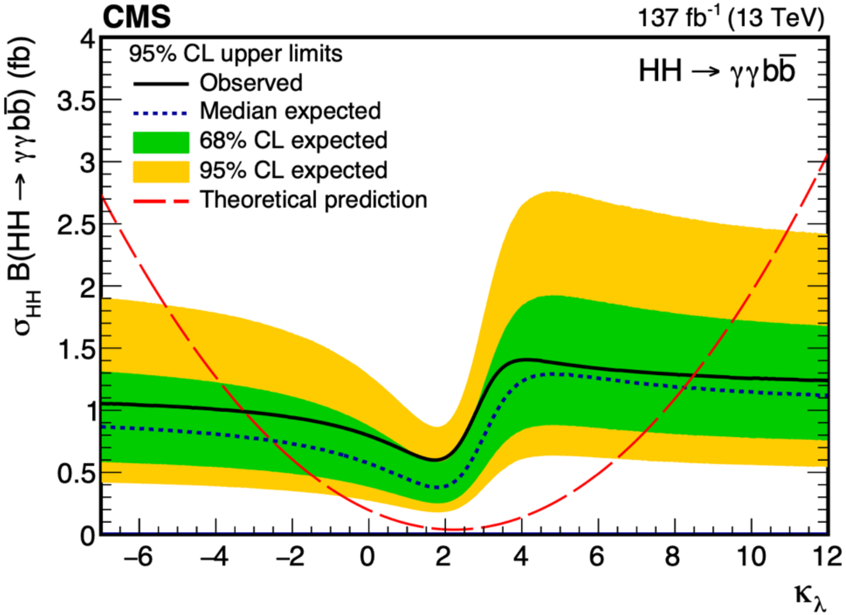
Obs. (exp.) constraints

XS: 4.0 (5.0) × σ_{SM}

κ_λ: [-1.4, 6.9] ([-2.8, 7.8])

κ_{2V}: [-0.5, 2.7] ([-1.1, 3.3])

JHEP 03 (2021) 257



Obs. (exp.) constraints

XS: 7.7 (5.2) × σ_{SM}

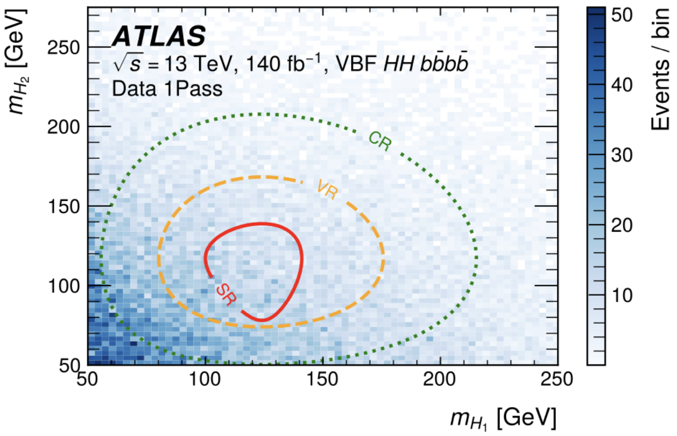
κ_λ: [-3.3, 8.5] ([-2.5, 8.2])

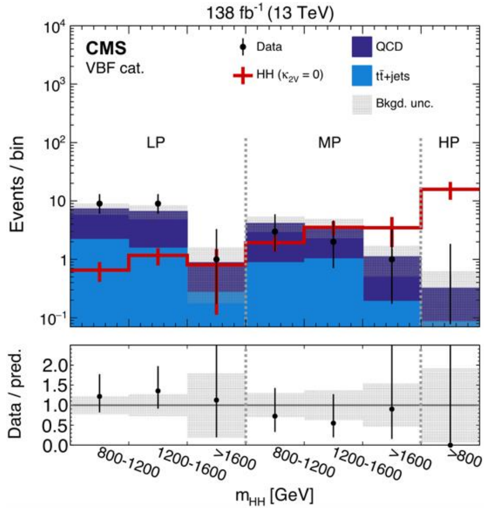
κ_{2V}: [-1.3, 3.5] ([-0.9, 3.1])

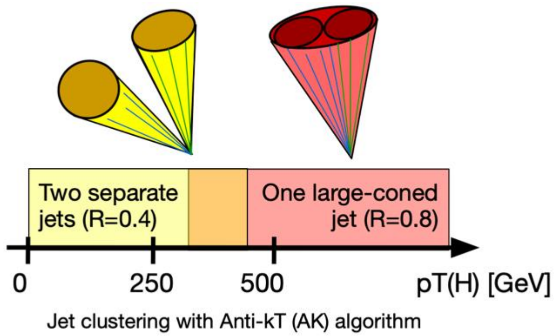
Talk by Ligang Xia

HH→bbbb

- Largest BR, but suffering from large QCD and ttbar background
- Two scenarios: resolved and boosted (sensitive to VBF topology)
- Resolved: cut-based categorization for ATLAS; CMS categorized events with m_{HH} and BDT
- Boosted: DNN-based tagger for ATLAS; ParticleNet GNN tagger for CMS

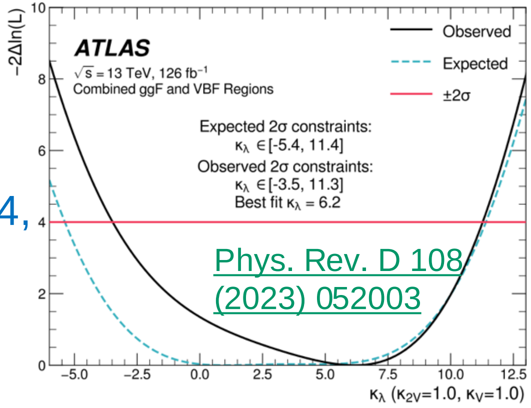




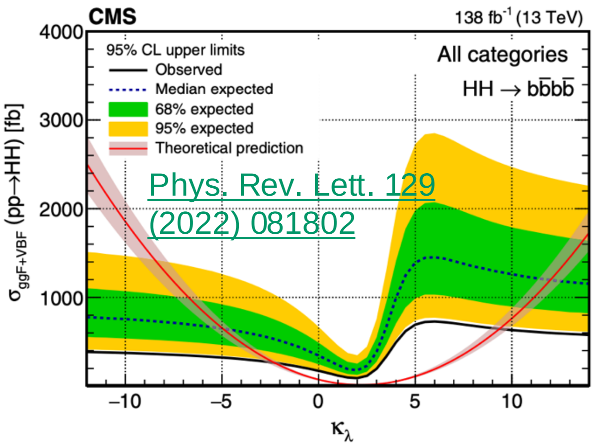


HH→bbbb Results

XS: 4.0 (5.0) × σ_{SM}
κ_λ: [-3.5, 11.3] ([-5.4, 11.4])



Phys. Rev. D 108 (2023) 052003

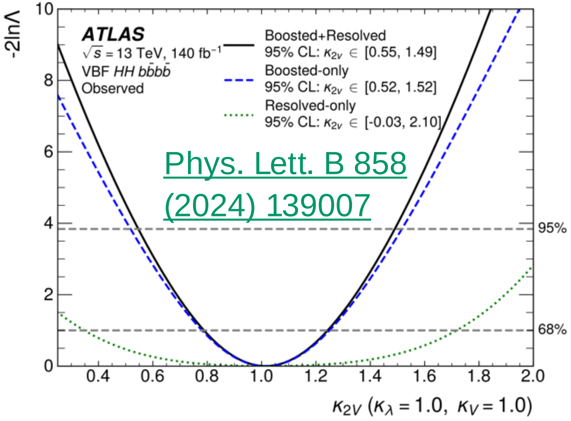


Phys. Rev. Lett. 129 (2022) 081802

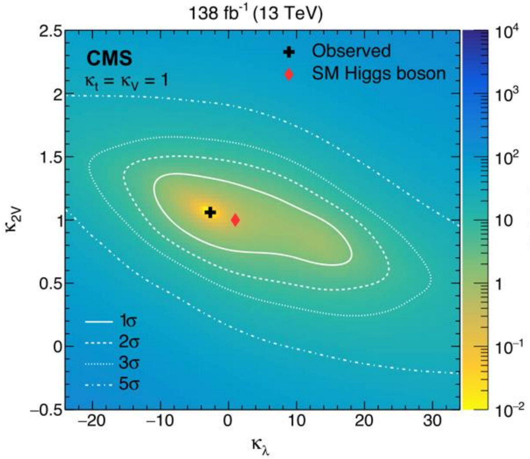
XS: 3.9 (7.8) × σ_{SM}
κ_λ: [-2.3, 9.4] ([-5.0, 12])

κ_{2V}: [0.55, 1.49] ([0.37, 1.67])

Talk by Zhen Wang



Phys. Lett. B 858 (2024) 139007

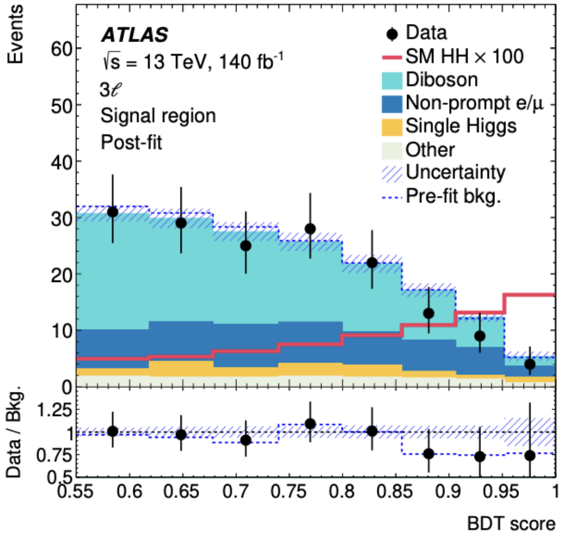


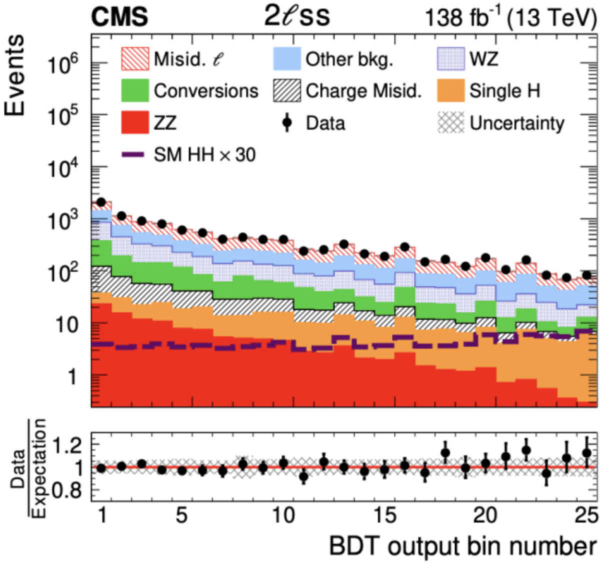
κ_{2V}: [0.62, 1.41] ([0.66, 1.37])

Phys. Rev. Lett. 131 (2023) 041803

HH→Multilepton

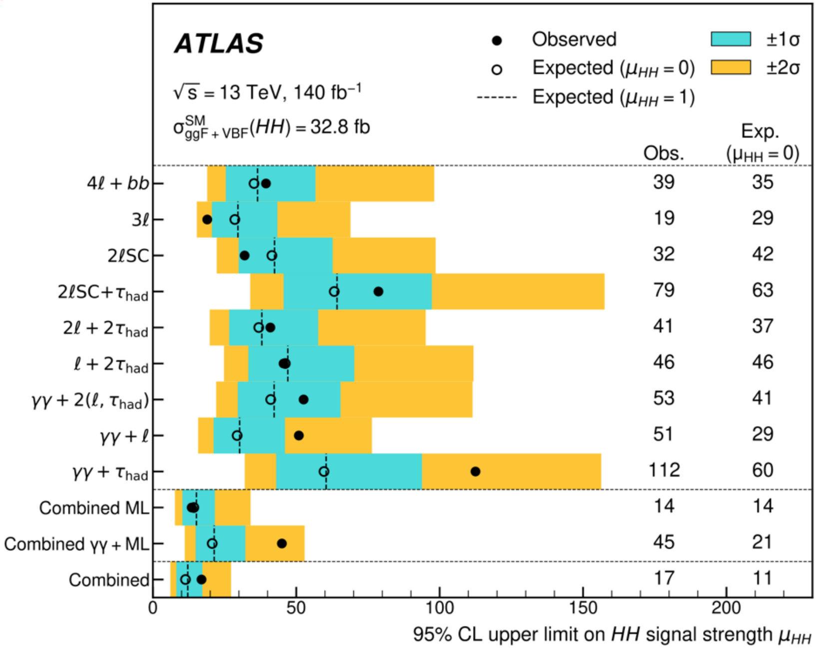
- Complementary way to probe HH with leptons, hadronic taus, and photons
- ATLAS: targeting HH→bbZZ, 4V ($V = W/Z$), $VV\tau\tau$, 4τ, $\gamma\gamma VV$ and $\gamma\gamma\tau\tau$
- CMS: targeting HH→ WW*WW*, WW*$\tau\tau$, and $\tau\tau\tau\tau$
- Both experiments utilized MVA to enhance signal sensitivity





HH→Multilepton Results

JHEP 08 (2024) 164

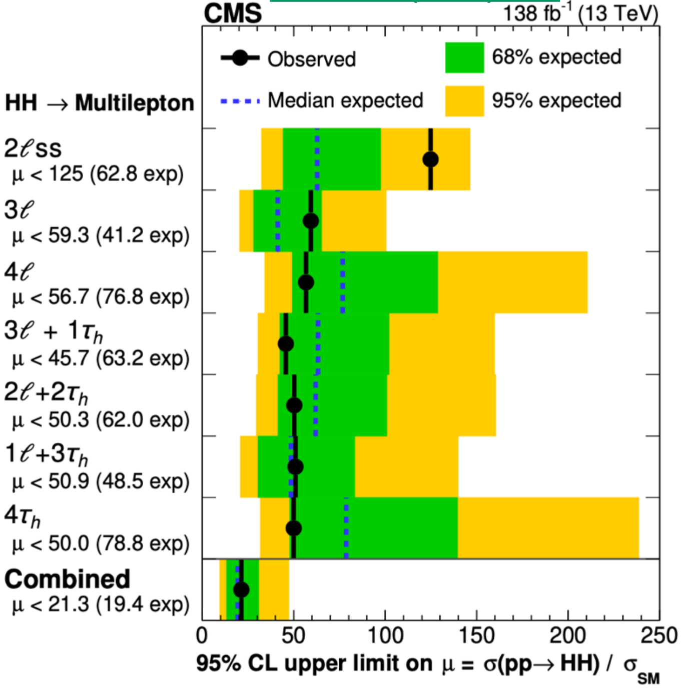


XS limit: 17 (11) × σ_{SM}

κ_λ: [-6.2, 11.6] ([-4.5, 9.6])

κ_{2V}: [-2.5, 4.6] ([-1.9, 4.1])

JHEP 07 (2023) 095



XS limit: 21.3 (19.4) × σ_{SM}

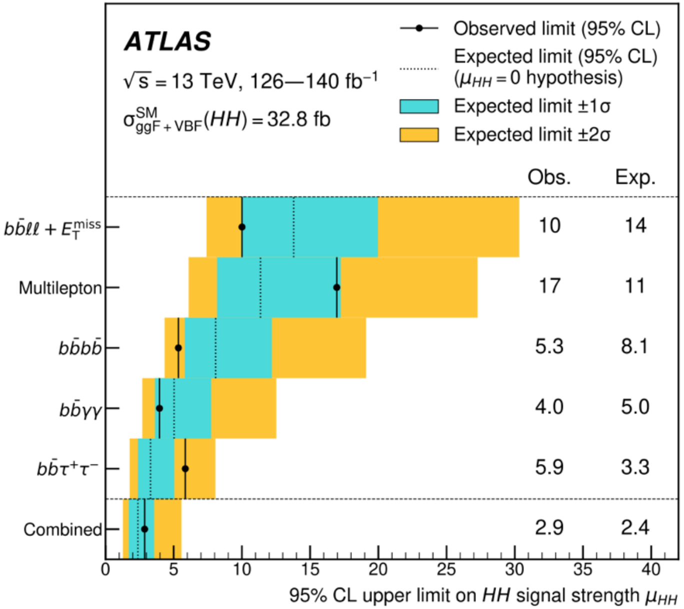
κ_λ: [-6.9, 11.1] ([-6.9, 11.7])

Talk by Qiyu Sha

HH Combination

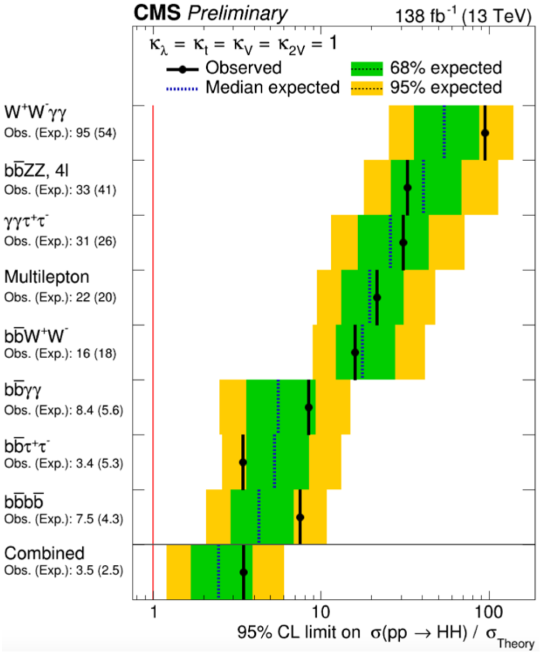
- Combination of the major decay channels to maximize sensitivity

Phys. Rev. Lett. 133 (2024) 101801



XS limit: 2.9 (2.4) × σ_{SM}
κ_λ: [-1.2, 7.2] ([-1.6, 7.2])
κ_{2V}: [0.6, 1.5] ([0.4, 1.6])

PAS-HIG-20-011

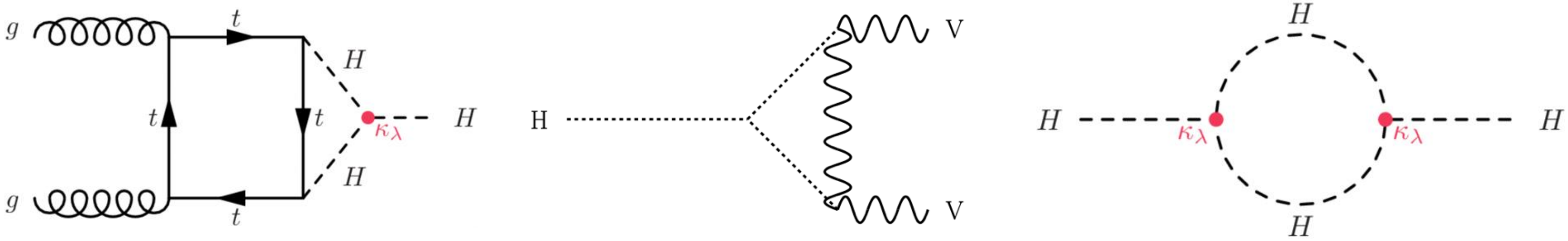


Talk by Chen Zhou

XS limit: 3.5 (2.5) × σ_{SM}
κ_λ: [-1.4, 7.0] ([-1, 7.2]) → best expected constraint
κ_{2V}: [0.6, 1.4] ([0.7, 1.4])

κ_λ Constraint from Single Higgs

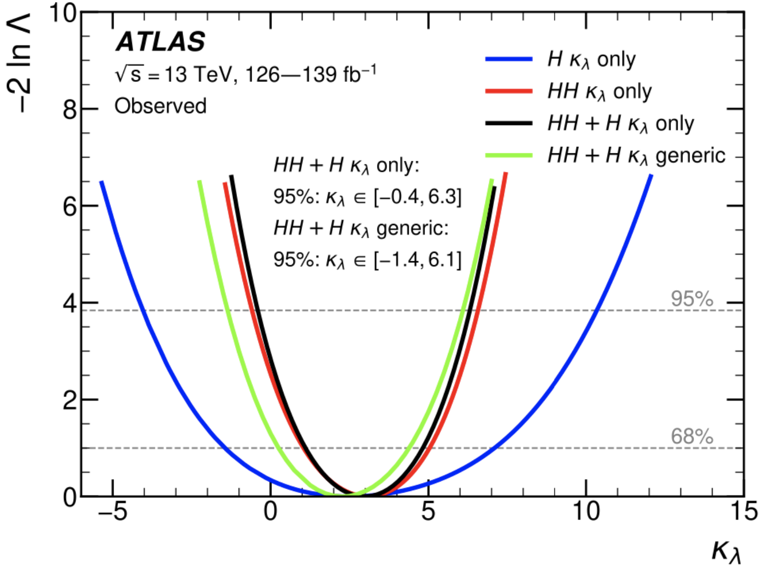
- κ_λ also can be probed through NLO EW correction of single Higgs processes (e.g. in the production, decay, Higgs self-energy)



- Combination of HH and single Higgs is expected to provide the most sensitive results of κ_λ

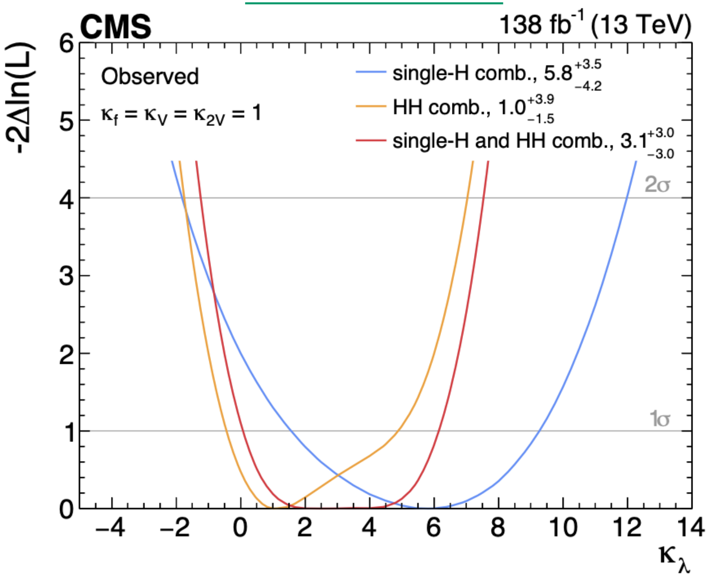
Results from HH+H Combination

Phys. Lett. B 843 (2023) 137745



Obs. (exp.) κ_λ constraint: [-0.4, 6.3] ([-1.9, 7.6])

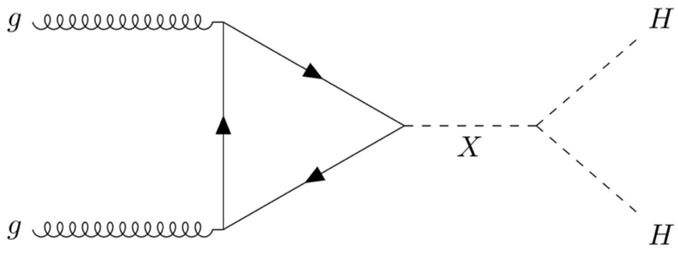
arXiv:2407.13554



Obs. (exp.) κ_λ constraint: [-1.2, 7.5] ([-2.0, 7.7])

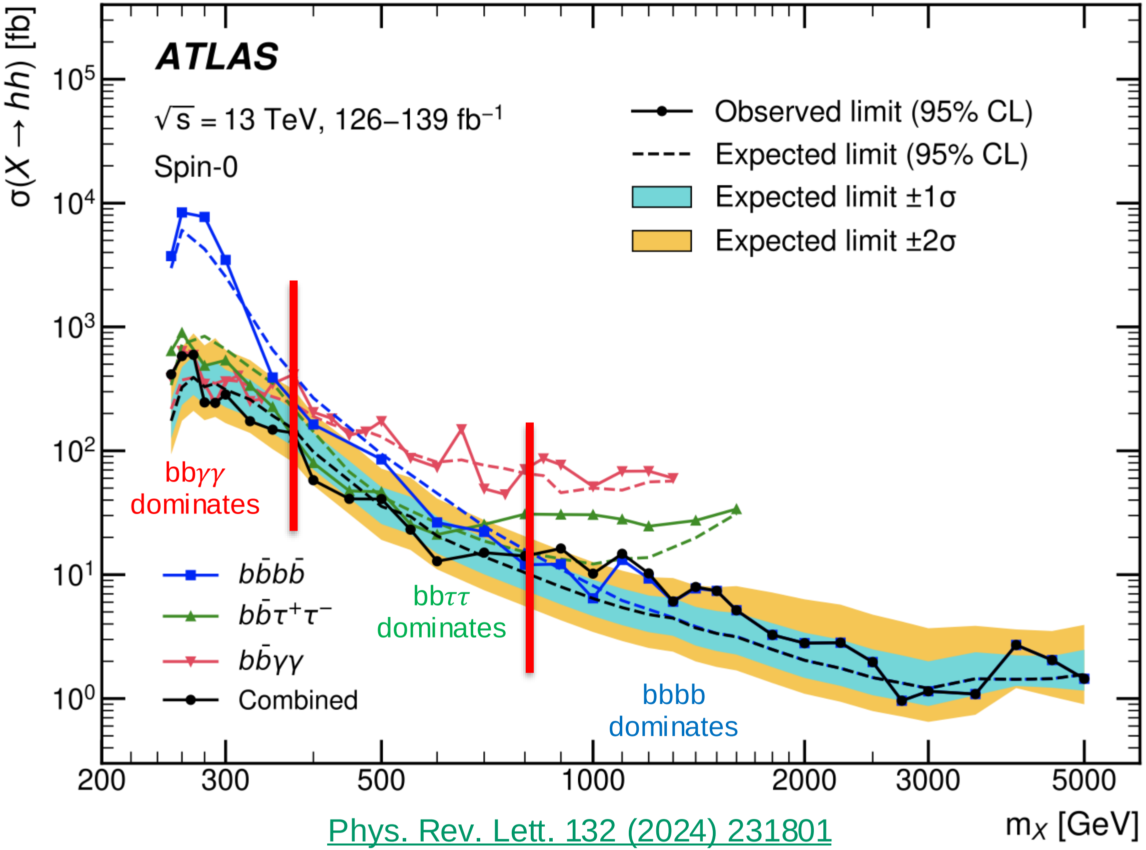
Search for Resonant HH Production

- Various BSM theories predict heavy resonances which can decay into Higgs bosons pair, such as
  - ➢ Spin-0 heavy scalars
  - ➢ Spin-2 gravitons from the Randall–Sundrum model
- ATLAS performed a combination of HH→bb$\tau\tau$, bb$\gamma\gamma$, bbbb
- CMS combination also included bbWW and multilepton channels



Due to time constraint, will only show the combination results of searching ggF X→HH

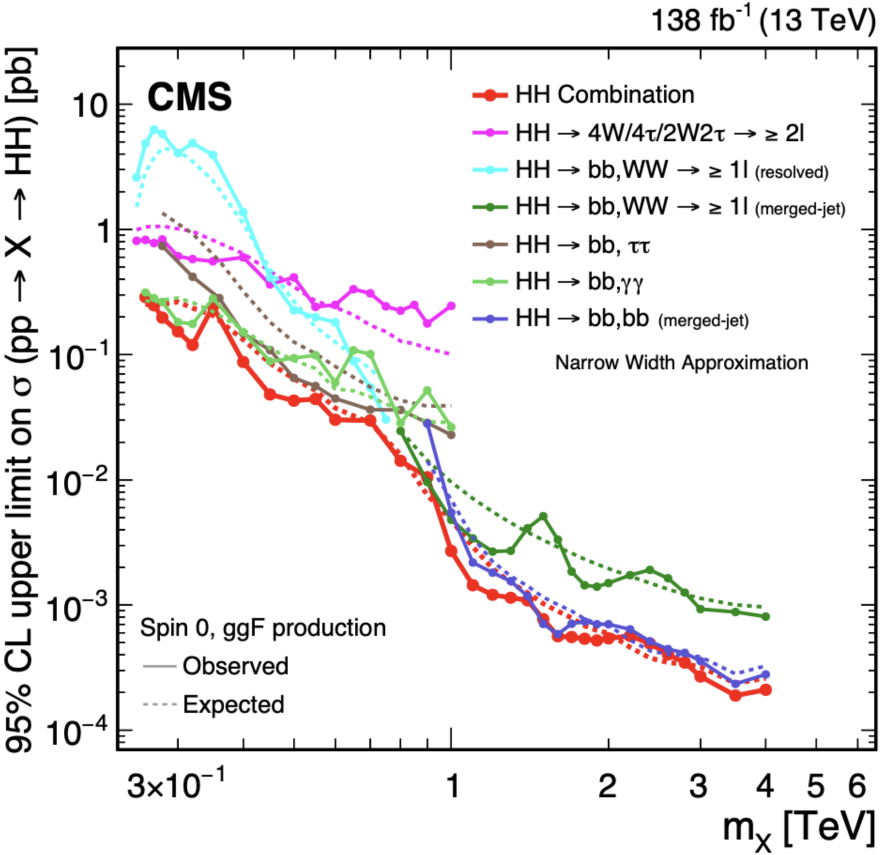
ATLAS X→HH Combination Result



Phys. Rev. Lett. 132 (2024) 231801

No statistically significant excess found, largest excess at 1.1 TeV: local (global) significance is 3.3σ (2.1σ)

CMS X→HH Combination Result



No deviation >2σ from prediction is observed
Strongest observed limits to date

Talk by Zhenxuan Zhang

Phys. Rev. Lett. 132 (2024) 231801

HL-LHC Projection for ATLAS HH→bb$\tau\tau$

$L_{\text{int}} = 3000\,\text{fb}^{-1}$	$b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$	$b\bar{b}\tau_{\text{had}}\tau_{\text{had}}$	Combination
No syst. unc.	2.3	4.0	4.6
Baseline	1.8	3.1	3.5
Baseline with MC luminosity scaled	1.7	3.0	3.4
MC luminosity scaled	1.6	2.4	2.7
Theoretical unc. halved	1.0	1.9	2.2
Run 2 syst. unc.	0.9	1.8	1.9

ATL-PHYS-PUB-2024-016

HHH coupling modifier κ_λ

Uncertainty configuration	95% confidence interval	
	$2000\,\text{fb}^{-1}$	$3000\,\text{fb}^{-1}$
No syst. unc.	$[0.1, 2.4] \cup [4.9, 5.9]$	$[0.3, 2.1]$
Baseline	$[-0.2, 6.7]$	$[-0.1, 2.7] \cup [4.5, 6.4]$
Baseline with MC luminosity scaled	$[-0.3, 6.8]$	$[-0.1, 2.9] \cup [4.3, 6.5]$
MC luminosity scaled	$[-0.6, 7.1]$	$[-0.5, 6.8]$
Theoretical unc. halved	$[-0.5, 7.3]$	$[-0.4, 7.2]$
Run 2 syst. unc.	$[-0.8, 7.6]$	$[-0.7, 7.5]$

HL-LHC projection of HH→bb$\tau\tau$ from 2015

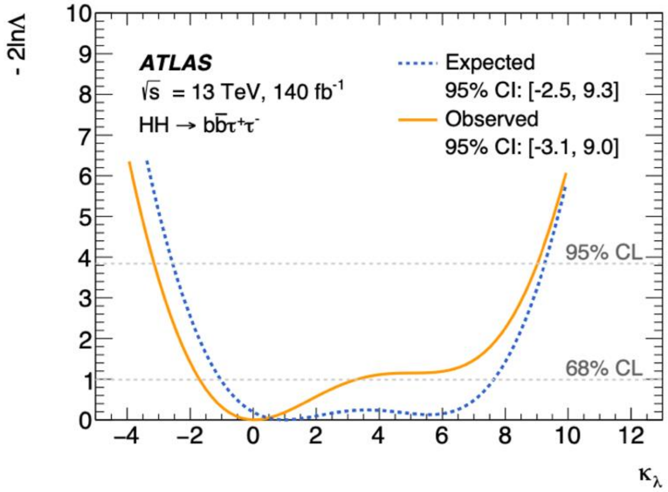
ATL-PHYS-PUB-2015-046

ing SM background and SM signal, we expect to set an upper limit of the cross section for the di-Higgs production of $4.3 \times \sigma(HH \rightarrow b\bar{b}\tau^+\tau^-)$ at 95% Confidence Level. Using an effective Lagrangian for the Higgs potential, and allowing its trilinear self-coupling to vary, we can project an exclusion of $\lambda_{HHH}/\lambda_{SM} \leq -4$ and $\lambda_{HHH}/\lambda_{SM} \geq 12$.

We Surpassed this with just Run-2 Data

ATL-PHYS-PUB-2015-046

ing SM background and SM signal, we expect to set an upper limit of the cross section for the di-Higgs production of $4.3 \times \sigma(HH \rightarrow b\bar{b}\tau^+\tau^-)$ at 95% Confidence Level. Using an effective Lagrangian for the Higgs potential, and allowing its trilinear self-coupling to vary, we can project an exclusion of $\lambda_{HHH}/\lambda_{SM} \leq -4$ and $\lambda_{HHH}/\lambda_{SM} \geq 12$.



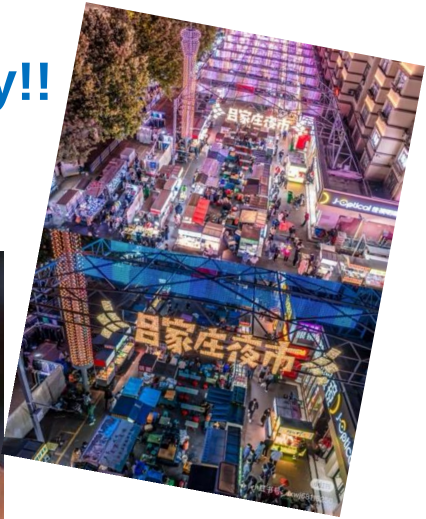
Exp. limit on XS: $3.3 \times \sigma_{SM}$
Exp. κ_λ constraint: $-2.5 \leq \kappa_\lambda \leq 9.3$
The HL-LHC projection ($3\ ab^{-1}$) in 2015 was surpassed with just $140\ fb^{-1}$ Run-2 data

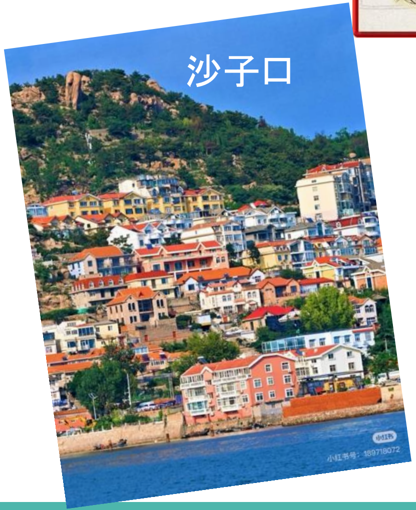
Summary

- Presented the latest HH results based on the Run 2 dataset at LHC: no deviation from SM prediction seen, stringent constraints obtained for HH XS and κ_λ
- Many other interesting results (VHH, HHH, EFT interpretation, etc) can be seen in the parallel sessions (apologize for not covering them today)
- Run 3 and HL-LHC provide more room for exploring the Higgs potential!

More discussions on Higgs potential:
https://indico.pnp.ustc.edu.cn/event/2009/

A warm welcome to Qingdao! Enjoy your stay!!





Backup

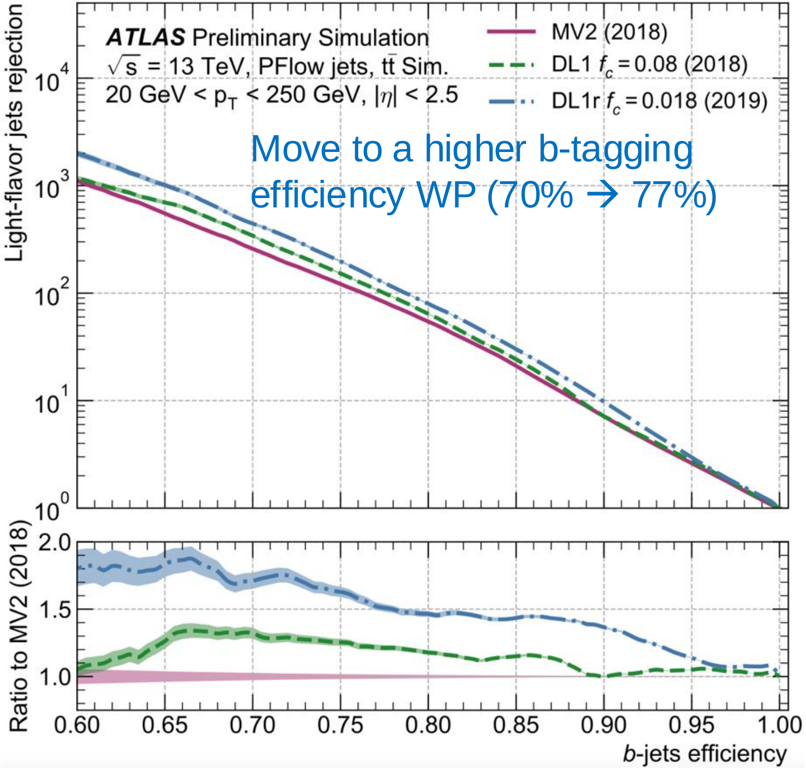
HL-LHC Projection

ATL-PHYS-PUB-2022-053

	Significance [σ]			
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination
No syst. unc.	2.3	4.0	1.8	4.9
Baseline	2.2	2.8	0.99	3.4
Theoretical unc. halved	1.1	1.7	0.65	2.1
Run 2 syst. unc.	1.1	1.5	0.65	1.9

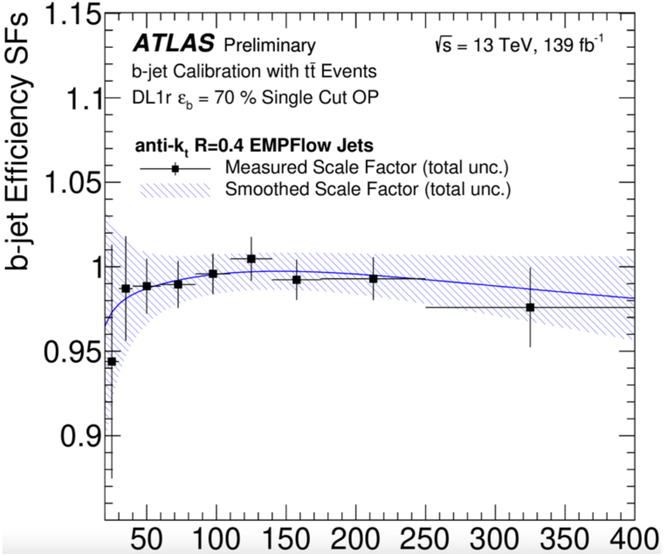
Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

Flavor Tagging Improvement

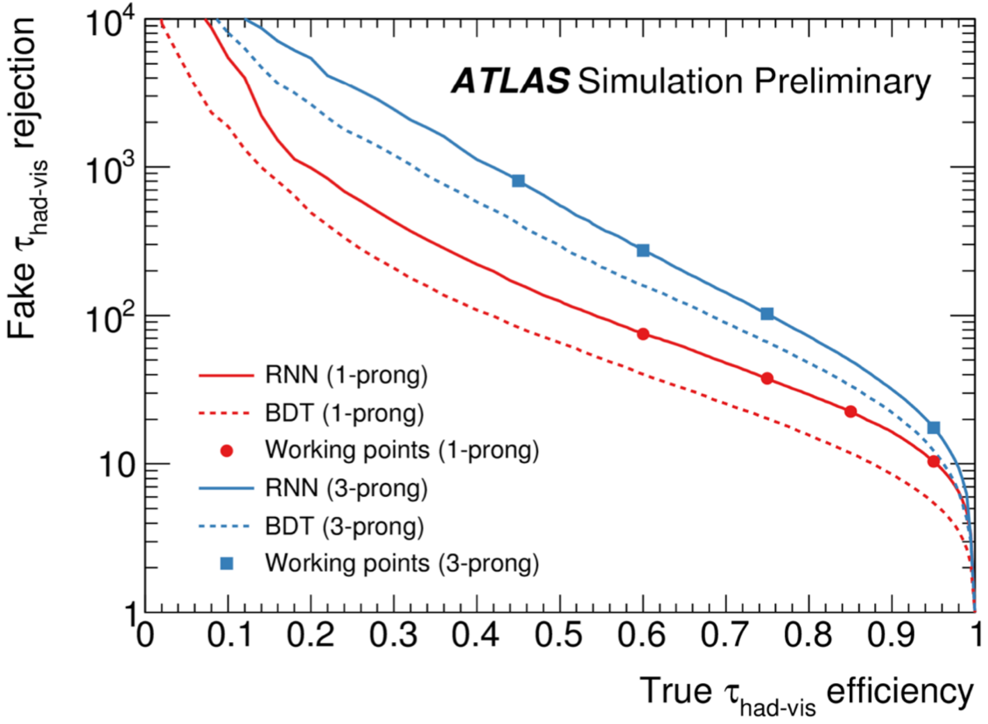


Move to a higher b-tagging efficiency WP (70% → 77%)

Likelihood-based calibration provides >2x reduction in uncertainties



τ Identification Improvement



RNN ID shows 2x improvement compared with BDT

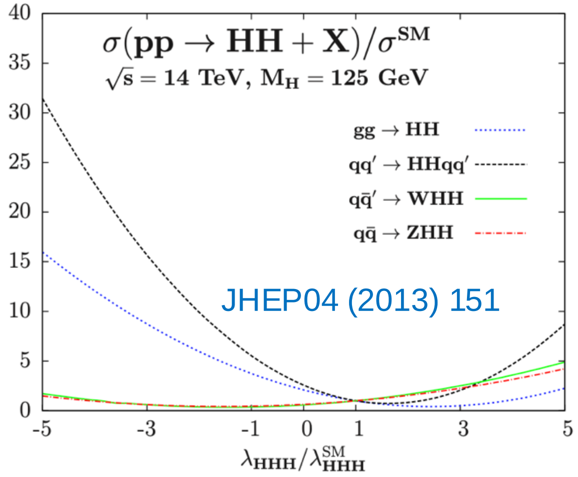
Moved from “medium” to “loose” WP

Per-tau efficiency:

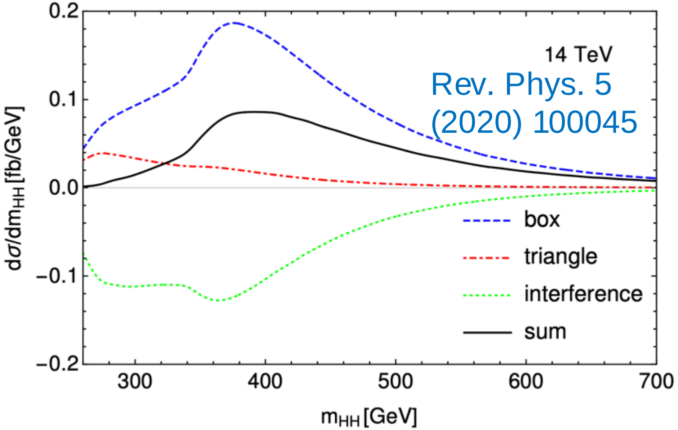
1-prong: 75% → 85%

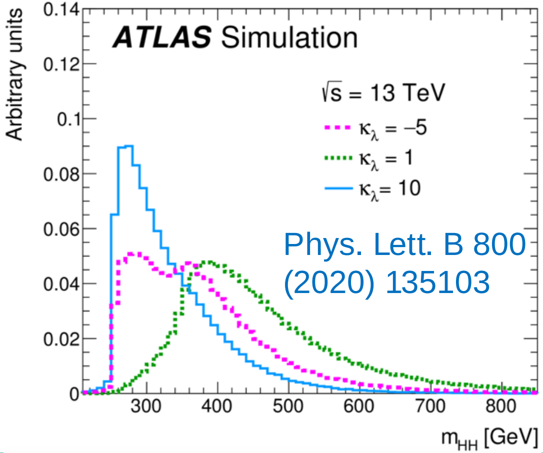
3-prong: 60% → 75%

BSM Physics in HH Processes

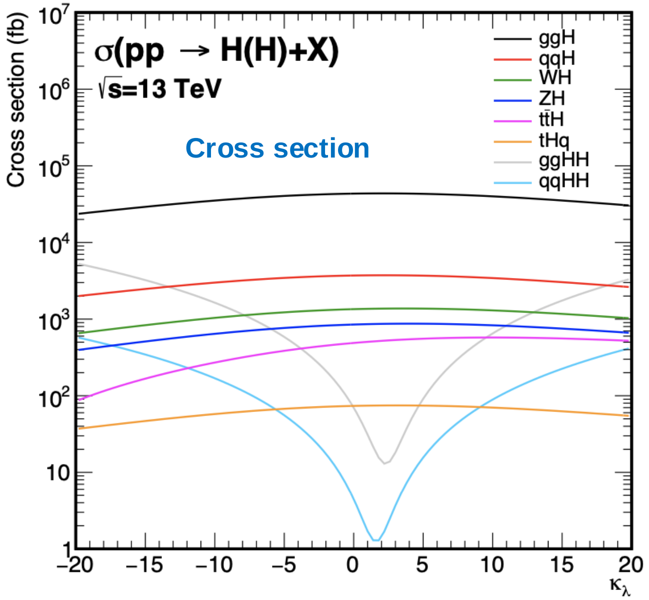


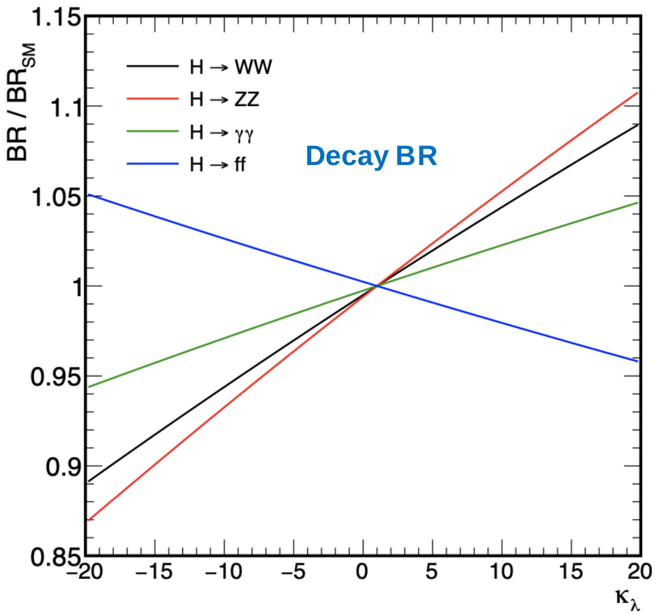
Anomalous κ_λ would result in enhanced HH XS and modified kinematics of the process due to different contributions and interference of diagrams

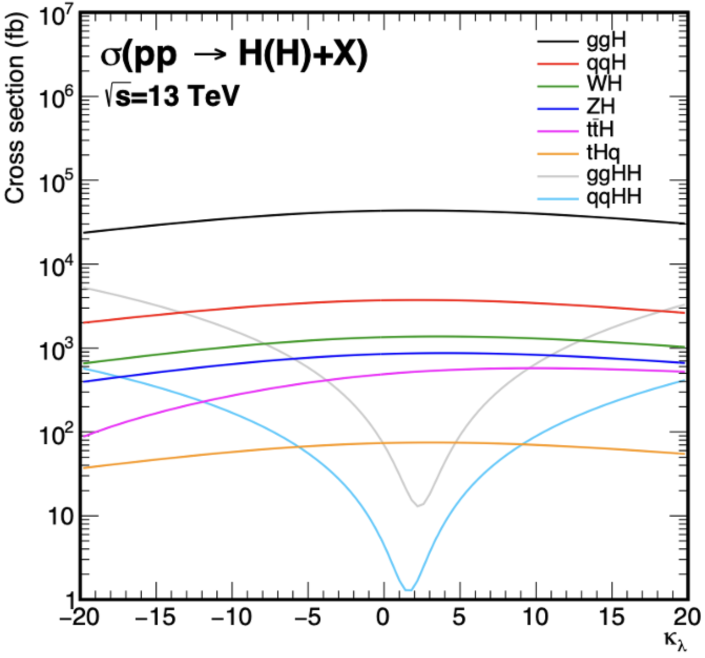


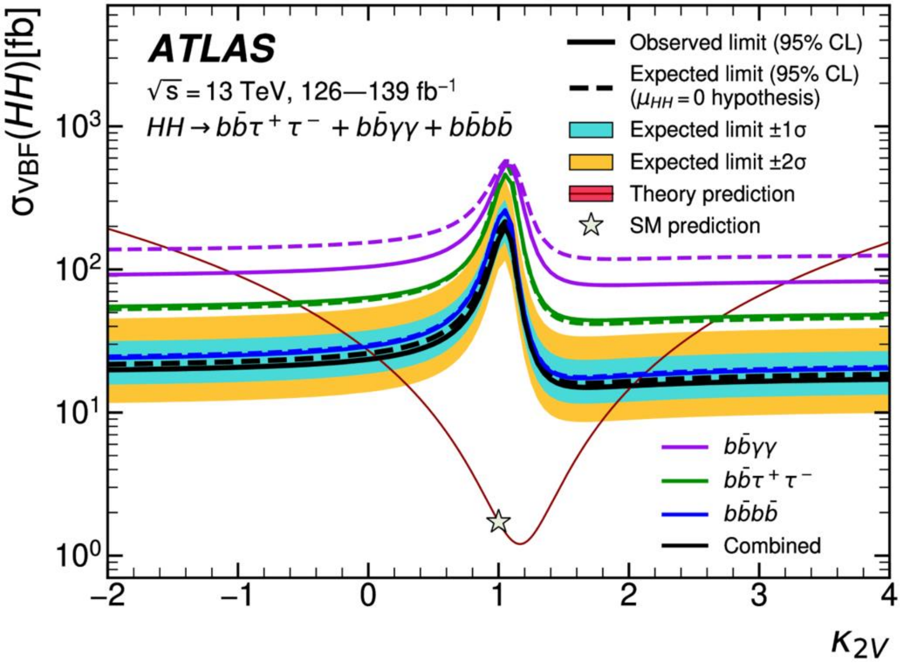


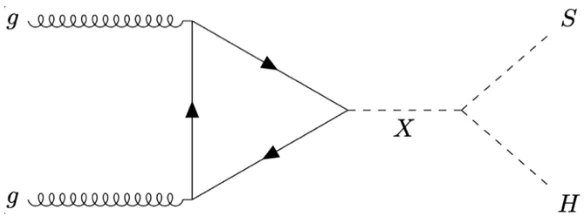
κ_λ-dependence of XS and BR

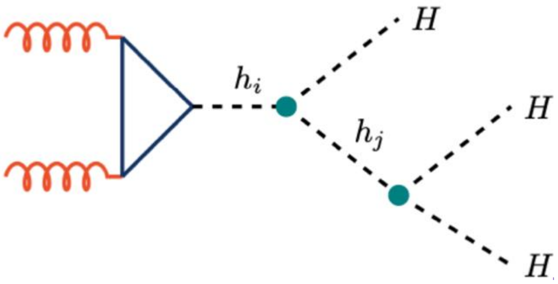





σ(pp → H(H)+X)
√s=13 TeV
Cross section (fb)
ggH
qqH
WH
ZH
tt̄H
tHq
ggHH
qqHH
κλ


ATLAS
√s = 13 TeV, 126—139 fb⁻¹
HH → bb̄τ⁺τ⁻ + bb̄γγ + bb̄bb̄
Observed limit (95% CL)
Expected limit (95% CL)
(μHH = 0 hypothesis)
Expected limit ±1σ
Expected limit ±2σ
Theory prediction
SM prediction
bb̄γγ
bb̄τ⁺τ⁻
bb̄bb̄
Combined
σVBF(HH)[fb]
κ2V


g
g
X
S
H


h_i
h_j
H
H
H