Higgs Self-coupling at LHC ATLAS+CMS

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ATLAS EXPERIMENT

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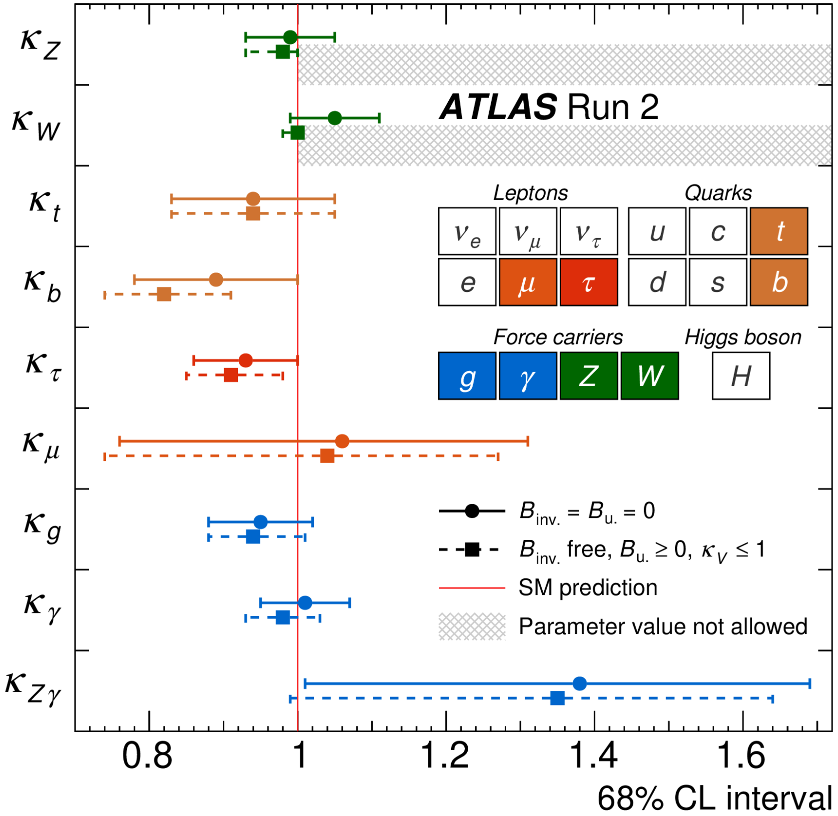
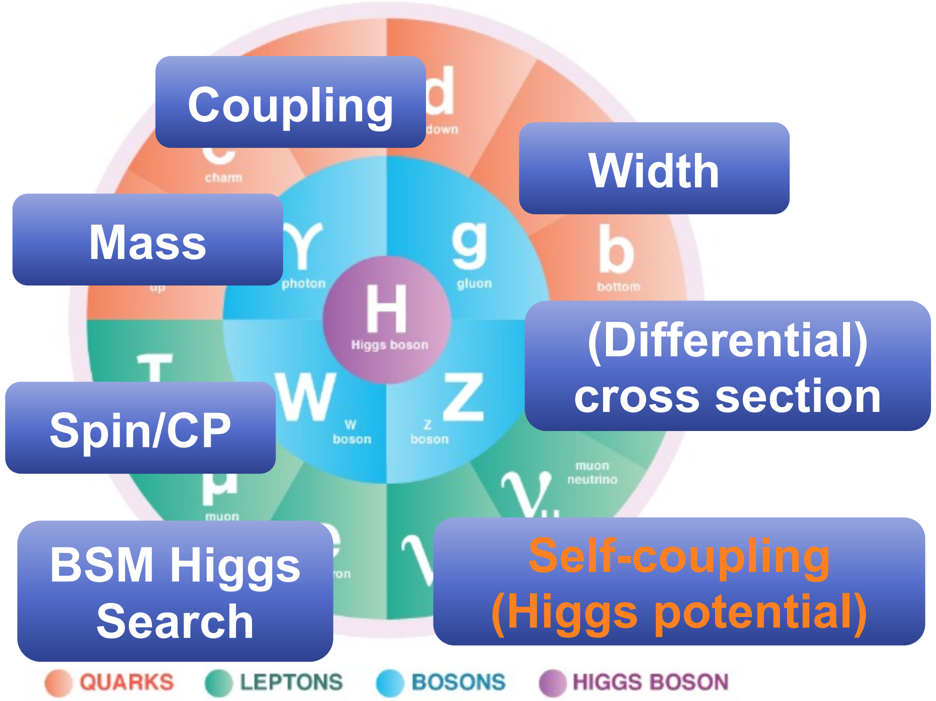
Higgs Measurement Overview at LHC

- Higgs boson discovery providing plenty of fundamental measurements
- **Higgs mass** (ATLAS: H→ZZ→4l): **124.99±0.18(stat)±0.04(sys) GeV**

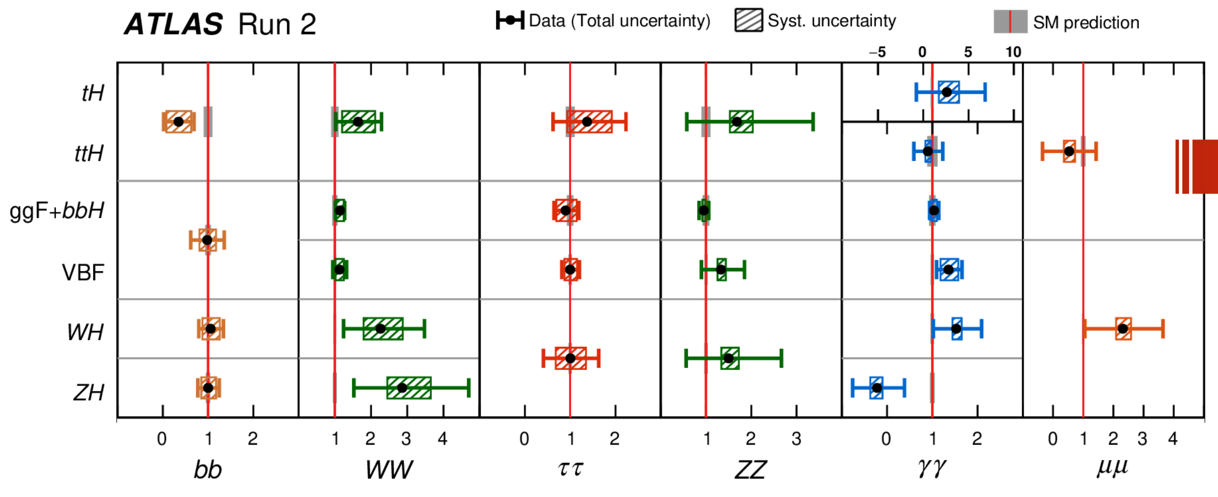


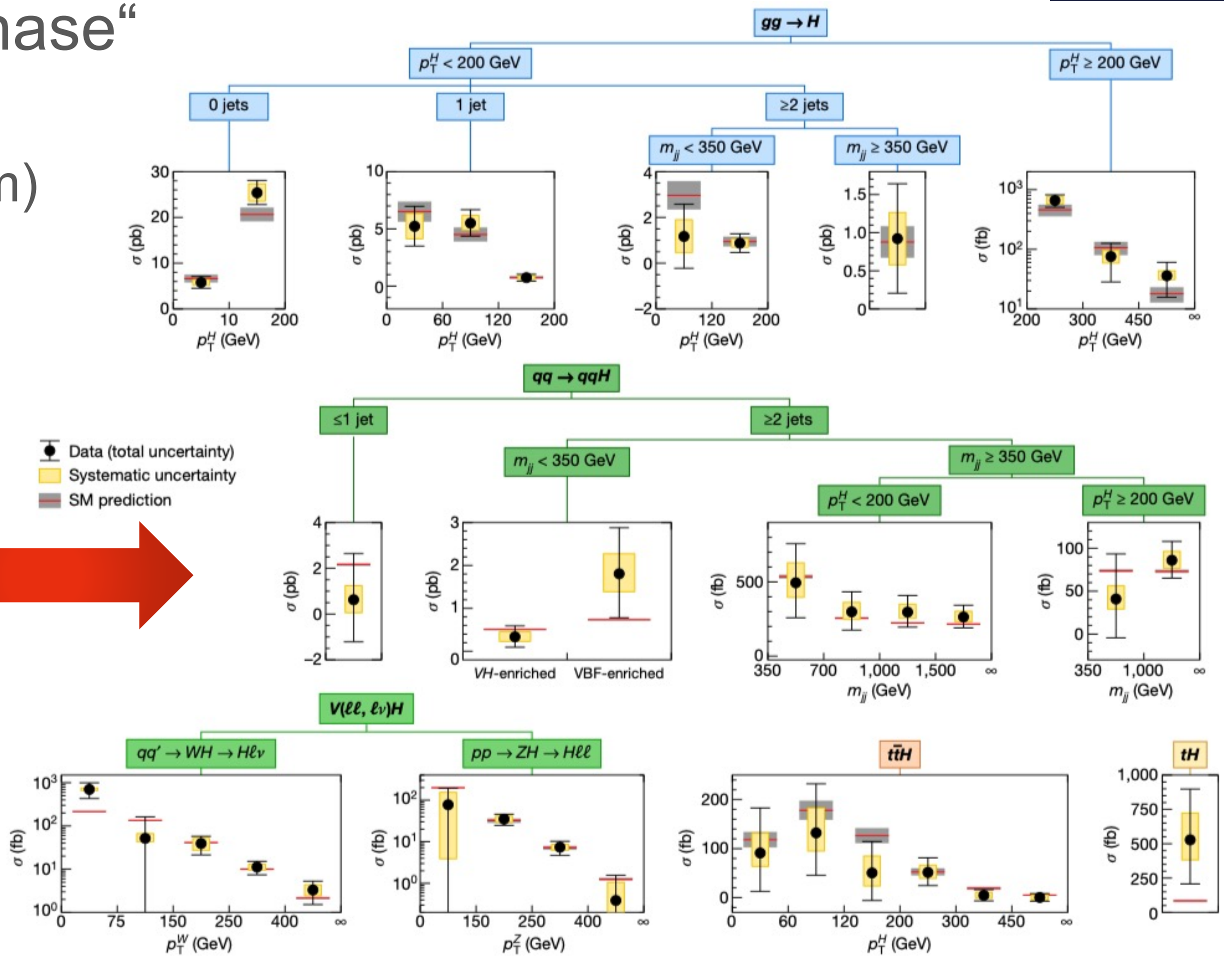


- **Higgs coupling**
  - Measure coupling modifiers($\kappa = g_x^{measure} / g_x^{SM}$) using various production and decay modes
  - **7-11% for 3rd generation fermion, W/Z**
  - **~30% for μ, ≫ 100% for charm**
  - **Upper limit on BR(H→invisible) 7.7%**

Higgs Measurement Overview at LHC

- Higgs measurement entering to the "2nd phase"
  - Rare production and decay measurement
    - tH production, 2nd generation fermion (μ, charm)
  - More difficult measurements
  - ✓ Inclusive ➔ differential measurement

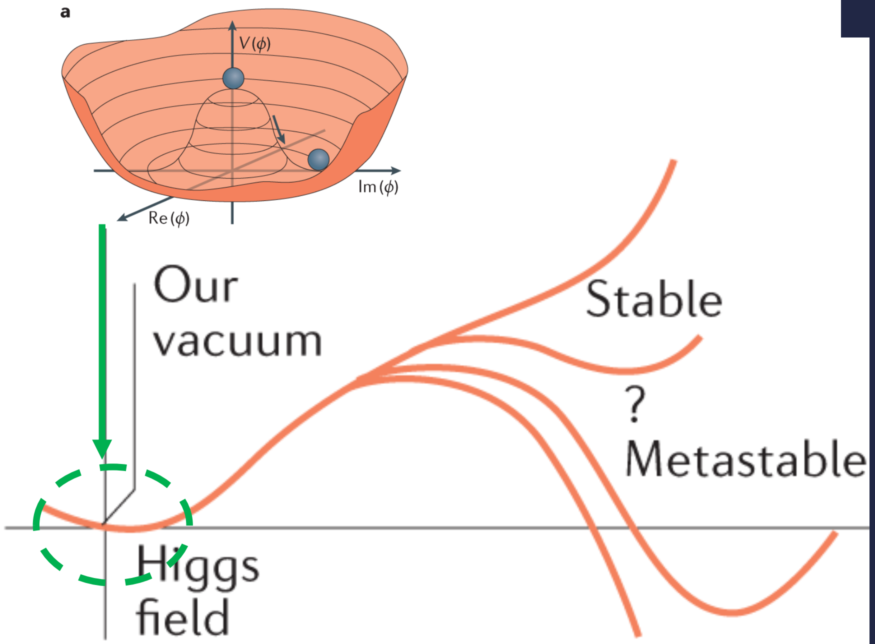




No significant deviation from SM observed (yet!)

Higgs self-coupling is a key of NP?

- Higgs self-coupling is not well constrained experimentally
- Self-coupling parameter(λ) provides the shape of Higgs potential



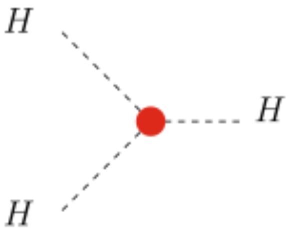
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + \cdots$$

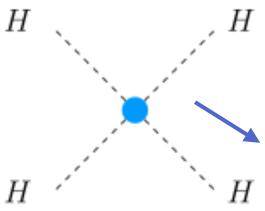
Higgs mass term — **Higgs self-coupling**

<u>In SM</u>

$$\lambda (= \lambda_3 = \lambda_4) = \frac{m_H^2}{2v^2} \sim 0.13$$

$m_H \sim 125$ GeV, $v \sim 246$ GeV





Not reachable even for HL-LHC

- λ_3 can be directly accessed and measured via Higgs pair production (HH)
- It may connect to the fundamental issues of HEP (Stability of Universe, Baryogenesis...)
  ➔ **λ may significantly deviate from SM in the BSM scenario**

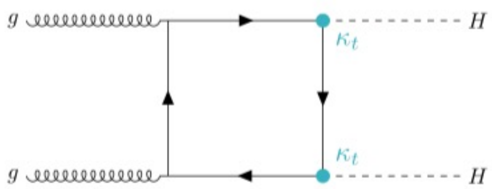
Higgs pair production at LHC

- pp→HH production cross section is quite small (**~30fb**) at LHC (13 TeV)
  - >1000 times lower than pp→H (**55.6pb**)
  - VERY challenging to observe HH process(and measure λ_{HHH})

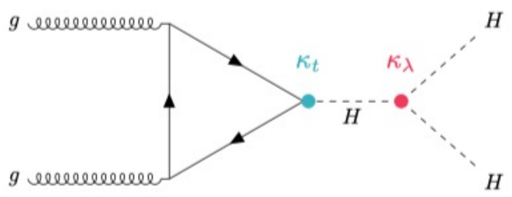
Dominant processes

$\kappa_x = \sigma/\sigma_{SM}$

ggF (~31.05fb at NNLO QCD+NLO EW)

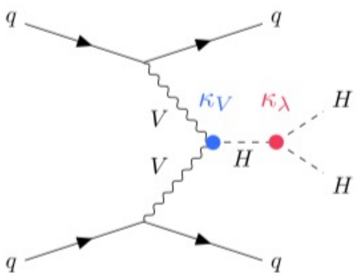


$\sigma \sim \kappa_t^2$

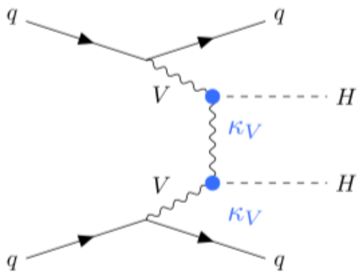


$\sigma \sim \kappa_t \times \kappa_\lambda$ (HHH coupling)

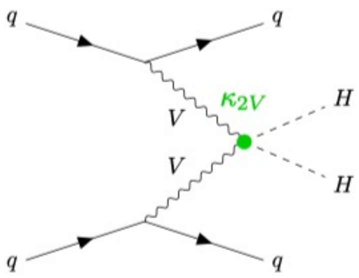
VBF (~1.73fb at N³LO QCD)



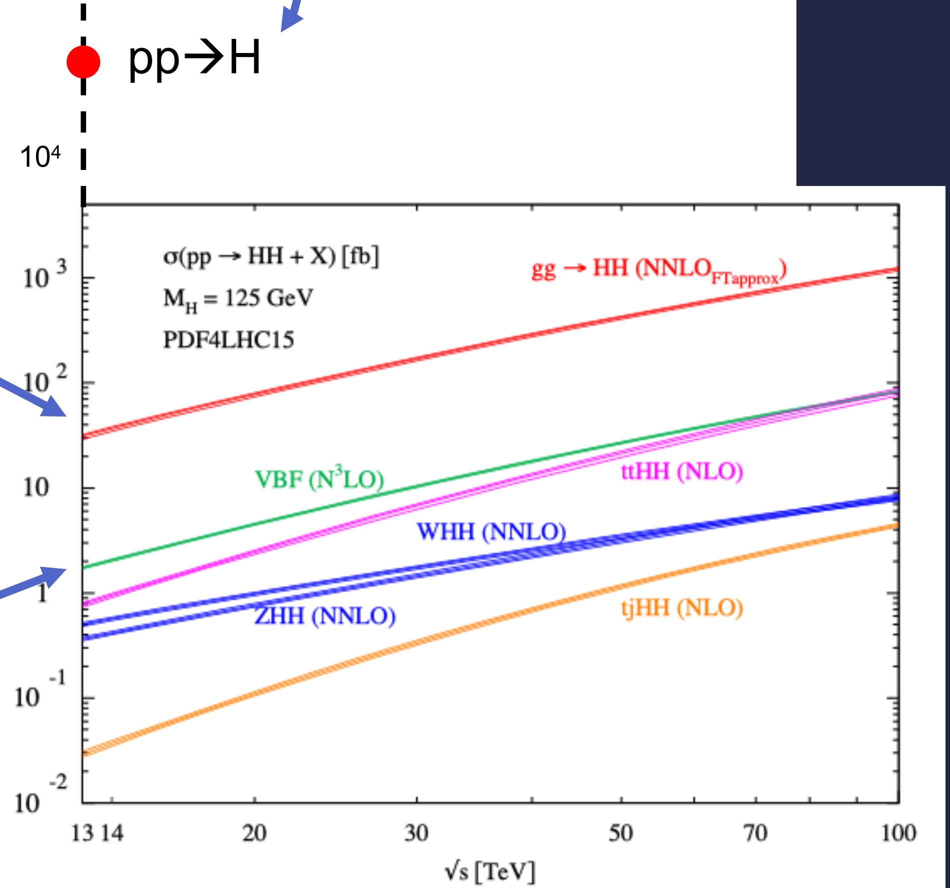
$\sigma \sim \kappa_V \times k_\lambda$



$\sigma \sim \kappa_V^2$

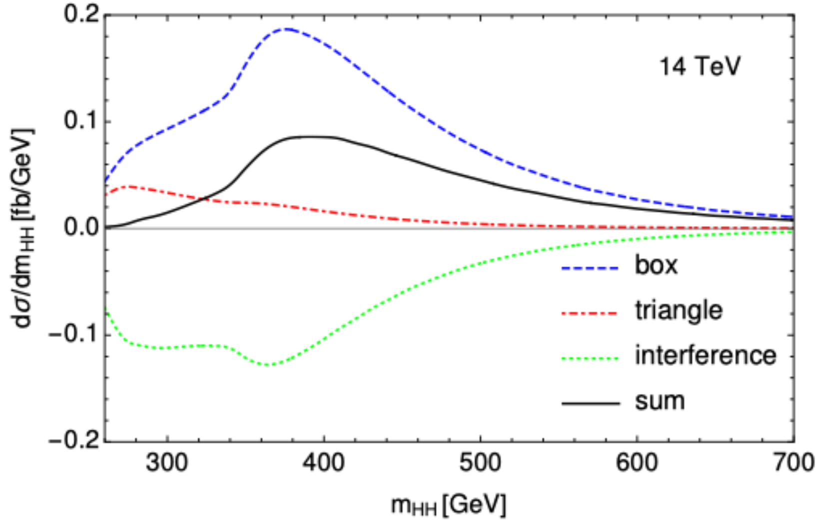


$\sigma \sim \kappa_{2V}$ (VVHH coupling)



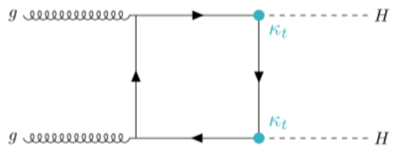
Higgs pair production at LHC

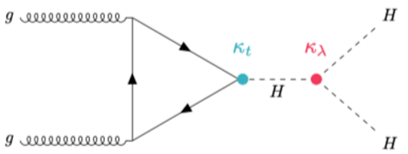
- pp→HH processes include diagrams with/without self-coupling
  - **Interfere non-κ_λ and κ_λ diagrams (destructive interference))**



ggF (~31.05fb at NNLO QCD+NLO EW)

$\kappa_x = \sigma/\sigma_{SM}$

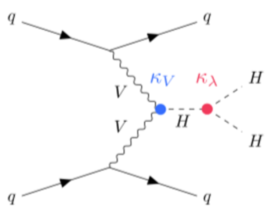


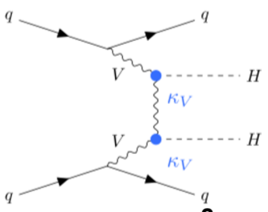


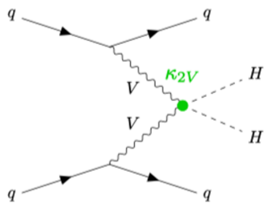
$\sigma \sim \kappa_t^2$ **$\sigma \sim \kappa_t{*}\kappa_\lambda$ (HHH coupling)**

Interference

VBF (~1.73fb at N³LO QCD)

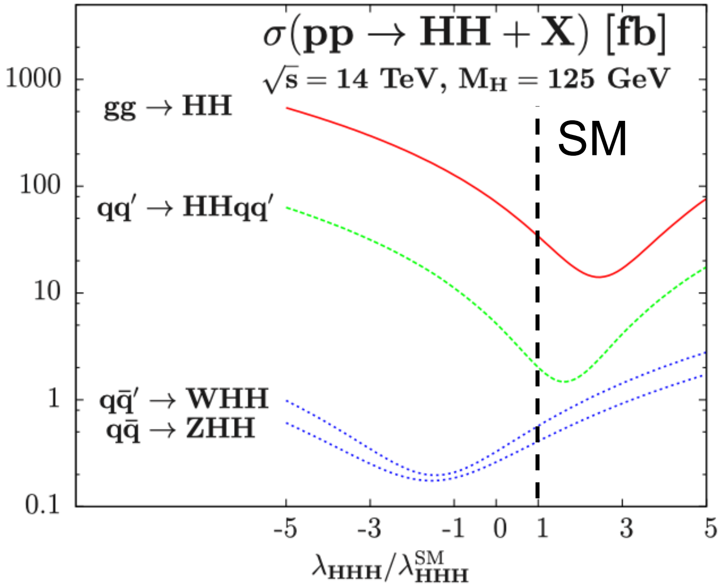






$\sigma \sim \kappa_V{}^*\kappa_\lambda$ **$\sigma \sim \kappa_V{}^2$** **$\sigma \sim \kappa_{2V}$ (VVHH coupling)**

Interference



Cross section depends on κ_λ
"κ_λ = 0" is not the lowest cross section

In ggF, minimum cross section at κ_λ = ~2.5

DiHiggs Decay and Analysis Strategy

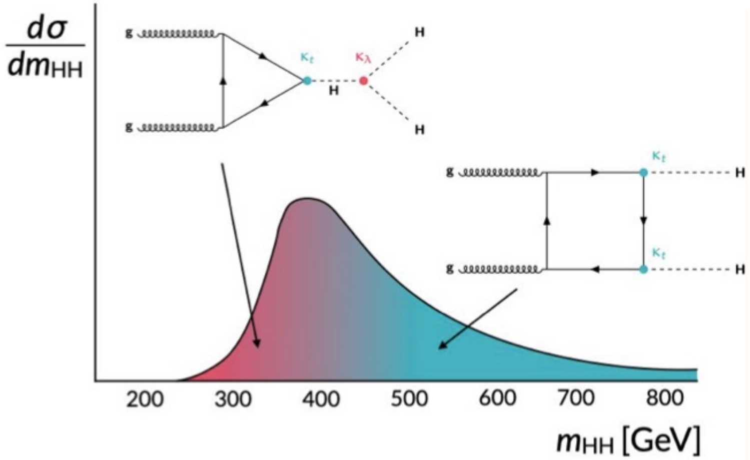
- Two Higgs boson decays
  ➔ variety of final states can be studied

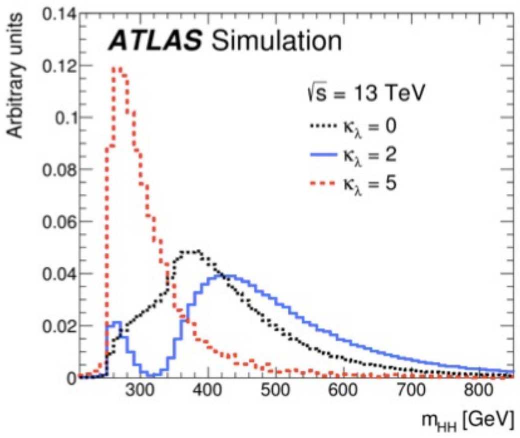
- **Golden channels: H(→bb)+H(→XX)**
  - H→bb: Highest branching ratio (~58%), but not clean in hadron collider
  - **HH→bbbb: Highest yield, but lot of BG**
    - **Hayashida-kun's talk later**
  - **HH→bbττ: Low yield, but cleaner**
  - **HH→bbγγ: Very low yield, very clean**

High yield
Dirty

	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%

Low yield
Clean

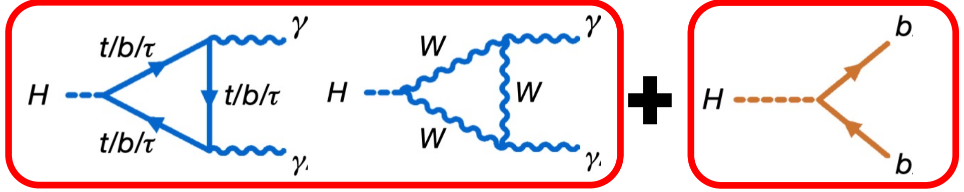




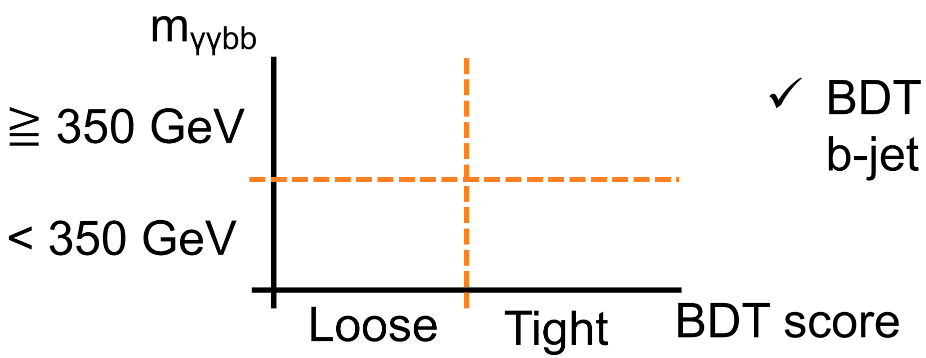
HH kinematics depends on κ_λ value
➔ Keep sensitivity in wider κ_λ range

Analysis

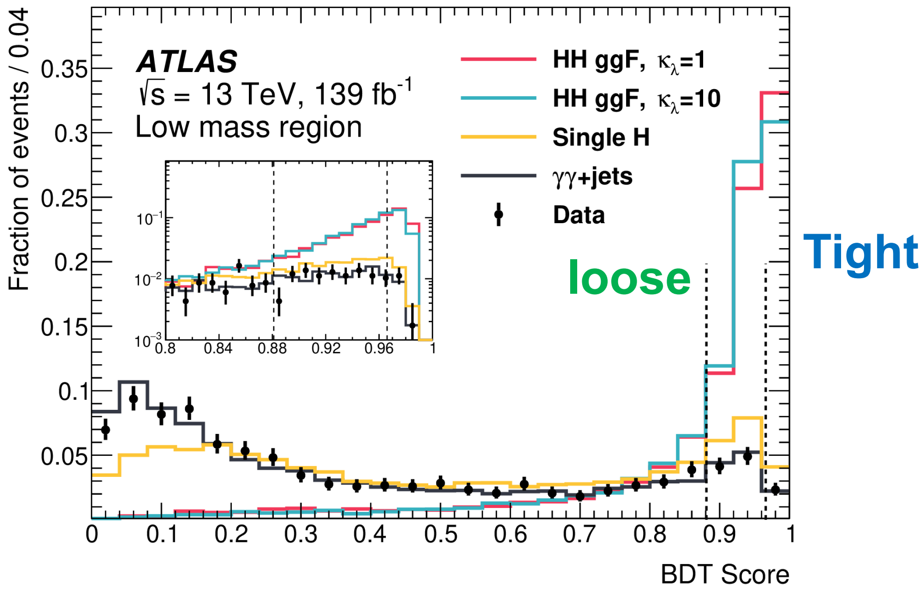
HH→bbγγ

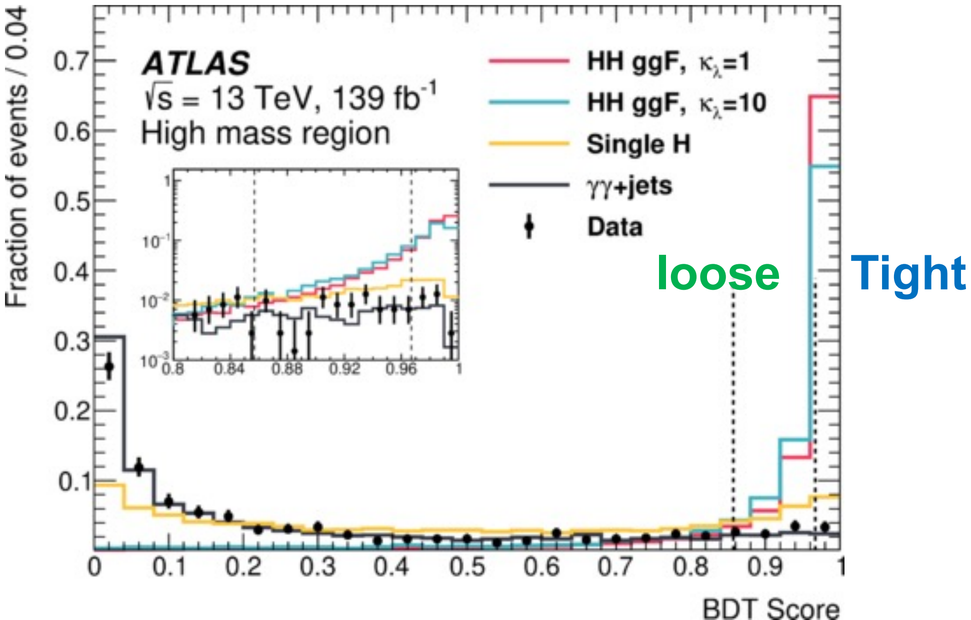


- Cleanest channel
  - At least 2 photon (narrow $m_{\gamma\gamma}$ resonance)
  - Exact 2 b-jets
- Event Categorization (BDT score vs $m_{\gamma\gamma bb}$)



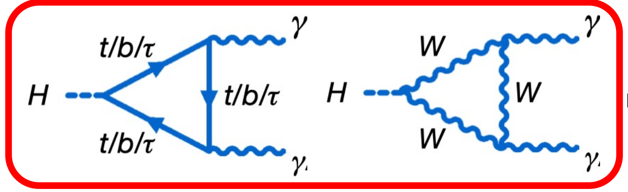
✓ BDT inputs: m_{bb}, b-jet kinematics

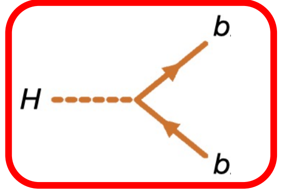




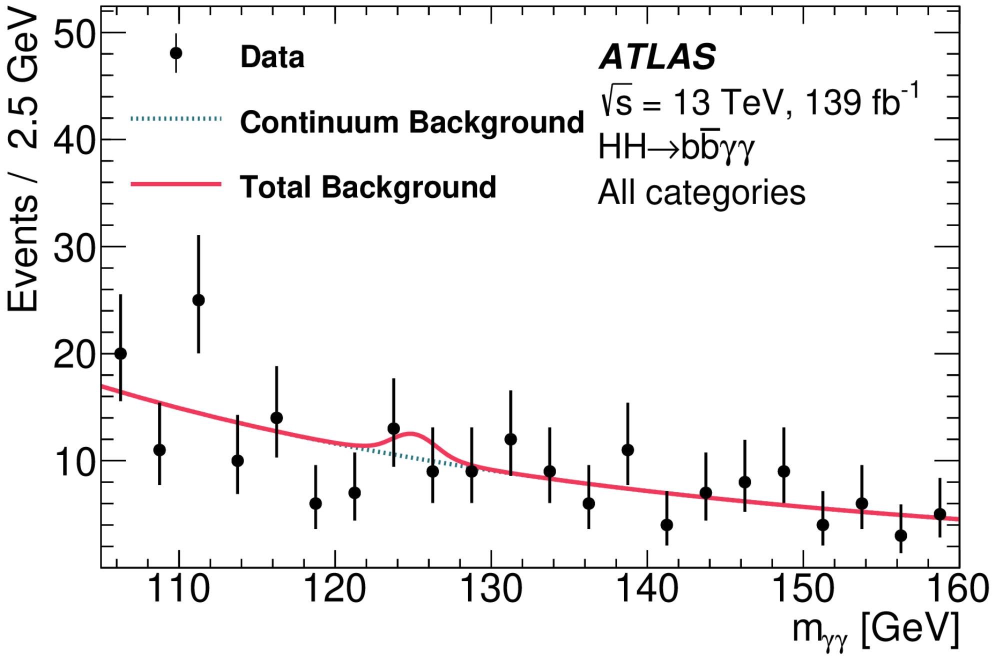
- Main Background
  - γγ+jets(bb), γ+jets (fake γ)
  - Single Higgs(H→γγ)+jets
- Final discriminant: diphoton mass ($m_{\gamma\gamma}$)
  - BDTs do not lead bias in $m_{\gamma\gamma}$

HH→2b2γ

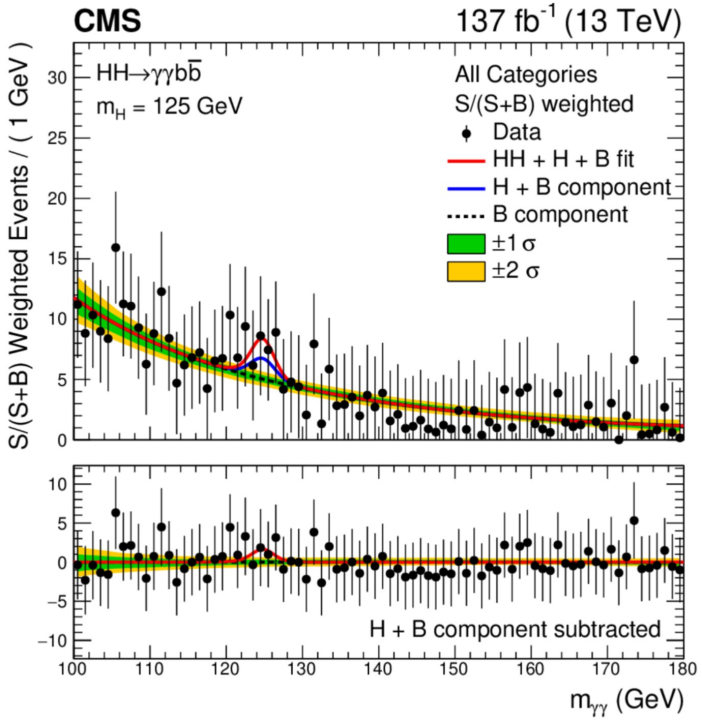




- Background parametrization: analytical function (non-resonant + single Higgs)
- No significant excess observed
- 95% CL upper limit on cross-section
  - **4.2 × SM (exp. 5.7 × SM)**
- Constraints on κ_λ
  - **$-1.5 < \kappa_\lambda < 6.7$ (exp. $-2.4 < \kappa_\lambda < 7.7$)**



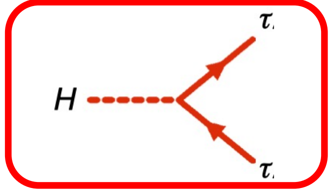
CMS also has similar analysis strategy
12 ggF category
2 VBF category



7.7 × SM
(exp. 5.2 × SM)

$-3.3 < \kappa_\lambda < 8.5$
(exp. $-2.5 < \kappa_\lambda < 8.2$)

HH→2b2τ



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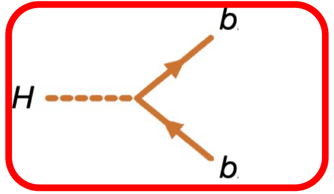
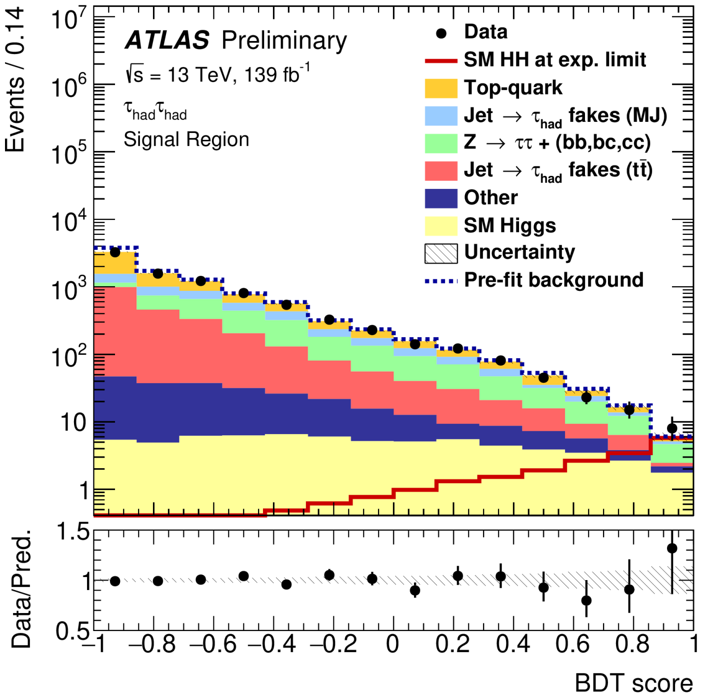
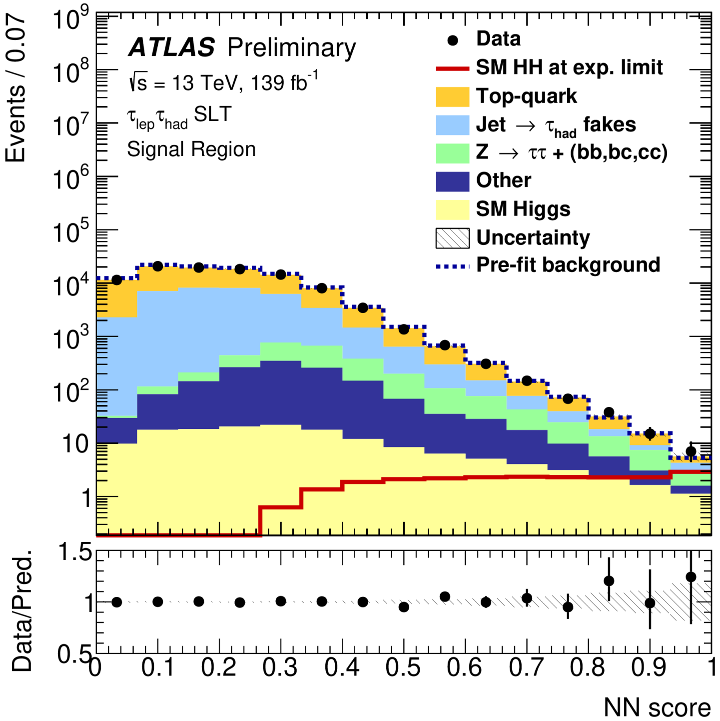
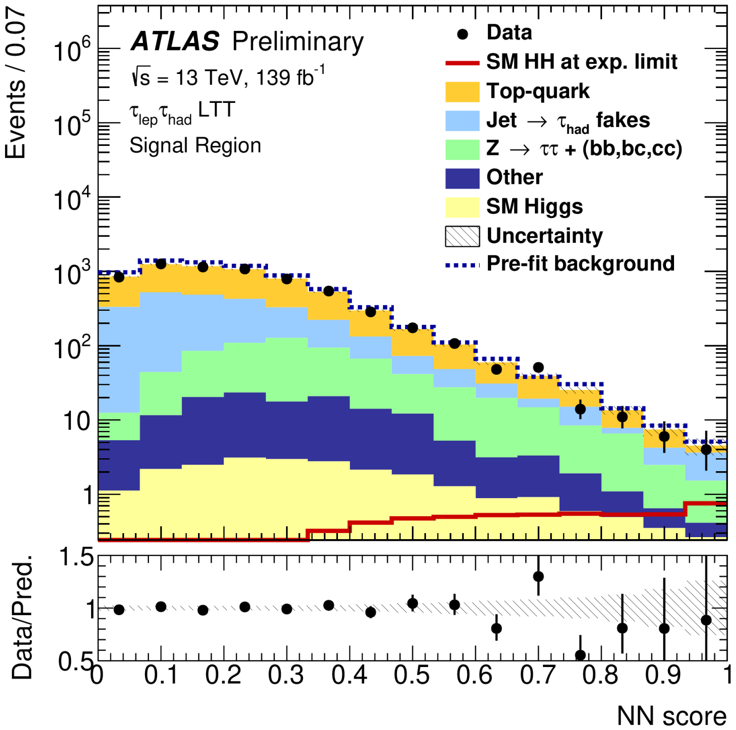


- Require 2τ and 2 b-jets
- Categorized by $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channels
  - Further subdivided by the trigger
  - Optimize selection/MVA for each category
- Final discriminant: MVA (BDT or NN) scores
  - Both H→ττ and H→bb event kinematics are used

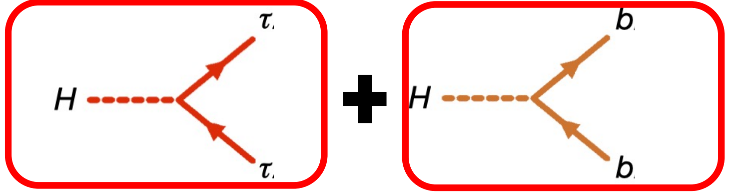
Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_T(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet p_T		✓	
m_T^W		✓	
E_T^{miss}		✓	
$\mathbf{p}_T^{miss}$ ϕ centrality		✓	
$\Delta\phi(\ell\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_T^{miss})$			✓
$\Delta\phi(\ell\tau, \mathbf{p}_T^{miss})$			✓
S_T			✓







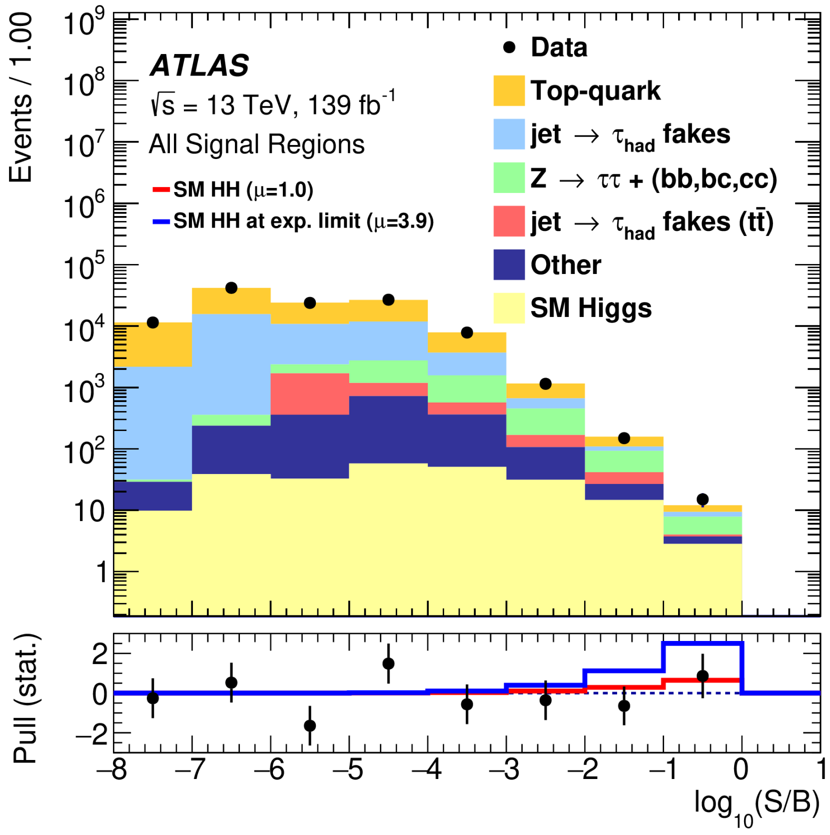
HH→2b2τ

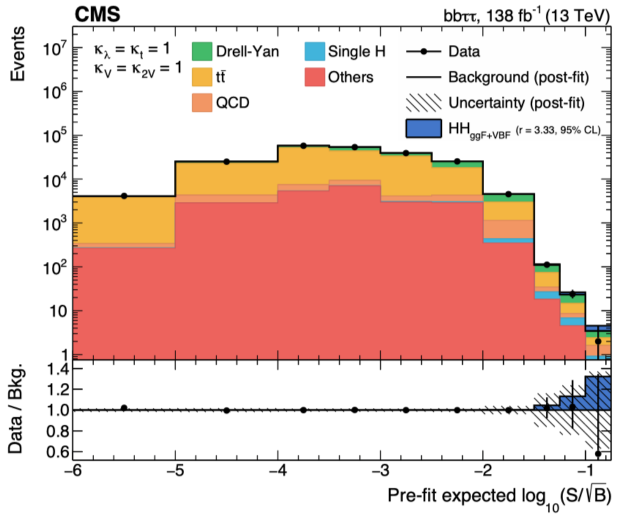


- No significant excess observed in the data
- Set 95% CL upper limit on the cross section
  - **4.7×SM (exp. 3.9×SM)**
  - Most sensitive channel in Run2

MVA did great job to extract small signal from huge background S/B ~0.05-0.3

Most signal-like bin	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ (SLT)	$\tau_{lep}\tau_{had}$ (LTT)
ggF HH signal	**1.58±0.27**	**0.77±0.13**	**0.25±0.05**
VBF HH signal	**0.023±0.002**	**0.008±0.001**	**0.005±0.0004**
Total background	6.1±0.8	6±1	6±1
Observed data	8	7	7

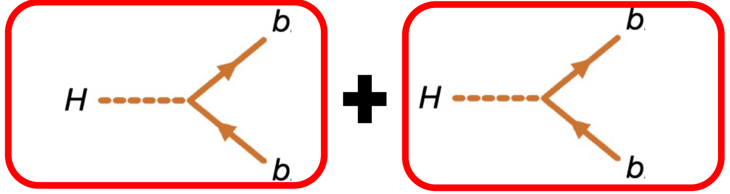




CMS uses DNN scores as final discriminants

3.3×SM (exp. 5.2×SM)

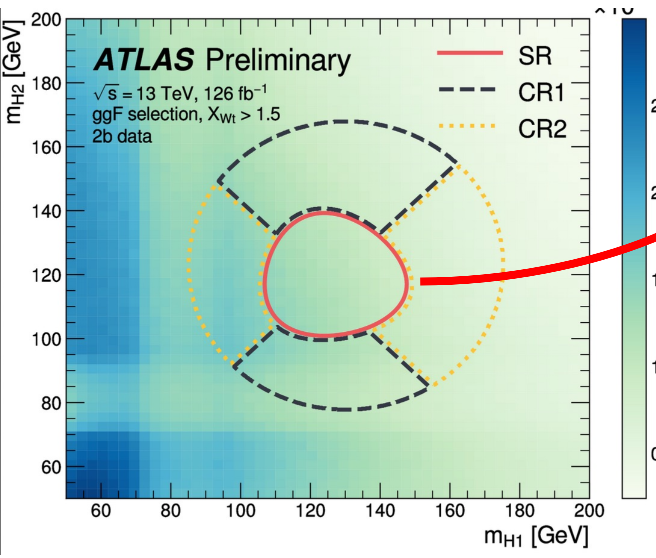
HH→4b

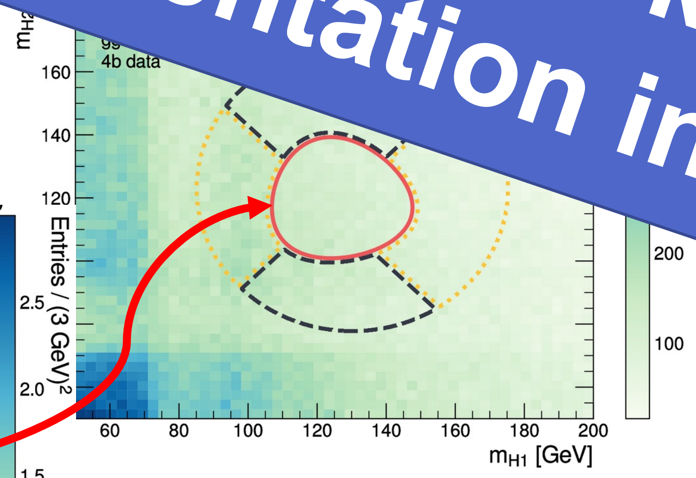


- Highest branching ratio BR(HH→4l) ~34%
- Backgrour … multi b-jets ➔ difficult to model in MC
- Extrapola … 4b SR using reweighting factor estimated from NN

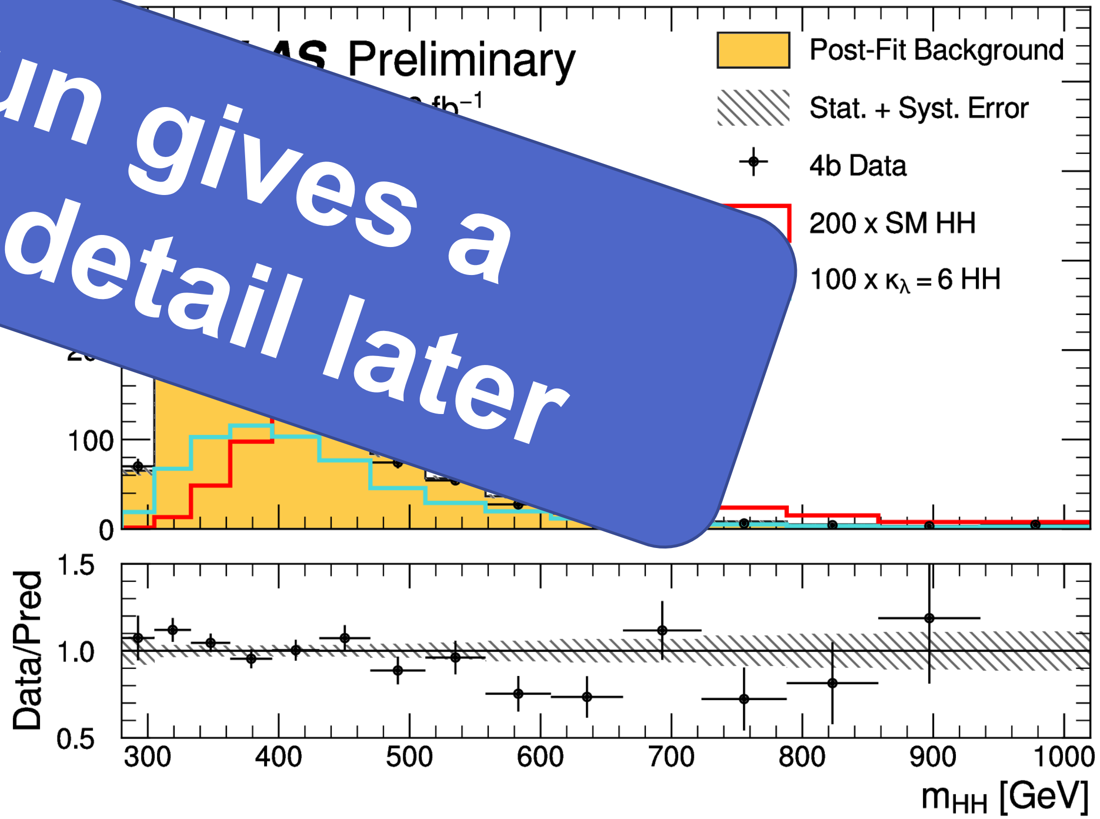
Hayashida-kun gives a presentation in detail later

2b data

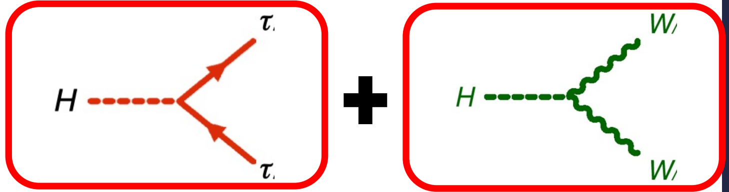




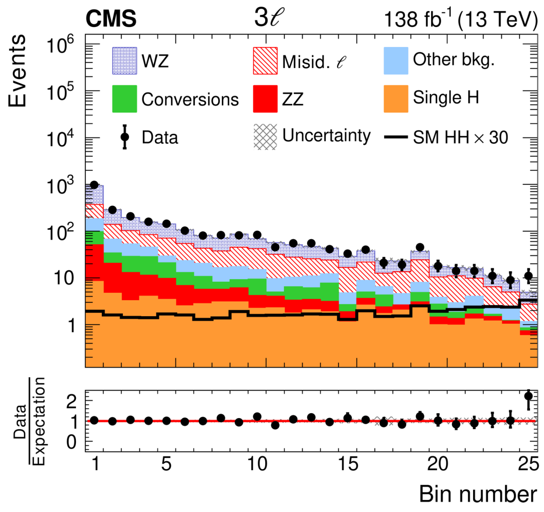
4b data

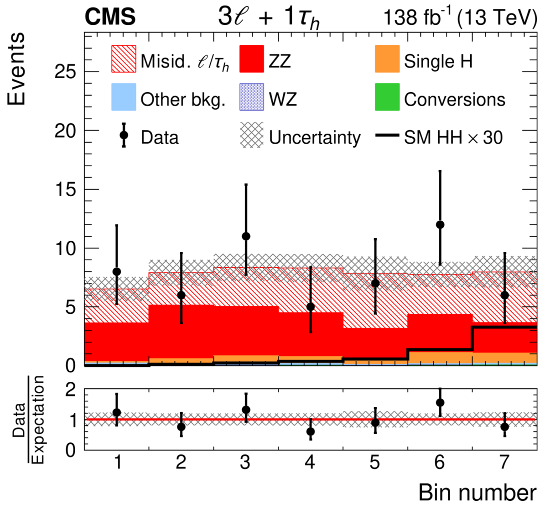


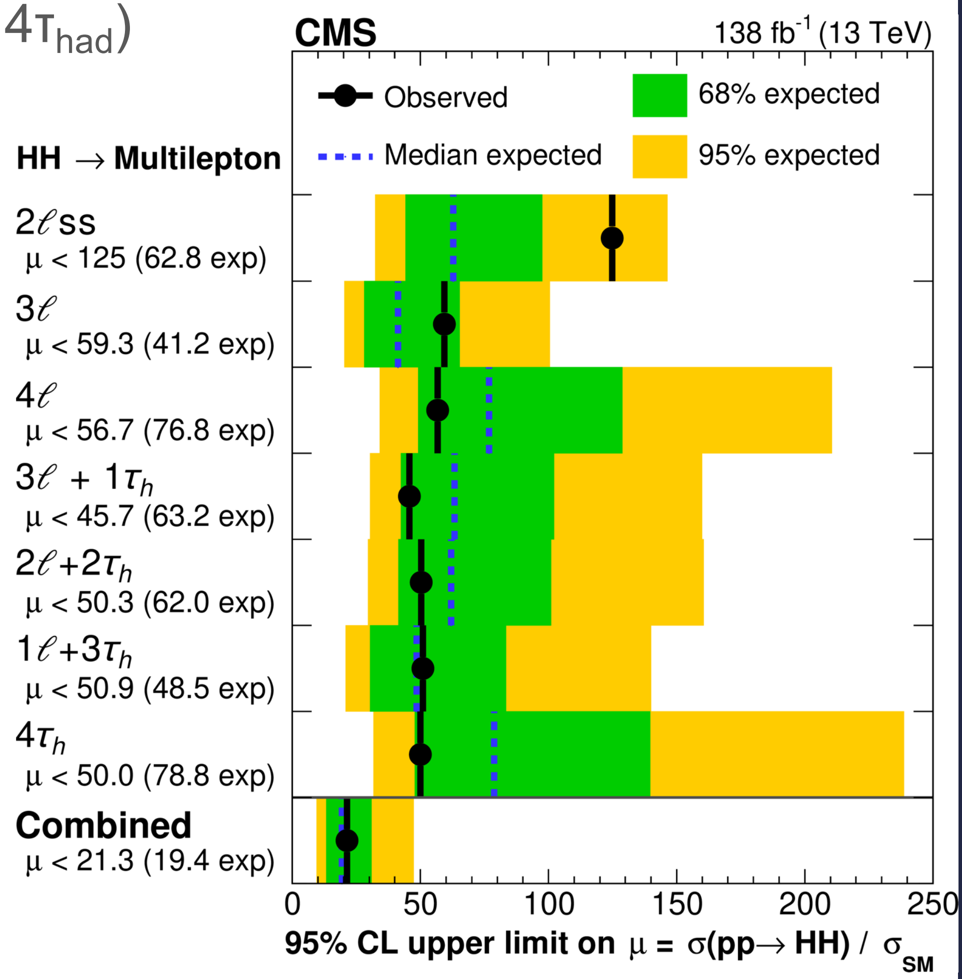
Other channels (Multi-Leptons)



- Target multi-lepton final states (WWWW, WWττ, ττττ)
- Events categorized by the number of e/μ/τ_{had} objects
  - 7 categories (2lSS, 3l, 4l, 3l+1τ_{had}, 2l+ 2τ_{had}, 1l+3τ_{had}, 4τ_{had})
- Train BDTs for each category
  - Input: lepton kinematics, MET, angular correlations







ML Combined upper limit: 21.3×SM (19.4 exp.)

-6.9 < κ_λ < 11.1 (-6.9 < κ_λ < 11.7) (95% CL)

Combination: Upper limit on μ_{HH}

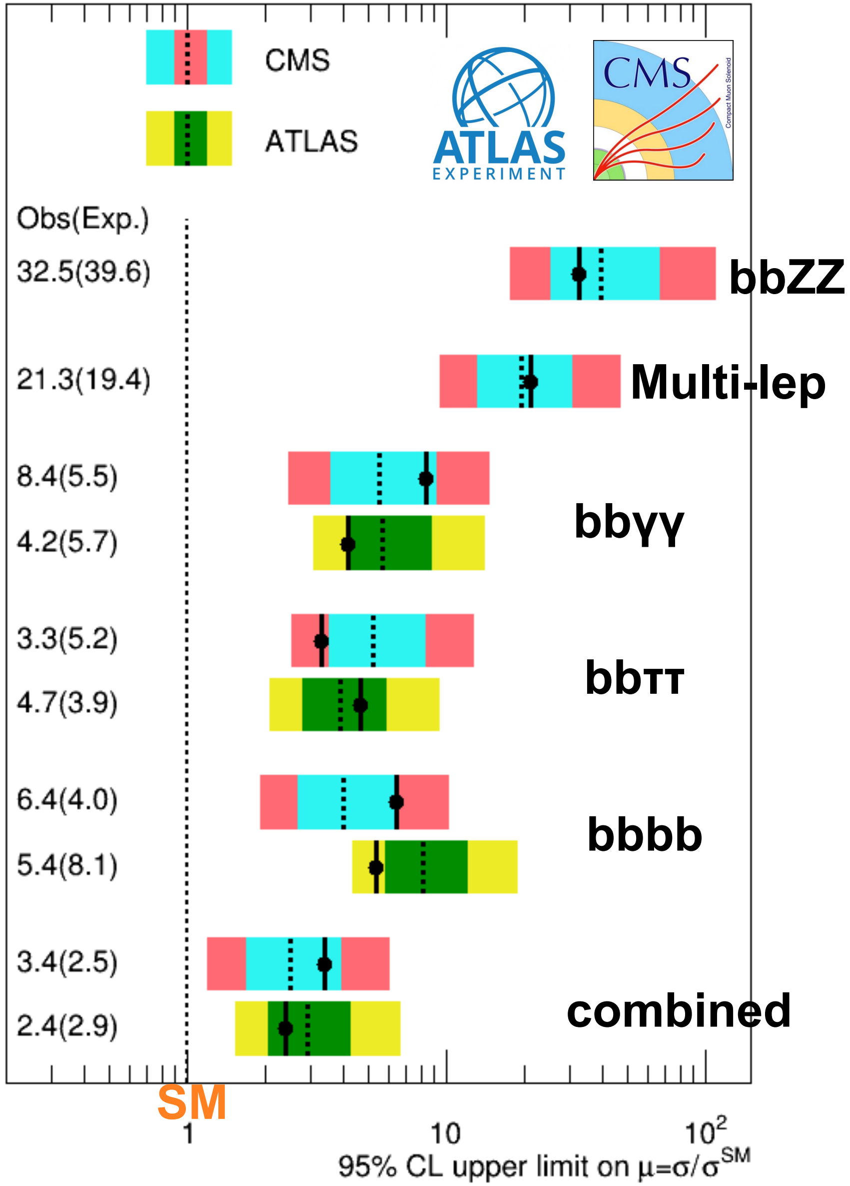
- Various channels are studied, however, no strong channel in HH ➔ Combination is crucial!!

Combined limit on μ_{HH}

ATLAS: 2.4×SM (exp. 2.9×SM)

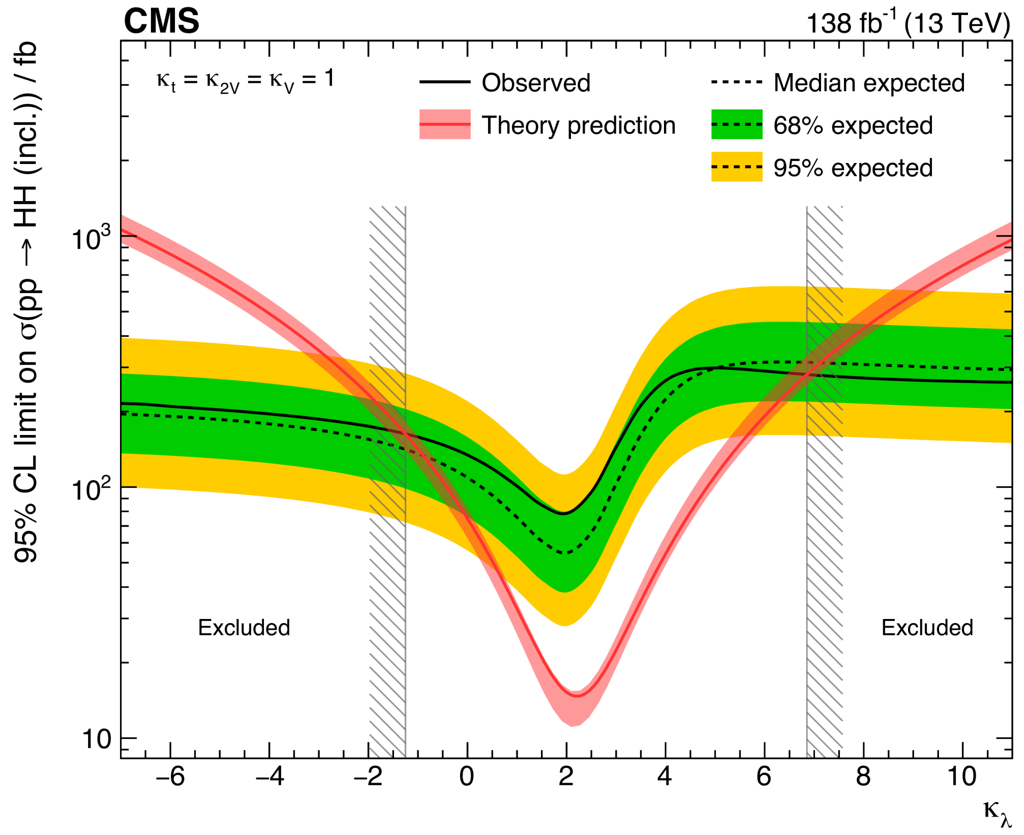
CMS: 3.4 × SM (exp. 2.5 × SM)

- Overall quite comparable results between ATLAS and CMS
- CMS HH→4b sensitivity is better than ATLAS ➔ Combined boosted 4b channel (strong boosted H→bb tagger)
- Significant analysis improvement during Run2 **➔ reach SM cross section in ATLAS+CMS combination in Run3 (+ further analysis improvements)!?**

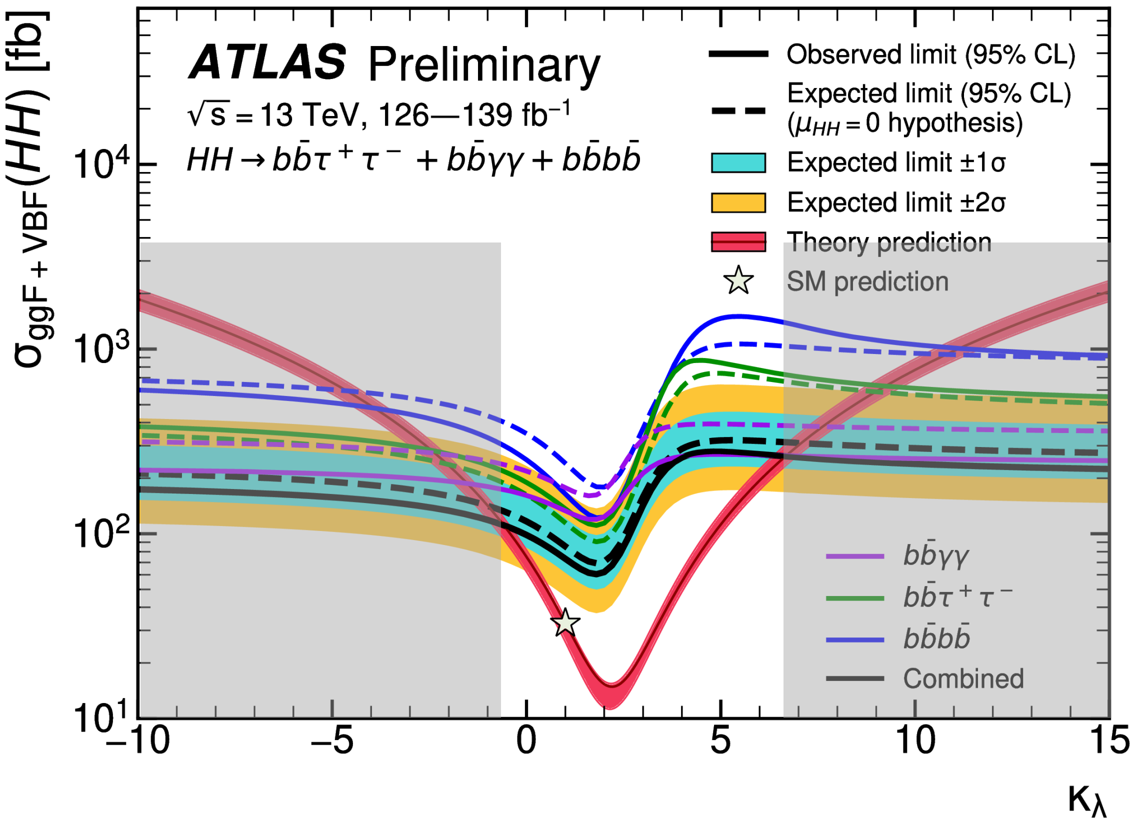


Combination: Constraint on κ_λ

- Comparable constraints on k_λ in both experiments



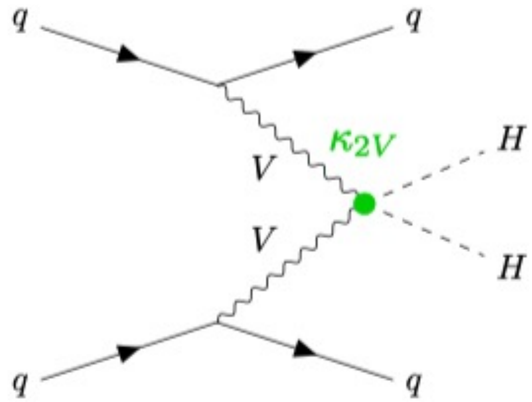
-1.2 < κ_λ < 6.5 @ 95% CL
(exp. -2.3 < κ_λ < 7.9)

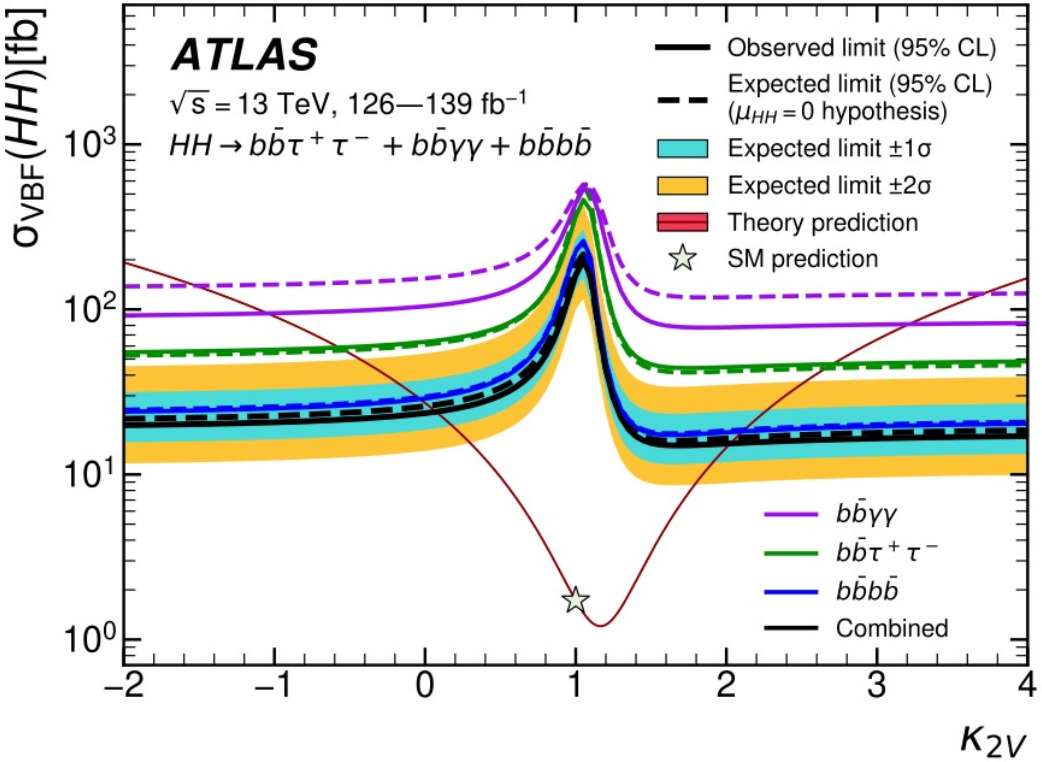


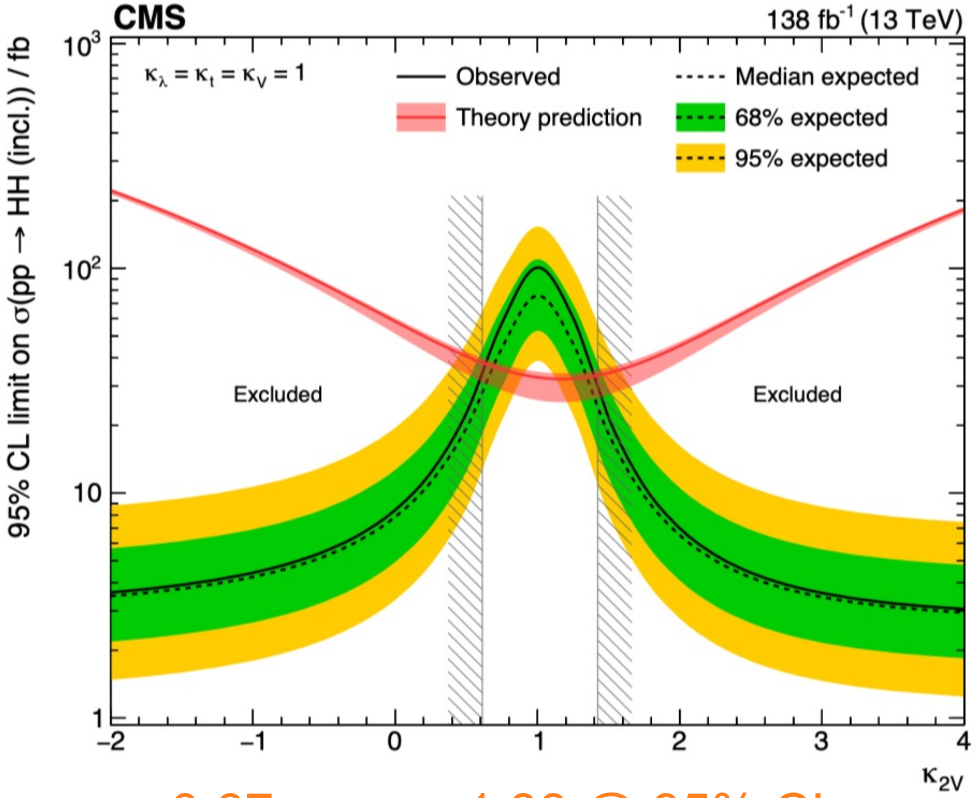
-0.6 < κ_λ < 6.6 @ 95% CL
(exp. -2.1 < κ_λ < 7.8)

κ_{2V} limit

- VBF HH production is unique channel which is sensitive to quartic k_{2V} coupling







$0.1 < \kappa_{2V} < 2.0$ @ 95% CL

$0.67 < \kappa_{2V} < 1.38$ @ 95% CL

No significant deviation from SM. Non-zero k_{2V} excluded by 6.6σ

Single Higgs can constrain κ_λ?

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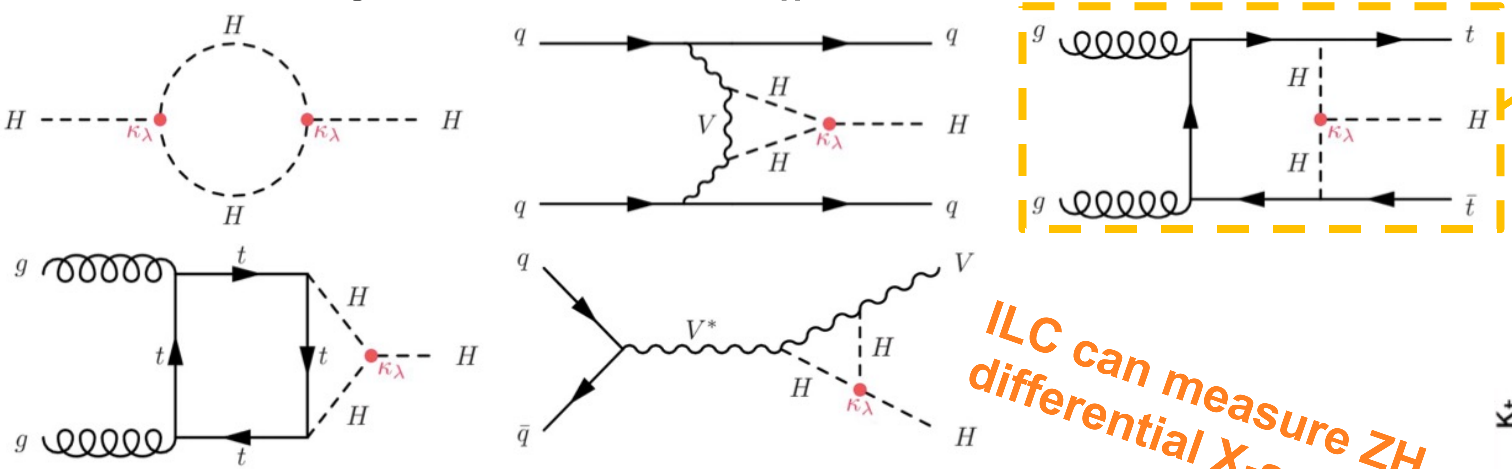
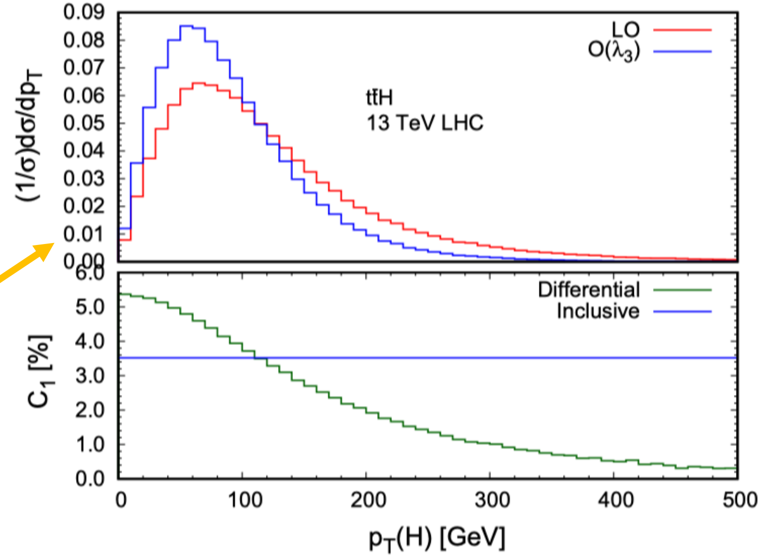
- Single Higgs productions also depends self-coupling contribution via NLO EW correction
  ➔ **Indirectly constraint on κ_λ**

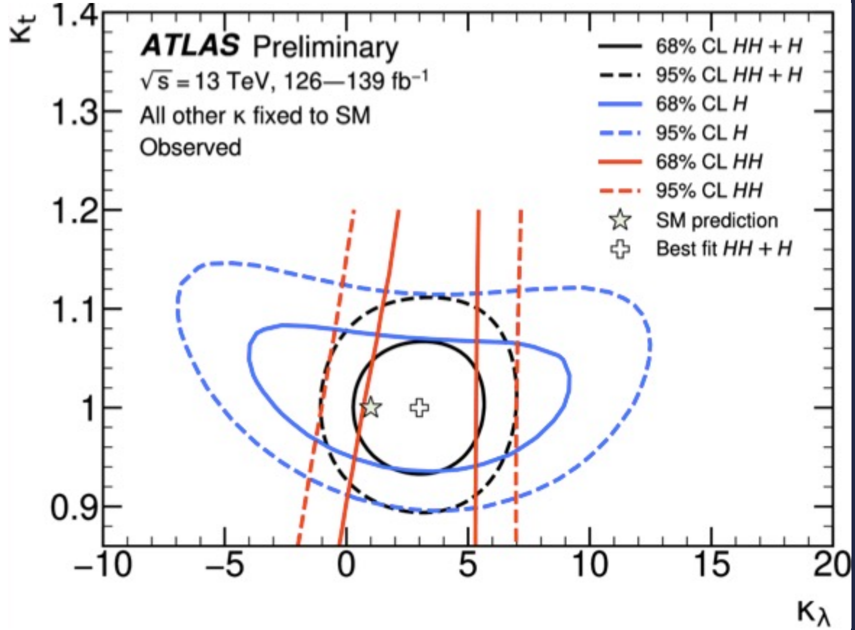


ILC can measure ZH differential X-sec!?

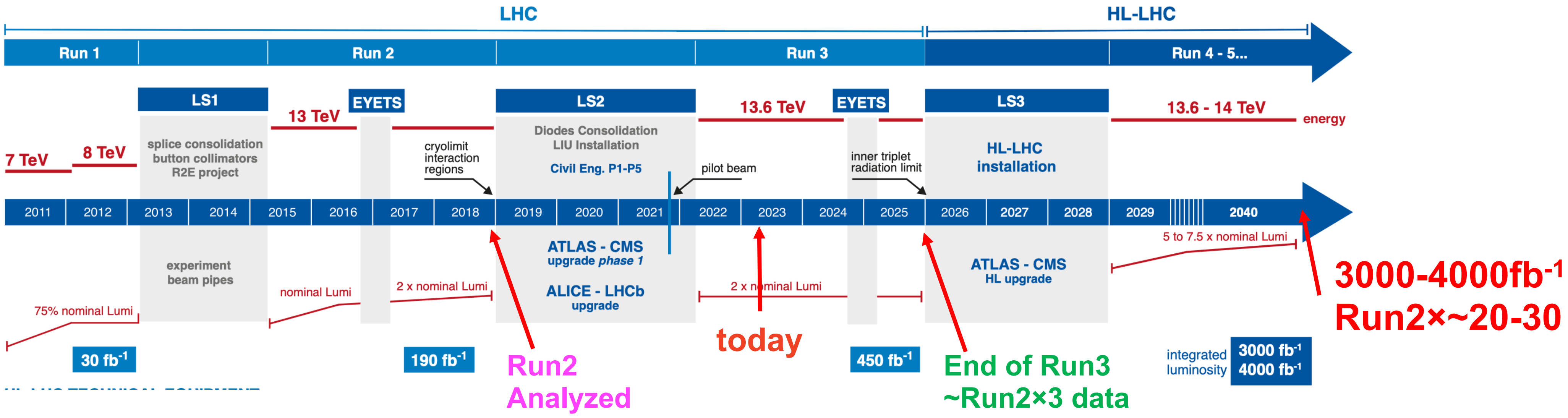


- **κ_λ dependence by a function of Higgs p_T**
  ➔Precision measurement on differential cross section is crucial

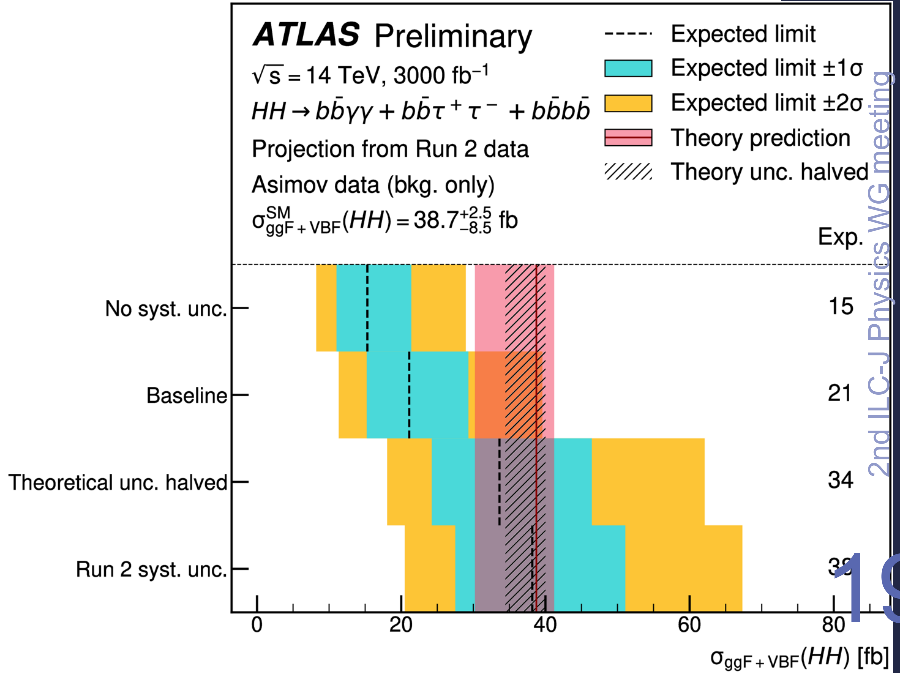
- Perform combined fit with single Higgs (STXS) and HH
  ➔ Possible to constrain other coupling parameters (κ_t) simultaneously
  ➔ ~5-10% improvement on κ_λ constraint



Future (HL-LHC) Prospects (ATLAS)



- HL-LHC prospect combined bbγγ, bbττ and 4b channels
- Run2 analysis can be extrapolated to HL-LHC
- **Baseline extrapolation scenario**
  - **Detector performance is same**
  - **140fb^{-1} → 3000fb^{-1}**
  - **13 TeV → 14 TeV (Scaled signal and background cross-section)**
  - **b-tagging uncertainty and theory uncertainty → 50% down**
  - **Ignore MC stat uncertainties**



Future (HL-LHC) Prospects

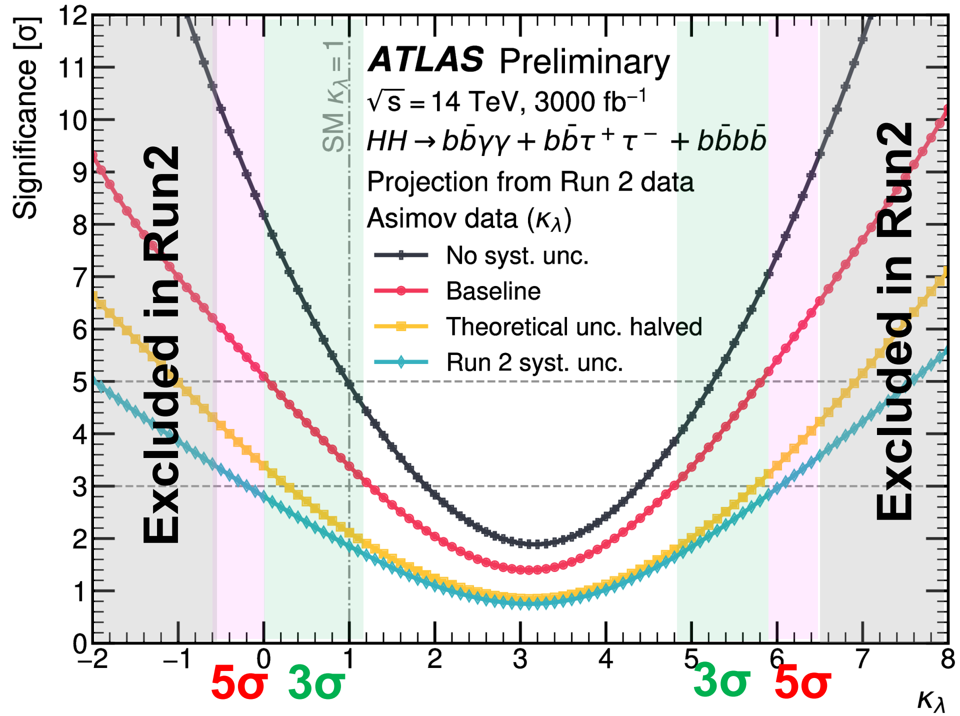
- Sensitivity on HH production at baseline scenario

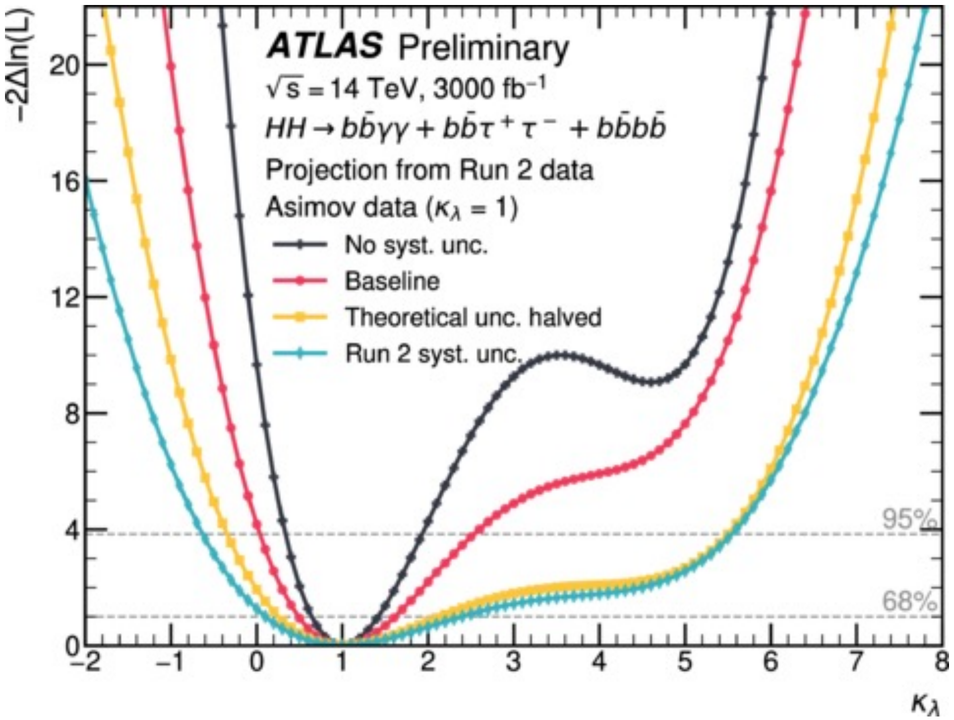
Evidence (3σ): κ_λ < 1.2 or κ_λ > 4.8,
Observation (5σ): κ_λ < 0.0 or κ_λ > 5.8

- κ_λ measurement (assuming SM, κ_λ=1)

0.5 < κ_λ < 1.6 (68% CI), 0.0 < κ_λ < 2.5(95% CI)

~50% accuracy on κ_λ in one experiment





Baseline would be "conservative" (many rooms to improve analysis!!)

✓ Ultimate HL-LHC scenario: 4000 fb^{-1}
✓ ATLAS+CMS combination (total 2×4000 fb^{-1})

Remark

- No one(?) believe we can access to self-coupling even HL-LHC at the beginning

- A lot of improvements during Run2
  - b-tagging and boosted bb tagging
  - ML technique in the analysis (cut-&-count → ML shape fit)

  ➔**Upper limit on HH production(95% CL)**

  2.4 × SM(3.4 × SM)

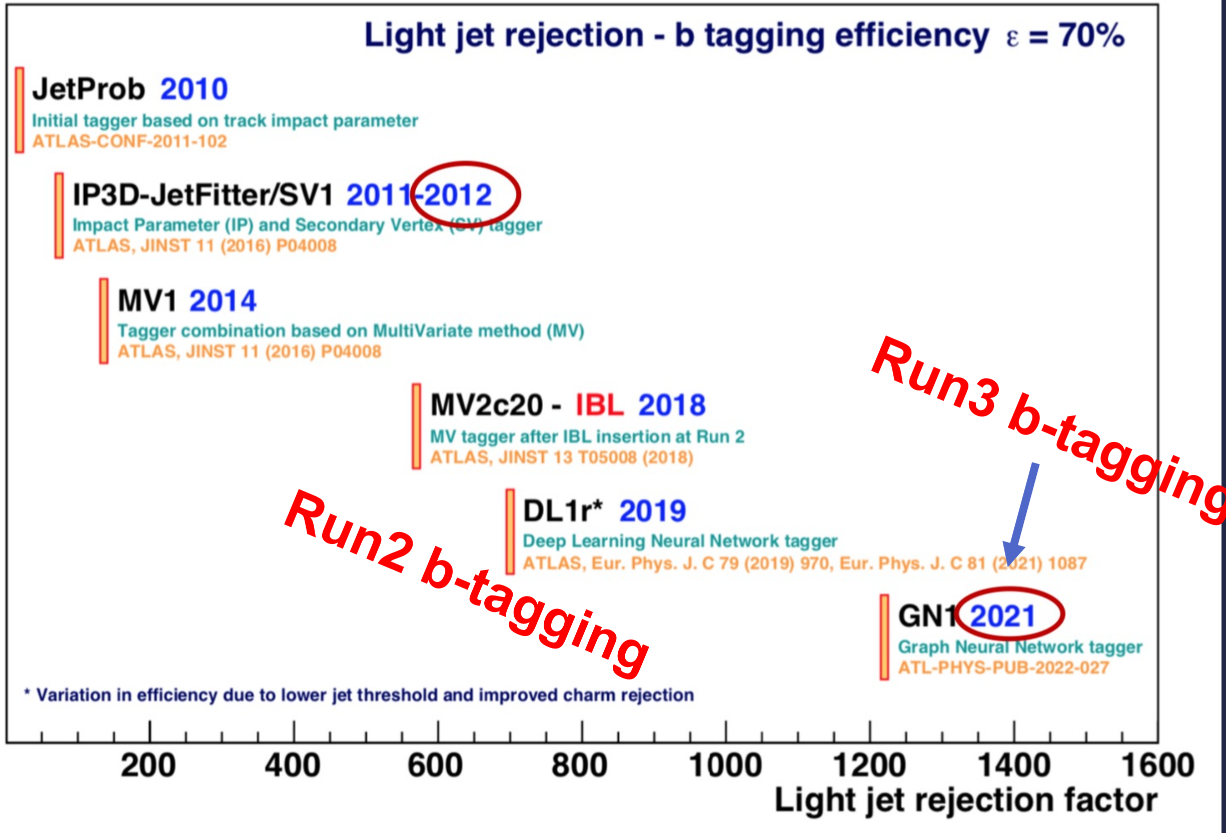
  ➔**Constraint on κ_λ**

  $-0.6 < \kappa_\lambda < 6.6$

HH already interesting phase in Run3

- Further improvements are needed
  - Additional production/decay modes
  - Improvement of τ ID and b-tagging, boosted bb/ττ tagging

  ➔ **Collaborate to development ?**



Reference

- ATLAS
  - HH→4b: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2022-03/
  - VHH: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-31/
  - HH→bbττ: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-40/
  - HH→4b reso: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-41/
  - HH→bbγγ: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-34/
  - boosted di-τ: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-22/
  - HH→bblvlv: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-33/
  - H+HH Combination: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2022-03/
  - Prospect: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-053/

- CMS
  - HH→2b+lep: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-20-004/index.html
  - HH→4W, WWττ, 4τ: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-21-002/index.html
  - HH→2b2τ: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-20-010/index.html
  - HH→4b: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-20-005/index.html
  - HH→2b2γ: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-19-018/index.html
  - HH→bbZZ: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-18-013/index.html
  - HH→WWγγ: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-21-014/index.html
  - Combinaton: http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-22-001/index.html

Backup

HH→bbγγ (non resonant) detail

- Object and Event Selectin
  - Photon
    - Tight ID
    - $Iso_{calo} < 0.065*E_T$, $Iso_{Trk} < 0.05*E_T$
  - b-jet
    - $p_T > 25$ GeV, $|y| < 4.4$
    - DL1r 77% WP (light rejection 130, c-jet rejection 4.9)
  - $105 < m_{\gamma\gamma} < 160$ GeV
  - At least 2 photon
    - $\frac{p_T^{1st}}{m_{\gamma\gamma}} > 0.35, \frac{p_T^{2nd}}{m_{\gamma\gamma}} > 0.35$
  - Expect 2 b-jets
    - b-jet energy correction (muon-in-jet, pT average correction)
  - $N_{jets} < 6$

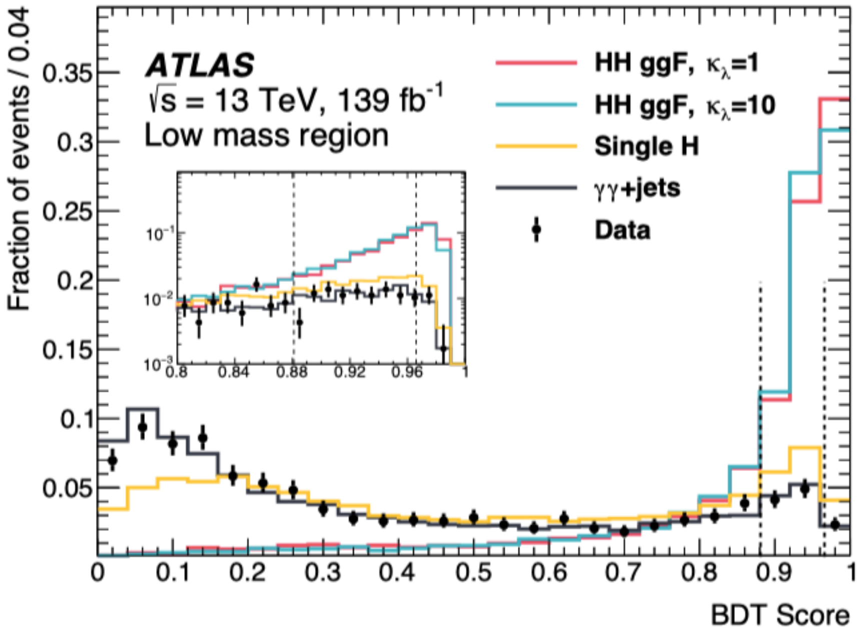
Event categorization
$m_{bb\gamma\gamma}^* = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV <(>) 350 GeV
BDT score: 2 (tight/loose) for each

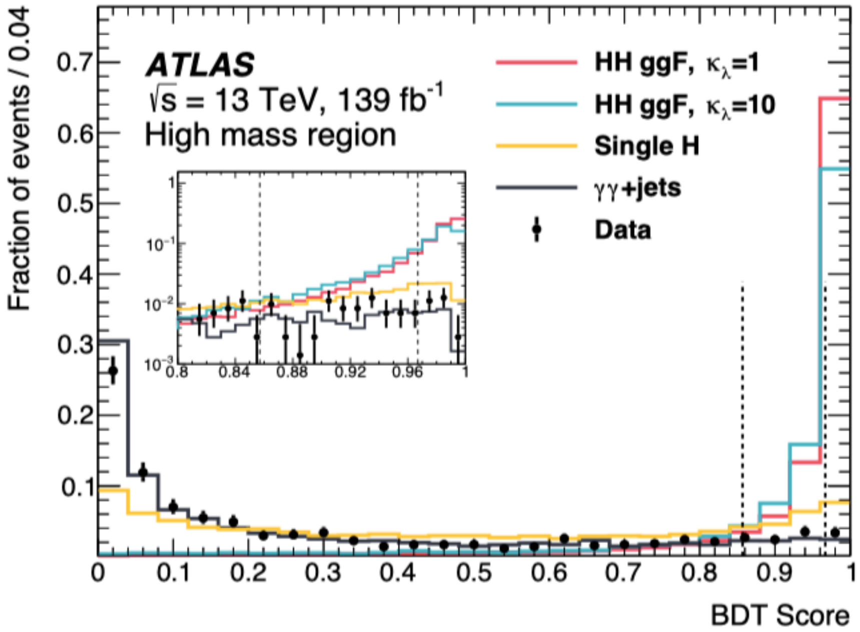
Variable	Definition
Photon-related kinematic variables	
$p_T/m_{\gamma\gamma}$	Transverse momentum of each of the two photons divided by the diphoton invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudorapidity and azimuthal angle of the leading and subleading photon
Jet-related kinematic variables	
b-tag status	Tightest fixed b-tag working point (60%, 70%, or 77%) that the jet passes
p_T, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of the two jets with the highest b-tagging score
$p_T^{b\bar{b}}$, $\eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudorapidity and azimuthal angle of the b-tagged jets system
$m_{b\bar{b}}$	Invariant mass of the two jets with the highest b-tagging score
H_T	Scalar sum of the p_T of the jets in the event
Single topness	For the definition, see Eq. (1)
Missing transverse momentum variables	
E_T^{miss} and ϕ^{miss}	Missing transverse momentum and its azimuthal angle

BDTs do not lead to the bias in mγγ

HH→bbγγ (non resonant) detail

- BDT score (2 signal regions for each)

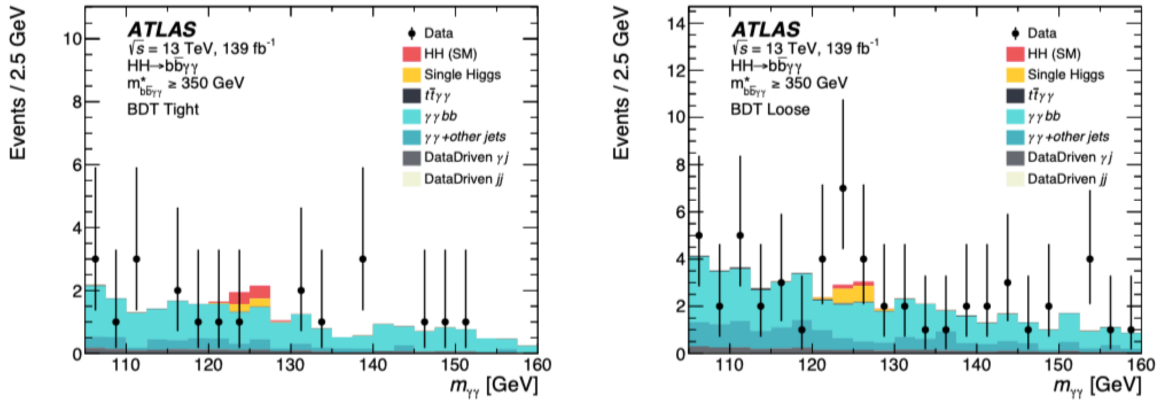




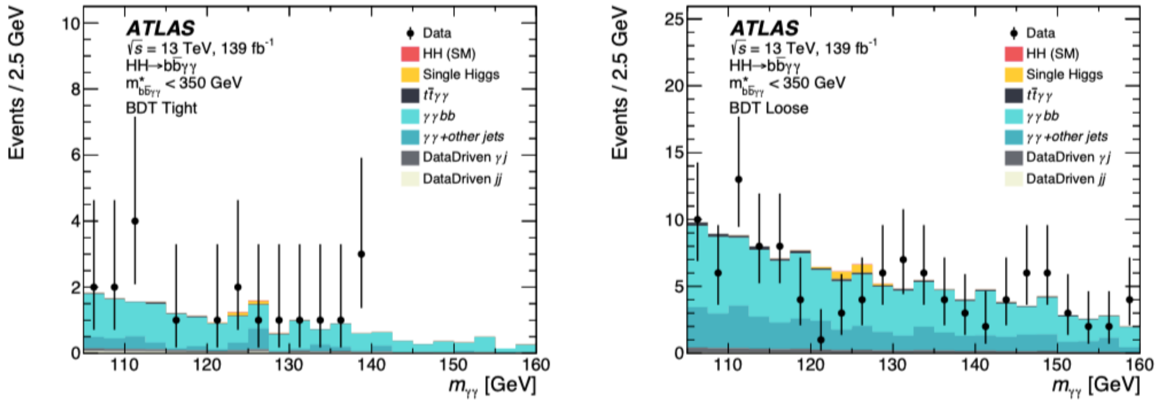
- Background estimation
  - main background γγ+jets(bb)
  - γ+jets fake
  - Single Higgs

HH→bbγγ (non resonant) detail

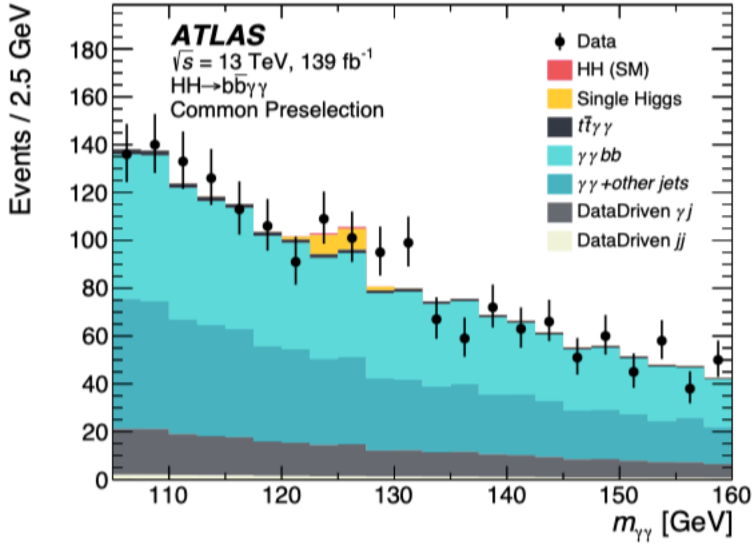
Signal Region



(a) High mass BDT tight selection (b) High mass BDT loose selection



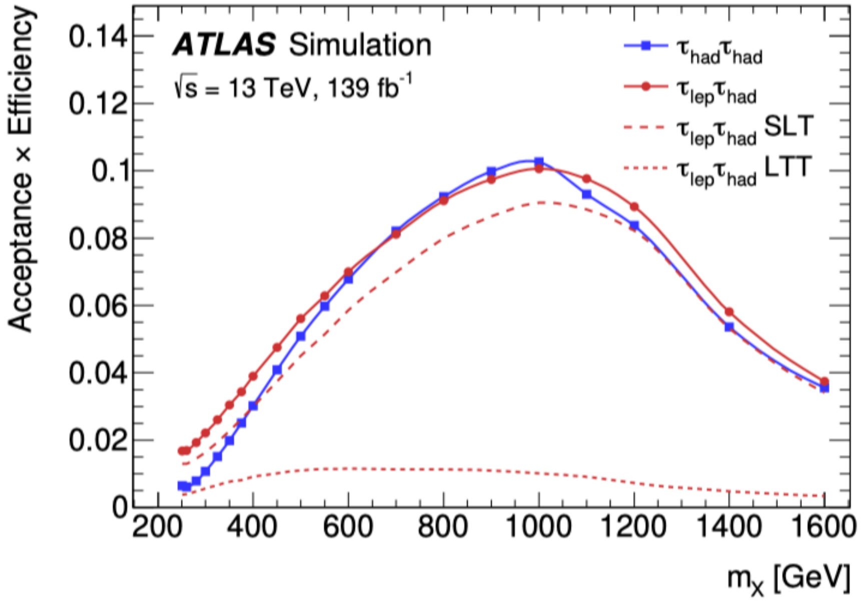
Preselection



Mass resolution (σ_{DSCB}): 1.3-1.6 GeV

HH→bbττ (non-resonant) Detail

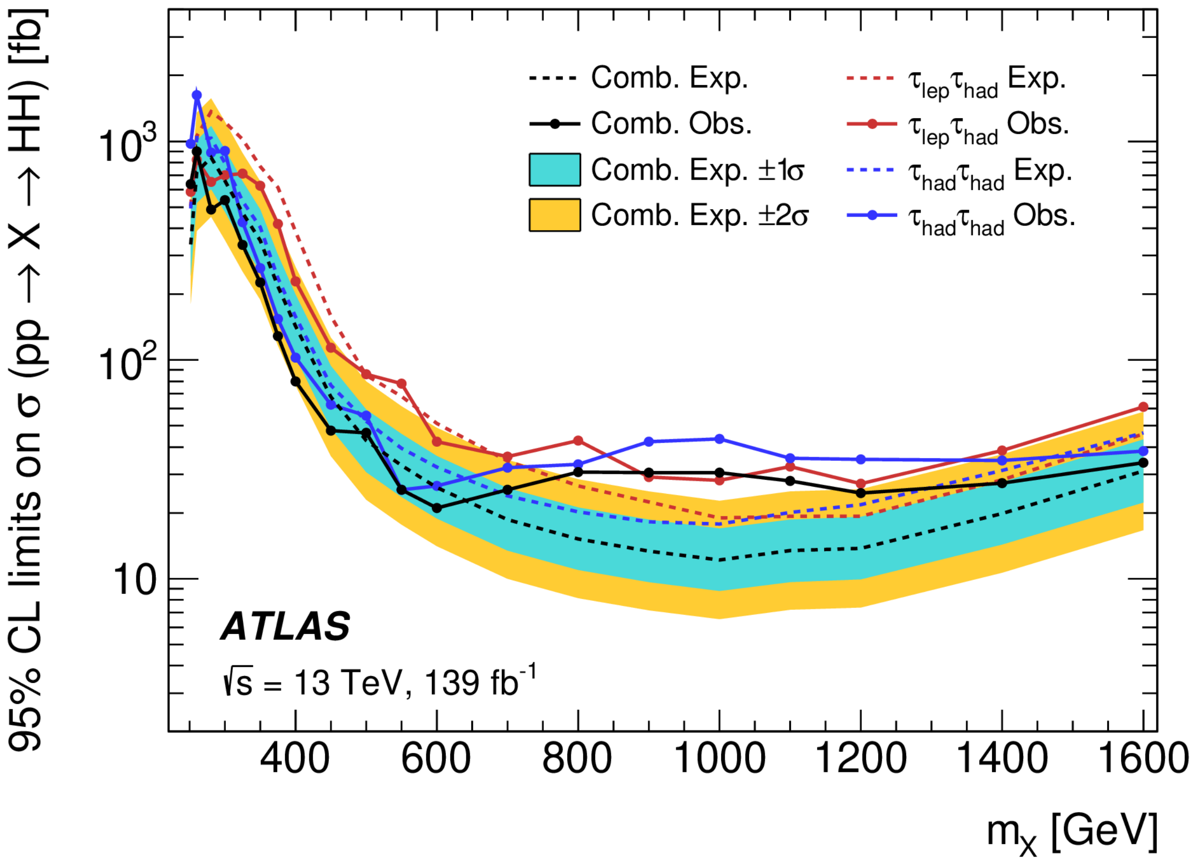
- Main event selection
  - Two decay modes: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$
  - Different triggers for each category
    - $\tau_{had}\tau_{had}$: single, double tau trigger
    - $\tau_{lep}\tau_{had}$: single lepton and lep+tau trigger
  - 2 b-tagged jets
  - $m_{\tau\tau}$ > 60 GeV, m_{bb} < 150 GeV
- MVA (BDT for $\tau_{had}\tau_{had}$, NN for $\tau_{lep}\tau_{had}$)
  - Final discriminant
  - Use both H→ττ and H→bb information and m_{HH}
- Background
  - Estimate in Z+bb (Z→ee/μμ) CR
  - Fake tau background (ttbar, multi-jet): estimate by data-driven way and MC



Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_T(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet p_T		✓	
m_T^W		✓	
E_T^{miss}		✓	
$\mathbf{p}_T^{miss}$ ϕ centrality		✓	
$\Delta\phi(\ell\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_T^{miss})$			✓
$\Delta\phi(\tau\tau, \mathbf{p}_T^{miss})$			✓
S_T			✓

X→HH→bbττ (Resonant excess)

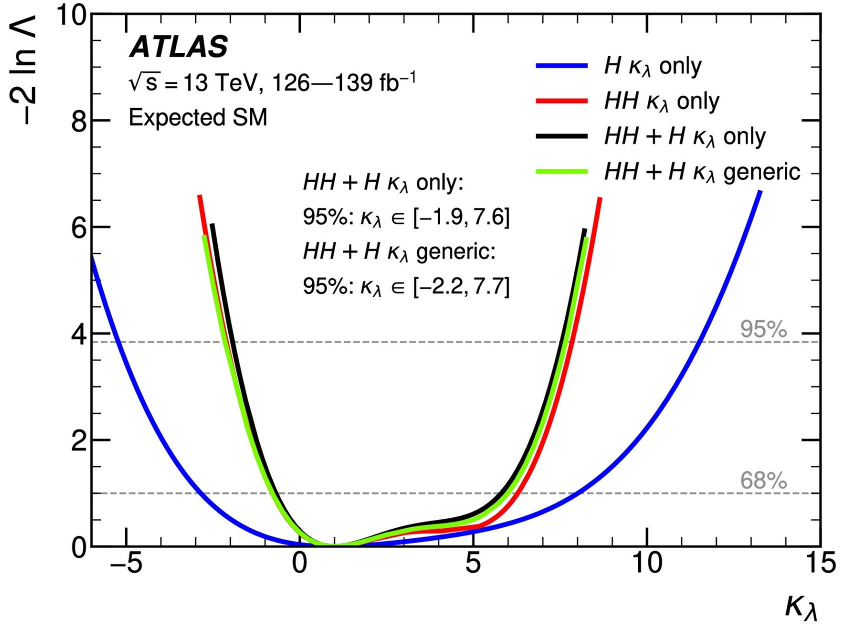
- Found mild and broad excess around 1 TeV in X→HH→bbττ resonance search
- Both $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$ observed in the same region
  - Local significance 3.1σ (2.0σ for global) at 1 TeV



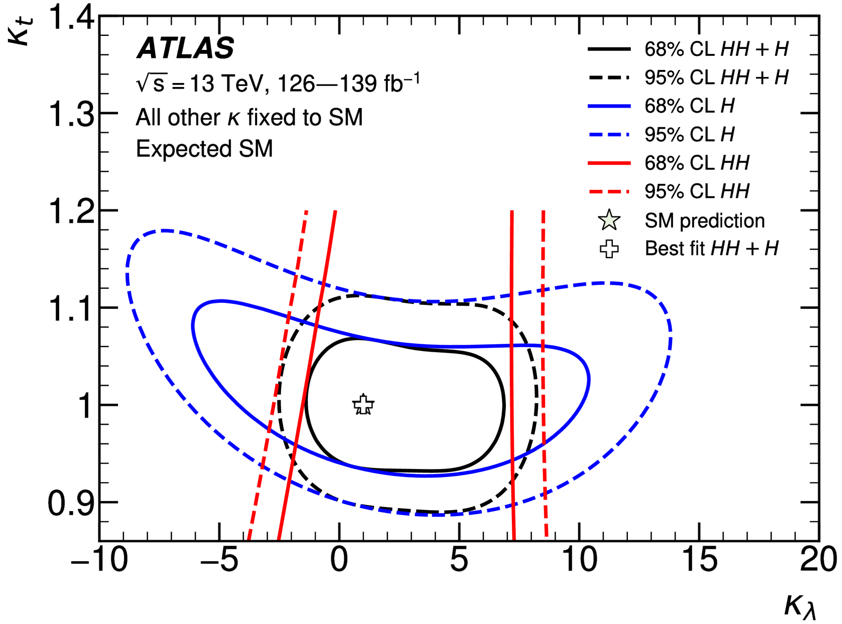
H+HH combination

- H+HH combination
- Simultaneous fit can constraint k_t and k_λ (Not possible in only HH anaysis)

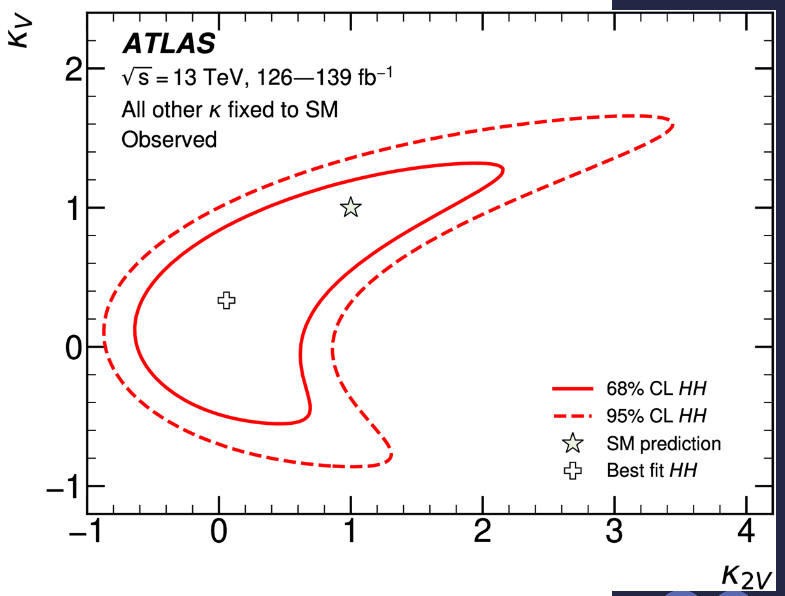
Float only κ_λ, other κ fixed to SM (expected)



Float only κ_λ and κ_t, other κ fixed to SM (expected)

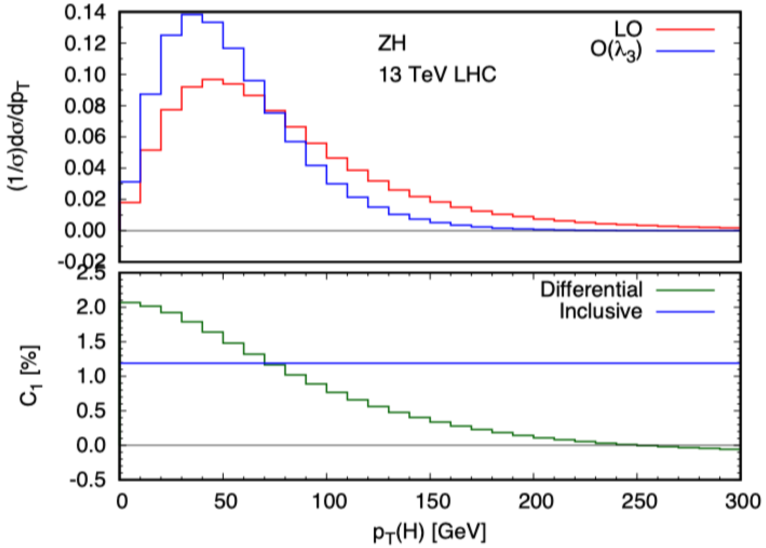


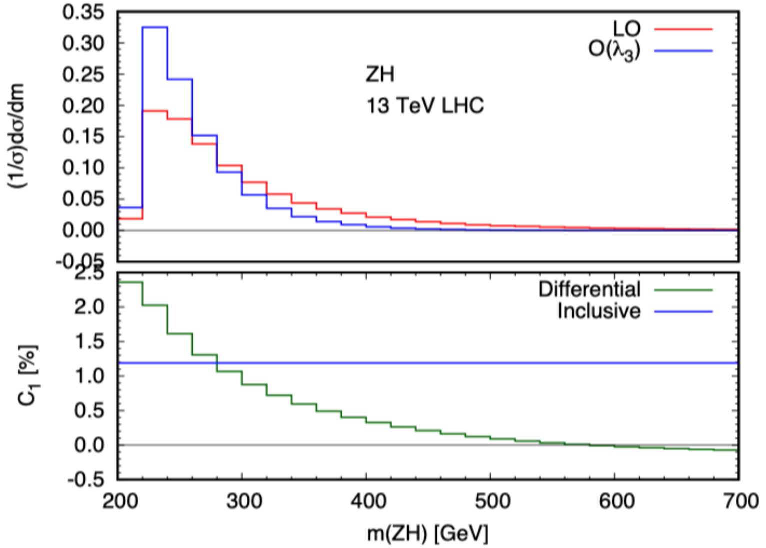
Float only κ_λ and κ_{2V}, other κ fixed to SM (observed)



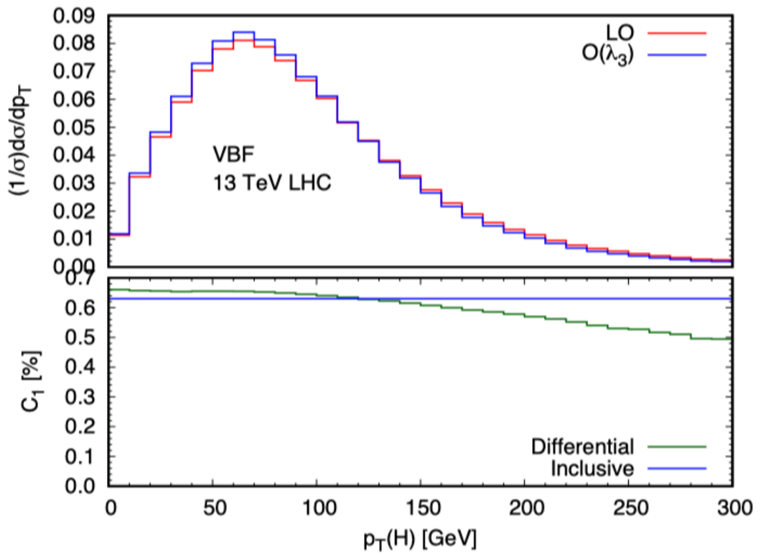
NLO EW correction

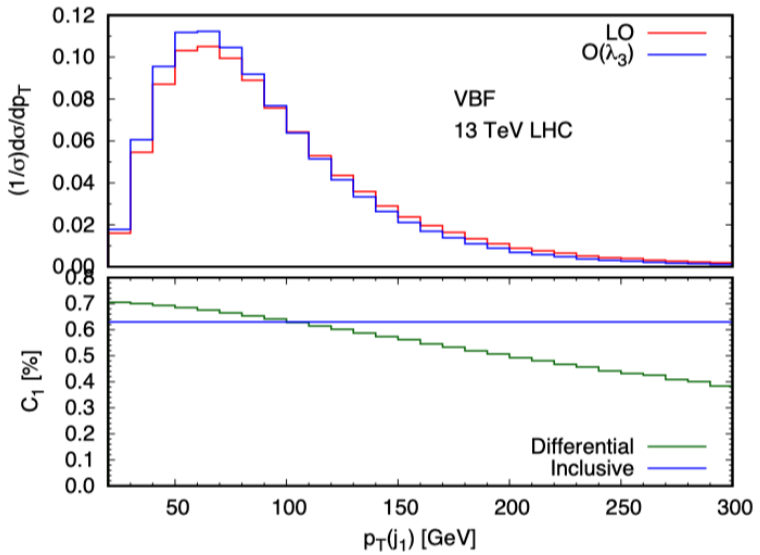
- ZH
  - Inclusive cross section: ~1.2% difference
  - differential distribution difference: ~2% (low-pTH, m(ZH)





- VBF
  - Inclusive cross section: 0.6% difference
  - differential: at most ~0.7%

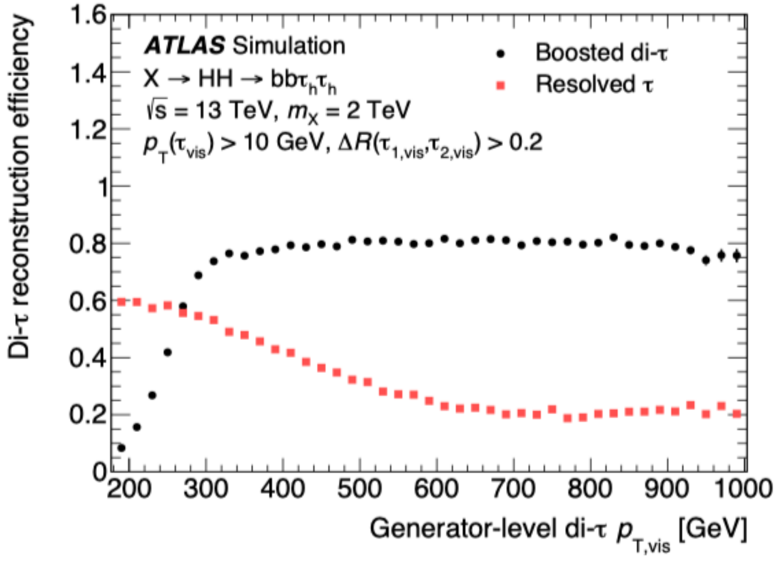


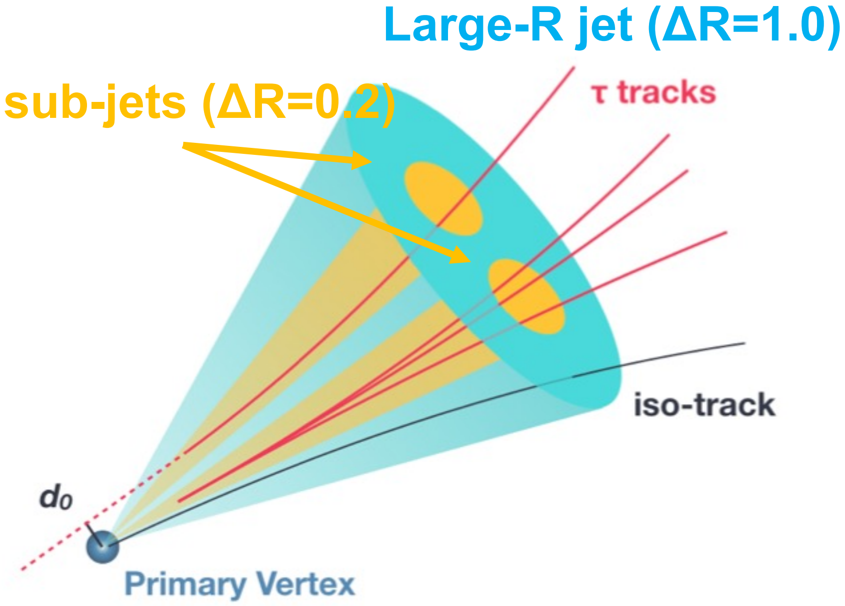


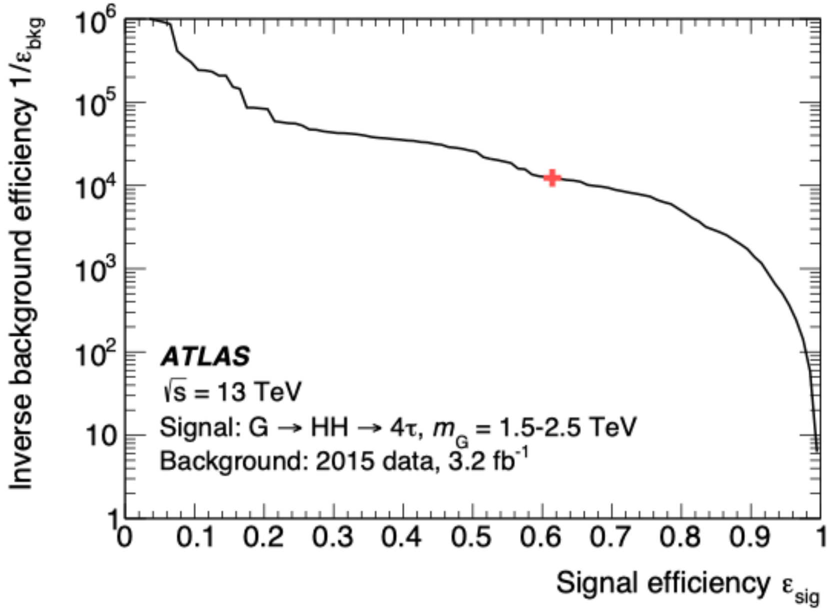
Ref: CMS tagger

boosted H→ττ tagger

- Standard Reco-efficiency decreased in high p_T di-τ
- di-τ identification with two sub-jets (ΔR=0.2) in Large R jet (ΔR=1.0)
- BDT is built to discriminate "ditau" from background (e.g. g→qq) (not tau-by-tau)
  - Input: p_T ratio (p_T^{subj}/p_T^{LRJ})and iso/τ track, angle information

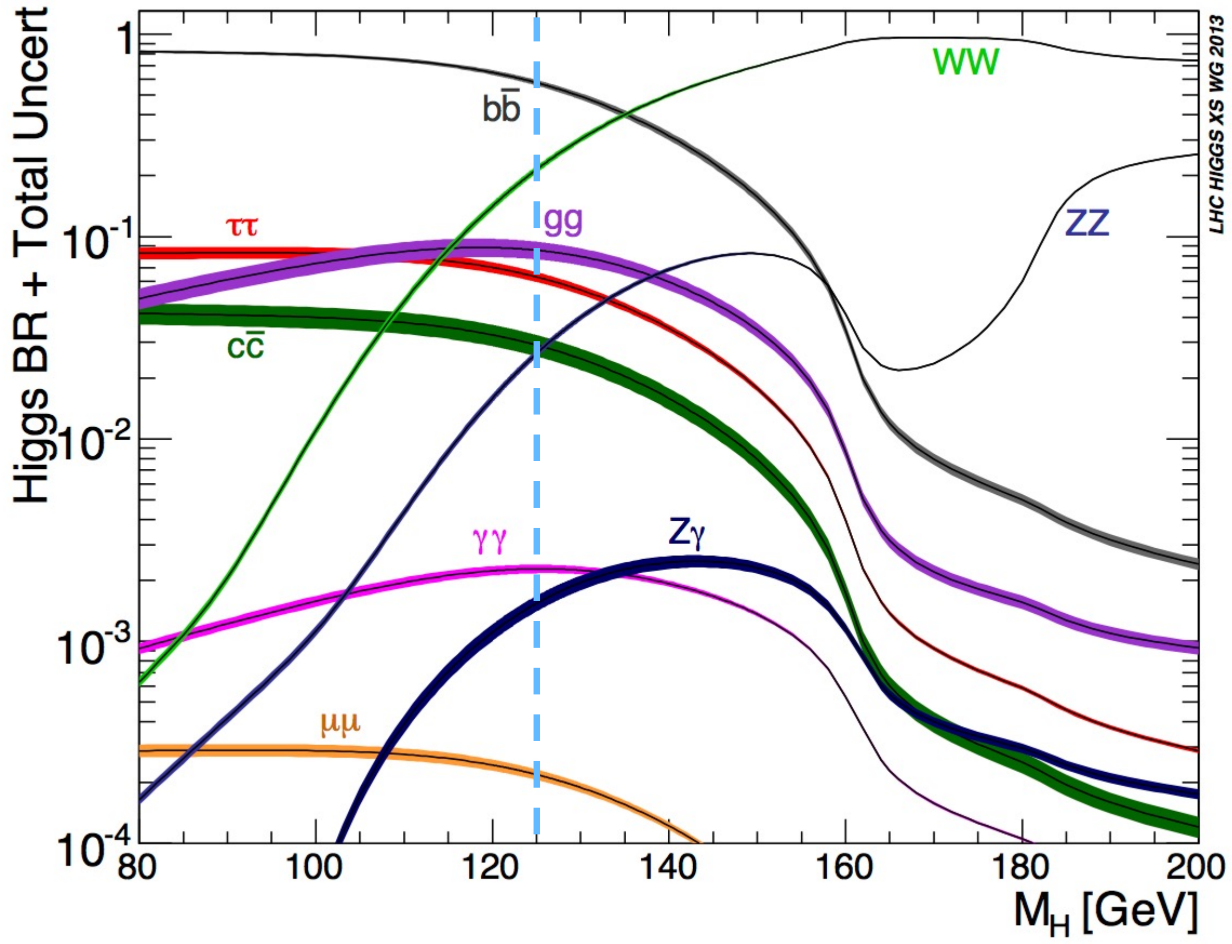






di-tau efficiency ~60%
background rejection ~10^4

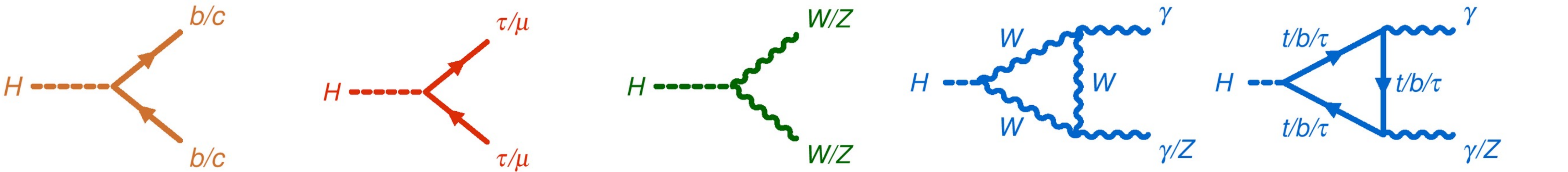
Higgs decay branching ratio



- Higgs boson decays to other SM particles
  - Observed Higgs mass(~125 GeV) is experimentally really good
  - Higgs boson is able to decay various particles
    ➔ Property measurement with different decay modes
  - H→bb decay mode is dominant

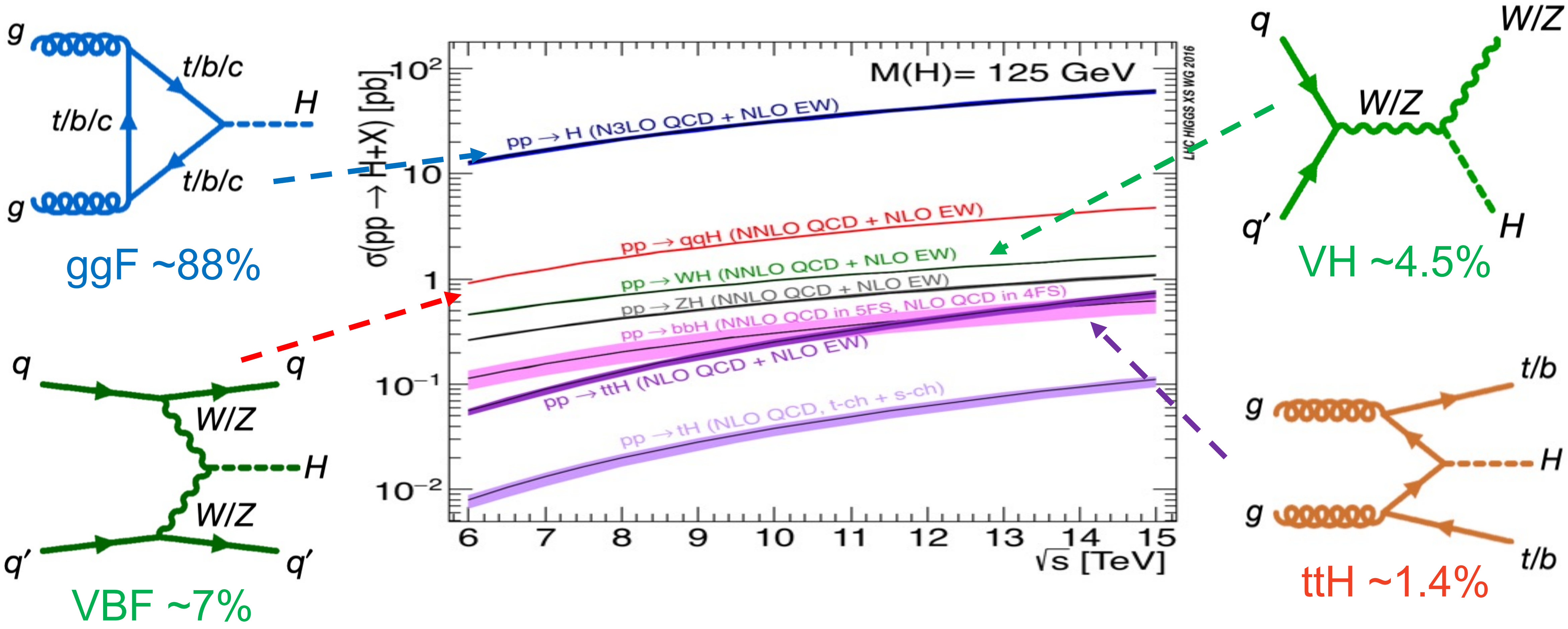
bb	WW	gg	ττ	cc	ZZ
58%	21%	8.2%	6.3%	2.9%	2.6%

γγ	Zγ	μμ
0.23%	0.15%	0.022%



Higgs Production at LHC

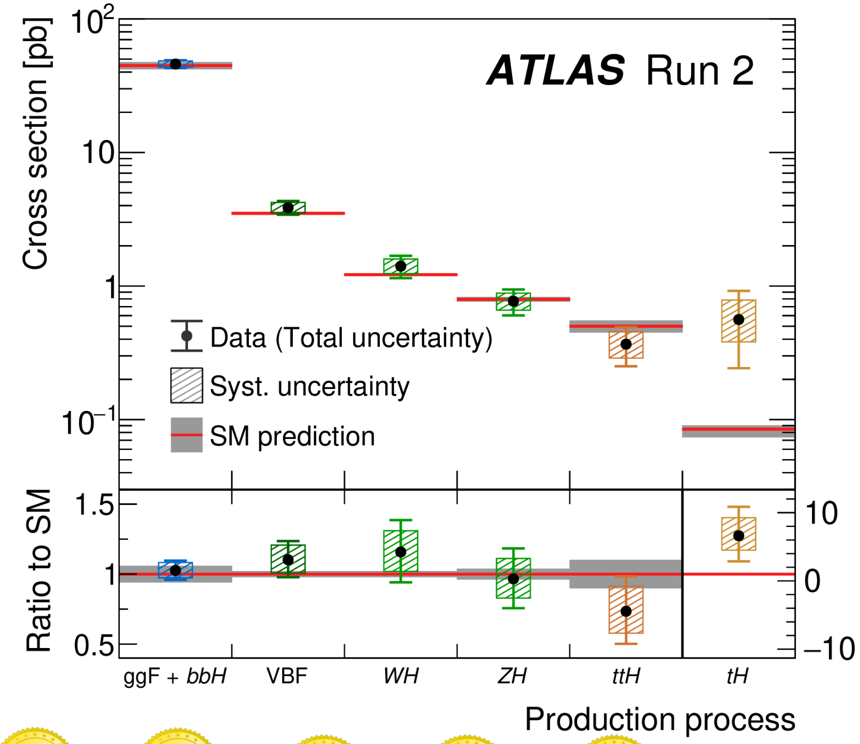
- Gluon-fusion process is dominant at LHC (Gluon collider!!)

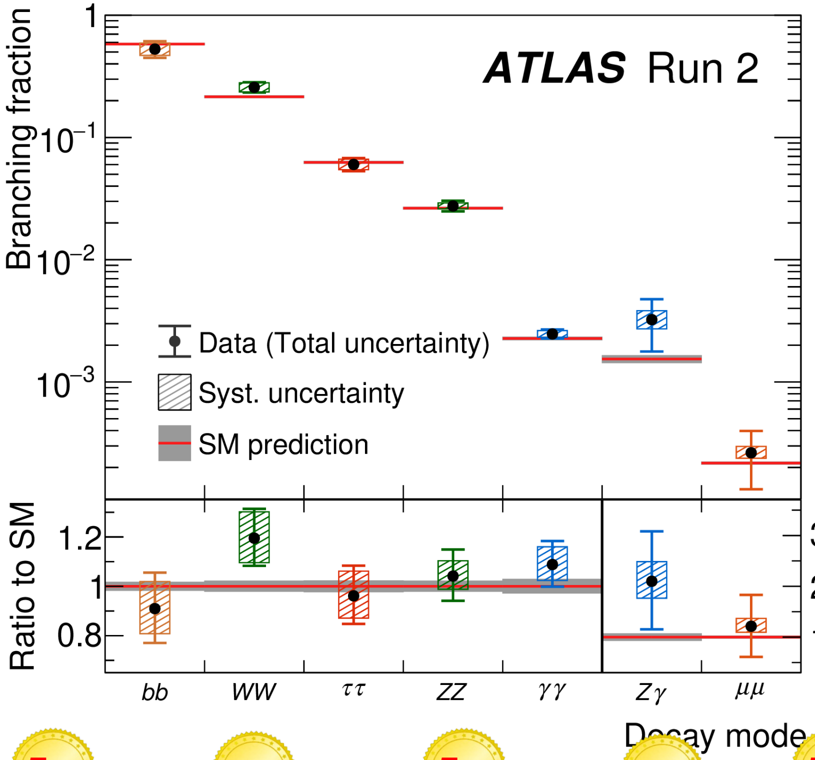


- Higgs physics strategy is built by the combination of production and decay (can not observe all Higgs events experimentally!!)
  - ➢ Lots of QCD background, not triggerable, detector coverage...

Higgs combined Results ~Production/Decay~

- Main Production channels and decay modes are already observed in Run1 and Run2 data





Start accessing rare production and decay mode

	ggF	VBF	WH	ZH	ttH	tH
	5σ	5σ	5σ	5σ	5σ	
	7%	13%	23%	22%	24%	~70%

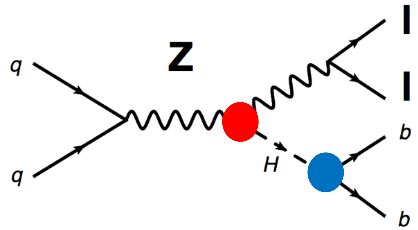
	H→bb	H→WW	H→ττ	H→ZZ	H→γγ	H→Zγ	H→μμ
	5σ	5σ	5σ	5σ	5σ		
	15%	12%	12%	11%	10%	~100%	~60%

No any significant deviation from SM (10-20% precision for main channels)

Higgs combined results ~Coupling~

- Measured couplings between Higgs boson and SM particles

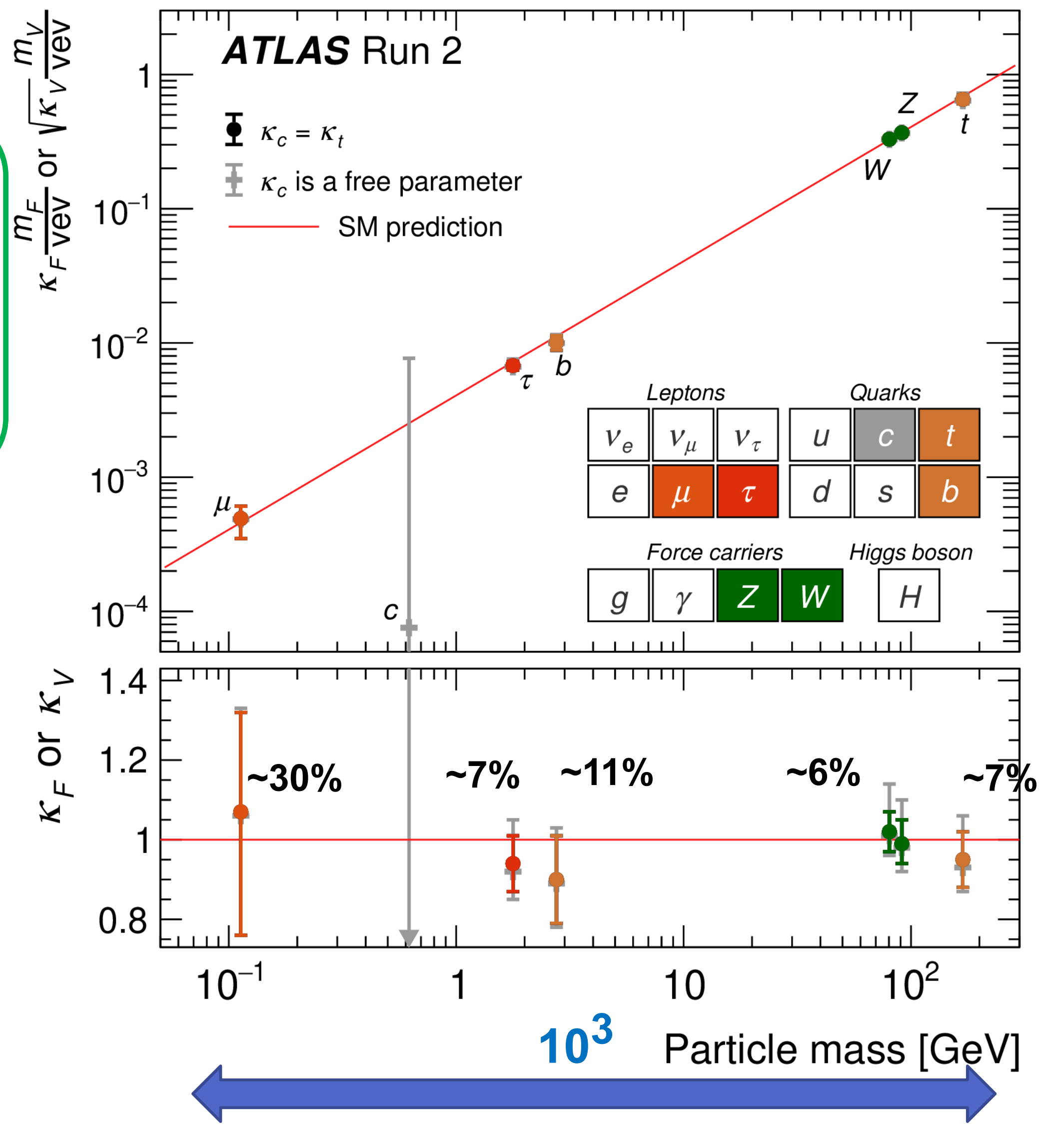
κ-framework: $\kappa = g_x^{measure} / g_x^{SM}$



$$\sigma(pp \to VH) \cdot BR(H \to bb)$$
$$= \frac{k_v^2 \cdot k_b^2}{k_H^2} \sigma_{SM} \cdot BR_{SM}$$

- Coupling modifier κ_t, κ_b, κ_τ, κ_μ, κ_W, κ_Z, (k_c) (measured coupling normalized to SM)
- Precision is 7-11% for top, W/Z, bottom, τ, ~30% for μ
  - Yukawa coupling works well in 10^3 different scale (O(100 MeV) ~ O(100 GeV))!!
  - Higgs boson builds generation of quark and lepton

$$Y_\mu \ll Y_\tau,\ Y_c < Y_b \ll Y_t$$



2023/2/22

2nd ILC-J Physics WG meeting