Indirect Higgs Self-coupling measurement using single Higgs production

Tatsuya Masubuchi

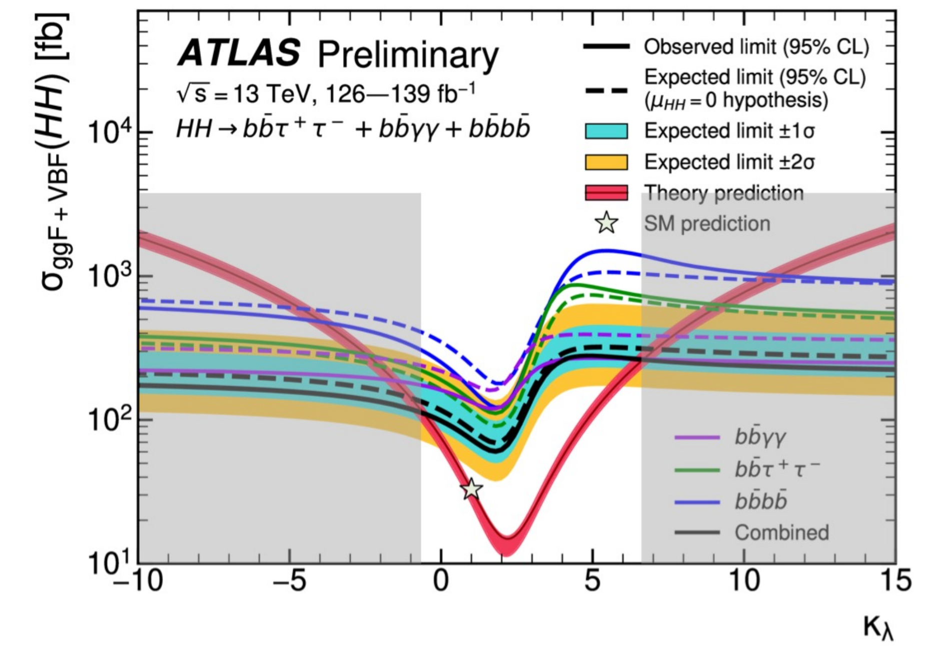
University of Tokyo (ICEPP)

ATLAS EXPERIMENT

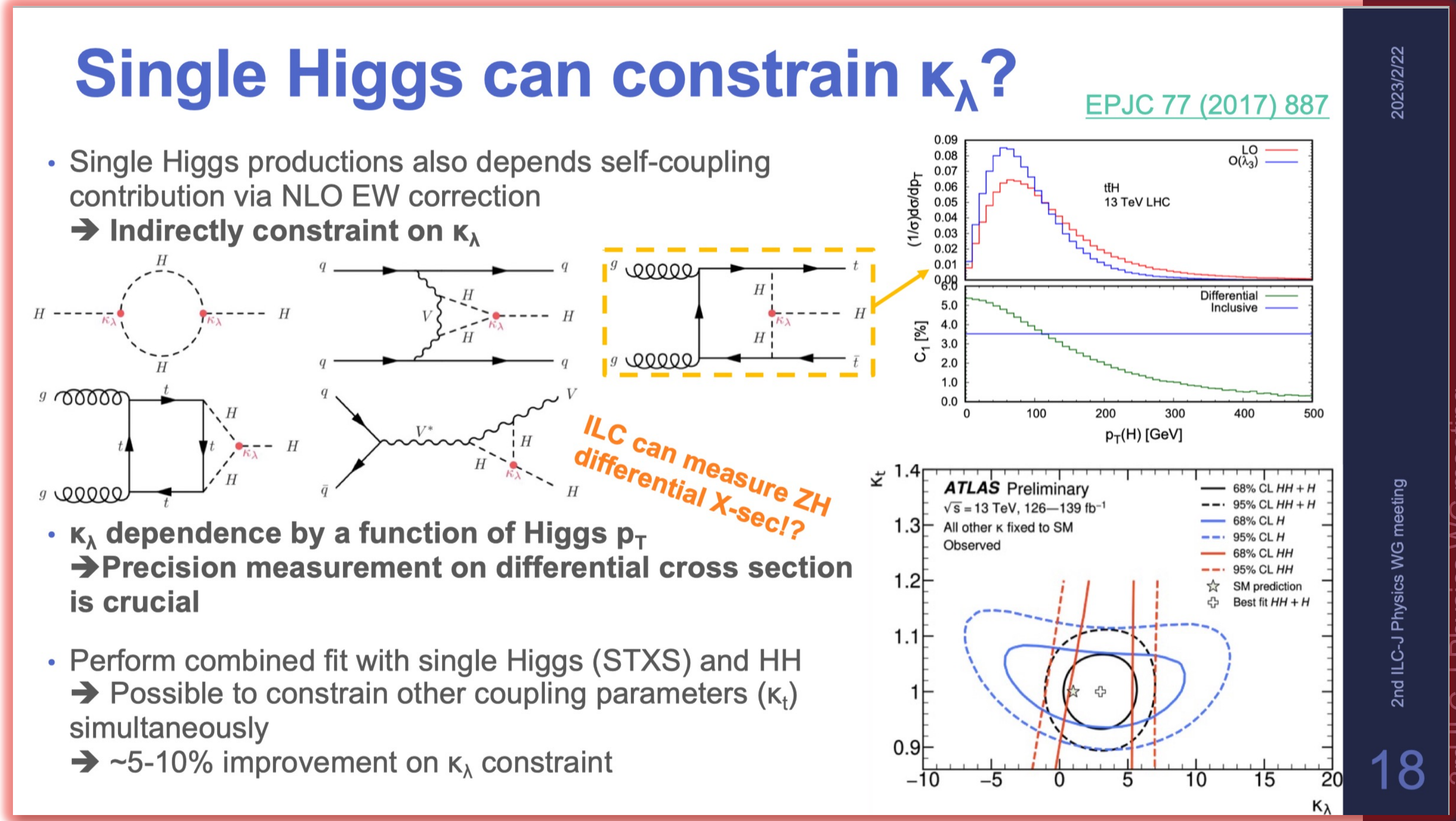
ICEPP The University of Tokyo

Introduction: ILC250 can constrain κ_λ?

- LHC can constrain κ_λ with both direct/indirect ways
  - Direct HH measurement is powerful, but indirect measurement may provide complemental information



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

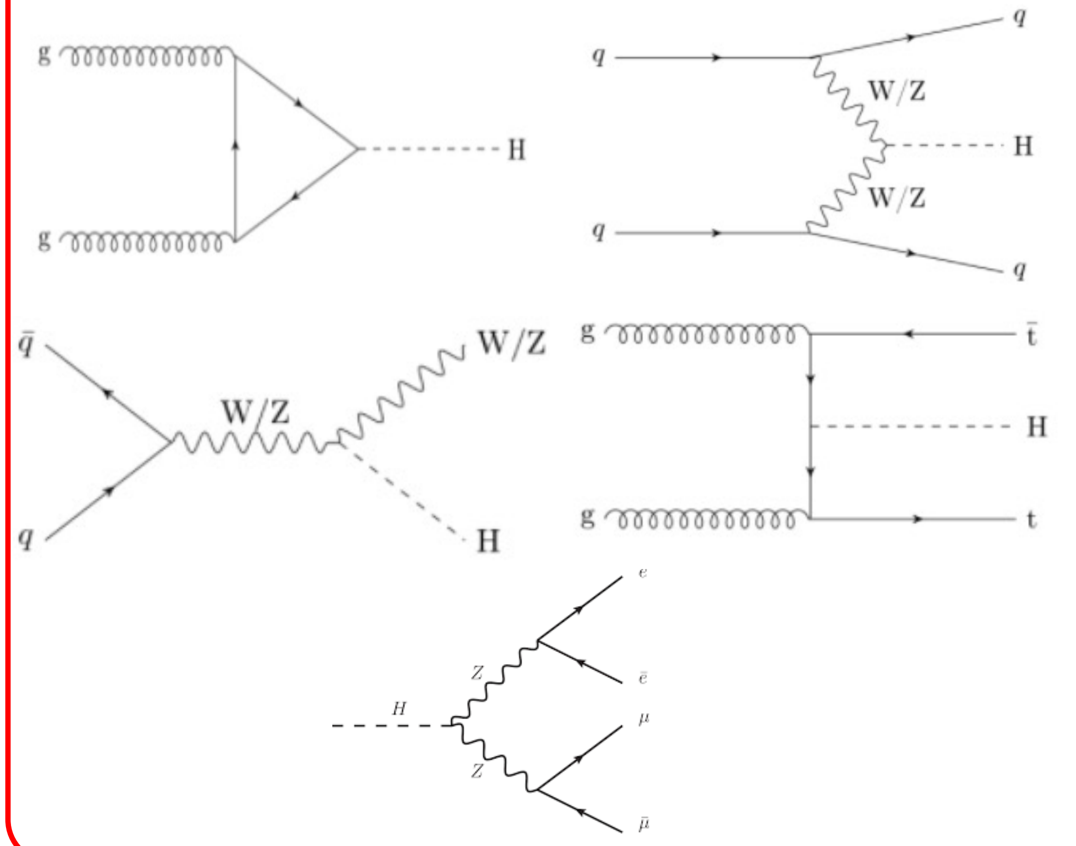


Today's focus

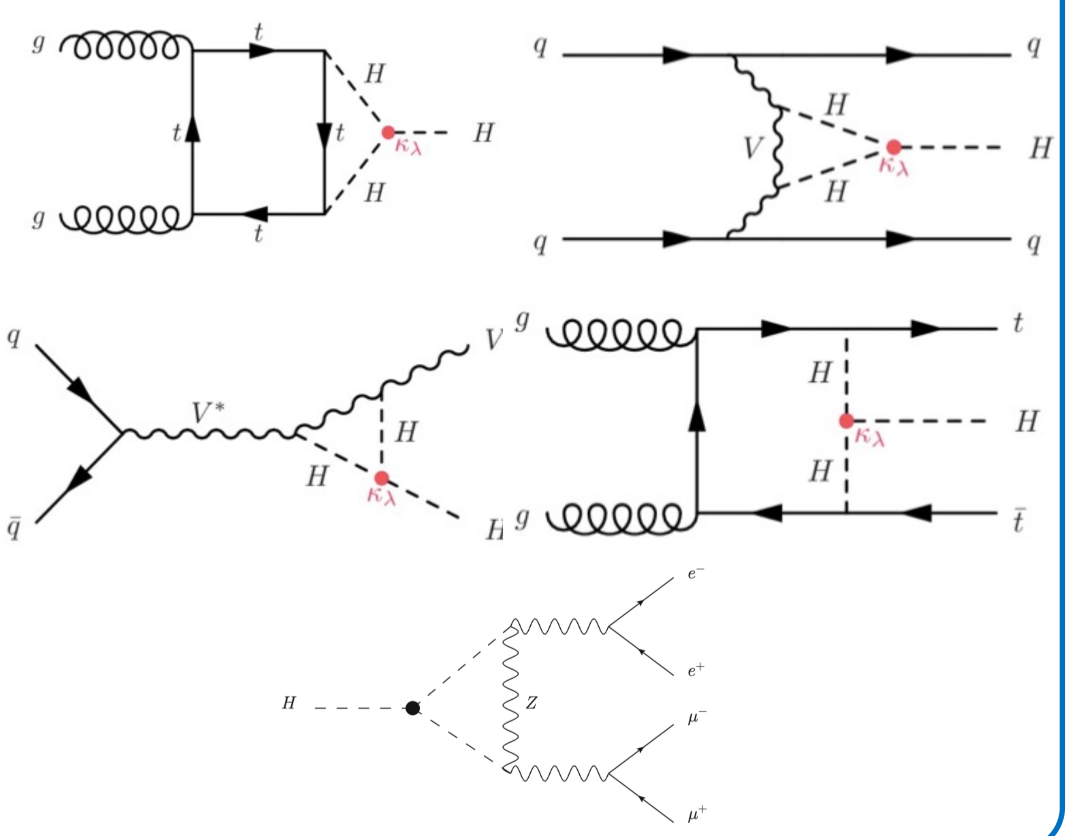
Indirect κ_λ measurement with single Higgs production

- Single Higgs production and decay does not depend on trilinear coupling λ in LO diagram
- Diagrams with trilinear coupling can contribute to higher order EW correction

LO diagram



LO diagram + NLO EW



Theoretical Setup

- Single Higgs production weakly depends on k_λ through NLO EW correction, but cross section is much larger than HH production ➔ Single Higgs measurement can constrain k_λ

$$\frac{\sigma_{NLO_{EW}}}{\sigma_{NLO\,EW,SM}} = \frac{Z_H^{BSM}\{\sigma_{LO,SM}[(k_\lambda - 1)C_1 + k_j K_{EW}]\}}{\sigma_{LO,SM} K_{EW}}$$

$$Z_H^{BSM} = \frac{1}{1-(k_\lambda^2 - 1)\delta Z_H}$$

arXiv:1709.08649

$$\frac{\sigma_{NLO_{EW}}}{\sigma_{NLO\,EW,SM}} = Z_H^{BSM}\left[\frac{(k_\lambda - 1)C_1}{K_{EW}} + k_j^2\right] \xrightarrow{\kappa_\lambda=1,k_j=1} 1(\mathrm{SM})$$

Full set of NLO EW effect (kinematic dependent)

Process independent correction (k_λ^2 dependence)

k_λ dependent NLO EW correction effect (C_1=NLO/LO) (Production/decay dependent, kinematic dependent)

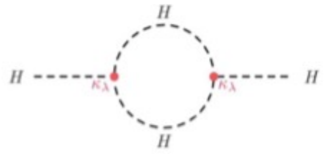


Table 1 C_1 for different Higgs production processes at 13 TeV LHC and the $H \to 4\ell$ decay

Channels	ggF	VBF	ZH	WH	$t\bar{t}H$	tHj	$H \to 4\ell$
$C_1(\%)$	0.66	0.63	1.19	1.03	3.52	0.91	0.82

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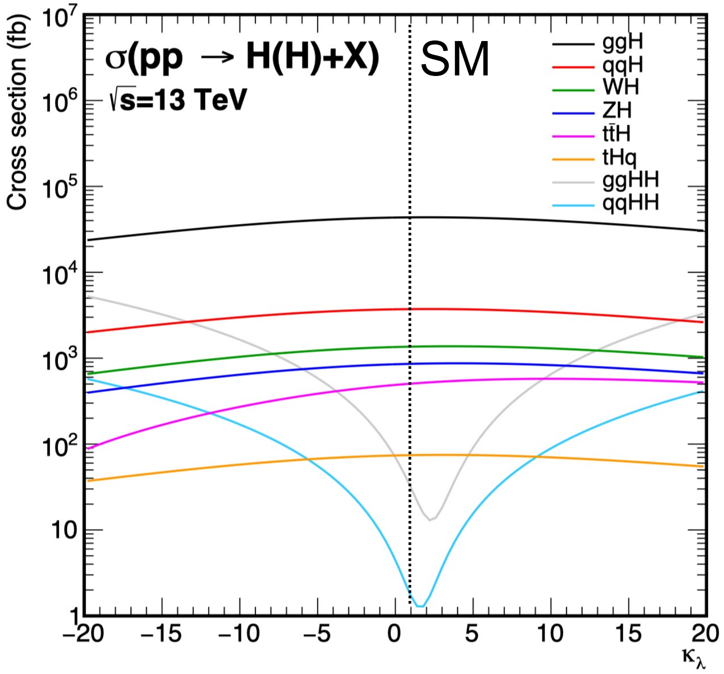
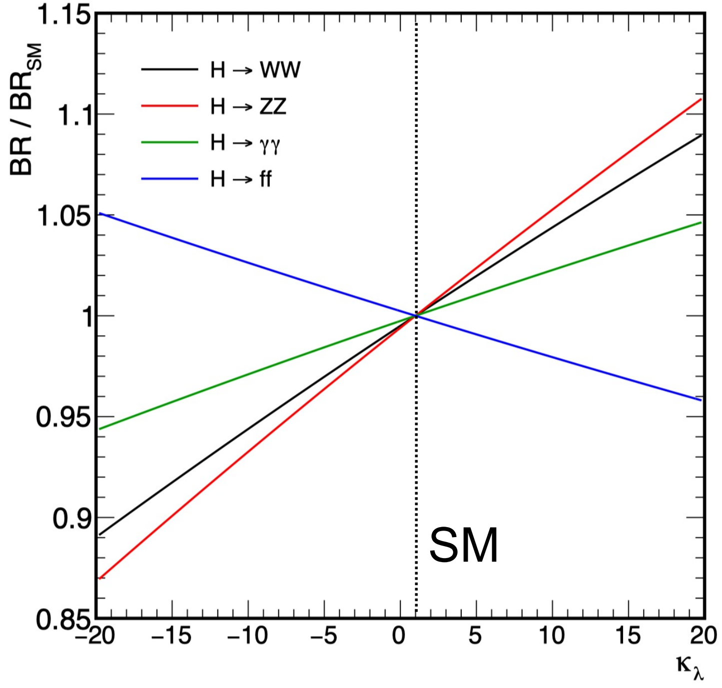
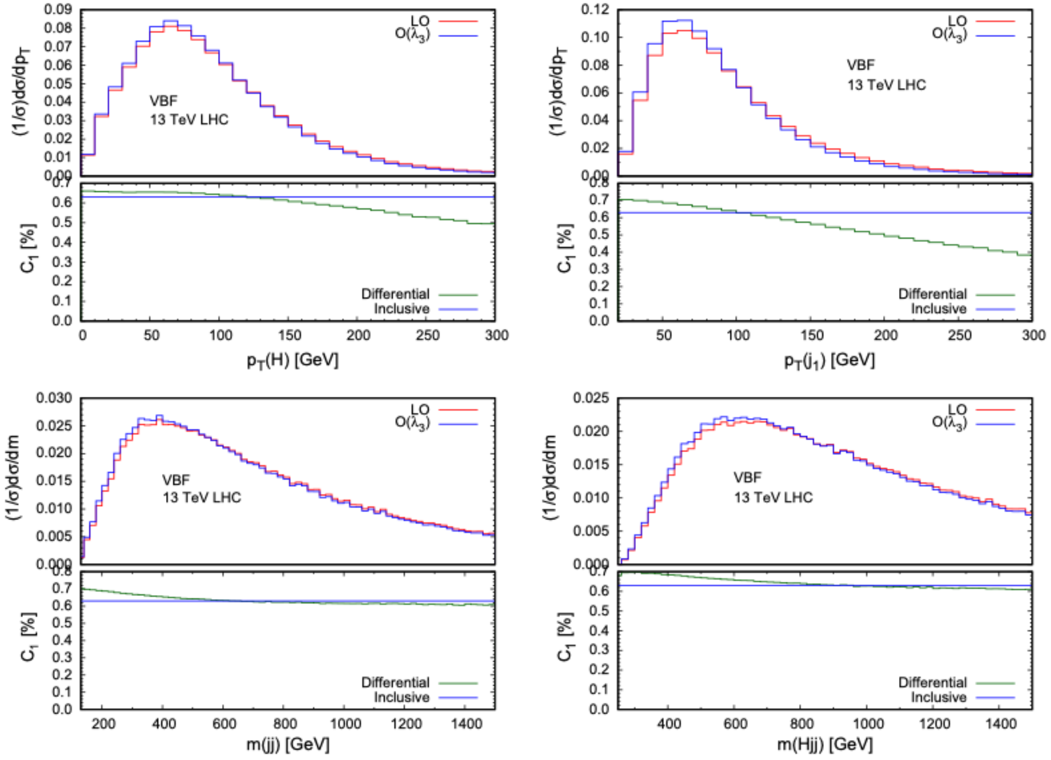


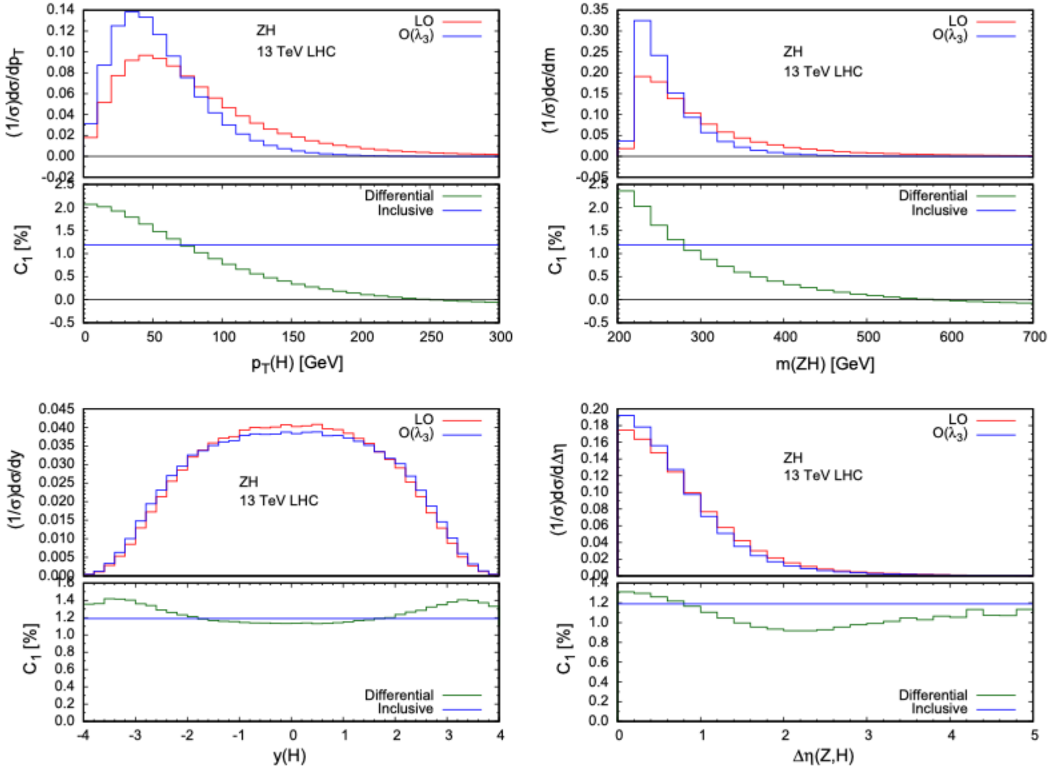


Kinematic dependence on C_1

arXiv:1709.08649

- C_1 and K_{EW} depends on the kinematics
  ➔ Differential measurement would be more sensitive to κ_λ





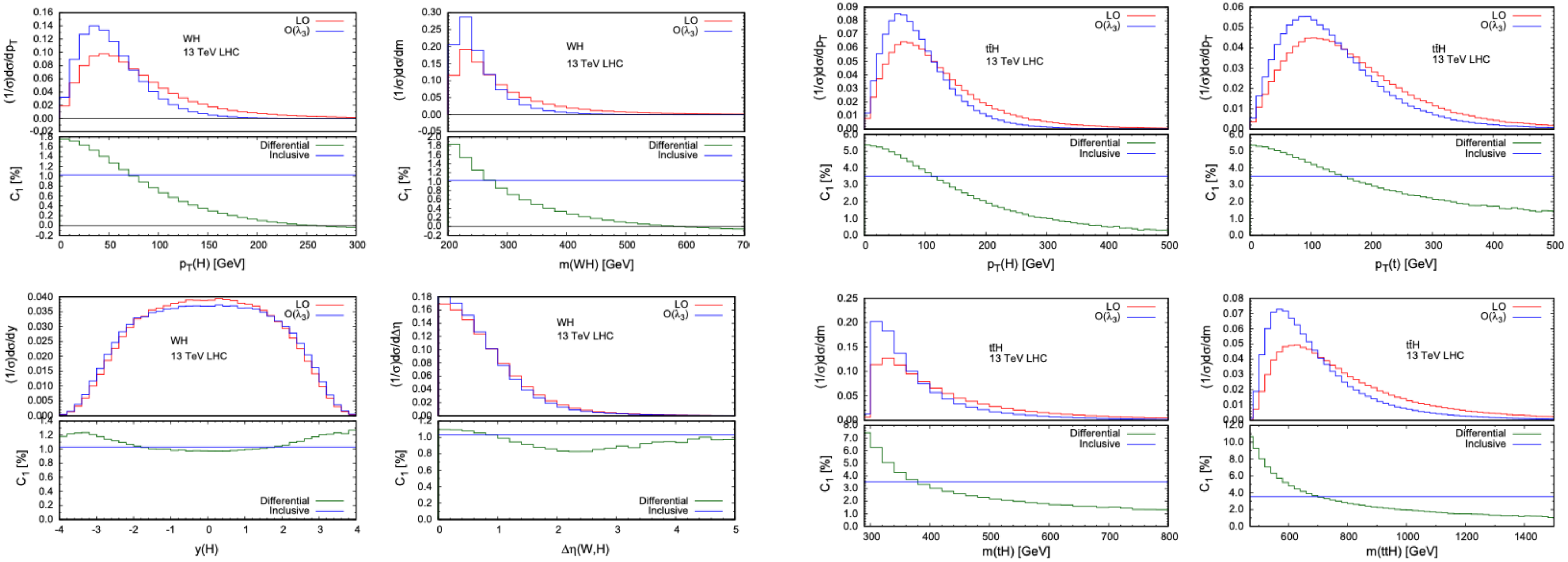
VBF production
Inclusive ~0.6%
Kinematic dependence is not so large
(slight dependence on p_T^H and p_T^{j1})

ZH production
Inclusive ~1.2%
Kinematic dependence on p_T(H) and m(ZH)
Sensitive in low p_T region

Kinematic dependence on C_1

arXiv:1709.08649

- C_1 and K_{EW} depends on the kinematics
  ➔ Differential measurement would be more sensitive to κ_λ



WH production
Inclusie ~1.0%
Kinematic dependence on $p_T(H)$ and m(WH)
Sensitive in low p_T

ttH production
Inclusive 3.5%
$p_T(H)$ and $p_T(t)$ dependence is large
~5% in low p_T, 7-10% on m(tH), m(ttH)

How to measure?

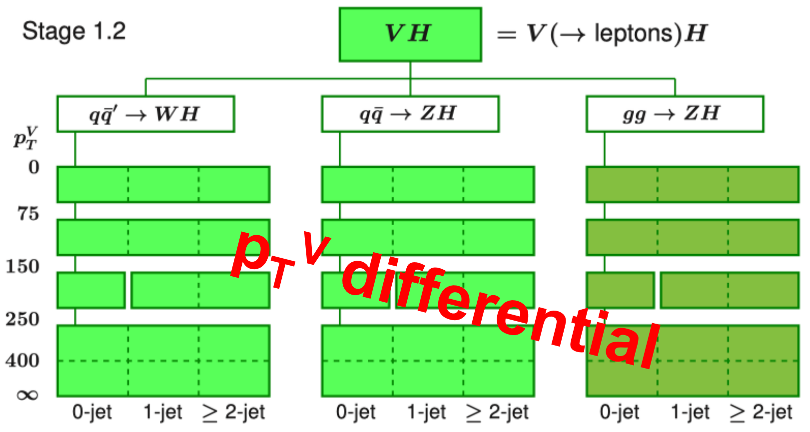
- To maximize the sensitivity to κ_λ, use all available production and decay modes for single Higgs analyses
- Inclusive production cross section + decay (κ-framework)
- Differential cross section measurement (Simplified Template Cross Section, STXS) for VBF, VH, ttH

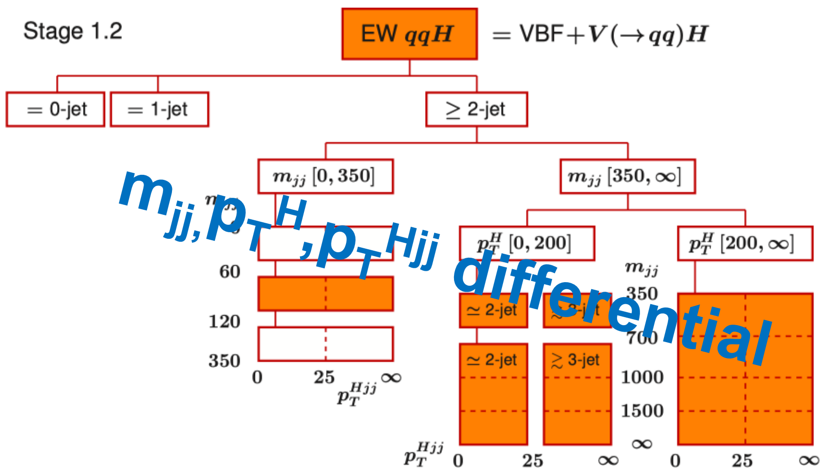
Decay	Production mode
H→γγ	ggF, VBF, VH, ttH, tH
H→ZZ→4l	ggF, VBF, VH, ttH, tH
H→ττ	ggF, VBF, VH, ttH, tH
H→WW	ggF, VBF
H→bb	VBF, VH, ttH

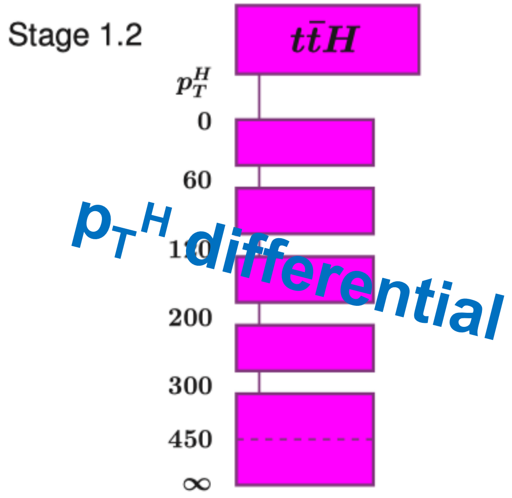
$$n_{i,f}^{sig}(\kappa_\lambda,\kappa_m) \propto \boxed{\mu_i(\kappa_\lambda,\kappa_m)} \times \sigma_i^{SM} \times \boxed{\mu_f(\kappa_\lambda,\kappa_m)} \times BR_f^{SM} \times (\epsilon \times A)_{if}$$

Correction of STXS bin(i) **Correction of decay(f)**

***No available EW correction for ggF ➔ use only inclusive measurement**







Experimentally, difficult to measure differential cross-section (STXS) in all phase spaces!

Parametrize ELO effect in STXS bin

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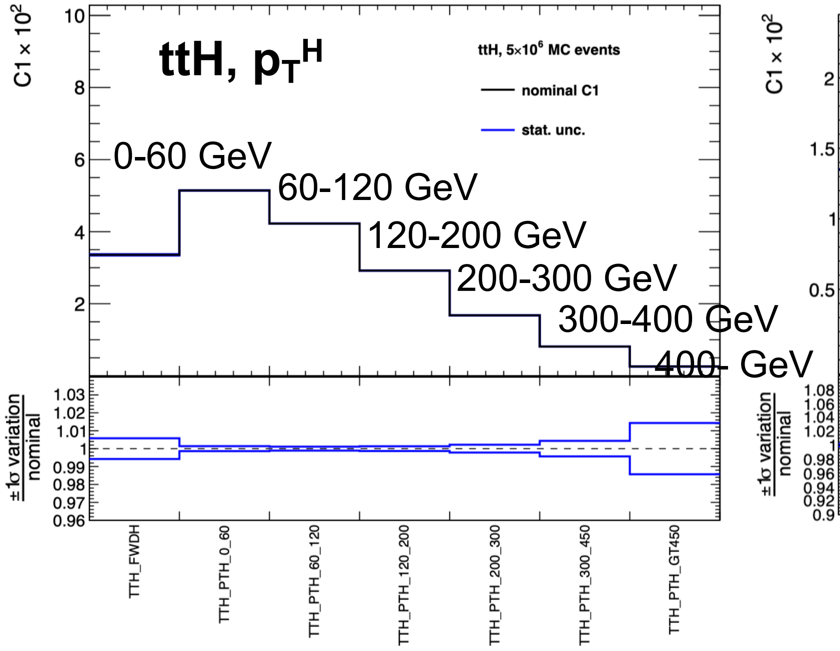
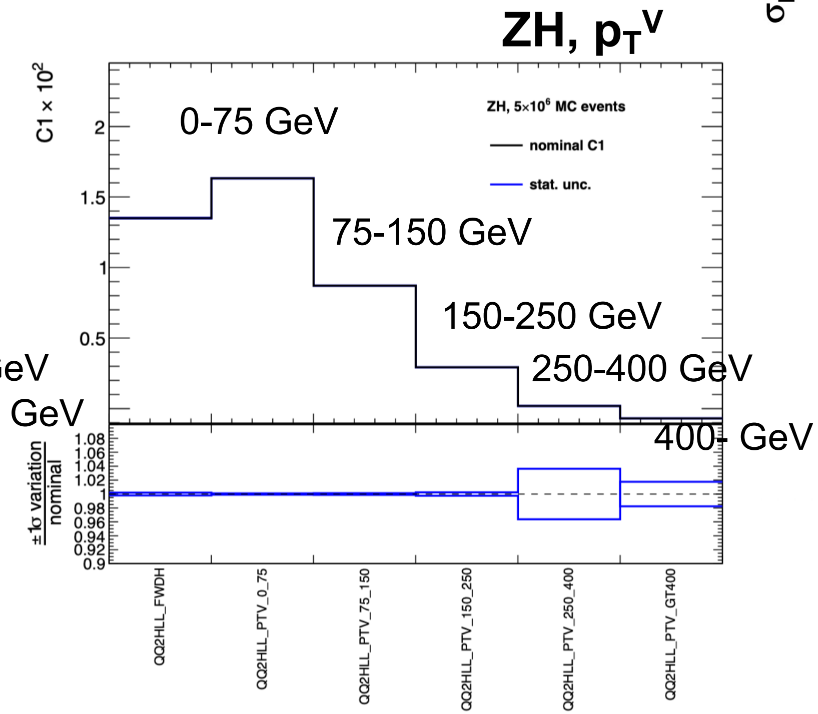
- Equation expands to STXS bins (j=STXS bin)
  - Measure cross section for each STXS bin(differential info)

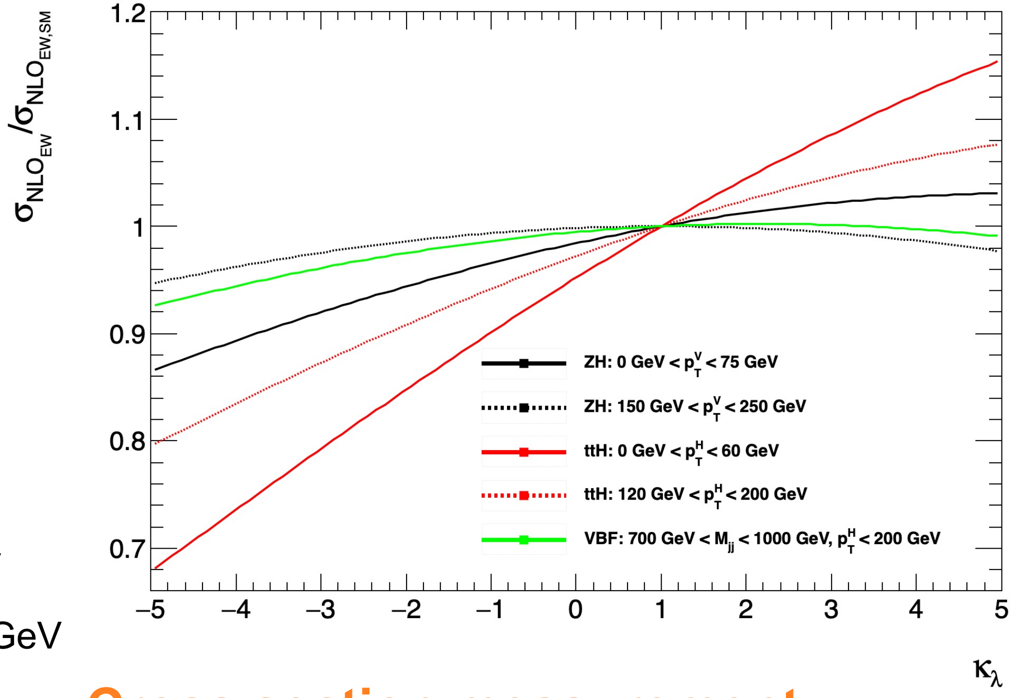
$$\frac{\sigma^{i}_{NLO_{EW}}}{\sigma_{NLO}{}^{i}_{EW,SM}} = Z_H^{BSM}\left[\frac{(k_\lambda - 1)\boldsymbol{C_1^i}}{\boldsymbol{K_{EW}^i}} + 1\right]$$

Parametrization of C1 in STXS bins

- STXS bins provide enough kinematic dependence
  - p_T^H for ttH, p_T^V for VH





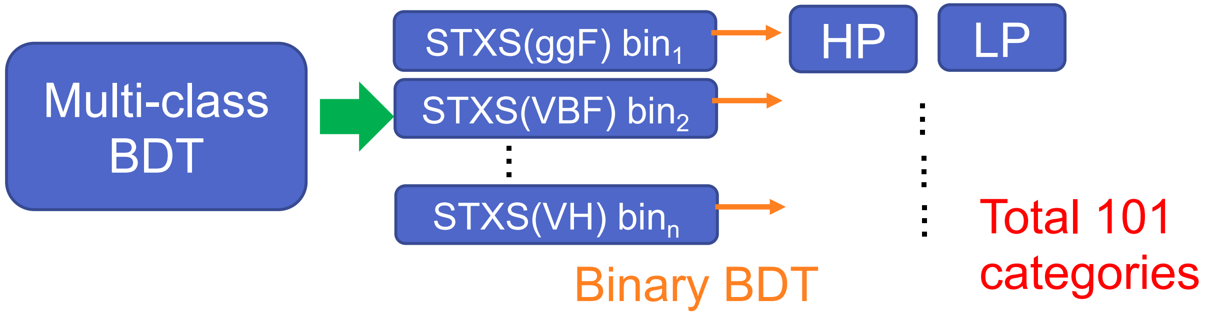


Cross section measurement can constrain k_λ

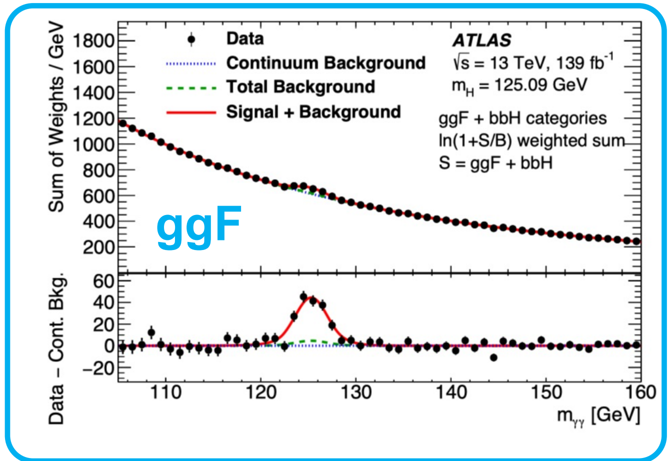
Experimental Measurement

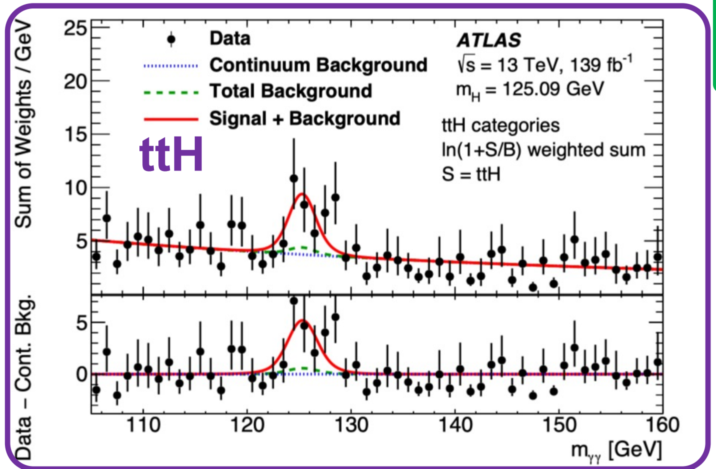
STXS measurement (H→γγ)

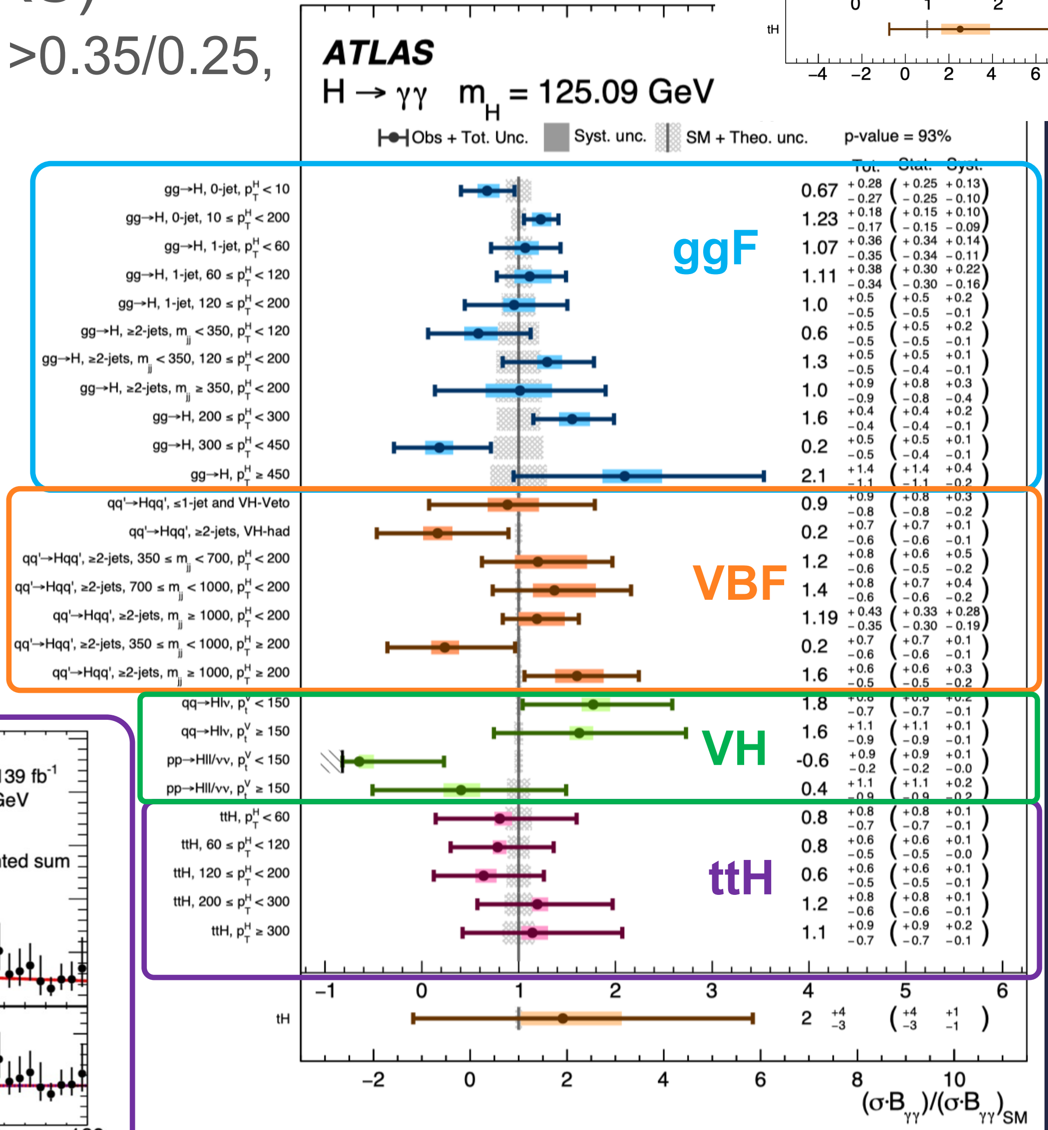
- H→γγ (simple analysis but complicated STXS)
  - Very simple selection for Higgs candidate: $p_T^{\gamma}/m_{\gamma\gamma}$ >0.35/0.25, $|\eta_{\gamma}| < 2.37$ (excl. $1.37 < |\eta_{\gamma}| < 1.52$)
  - Separate each signal process by multi-class BDT using jet/lepton kinematics, top reconstruction

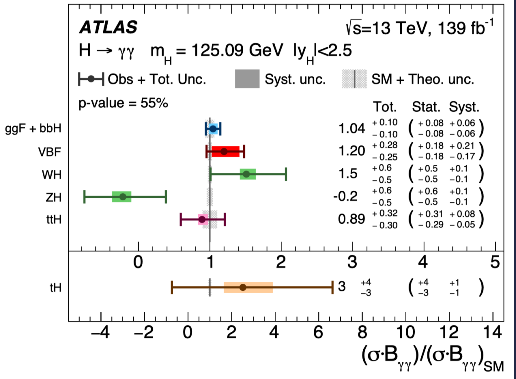


  - Extract cross section by fitting $m_{\gamma\gamma}$ distribution



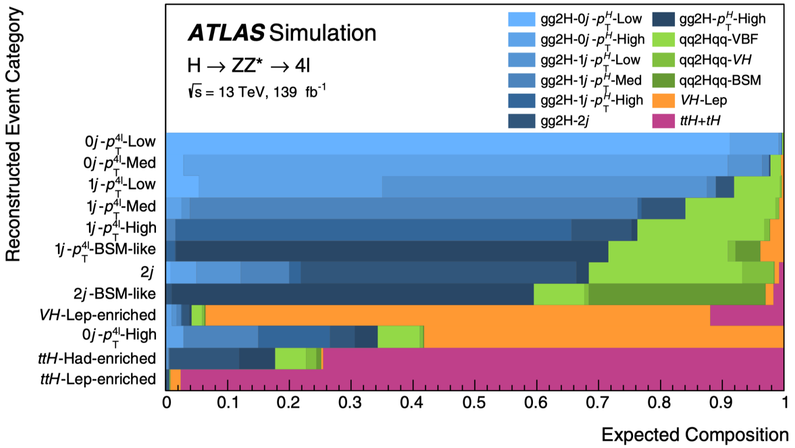


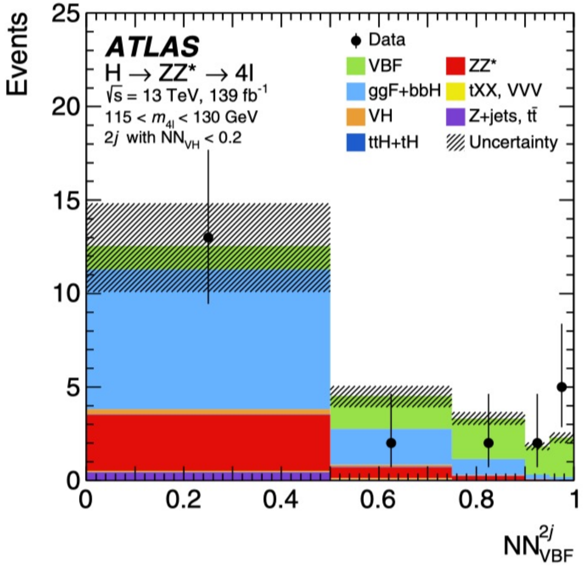


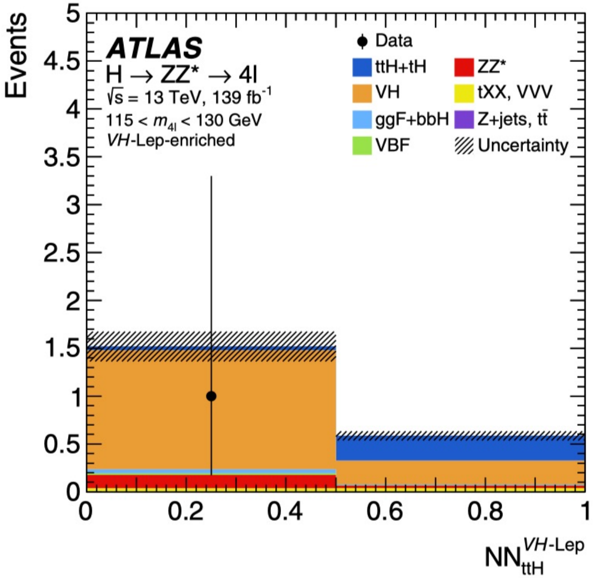


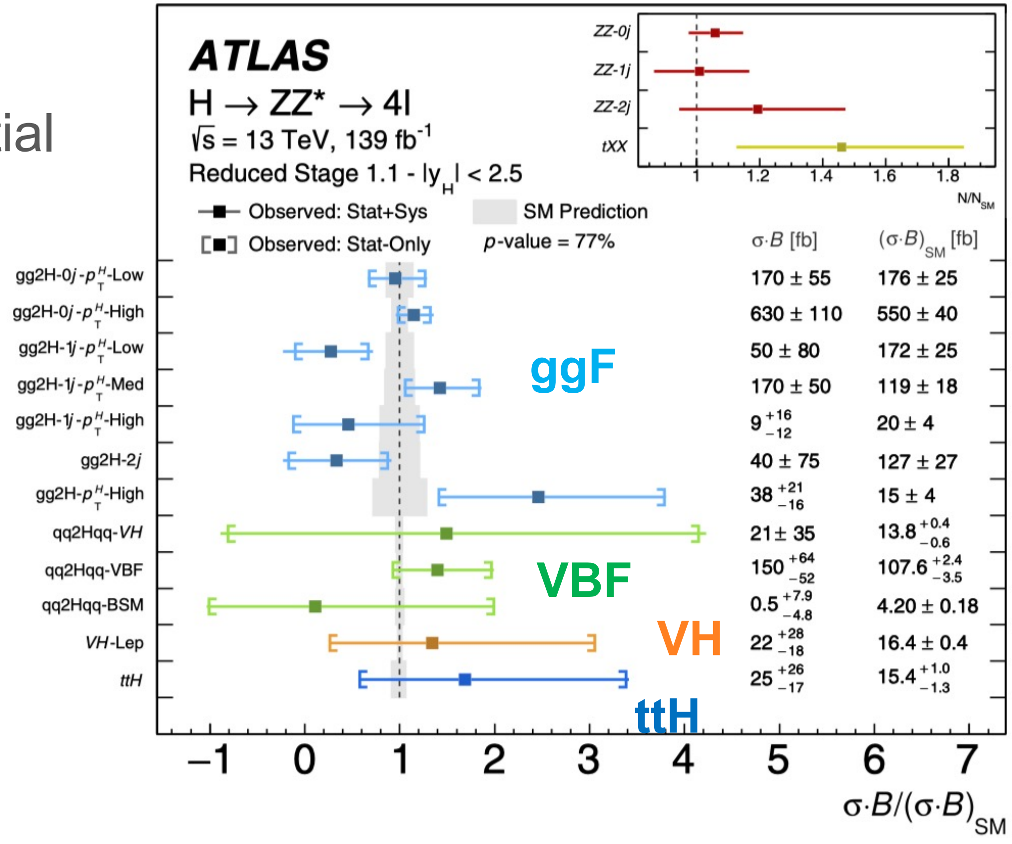
STXS measurement (H→ZZ)

- H→ZZ→4l
  - Purity of Signal is quite high but statistically very limited (for non ggF category)
  - Event categorization done sequentially (ttH→VH→H+2j(VBF),H+0/1j(ggF)) using kinematic info
  - NN specified each production mode is final discriminant
  - Still not enough sensitivity(statistics) to measure differential cross section for VH and ttH



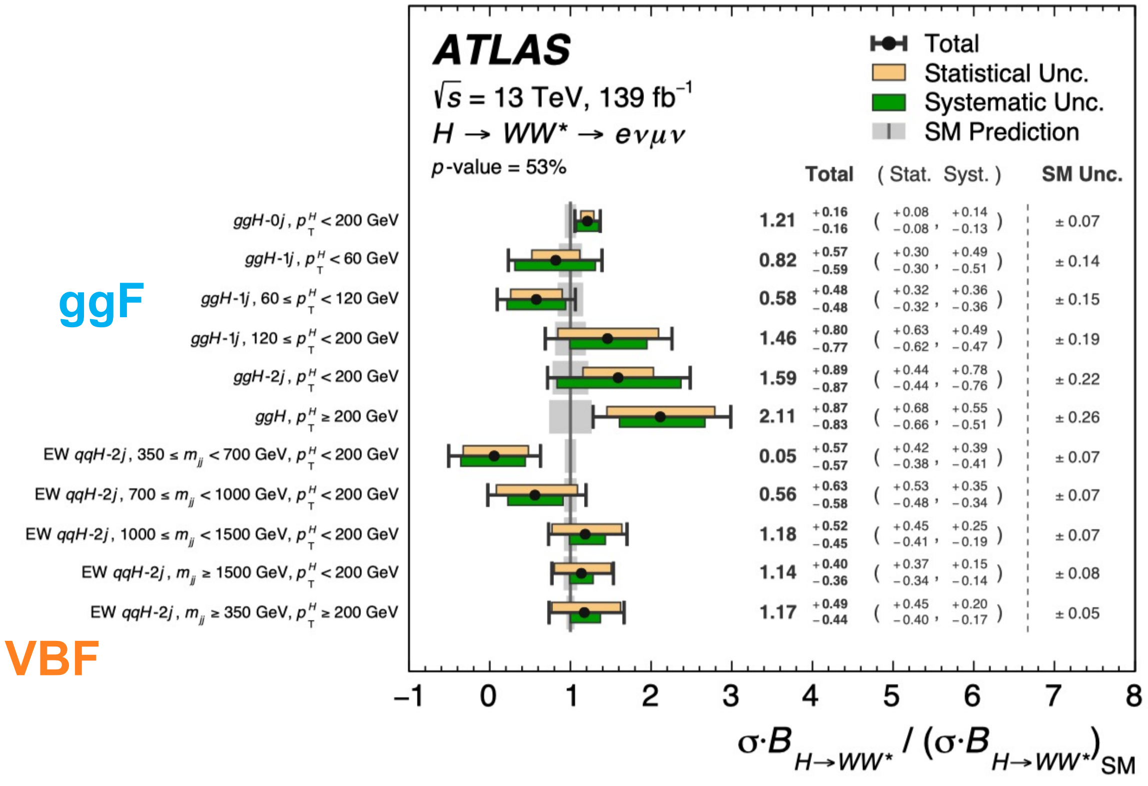




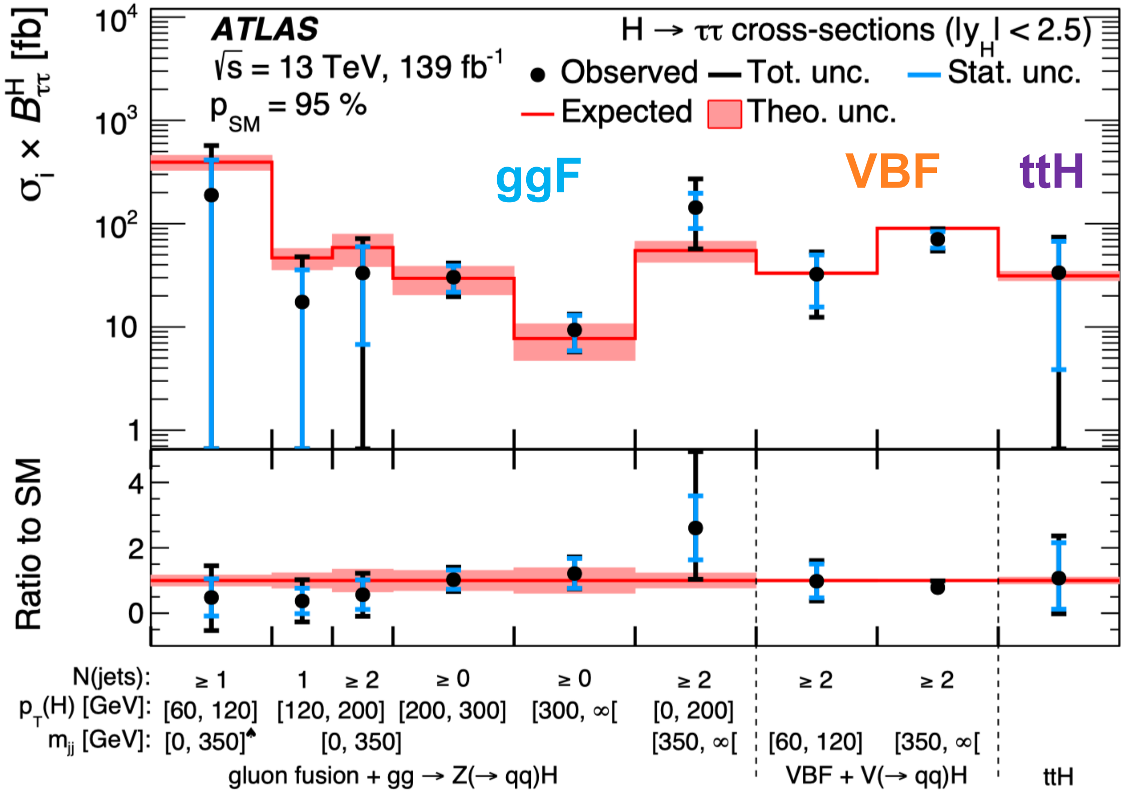


STXS measurement (H→WW, H→ττ)

- H→WW→lvlv
  - Measure STXS for only ggF and VBF production modes (6 ggF bin, 5 VBF bin)

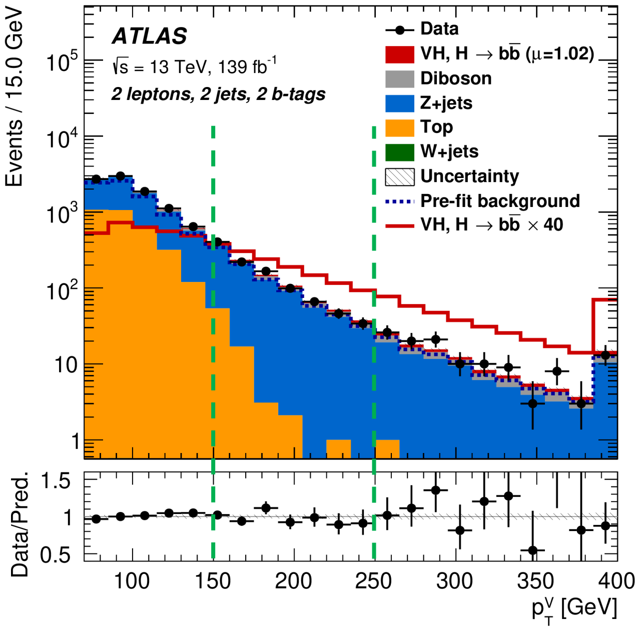


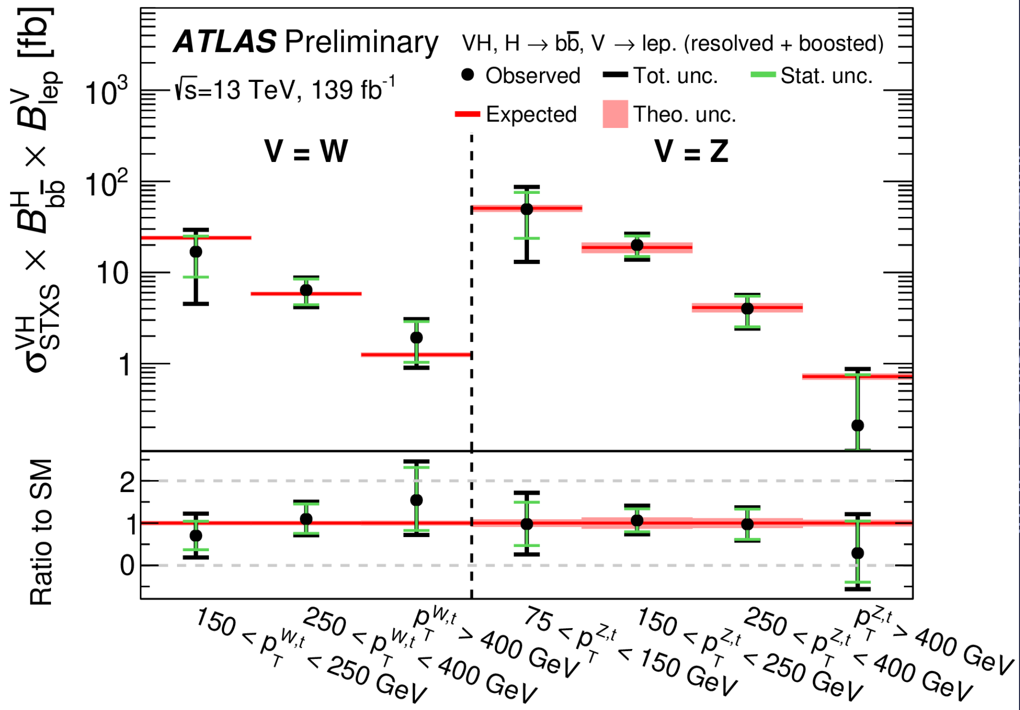
- H→ττ
  - High sensitivity for VBF production (no differential measurement yet)
  - One ttH bin



STXS measurement (VH→bb)

- One of most sensitive channel for VH production mode
- Optimize the analysis for 0-lepton (ZH→vvbb), 1-lepton(WH→lvbb), 2-lepton(ZH→llbb) separately
- Boosted H→bb events used for p_T^V > 400 GeV
- Very difficult to access to lower p_T^V region due to high background rate and trigger threshold
  - **0-lepton (p_T^Z > 150 GeV)**
  - **1-lepton (p_T^W > 150 GeV)**
  - **2-lepton (p_T^Z > 75 GeV)**

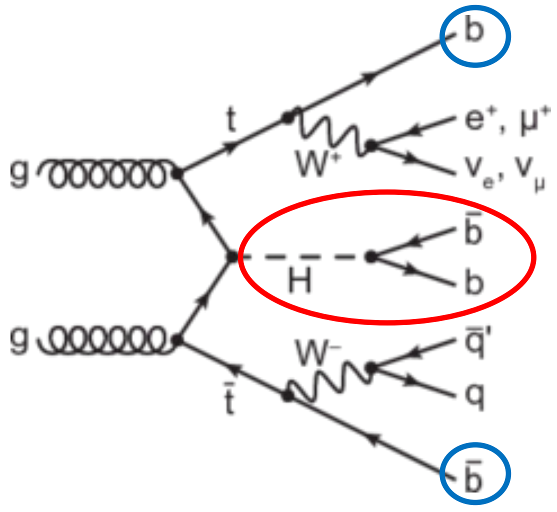


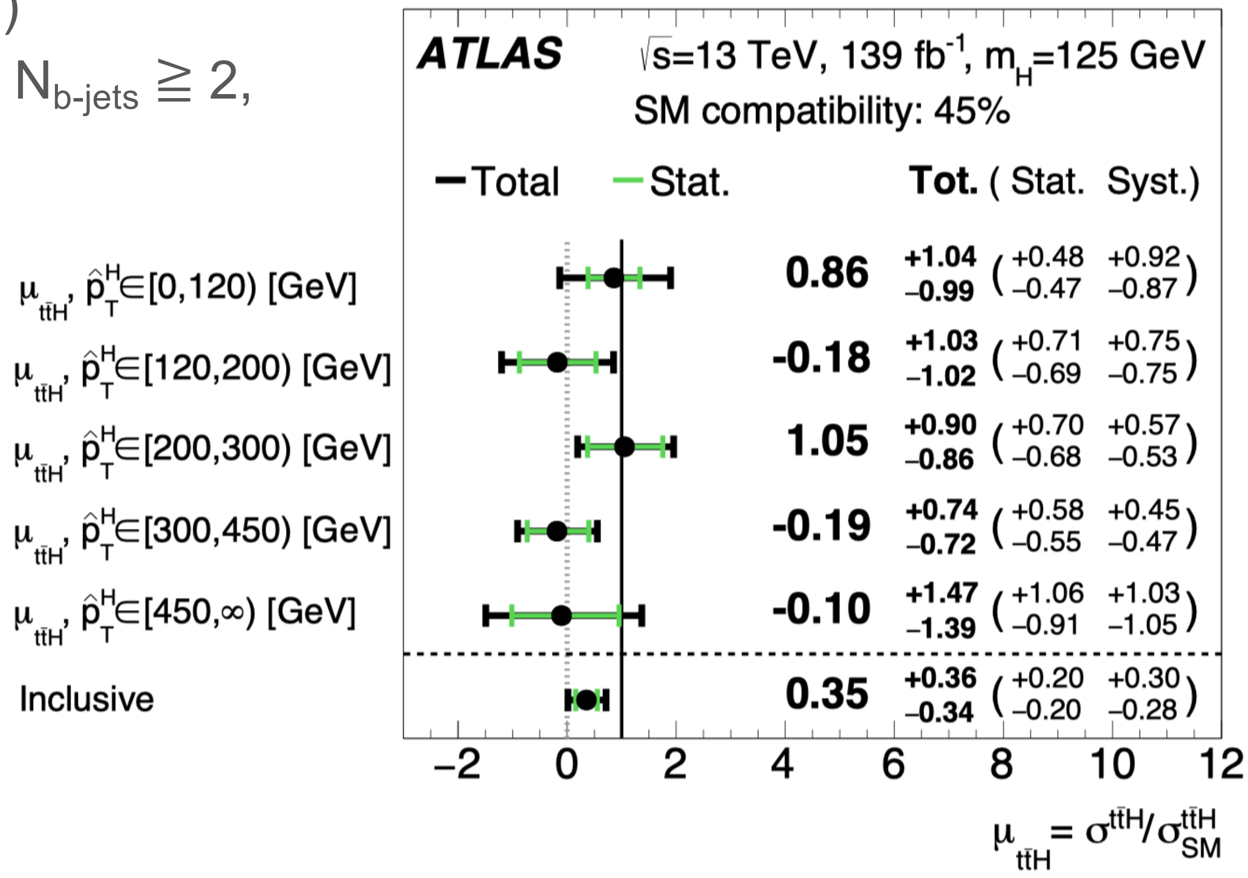


STXS region Process	$p_T^{V,t}$ interval	SM prediction [fb]	Measurement [fb]	Stat. unc. [fb]	Syst. unc. [fb] Th. sig.	Th. bkg.	Exp.
$W(\ell\nu)H$	150–250 GeV	24.0 ± 1.1	16.9 ± 12.4	8.1	0.8	7.3	5.7
$W(\ell\nu)H$	250–400 GeV	5.8 ± 0.3	6.4 ± 2.3	2.0	0.3	0.9	0.6
$W(\ell\nu)H$	> 400 GeV	1.3 ± 0.1	1.9 ± 1.1	0.9	0.2	0.4	0.3
$Z(\ell\ell/\nu\nu)H$	75–150 GeV	50.6 ± 4.1	49.5 ± 36.9	25.9	6.3	18.5	20.6
$Z(\ell\ell/\nu\nu)H$	150–250 GeV	18.8 ± 2.4	20.0 ± 6.4	5.1	1.8	2.5	2.2
$Z(\ell\ell/\nu\nu)H$	250–400 GeV	4.1 ± 0.5	4.0 ± 1.6	1.5	0.4	0.4	0.3
$Z(\ell\ell/\nu\nu)H$	> 400 GeV	0.7 ± 0.1	0.2 ± 0.6	0.5	0.1	0.3	0.2

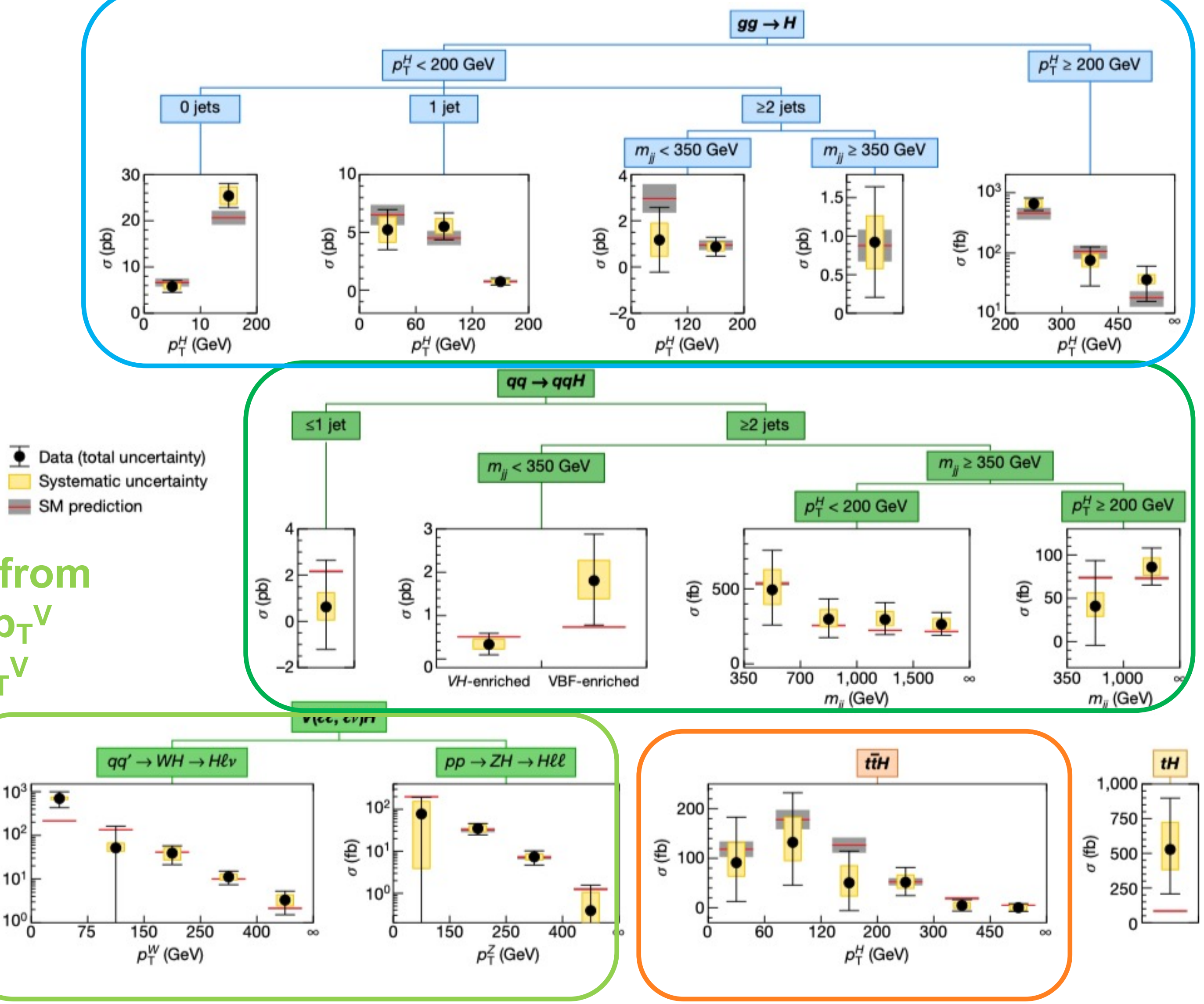
STXS measurement (ttH→bb)

- One of important channels for ttH production cross section measurements
- Analysis region
  - Dilepton (2 leptons, $N_{b\text{-jets}} \geqq 4$)
  - Single-lepton (1 lepton, $N_{jets} \geqq 6$, $N_{b\text{-jets}} \geqq 4$)
  - Boosted Higgs channel (1 lepton, $N_{jets} \geqq 4$, $N_{b\text{-jets}} \geqq 2$, $\geqq$ 1 large-R jet with $p_T \geqq 300$ GeV)
- Complicated and difficult channels
  - Higgs reconstruction: jet assignments determined by BDT for resolved, DNN for boosted channel
    ➔ **Reconstruct Higgs p_T**
  - large tt+bb background: Use BDT (signal vs background) as final discriminant
  - tt+bb theory uncertainties are limiting systematics





Combined STXS measurements



Many channels contributes, but no differential calculation on λ (Used only inclusive information)

Many channels contributes, but no strong dependence on λ

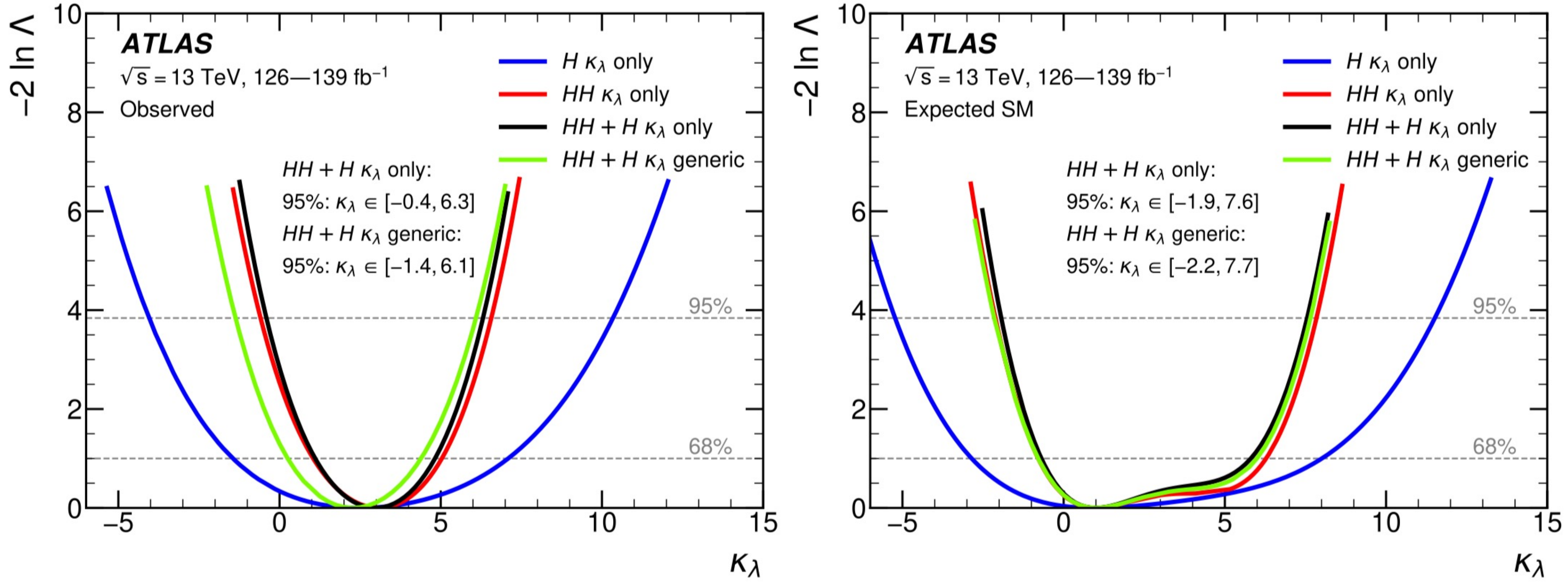
Sensitivity comes from VH(→bb) for high p_T^V VH(→γγ) for low p_T^V

Sensitivity comes from ttH(→bb) for high p_T^H ttH(→γγ) for low p_T^H

Constraint on k_λ from single H

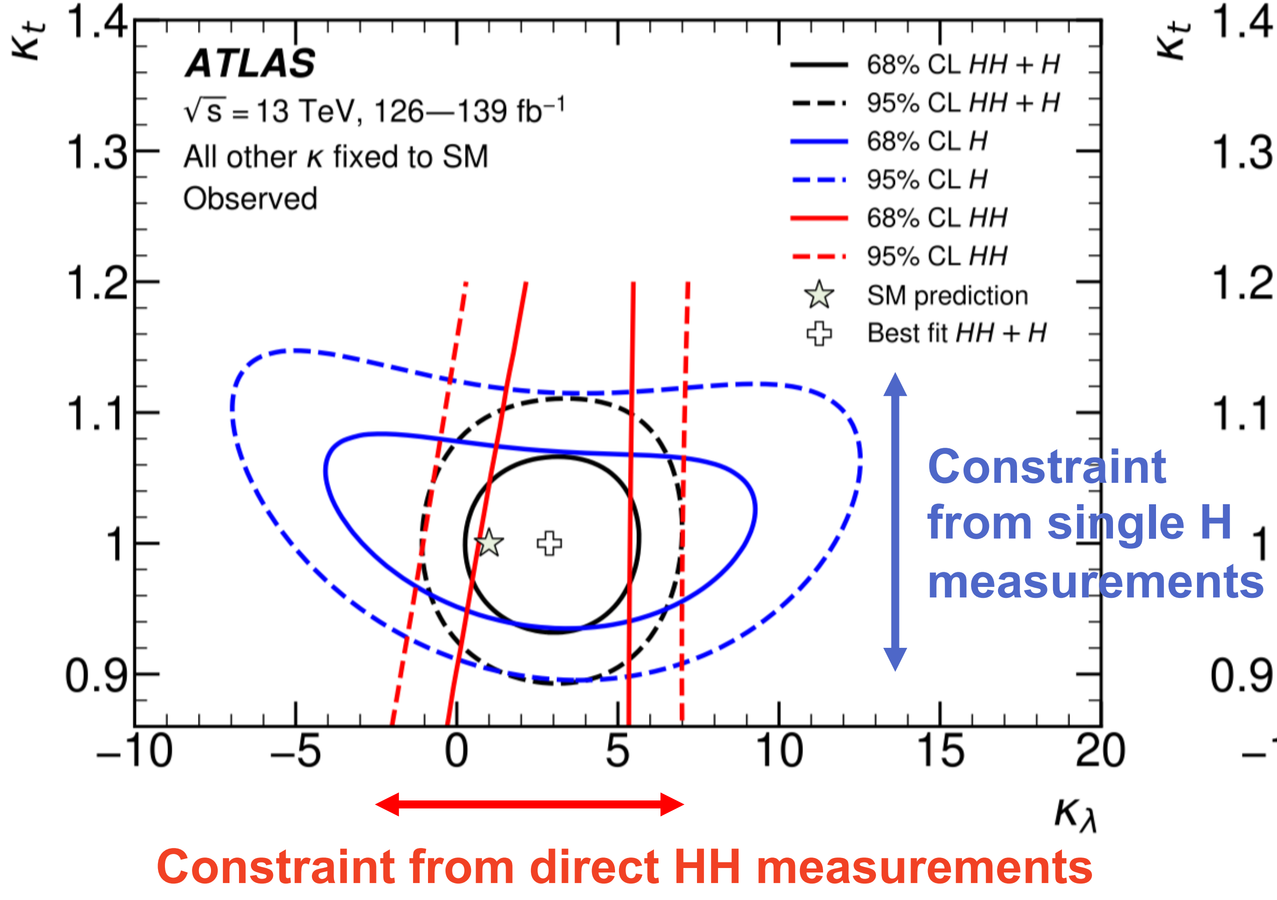
- Constrain κ_λ with measured “differential(STXS bin)”, inclusive cross section and BR
- constrain κ_λ from single Higgs:

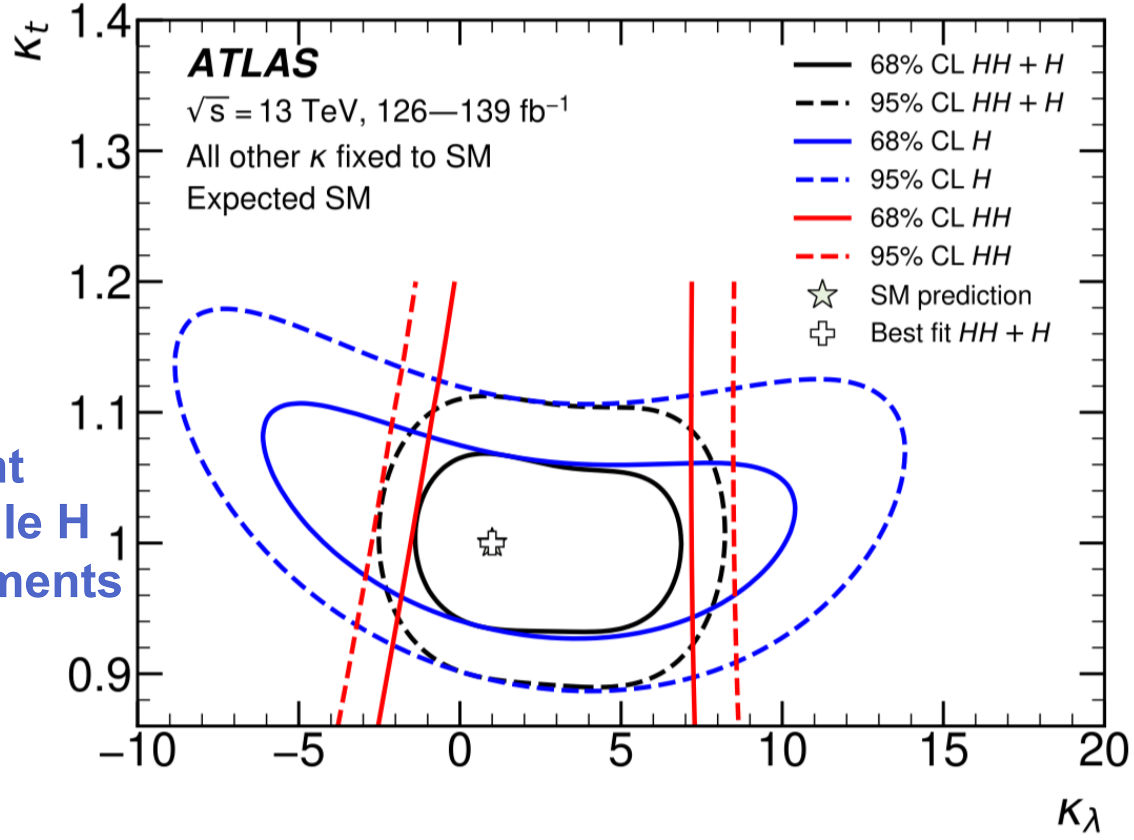
  obs: -4.0 < κ_λ < 10.3 (exp: -5.2 < κ_λ < 11.5) at 95% CL (other couplings fixed to 1)



κ_λ-κ_t constraint

- HH direct measurement can't constraint both k_t and k_λ simultaneously
- Combined measurements of H+HH constrain k_t and k_λ





Summary

- Introduced differential cross section measurement for VBF/VH/ttH production to constrain k_λ
- Theoretically, low pT regions are more important to constrain k_λ, but experimentally challenging to measure sensitive regions at LHC
  - More differential measurements will come in Run2 data (e.g. VH→ττ, VH(→WW)
  - Measure difficult regions using clean channels with Run3 (and HL-LHC) data

- **Is it possible to apply to ILC? Can measure ZH differential cross section?**

➔ **Maybe able to provide complemental information (combine with LHC?)**

Backup

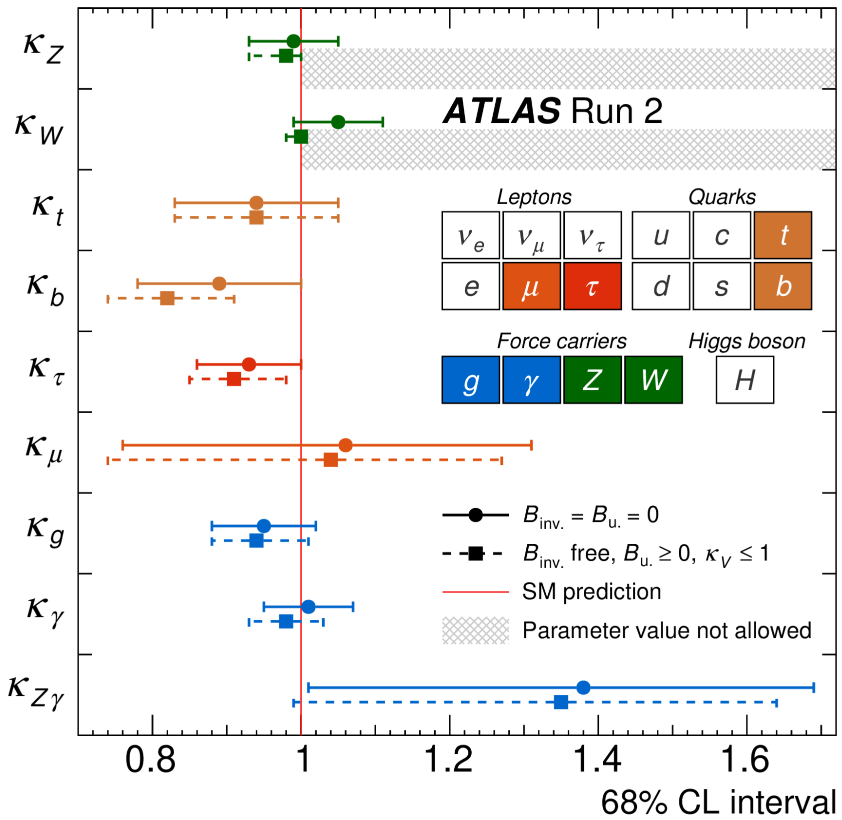
Reference

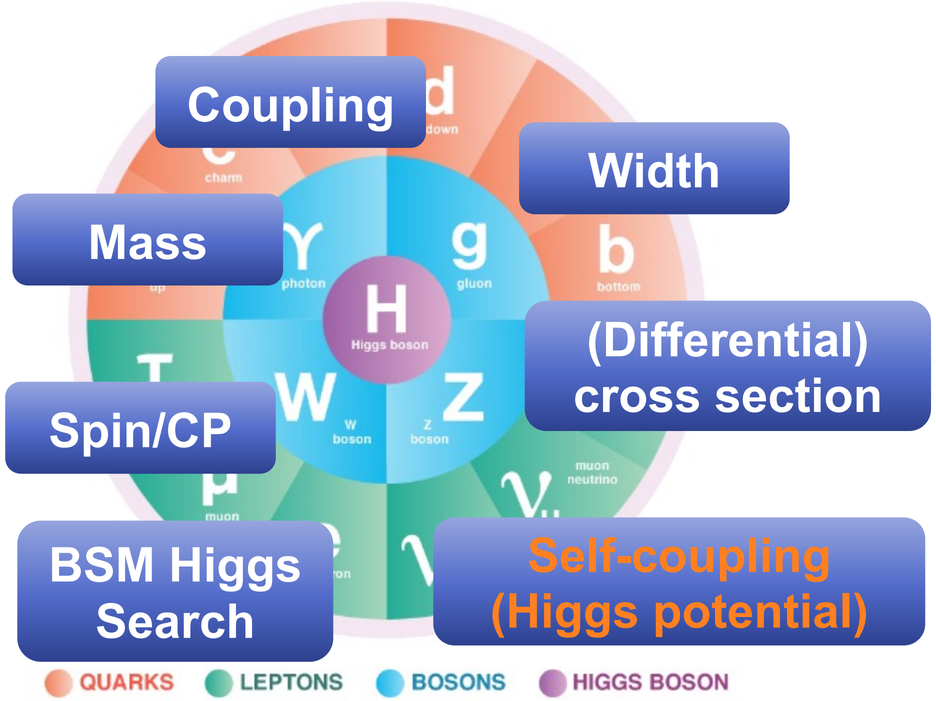
- ATLAS
  - HH→4b: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2022-03/
  - VHH: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-31/
  - HH→bbττ: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-40/
  - HH→4b reso: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-41/
  - 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

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%**

Self-coupling impact on Single-Higgs

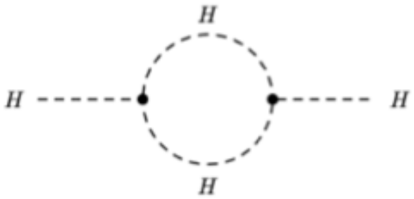
$$\mu_{if}(\kappa_\lambda) = \mu_i(\kappa_\lambda) \times \mu_f(\kappa_\lambda)$$

- Impacts on the production modes (i) and the decay channels (f) expressed as:

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\mathrm{BSM}}}{\sigma^{\mathrm{SM}}} = Z_H^{\mathrm{BSM}}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\mathrm{EW}}^i}\right]$$

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\mathrm{BR}_f^{\mathrm{BSM}}}{\mathrm{BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \mathrm{BR}_j^{\mathrm{SM}}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

  - Z^{BSM}_H: wave function renormalization, accounts for the universal correction



$$Z_H^{\mathrm{BSM}}(\kappa_\lambda) = \frac{1}{1 - (\kappa_\lambda^2 - 1)\delta Z_H}, \text{ with } \delta Z_H = -1.536 \times 10^{-3}$$

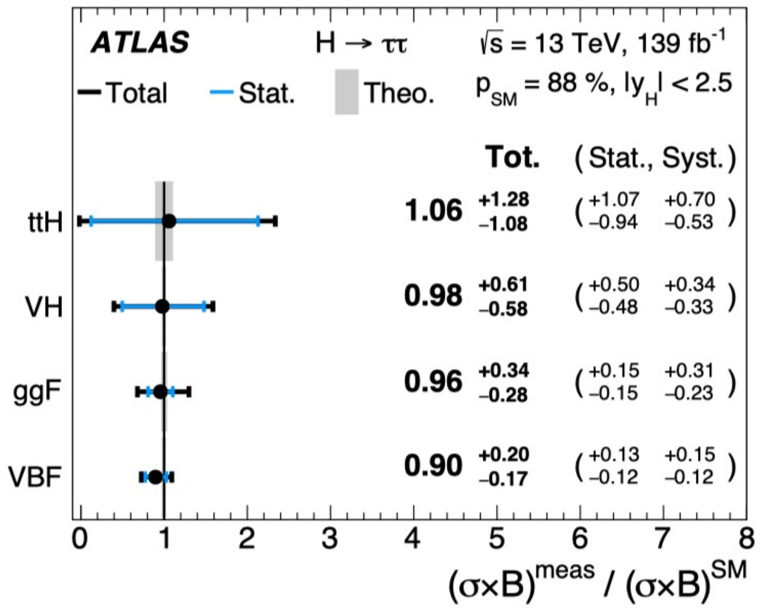
  - C_1: process and kinematic-dependent coefficients, it encodes the magnitude of the κ_λ-dependent linear correction

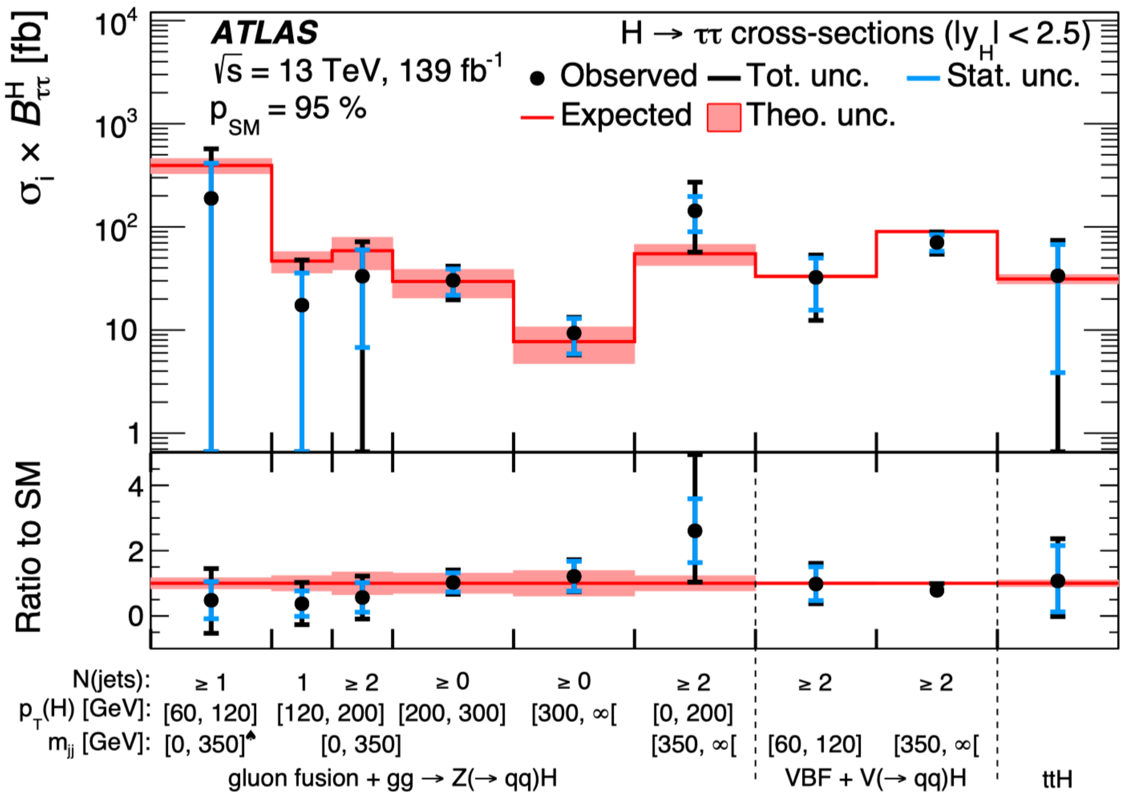
  - K_{EW}: represents the full set of NLO EW corrections

  - κ_f and κ_i consist of: κ_λ , κ_V (= κ_W = κ_Z), κ_t, κ_b, κ_τ, κ_c (= κ_t), κ_s (= κ_b), κ_μ (= κ_τ)

STXS measurement H→ττ

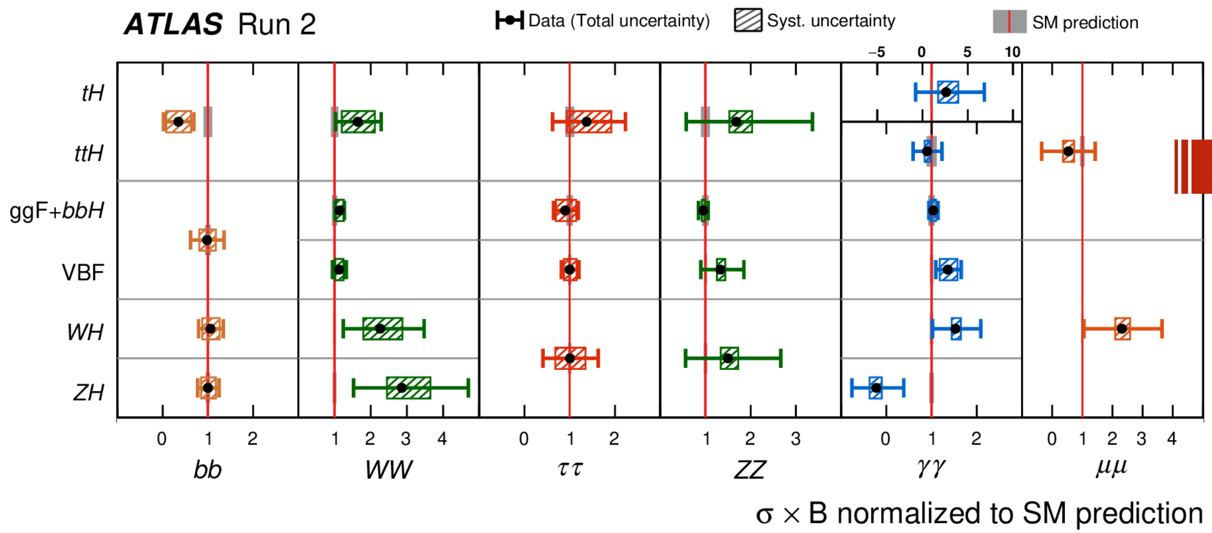
- Experimentally, not possible to measure differential cross-section (STXS) in all phase spaces

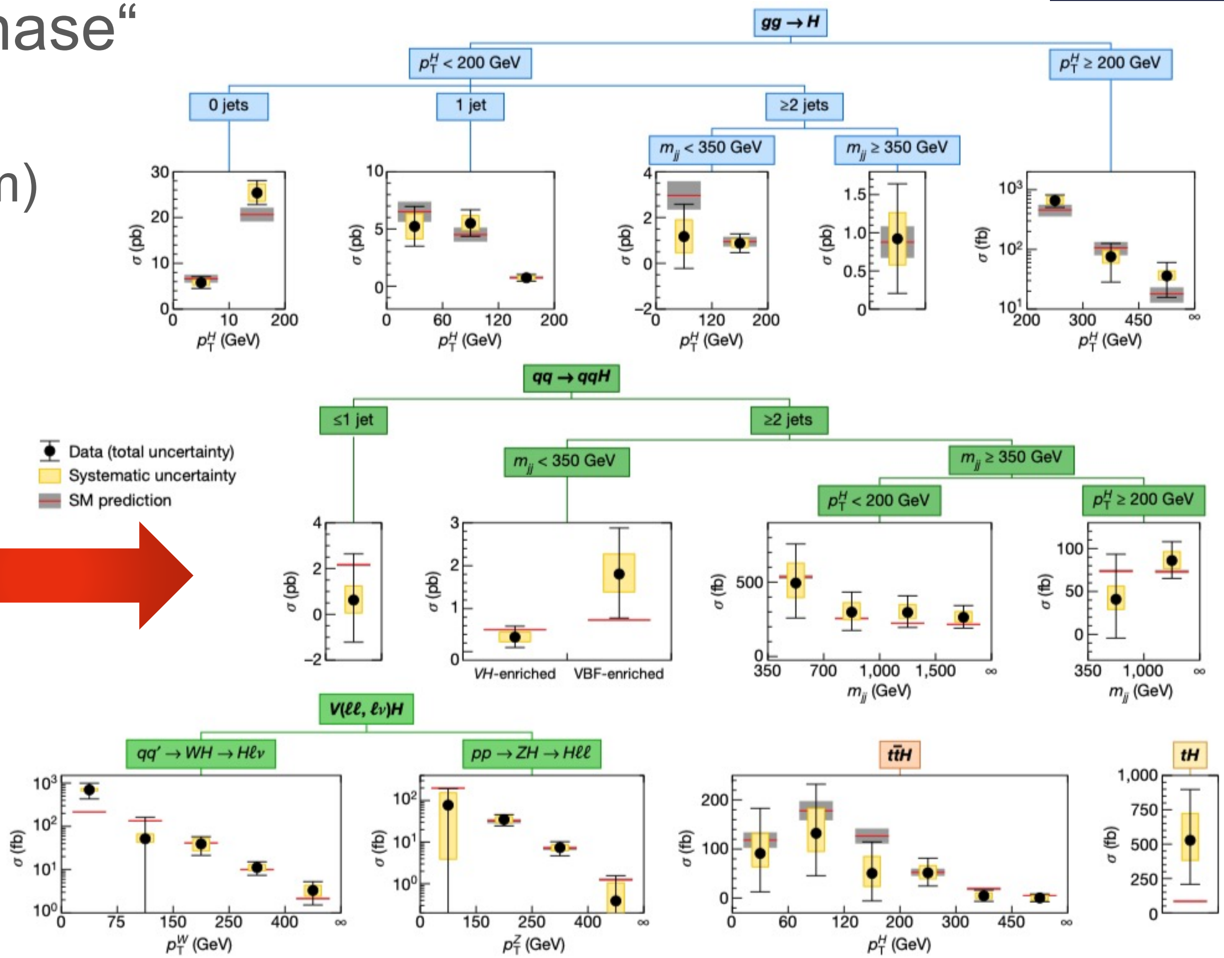




Higgs Measurement Overview at LHC

- 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

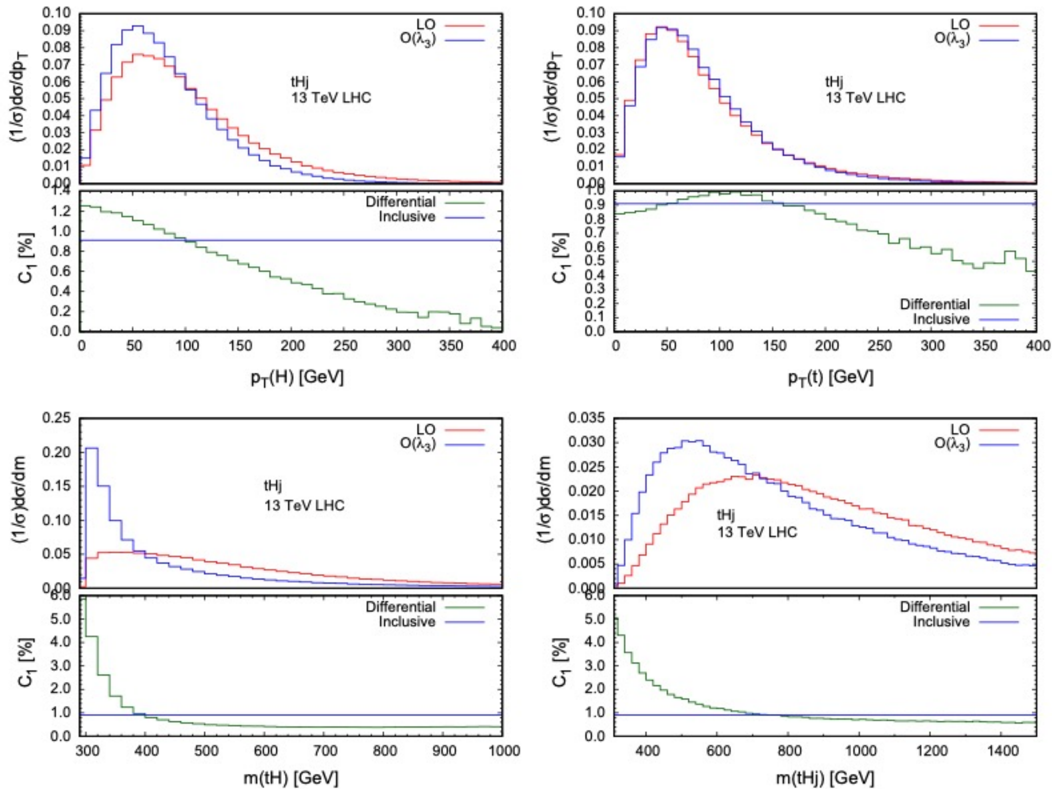




No significant deviation from SM observed (yet!)

Kinematic dependence on C_1

- C1 and K_{EW} depends on the kinematics
  ➔ Differential measurement would be more sensitive to κ_λ



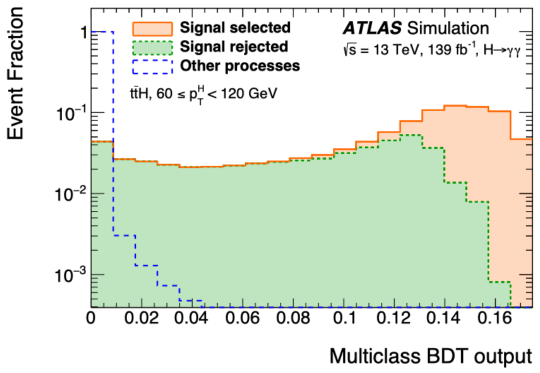
tH production
pTH and ptT depencende is small
~5% on m(tH), m(tHj)

H→γγ STXS measurement

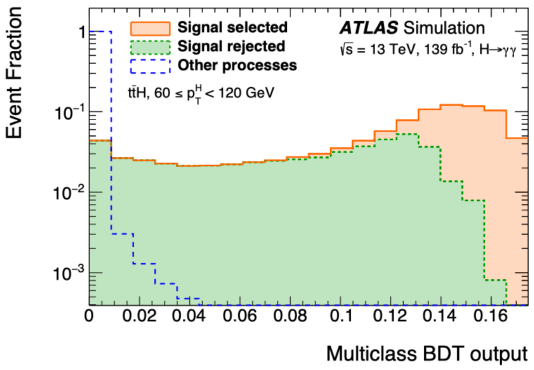
- Remove variables which distort $m_{\gamma\gamma}$ mass distribution (>5% liniear correlation with $m_{\gamma\gamma}$)

$\eta_{\gamma_1}, \eta_{\gamma_2}, p_T^{\gamma\gamma}, y_{\gamma\gamma}$,
$p^{\dagger}_{T,jj}, m_{jj}$, and $\Delta y, \Delta\phi, \Delta\eta$ between j_1 and j_2,
$p_{T,\gamma\gamma j_1}, m_{\gamma\gamma j_1}, p_{T,\gamma\gamma jj}\dagger, m_{\gamma\gamma jj}$
$\Delta y, \Delta\phi$ between the $\gamma\gamma$ and jj systems,
minimum ΔR between jets and photons,
invariant mass of the system comprising all jets in the event,
dilepton p_T, di-e or di-μ invariant mass (leptons are required to be oppositely charged),
E_T^{miss}, p_T and transverse mass of the lepton + E_T^{miss} system,
p_T, η, ϕ of top-quark candidates, $m_{t_1 t_2}$
Number of jets†, of central jets ($|\eta| < 2.5$)†, of b-jets† and of leptons,
p_T of the highest-p_T jet, scalar sum of the p_T of all jets,
scalar sum of the transverse energies of all particles ($\sum E_T$), E_T^{miss} significance,
$\left|E_T^{\text{miss}} - E_T^{\text{miss}}(\text{primary vertex with the highest } \sum p^2_{T,\text{track}})\right| > 30\,\text{GeV}$
Top reconstruction BDT of the top-quark candidates,
$\Delta R(W, b)$ of t_2,
$\eta_{j_F}, m_{\gamma\gamma j_F}$
Average number of interactions per bunch crossing.

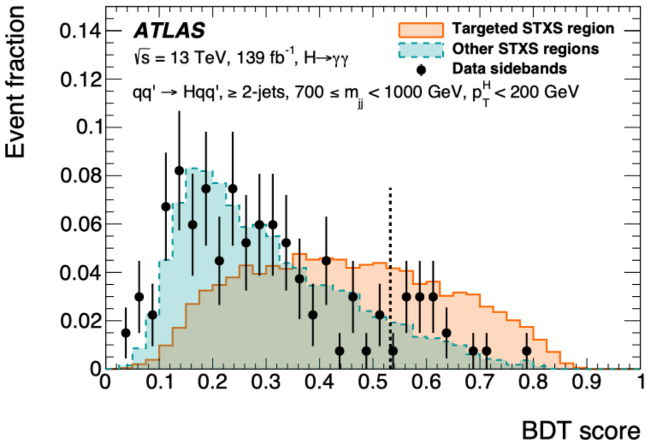
STXS classes	Variables
Individual STXS classes from $gg \to H$, $qq' \to Hqq'$, $qq \to H\ell\nu$, $pp \to H\ell\ell$, $pp \to H\nu\bar{\nu}$	All multiclass BDT variables, $p_T^{\gamma\gamma}$ projected to the thrust axis of the $\gamma\gamma$ system ($p_{Tt}^{\gamma\gamma}$), $\Delta\eta_{\gamma\gamma}$, $\eta^{\text{Zepp}} = \frac{\eta_{\gamma\gamma}-\eta_{jj}}{2}$, $\phi^*_{\gamma\gamma} = \tan\left(\frac{\pi-\|\Delta\phi_{\gamma\gamma}\|}{2}\right)\sqrt{1-\tanh^2\left(\frac{\Delta\eta_{\gamma\gamma}}{2}\right)}$, $\cos\theta^*_{\gamma\gamma} = \left\|\frac{(E^{\gamma_1}+p_z^{\gamma_1})\cdot(E^{\gamma_2}-p_z^{\gamma_2})-(E^{\gamma_1}-p_z^{\gamma_1})\cdot(E^{\gamma_2}+p_z^{\gamma_2})}{m_{\gamma\gamma}+\sqrt{m^2_{\gamma\gamma}+(p_T^{\gamma\gamma})^2}}\right\|$, Number of electrons and muons.
all $t\bar{t}H$ and tHW STXS classes combined	p_T, η, ϕ of γ_1 and γ_2, p_T, η, ϕ and b-tagging scores of the six highest-p_T jets, E_T^{miss}, E_T^{miss} significance, E_T^{miss} azimuthal angle, Top reconstruction BDT scores of the top-quark candidates, p_T, η, ϕ of the two highest-p_T leptons.
$tHqb$	$p_T^{\gamma\gamma}/m_{\gamma\gamma}, \eta_{\gamma\gamma}$, p_T, invariant mass, BDT score and $\Delta R(W, b)$ of t_1, p_T, η of t_2, p_T, η of j_F, Angular variables: $\Delta\eta_{\gamma\gamma t_1}, \Delta\theta_{\gamma\gamma t_2}, \Delta\theta_{t_1 j_F}, \Delta\theta_{t_2 j_F}, \Delta\theta_{\gamma\gamma j_F}$, Invariant mass variables: $m_{\gamma\gamma j_F}, m_{t_1 j_F}, m_{t_2 j_F}, m_{\gamma\gamma t_1}$, Number of jets with $p_T > 25$ GeV, Number of b-jets with $p_T > 25$ GeV*; Number of leptons*, E_T^{miss} significance*

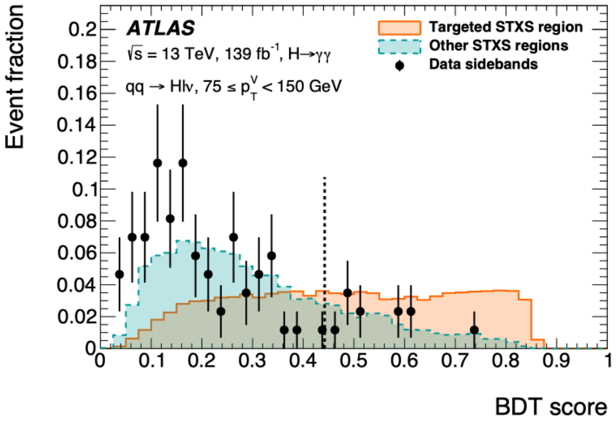


(d) $t\bar{t}H$, $60 \le p_T^H < 120\,\text{GeV}$



(d) $t\bar{t}H$, $60 \le p_T^H < 120\,\text{GeV}$

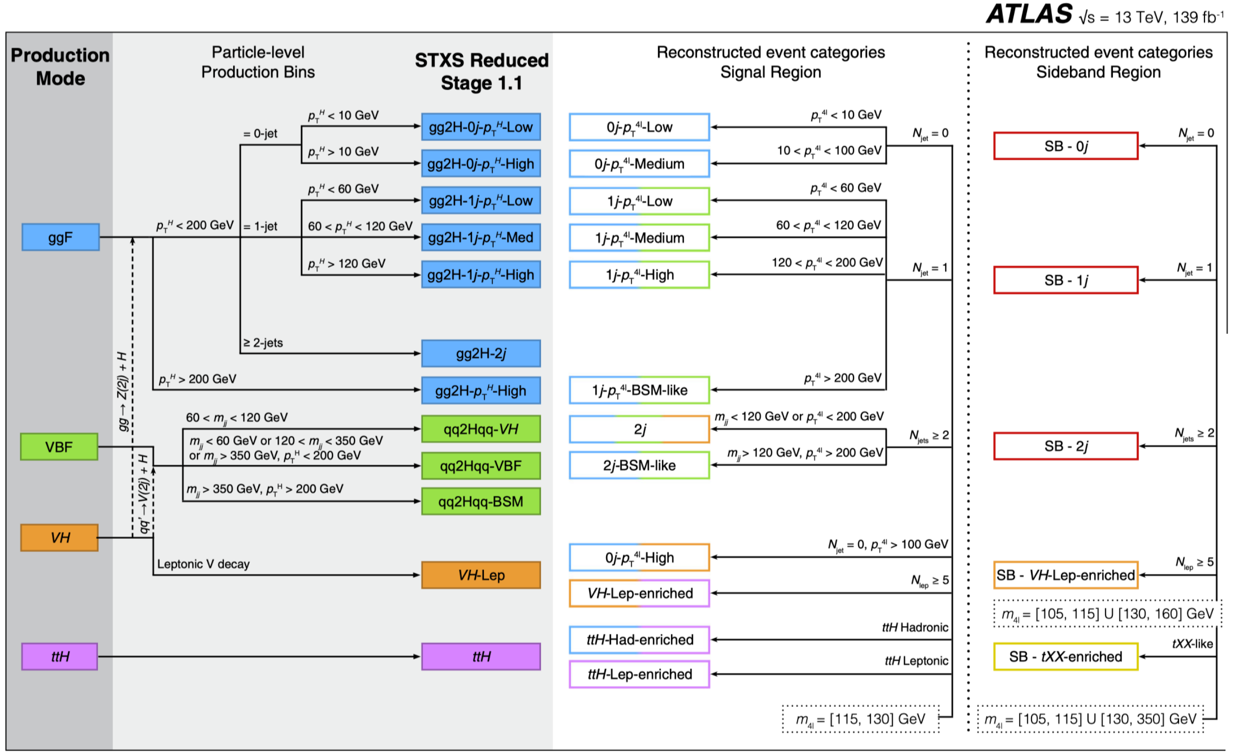


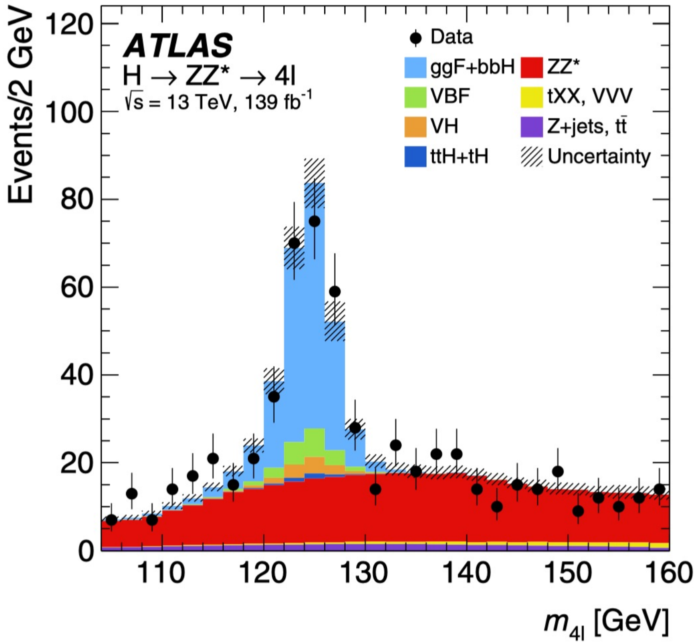


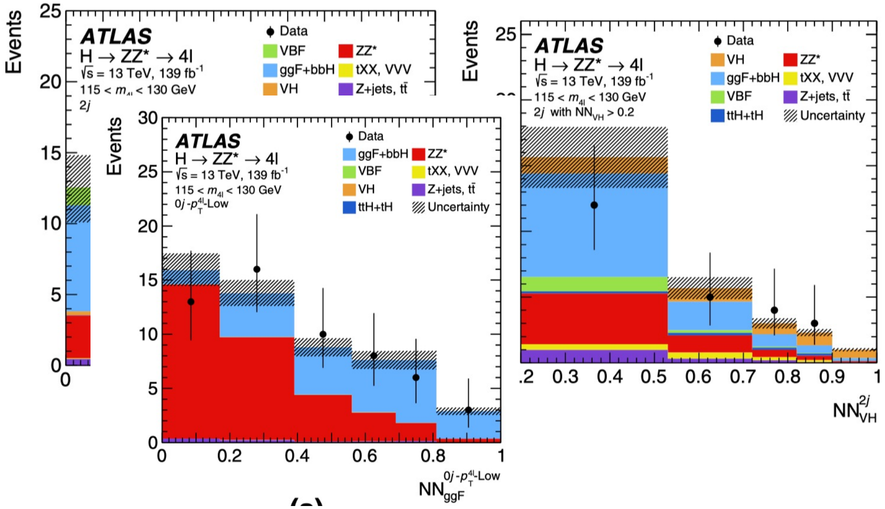
(c) $qq \to H\ell\nu$, $75 \le p_T^V < 150\,\text{GeV}$

H→ZZ→4l STXS

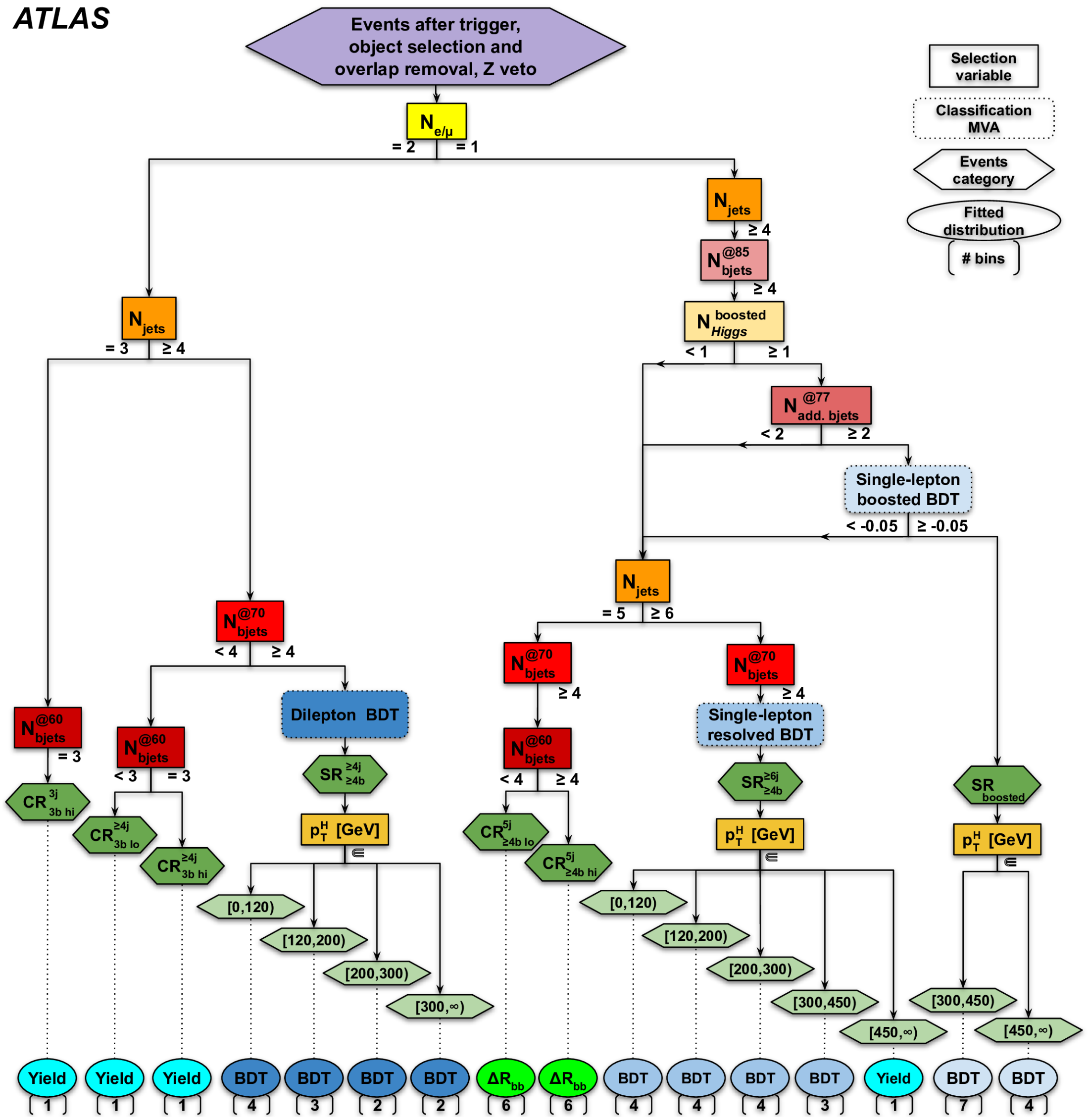
- Categorization

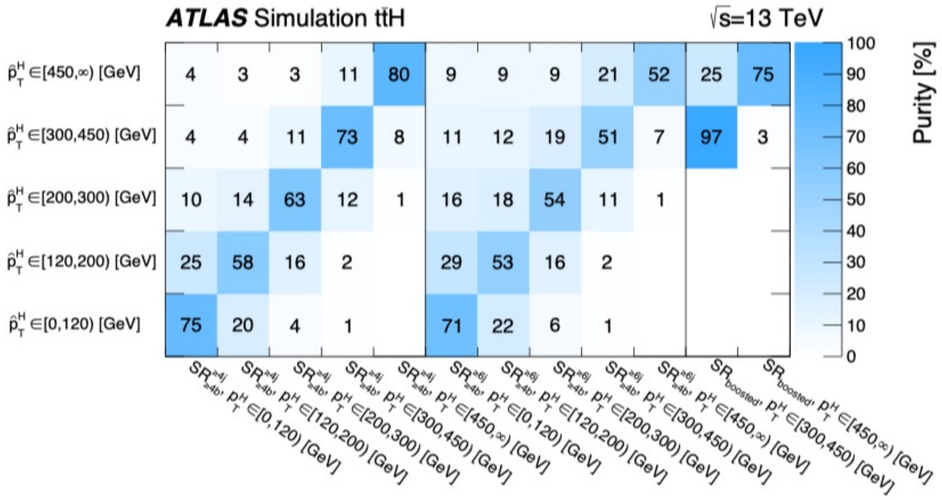


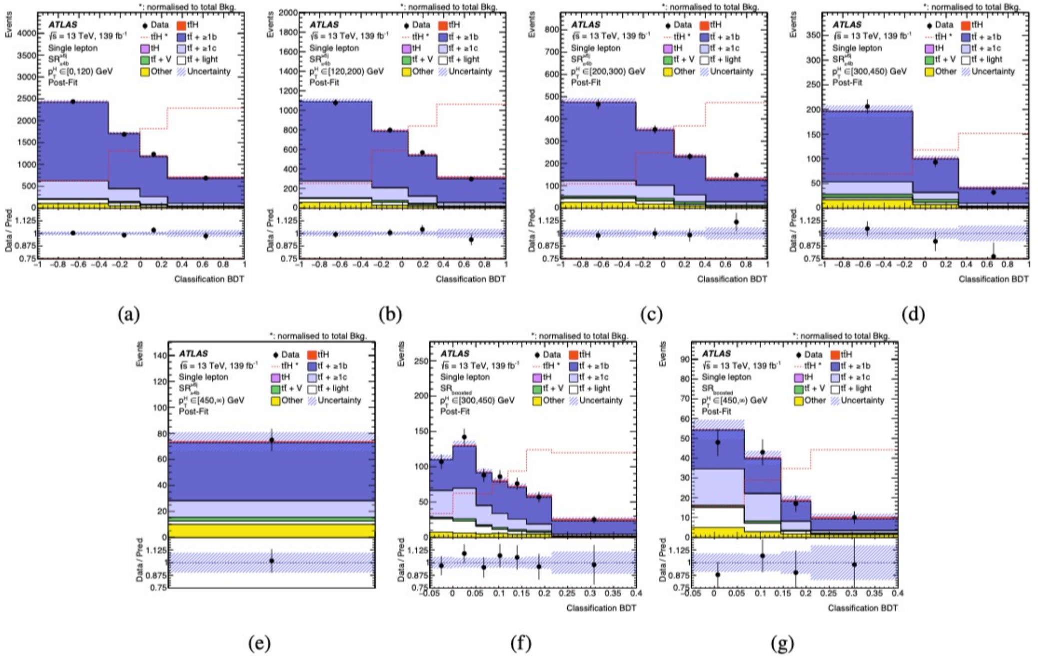




ttH STXS measurement



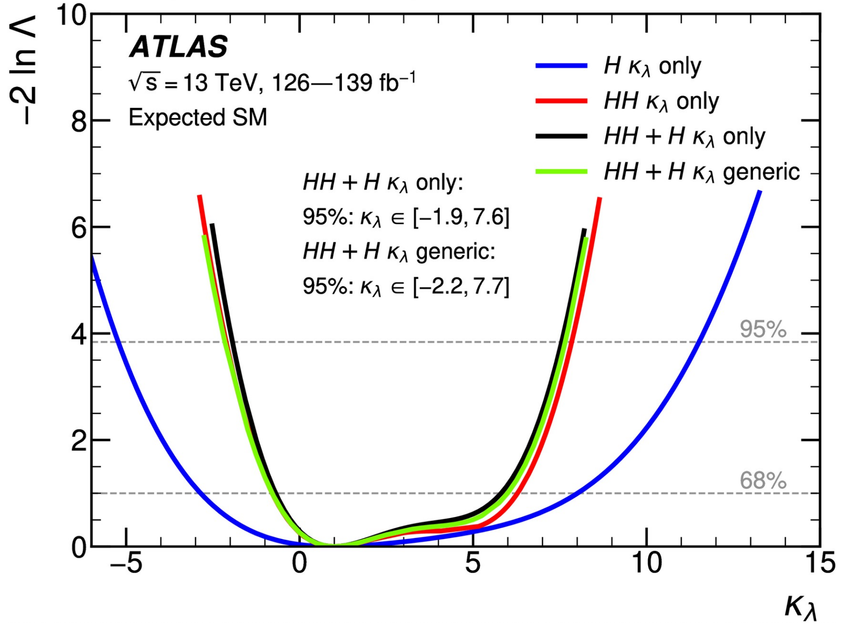




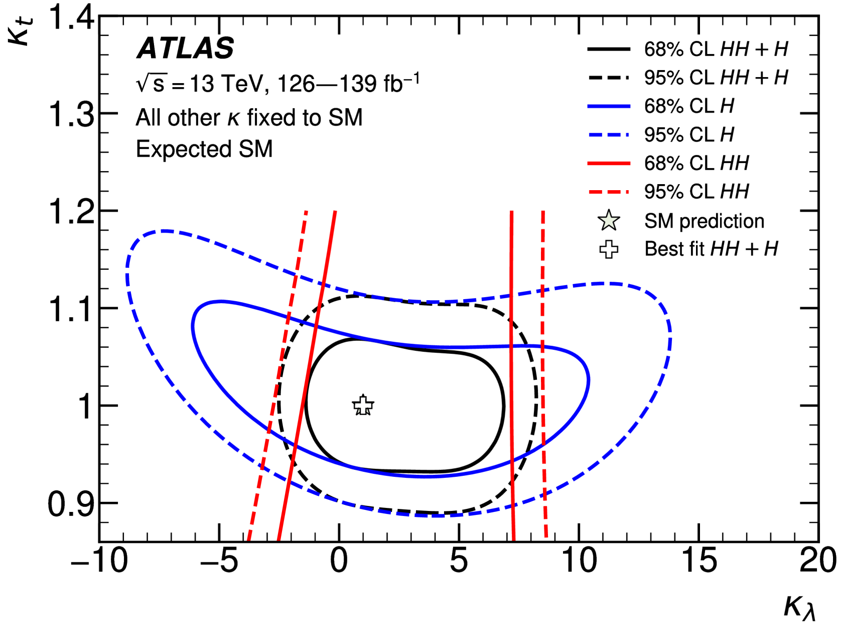
H+HH combination

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

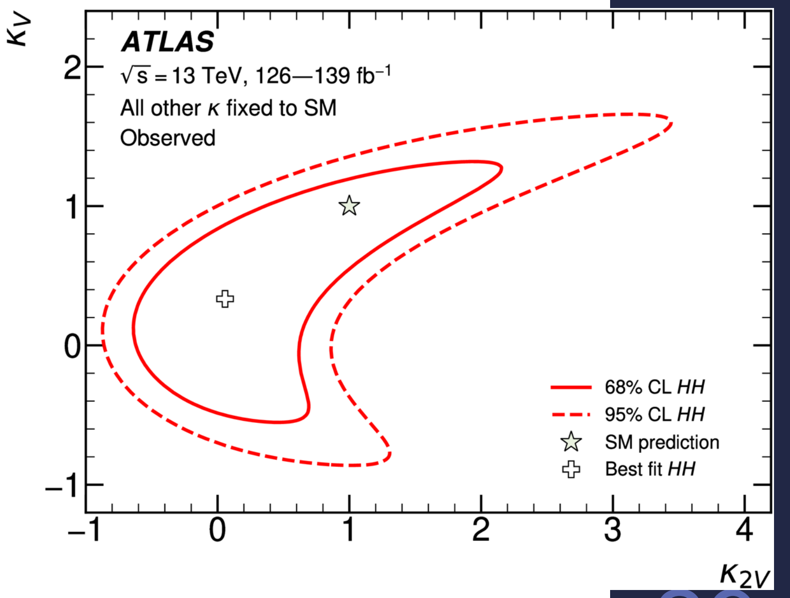
Float only κ$_\lambda$, other κ fixed to SM (expected)



Float only κ$_\lambda$ and κ$_t$, other κ fixed to SM (expected)

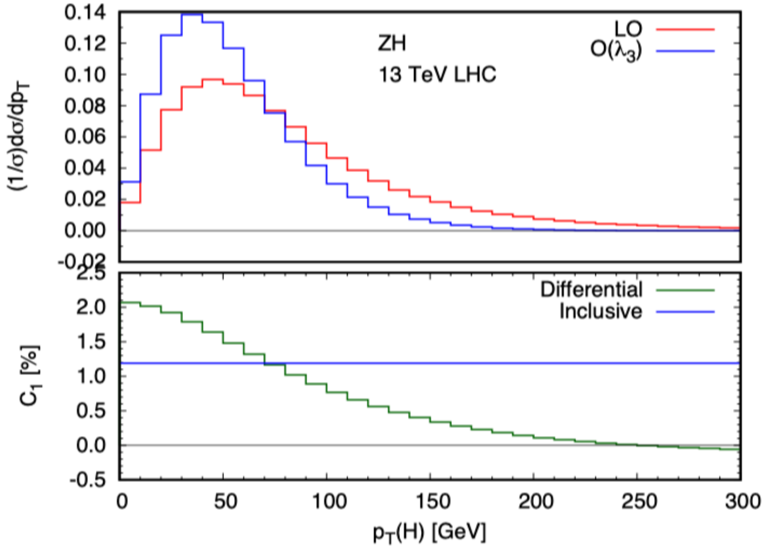


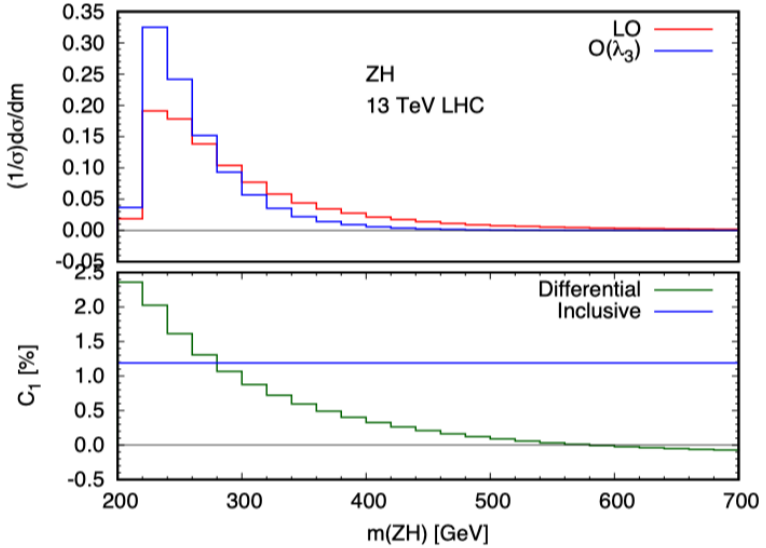
Float only κ$_\lambda$ and κ$_{2V}$, other κ fixed to SM (observed)



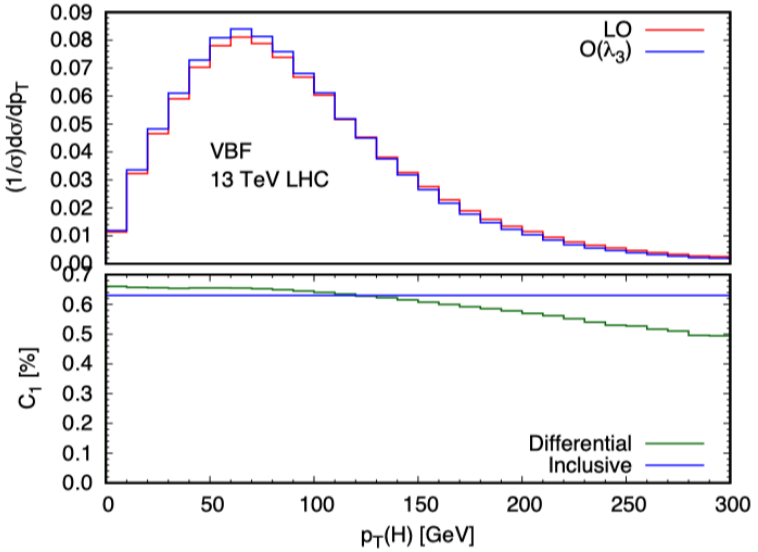
NLO EW correction

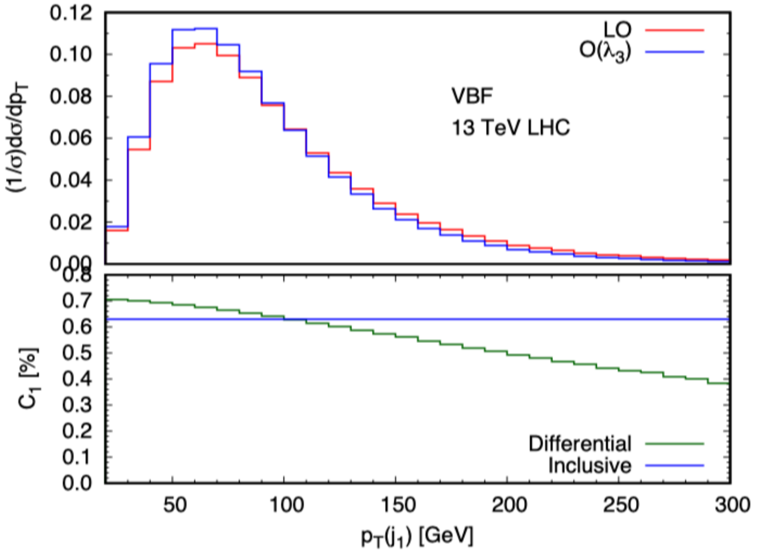
- ZH
  - Inclusive cross section: ~1.2% difference
  - differential distribution difference: ~2% (low-pTH, m(ZH)



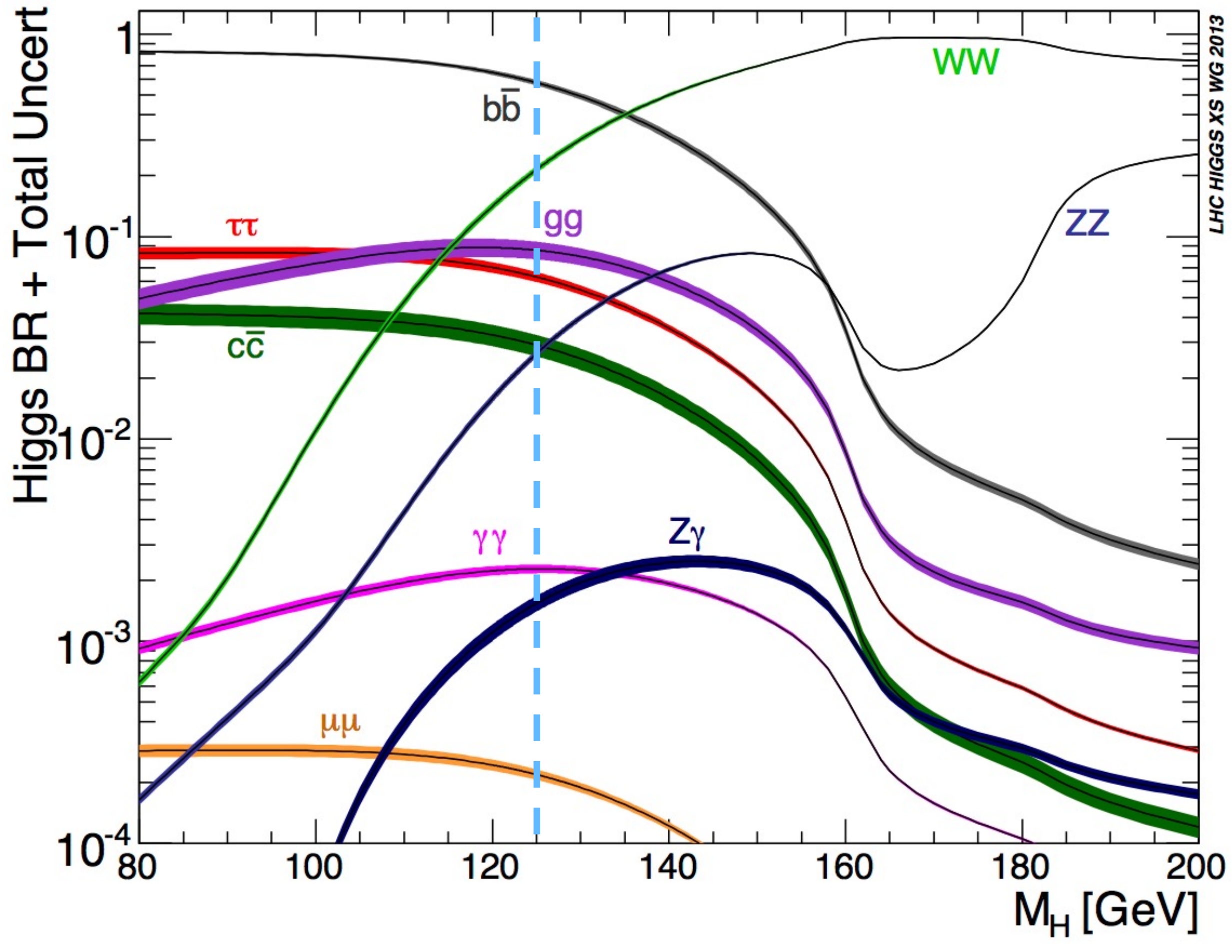


- VBF
  - Inclusive cross section: 0.6% difference
  - differential: at most ~0.7%





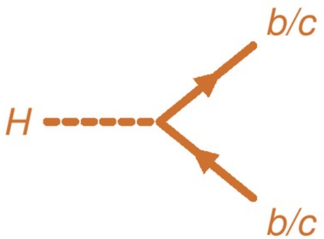
Higgs decay branching ratio

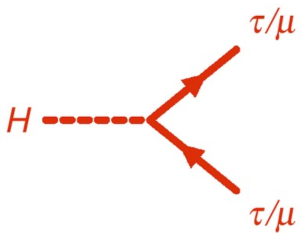


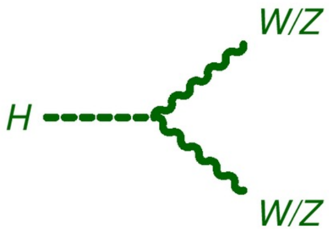
- Higgs boson decays to other SM particles
  - Observed Higgs mass(~125 GeV) is experimentally really good
  - Higgs boson is able to decay various particles
    ➔ Property measurement with different decay modes
  - H→bb decay mode is dominant

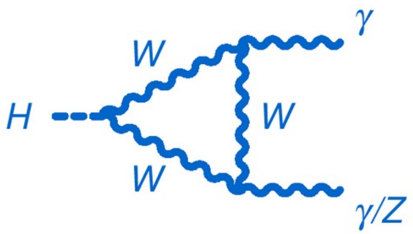
bb	WW	gg	ττ	cc	ZZ
58%	21%	8.2%	6.3%	2.9%	2.6%

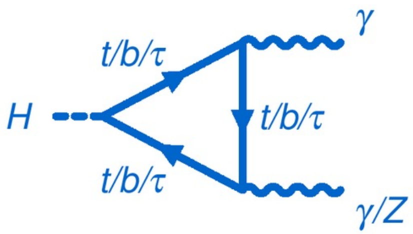
γγ	Zγ	μμ
0.23%	0.15%	0.022%





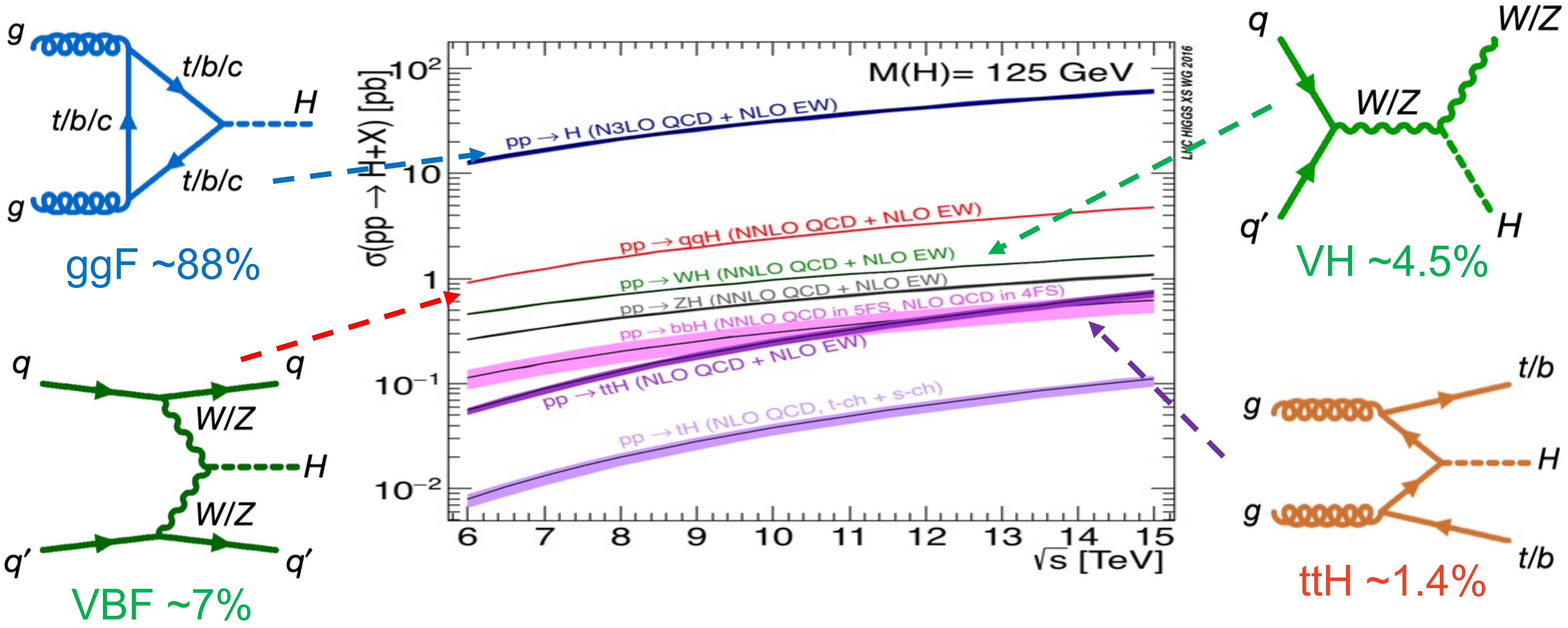






Higgs Production at LHC

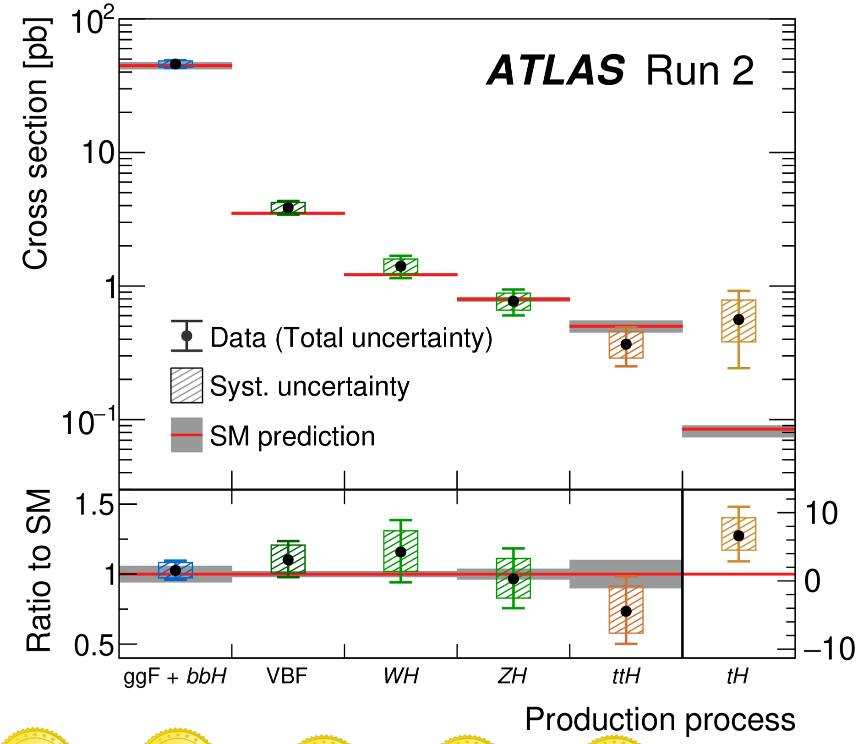
- Gluon-fusion process is dominant at LHC (Gluon collider!!)

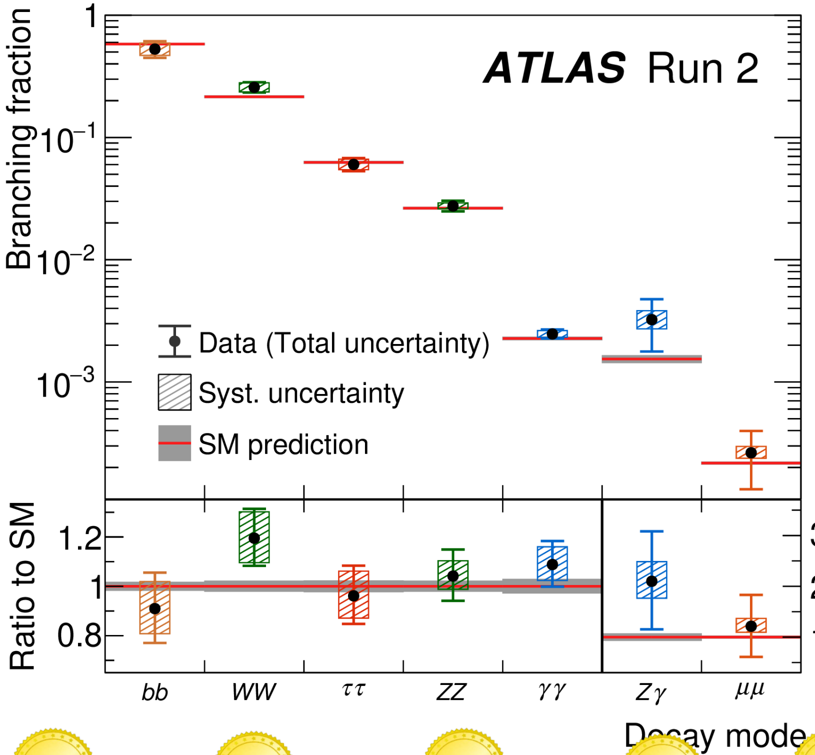


- Higgs physics strategy is built by the combination of production and decay (can not observe all Higgs events experimentally!!)
  - ➢ Lots of QCD background, not triggerable, detector coverage...

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%

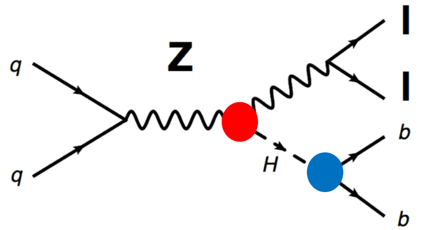
H→bb	H→WW	H→ττ	H→ZZ	H→γγ	H→Zγ	H→μμ
5σ	5σ	5σ	5σ	5σ		
15%	12%	12%	11%	10%	~100%	~60%

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

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