LHCHWG-2022-002

Modeling of STXS 1.2 for the determination of the Higgs boson trilinear self-coupling

29 March 2022

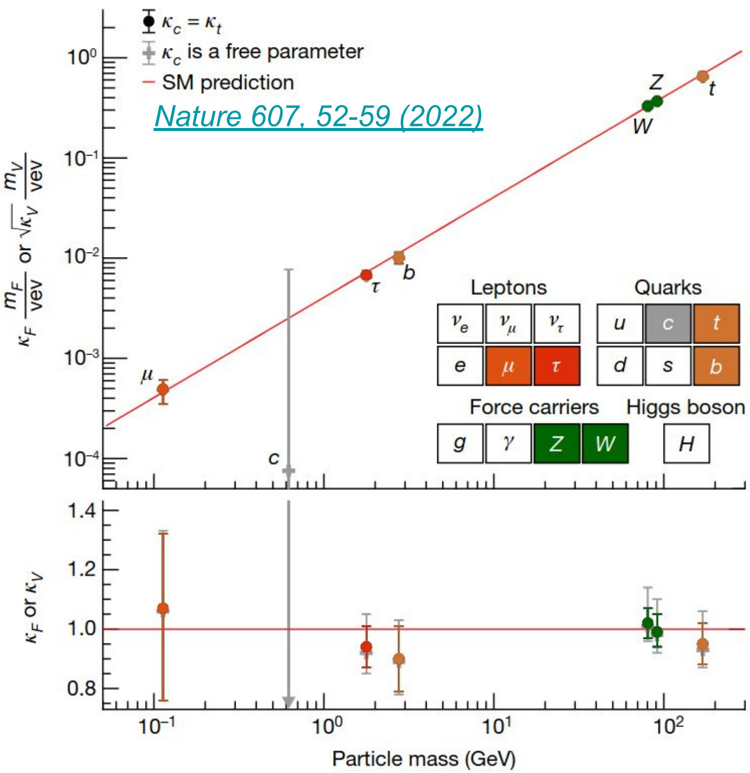
Carlo E. Pandini[1], Edward J. T. Scott[2], Fabio Monti[3], Fabio L. Alves[4], Hongtao Yang[5], Yanping Huang[3], Jin Wang[3], Jonathon M. Langford[2], Kunlin Ran[3], Mauro Donega[6], Mingshui Chen[3], Nicolas Berger[7], Nicholas Wardle[2], Osama Karkout[1], Shan Jin[4], Stefano Manzoni[8], Xinmeng Ye[9,10], Zirui Wang[10]

[1] *Nikhef, Amsterdam, the Netherlands*
[2] *Imperial College London, London, United Kingdom*
[3] *Institute of High Energy Physics, Chinese Academny of Science, Beijing, China*
[4] *Nanjing University, Nanjing, China*
[5] *Lawrence Berkeley National Lab., Berkeley(CA), USA*
[6] *ETH Zürich, Zürich, Switzerland*
[7] *Laboratoire d'Annecy de Physique des Particules, Annecy, France*
[8] *CERN, Meyrin, Switzerland*
[9] *University of Science and Technology of China, Hefei, China*
[10] *Michigan University, Ann Arbor(MI), USA*

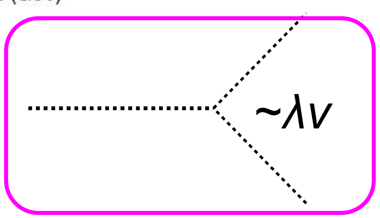
Outline

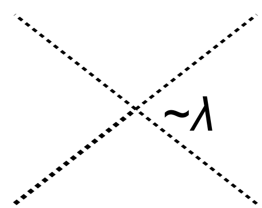
- Motivation for trilinear Higgs self-coupling measurement
- Methods and results
- Latest results from CMS and ATLAS
- Outlook for future

Motivation for trilinear self-coupling measurement



- Missing elements to complete the picture
  - H couplings to s quark and 1st generation charged fermions
  - HHVV coupling
  - H self-couplings





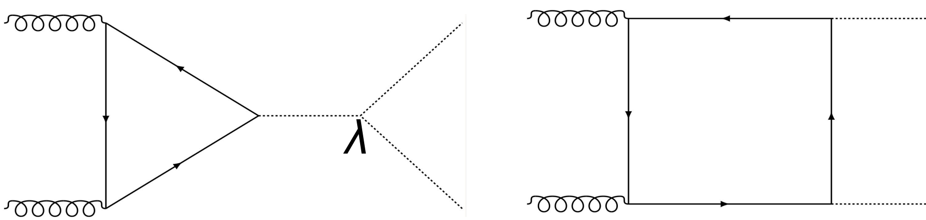
H trilinear coupling $\lambda_{SM} = m_H^2 / 2v^2 \sim 0.13 \rightarrow v$ = Higgs boson v.e.v.

λ measurement is a fundamental test of SM

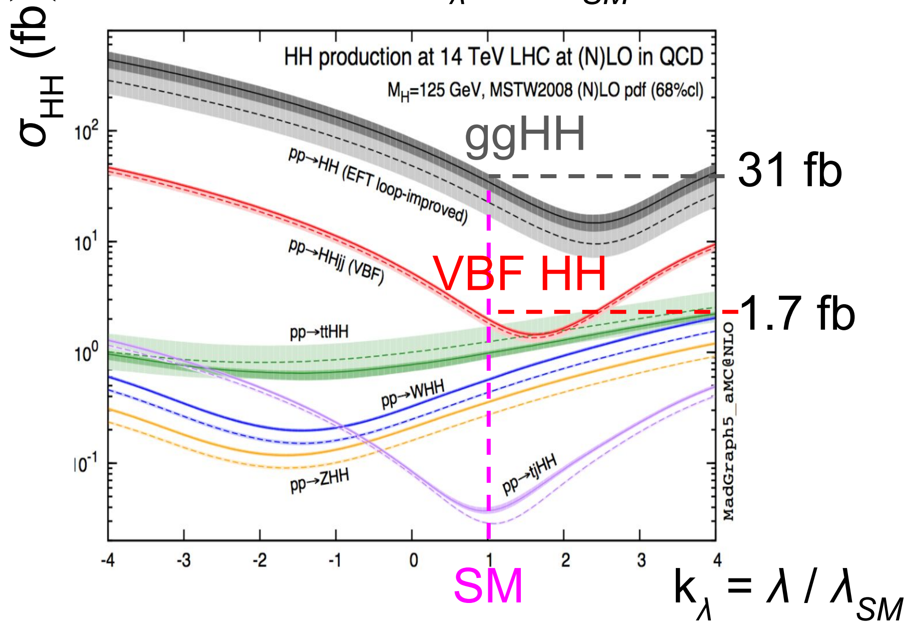
λ constraints from double-H searches

- λ entering in the LO HH cross section calculation

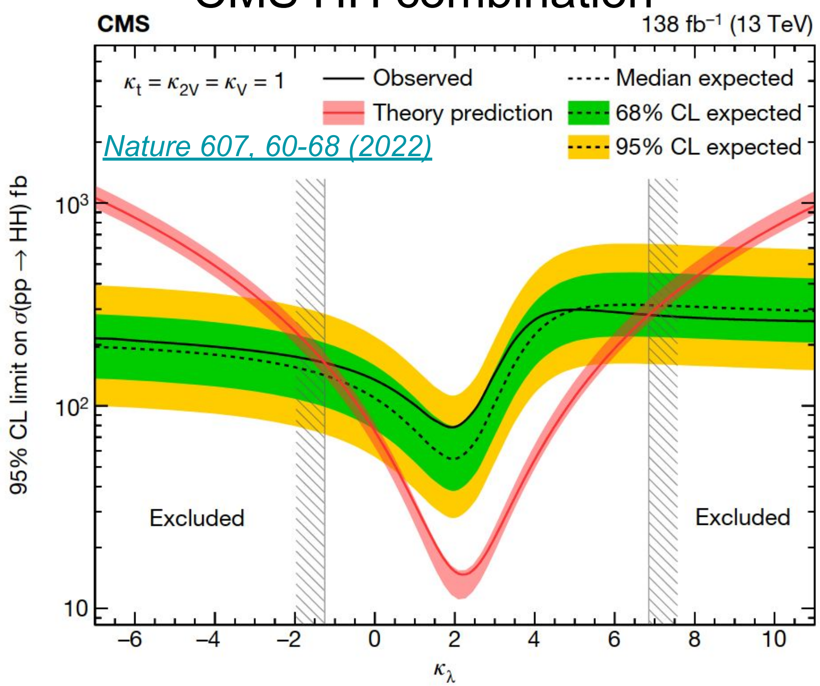
ggF production (ggHH) diagrams at LO



HH production cross section vs $k_\lambda = \lambda/\lambda_{SM}$



Upper limits on HH XS vs kl from CMS HH combination

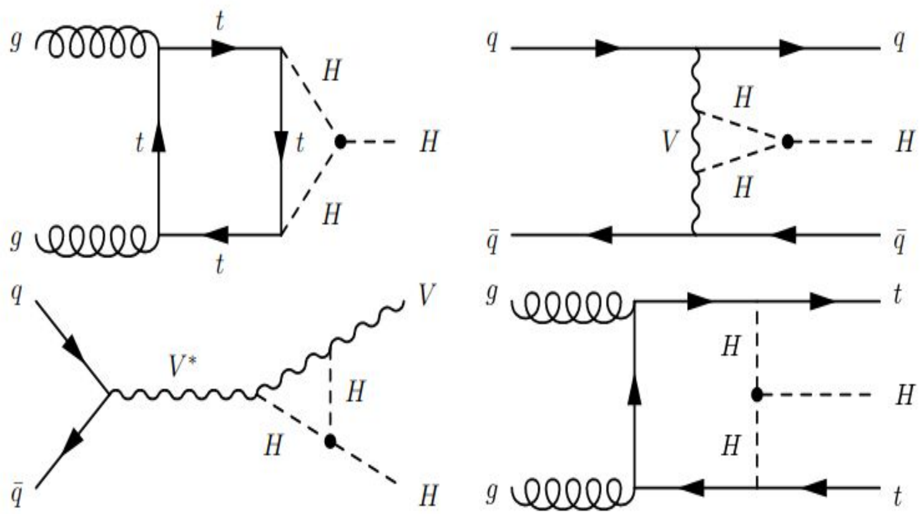


$-0.6 < k_\lambda < 6.6$ observed @95% CL in ATLAS HH comb. with Run 2 dataset

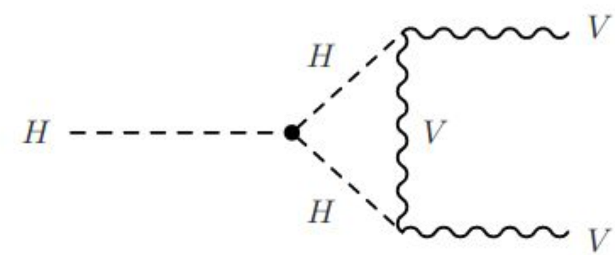
Trilinear self-coupling in single-H mechanisms

- λ-dependent NLO electroweak corrections to single-H XS and BR

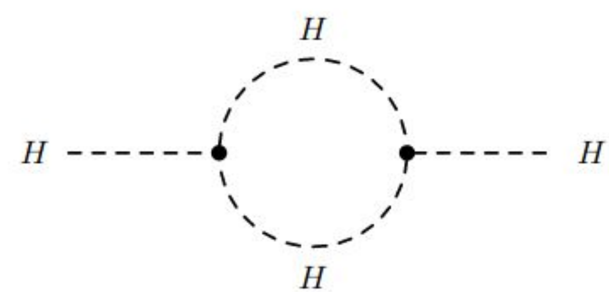
Examples of λ-dependent diagrams for single-H prod. mechanisms O(λ)



Example of λ-dependent diagrams for H→VV decay

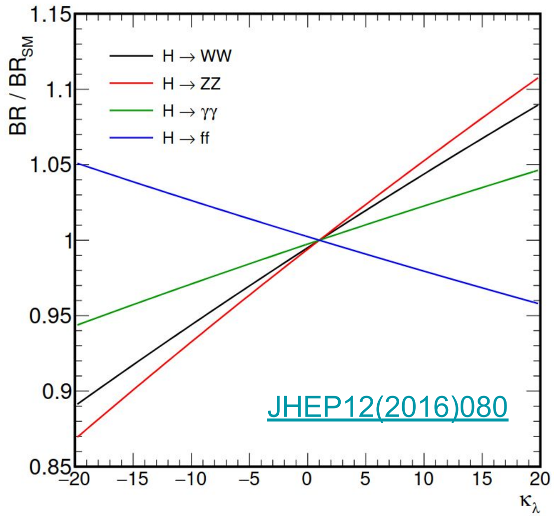


One universal correction for H wave-function renormalization O(λ^2)



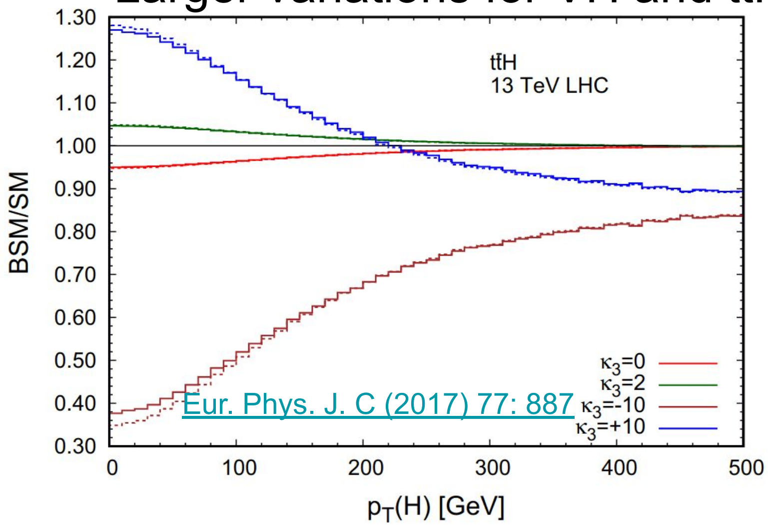
Effect of λ corrections on Higgs XS and BR

Modification of H BR vs $k_\lambda = \lambda/\lambda_{SM}$

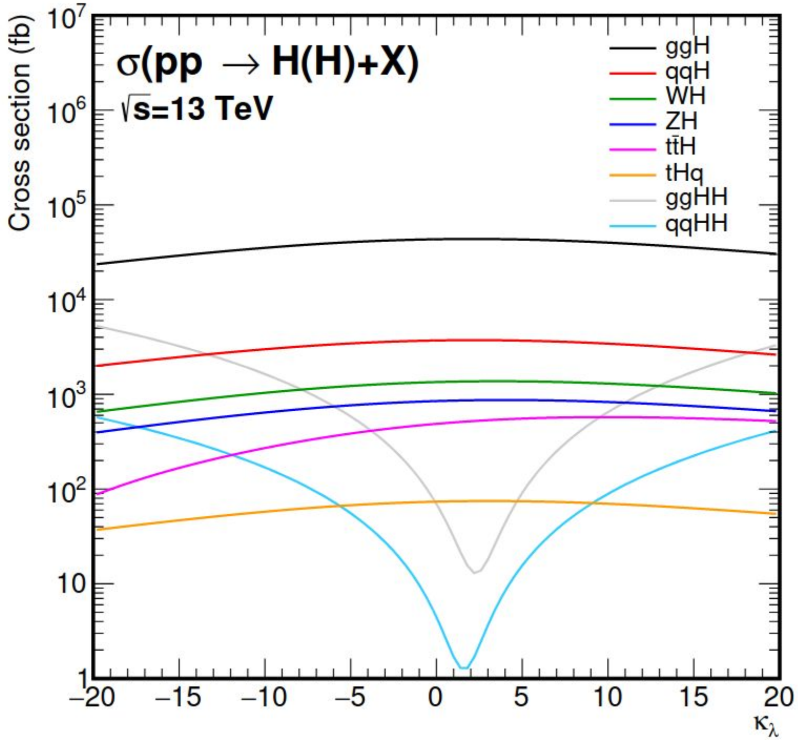


Modification of differential. XS

- Larger variations for VH and ttH



Modification of total XS vs k_λ



- Variation up to -30% / +14% for ttH
- single-H SM XS larger than double-H → sensitivity to smaller variations

XS(λ) and BR(λ) parametrization

Wavefunction renormalization

k_F or k_V scaling from k-framework

k_λ effect on single-H XS

- ➢ Production process & kinematics dependent

$$\frac{\sigma}{\sigma_{SM}} = \frac{1}{1-(\kappa_\lambda{}^2-1)d_{ZH}}\left[\kappa_i^2+(\kappa_\lambda-1)\cdot\frac{C_1}{K_{EW}}\right]$$

Universal coefficient

k-factor for NLO EW corrections not factorising with λ effects

- ➢ Production process and mildly kinematics dependent

Similarly for BR(λ) but no kinematics dependence

$$\frac{BR^f}{BR^f_{SM}} = \frac{\kappa_f^2+C_1^f(\kappa_\lambda-1)}{\sum_j BR^j_{SM}\left[\kappa_f^2+C_1^j(\kappa_\lambda-1)\right]}$$

JHEP12(2016)080

Eur. Phys. J. C (2017) 77: 887

XS(λ) parametrization

$$\frac{\sigma}{\sigma_{SM}} = \frac{1}{1-(\lambda^2-1)d_{ZH}}\left[\kappa_i^2 + (\kappa_\lambda - 1)\cdot\frac{C_1}{K_{EW}}\right]$$

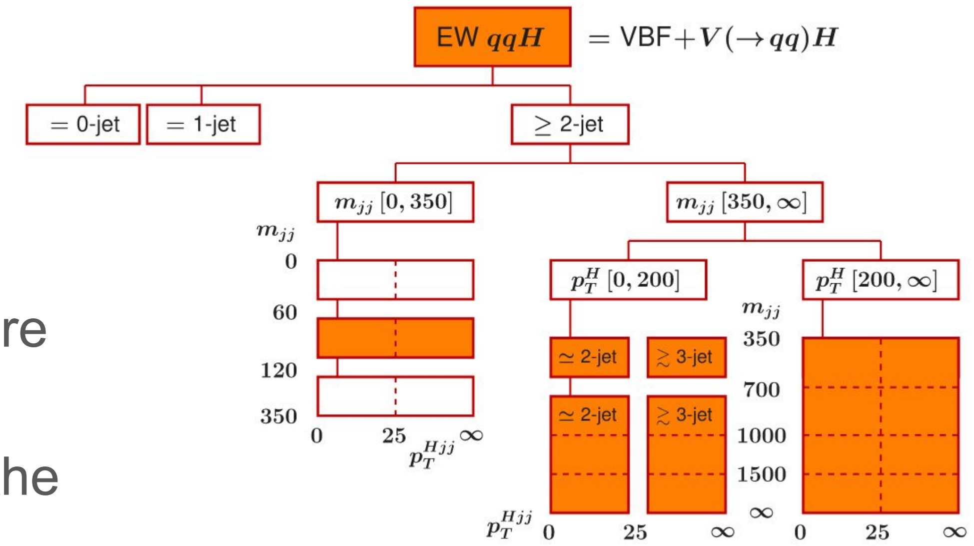
- C_1 values derived for each STXS 1.2 bin
  - Events generated @LO with `Madgraph_amc@nlo` and `PDF4LHC15_nlo_mc`
  - Reweight LO events to include NLO EW λ effects
  - Showering+hadronization with Pythia8
  - STXS 1.2 classification with Rivet

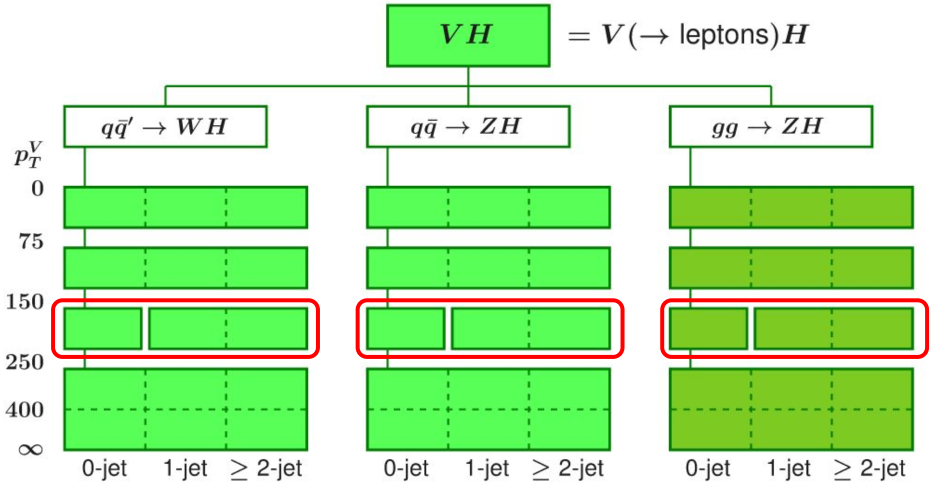
Use recipe from theory paper

- Inclusive XS(λ) scaling for ggH bins
  - Calculations not available for ggH
  - Small C_1 dependence on kinematics
- 5M MC events for WH, ZH, ttH, and qqH
- Estimate uncertainties from MC stat, μ_F&μ_R scales, & PDF
  - Negligible wrt syst. uncertainties affecting STXS measurements

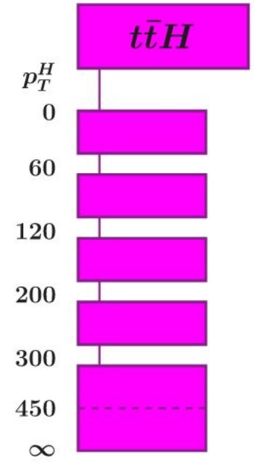
STXS 1.2 binning

- C_1 coefficients calculated for both full and reduced granularity
  - In reduced granularity ignore dashed lines
  - Granularity dependent on the specific CMS/ATLAS analysis



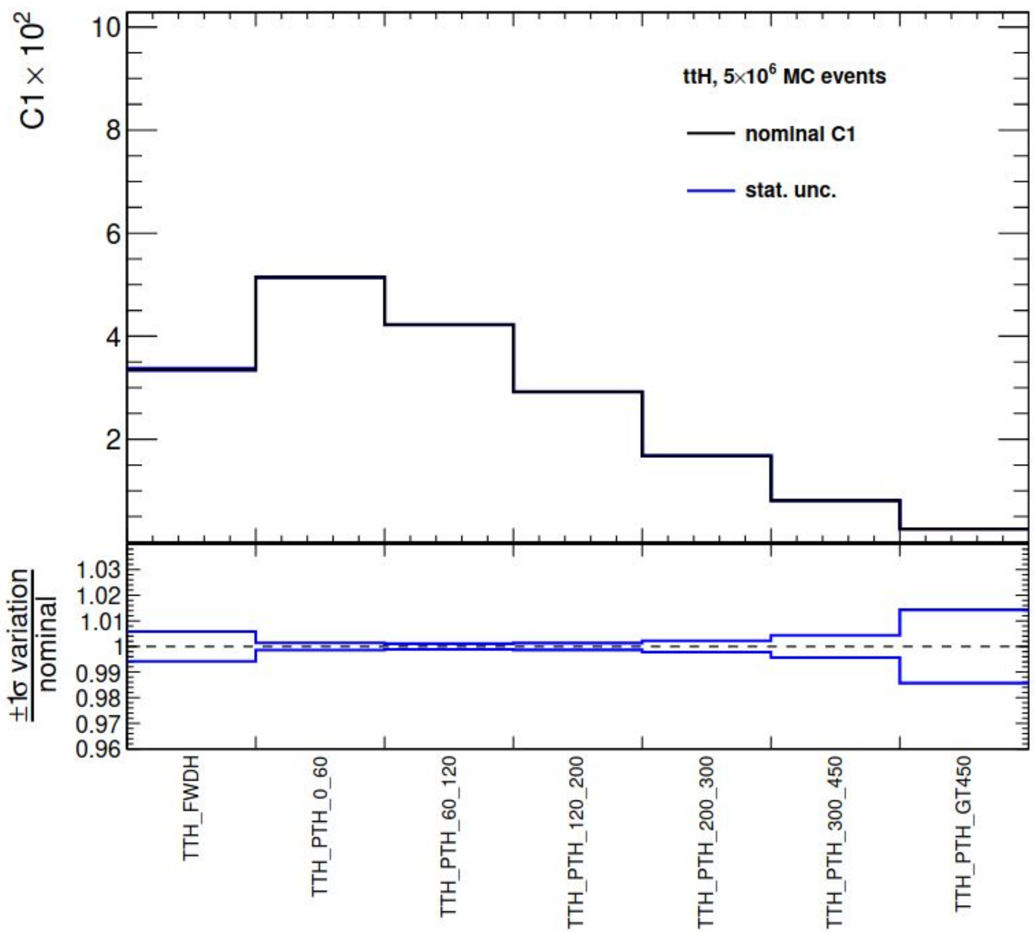


Njets splitting irrelevant for k_λ measurements →ignored



C_1 coefficients for ttH

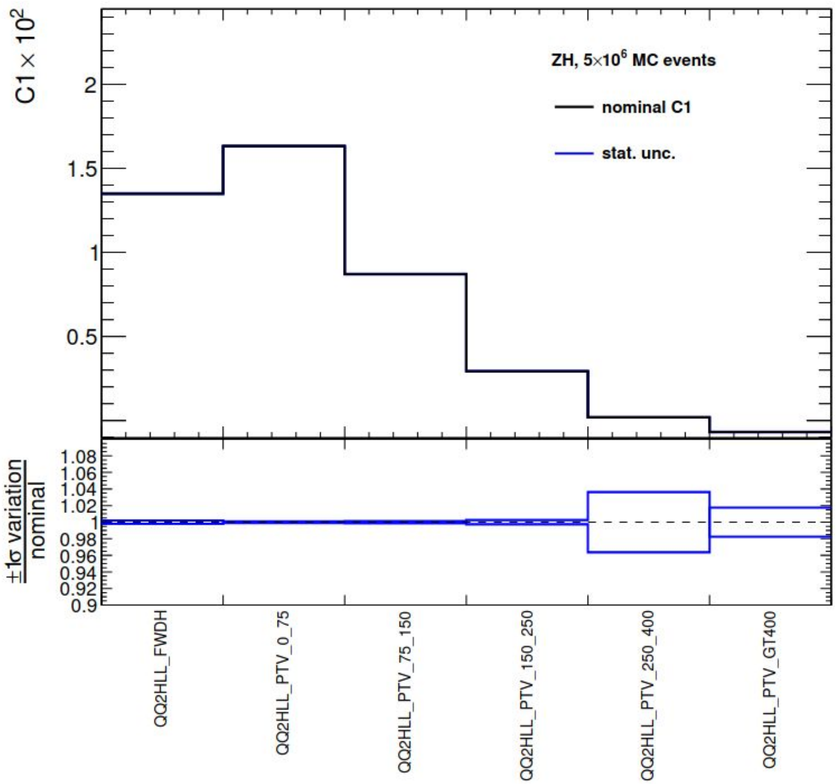
- Process with largest C_1→largest sensitivity to k_λ variations
- Large effect also at differential level



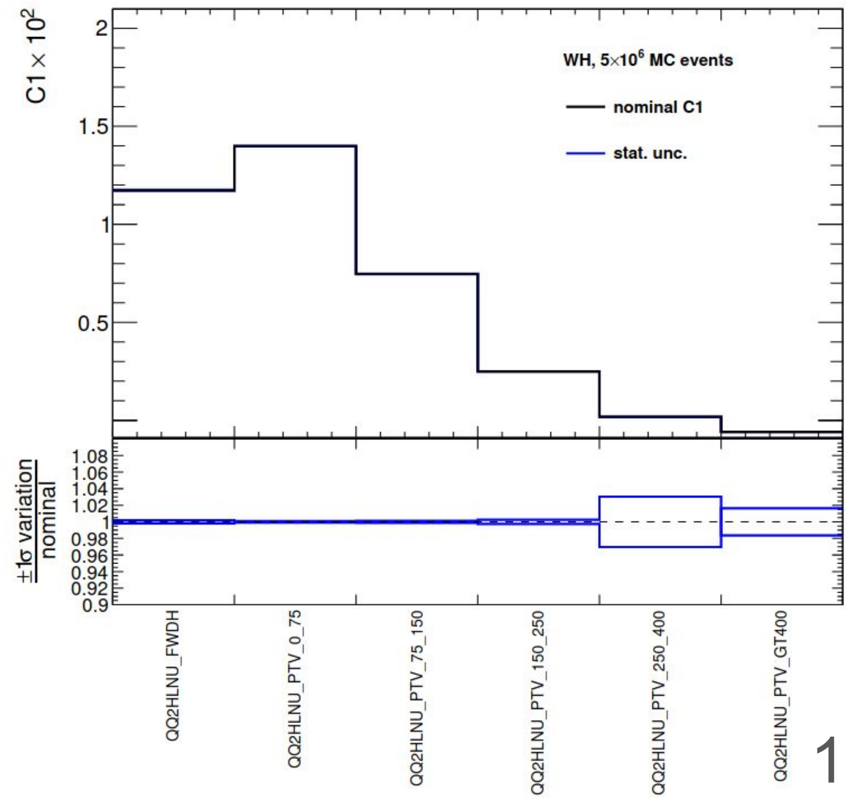
C_1 coefficients for VH leptonic

- Significant variation of C_1 vs $p_T(V)$
- Large relative uncertainty on some C_1 because value very close to zero → negligible impact on parametrization

ZH leptonic

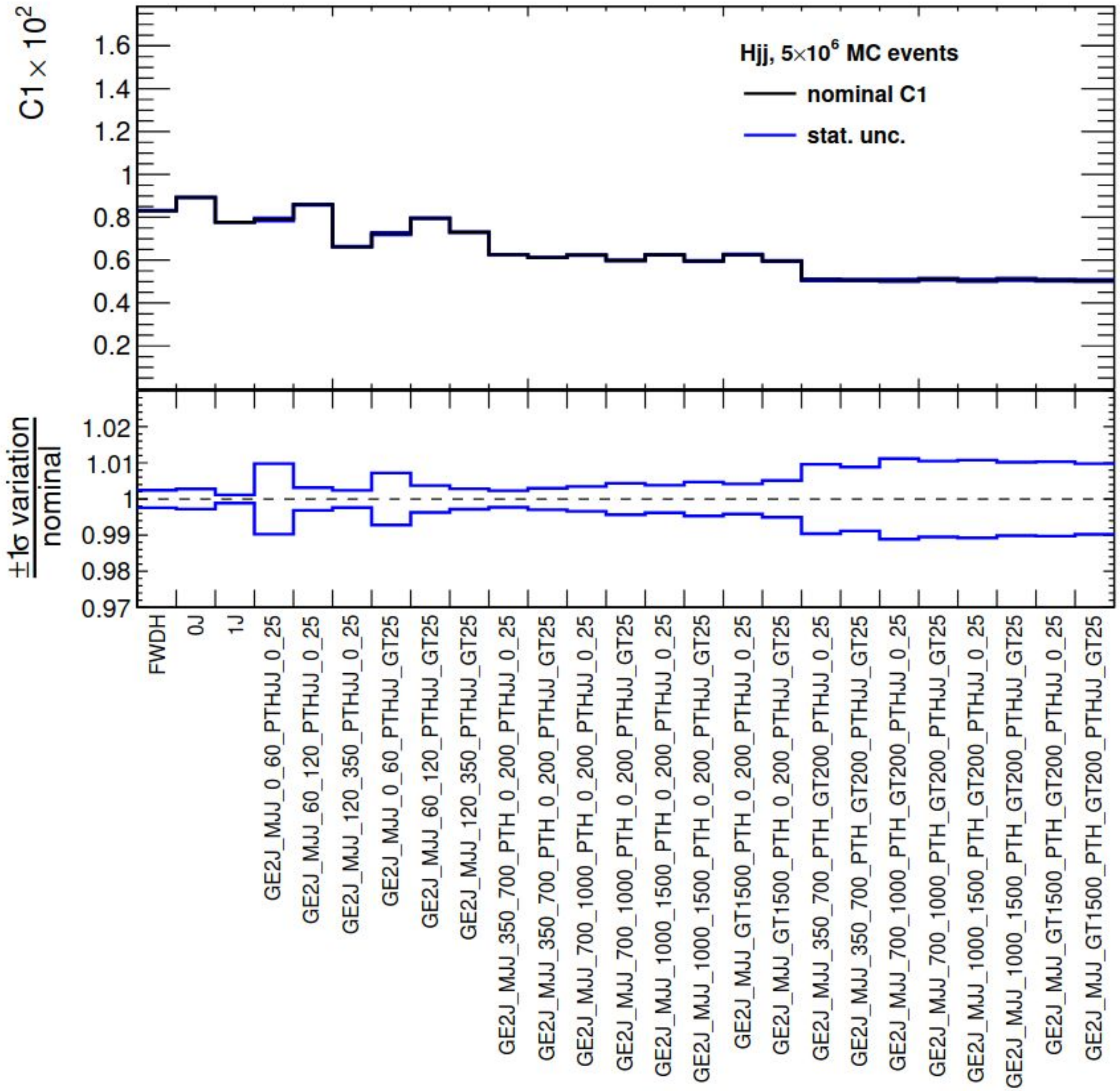


WH leptonic



C_1 coefficients for qqH

- Mild effect at differential level
- C_1 larger for low m_{jj} dominated by VH(had)



Recipe for k-factors for EW corrections

$$\frac{\sigma}{\sigma_{SM}} = \frac{1}{1-(\lambda^2-1)d_{ZH}}\left[\kappa_i^2 + (\kappa_\lambda - 1)\cdot\frac{C_1}{K_{EW}}\right]$$

Process and mildly kinematics dependent

- NLO EW corrections not factorising with λ effects
- K_{EW} with STXS 1.2 granularity provided by the note
  - For VH & qqH from previous works of LHCHWG and from YR4
  - For ttH new calculation using MG5_aMC@NLO 3.3.1

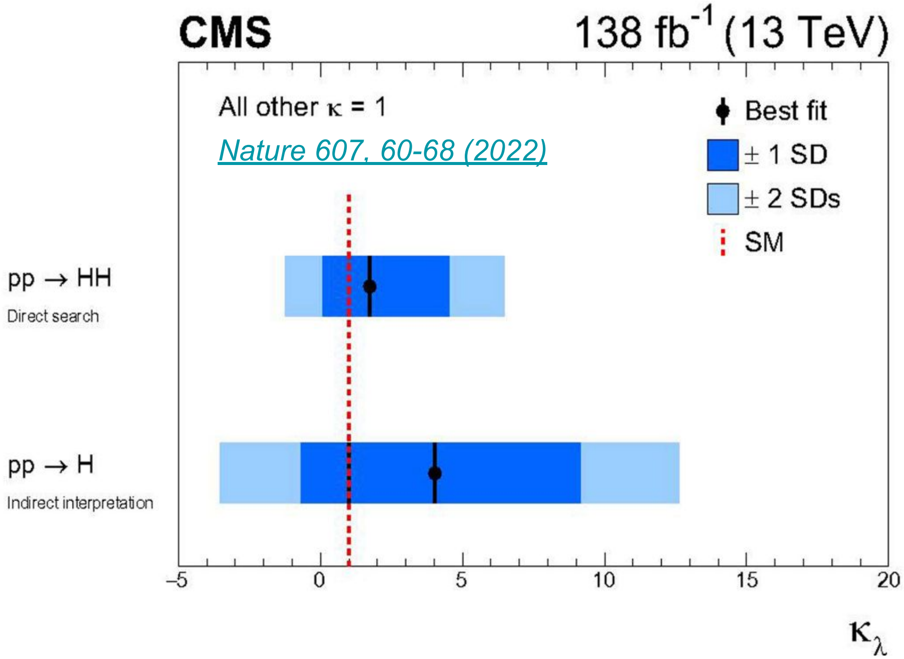
STXS BIN	K_{EW}
TTH_FWDH	1.017
TTH_PTH_0_60	1.041
TTH_PTH_60_120	1.025
TTH_PTH_120_200	1.002
TTH_PTH_200_300	0.978
TTH_PTH_300_450	0.956
TTH_PTH_GT450	0.923

- If inclusive K_{EW} used in both σ_{SM} and in parametric formula, then negligible difference in σ/σ_{SM}

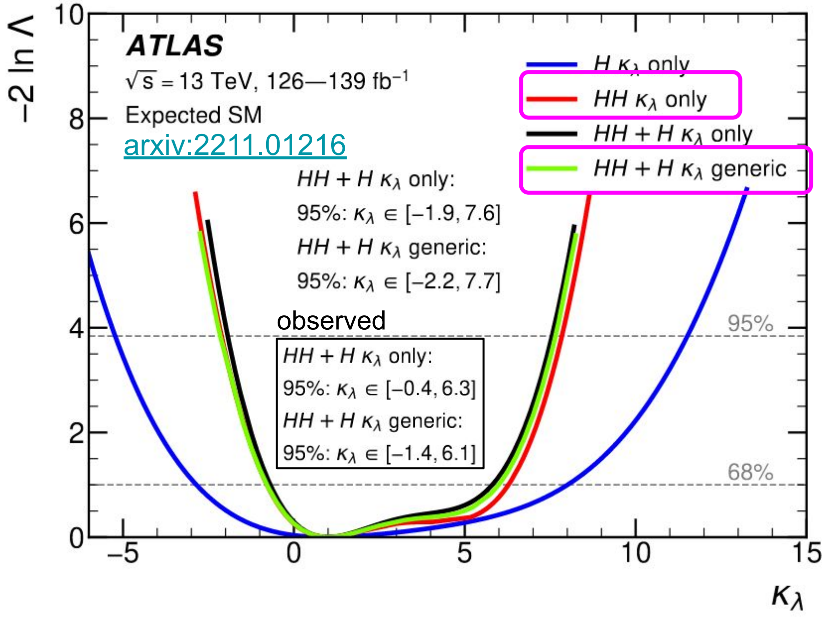
Available results from CMS & ATLAS

- Results of the note used in CMS & ATLAS public results

Constraints on k_λ from H or HH combination



k_λ likelihood scan from H and/or HH combination floating or fixing the H couplings to fermions and vector bosons



➢ Two-fold benefit from single-H
  - Solve degeneracy from additional parameters in the fit
  - Improve constraints on k_λ

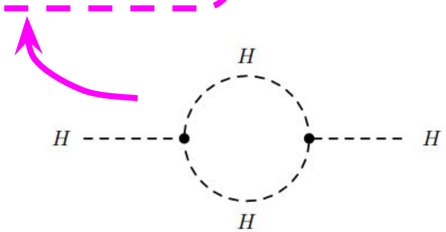
Outlook for the future

- Parametrization w/ incomplete perturbative order expansion
  - NLO EW in k_λ
  - LO in k_F, k_V, $k_{...}$ (kappa-framework) → missing NLO EW

➢ Negligible effect for small deviations of k_F, k_V, $k_{...}$ from 1

- Alternative approach using EFT?
  - In SMEFT is the effect of wavefunction renormalization reabsorbed by the c_H parameter?

$$\frac{\sigma}{\sigma_{SM}} = \frac{1}{1-(\lambda^2-1)d_{ZH}}\left[\kappa_i^2 + (\kappa_\lambda - 1)\cdot\frac{C_1}{K_{EW}}\right]$$



Summary

- k_λ measurement is a fundamental test of the SM
- k_λ can be determined from single-H XS measurements
  - Differential info improves accuracy and precision on k_λ
- Joint CMS and ATLAS effort for modeling STXS 1.2 to constrain k_λ → LHCHWG-2022-002
- Results of the note used in CMS & ATLAS public results
  - Single-H enriched categories solve degeneracy from additional parameters in the fit (e.g. k_V & k_F) and improve constraints on k_λ
- Alternative approach using EFT could be an interesting target

BACKUP

Setup for the calculation

- MADGRAPH5_AMC@NLO (v2.5.5) at LO accuracy interfaced with LHAPDF6 and PDF set PDF4LHC15_NLO_MC

$$G_F = 1.16638 \cdot 10^{-5}\ \mathrm{GeV}^{-2}$$
$$\alpha_s = 0.118$$
$$m_\mathrm{H} = 125\ \mathrm{GeV} \qquad \Gamma_\mathrm{H} = 3.5139\ \mathrm{MeV}$$
$$m_\mathrm{W} = 80.385\ \mathrm{GeV} \qquad \Gamma_\mathrm{W} = 2.0929\ \mathrm{GeV}$$
$$m_\mathrm{Z} = 91.1876\ \mathrm{GeV} \qquad \Gamma_\mathrm{Z} = 2.5048\ \mathrm{GeV}$$
$$m_\mathrm{t} = 172.5\ \mathrm{GeV} \qquad \Gamma_\mathrm{t} = 1.4058\ \mathrm{GeV}$$

- Pythia8 (v2.45) with default tune “Monash 2013”
  - Negligible changes of the C_1 values with alternative tunes
- μ_F and μ_R set dynamically equal to

$$\frac{1}{2}\sum_i \sqrt{p_{T,i}^2 + m_i^2}\,; \quad i = \text{particle in the final state}$$

Estimation of C_1 and uncertainties

- Each MC event bring two weights
  - w_{LO} = weight for the LO XS
  - w_{λ} = weight for λ-dependent corrections
- C_1 in a certain STXS bin *i* computed as

$$C_1^i = \frac{\sum_i w_\lambda^i}{\sum_i w_{LO}^i}$$

Sums over all MC events falling in the considered STXS bin

- Uncertainty on μ_F and μ_R from independent variations of the two scales of ×0.5 and ×2 the nominal ones
- Uncertainty on PDF from systematics variations provided by the considered PDF set & from C_1 computation with alternative PDF sets

Non-factorizing NLO EW corrections

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

$$\text{with } Z_{\mathrm{H}}^{BSM} = \frac{1}{1-(\kappa_\lambda{}^2 - 1)\delta Z_{\mathrm{H}}}$$

which simplifies to:

$$\frac{\sigma^i_{NLO_{EW}}}{\sigma^i_{NLO_{EW},SM}} = Z_{\mathrm{H}}^{BSM}\left[\frac{(\kappa_\lambda - 1)C_1^i}{K^i_{EW}} + \kappa_i^2\right]$$