Study of charm Yukawa couplings at the ATLAS detector

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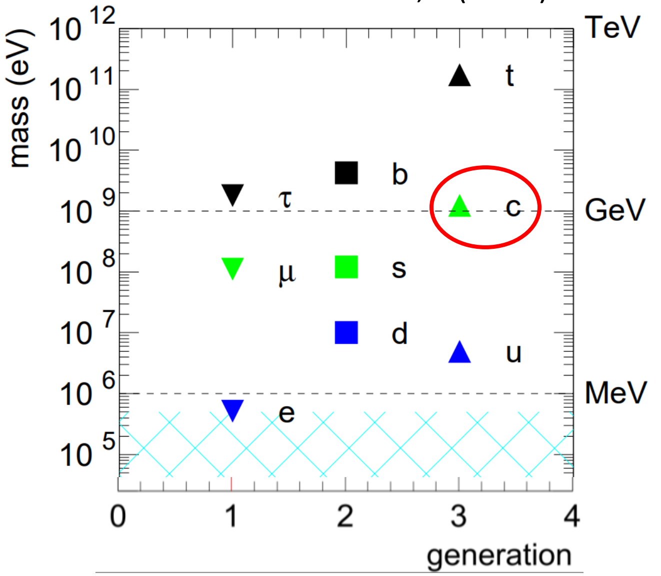
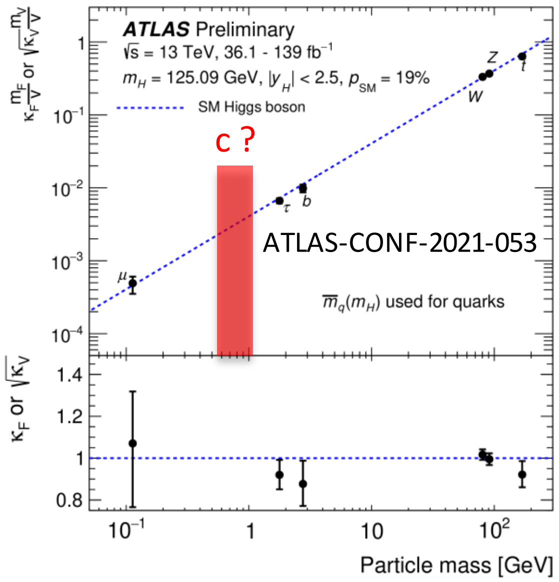
Introduction

- In the Standard Model, Higgs-fermion Yukawa interaction generates mass for fermions, and the coupling constant is proportional to fermion mass
- Coupling between Higgs boson and all 3rd generation quarks has been measured
- For the 2nd generation quarks, the Yukawa coupling is still not measured, yet not confirmed, in which the charm Yukawa coupling is the largest
- Measuring charm Yukawa coupling with good precision can proof source of second-generation quark mass for the first time and potentially constraint some BSM phenomenon

AIP Conf. Proc. 857, 3 (2006)

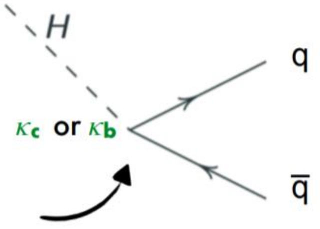




Current charm Yukawa coupling measurement

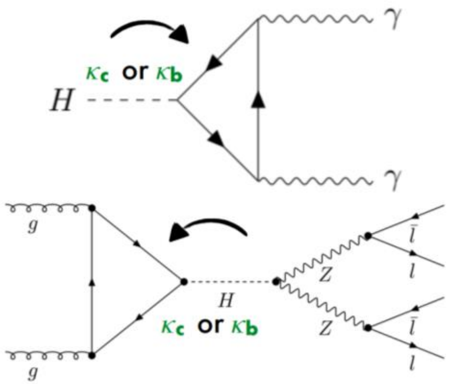
- Higgs coupling to charm quarks (κ_c*) can be constrained directly or indirectly:
  - Direct: constrain with H→cc via VH(cc) measurement, $|\kappa_c| < 8.5$ @95% CL (Run II) **
  - Indirect: constraint from p_T spectrum of H(ZZ) and H(γγ) ***

Direct



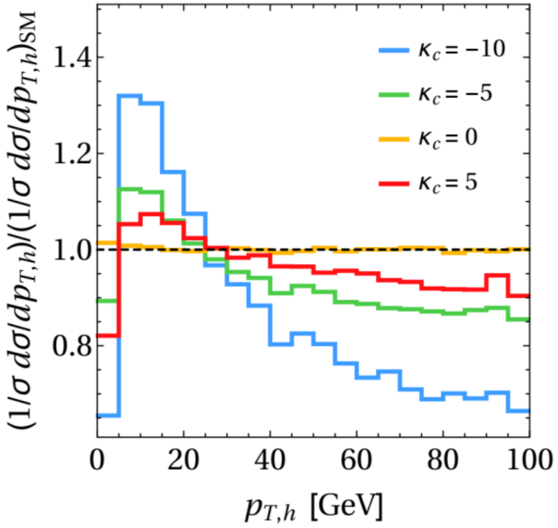
through Higgs to charm decay

Indirect



through ggH (production) or Hγγ (decay)

1606.09253

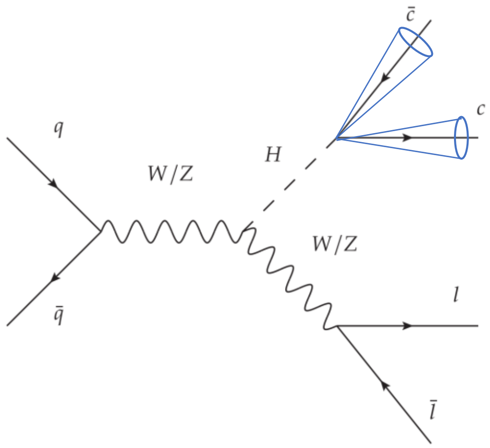


*: κ_c is the coupling modifier for charm Yukawa coupling
**: assume κ_c can only modify H→cc branch fraction
***: consider only κ_c can modify the Higgs p_T shape → $\kappa_c \in [-8.6,17.3]$ @95% CL; only κ_c can modify Higgs p_T shape and normalization → $\kappa_c \in [-2.3,2.3]$ @95% CL

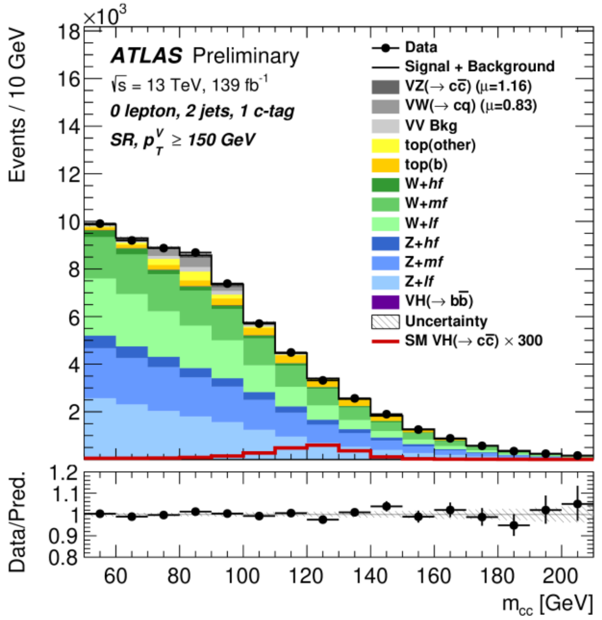
arXiv:2201.11428

VH(cc) – Direct constraint on κ_c

- VH(cc) channel is by far the most utilized channel to measure Higgs to charm decay directly
  - Utilizing the leptonic decay product of the vector boson, QCD backgrounds can be well suppressed
  - Channels: 0L (Z→νν), 1L (W→νl), 2L (Z→ll)
  - Fitting on m_{CC}, the di-jet invariant mass
  - Main backgrounds:
    - Z+jets
    - W+jets
    - ttbar and single top
  - Key points
    - Good modelling of backgrounds
    - Charm tagging
      - Current working point in ATLAS latest result c-jets (27%), b-jets (8.3%), light-jets (1.7%)



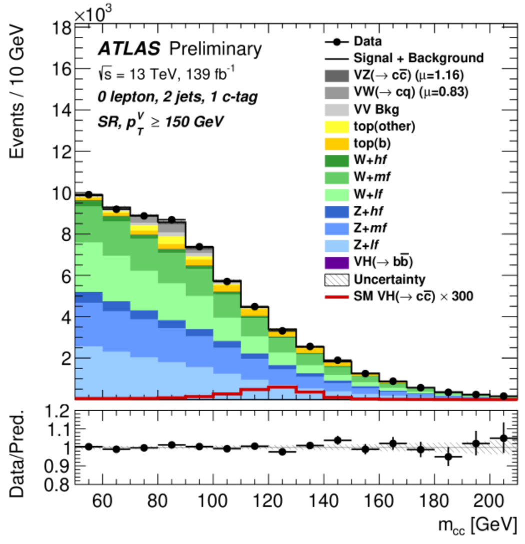
Feynman diagram for VH(cc)



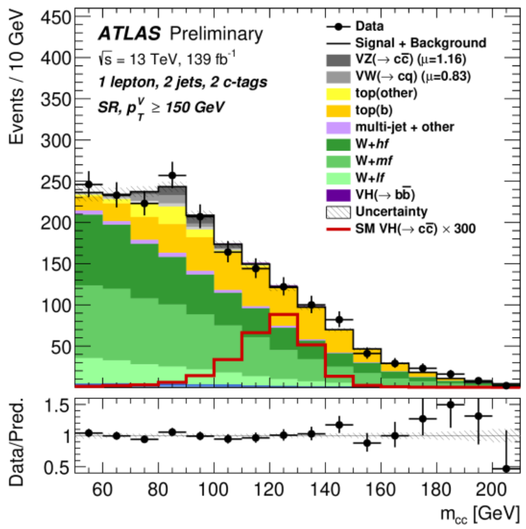
SRs and CRs

- In order to increase the sensitivity, a series of SRs has been carefully defined **(16 SRs in total)**
- To be able to constrain the backgrounds better, several control regions has been defined **(28 CRs in total)**

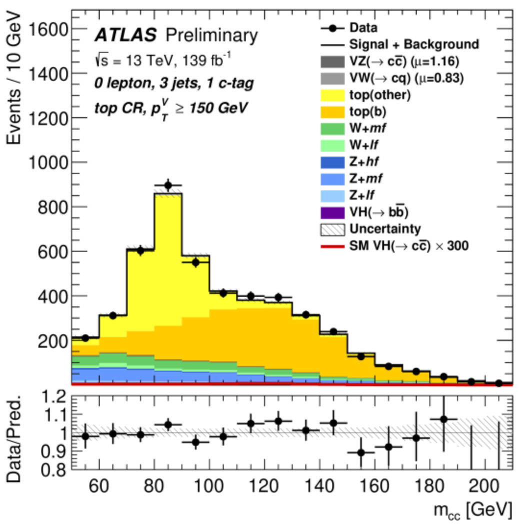
0 lepton 2 jets 1 c-tag SR



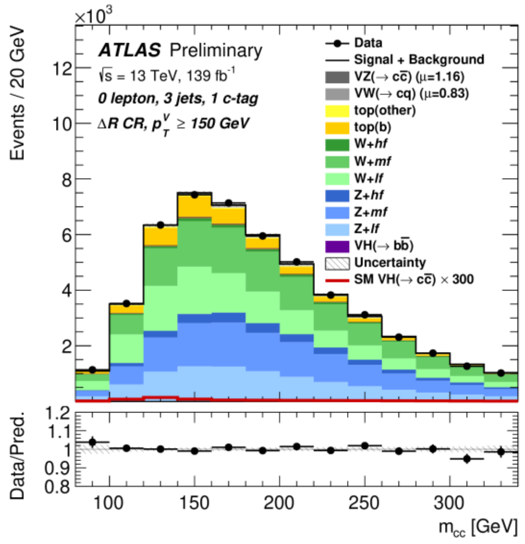
1 lepton 2 jets 2 c-tags SR



top control region

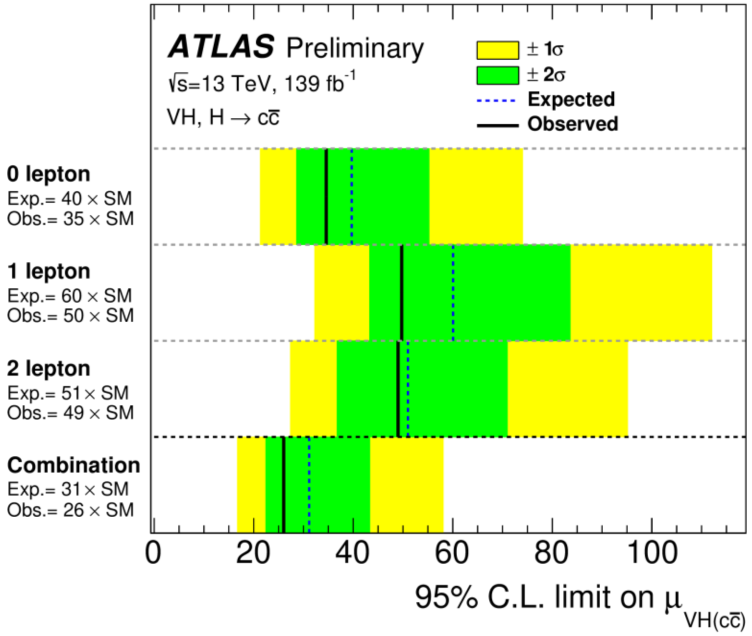


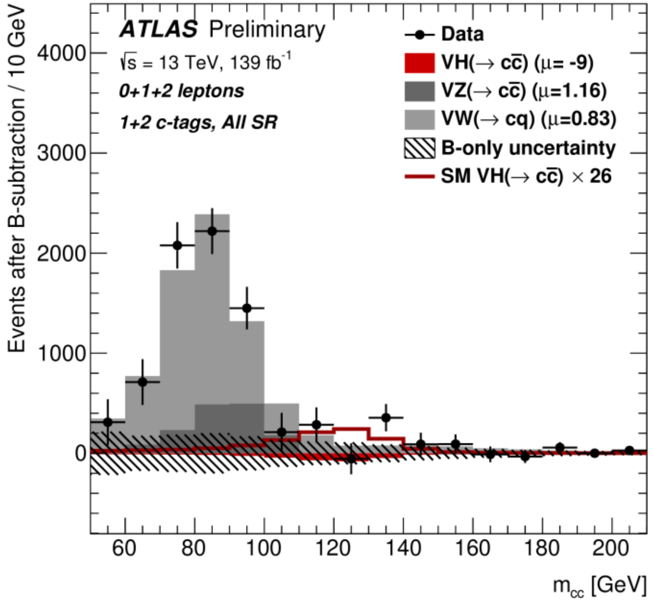
high ΔR control region



Direct constraint on $\mu_{\mathrm{VH(cc)}}$

- Observed VH(cc) limit of **26 x SM** (31 x SM expected)
  - Highest sensitivity in 0 lepton channel
  - Dominated by statistics, for systematic uncertainty, Z+jets modelling uncertainty is dominant





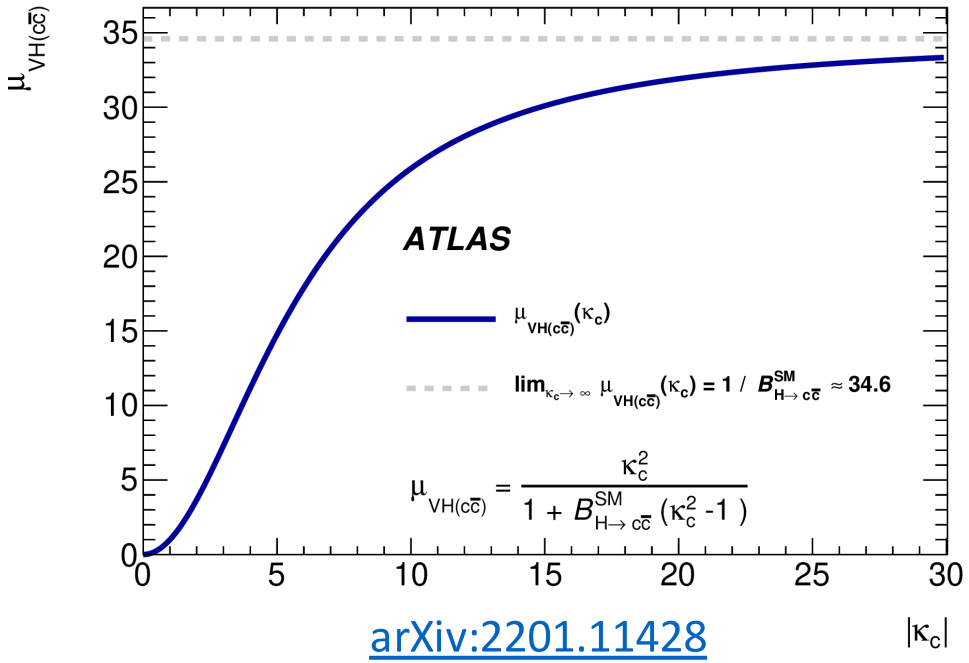
Less sensitive than CMS newest result because: 1. no machine learning technique applied; 2. boosted channel is not included

Direct constraint on κ_c

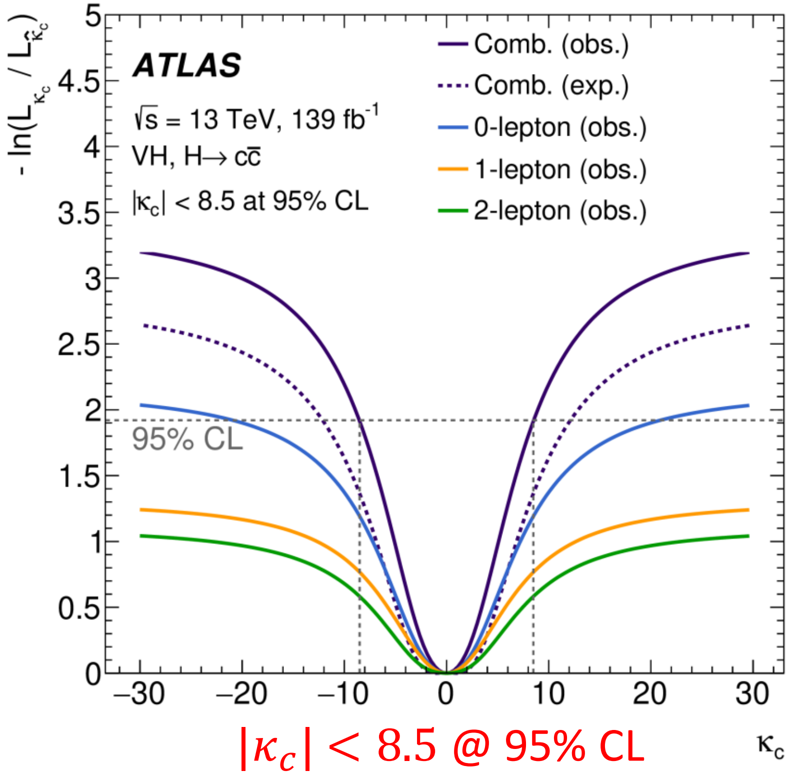
- κ framework is used to set limit on κ_c instead of VH(cc) signal strength

$$\mu_{\mathrm{VH(cc)}} = \frac{\kappa_c^2}{\kappa_H^2} = \frac{\kappa_c^2}{1 - \mathrm{BR_{cc}} + \mathrm{BR_{cc}}\kappa_c^2}$$

κ_c only affects Higgs decay branch fraction
all κ modifiers except κ_c set to be 1

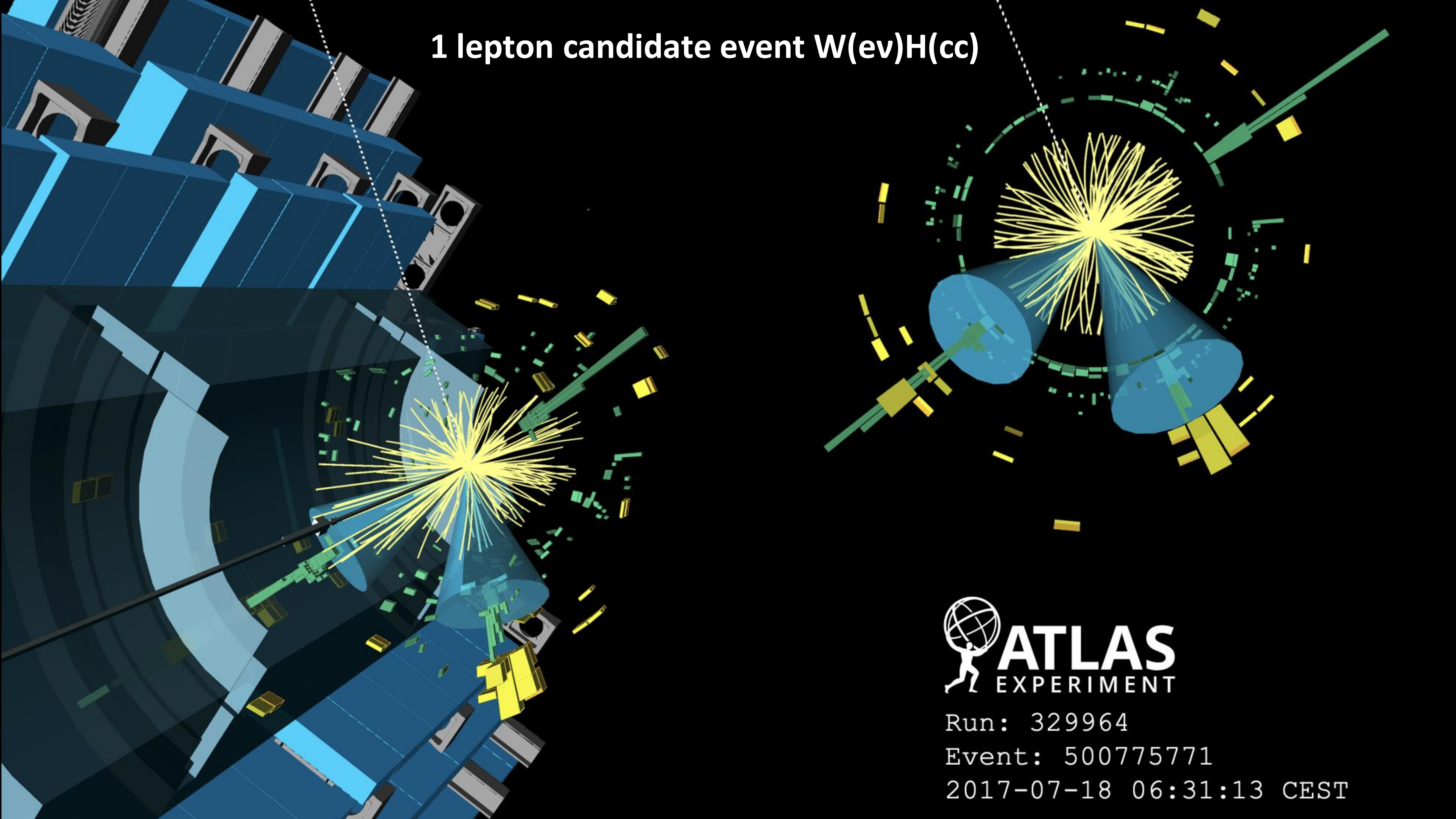


[arXiv:2201.11428](https://arxiv.org/abs/2201.11428)



$|\kappa_c| < 8.5$ @ 95% CL

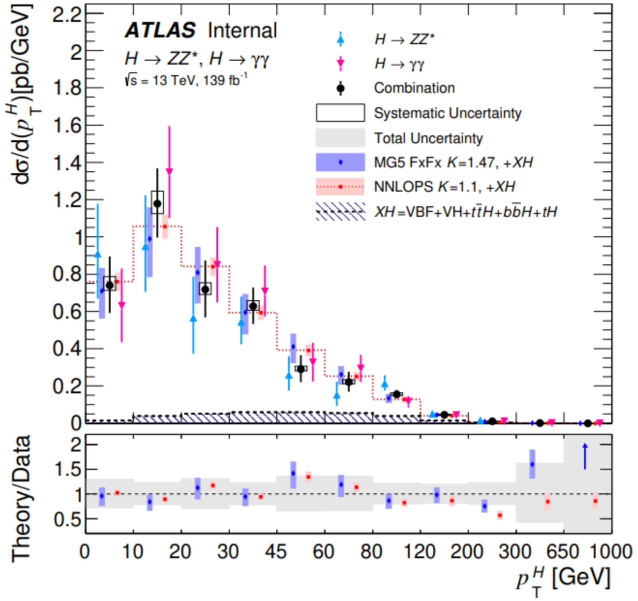
1 lepton candidate event W(eν)H(cc)

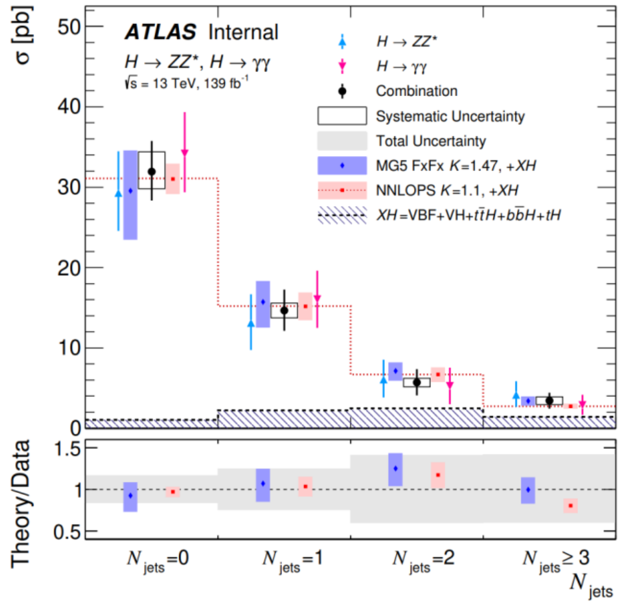


arXiv:2207.08615

$p_T(H)$ measurement – Indirect constraint on κ_c

- κ_c can be constrained in two ways via the $p_T(H)$ measurement
  - Shape of the differential cross section 1/σ dσ/d(pT(H)) depends on κ_c (and can also depend on κ_b)
  - Overall normalization of H→ZZ/γγ is proportional to $1/\kappa_H^2$ and κ_H depends on κ_c (and can also depend on κ_b) ⇨ *Additional input from VH(bb/cc) is needed to disentangle κ_b and κ_c*





Multiple **observables** for differential cross section measurement: $p_T(H)$, |y(H)|, Njets, $p_T(\text{jet})$, 2D $p_T(H)$ vs |y(H)|

Combining direct and indirect measurements

Resolved κ_H as function of $\kappa_b, \kappa_c, \mathrm{BR}_{\mathrm{BSM}}$:

Decay branch ratio to the rest final states

$$\kappa_H^2(\kappa_c,\kappa_b,\mathrm{BR}_{\mathrm{BSM}}) = \frac{\mathrm{BR}_{\mathrm{cc}}\kappa_c^2 + \mathrm{BR}_{\mathrm{bb}}\kappa_b^2 + \mathrm{BR}_{\gamma\gamma}\kappa_\gamma^2(\kappa_c,\kappa_b) + \mathrm{BR}_{\mathrm{gg}}\kappa_g^2(\kappa_c,\kappa_b) + \mathrm{BR}_{Z\gamma}\kappa_{Z\gamma}^2(\kappa_c,\kappa_b) + 1 - \mathrm{BR}_{\mathrm{cc}} - \mathrm{BR}_{\mathrm{bb}} - \mathrm{BR}_{\gamma\gamma} - \mathrm{BR}_{\mathrm{gg}} - \mathrm{BR}_{Z\gamma}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

$p_T(H)$

κ_c

κ_b

$\kappa_H(\kappa_c,\kappa_b,\mathrm{BR}_{\mathrm{BSM}})$

VH(bb/cc)

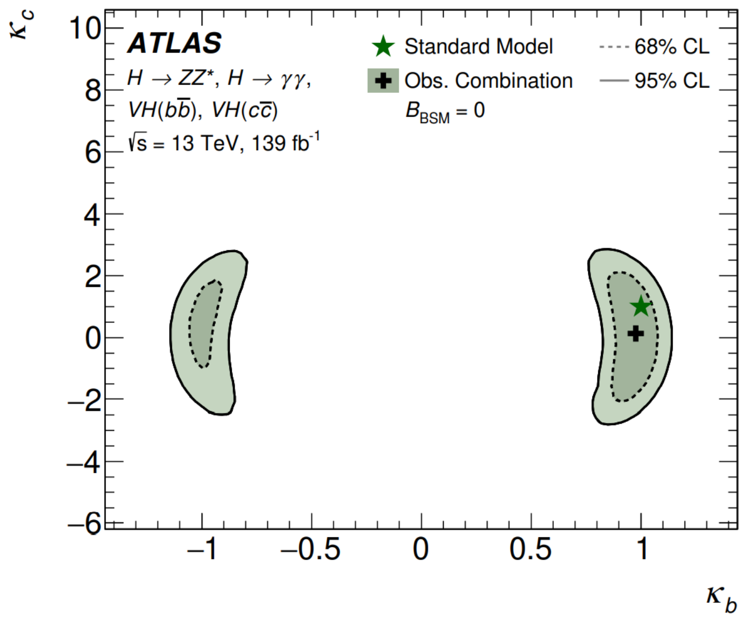
$$\mu_{\mathrm{VHcc}} = \frac{\kappa_c^2}{\kappa_H(\kappa_c,\kappa_b,\mathrm{BR}_{\mathrm{BSM}})^2}$$

$$\mu_{\mathrm{VHbb}} = \frac{\kappa_b^2}{\kappa_H(\kappa_c,\kappa_b,\mathrm{BR}_{\mathrm{BSM}})^2}$$

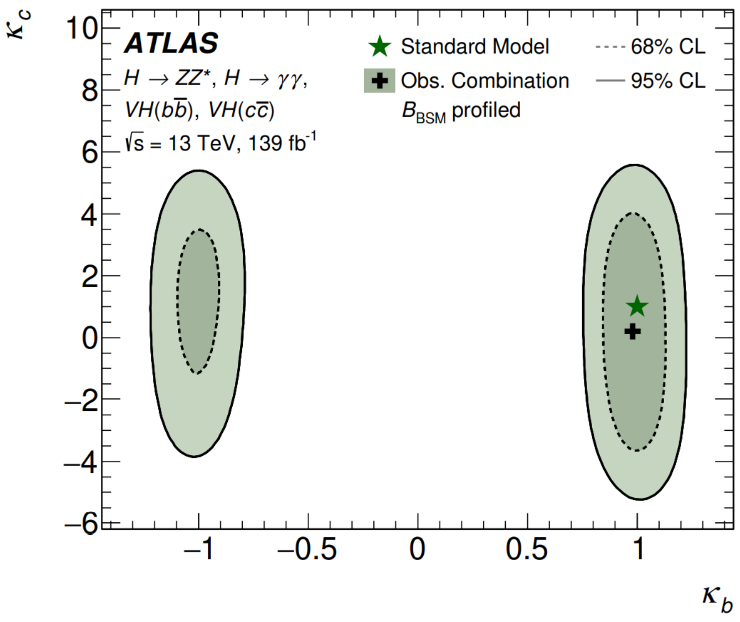
- Case 1: float BR(H→BSM), 3POIs ($\kappa_c, \kappa_b, \mathrm{BR}_{\mathrm{BSM}}$) in total, which has less assumption on Higgs total width
- Case 2: set BR(H→BSM)=0
  - Can give tighter constraint with the sacrifice of less model independency

Results after combination

2D negative log likelihood contours for κ_b and κ_c



set BR(H→BSM)=0,
i.e. only allow H→BSM decay



float BR(H→BSM), i.e.
allow H→BSM decay

1D confidence interval for κ_c with κ_b profiled:

- $\kappa_c \in [\mathbf{-4.5, 4.8}]$ @95% CL if H→BSM is allowed
- $\kappa_c \in [\mathbf{-2.5, 2.5}]$ @95% CL if only H→SM is allowed

Very stringent limit on κ_c

Summary

- Measuring charm Yukawa coupling with good precision will proof the source of second-generation quark mass for the first time
- The current measurement on charm Yukawa coupling can be performed either directly or indirectly, with the direct way utilizing VH(cc) channel and the indirect way using Higgs p_T spectrum and overall normalization to set constrain
- By combining the direct and indirect approaches, we've been able to achieve very stringent limit on κ_c ($\kappa_c \in [-\mathbf{4.5}, \mathbf{4.8}]$ @95% CL with relatively small assumption on Higgs total width)
- Given the aim for measuring charm Yukawa coupling to the observation of charm Yukawa coupling, we are just at the starting point, a journey still awaits


A JOURNEY AWAITS