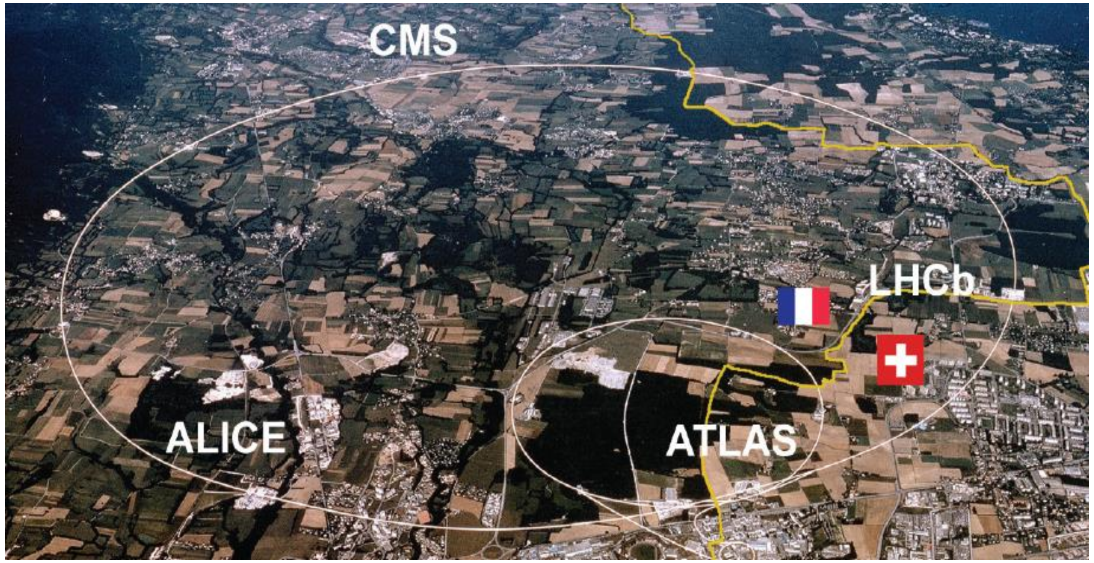
Recent Higgs boson results from ATLAS

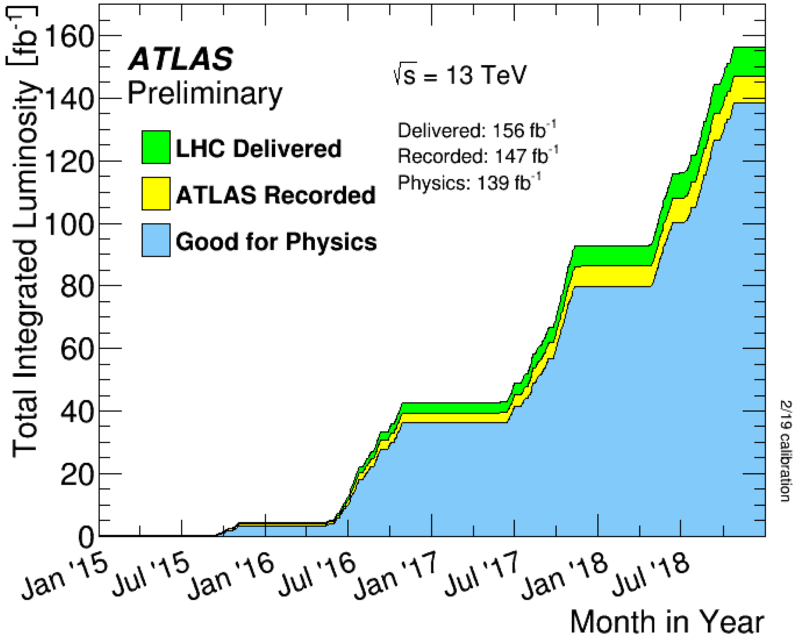
Soshi Tsuno (KEK)

Introduction

- Located at CERN, Switzerland,
- 27km long, proton-proton collision, E_{CM}=14TeV (design)
- 4 experiments : ATLAS, CMS, ALICE, LHCb
- Discover Higgs boson in 2012.

Large Hadron Collider





- Collected ~140fb^{-1} data.

  σ_{tot}(H) ~ 55pb@13TeV => **7.7x10^6 Higgs are produced.**

- Large QCD background

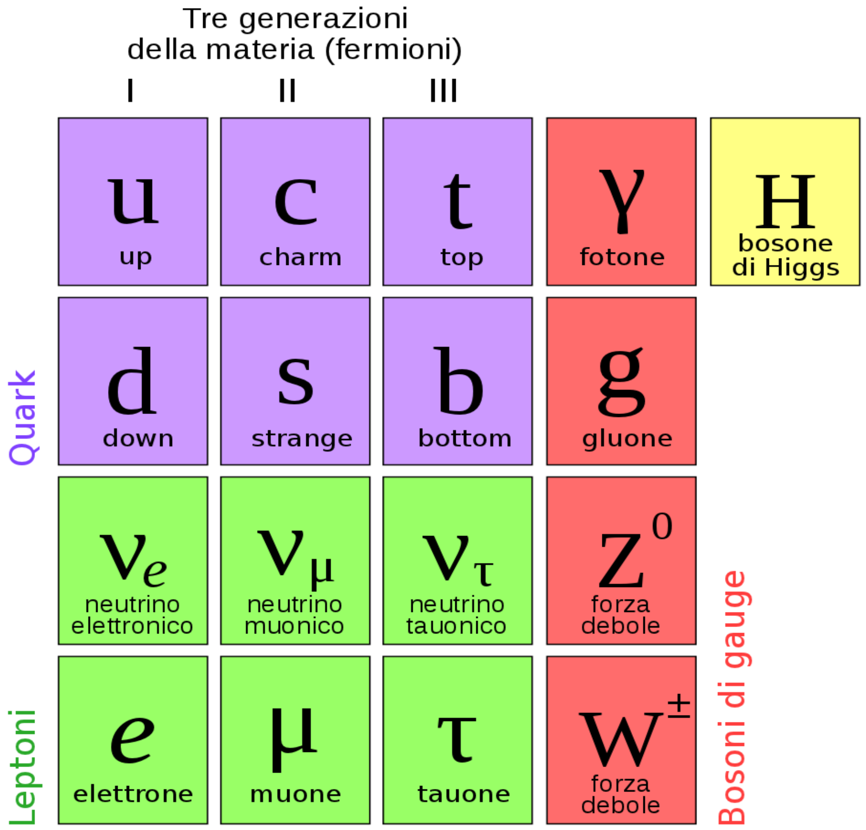
  Promising channels: Br(H->$\gamma\gamma$) ~0.2%
  Br(H->ZZ->llll)~0.01%

=> 100 – 10000 events should be observed.

Outline

ATLAS Higgs talks:

- Celebrating Higgs discovery ... B. Moser
- Property measurements ... B. Lee
- Differential cross sections ... Y. Horii
- Coupling couplings ... G. Aad

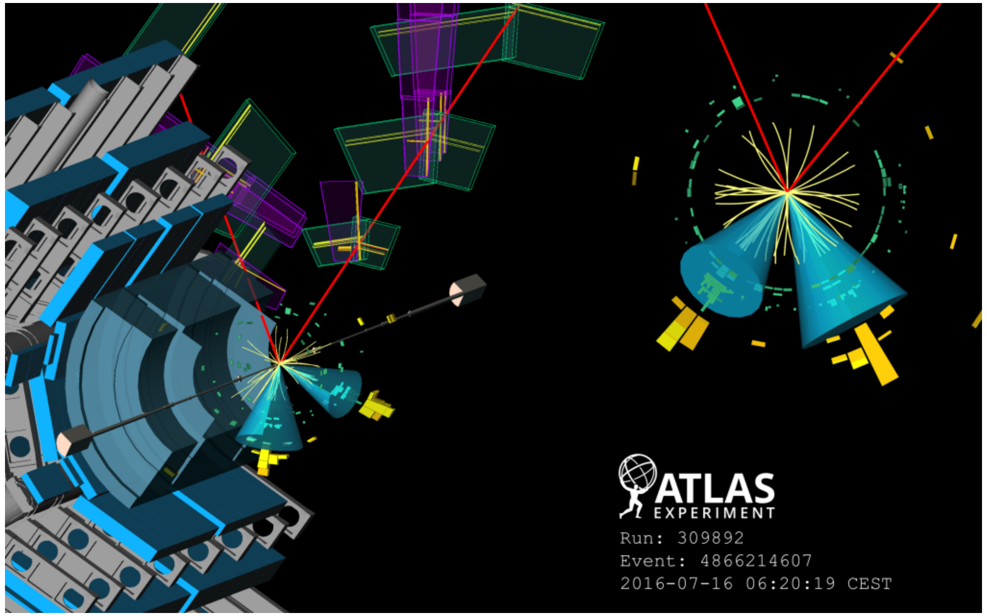


My talk: (selected topics) Recent Higgs results

- 2^{nd} generation coupling (H->cc),
- Self-coupling,
- Rare decays

<u>Important for the next milestones</u>

H->cc coupling measurements



H->cc coupling measurements

Nature (2022)

Three approaches:

Direct charm tagging,

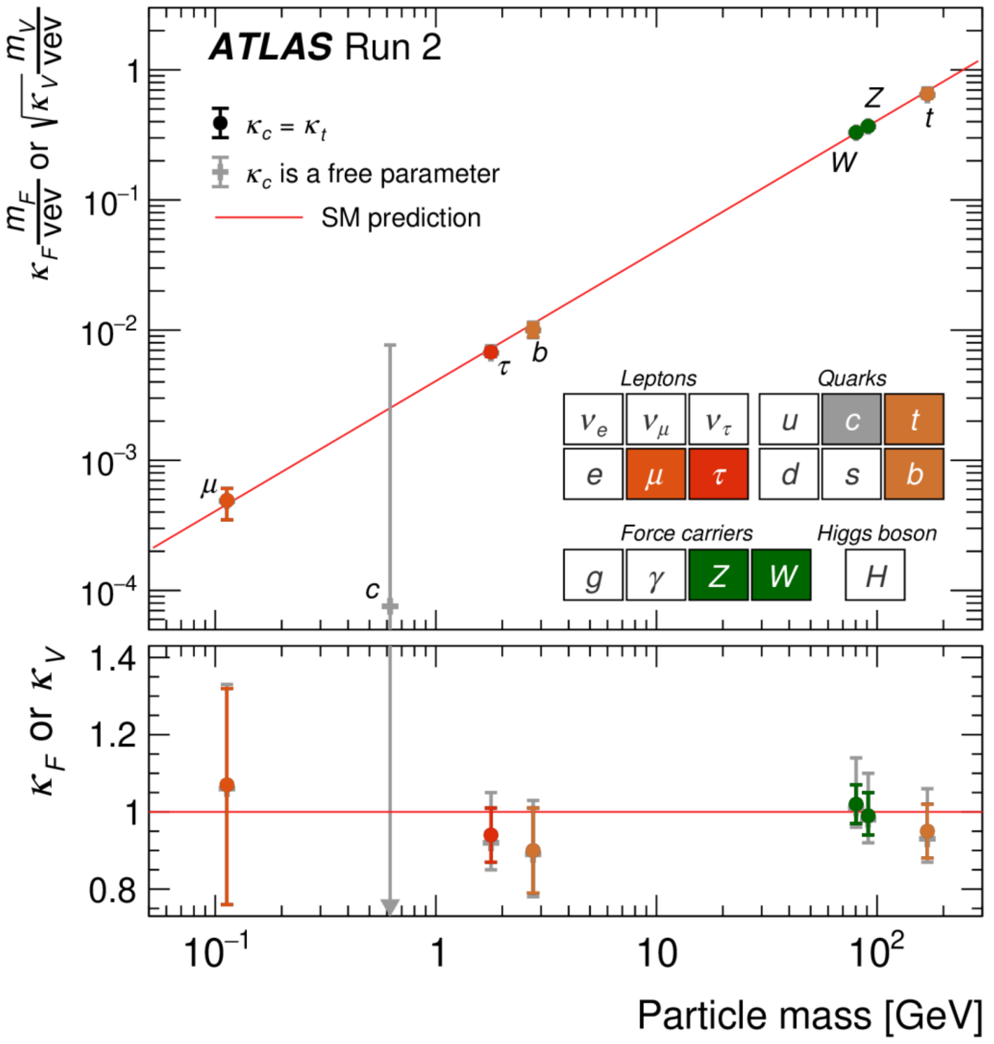
Indirect probing using p_{TH}

Rare decays using $J/\psi + \gamma$

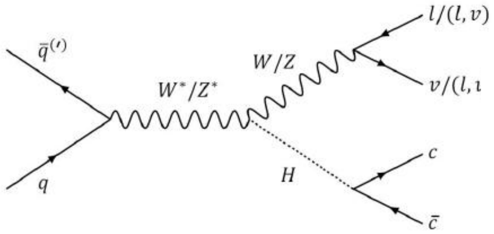
Challenge:

Br(H->cc) ~ 2.9% (x20 smaller than Br(H->bb))

Very large background



Direct search: VH, H->cc



- **Charm-jet tagging**

  Critically depend of the tagging performance

  Hybrid of BDT and DNN

  Optimized 27% c-tagging eff. while 8% b- 1.6% light-jet mis-id

- **Analysis**

  16 signal regions based on # of lepton, jets, c-jet and p_{TV}

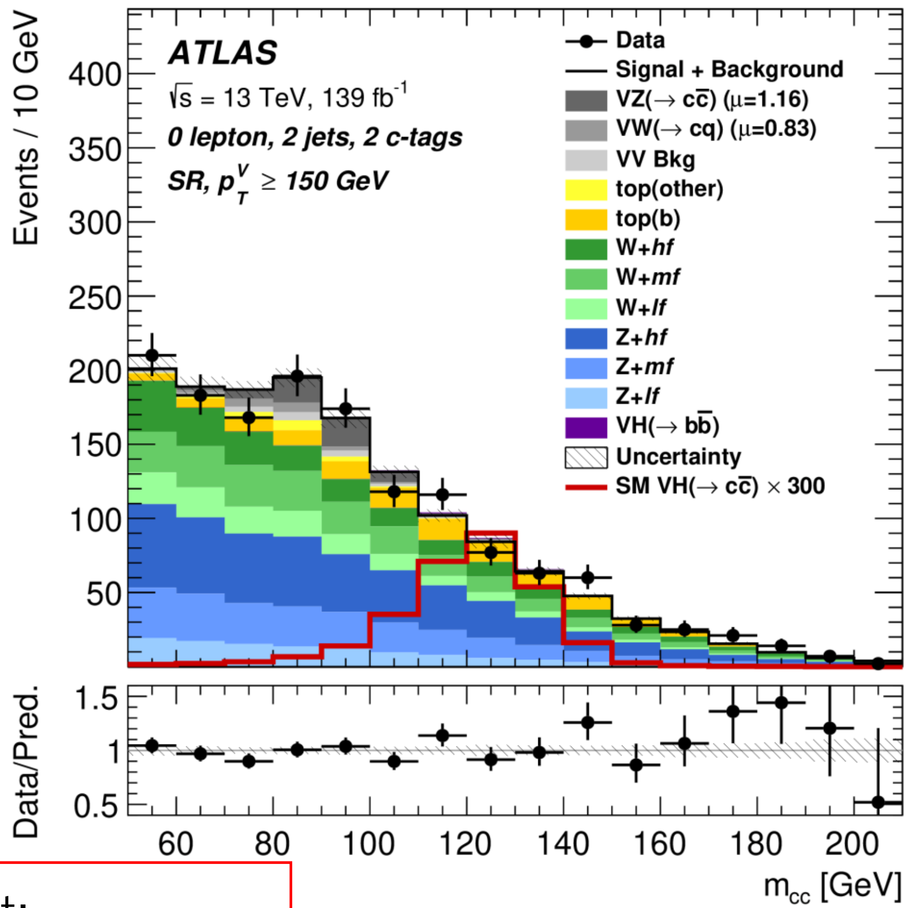
  Fit m_{cc} ; measure di-boson as well as VH

  Stat. uncertainty is compatible with systematic uncert.

  Main systematics: background modeling

  (V + single b/c prod.)

Eur. Phys. J. C 82 (2022) 717



Observed (expected) significance:

3.8σ (4.6σ) for VW(cq)

2.6σ (2.2σ) for VZ(cc)

Observed (expected) limit:

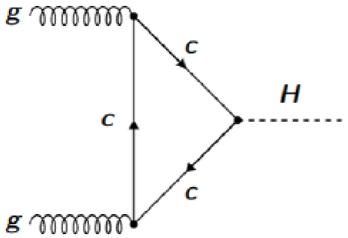
Br(H->cc) < 26 (31) x SM@95% CL

Indirect probe using p_{TH}

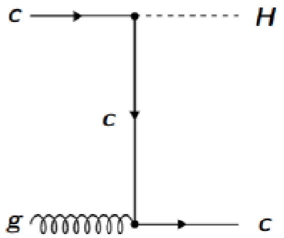
Precise measurement constraints y_b and y_c ratio(Yukawa).

- Sensitive to the Higgs p_T spectrum

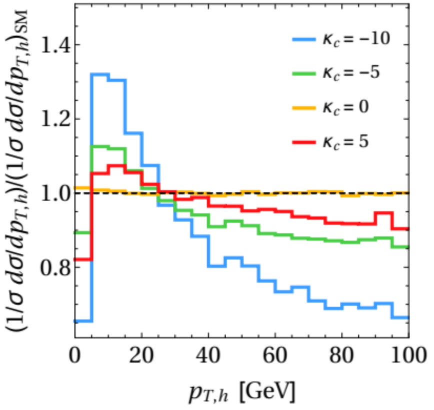
=> At low p_T the b/c-quark contribution dominates.



ggF with *c*-quark loop



c-quark initiated production



PRL **118** (2017) 12, 121801

- Use H->γγ and H->ZZ channels

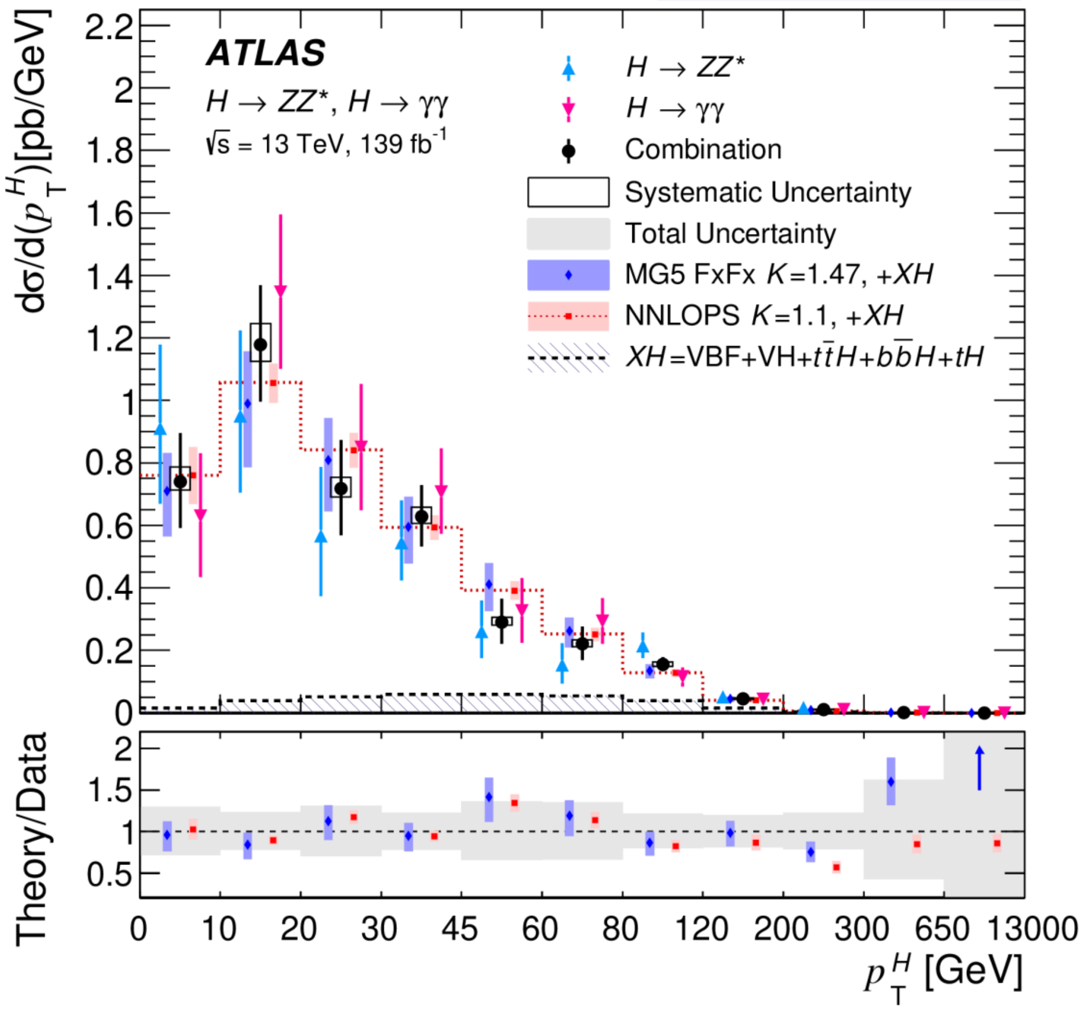
Observed (expected) confidence interval:

$$-2.1(-2.2) < k_b < 7.4(7.4)$$

$$-10.1(-10.3) < k_c < 18.3(16.6)$$

$$k_x = y_x / y_{SM}$$

arXiv:2207.08615



Constraint of k_c v.s. k_b

Probed by p_{TH} or VH->bb/cc :

Based on kappa-framework:

$$\kappa_c = \frac{y_c}{y_c^{SM}}$$

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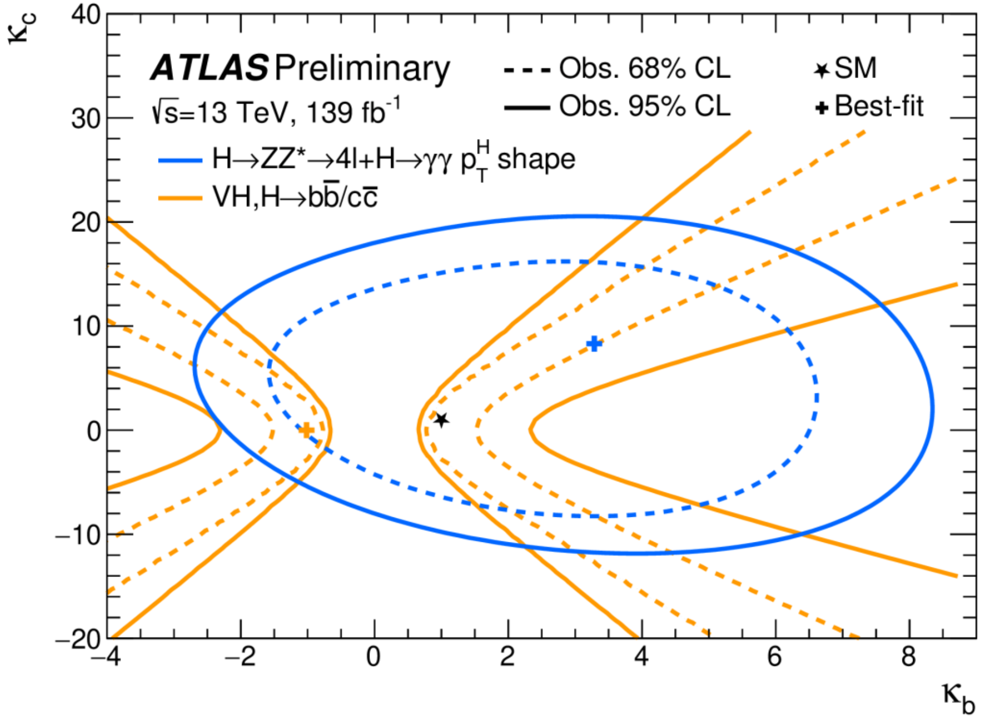
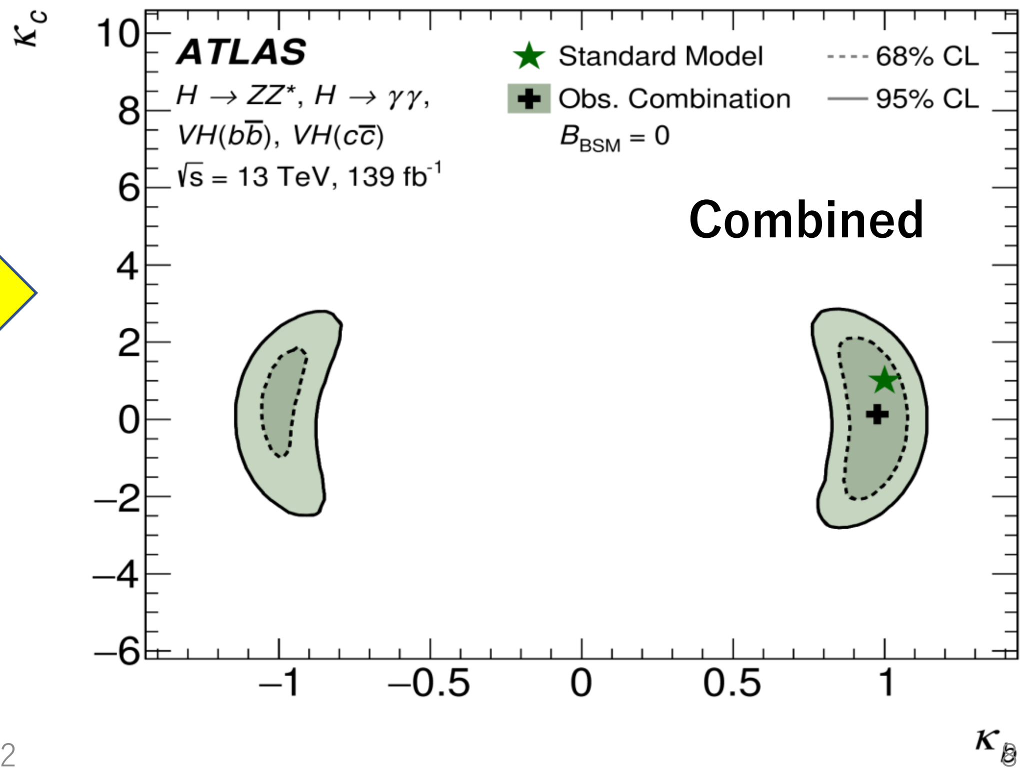
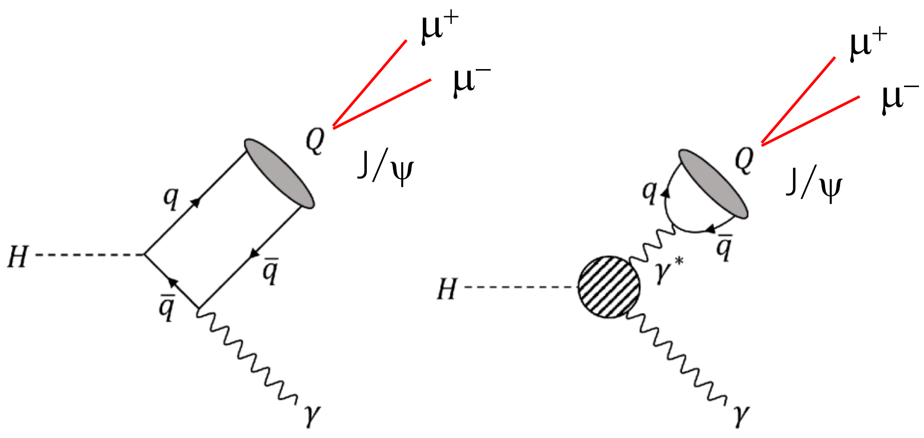


So far, results are consistent with the SM.



Rare decay: H->J/ψ γ and ψ(2S)γ



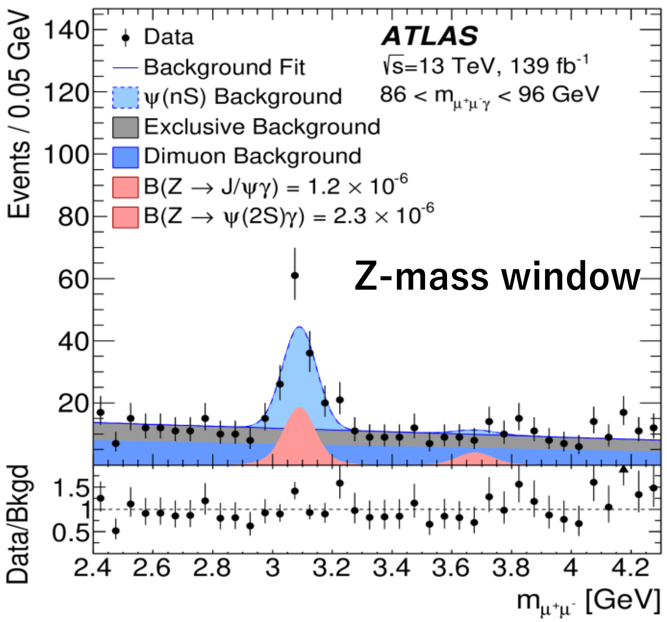
Very small Br(H->J/$\Psi\gamma$) ~ 3x10^{-6}

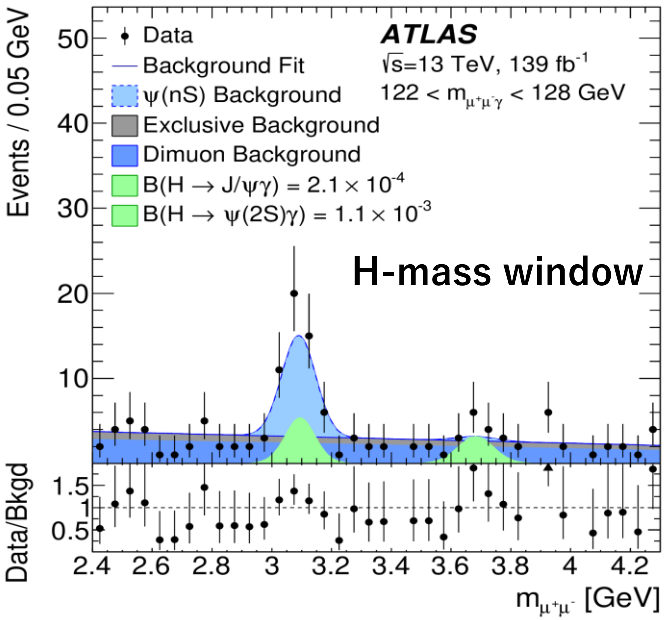
=> σ_{tot} x L x Br = 55[pb] x 140[fb^{-1}]x 3x10^{-6}
= **23 events expected!**

- Trigger efficiency: photon (35GeV) + muon (18GeV) ~97%
- 2D fit: $m_{\mu\mu}$ v.s. $m_{\mu\mu\gamma}$

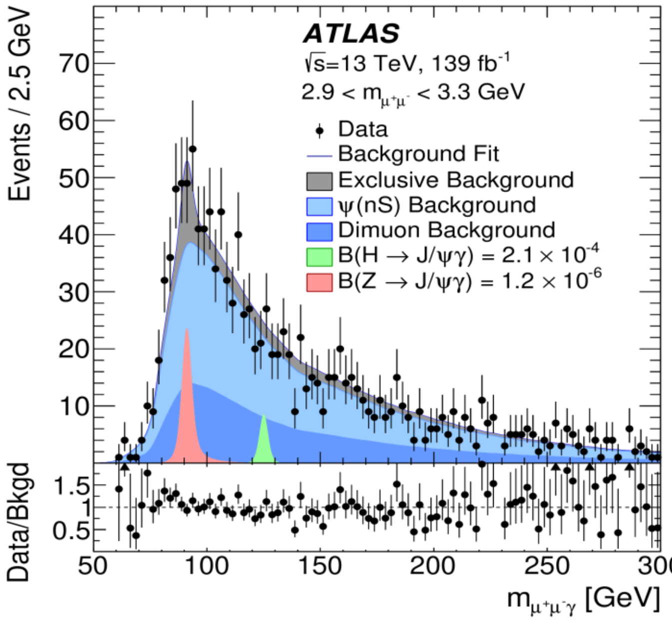
=> Br(H->J/$\psi\gamma$)<2.1x10^{-4} and Br(H->J/ψ(2S)γ)<10.9x10^{-4}

arXiv:2208.03122

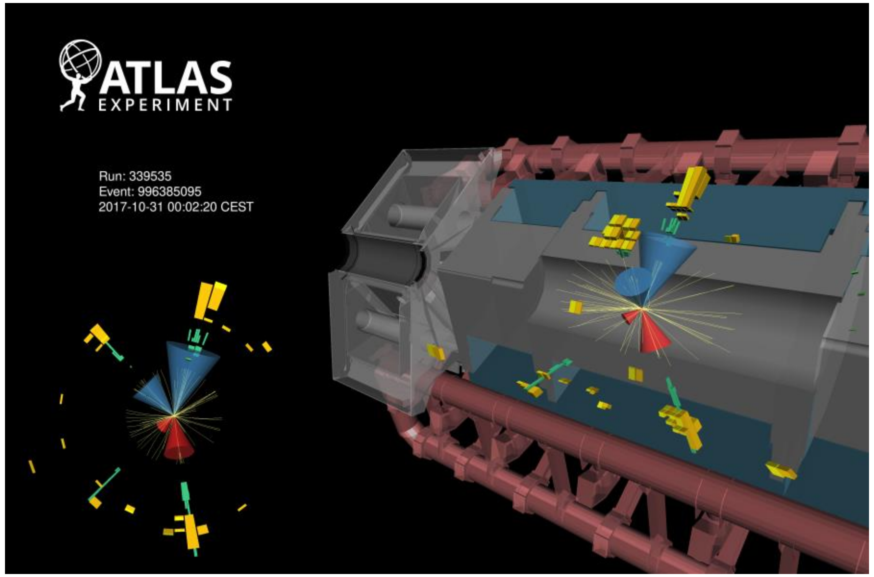




J/ψ -mass window

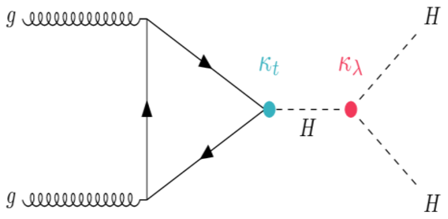


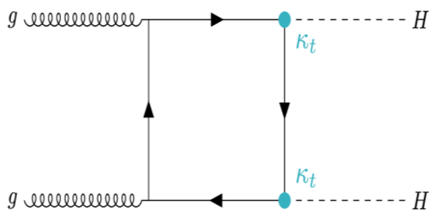
Self-coupling measurements



Self-coupling

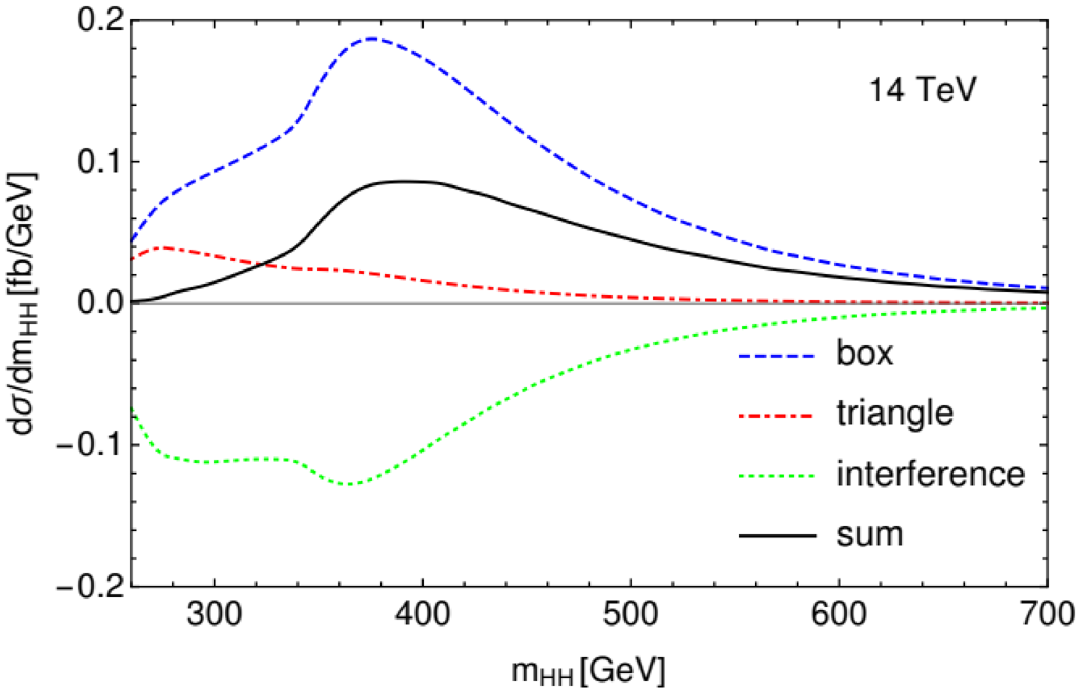
Direct searches: Di-Higgs prodution



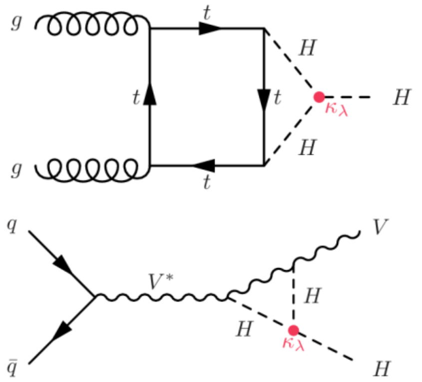


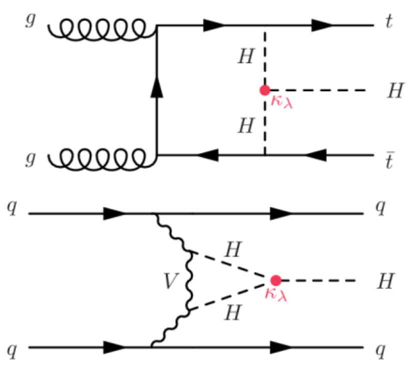
=> Large negative interference

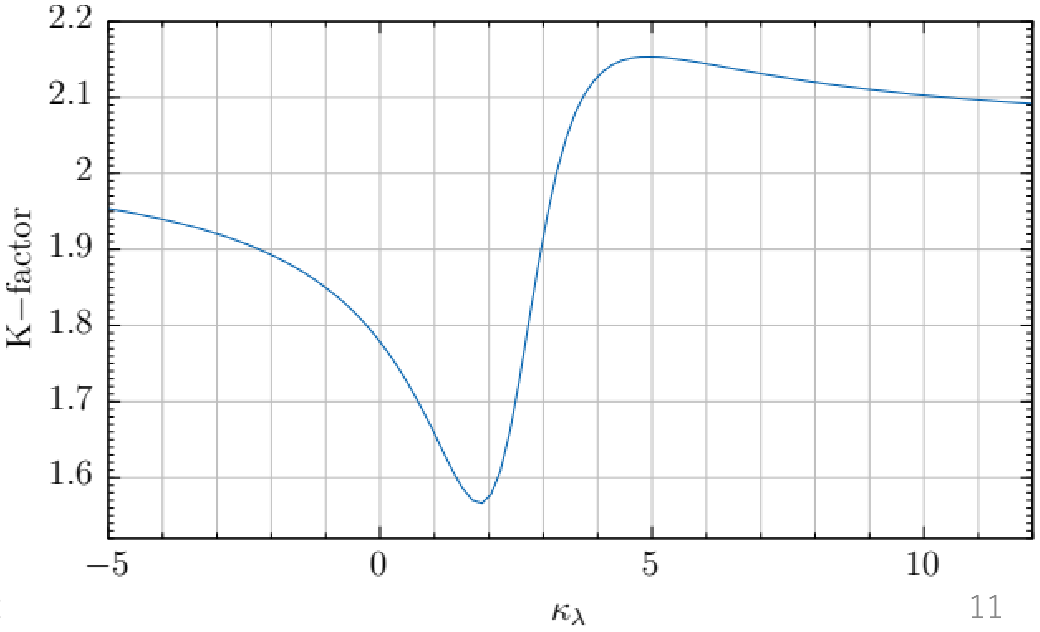
Sensitive to new physics



Indirect constraints: Differential distributions







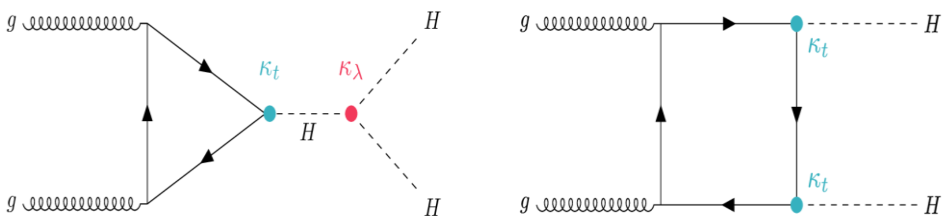
Direct searches: HH->bbbb, bbγγ, bbττ

Largest Br, relatively clean in γγ-channel

Non-resonant process => rely on MVA

Set a combined limit on

$-1.0(-1.2) < k_{\lambda} < 6.6(7.2)$



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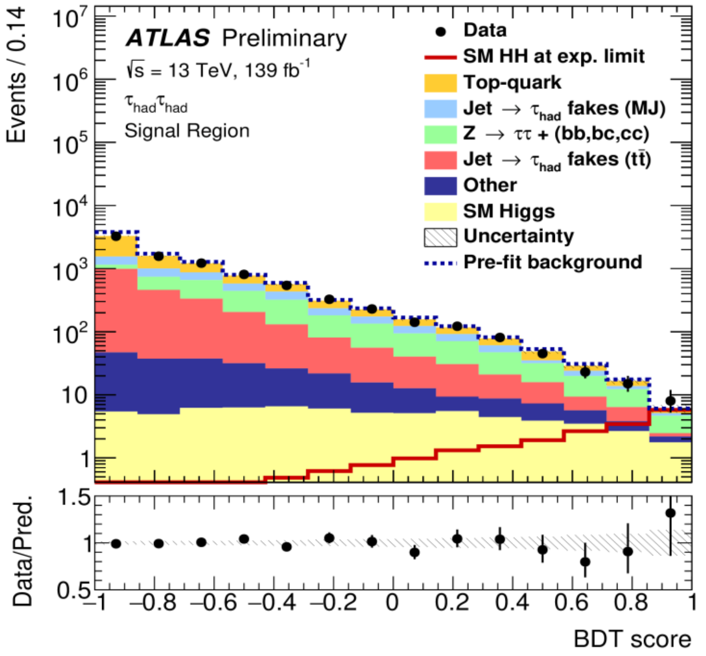
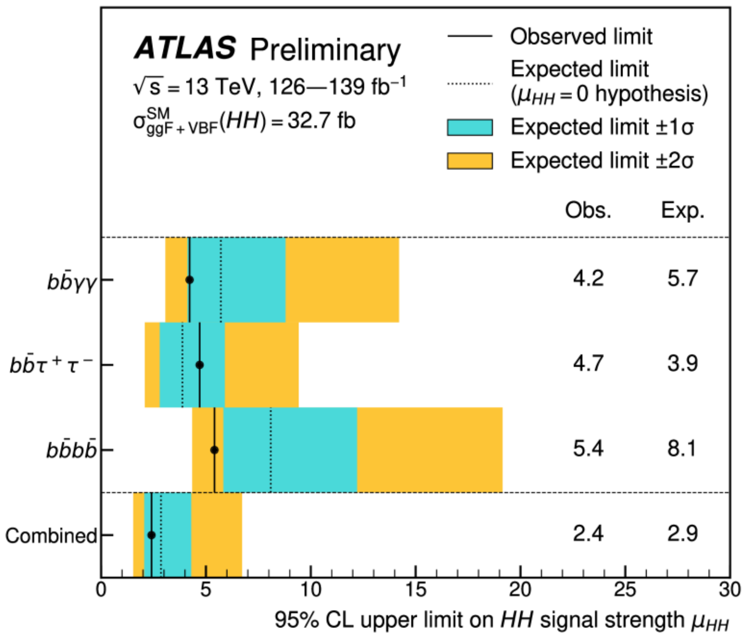
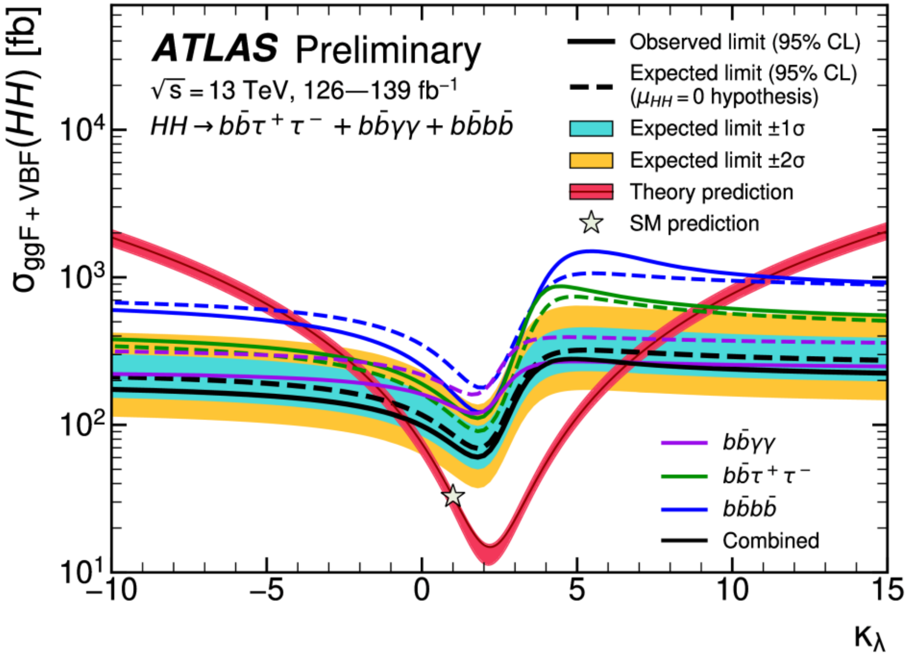




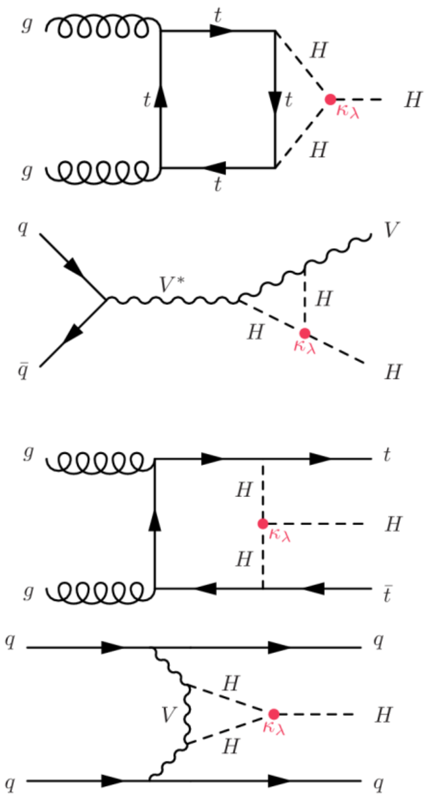


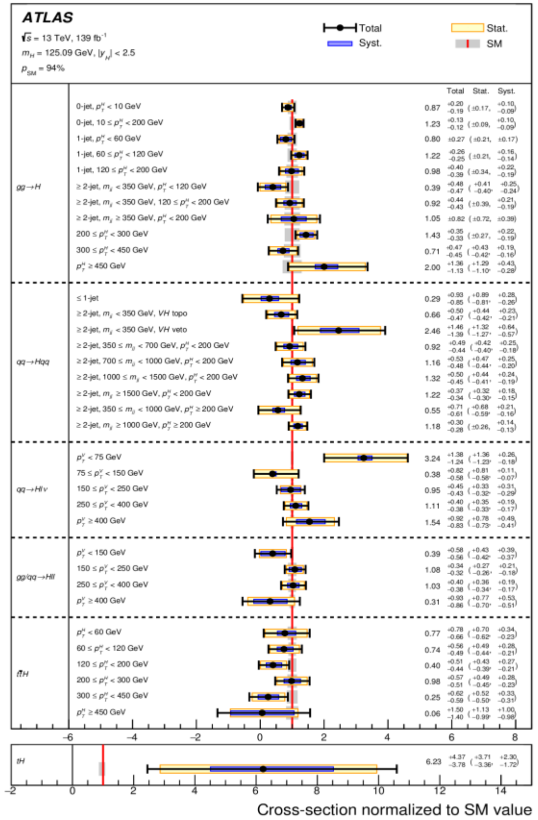
Indirect searches

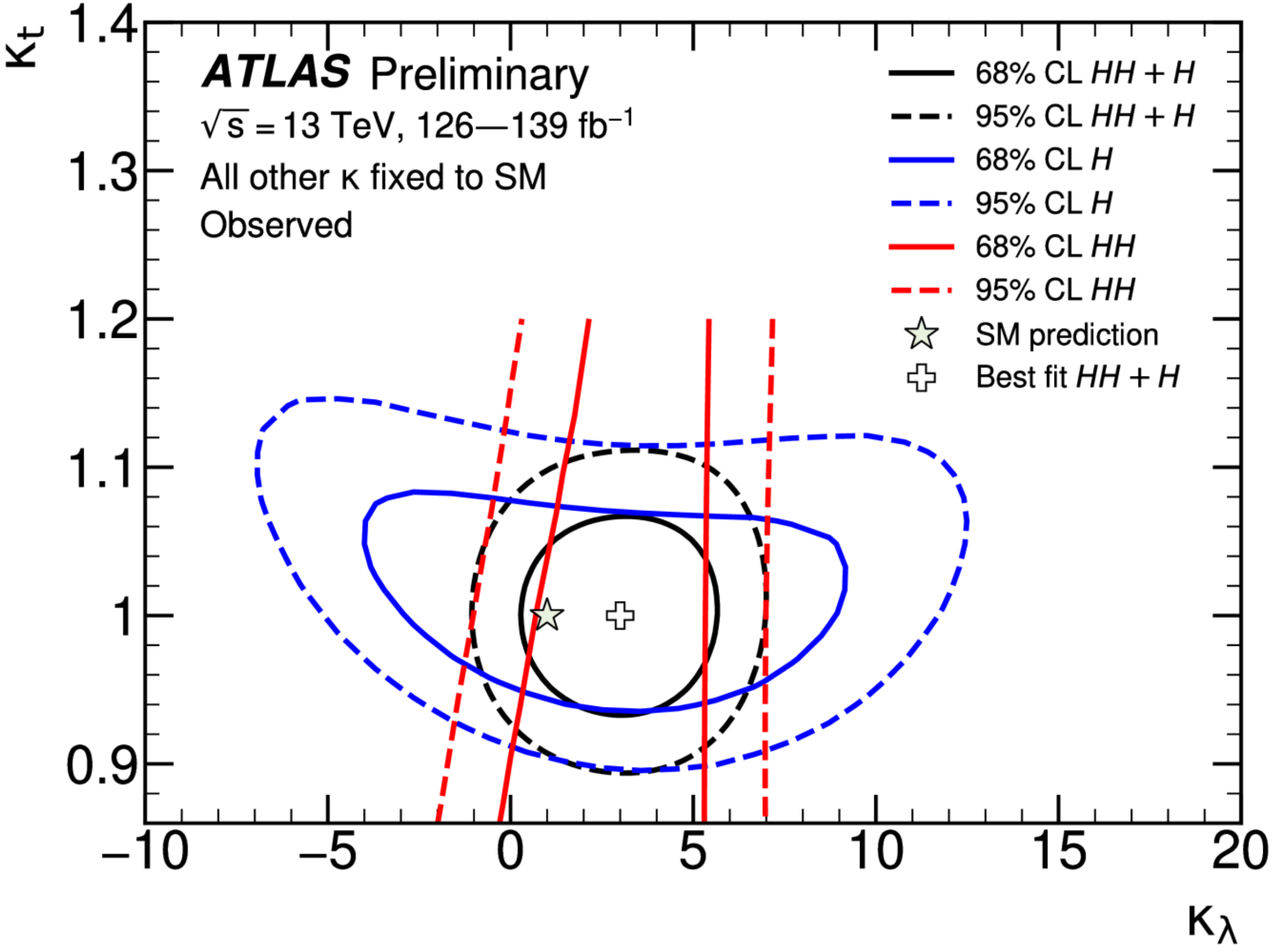
Use all single Higgs results:

- fix coupling parameters as the SM,
- allowing to float k_λ and k_t

Nature (2022)



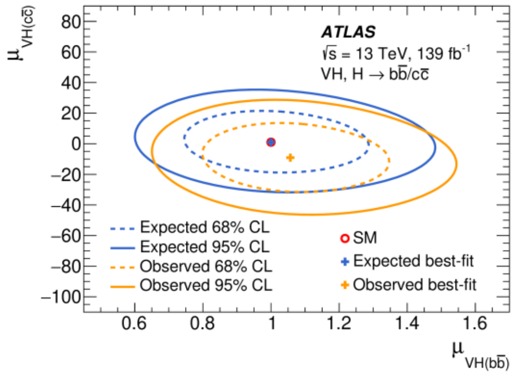


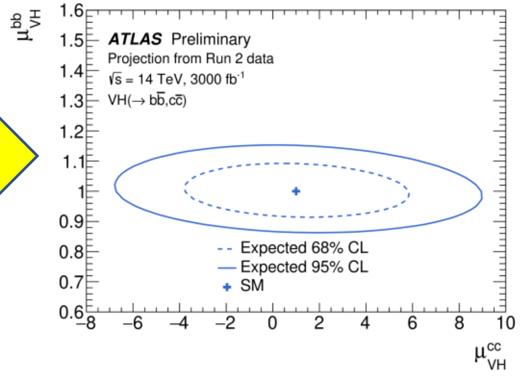


HH search (direct) does not limit k_t while single H does.

Prospect to HL-LHC

RUN2 **HL-LHC projection**





~ x3 better precision @3000fb^{-1}

RUN2	HL-LHC
$\|k_c\| < 12.4$	$\|k_c\| < 3.0$
$-1.2 < k_\lambda < 7.2$	$2.0 < k_\lambda < 4.1$

(%) HH->bbbb is not included for HL-LHC.

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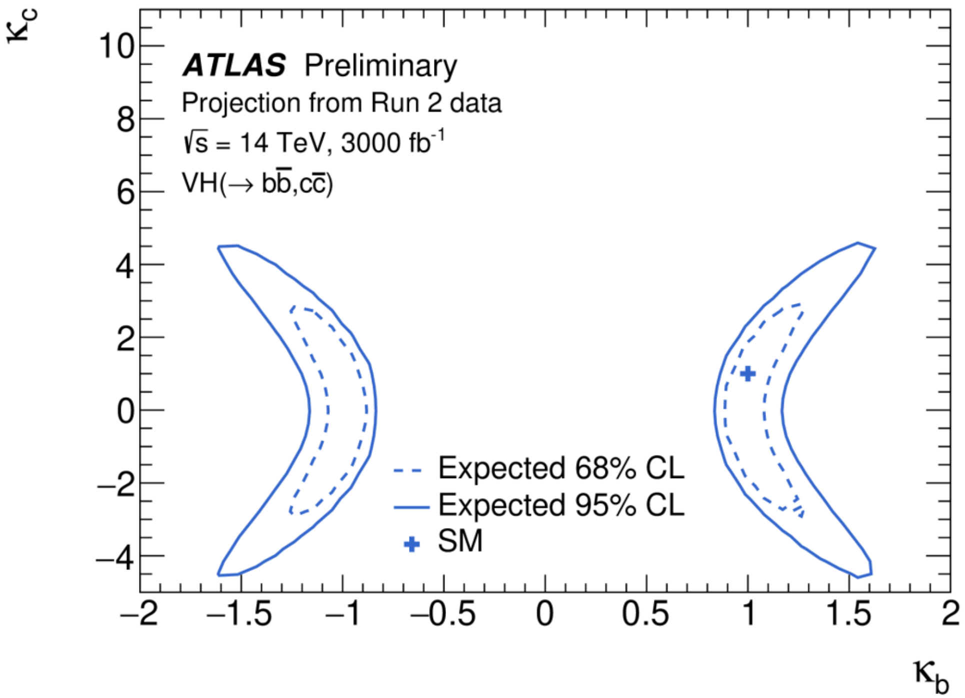
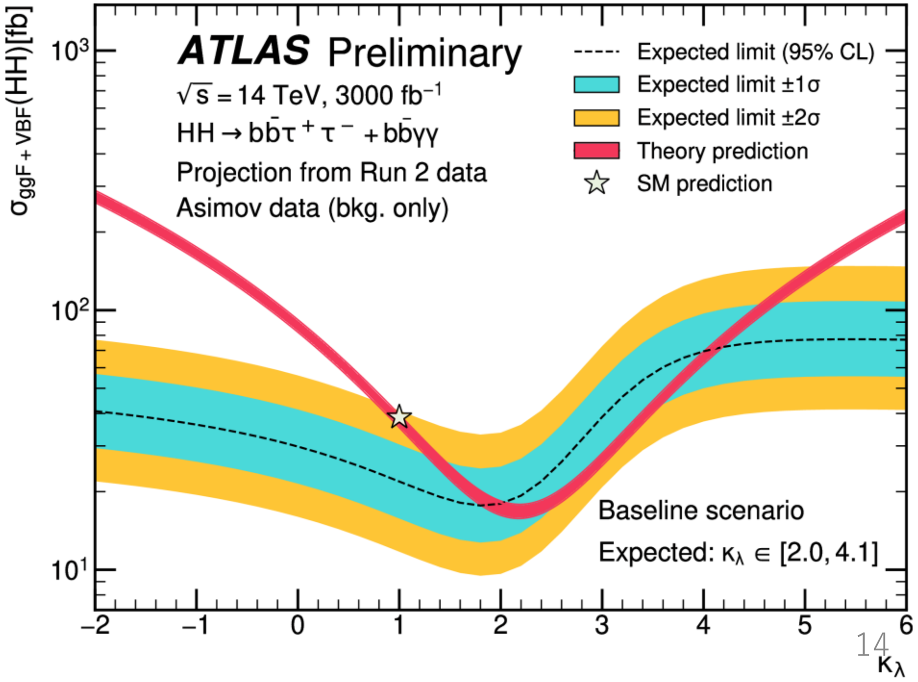




Summary

Coupling measurements with 2nd generation is the major milestone for RUN3 and HL-LHC.

Self-coupling is the ultimate goal for HL-LHC.

Many results were updated with full RUN2 dataset ($140fb^{-1}$).

Both direct and indirect measurements strongly constraint the coupling strength.

So far, limits are set x5-10 of SM prediction. **HOWEVER…**

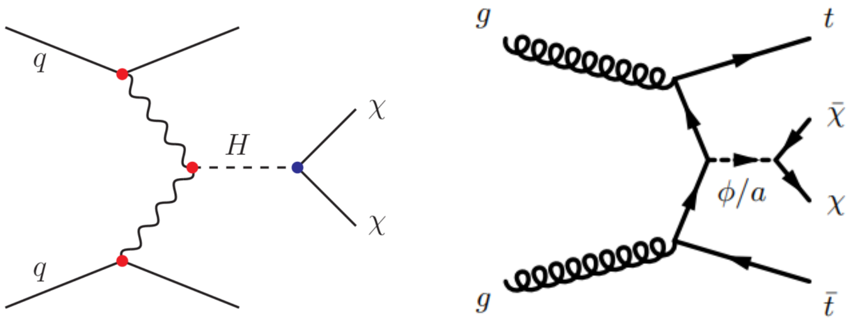
Should expect further improvements for future.

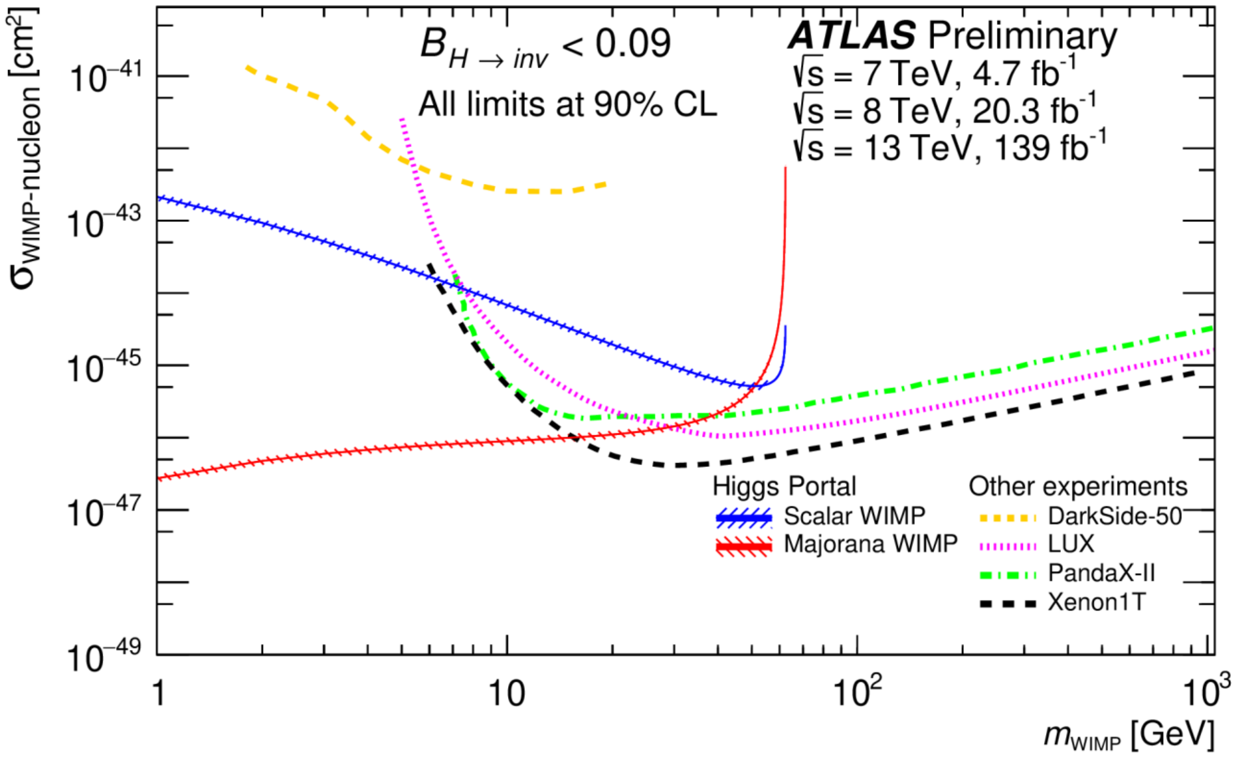
Backup

Dark matter interpretation

Massive DM (< 0.5 m_H) must have a couple with Higgs boson in order to obtain their mass.

(Recall Higgs boson couples all particles.)





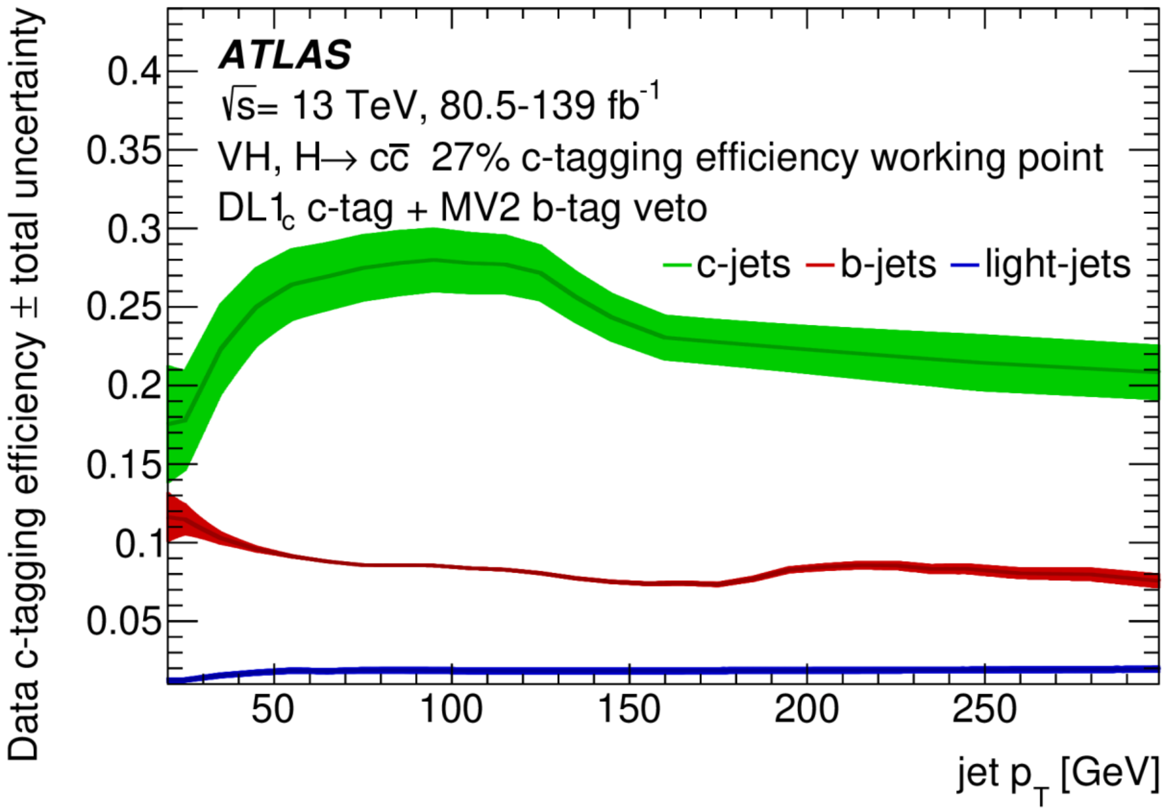
Many models predict DM, but H(X)->invisible is rather model independent approach.

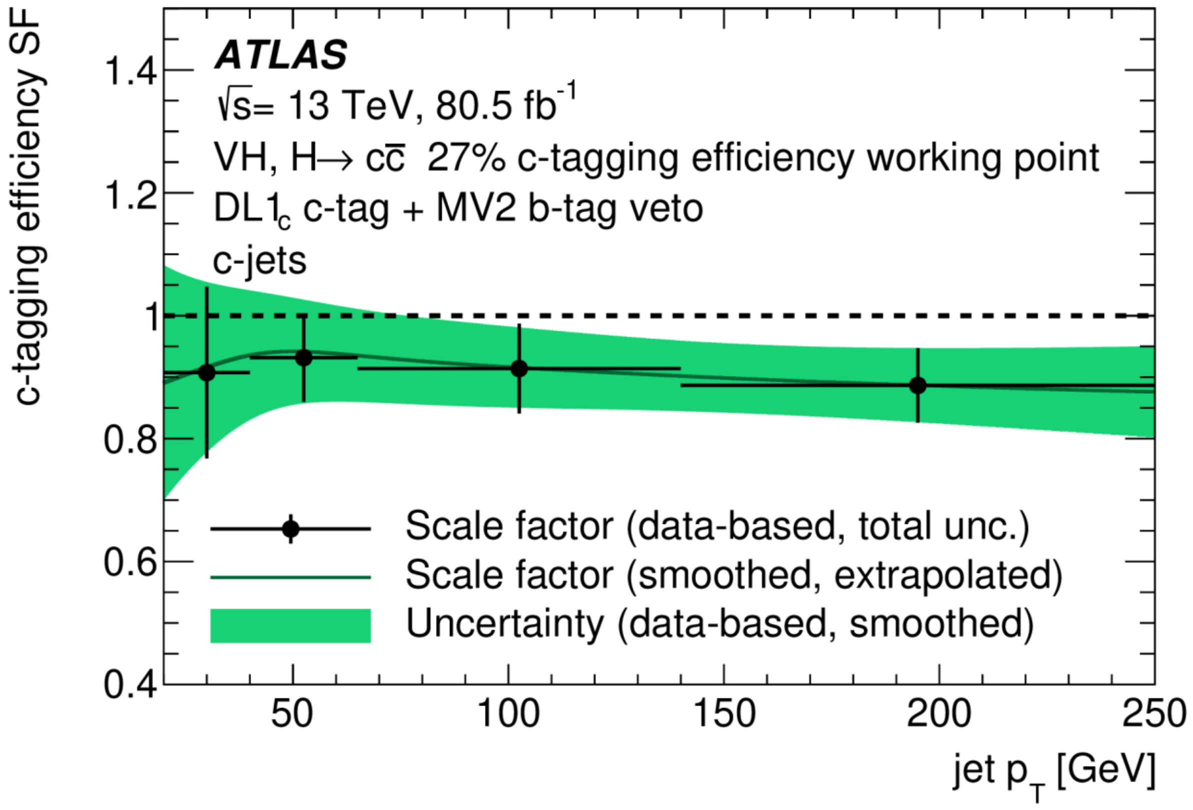
Recently, VBF-dedicated topology study is released: ***JHEP 08 (2022) 104***

Full combination with RUN1+2 gives Br_{inv} < 0.09 @95% CL

$$\kappa_H^2(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}}) = \frac{\sum_p B_p^{\text{SM}} \kappa_p^2}{(1 - B_{\text{inv.}} - B_{\text{u.}})}$$

Charm-tagging

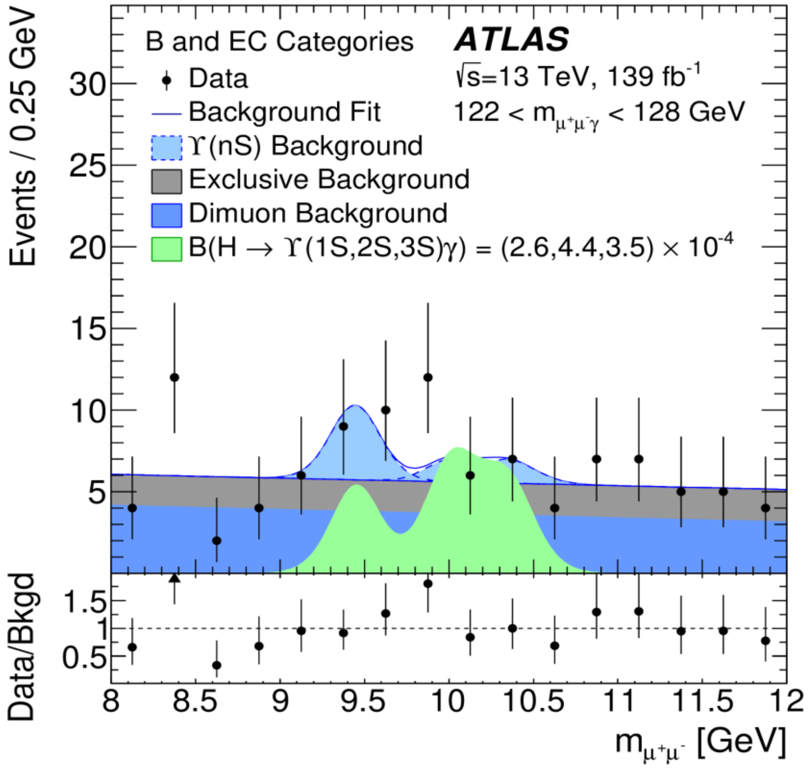


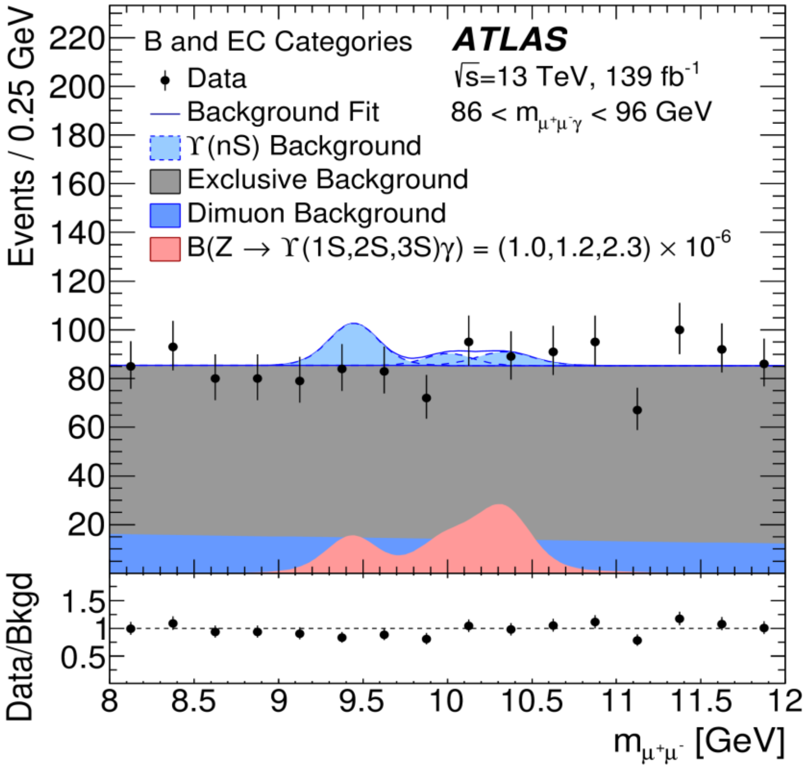


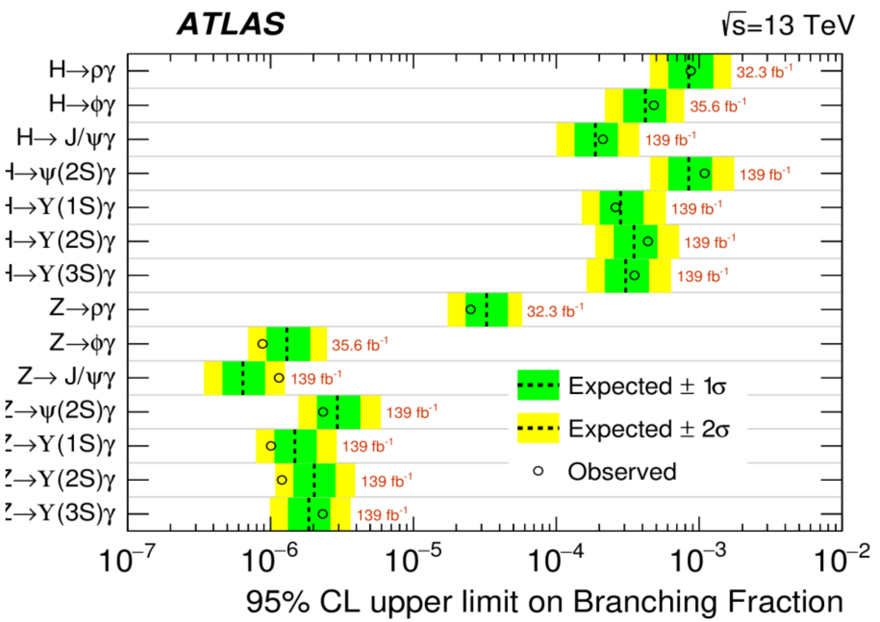
Systematics on H->cc

Source of uncertainty		$\mu_{VH(c\bar{c})}$	$\mu_{VW(cq)}$	$\mu_{VZ(c\bar{c})}$
Total		15.3	0.24	0.48
Statistical		10.0	0.11	0.32
Systematic		11.5	0.21	0.36
Statistical uncertainties				
Signal normalisation		7.8	0.05	0.23
Other normalisations		5.1	0.09	0.22
Theoretical and modelling uncertainties				
$VH(\rightarrow c\bar{c})$		2.1	< 0.01	0.01
$Z+$jets		7.0	0.05	0.17
Top quark		3.9	0.13	0.09
$W+$jets		3.0	0.05	0.11
Diboson		1.0	0.09	0.12
$VH(\rightarrow b\bar{b})$		0.8	< 0.01	0.01
Multi-jet		1.0	0.03	0.02
Simulation samples size		4.2	0.09	0.13
Experimental uncertainties				
Jets		2.8	0.06	0.13
Leptons		0.5	0.01	0.01
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.2	0.01	0.01
Pile-up and luminosity		0.3	0.01	0.01
Flavour tagging	c-jets	1.6	0.05	0.16
	b-jets	1.1	0.01	0.03
	light-jets	0.4	0.01	0.06
	τ-jets	0.3	0.01	0.04
Truth-flavour tagging	ΔR correction	3.3	0.03	0.10
	Residual non-closure	1.7	0.03	0.10

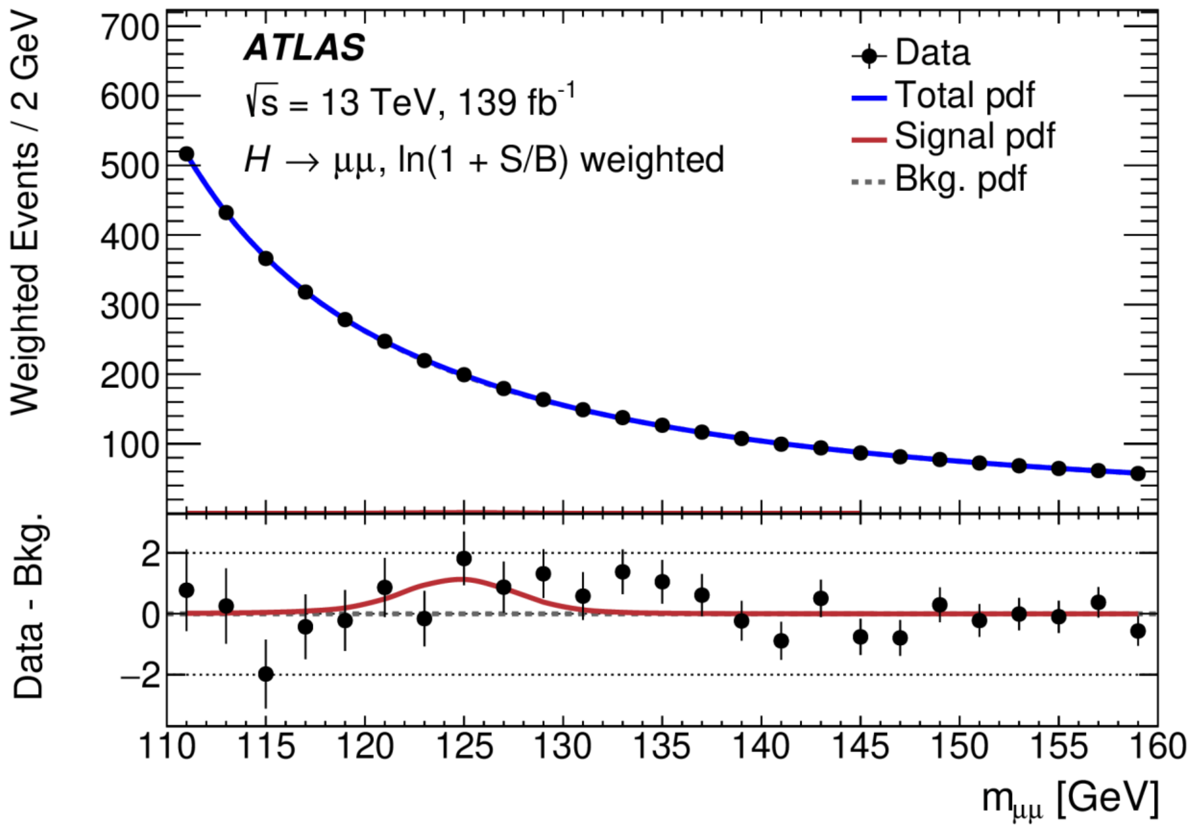
Rare decays

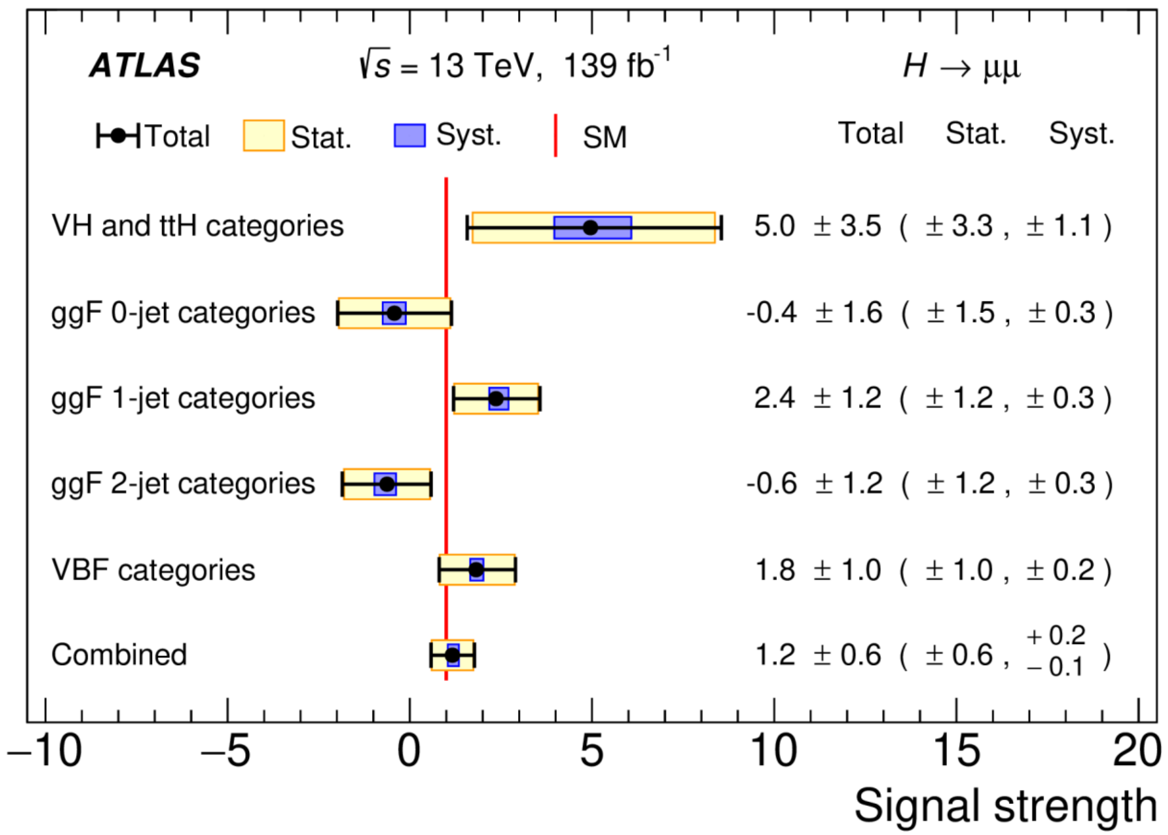

B and EC Categories
ATLAS
Data
$\sqrt{s}$=13 TeV, 139 fb^{-1}
Background Fit
122 < $m_{\mu^+\mu^-\gamma}$ < 128 GeV
Υ(nS) Background
Exclusive Background
Dimuon Background
B(H → Υ(1S,2S,3S)γ) = (2.6,4.4,3.5) × 10^{-4}
Events / 0.25 GeV
Data/Bkgd
$m_{\mu^+\mu^-}$ [GeV]


B and EC Categories
ATLAS
Data
$\sqrt{s}$=13 TeV, 139 fb^{-1}
Background Fit
86 < $m_{\mu^+\mu^-\gamma}$ < 96 GeV
Υ(nS) Background
Exclusive Background
Dimuon Background
B(Z → Υ(1S,2S,3S)γ) = (1.0,1.2,2.3) × 10^{-6}
Events / 0.25 GeV
Data/Bkgd
$m_{\mu^+\mu^-}$ [GeV]

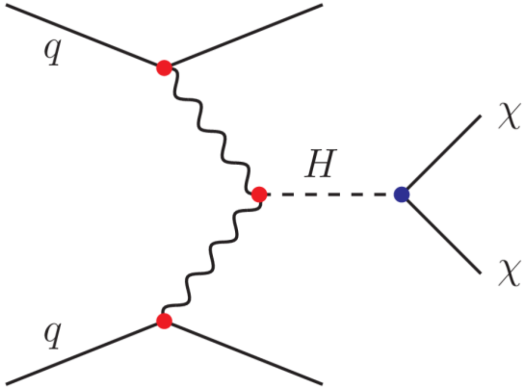

ATLAS
$\sqrt{s}$=13 TeV
H→ργ
H→φγ
H→ J/ψγ
H→ψ(2S)γ
H→Υ(1S)γ
H→Υ(2S)γ
H→Υ(3S)γ
Z→ργ
Z→φγ
Z→ J/ψγ
Z→ψ(2S)γ
Z→Υ(1S)γ
Z→Υ(2S)γ
Z→Υ(3S)γ
32.3 fb^{-1}
35.6 fb^{-1}
139 fb^{-1}
Expected ± 1σ
Expected ± 2σ
Observed
95% CL upper limit on Branching Fraction

H->μμ

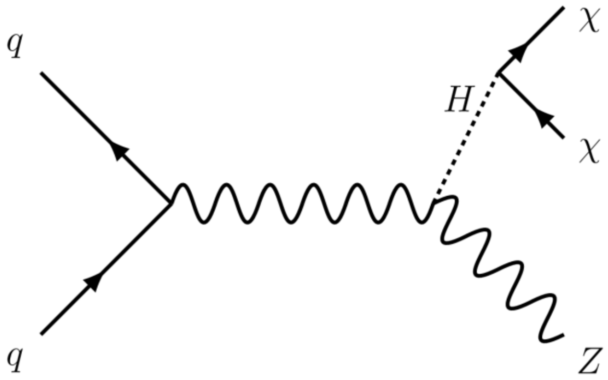

ATLAS
√s = 13 TeV, 139 fb-1
H → μμ, ln(1 + S/B) weighted
Data
Total pdf
Signal pdf
Bkg. pdf
Weighted Events / 2 GeV
Data - Bkg.
mμμ [GeV]


ATLAS
√s = 13 TeV, 139 fb-1
H → μμ
Total
Stat.
Syst.
SM
Total Stat. Syst.
VH and ttH categories 5.0 ± 3.5 (± 3.3 , ± 1.1)
ggF 0-jet categories -0.4 ± 1.6 (± 1.5 , ± 0.3)
ggF 1-jet categories 2.4 ± 1.2 (± 1.2 , ± 0.3)
ggF 2-jet categories -0.6 ± 1.2 (± 1.2 , ± 0.3)
VBF categories 1.8 ± 1.0 (± 1.0 , ± 0.2)
Combined 1.2 ± 0.6 (± 0.6 , +0.2 −0.1)
Signal strength

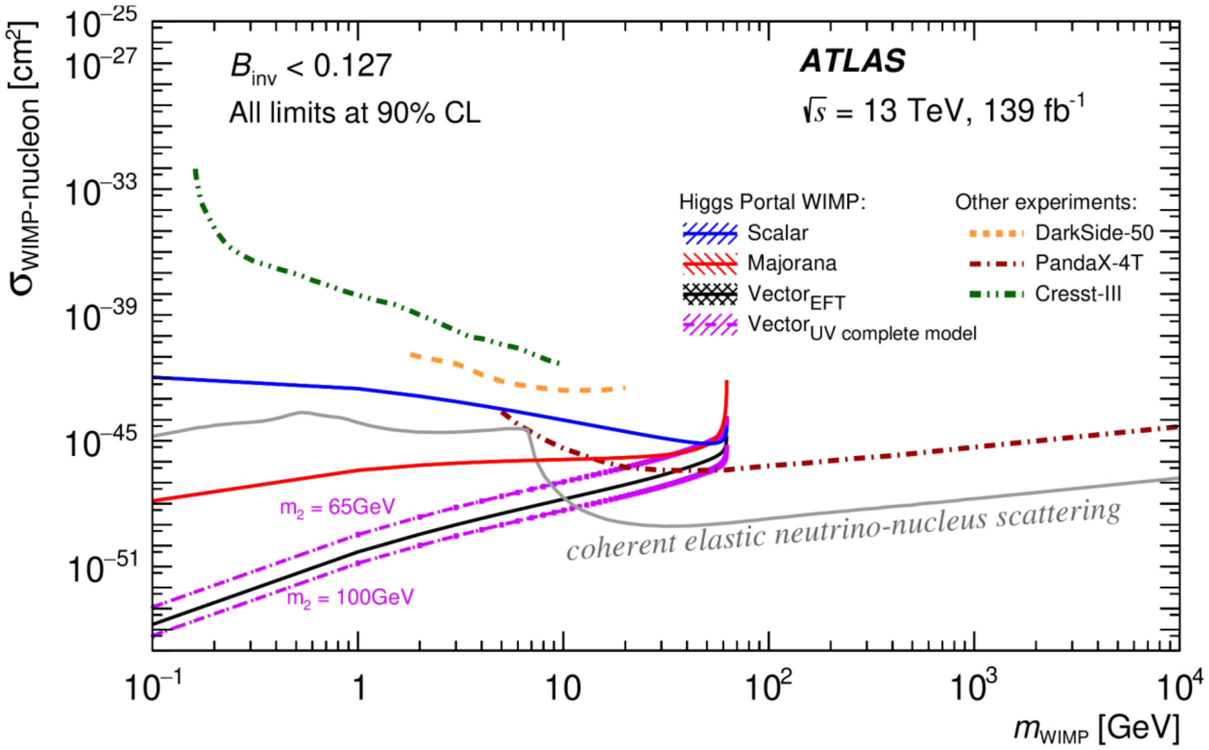
DM searches



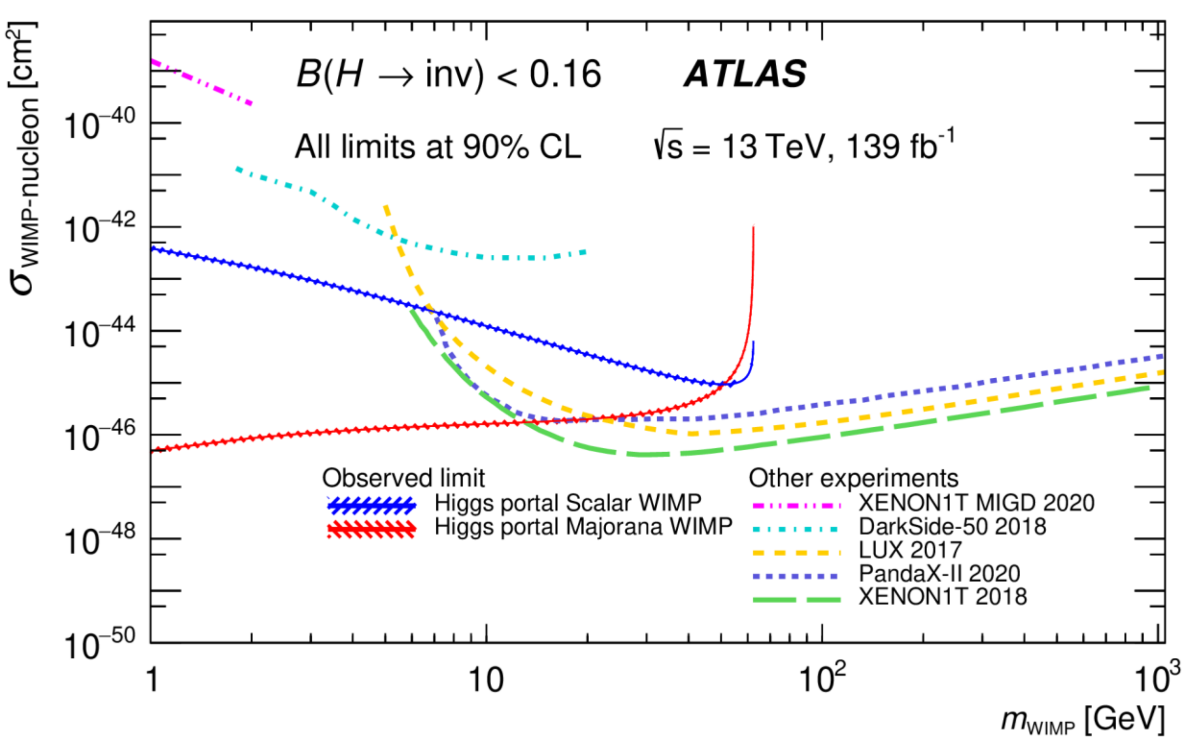
q
q
H
χ
χ



q
q
H
χ
χ
Z



$B_{\mathrm{inv}} < 0.127$
All limits at 90% CL
ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Higgs Portal WIMP:
Scalar
Majorana
Vector$_{\mathrm{EFT}}$
Vector$_{\mathrm{UV\ complete\ model}}$
Other experiments:
DarkSide-50
PandaX-4T
Cresst-III
m_2 = 65GeV
m_2 = 100GeV
coherent elastic neutrino-nucleus scattering
$\sigma_{\mathrm{WIMP\text{-}nucleon}}$ [cm^2]
m_{WIMP} [GeV]



$B(H \rightarrow \mathrm{inv}) < 0.16$
ATLAS
All limits at 90% CL
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Observed limit
Higgs portal Scalar WIMP
Higgs portal Majorana WIMP
Other experiments
XENON1T MIGD 2020
DarkSide-50 2018
LUX 2017
PandaX-II 2020
XENON1T 2018
$\sigma_{\mathrm{WIMP\text{-}nucleon}}$ [cm^2]
m_{WIMP} [GeV]

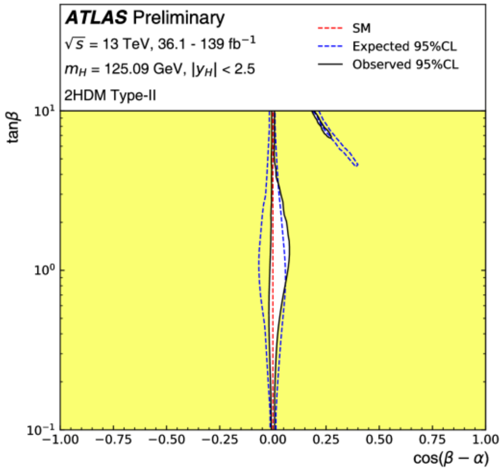
MSSM interpretation

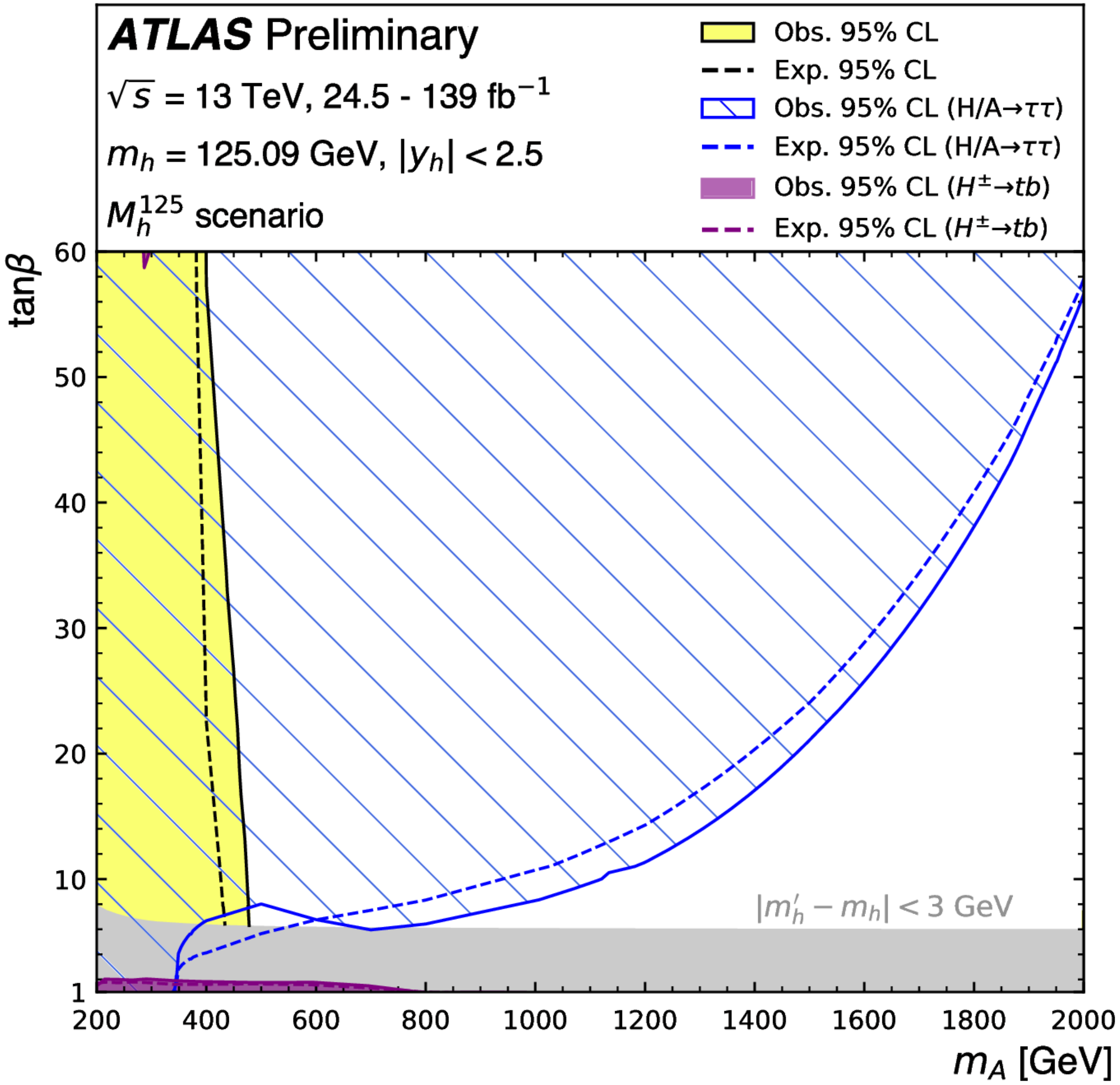
(minimal) 2HDM : 5 parameters

(m_h(125), m_A, m_H, α, β)

Decoupling limit ($\cos(\beta-\alpha)\sim0$, e.g. no mixing) seems current consensus.

- H/A->$\tau\tau$ search explores wide parameter space,
- Constraint from the SM H measurements provide absolute limits.





(%) m_h scenario: all SUSY particles are large enough.