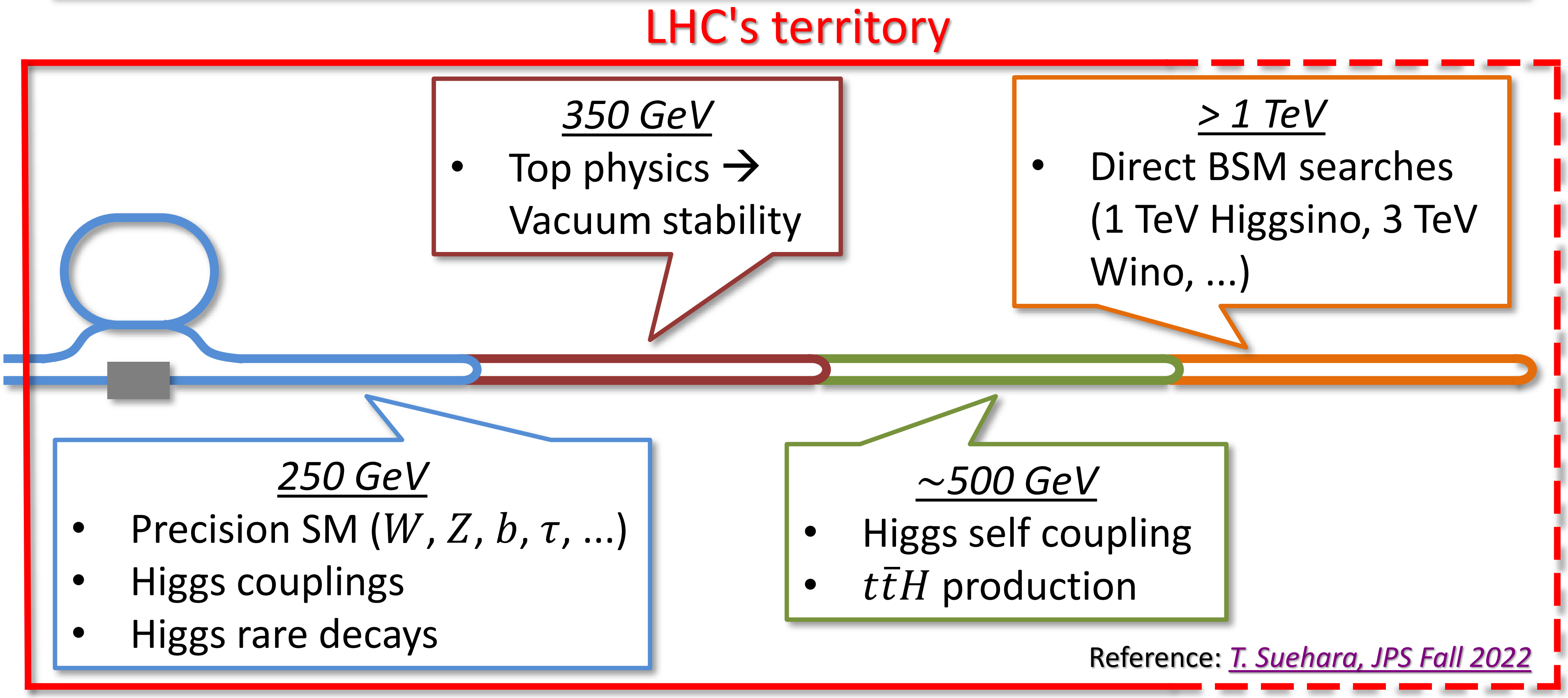
Recent results from LHC
(focusing on Higgs)
and synergy to Higgs Factories

25 November 2022, ILC-Japan Physics WG meeting

Shigeki Hirose (University of Tsukuba)

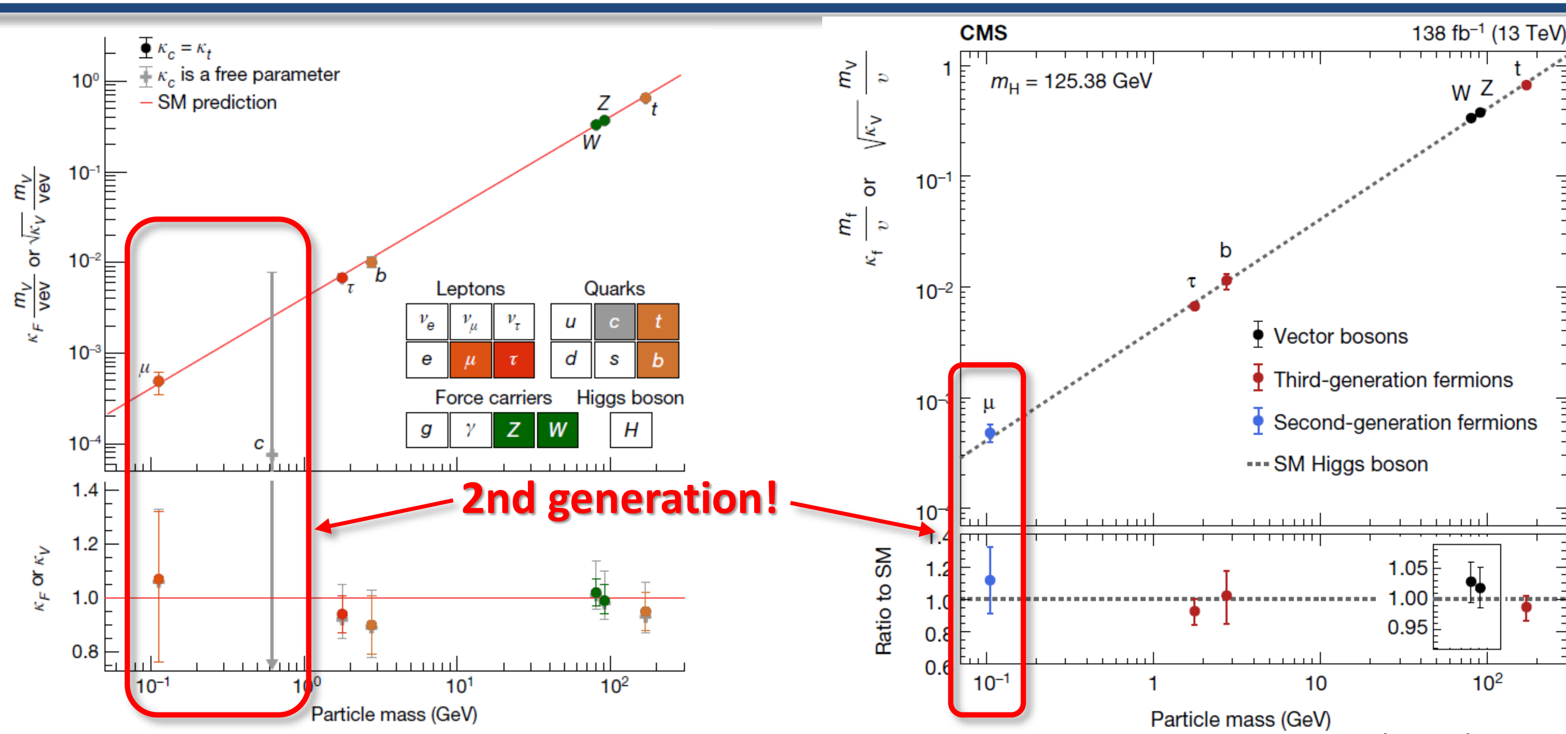
■ LHC and ILC



- ILC can realise precision measurements, but needs extension to reach higher energy processes
- LHC can cover wider range (depending on parton distribution), but large theory uncertainties and QCD background in general

<u>Interplay between (HL-)LHC and ILC is important!</u>

Recent Higgs results



ATLAS, Nature 607, 52 (2022)

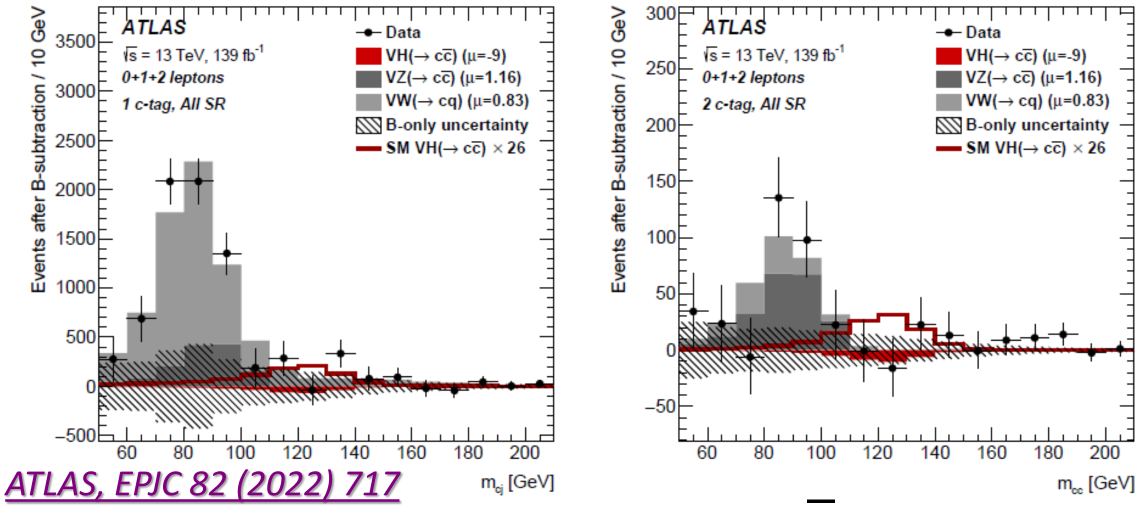
CMS, Nature 607, 60 (2022)

$\mu = 1.05 \pm 0.06$

$\mu = 1.002 \pm 0.057$

- Both experiments achieved the inclusive precision of 6%!
  - Entering the second generation (μ, c)
- Understanding of experimental / theoretical uncertainties are being more important

■ Recent developments of $H \to c\bar{c}$



ATLAS, EPJC 82 (2022) 717

- Similar analysis technique with $H \to b\bar{b}$
  - Use the VH production; existence of V suppresses QCD background
- Result: $\mu < 26$ obs. (< 31 exp.)
  - Significantly improved from the previous publication: $\mu < 110$ (150)
    - 3.9x more statistics
    - Better performance DNN-based c-tagging algorithm
    - Better c-tagging calibration, allowing to significantly reduce systematics

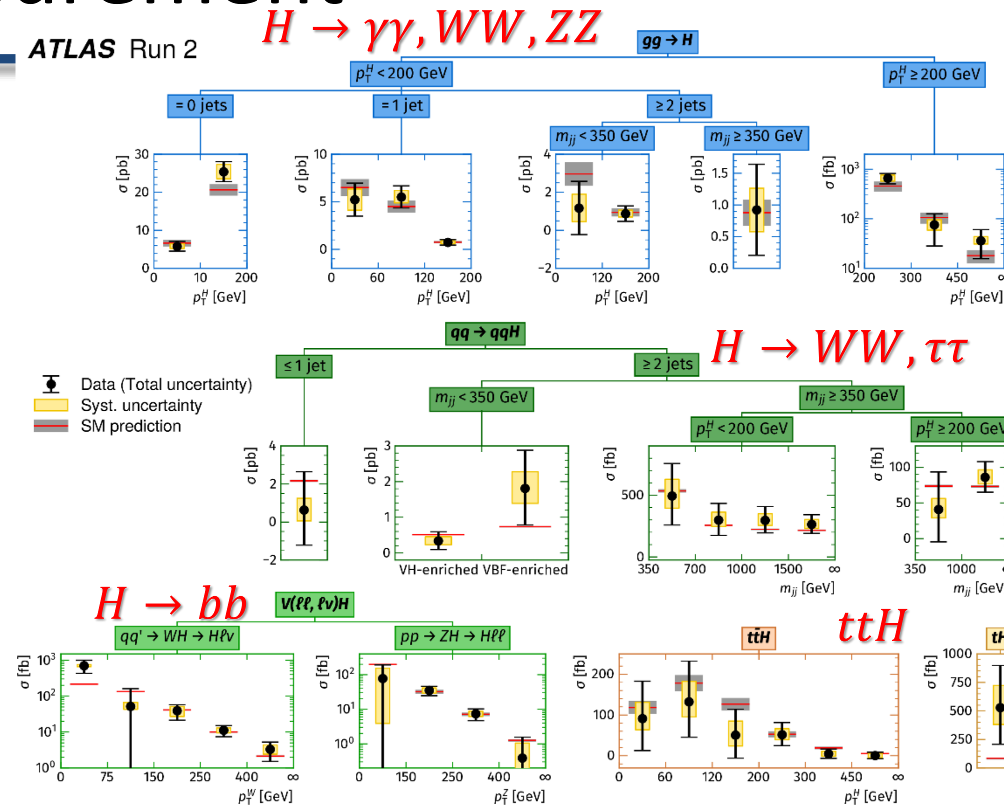
ATLAS, PRL 120 (2018) 211802

- CMS: $\mu < 14.4$ obs. ($\mu < 7.60$ exp.) CMS, arXiv:2205.05550 [accepted by PRL]
  - Good sensitivity thanks to the boosted SR

■ Differential measurement

[ATLAS, Nature 607, 52 (2022)](#)

- Differential measurements are more important
  - Simplified Template Cross Section (STXS) framework allows combinations from various measurements
  - Important to measure with as many different channels as possible
  - Precision of ∼20-100% is achieved



Main contributing channels are shown by red

- Genuine differential measurements beyond the STXS framework is also being attempted
  - $H \to \gamma\gamma$
  - $H \to ZZ^* \to 4\ell$
  - $H \to WW^*$
  - $H \to \tau\tau$

} [ATLAS-CONF-2021-053](#)

[Presented at Higgs 2022](#)
(CONF note coming soon)

Work In Progress

[CMS, arXiv:2208.12279](#)

[CMS-PAS-HIG-21-009](#)

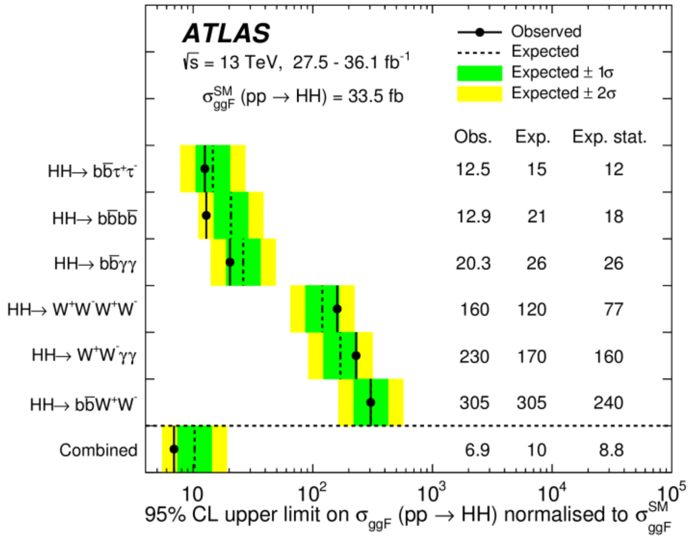
[CMS, JHEP 03 (2021) 003](#)

[CMS, PRL 128 (2022) 081805](#)

Higgs self-coupling

ATLAS, PLB 800 (2020) 135103

(Three years ago...)

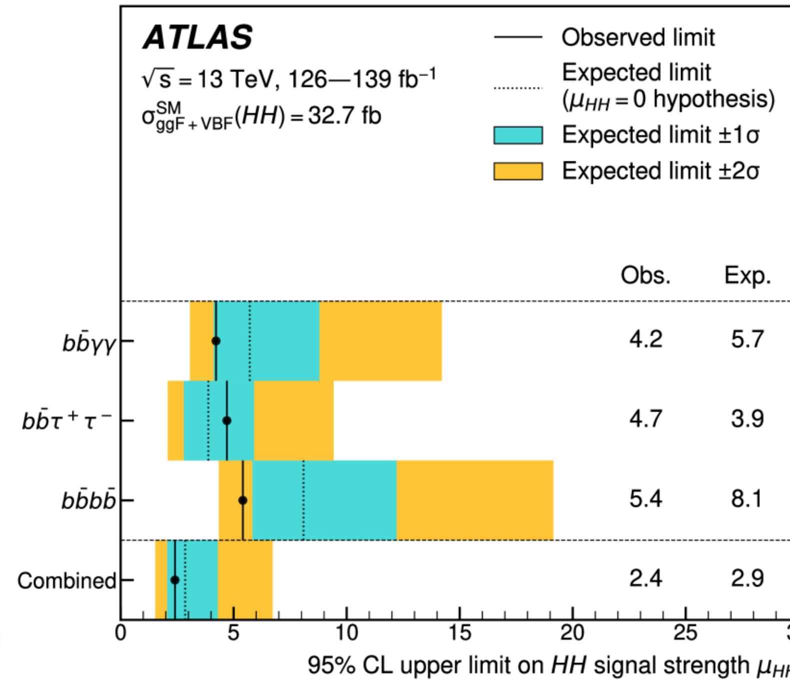


$\sigma/\sigma_{\rm SM}$ < 3.4 obs. (< 2.5 exp.)

-1.24 < κ_λ < 6.49

ATLAS, arXiv:2211.01216

(Now!)

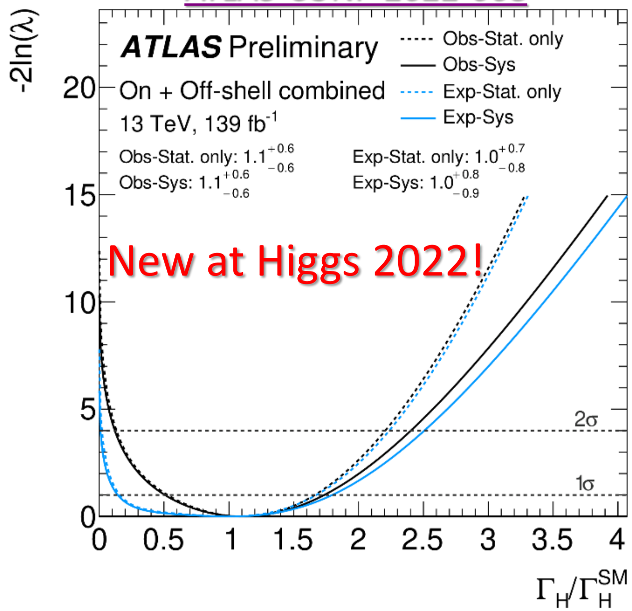


-0.4 < κ_λ < 6.3 at 95% CL

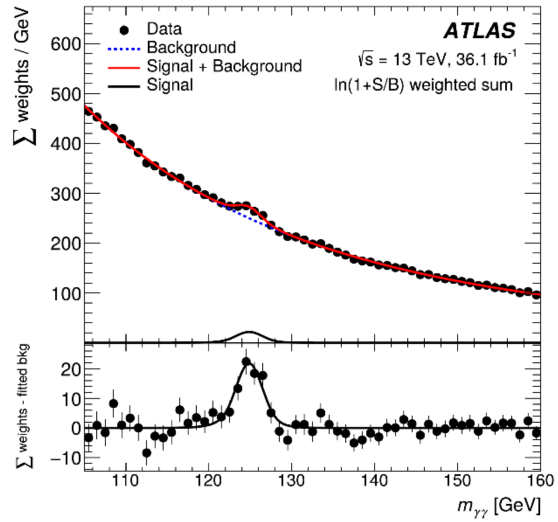
- All of the main channels are now (almost) complete
  - Significant improvements w.r.t. the previous publication!
    - From $\sigma/\sigma_{\rm SM}$ < 10 to < 2.9 (in expectations) with 3.9x more statistics
- CMS also shows good results

Other Higgs properties

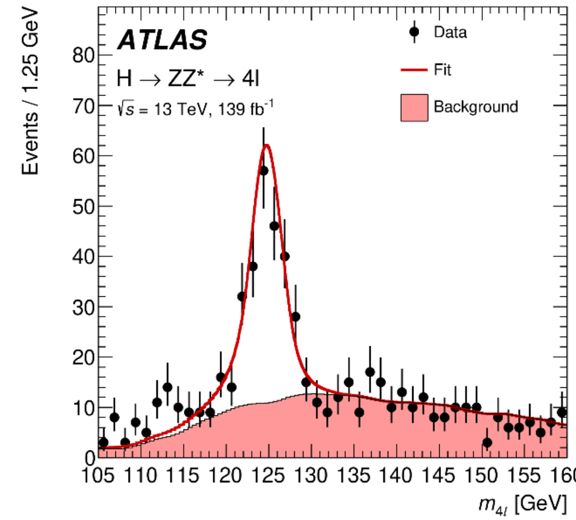
ATLAS-CONF-2022-068



ATLAS, PLB 784 (2018) 345



ATLAS, arXiv:2207.00320



$\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV

4ℓ: 124.92 $\pm$ 0.19 (stat) $^{+0.09}_{-0.06}$ (syst) GeV
$\gamma\gamma$: 124.93 $\pm$ 0.21 (stat) $\pm$ 0.34 (syst) GeV

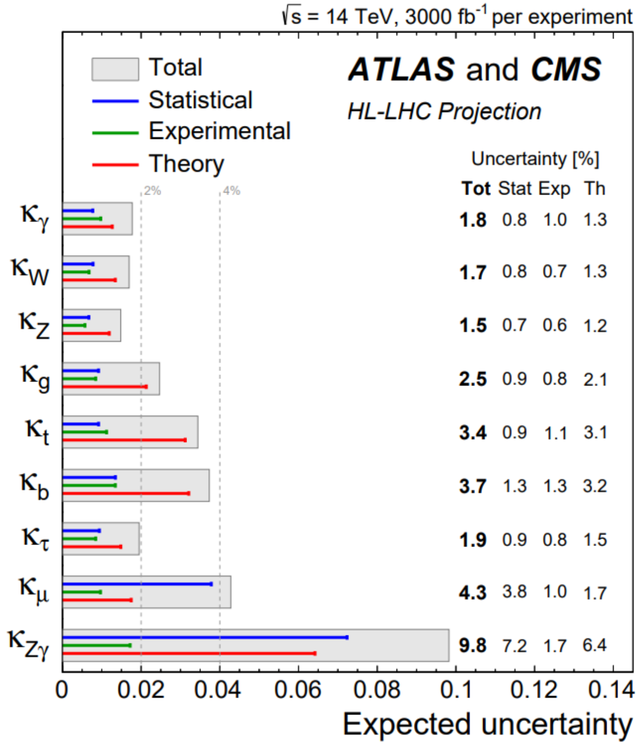
- Total decay width can be determined using off-shell $H^* \to ZZ$

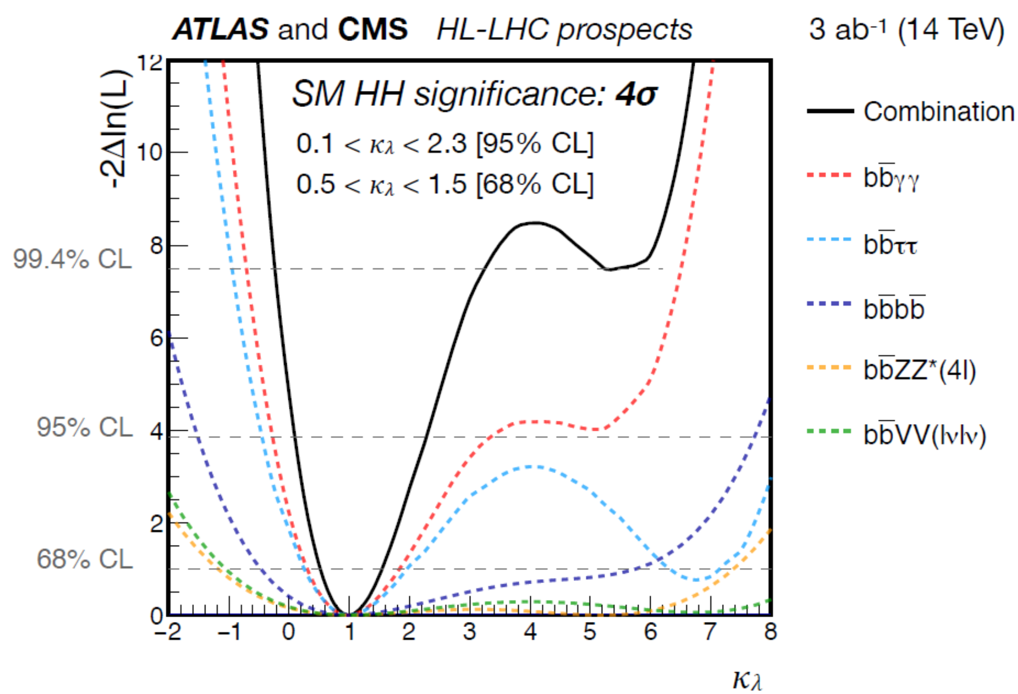
$$\mu_{\text{off-shell}}/\mu_{\text{on-shell}} = \Gamma_H/\Gamma_H^{\text{SM}}$$

- Mass: $H \to \gamma\gamma$ being dominated by systematics while $H \to ZZ^* \to 4\ell$ still statistically limited
- CP-odd/even mixing on Higgs couplings being probed

Projections to HL-LHC

CERN Yellow Report (2018)



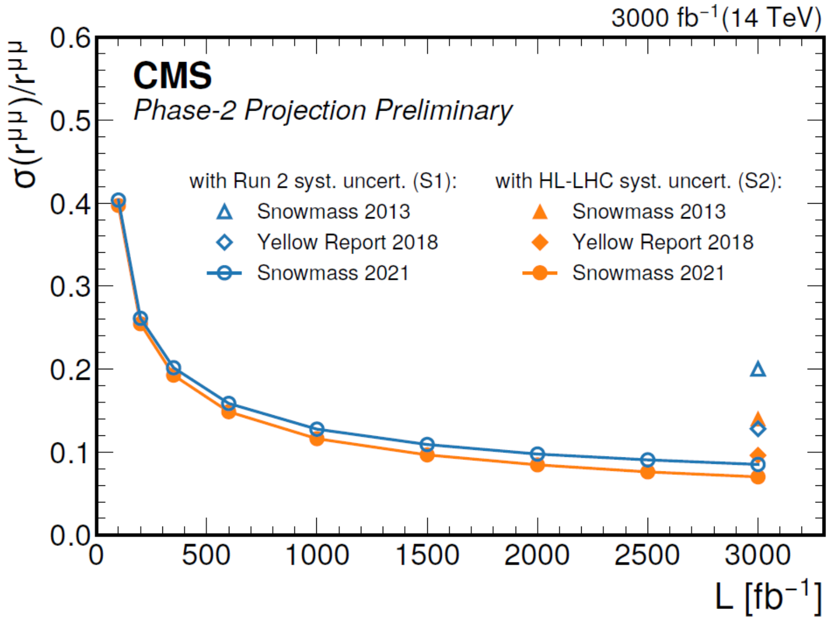


- Realistic prospects for HL-LHC is made based on the latest analysis techniques at Run 2
  - *Not* full simulations with upgraded detector geometries
  - Some assumptions in estimates of systematics
  - Various new updates in the past months for Snowmass 2022 process

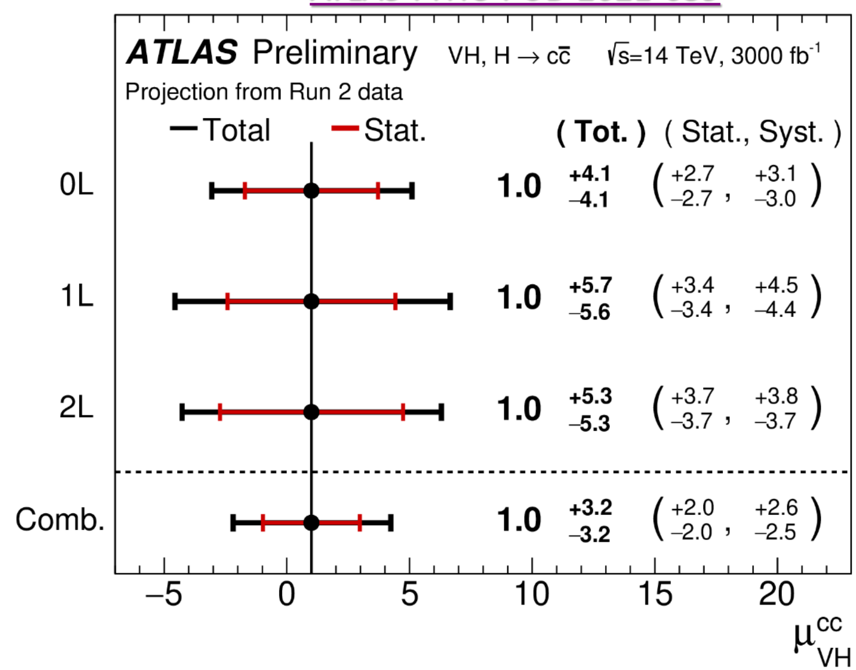
ATL-PHYS-PUB-2022-018

2nd generation fermions at HL-LHC

CMS-PAS-FTR-21-006



ATLAS-PHYS-PUB-2021-039



- $H \to \mu\mu$ projection by CMS
  - Included better tracking resolution and wider muon acceptance of the upgraded detector
- Direct $H \to c\bar{c}$ search included for the first time

	ATLAS	CMS
κ_μ	7.7% (7.7%)	3.5% (5.0%)
$\lvert\kappa_c\rvert$	< 3.0	< 3.4

→ ATLAS result not updated since YR18

→ $|\kappa_c|$ < 2.5-5.5 was estimated by theorists G. Perez et al., PRD 93, 013001 (2016)

Higgs self-coupling at HL-LHC

ATLAS EXPERIMENT

	2018 [1]	Latest (2022)
$HH \to b\bar{b}b\bar{b}$	0.61σ	1.0σ [4]
$HH \to b\bar{b}\tau\tau$	2.1σ	2.8σ [2]
$HH \to b\bar{b}\gamma\gamma$	2.0σ	2.2σ [3]
All combined	3.0σ	3.4σ [4]

[1] ATL-PHYS-PUB-2018-053
[2] ATL-PHYS-PUB-2021-044
[3] ATL-PHYS-PUB-2022-001
[4] ATL-PHYS-PUB-2022-053

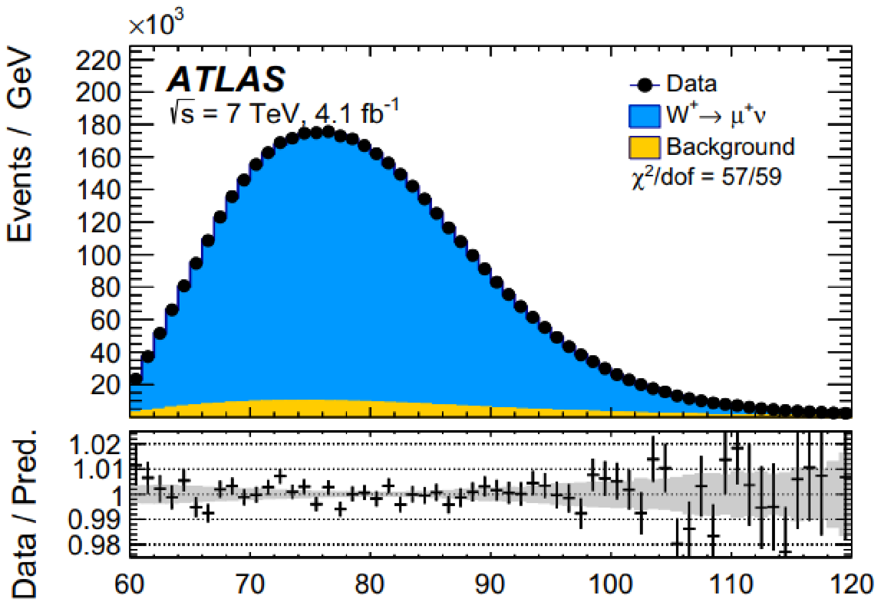
CMS

	2018 [1]	Latest (2022)
$HH \to b\bar{b}b\bar{b}$	0.95σ	
$HH \to b\bar{b}\tau\tau$	1.4σ	
$HH \to b\bar{b}\gamma\gamma$	1.8σ	2.16σ [2]
$HH \to b\bar{b}WW^*$	0.56σ	
$HH \to b\bar{b}ZZ^*$	0.37σ	
All combined	2.6σ	

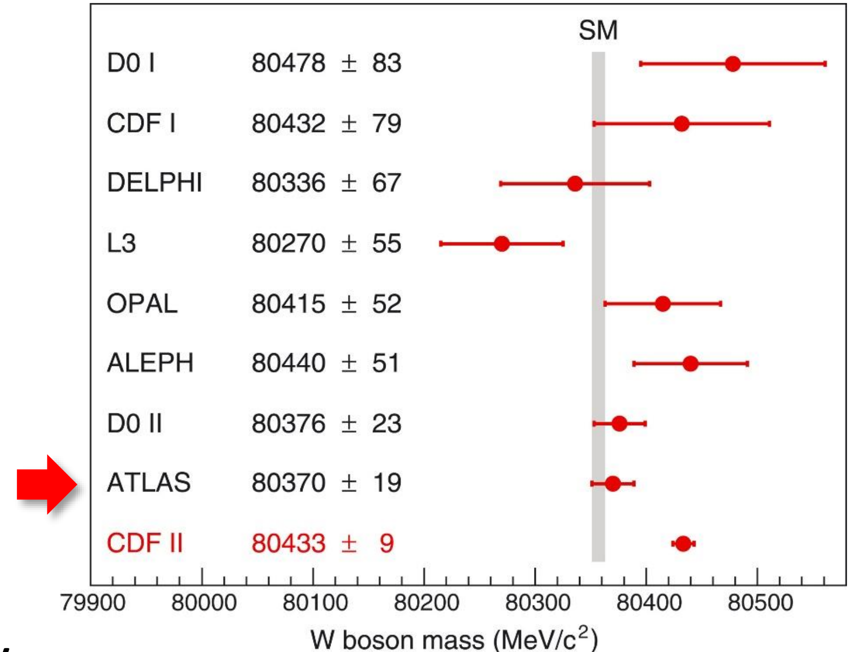
[1] CMS-FTR-18-019
[2] CMS-FTR-21-004

- Three main channels ($b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$) lead sensitivities
  - 4.0σ (0.52 < κ_λ < 1.5) was predicted for 3000 fb^{-1} in YR18
- Various improvements developed in full Run-2 analyses
  - N.B. current nominal luminosity for HL-LHC is 4000 fb^{-1}
    (Observation of the HH production probably achievable at HL-LHC?)

■ EW precision: W mass



[ATLAS, EPJC 78 (2018) 110]

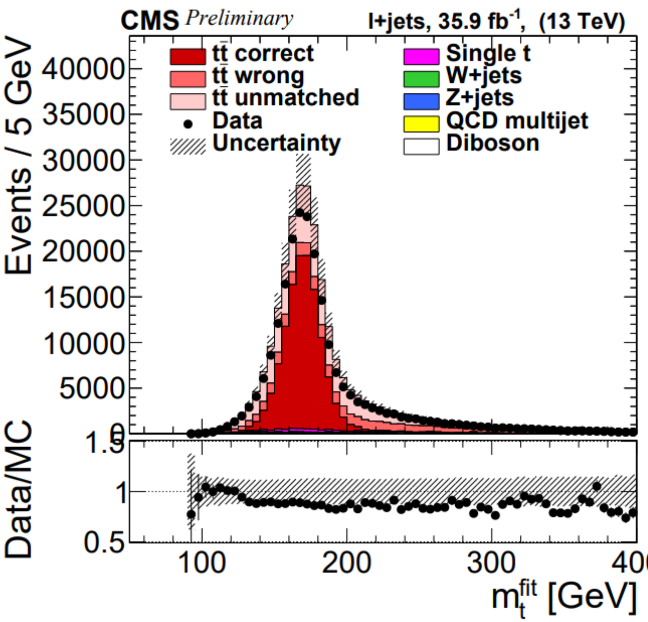


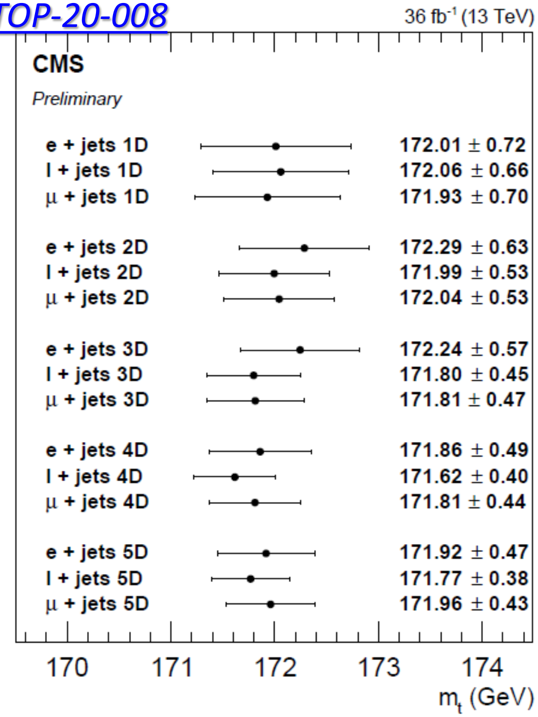
[CDF II, Science 376, 170 (2022)]

- ATLAS measured m_W at 7 TeV
  - Less advantageous w.r.t. Tevatron due to pp collisions and higher $\sqrt{s}$
  - χ^2 fit of the templates with changing shape as a function of m_W
  - Update with improved methods is work in progress
- Low pileup data were taken during Run 2
  - Need low pileup data to not degrade resolutions
  - 636 pb^{-1} data were collected at pileup $\sim$2

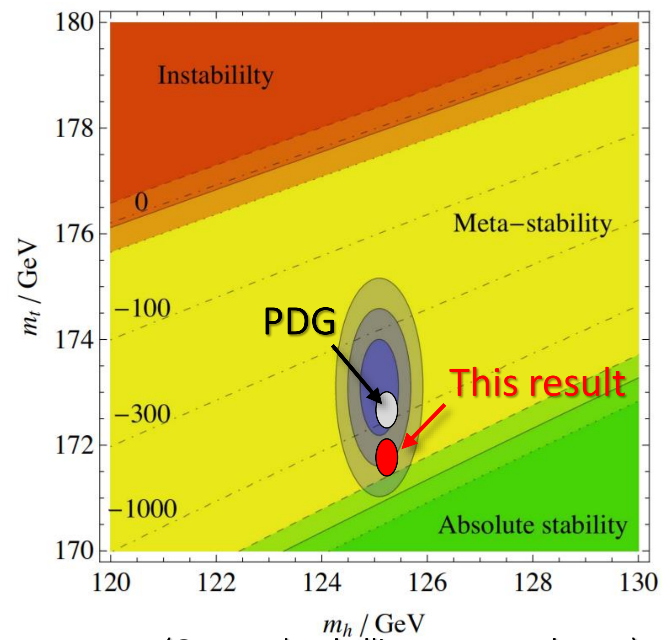
■ EW precision: top mass

CMS-PAS-TOP-20-008





S. Chigusa et al., PRD 97, 116012 (2018)



(Grey and red ellipses are put by me)

- Latest CMS results with the lepton+jet channel
  - Kinematic fit using the $m_t = m_{\bar{t}}$ to improve resolution
  - Five-dimensional fit to constrain systematics

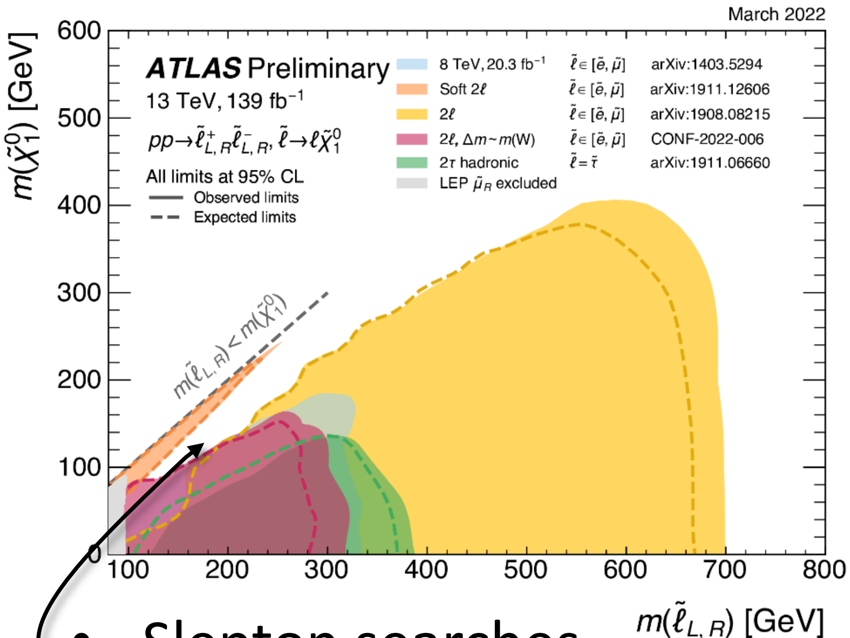
$$m_t = 171.77 \pm 0.04\ \text{(stat)} \pm 0.38\ \text{GeV}$$

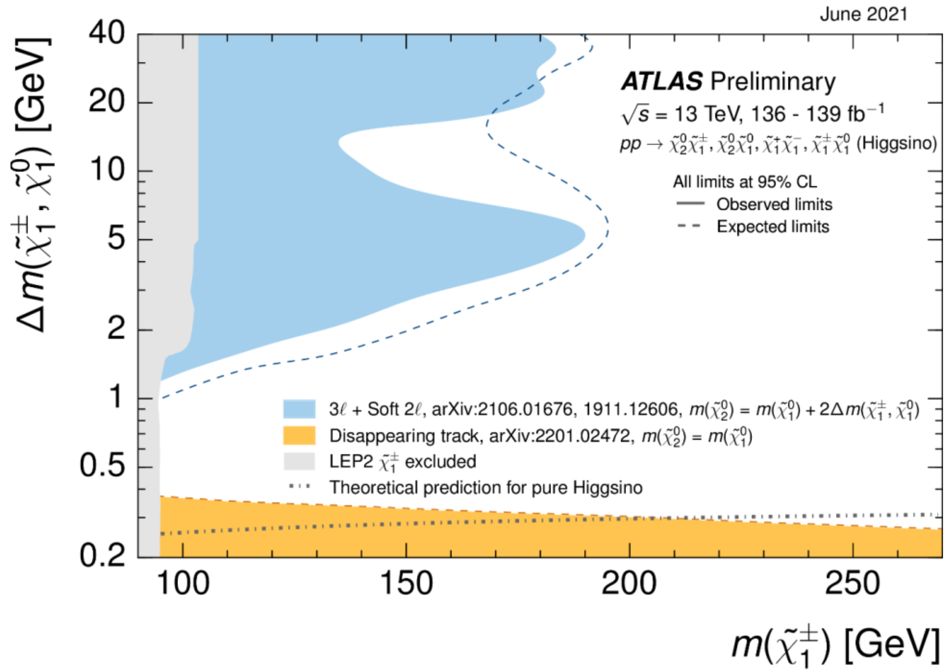
PDG: 172.69 ± 0.30 GeV

- Good precision is achieved; the value moved slightly towards Absolute Stability

EW SUSY

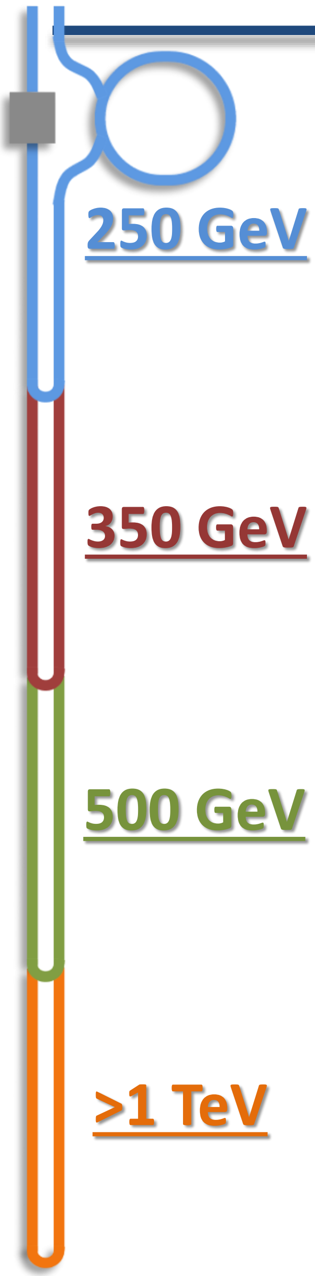
[ATL-PHYS-PUB-2022-013]





- Slepton searches
  - There is a gap at $m(\tilde{\ell}) - m(\tilde{\chi}_1^0)$~40 GeV due to similarity to SM WW; but this phase space is motivated by the $(g-2)_\mu$ anomaly
  - A dedicated analysis to tackle this region [ATLAS, arXiv:2209.13935]
- Higgsino searches
  - Intermediate region below $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0)$~1 GeV but still large enough to not be long-lived $\tilde{\chi}_1^\pm$

■ Synergy with ILC



Higgs properties

- **Coupling**: better precision expected in ILC if BR > O(1%)
  - HL-LHC has an advantage for $H \to \mu\mu$ and $H \to \gamma\gamma$ and $t\bar{t}H$ (w.r.t. ILC250)
- **Self-coupling:** HL-LHC important until ILC500 is realised
- **Decay width:** will be determined with ~20% precision at HL-LHC; will be drastically improved at ILC500 where WW fusion is usable (with model-independent method)
- **CP properties:** HL-LHC and ILC may complement measurements each other? Good statistics in HL-LHC, while cleaner environment in ILC

Top properties

- **Top mass:** precise measurements (~100 MeV or less?) by the $t\bar{t}$ threshold scan
  - HL-LHC prospect is ~200 MeV
- **Kinematic properties:** top quark dynamics can be probed using enormous $t\bar{t}$ events at HL-LHC: $O(10^9)$ with 4000 fb^{-1}

Heavy BSM searches

- **Strong production:** high statistics at HL-LHC may enable us to discover them (if within the range of HL-LHC)
- **EW production:** ILC>1000 may be possible to access O(TeV) BSM resonances, such as 1 TeV Higgsino?
  - ILC350-500 can already open new phase space w.r.t. HL-LHC?

N.B. various other topics (SM precision measurements, light resonance searches, ...) are of course important!

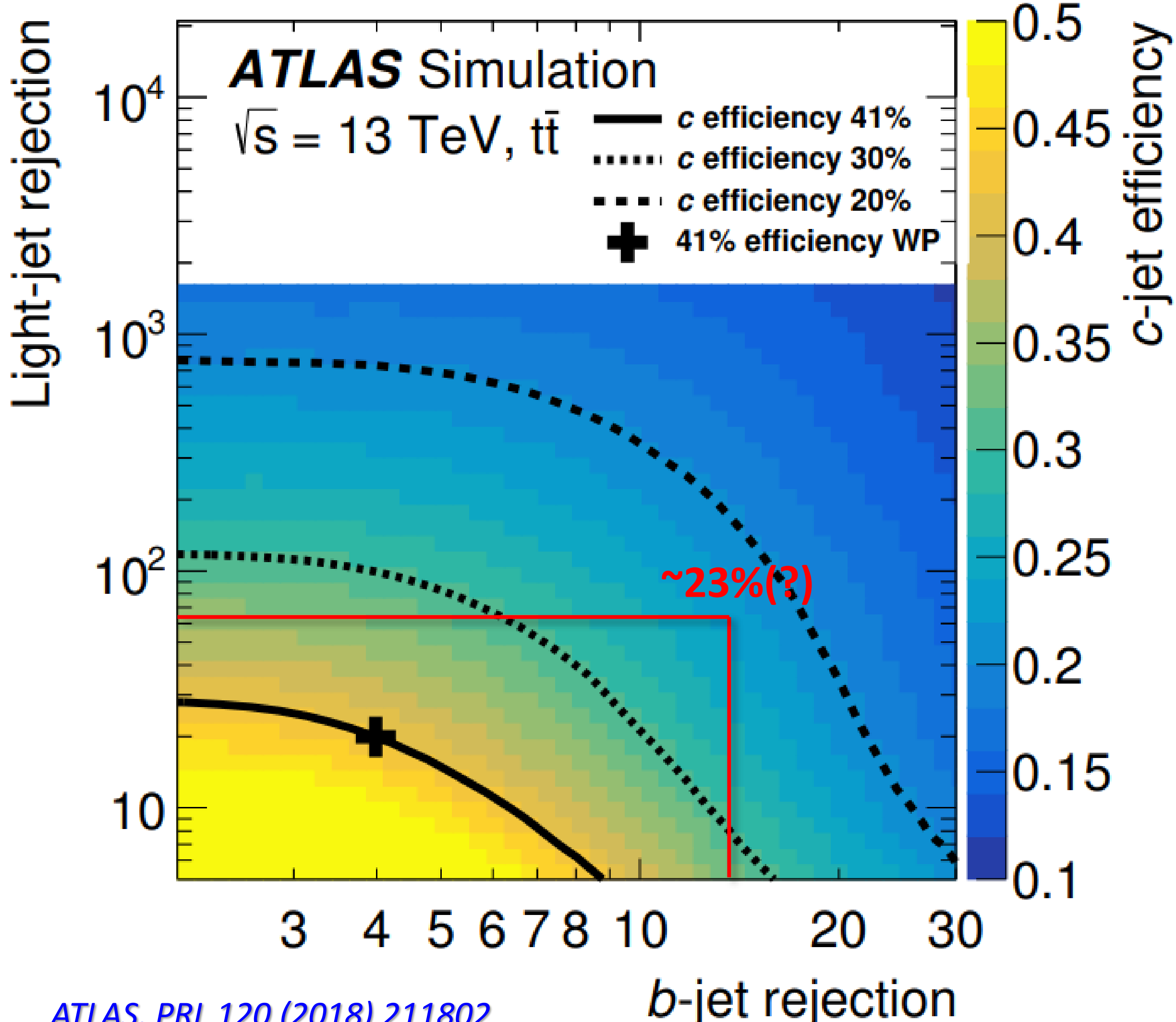
■ Summary

- Diverse physics programs are ongoing at LHC
  - The topics shown today are only tiny part of them
  - High mass resonance searches (heavy Higgs, SUSY, LQ, ...) are of course important (though not well covered today)
  - Statistics will be ~tripled by the end of Run 3 (139 fb^{-1} → 400 fb^{-1})

  → Physics at Run 3 must be very interesting!
- Projections to HL-LHC
  - Not only statistics, but also analysis techniques which are being improved
  - The prospect of σ_{HH} significance at HL-LHC was improved by >10% in four years
- Interplay with ILC will be more important at the HL-LHC era
  - Some processes are already being limited by theory systematics → ILC may reach better precisions than HL-LHC
  - If we see deviations from expectations, LHC can *directly* tackle possible BSM resonances

ATLAS c-tagging

- eff(c) = 27%



ATLAS, PRL 120 (2018) 211802

Hcc: systematics

ATLAS, PRL 120 (2018) 211802

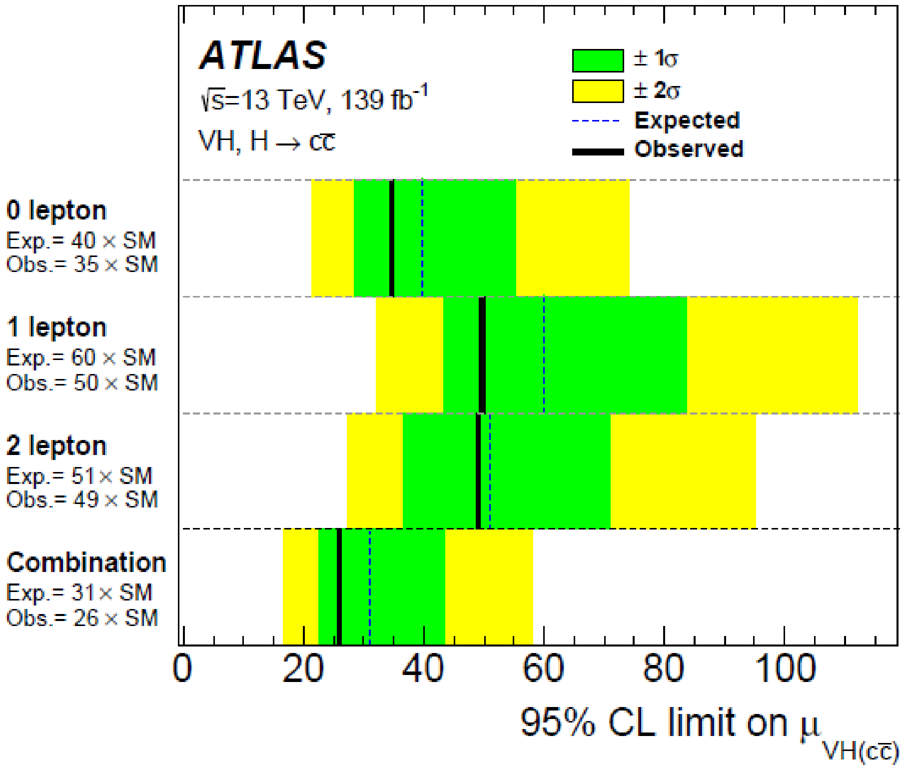
Source	σ/σ_{tot}
Statistical	**49%**
Floating Z + jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

ATLAS-PHYS-PUB-2021-039

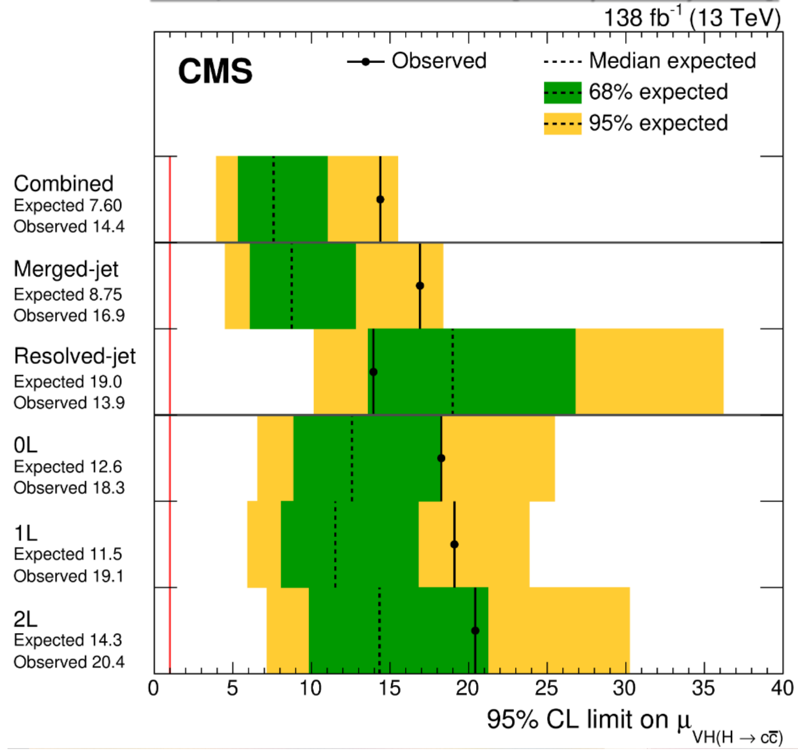
Source of uncertainty		$\mu_{VH(c\bar{c})}$	$\mu_{VW(cq)}$	$\mu_{VZ(c\bar{c})}$
Total		15.3	0.24	0.48
Statistical		10.0	0.11	0.32
Systematic		11.5	0.21	0.36
Statistical uncertainties				
Signal normalisation		7.8	0.05	0.23
Other normalisations		5.1	0.09	0.22
Theoretical and modelling uncertainties				
$VH(\to c\bar{c})$		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
$VH(\to b\bar{b})$		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_T^{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

VHcc: ATLAS vs CMS

ATLAS, EPJC 82 (2022) 717



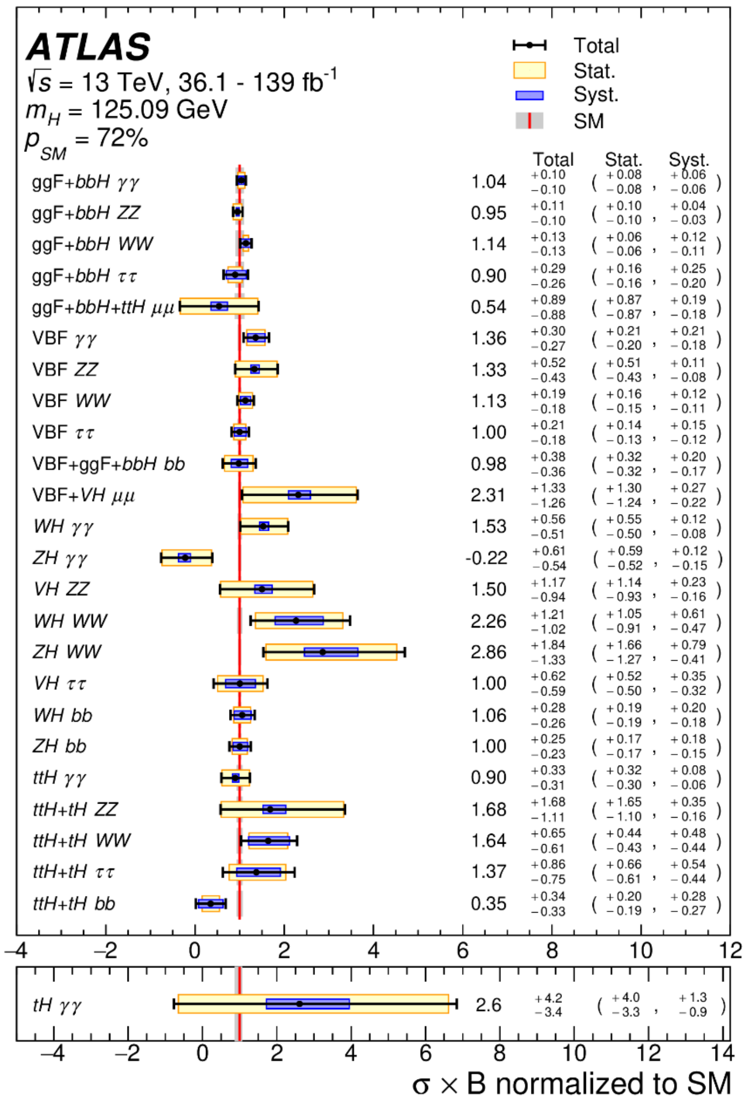
CMS, arXiv:2205.05550 [accepted by PRL]



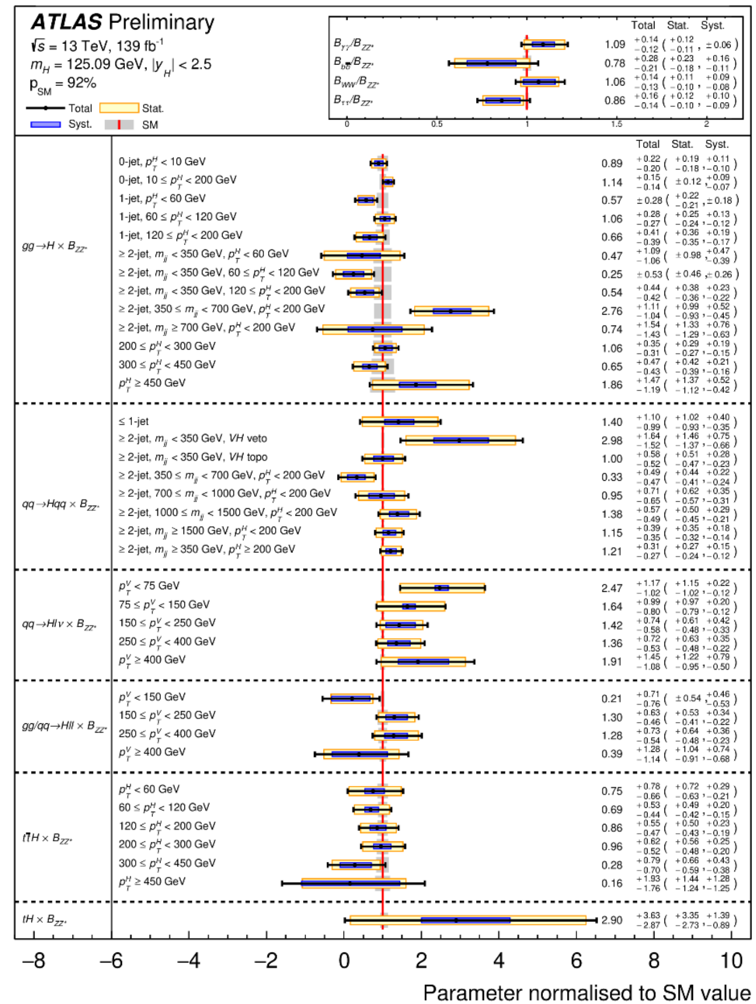
- CMS shows a better result
  - Boosted region plays a good job; probably thanks to good S/N though expected signals are small

■ STXS/differential

ATLAS, Nature 607, 52 (2022)

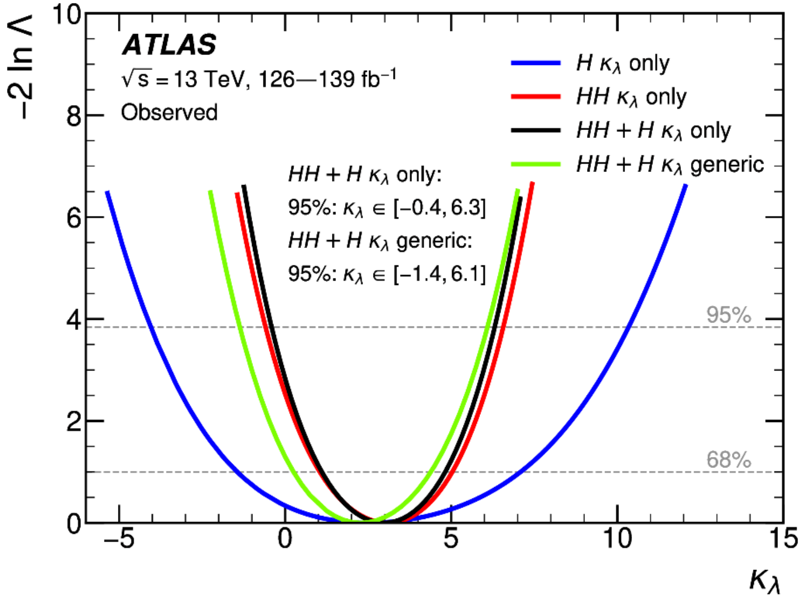


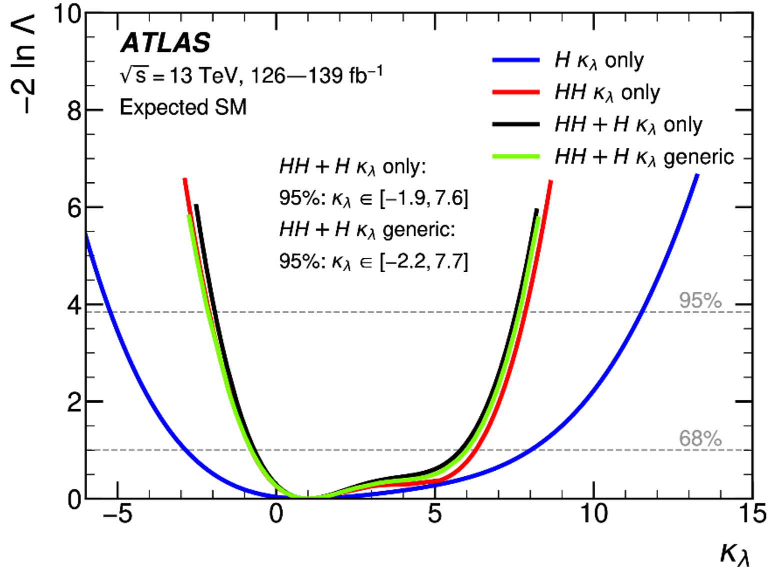
ATLAS, ATLAS-CONF-2021-053



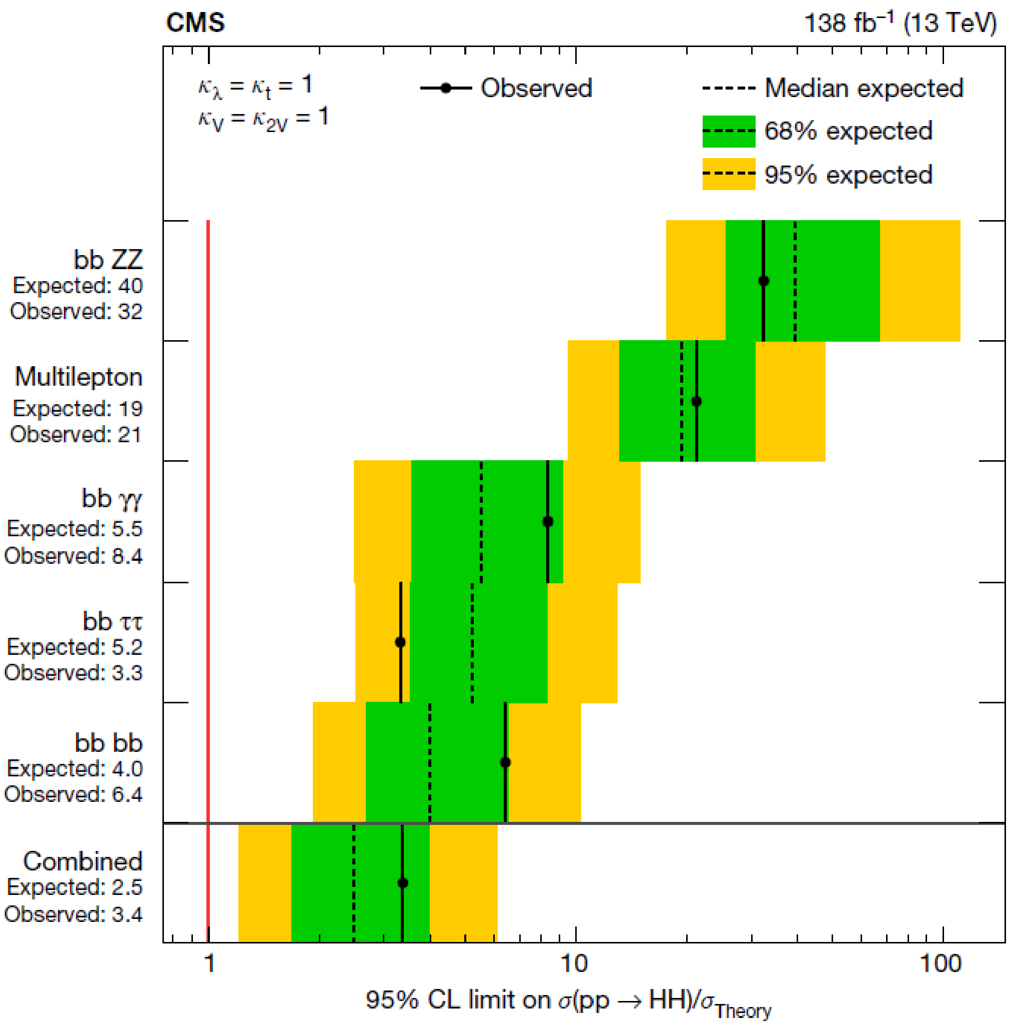
Contributions to κλ

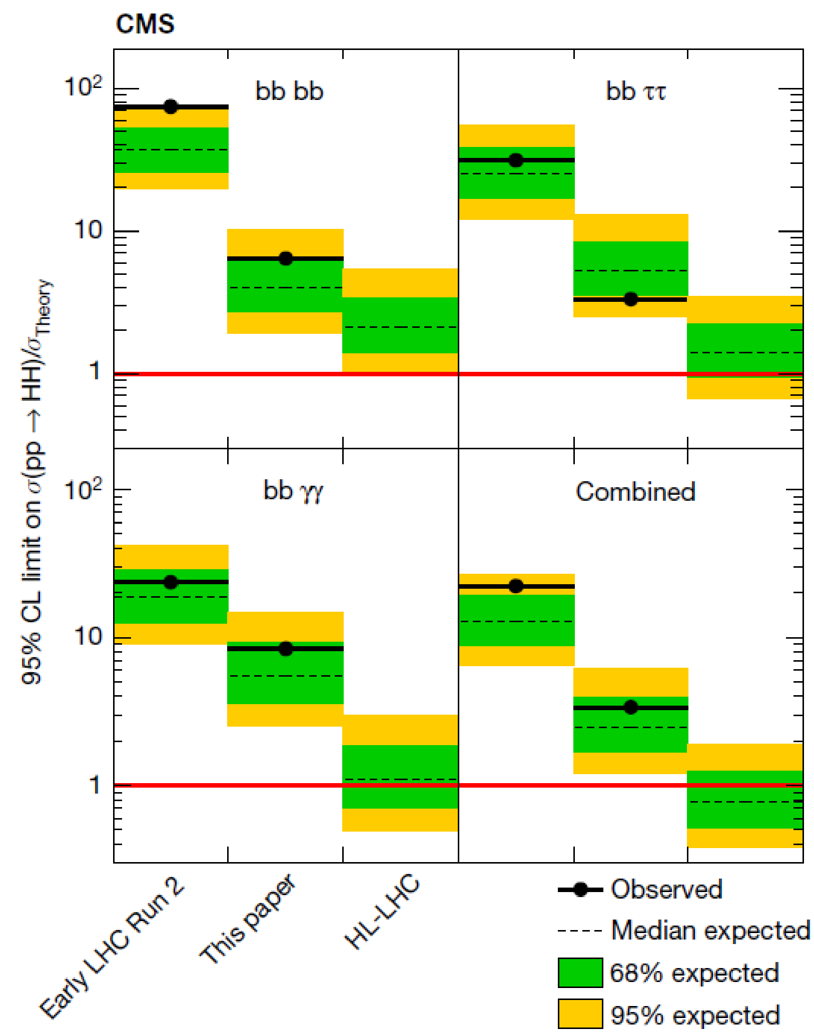
ATLAS, arXiv:2211.01216





HH search at CMS

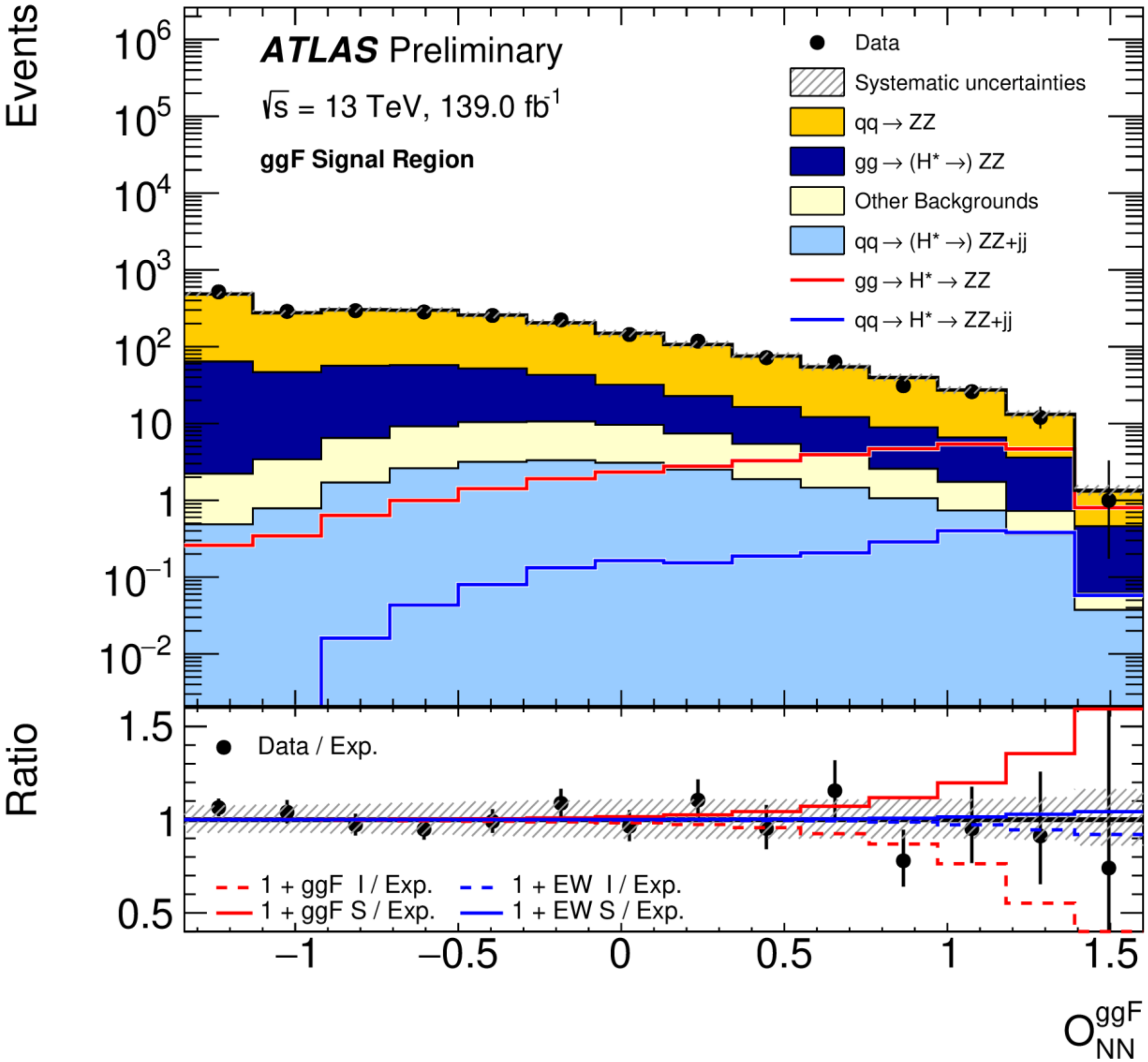


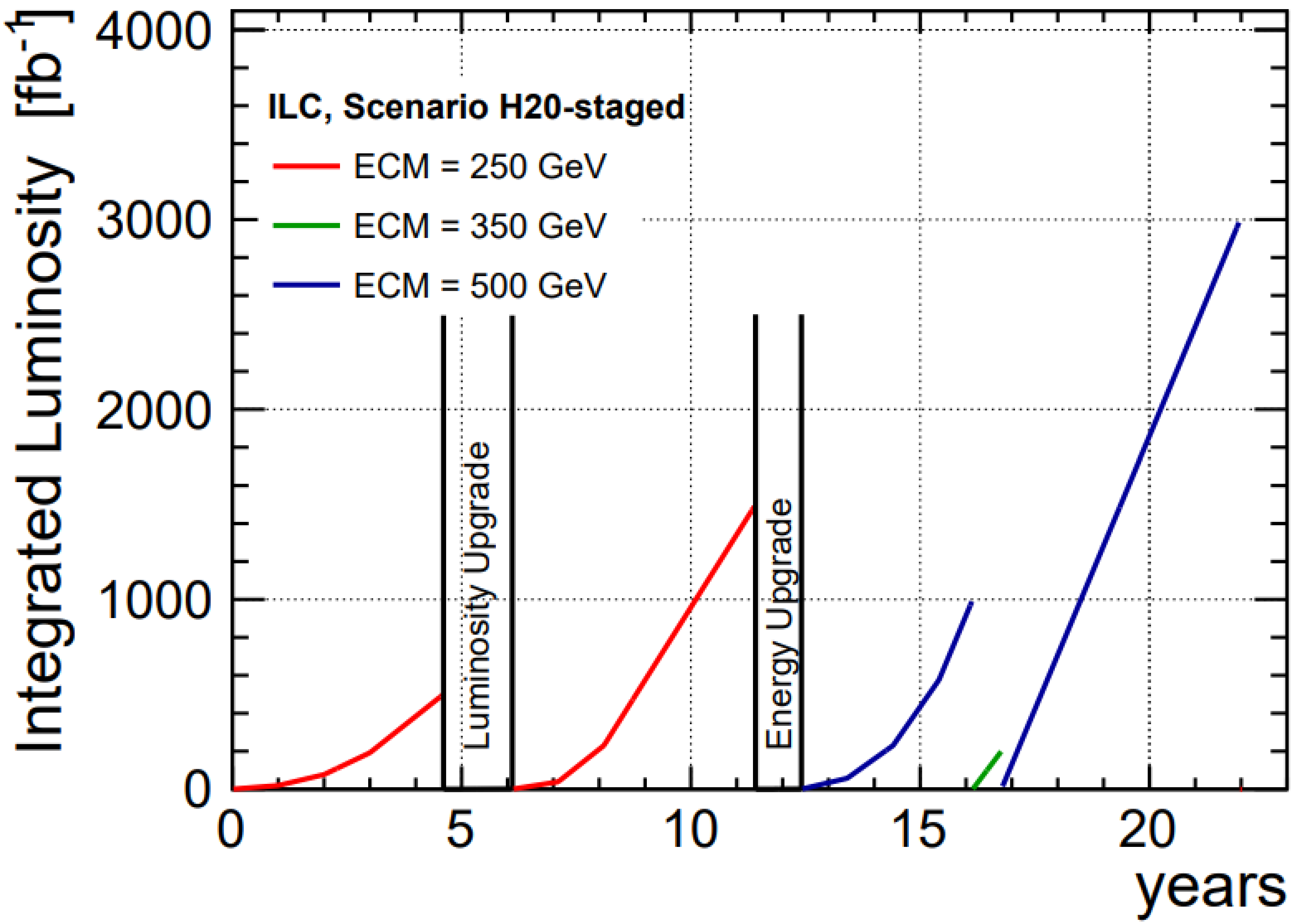


Off-shell H→ZZ

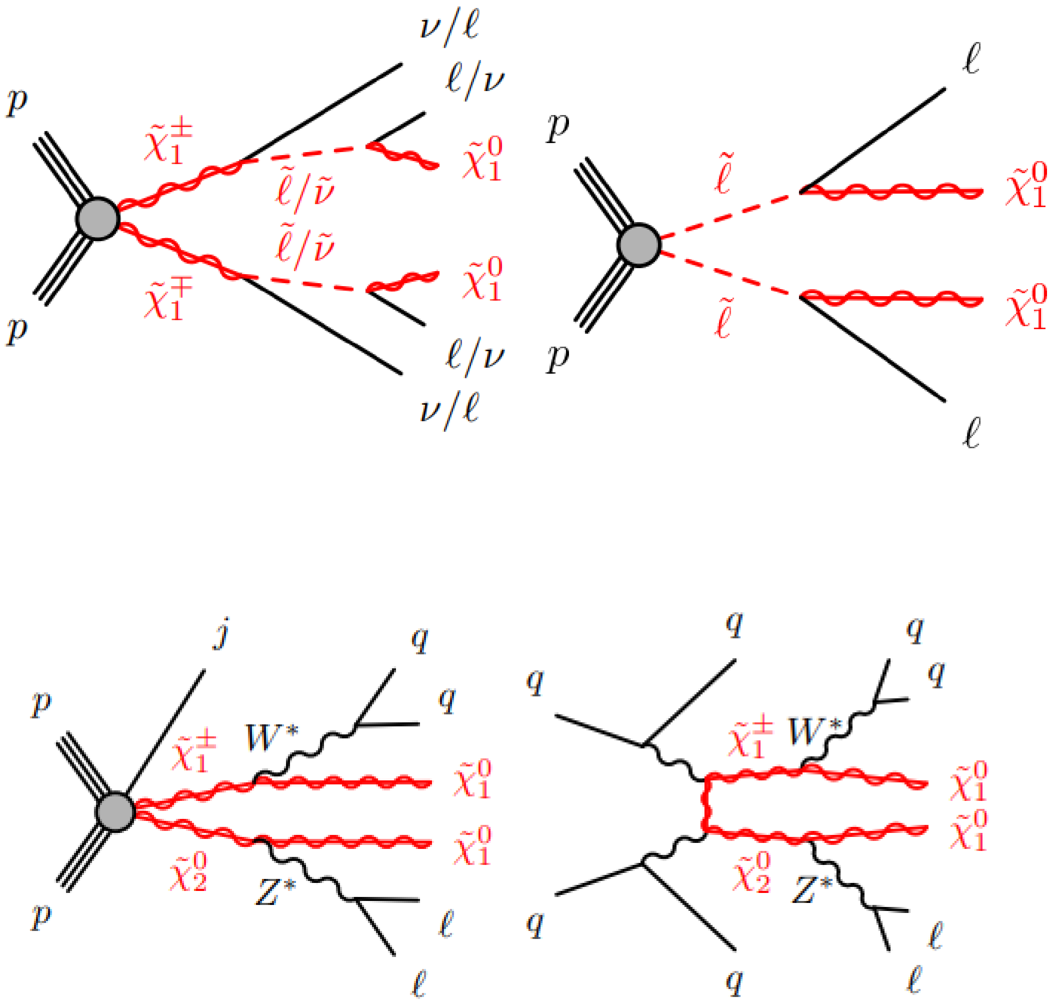
- 4 lepton channel: use optimal observables

ATLAS-CONF-2022-068





Integrated Luminosity [fb^{-1}]
4000
3000
2000
1000
0
ILC, Scenario H20-staged
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
Luminosity Upgrade
Energy Upgrade
0
5
10
15
20
years



p
p
$\tilde{\chi}_1^{\pm}$
$\tilde{\chi}_1^{\mp}$
$\tilde{\ell}/\tilde{\nu}$
$\tilde{\ell}/\tilde{\nu}$
ν/ℓ
ℓ/ν
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
ℓ/ν
ν/ℓ
p
p
$\tilde{\ell}$
$\tilde{\ell}$
ℓ
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
ℓ
p
p
j
$\tilde{\chi}_1^{\pm}$
W^*
q
q
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_2^0$
Z^*
ℓ
ℓ
q
q
q
q
$\tilde{\chi}_1^{\pm}$
W^*
q
q
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_2^0$
Z^*
ℓ
ℓ