Higgs at the HL-LHC: Ultimate reaches and challenges

Nicholas Wardle on behalf of the ATLAS and CMS collaborations

ECFA WHF WG1: 1st Workshop of the Higgs/Top/EW group

CERN

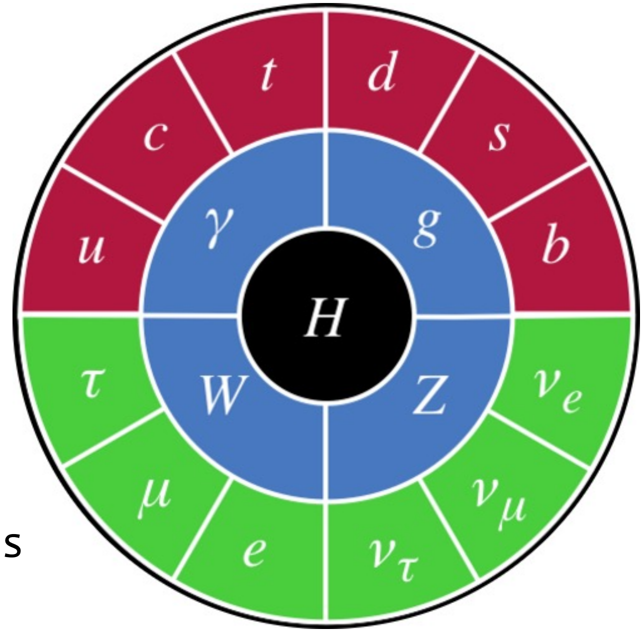
20/04/2022

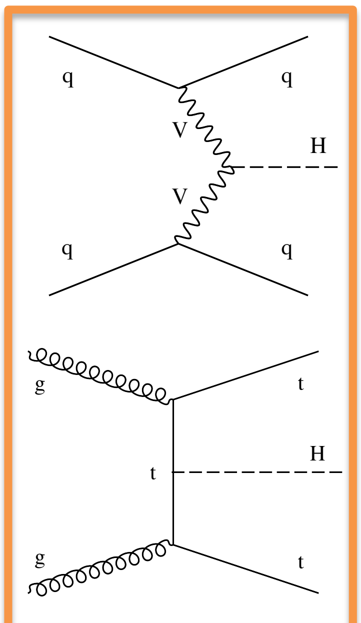
Completing the SM

Discovery of the Higgs boson completed the Standard Model

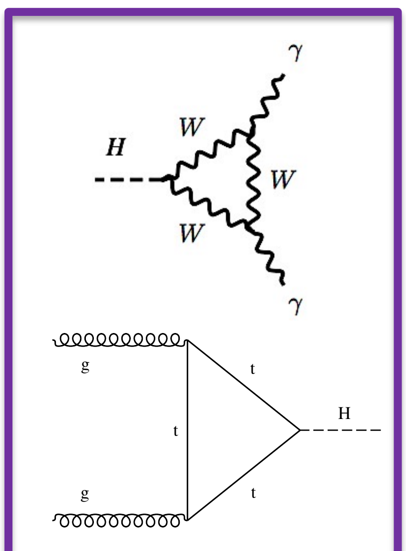
→ Great success of LHC (Run-1)

→ Coupling structure in SM allows for rich program of Higgs boson studies @ LHC/HL-LHC

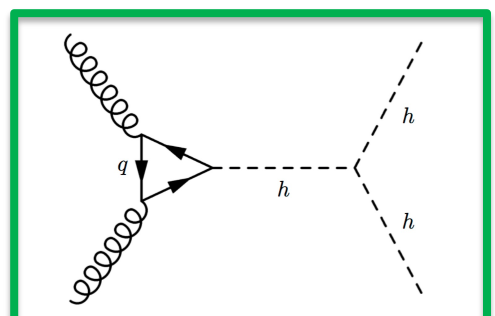




Tree level coupling to vector bosons and heavy fermions



Loop induced processes sensitive to interference & BSM effects

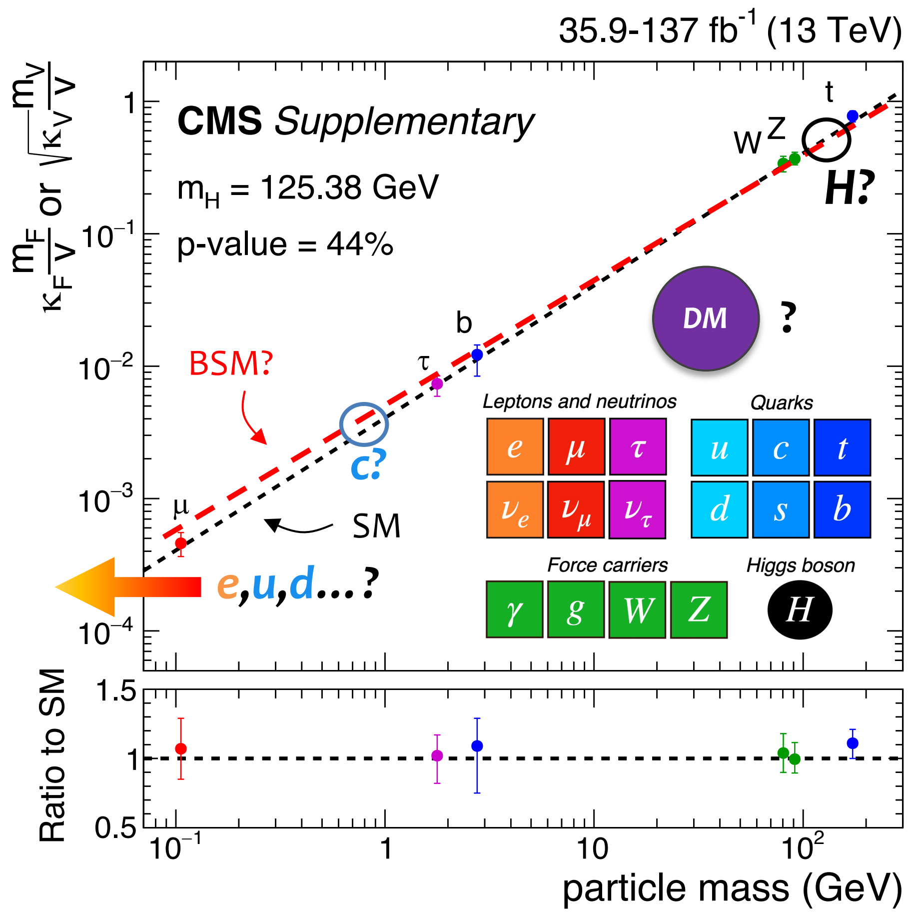


Higgs boson **couples to itself**!

We aren't done yet!

The **Higgs boson** was the **missing piece of the SM** and we've had it now for ~10 years …

- **Is the Higgs sector SM-like ? →** Do all the SM particles lie on that line?
- **What is Dark Matter (DM)? →** if DM are massive particles, wouldn't they couple to the Higgs too?
- **Why is there more matter than anti-matter? →** Can the Higgs potential explain the evolution of the early universe (baryogenesis)?



These are **fundamental questions** in physics
→ The **Higgs boson** is a unique tool to search for **physics beyond the SM** (BSM)

Higgs at Snowmass

The "**Energy Frontier (EF)**" group is exploring the TeV energy scale and beyond

EF01: EW Physics: Higgs boson properties and couplings

EF02: EW Physics: Higgs boson as a portal to new physics

Document summarizes expected performance from YR18 + **several new analyses** for Higgs studies at the HL-LHC

ATLAS-PHYS-PUB-2022-018/
CMS-PAS-FTR-22-001

I won't cover all new results (please forgive personal biases)

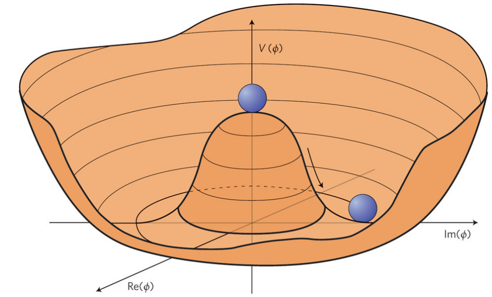
ATLAS PUB Note
CMS PAS Note
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001
17th March 2022

Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors

The ATLAS and CMS Collaborations

The ATLAS and CMS Collaborations actively work on developing the physics program for the High-Luminosity LHC. This document contains short summaries of physics contributions to the Energy Frontier and to the Rare Processes and Precision Measurements groups of Snowmass 2021. The summary is based on the physics potential estimates that were included in the CERN Yellow Report "Physics at the HL-LHC, and Perspectives for the HE-LHC", and also contains a number of recent results.

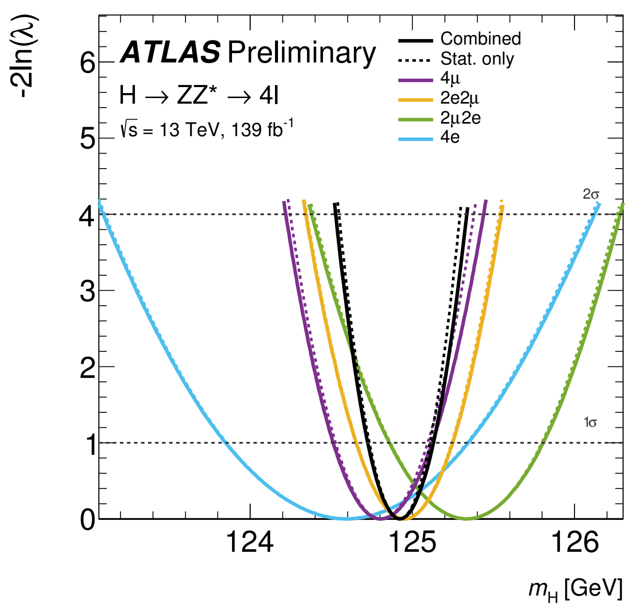
Higgs boson mass

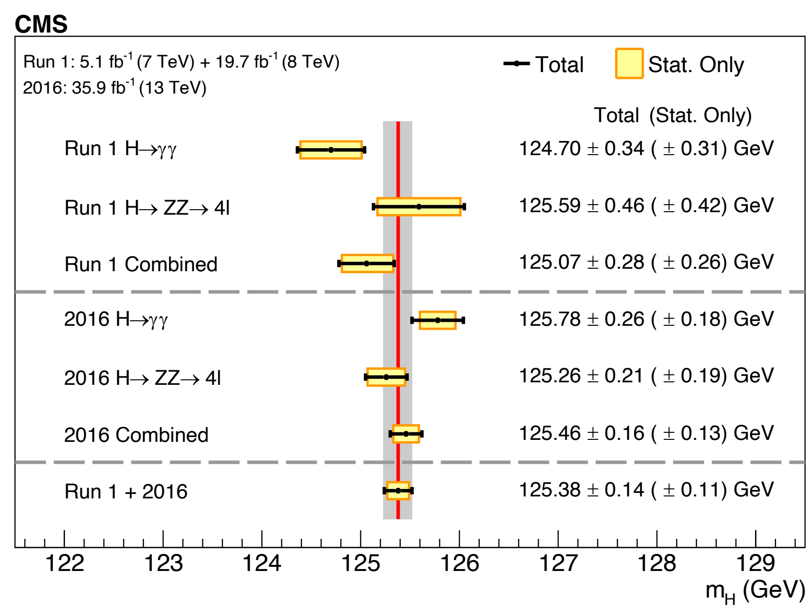


Higgs boson determines couplings to SM particles
→ Precision in mass required to precisely specify "SM"

Current precision from Full (partial) Run-2 (+Run-1) data at ATLAS (CMS)

ATLAS H→4l (ATLAS-CONF-2020-005)	$m_H = 124.92^{+0.21}_{-0.20}$ GeV
CMS H→γγ + H→4l (Phys. Lett. B 805 (2020))	$m_H = 125.38 \pm 0.14$ GeV

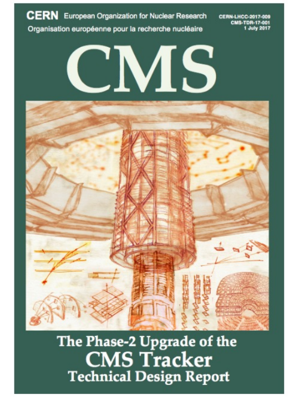




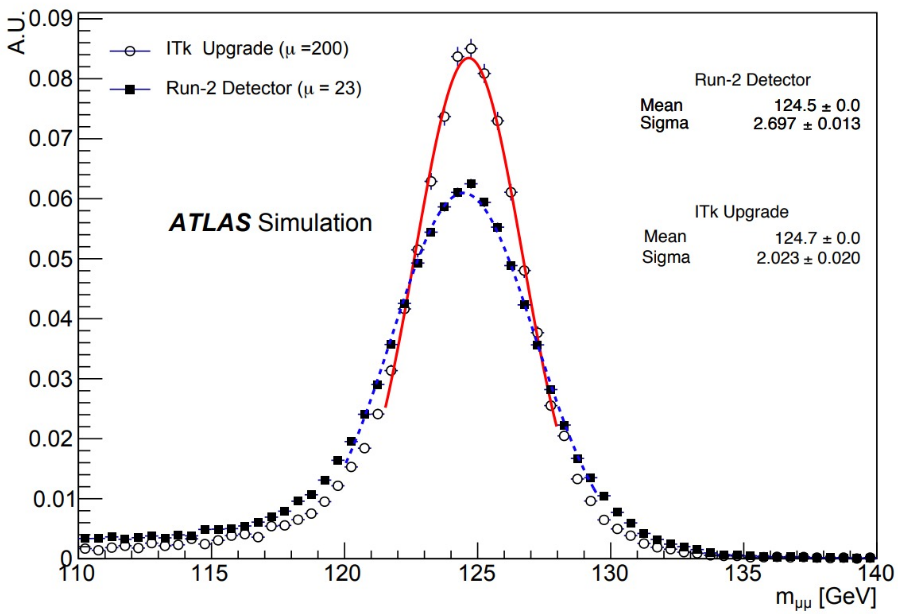
Higgs boson mass @ HL-LHC

In addition to additional luminosity, can expect major improvements from ATLAS and CMS upgrades

Upgraded/Extended tracking up to |η|~4, improved PU rejection from timing detectors |η|<3 (CMS) 2.4 < |η| <4 (ATLAS)



ATLAS-TDR-025



Additional muon stations (ATLAS and CMS) extends muon tracking capability

Improved stability and precision of calorimetry (+new high-granularity calorimeters at |η|>2.5 at CMS)

Expect improvements in

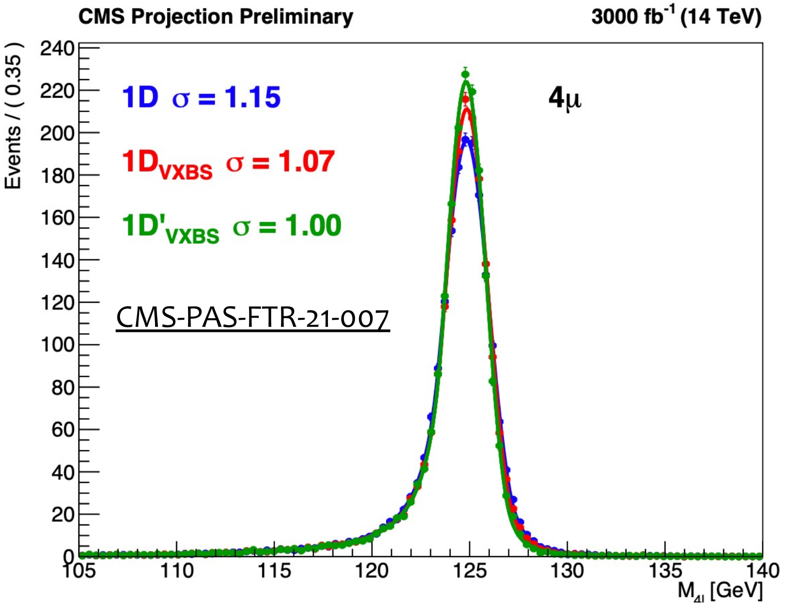
- muon momentum
- electron/photon energy resolution
- improved vertexing

→ Vital for H→γγ and H→4l channels

Higgs boson mass @HL-LHC

H→4l : Projection based on Run-2 analysis + new muon momentum constraints from vertex BS and on-shell Z mass

m_H uncert (MeV)	4μ	4e	2e2μ	2μ2e	combined
Total	32	206	107	112	**30**
Syst component	15	189	94	95	**20**

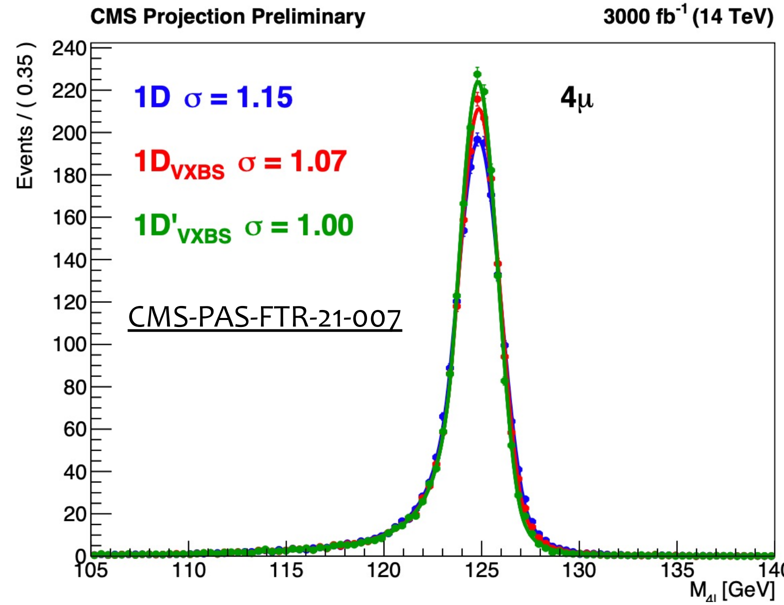


Can expect further reduction in statistical uncertainty due to improved tracking
→ total uncertainty **could reach 25 MeV!**

Higgs boson mass @HL-LHC

H→4l : Projection based on Run-2 analysis + new muon momentum constraints from vertex BS and on-shell Z mass

m_H uncert (MeV)	4μ	4e	2e2μ	2μ2e	combined
Total	32	206	107	112	**30**
Syst component	15	189	94	95	**20**



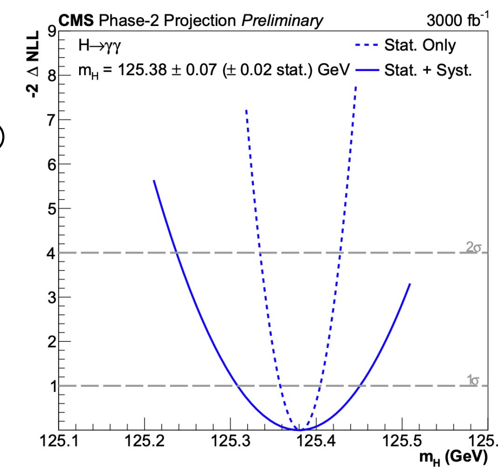
Can expect further reduction in statistical uncertainty due to improved tracking
→ total uncertainty **could reach 25 MeV!**

H→γγ : Projection based on 2016 analysis correcting for expected improvements in photon energy resolution

More data at HL-LHC will lead to increased granularity of calibrations ☺

Sources of systematic uncertainty	Contribution [GeV]
Electron energy scale and resolution corrections	0.06
Residual p_T dependence of the photon energy scale	0.05
Modelling of the material budget	0.02
Statistical uncertainty	0.02
Total uncertainty	0.07

Background modeling strategy may not scale to 3000/fb ☹



CMS-PAS-FTR-21-008

Higgs Couplings @ HL-LHC

Expect to reach O(%)-level precision in many couplings!

Assumes trigger & detector performance / reconstruction similar to Run-2

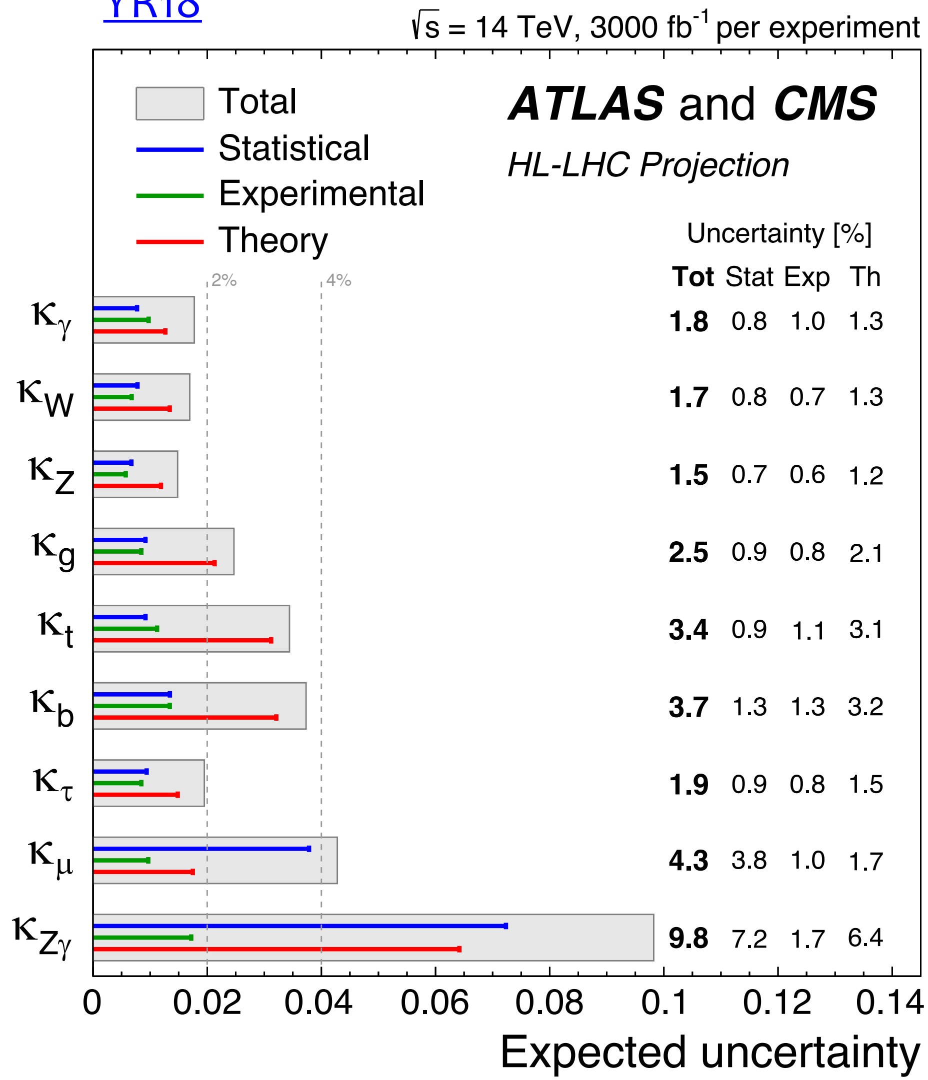
Uncertainty scaling:

Statistical Uncertainties	$\propto 1/\sqrt{L}$
Experimental Uncertainties	$\propto 1/\sqrt{L}$ Until floor reached
Theoretical Uncertainties	x 0.5

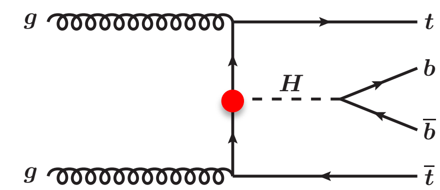
Uncertainty dominated by systematic components in many cases for coupling (inclusive) measurements

Caveat! Higgs boson couplings based on partial Run-2 data - Represents only ~few % of total expected HL-LHC dataset.

YR18



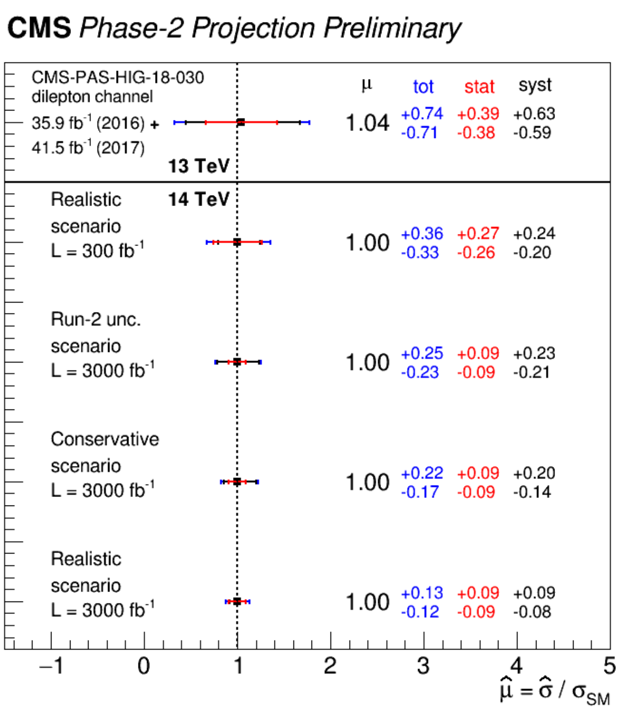
Top-Yukawa



Direct access to κ_t from ttH measurements → ttH(bb) channel among the most sensitive at Run-2

New CMS HL-LHC projection based on new analysis for ttH(bb)-OS DL channel

- Fit to m_{bb} - reconstructed through kinematic fit of ttH system
- Backgrounds (incl. dominant tt) estimated from 2b events (ATLAS Tag Rate Function method JHEP05(2016)160), corrected with MC simulation



CMS-PAS-FTR-21-002

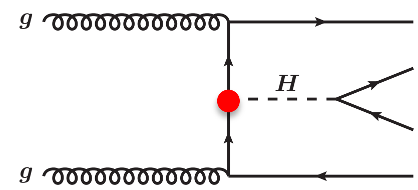
Expected uncertainty on the signal cross-section **~12% at HL-LHC**

Assume only statistical part scales

Assumes background systematics don't scale

Uncert. based on YR18 S2

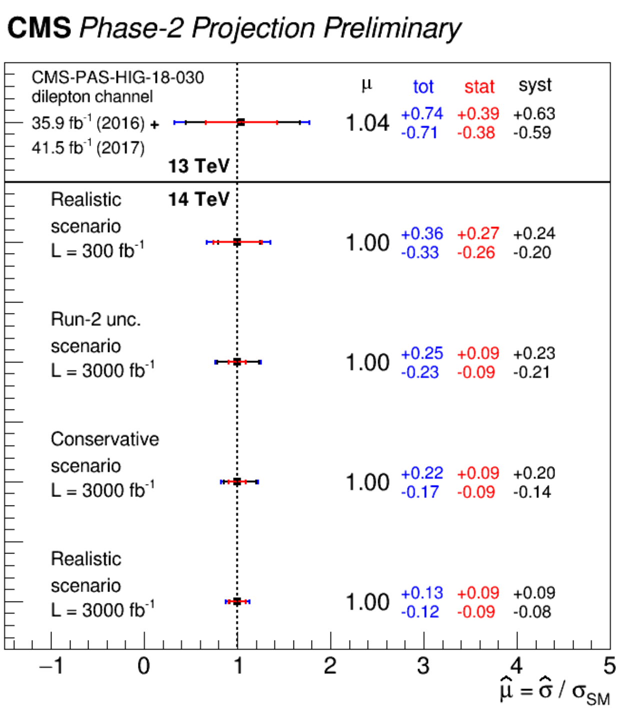
Top-Yukawa



Direct access to κ_t from ttH measurements → ttH(bb) channel among the most sensitive at Run-2

New CMS HL-LHC projection based on new analysis for ttH(bb)-OS DL channel

- Fit to m_{bb} - reconstructed through kinematic fit of ttH system
- Backgrounds (incl. dominant tt) estimated from 2b events (ATLAS Tag Rate Function method JHEP05(2016)160), corrected with MC simulation



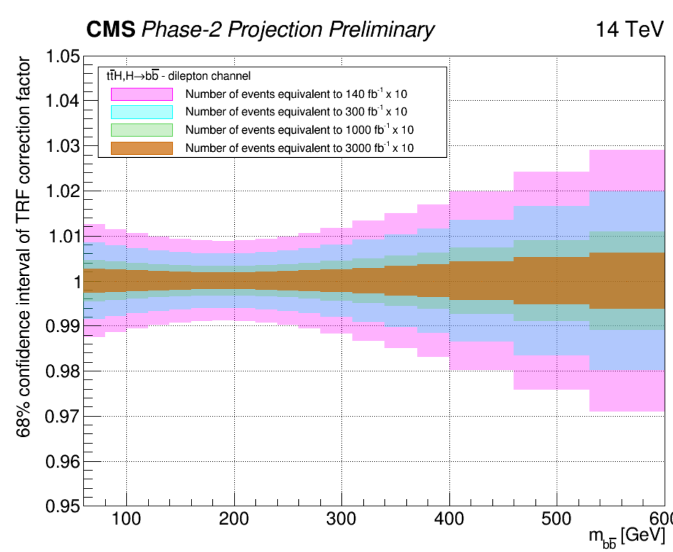
CMS-PAS-FTR-21-002

Assume only statistical part scales

Assumes background systematics don't scale

Uncert. based on YR18 S2

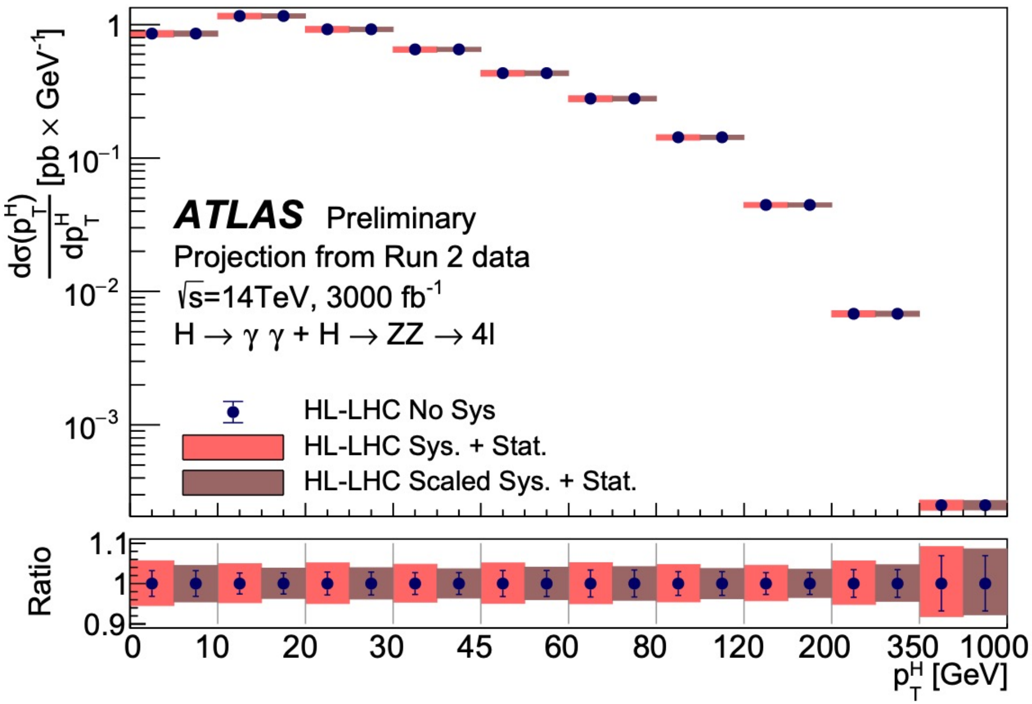
Expected uncertainty on the signal cross-section **~12% at HL-LHC** → Need to keep high equiv. # of MC events to keep background model under control

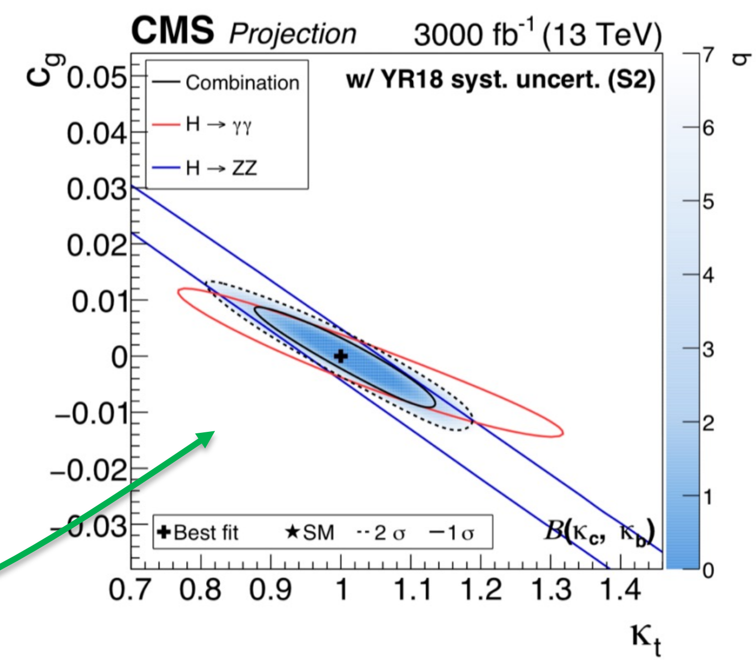


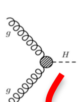
Top-Yukawa

Additional constraints on t-H coupling from differential measurements @HL-LHC [1] → complementary to direct measurements of κ_t

YR18







$$\mathcal{O}_1 = |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}\,, \quad \mathcal{O}_2 = |H|^2 \bar{Q}_L H^c u_R + h.c.\,, \quad \mathcal{O}_3 = |H|^2 \bar{Q}_L H d_R + h.c.$$

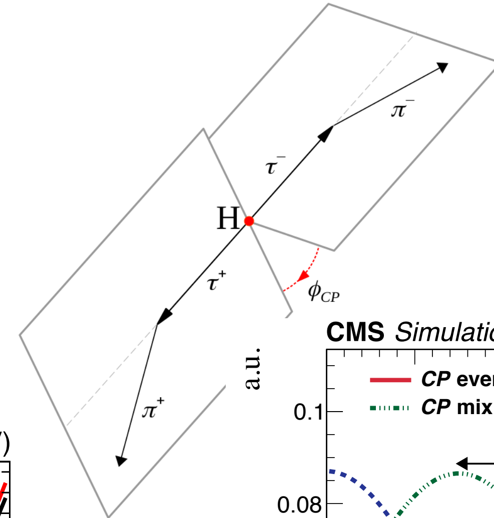
Yukawas

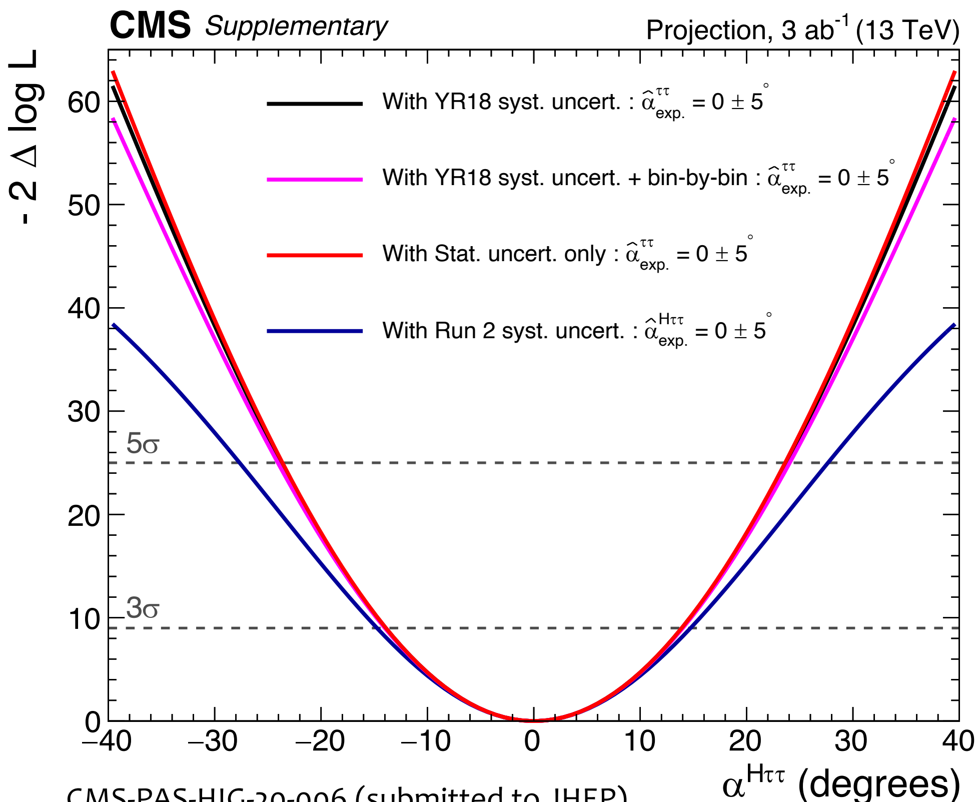
[1] https://arxiv.org/abs/1705.05143

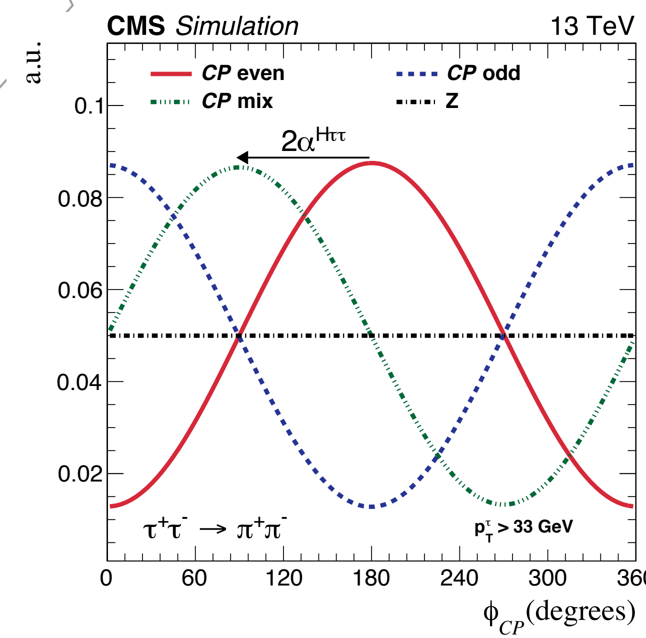
CP in H→ττ

Measure H→ττ decays differentially in Φ_{CP} to access potential CP-odd contributions to H-τ coupling

$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$



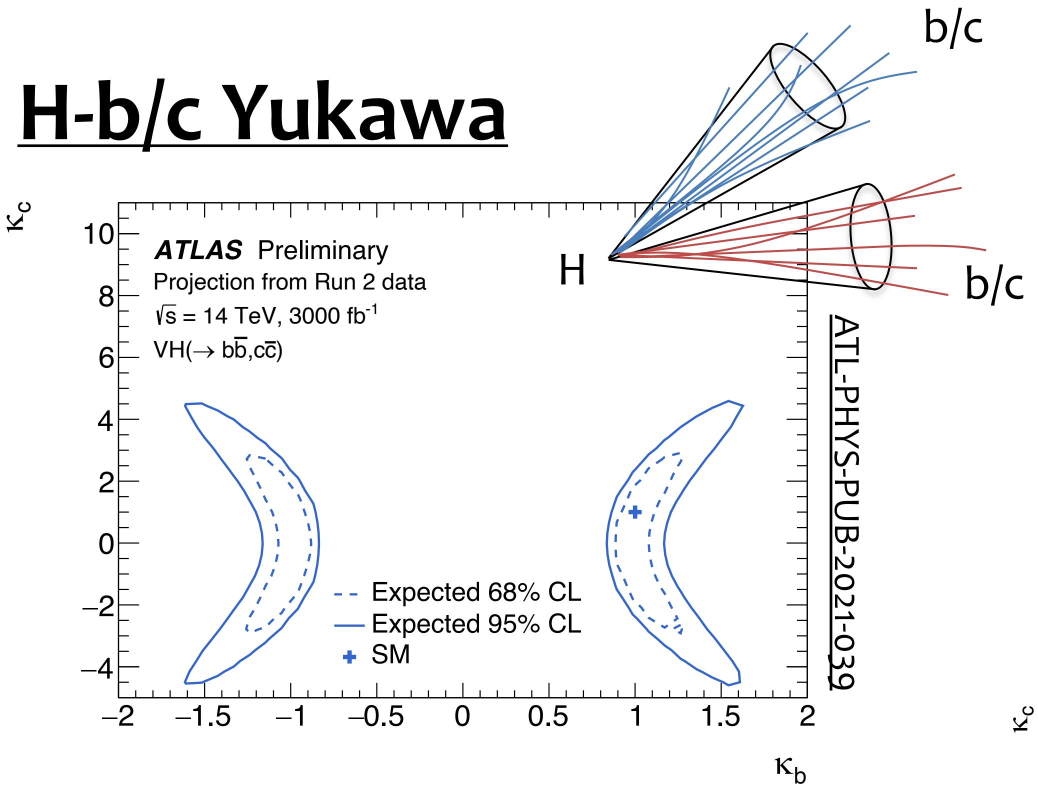




CMS-PAS-HIG-20-006 (submitted to JHEP)

Projection of Run-2 analysis at CMS
→ Expect to constrain CP-mixing angle ($\alpha^{H\tau\tau}$) to 5 degrees at HL-LHC!

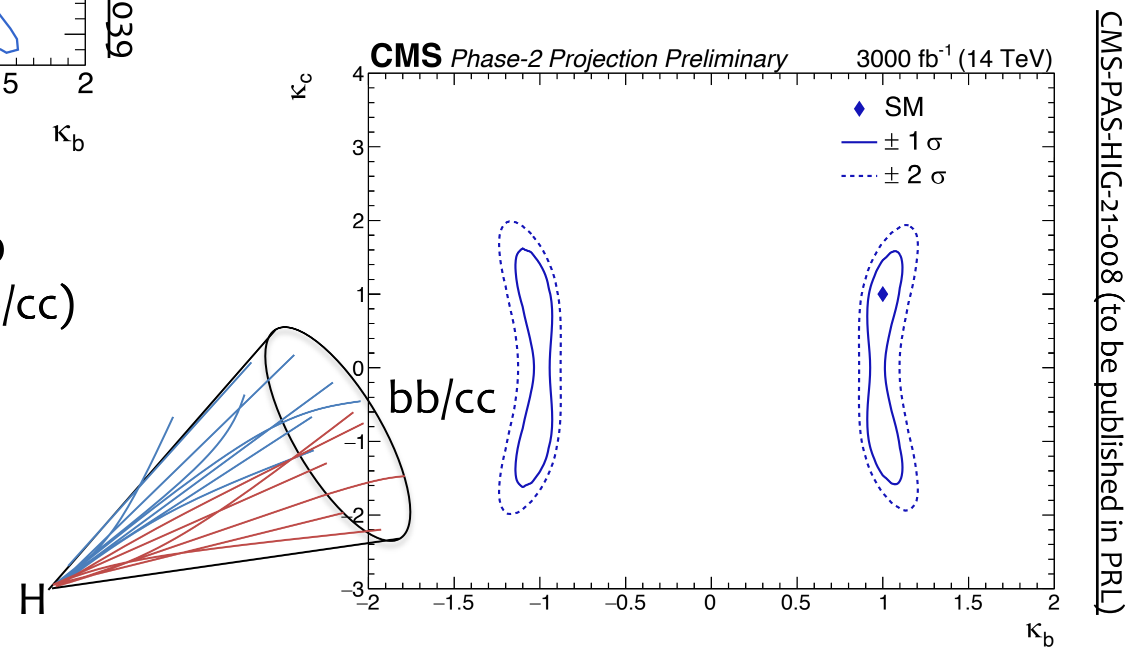
H-b/c Yukawa



VH→bb/cc measurements sensitive to b-quark and c-quark couplings

Expected measurements of κ_b-κ_c at HL-LHC from STXS VH→bb (STXS measurement) and VH→cc (inclusive search) in resolved di-jet events (ATLAS)…

… and in boosted events (p_T>200 GeV) using ParticleNet [1,2] H(bb/cc) merged-jet tagging



[1] CERN-CMS-DP-2020-002

[2] PRD **101**, 056019

Second gen lepton couplings

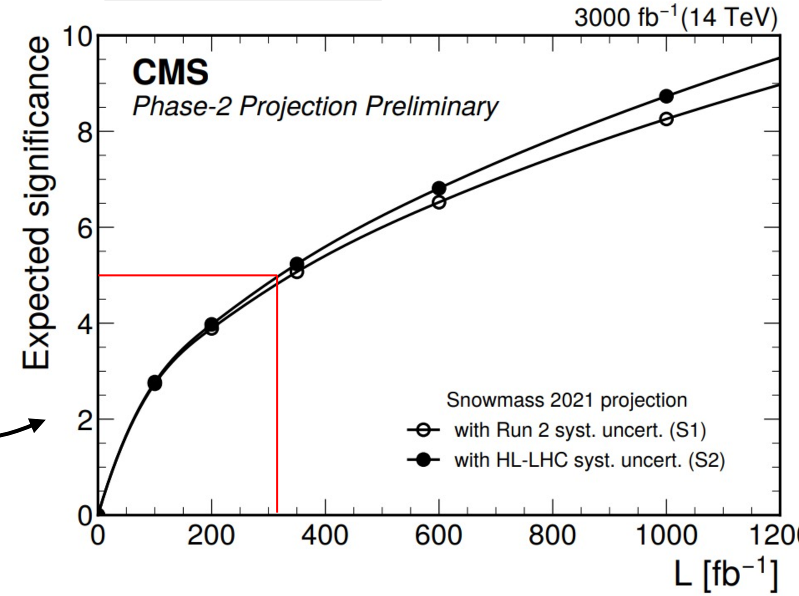
Evidence for H→μμ decay in Run-2

- ATLAS: 2.0σ (1.7σ) obs (exp) Phys. Lett. B 812 (2021)
- CMS: 3.0σ (2.5σ) obs (exp) JHEP 01 (2021) 148

New projection from CMS based on Run-2 analysis

- Expect to reach 5σ @~300/fb – by the end of LHC Run-3
- Combination with ATLAS to reach 5σ sooner!

CMS-PAS-FTR-21-006



Second gen lepton couplings

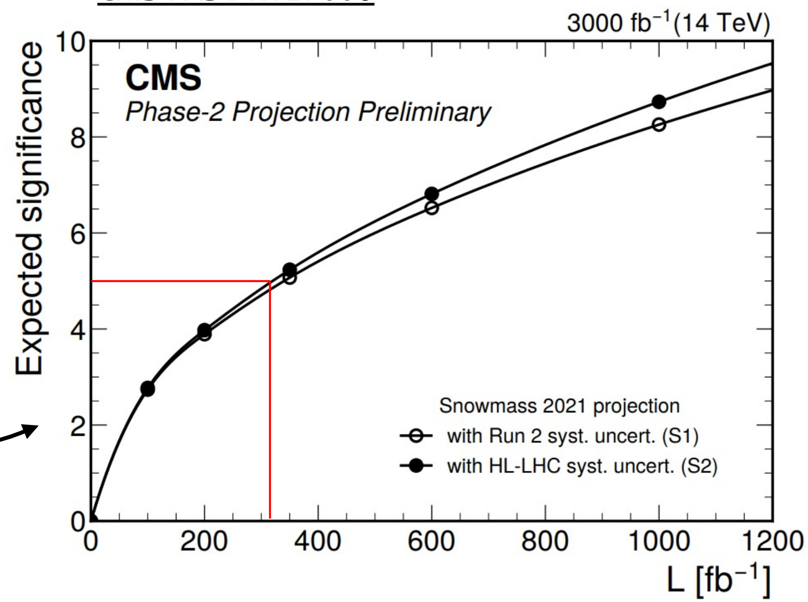
Evidence for H→μμ decay in Run-2

- ATLAS: 2.0σ (1.7σ) obs (exp) Phys. Lett. B 812 (2021)
- CMS: 3.0σ (2.5σ) obs (exp) JHEP 01 (2021) 148

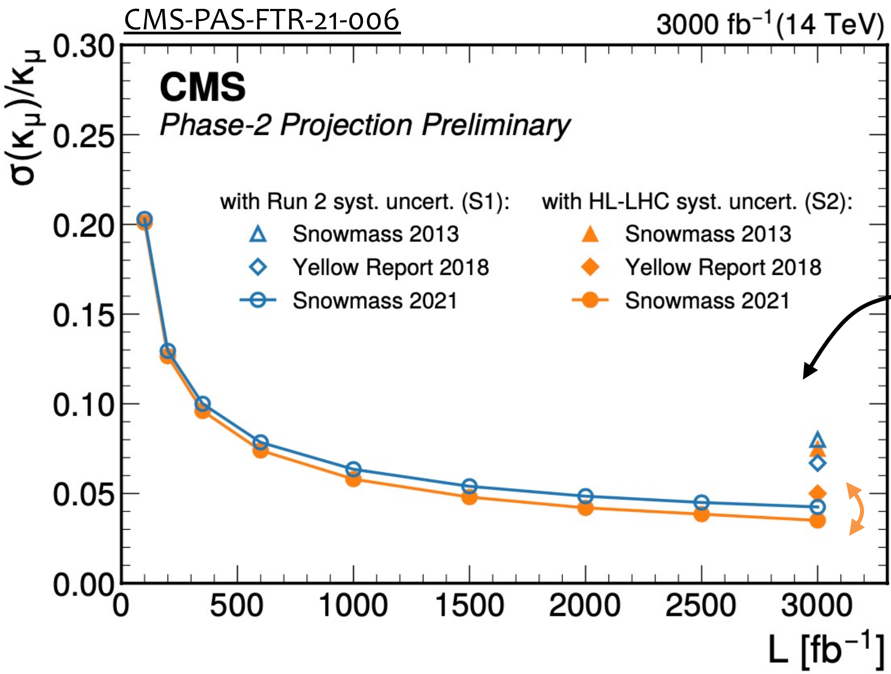
New projection from CMS based on Run-2 analysis

- Expect to reach 5σ @~300/fb – by the end of LHC Run-3
- Combination with ATLAS to reach 5σ sooner!

CMS-PAS-FTR-21-006



CMS-PAS-FTR-21-006



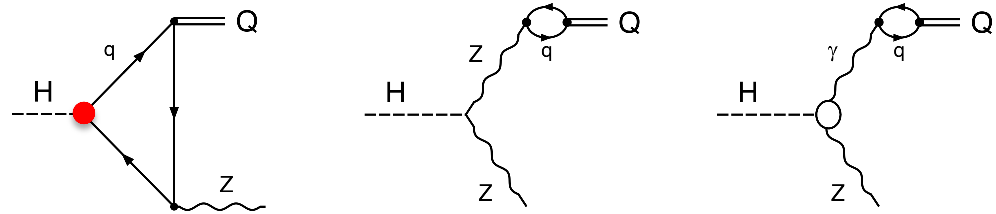
→ Expected improvement in mass resolution ~30% at HL-LHC brings sensitivity gain beyond sqrt(L)

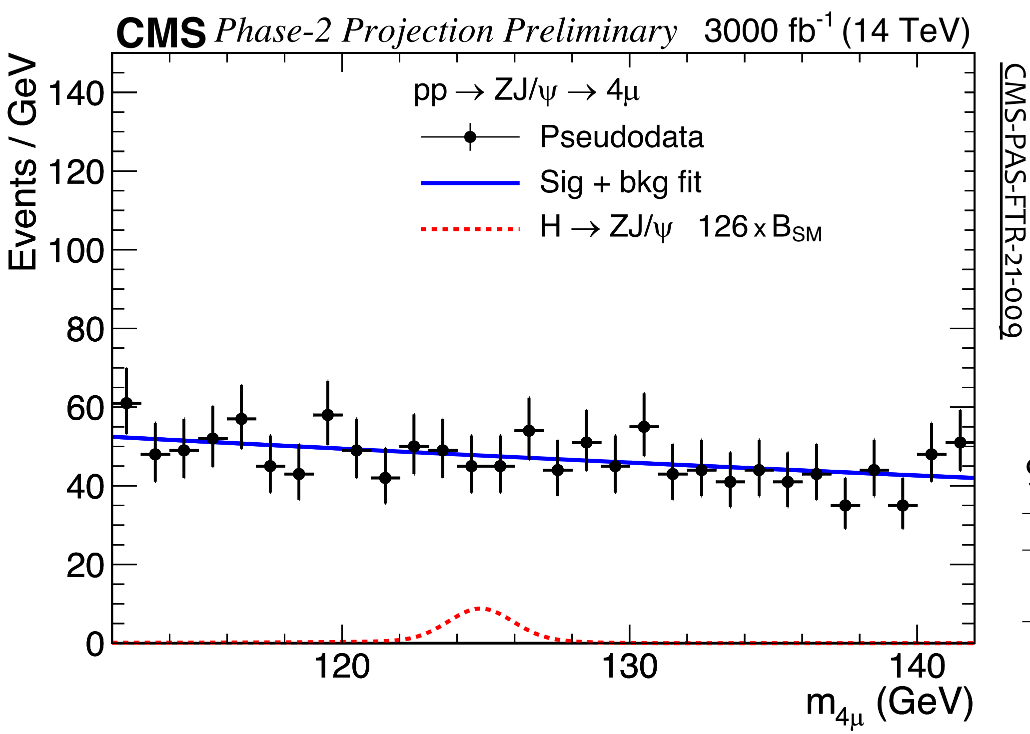
Uncertainty in coupling ~4-5% at HL-LHC

Improvement compared to 2016 analysis projection

Rare decays

Beyond SM physics can lead to large modifications of 1st generation quark Yukawas → possible enhancement in H→ZQ/QQ compared to SM





Projection of Run-2 search for H→Z J/ψ → 4μ and H→ YY → 4μ

Analysis still very statistics limited at HL-LHC → 3 events in H→YY Higgs peak would constitute discovery!

95% CL Upper limit on B(H→X) at (extended) HL-LHC

Channel	3000 fb^{-1}	(×SM)	4500 fb^{-1}	(×SM)
$H \to ZJ/\psi$	2.9×10^{-4}	(126)	2.7×10^{-4}	(117)
$H \to \Upsilon(mS)\Upsilon(nS)$	1.3×10^{-5}	(0.2)	8.5×10^{-6}	(0.14)

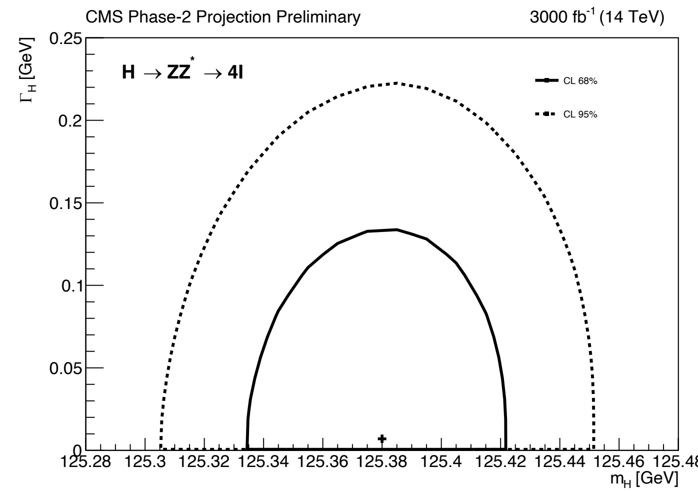
BSM in Higgs decays

Additional (BSM) decays of the Higgs boson results in modified Higgs boson width

- Indirect from total width from coupling measurements (+ offshell) measurements
- Direct measurement from H→4l mass peak

CMS-PAS-FTR-21-007

Γ_H expected upper limit (MeV)	Projection	Optimistic	Pessimistic
Total	177	155	177
Syst impact	150	123	150
Stat only	94		

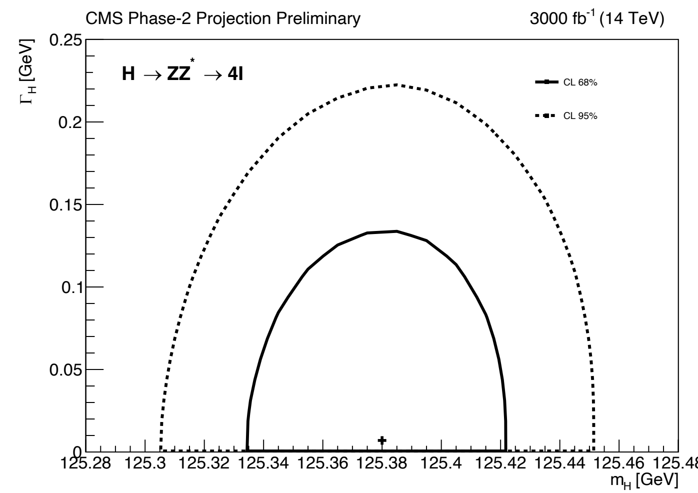


Limited by experimental resolution (Γ_H ~ 4 MeV in SM)!

BSM in Higgs decays

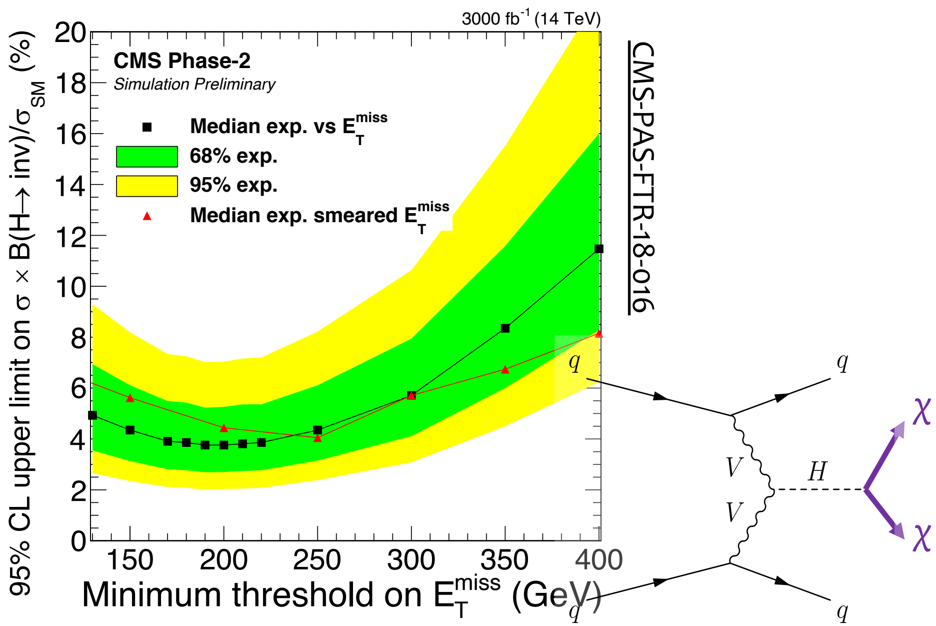
Additional (BSM) decays of the Higgs boson results in modified Higgs boson width

- Indirect from total width from coupling measurements (+ offshell) measurements
- Direct measurement from H→4l mass peak
- Limited by experimental resolution ($\Gamma_H \sim$ 4 MeV in SM)!



CMS-PAS-FTR-21-007

Γ_H expected upper limit (MeV)	Projection	Optimistic	Pessimistic
Total	177	155	177
Syst impact	150	123	150
Stat only	94		



Direct searches for VBF H→invisible decays benefit from improved forward tracking & calorimetry

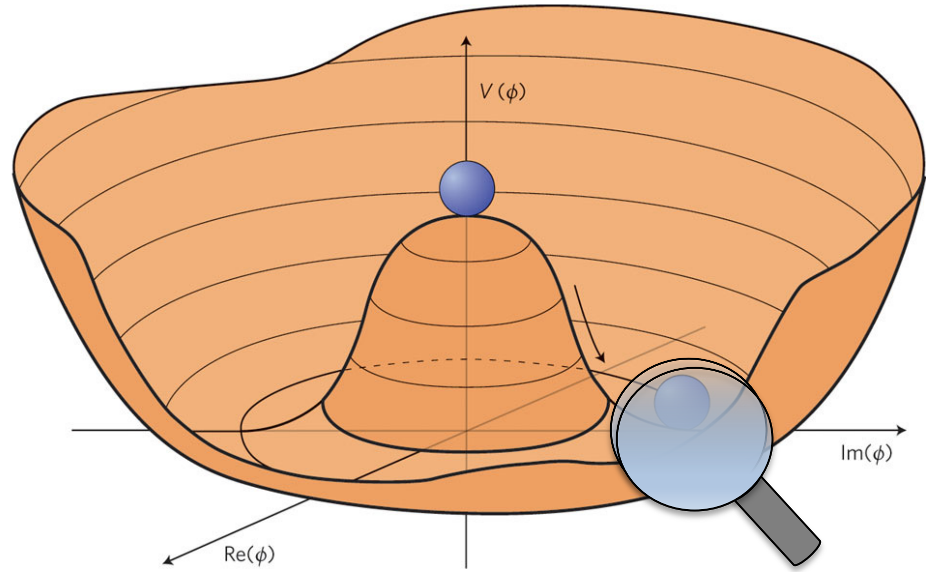
→ Sensitivity limited by trigger/selection thresholds achievable at HL-LHC

→ Need to get smarter to maintain or do better than sqrt(L)!

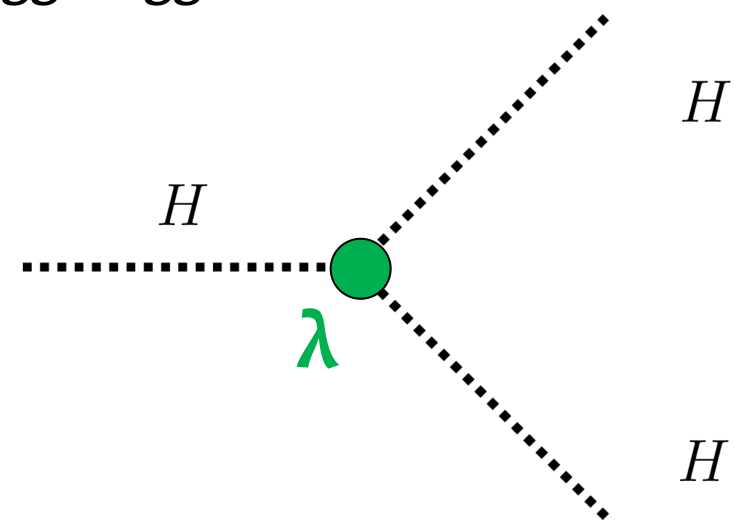
Self-coupling

Remember in the SM, the **Higgs potential** includes ***H*³** terms

$$V(H) = \frac{m_H^2}{2}H^2 + \boxed{\lambda v H^3} + \lambda H^4$$

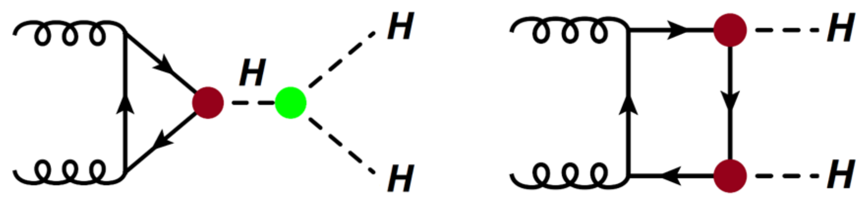


"self-coupling" generates **Higgs-Higgs** interactions



Direct searches for **Double Higgs** production one way to constrain the Higgs boson self-coupling!

Self-coupling

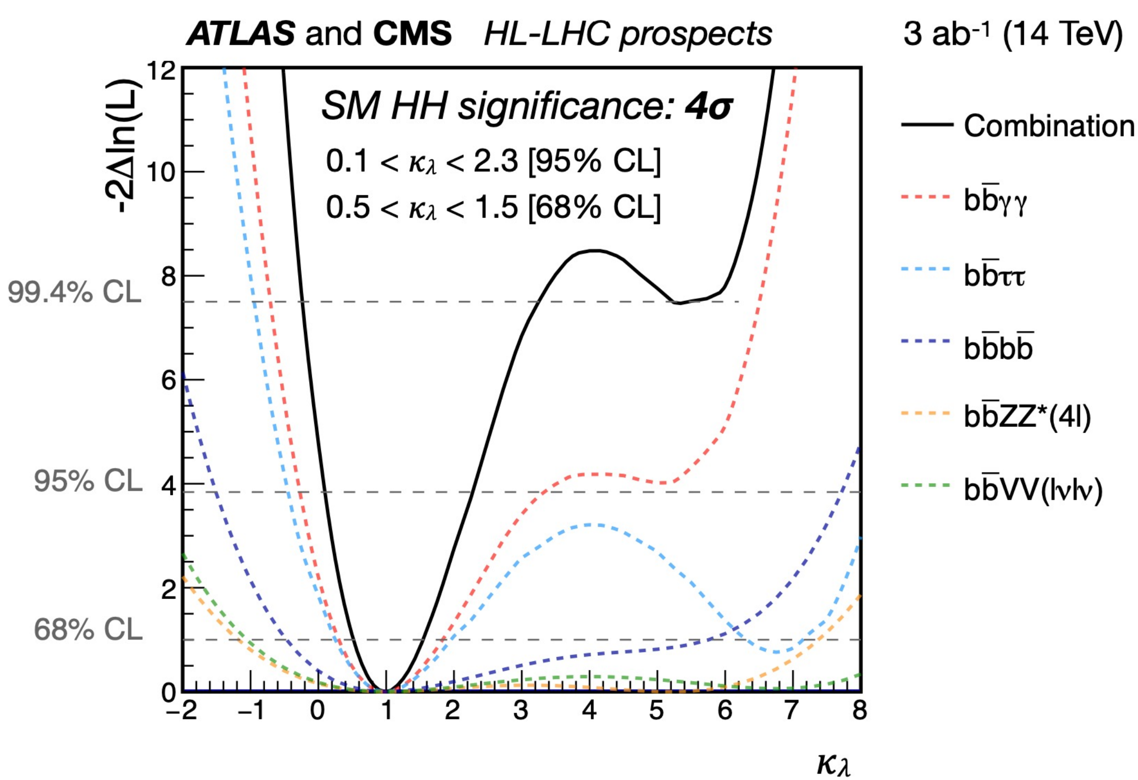


Cancellation of diagrams leads to cross section of dominant production mode ~1000 times smaller than gg→H!

HL-LHC dataset will be crucial for **ATLAS+CMS** to probe Higgs self-coupling at meaningful level

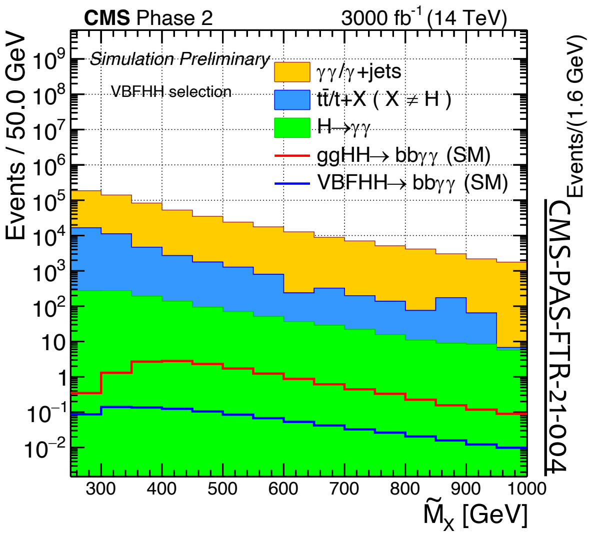
→ Combined searches for HH production in bbbb,bbγγ,bbττ +(bbVV(llνν),bbZZ CMS only) decay modes

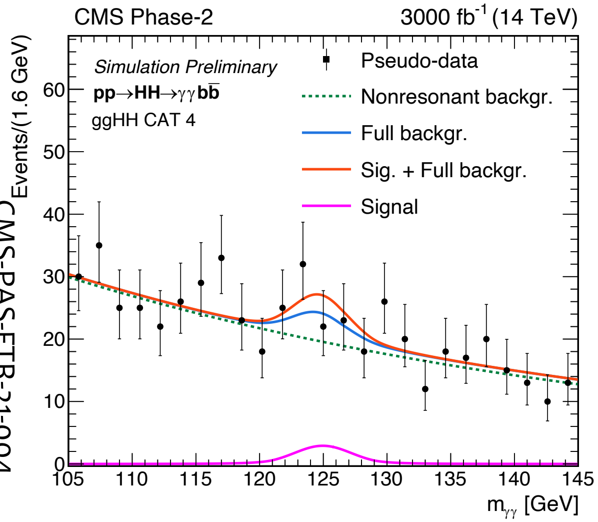
→ Approach **~50% uncertainty on κ_λ**



Can we do any better?

HH→bbγγ updates





CMS: 2D fit in m_{bb}-$m_{\gamma\gamma}$ to extract HH→bbγγ signal

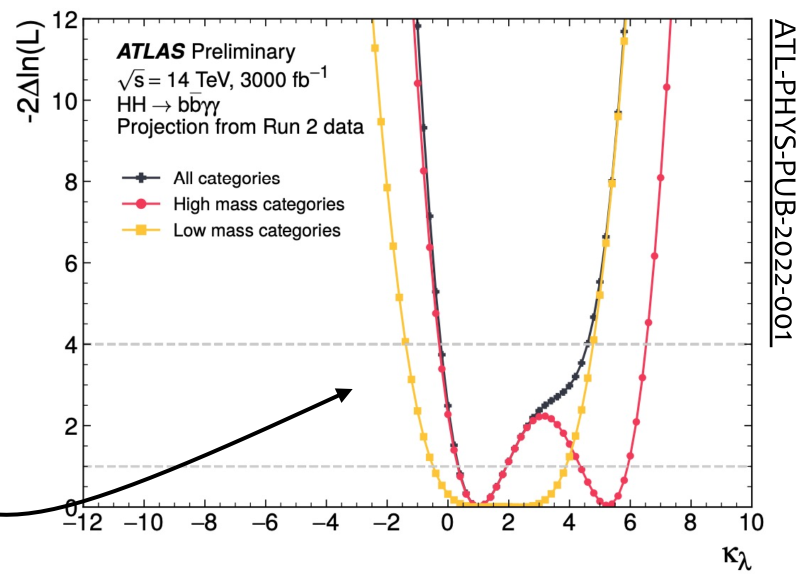
Categorisation based on BDT and
$$\tilde{M}_X = m_{bb\gamma\gamma} - (m_{bb} - 125) - (m_{\gamma\gamma} - 125)$$

Improved ttH rejection & dedicated VBF-HH categories lead to expected significance of 2.16σ (cf 1.86σ in YR18)

ATLAS: Projected Run-2 analysis with improved categorization & inclusion of VBF-HH

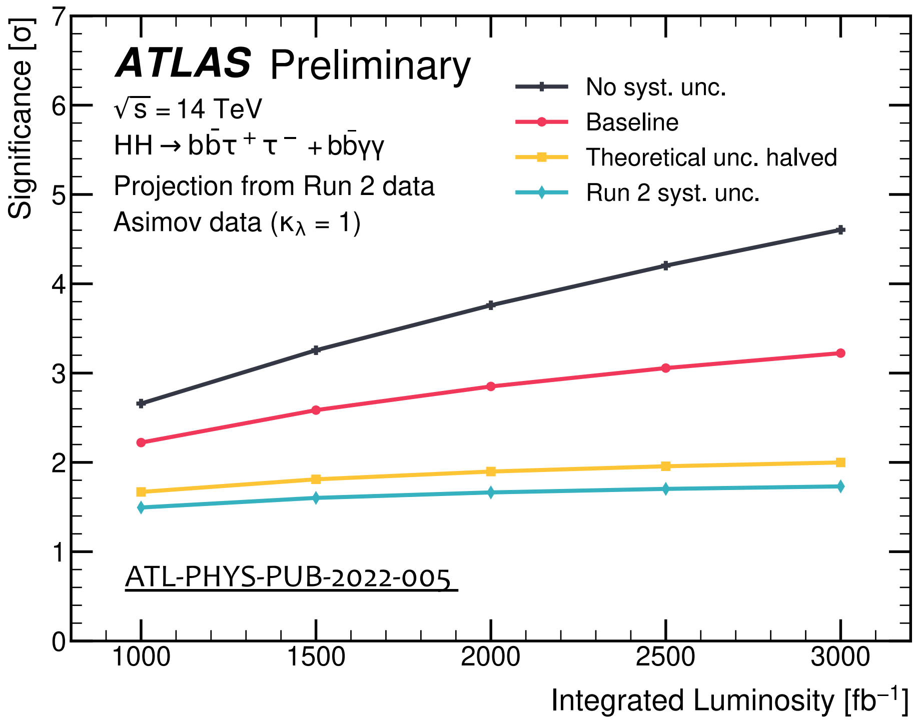
- 95% CL UL on HH signal from 1.2→0.93
- Significance 2.0σ →2.2σ with baseline uncertainty scenario compared to YR18

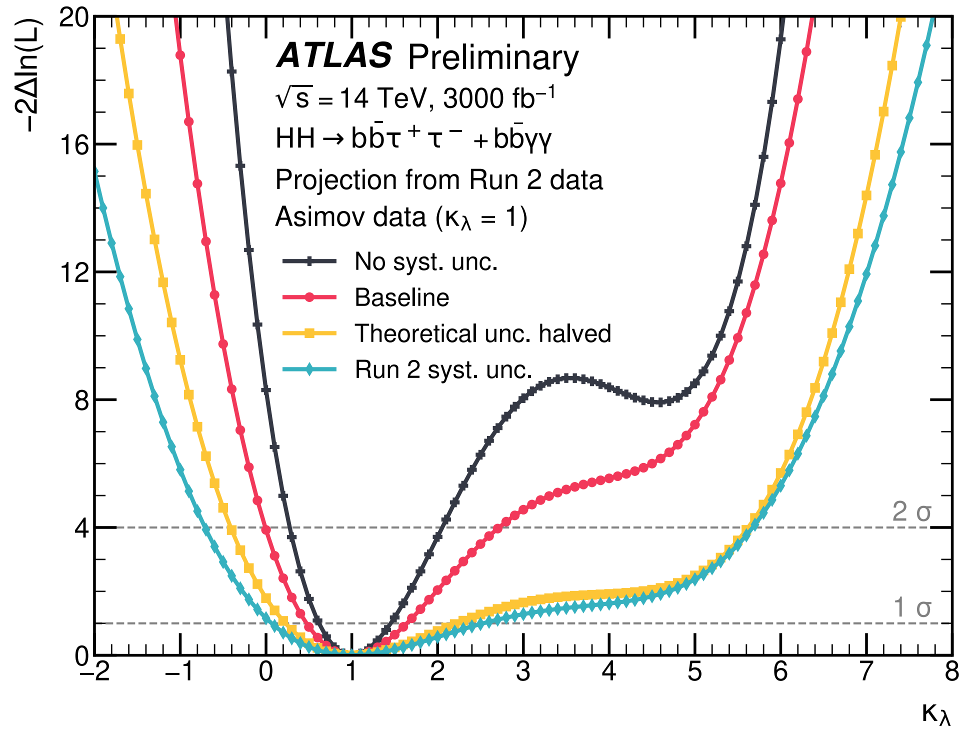
Use of low (M_X<350 GeV) and high (M_X>350 GeV) mass categories allows to lift degeneracy in κ_λ



+HH→bbττ update in comb

Additional update of **bbττ** with improvement of ~28% due to updated reconstruction algorithms and analysis methods used in the Full Run 2 search compared to YR18





Main limitations in sensitivity due to

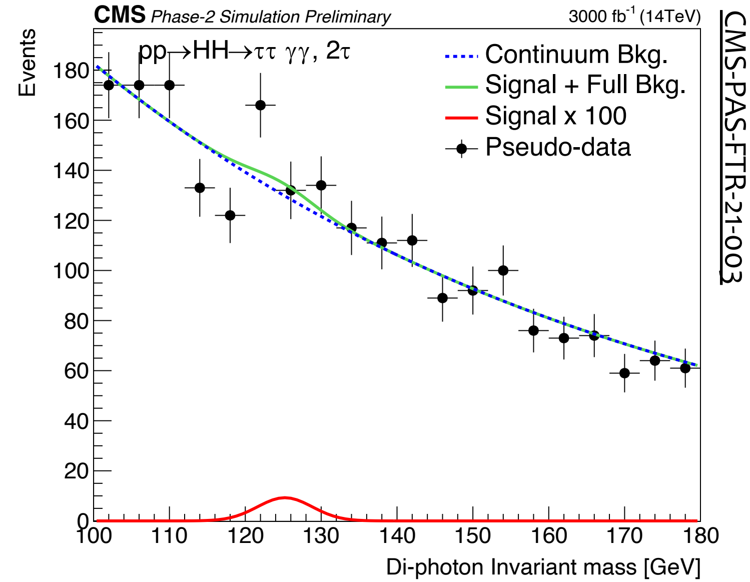
- Theory uncertainties on the HH cross-section + HF jet radiation single Higgs boson production
- Limited MC statistics in bbττ
- Background modelling (spurious signal) in bbγγ

New channels in decay

CMS HL-LHC analysis of WWγγ + ττγγ

- Lower branching fraction than main channels
- leptons+photons in final state help reduce backgrounds and provide narrow peaks

Final State	Significance (stat+exp+theory)
$WW\gamma\gamma$	0.21
$\tau\tau\gamma\gamma$	0.08
Combination	0.22

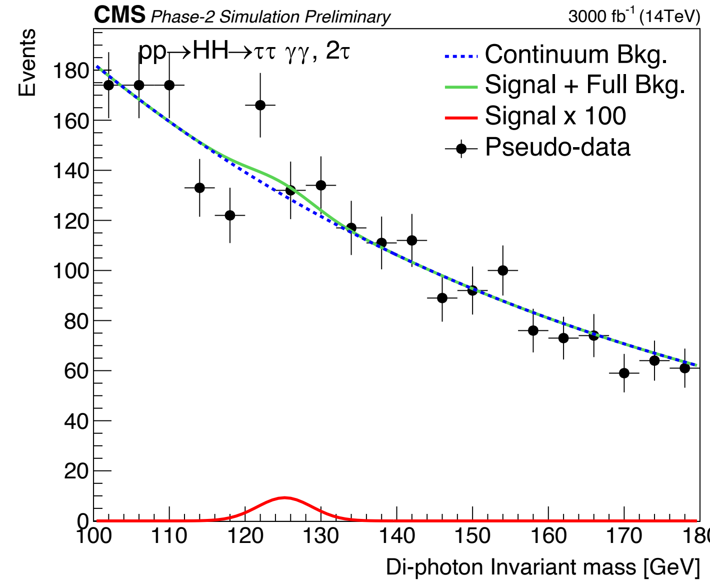


New channels in decay + production

CMS HL-LHC analysis of WWγγ + ττγγ

- Lower branching fraction than main channels
- leptons+photons in final state help reduce backgrounds and provide narrow peaks

Final State	Significance (stat+exp+theory)
$WW\gamma\gamma$	0.21
$\tau\tau\gamma\gamma$	0.08
Combination	0.22

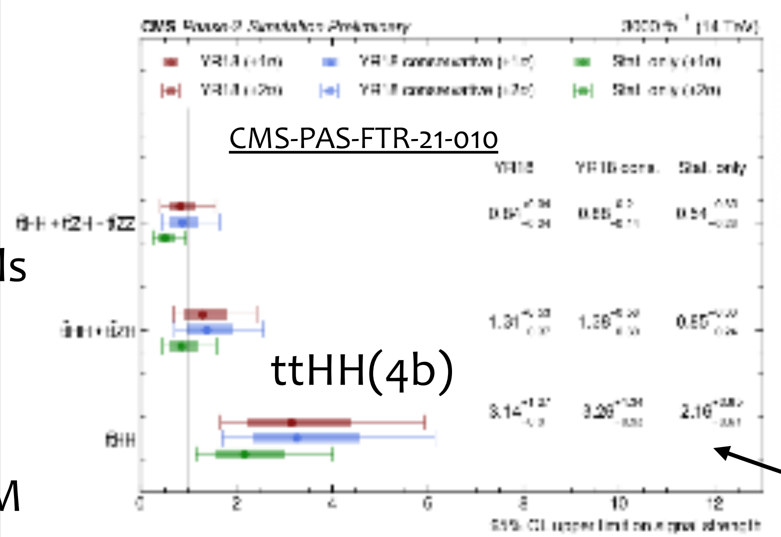


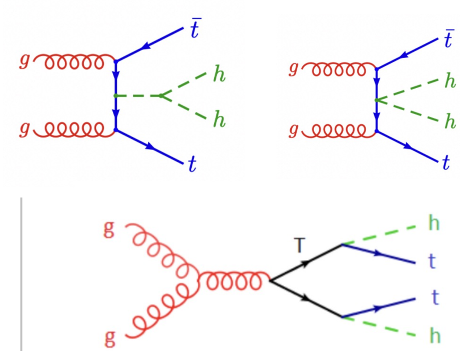
CMS-PAS-FTR-21-003

ttHH signature can be enhanced through

- Non-SM κ_λ
- Composite Higgs models
- Presence of heavy top partners

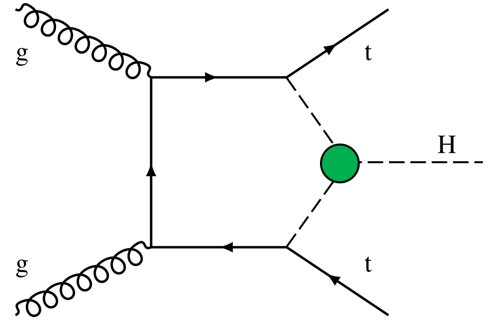
CMS ttHH(4b) analysis expectes σ(ttHH)<3.14 xSM

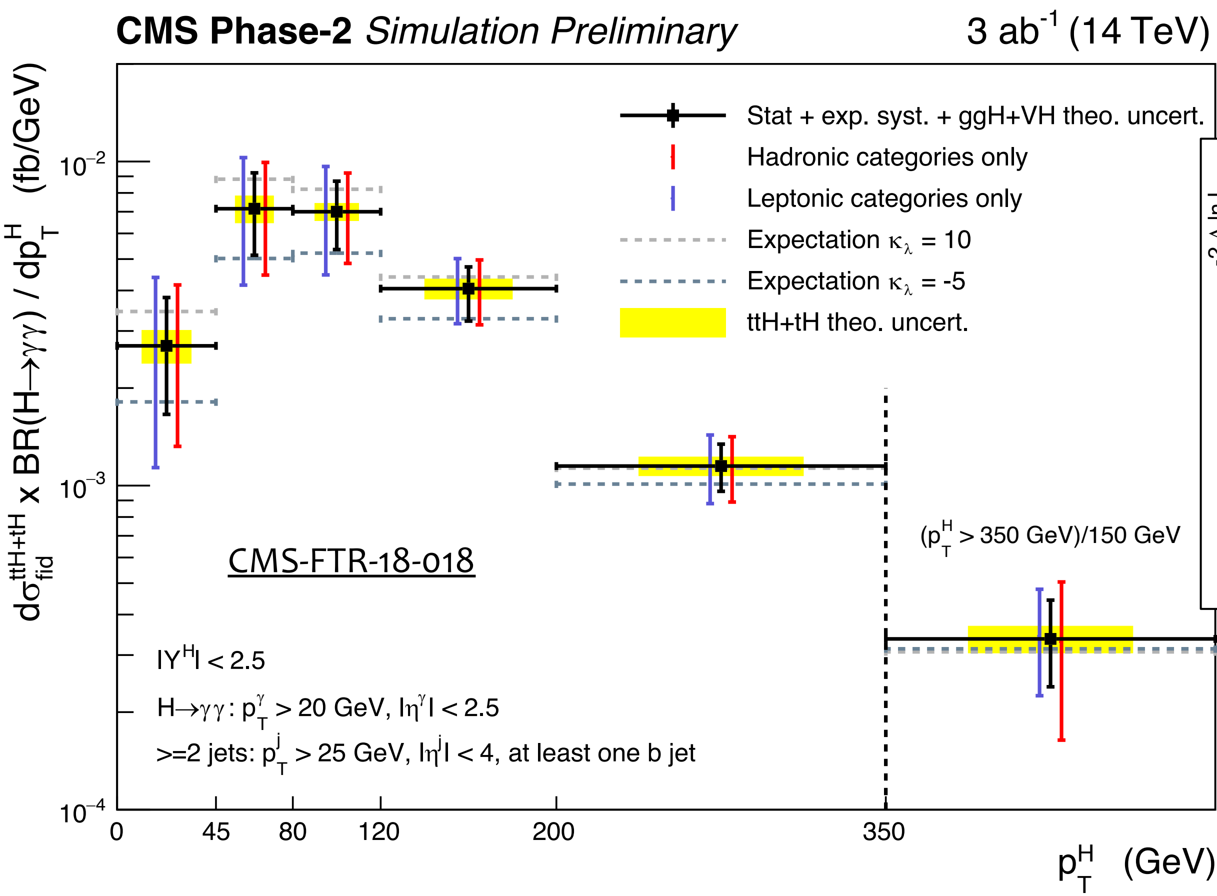


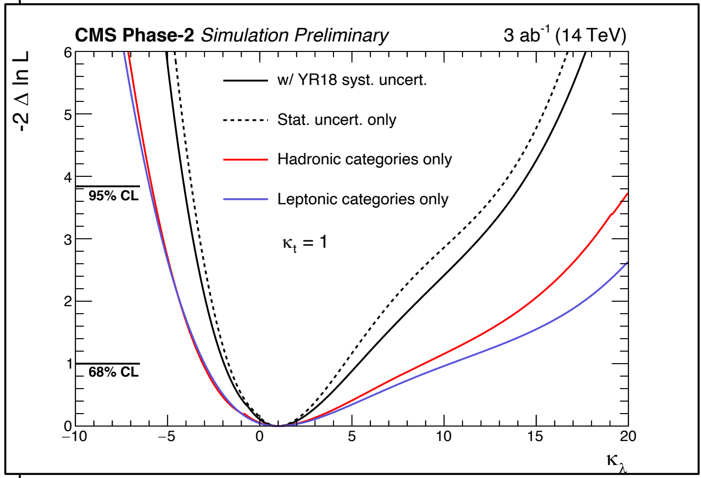


New angles of attack

Combinations with **precision differential measurements** of **Higgs production** will push even further!



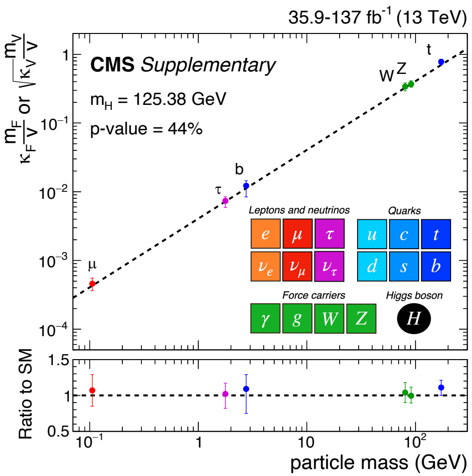




$\mathcal{L}_{int}$ (ab^{-1})	68% interval	95% interval
1	[-3.1,10.9]	[-6.2,20+]
2	[-2.2,6.5]	[-4.6,17.0]
3	[-1.9,5.3]	[-4.1,14.1]

Maximising reach in New Physics

On-shell

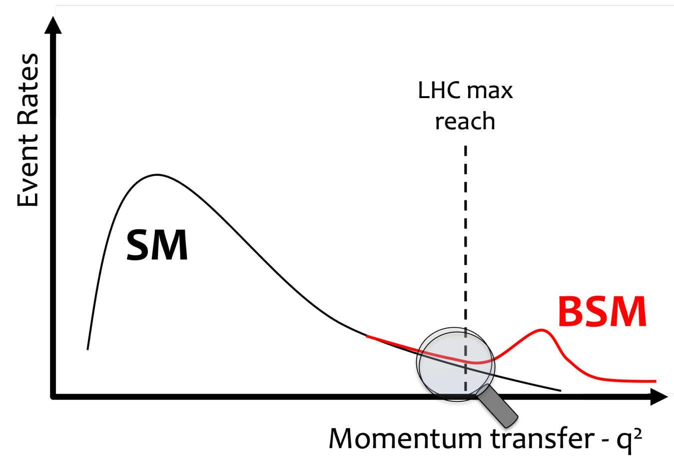


$$\delta \sim \left(\frac{v}{\Lambda}\right)^2$$

Inclusive κ : high-precision yields precision on new physics scale

δ_κ = 1% → Λ ~ 2.5 TeV

Off-shell / large q^2



$$\delta \sim \left(\frac{q}{\Lambda}\right)^2$$

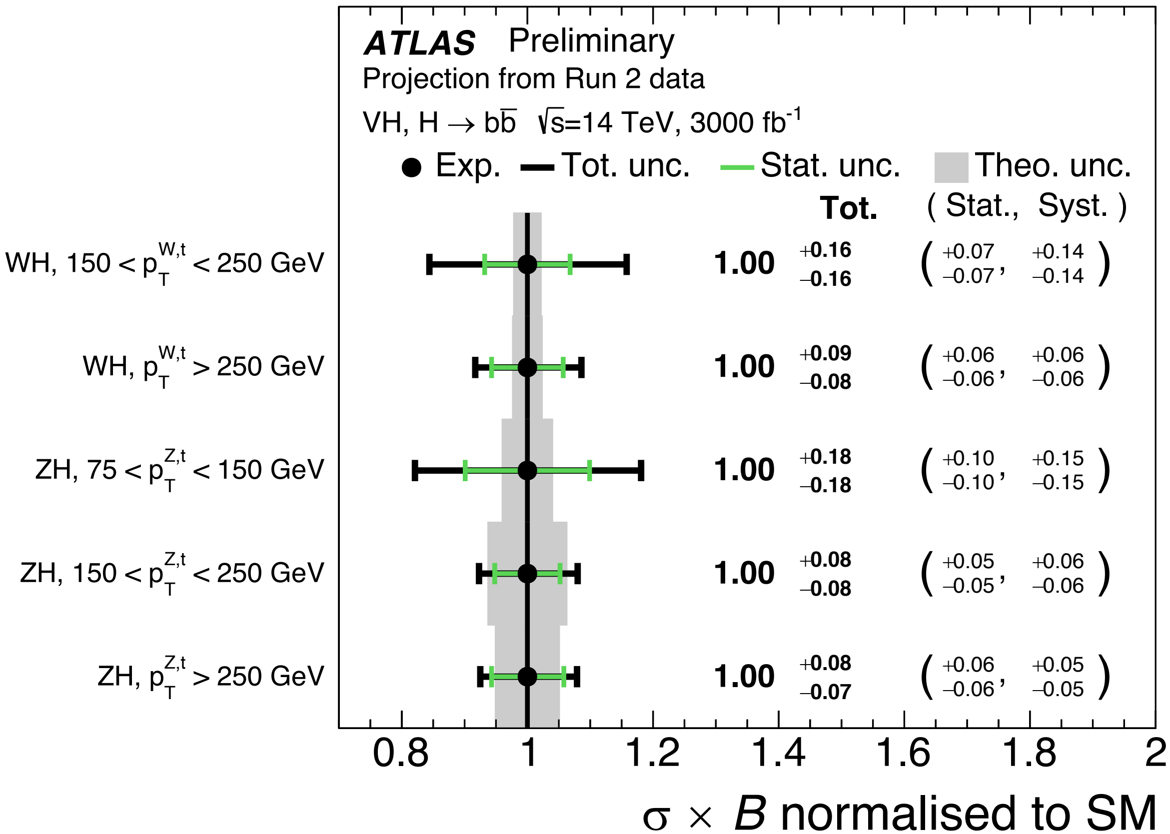
Differential: High momentum production sensitive to new physics

δ_σ = 15% (*q*=1TeV) → Λ ~ 2.5 TeV

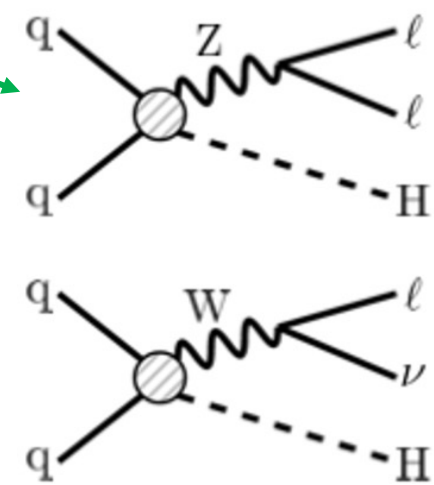
Include **differential measurements** to exploit sensitivity at LHC!

Differential VH→bb

At HL-LHC, expect comparable experimental and theoretical uncertainty at High $p_T(V)$ bins → high $p_T(V)$ bins sensitive to operators with anomalous qqZH interactions!



ATL-PHYS-PUB-2021-039



MC stats uncert ~5% impact in high p_T (not included here)
→ Need to ensure we can produce high statistics MC samples at HL-LHC!

STXS H→ττ

Simplified Template Cross Sections designed in stages as more data are collected

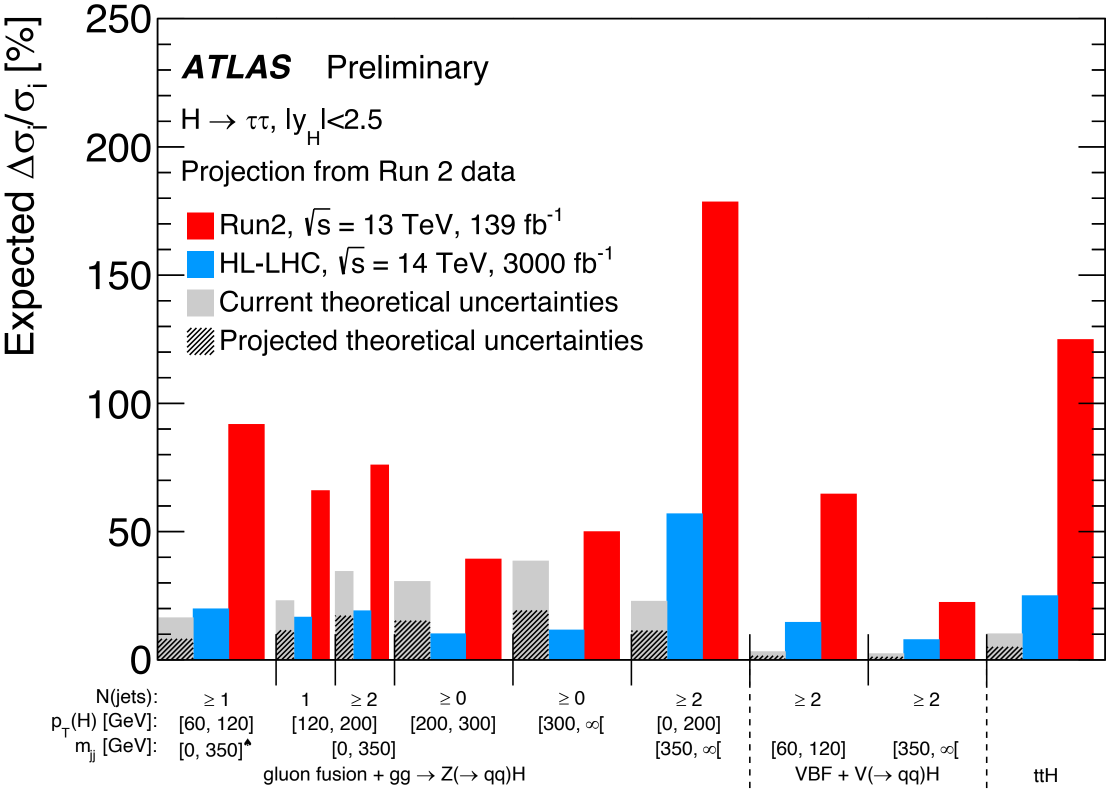
- Designed to be an evolution of the signal strength measurements with kinematic bins to reduce theoretical uncertainty

ATL-PHYS-PUB-2022-003

ATLAS STXS Stage 1.2 measurements in H→ττ projected to HL-LHC

- Several scenarios in which experimental precision will be greater than theoretical!

- With 3/ab of data, expect finer binning possible → greater sensitivity to EFT

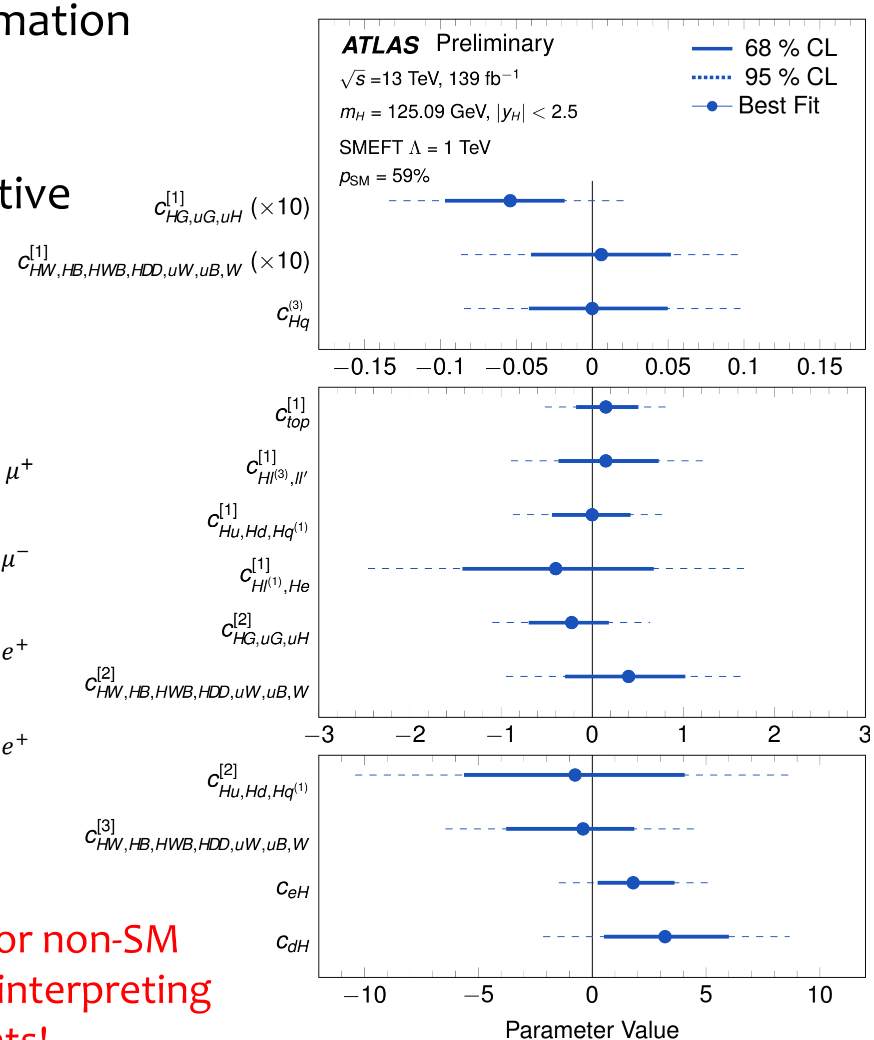


EFT Interpretations – caveat 1.

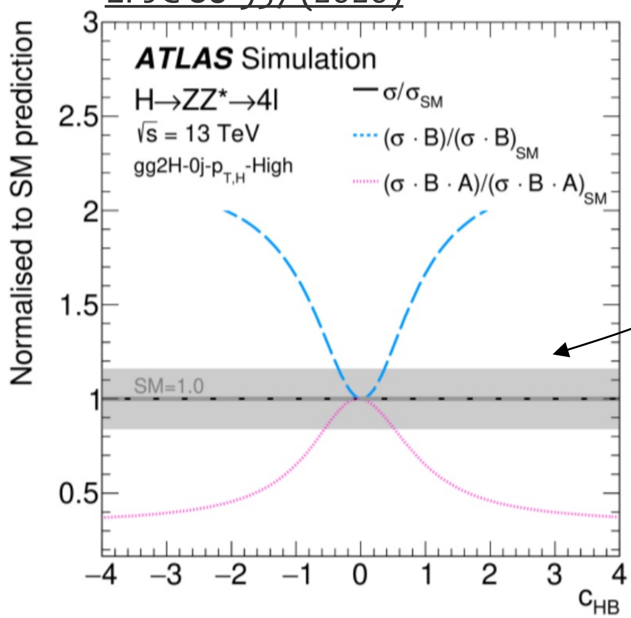
ATLAS-CONF-2021-053

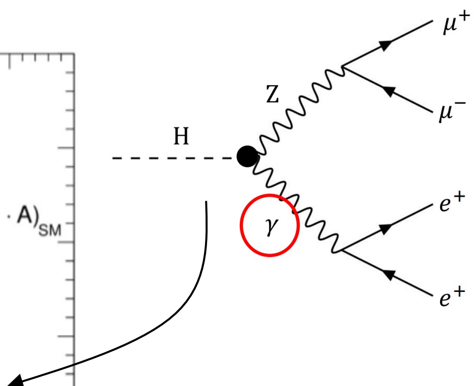
STXS measurements don’t include relevant information about decay of the Higgs

- Angular information (eg in 4l final state) sensitive to BSM effects
- ATLAS/CMS use MELA/BDT to exploit this information



EPJC **80** 957 (2020)



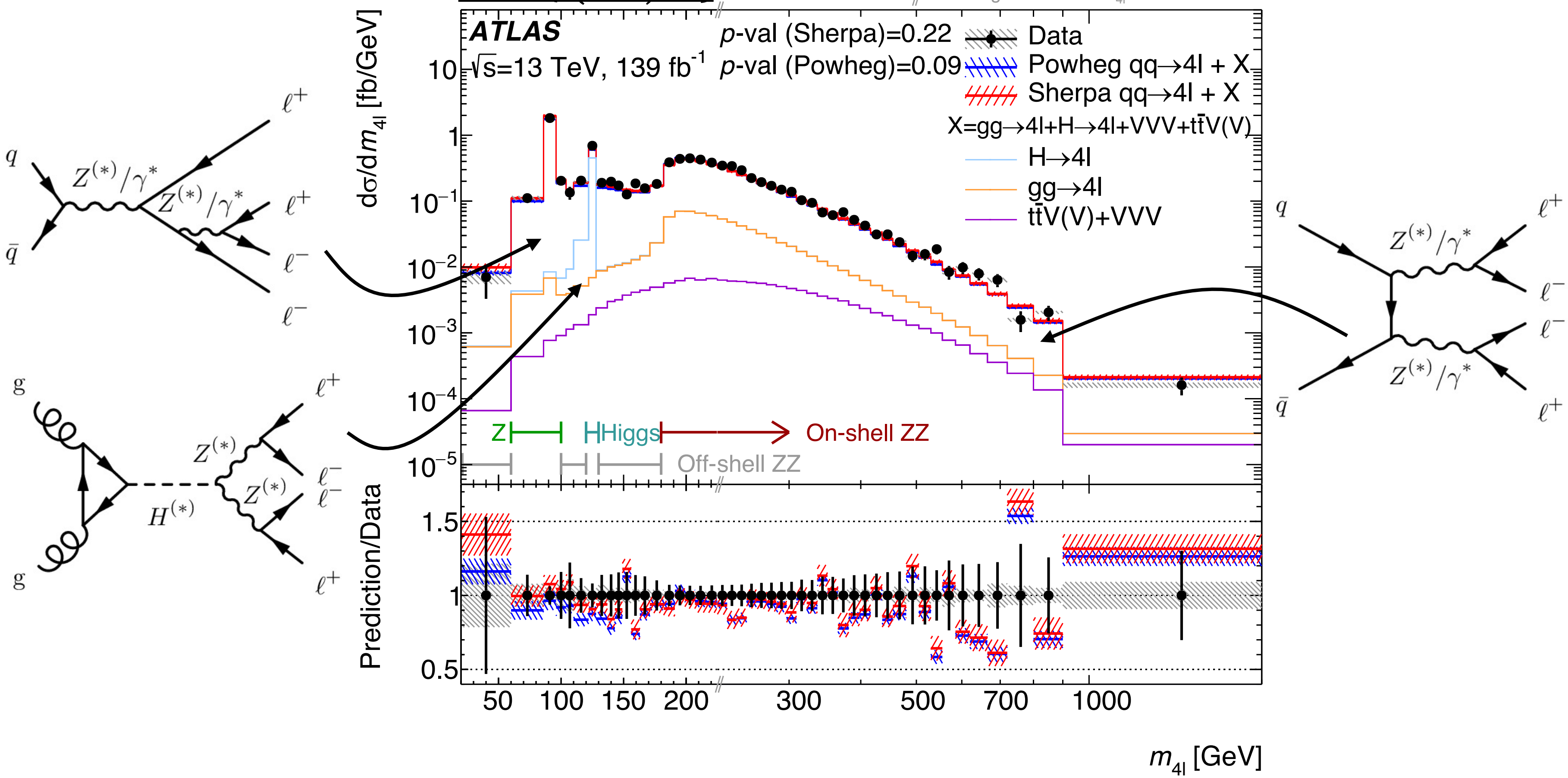


Need to account for non-SM acceptance when interpreting STXS measurements!

EFT Interpretations – caveat 2.

CMS/ATLAS are used to thinking of **Signal** / **Background** → But EFT is a global approach!

JHEP 07 (2021) 005

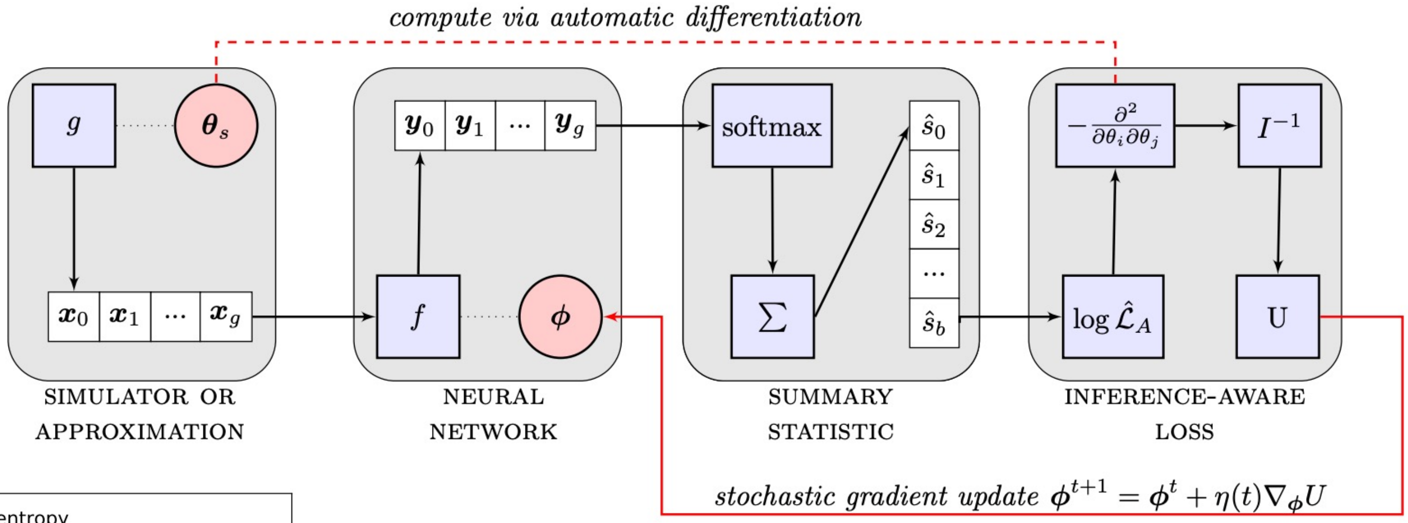


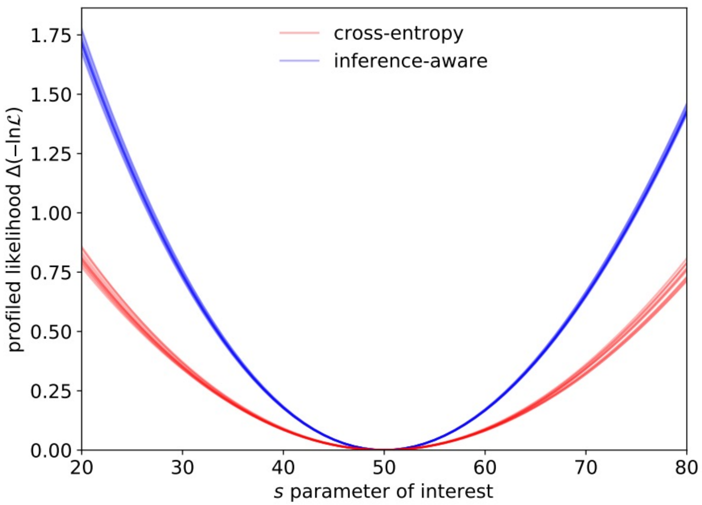
Full pp→4l combinations are the correct way to interpret the data

→Need to consider all contributions together to fully exploit our data

New ideas to reduce effect of systematics

At HL-LHC, many (precisions Higgs boson) measurements will be systematics limited
→ can we do better at reducing their impact?





Machine learning ubiquitous for signal-vs-background / signal classification → Typically not tuned for inference

INFERNO: Inference-Aware Neural Optimisation (https://arxiv.org/abs/1806.04743)

See also:
https://arxiv.org/abs/1611.01046 (adversarial training to reduce effects of systematics)
https://arxiv.org/abs/2003.07186 (including parametric uncertainties in the optimization metric)

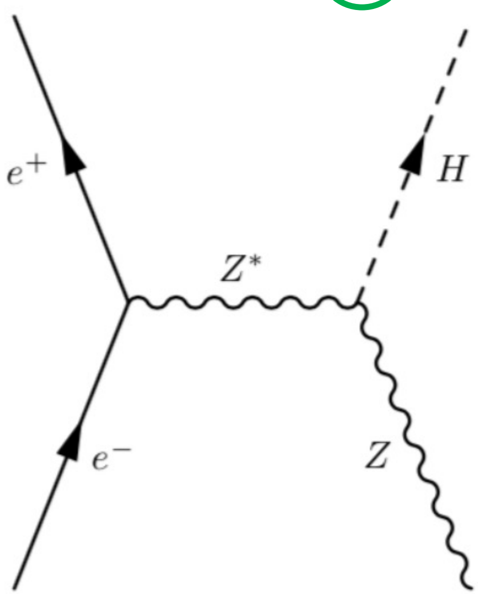
Next generation

Future e^+e^- colliders (eg FCC-ee) will provide ultimate precision in certain couplings

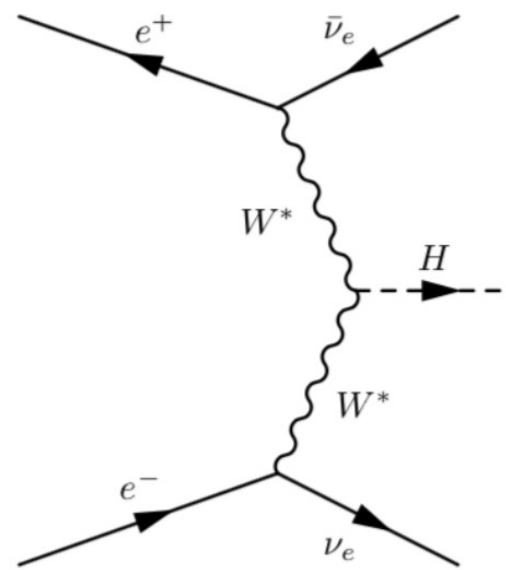
Total ZH cross-section measured from "missing mass" $m^2_{\text{recoil}} = (\sqrt{s} - E_{ll})^2 - |\vec{p}_{ll}|^2$ combined with total VBF cross-section

→ Access to **total width** and precision Higgs couplings

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{X}\overline{\mathrm{X}}) \propto \frac{g^2_{\mathrm{HZZ}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$



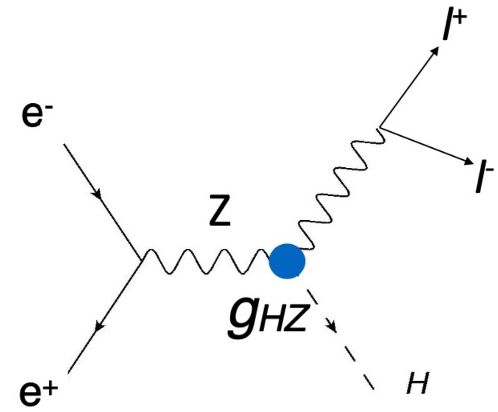
$$\sigma_{\mathrm{H}\nu_e\bar{\nu}_e} \times \mathcal{B}(\mathrm{H} \to \mathrm{X}\overline{\mathrm{X}}) \propto \frac{g^2_{\mathrm{HWW}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

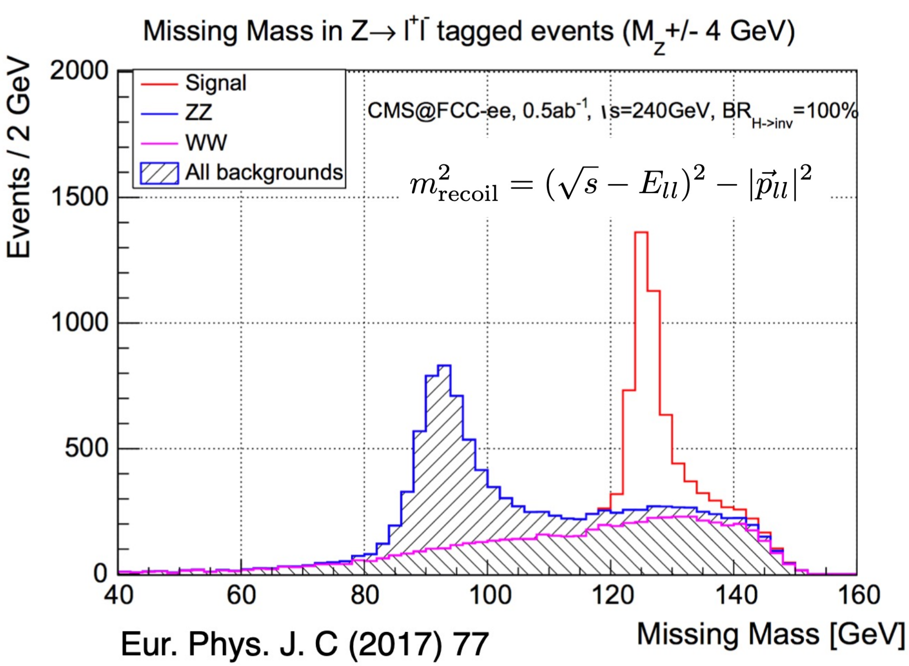


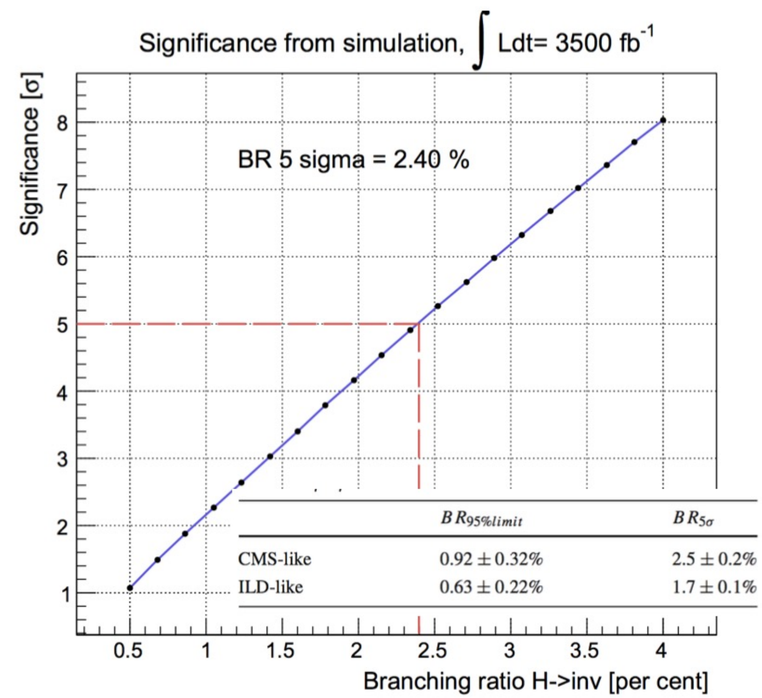
Next generation

Future e^+e^- colliders (eg FCC-ee) will provide ultimate precision in certain couplings

→ Access to **total width** and precision Higgs couplings
→ B(H→inv) as small as 2.4% observable at 5σ @FCC-ee







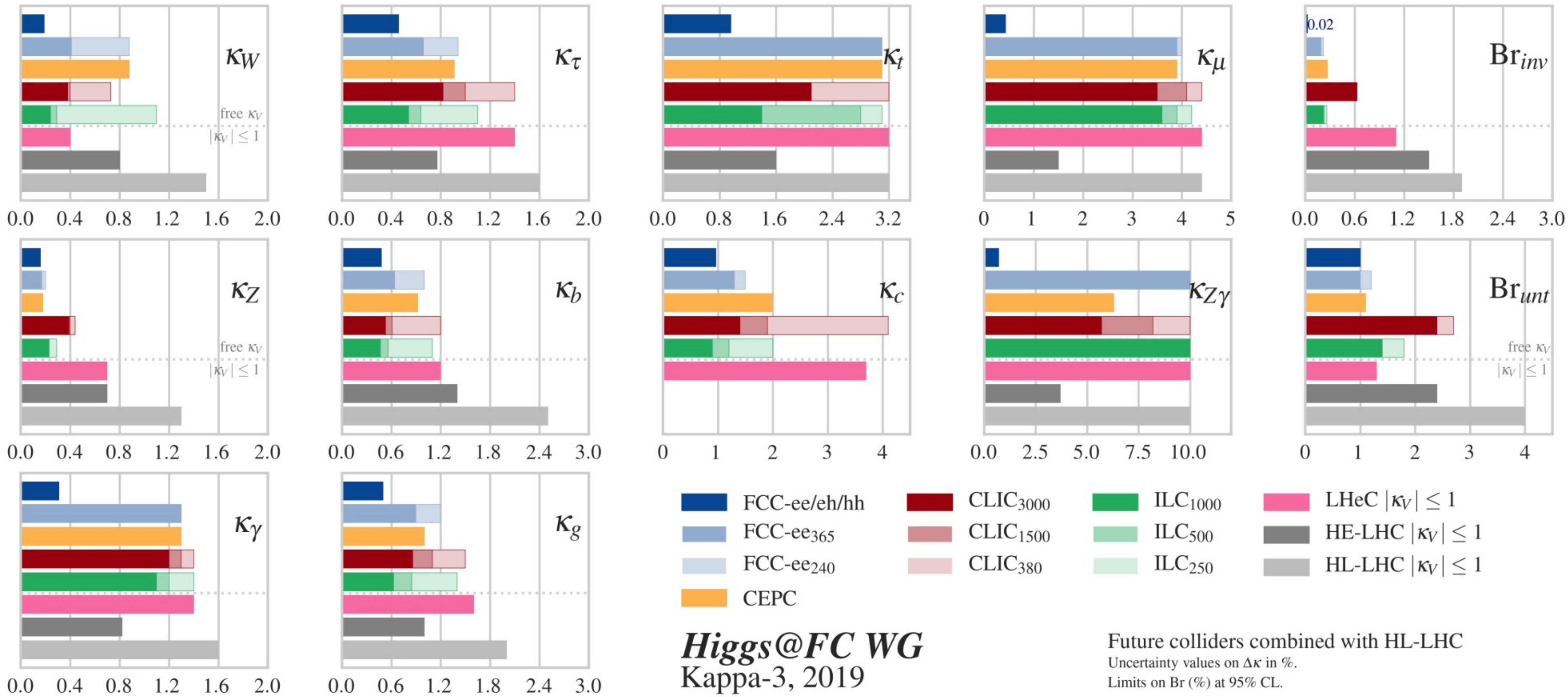
	$BR_{95\%limit}$	$BR_{5\sigma}$
CMS-like	$0.92 \pm 0.32\%$	$2.5 \pm 0.2\%$
ILD-like	$0.63 \pm 0.22\%$	$1.7 \pm 0.1\%$

Next generation

Sub-percent precisions achievable during FCC program (W, Z, b, τ)!

- Couplings to μ/γ/Zγ benefit the most from the large dataset available at HL-LHC
- High energy collider required to improve on H-top coupling

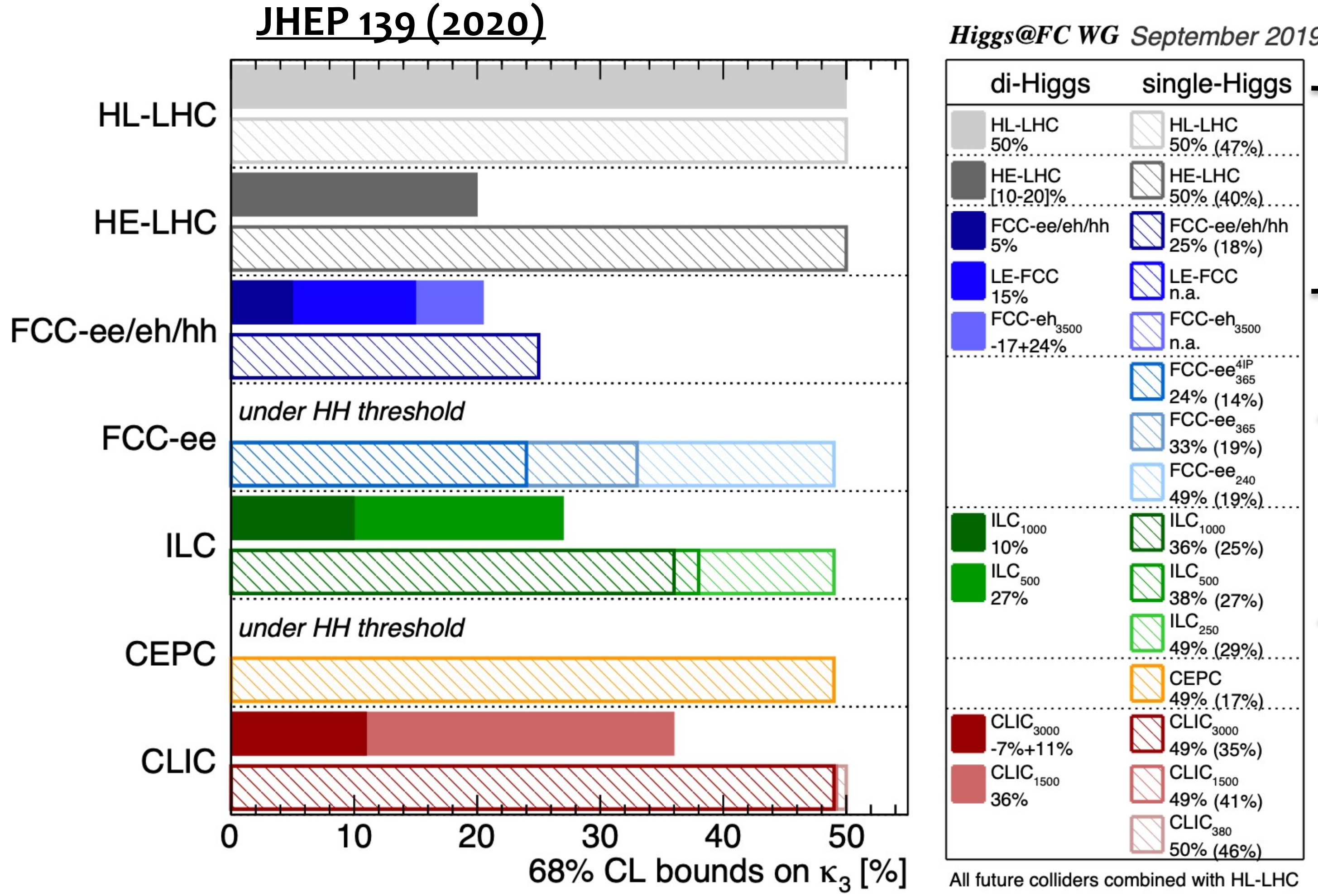
JHEP 139 (2020)

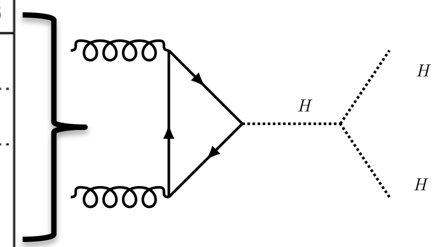


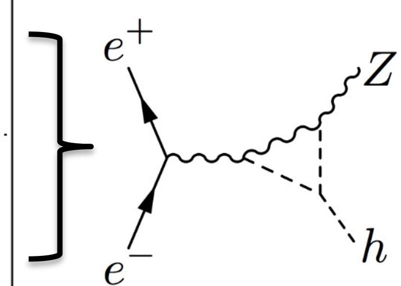
Next-Next generation?

Higgs self-coupling @ future colliders → complimentary approaches provide ultimate reach in self-coupling

JHEP 139 (2020)







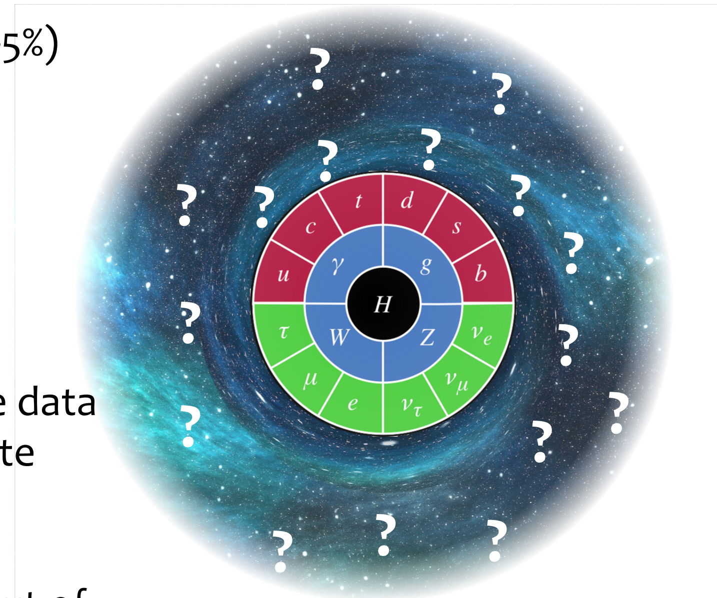
Summary

The Higgs boson turns 10 this year but we are far from finished studying it

- LHC has collected ~few % of its total dataset

Many studies available to explore the reach of the HL-LHC

- Higgs boson couplings could be measured down to O(2-5%) level in many cases!
- Several recent updates submitted for Snowmass show improvements to analyses during Run-3



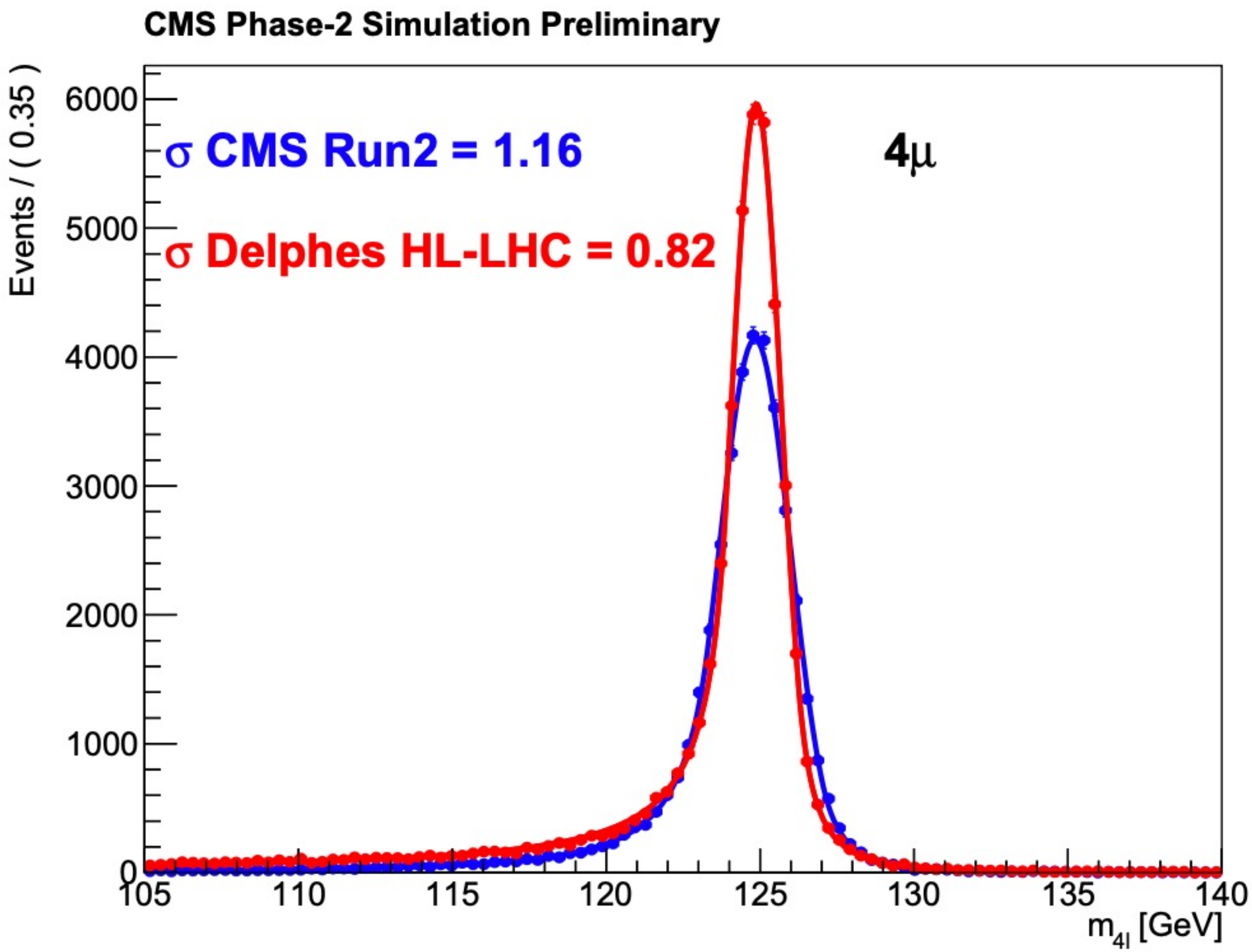
More data brings new techniques/opportunities!

- Moving away from inclusive measurements (going differential) brings new insights only possible with more data
- Need to make sure our analyses methods keep up to date with the data → triggers, ID/tagging, MC simulation production must maintain / improve in performance
- New ideas for data analysis available to squeeze more out of the data!

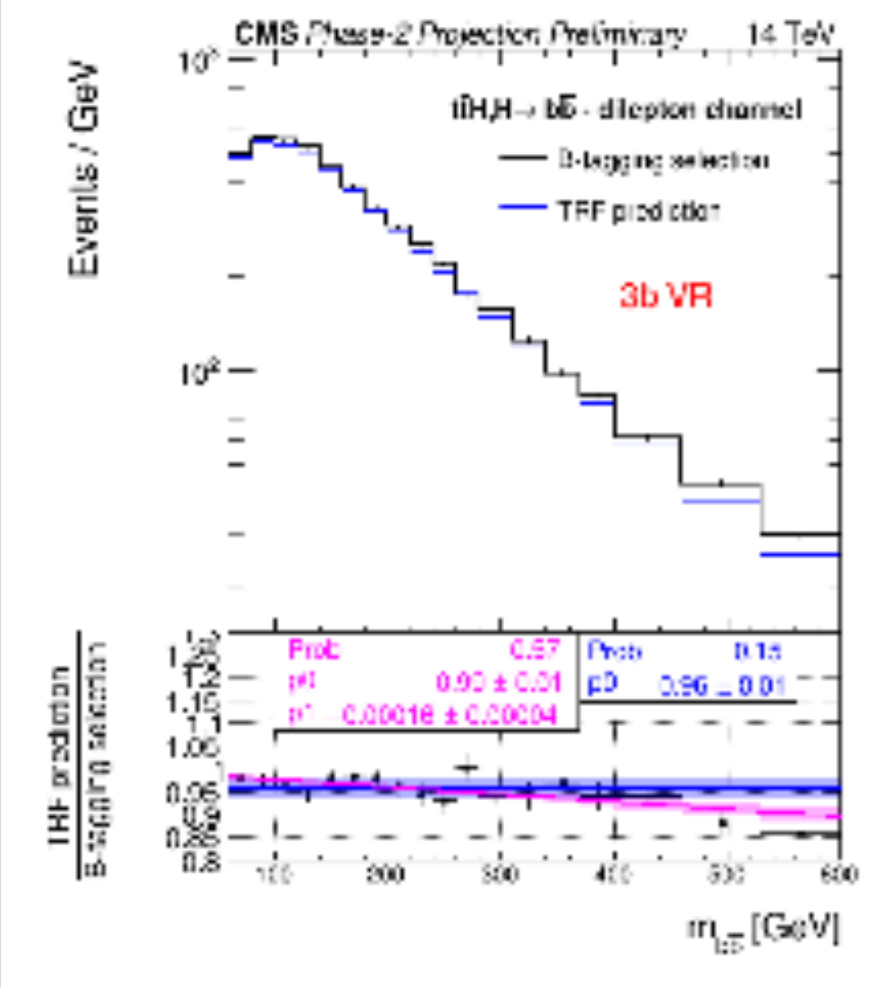
Next generation lepton-collider will provide new measurements (Γ_H) but several measurements (rare decays, self-coupling) will need the HL-LHC & higher energy machines to pin down!

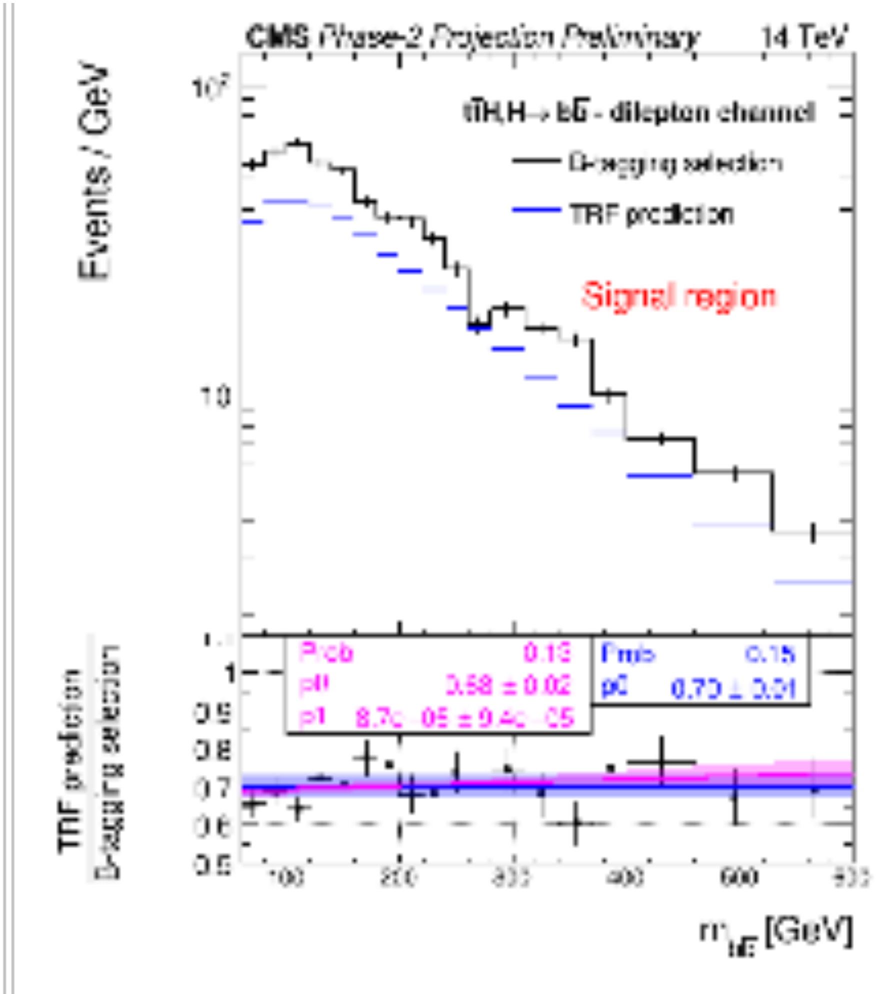
Backup

H→4l mass resolution



ttH→bb TRF method





ttH→bb Uncertainty scenarios

- **Statistical uncertainties only** This scenario indicates the ultimate precision limit. Statistical uncertainties are scaled by $1/\sqrt{L}$, while systematic uncertainties are neglected.
- **Run 2 uncertainties scenario** For the second uncertainty scenario the current Run 2 uncertainty values are used for all integrated luminosity projections. This scenario is unrealistically pessimistic since by definition there will be an increase in the available number of data and simulated events which in this case is not taken into account. This projection is shown to highlight how the sensitivity would evolve by only reducing the statistical uncertainties.
- **Conservative scenario** The third uncertainty scenario depicts the worst case one, where the background normalization uncertainty, originating from the data and simulation agreement in the CR, remains the same. With the current available number of events we do not see any difference between data and simulation within the 2% uncertainty level. In this case, we assume that while the available number of events increases, this 2% factor remains. The background shape uncertainty, related with the background correction factor obtained from simulation, is scaled according to the expected MC luminosity as $1/\sqrt{L}$. For this, the current ratio of simulated to data events ($\times 10$) is used. For all additional sources of systematic uncertainties, the Run 2 values are used. The evolution of the uncertainties can be seen in Fig. 5.
- **Realistic scenario** The final uncertainty scenario is considered the most realistic one, where both the background normalization and the background shape uncertainties are scaled with the increase in luminosity as $1/\sqrt{L}$. The background normalization uncertainty depends on the number of data events and its evolution as a function of the integrated luminosity can be seen in Fig. 6. For the background shape uncertainty projection, which depends solely on the number of available simulated events, the evolution can be observed in Fig. 6 and Fig. 5 where ten times more MC than data events are assumed. For the theoretical uncertainties related to the signal (QCD scale and PDF+α_s uncertainties) the YR18 recommendations [44] are followed. According to these, the current uncertainty values, which are calculated at 14 TeV [11], are reduced by a factor of two. For all additional sources of systematic uncertainties, the Run 2 values are considered.

ATLAS ttH(bb)

tt+HF modeling based on MC
Dominant uncertainties at Run-2 but with HL-LHC, expect additional data to help constrain nuisance parameters via profiing

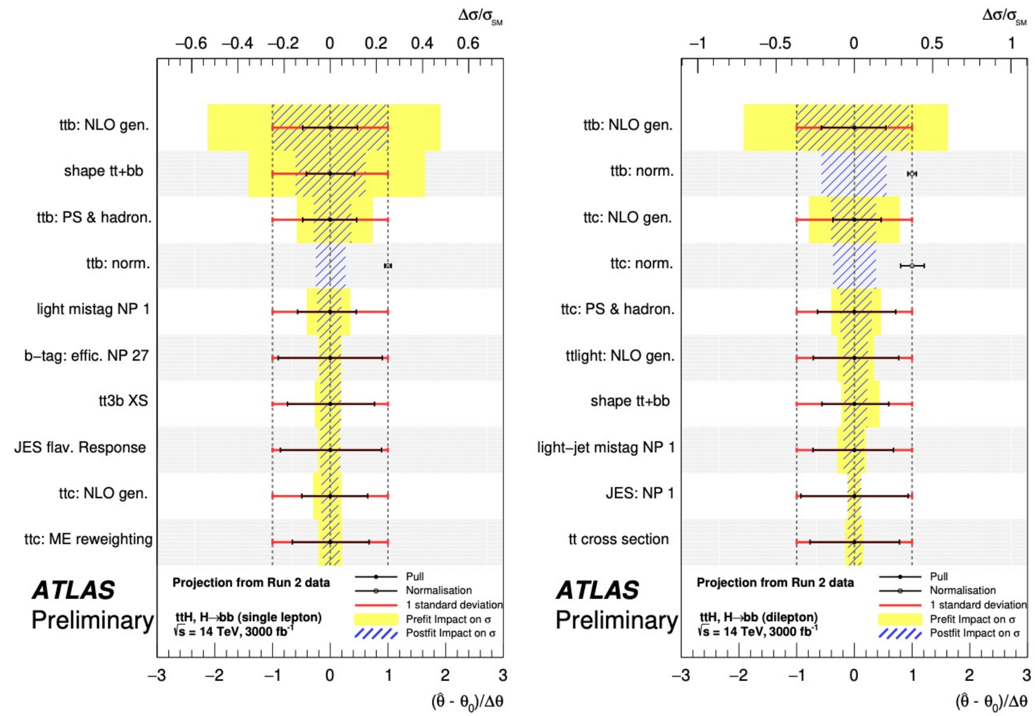


Fig. 20: Ranking of the ten most significant systematics uncertainties under S2 in the single lepton (a) and di-lepton (b) final states at ATLAS listed in accordance to their post-fit impact on the $t\bar{t}H$ cross section.

Final state	Scenario	Δ_{tot}/σ_{SM}	$\Delta_{stat}/\sigma_{SM}$	Δ_{exp}/σ_{SM}	Δ_{sig}/σ_{SM}	Δ_{bkg}/σ_{SM}	$\Delta\mu_{sig}$
$t\bar{t}H, H \to b\bar{b}$ (single lepton)	Run 2, 36 fb^{-1}	$^{+0.61}_{-0.61}$	$^{+0.22}_{-0.22}$	$^{+0.27}_{-0.28}$	$^{+0.10}_{-0.09}$	$^{+0.47}_{-0.47}$	$^{+0.15}_{-0.15}$
	HL-LHC S1	$^{+0.25}_{-0.20}$	$^{+0.02}_{-0.02}$	$^{+0.10}_{-0.10}$	$^{+0.08}_{-0.06}$	$^{+0.22}_{-0.17}$	$^{+0.10}_{-0.11}$
	HL-LHC S2	$^{+0.18}_{-0.15}$	$^{+0.02}_{-0.02}$	$^{+0.09}_{-0.09}$	$^{+0.06}_{-0.05}$	$^{+0.14}_{-0.11}$	$^{+0.08}_{-0.07}$
$t\bar{t}H, H \to b\bar{b}$ (di-lepton)	Run 2, 36 fb^{-1}	$^{+1.06}_{-1.08}$	$^{+0.51}_{-0.51}$	$^{+0.32}_{-0.31}$	$^{+0.11}_{-0.12}$	$^{+0.90}_{-0.92}$	$^{+0.14}_{-0.14}$
	HL-LHC S1	$^{+0.32}_{-0.26}$	$^{+0.06}_{-0.06}$	$^{+0.13}_{-0.13}$	$^{+0.08}_{-0.07}$	$^{+0.27}_{-0.21}$	$^{+0.11}_{-0.09}$
	HL-LHC S2	$^{+0.23}_{-0.20}$	$^{+0.06}_{-0.06}$	$^{+0.11}_{-0.11}$	$^{+0.06}_{-0.06}$	$^{+0.17}_{-0.15}$	$^{+0.08}_{-0.08}$

Reinterpretation recommendations

S. Kraml @Reinterp2021

Recommendations emphasise:

1. Prompt availability of numerical analysis data in digitised electronic form to enable re-use.
2. More complete publication of full-detail experimental data:
   - correlation information
   - public likelihoods
   - Open Data
   - forensic analysis code preservation
   - ....
3. Community-wide dialogue regarding re-use of unbinned fits and machine-learning algorithms.

Moreover, theorists should (start) to follow the same reproducibility requirements as we ask them from the experiments.

SciPost SciPost Phys. 9, 022 (2020)

Reinterpretation of LHC results for new physics: status and recommendations after run 2

The LHC BSM Reinterpretation Forum

SciPostPhys.9.2.022 (2020)

Abstract

We report on the status of efforts to improve the reinterpretation of searches and measurements at the LHC in terms of models for new physics, in the context of the LHC Reinterpretation Forum. We detail current experimental offerings in direct searches for new particles, measurements, technical implementations and Open Data, and provide a set of recommendations for further improving the presentation of LHC results in order to better enable reinterpretation in the future. We also provide a brief description of existing software reinterpretation frameworks and recent global analyses of new physics that make use of the current data.

Received 02-04-2020
Accepted 06-08-2020
Published 21-08-2020
doi:10.21468/SciPostPhys.9.2.022

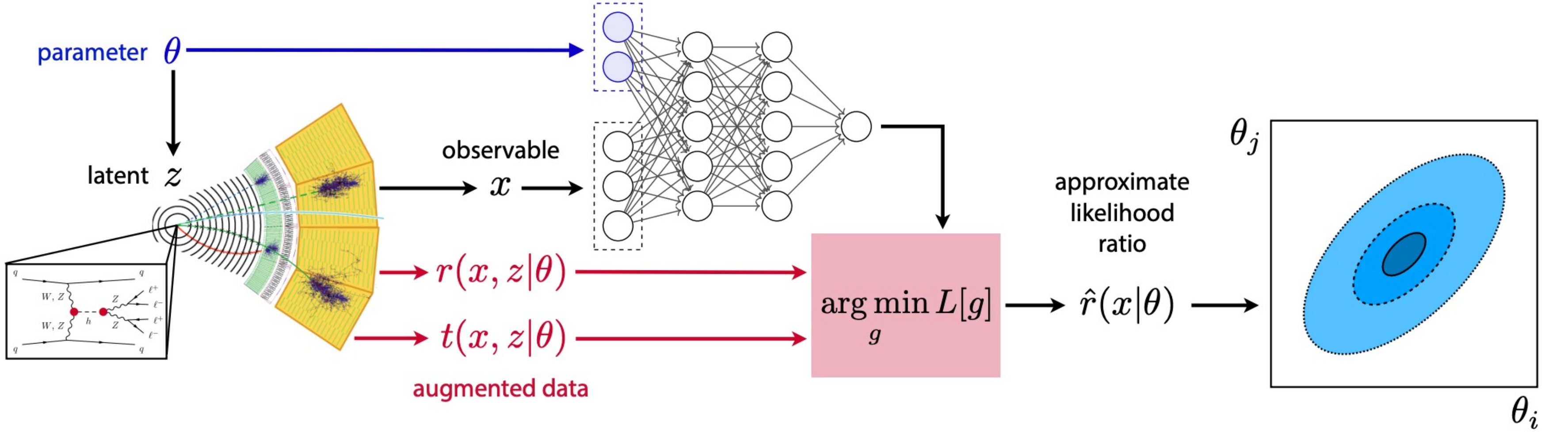
Check for updates

New whitepaper on open likelihoods!
SciPost open likelihoods

"Re-use means a ***longer legacy*** *for analyses, as well as compliance with ever stricter requirements of data-publication and reusability for publicly funded research."*

Optimal analyses

The future @ LHC could be to perform optimal analyses and inference that can be packaged up and preserved in totality!



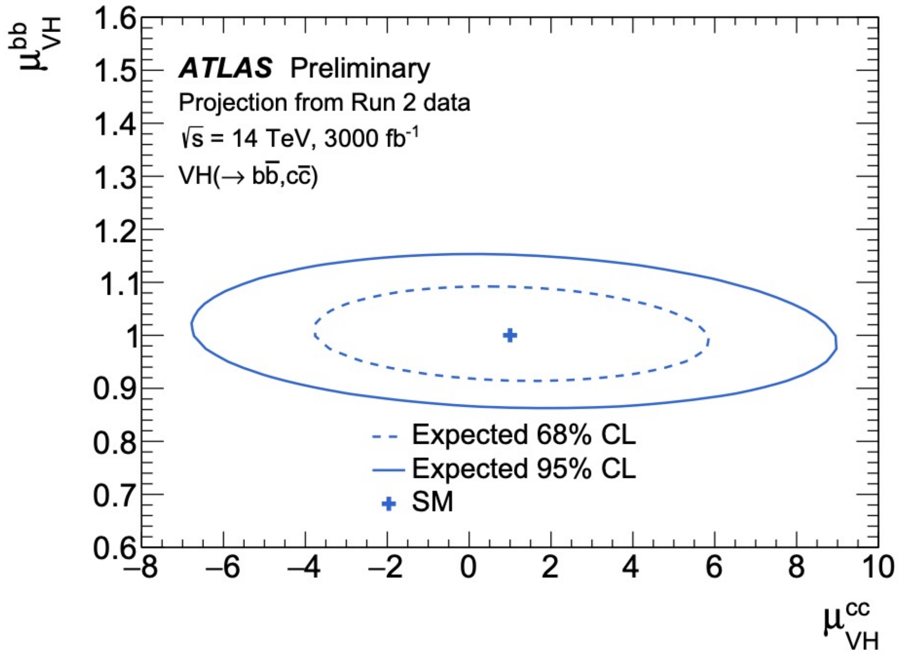
Simulation	Machine Learning	Inference
"Mining gold": Extract additional information from simulator	Use this information to train estimator for likelihood ratio	Limit setting with standard hypothesis tests

+ Open Neural Network Exchange — The open standard for machine learning interoperability: distribution

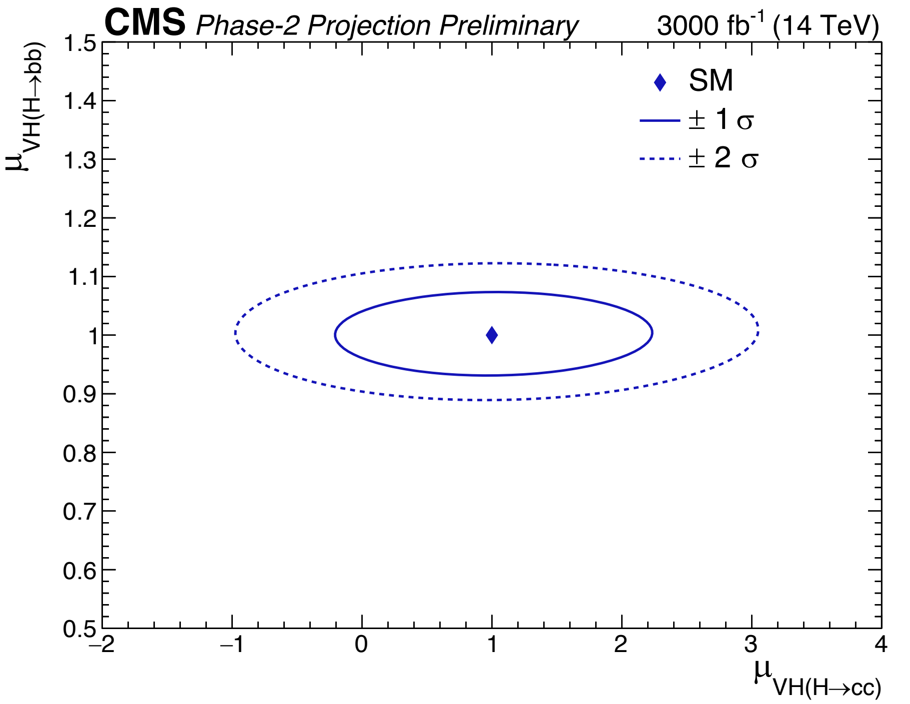
+ CI/CD: automation

https://github.com/diana-hep/madminer

VH→cc

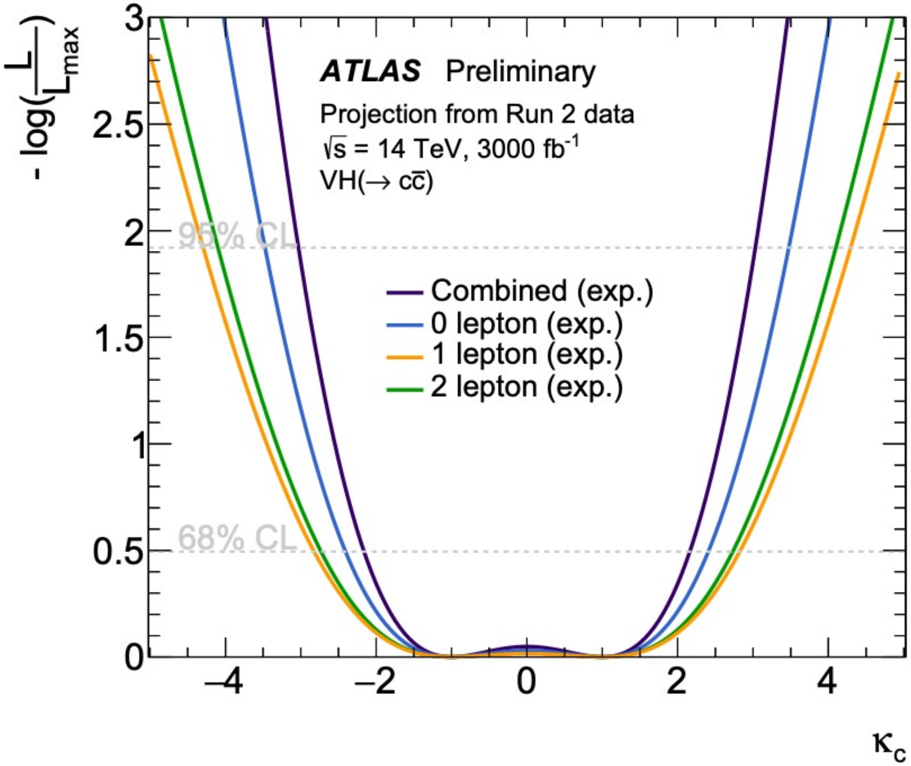


Jet-tagging (b/c separation) crucial to maintain minimal correlation.



VH→cc (ATLAS)

Channel	Expected Limit 68% CL	Expected Limit 95% CL
0-lepton	[-2.4, 2.4]	[-3.5, 3.5]
1-lepton	[-2.8, 2.8]	[-4.3, 4.3]
2-lepton	[-2.7, 2.7]	[-4.1, 4.1]
Combination	[-2.2, 2.2]	[-3.0, 3.0]



VH→bb (ATLAS @Run2)

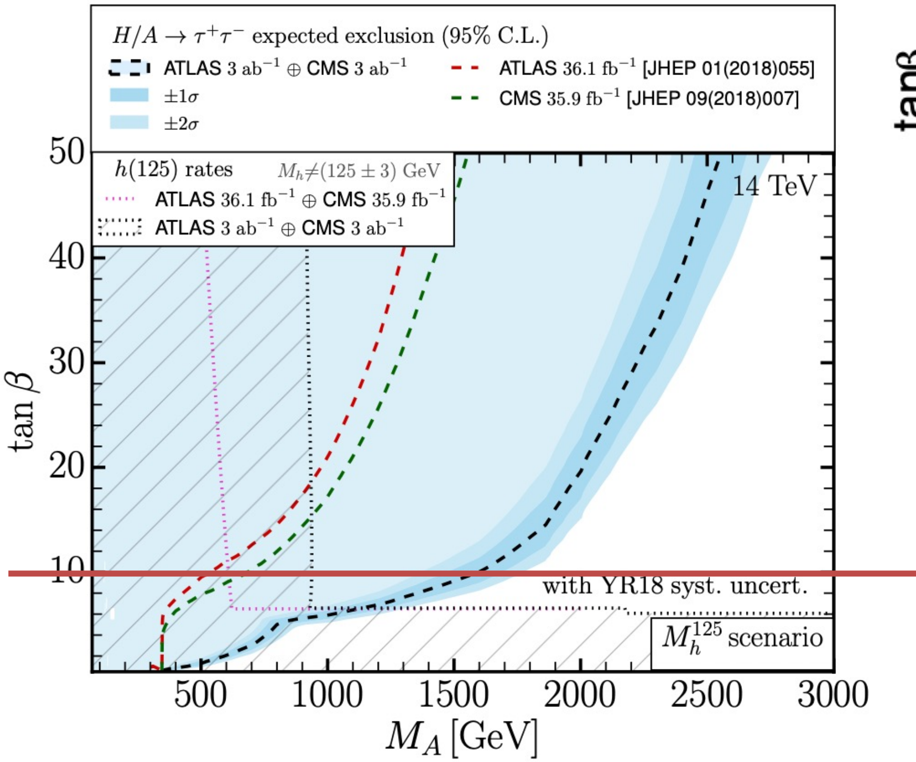
Table 12 Breakdown of the contributions to the uncertainty in μ_{VH}^{bb} for the VH, WH and ZH signal strength measurements. The sum in quadrature of the systematic uncertainties attached to the categories differs from the total systematic uncertainty due to correlations

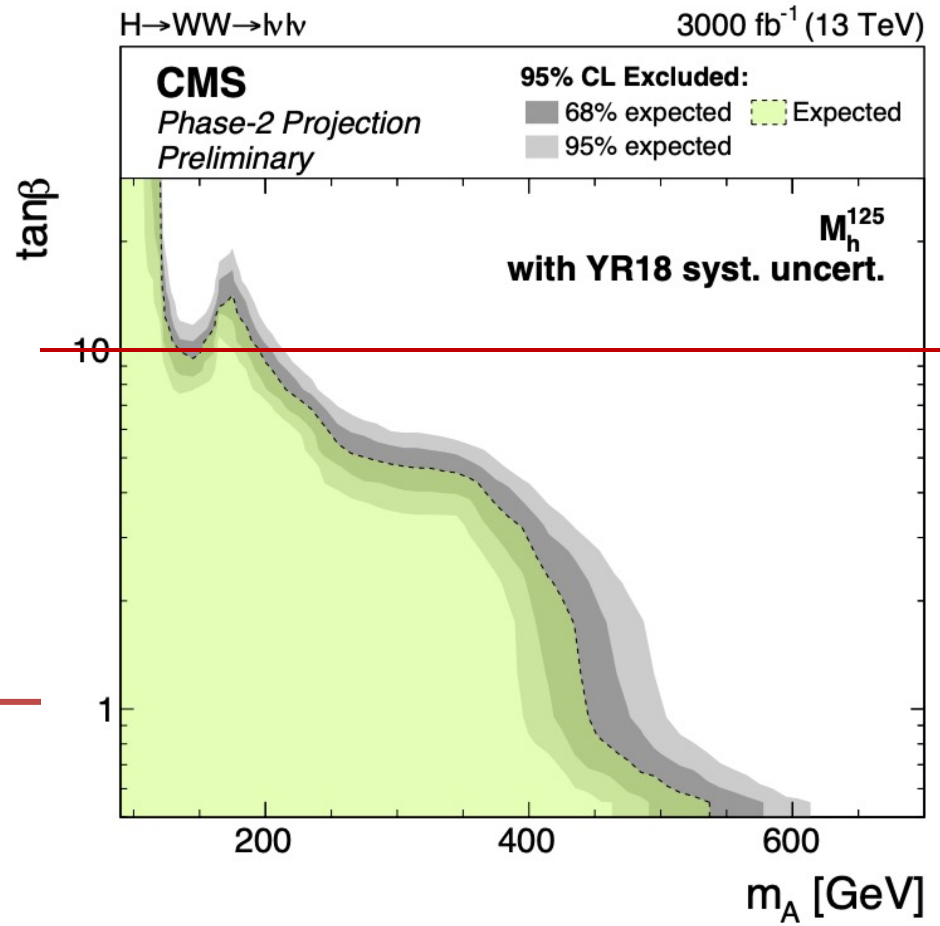
Source of uncertainty		σ_μ VH	WH	ZH
Total		0.177	0.260	0.240
Statistical		0.115	0.182	0.171
Systematic		0.134	0.186	0.168
Statistical uncertainties				
Data statistical		0.108	0.171	0.157
$t\bar{t}$ $e\mu$ control region		0.014	0.003	0.026
Floating normalisations		0.034	0.061	0.045
Experimental uncertainties				
Jets		0.043	0.050	0.057
E_T^{miss}		0.015	0.045	0.013
Leptons		0.004	0.015	0.005
b-tagging	b-jets	0.045	0.025	0.064
	c-jets	0.035	0.068	0.010
	light-flavour jets	0.009	0.004	0.014
Pile-up		0.003	0.002	0.007
Luminosity		0.016	0.016	0.016
Theoretical and modelling uncertainties				
Signal		0.072	0.060	0.107
Z + jets		0.032	0.013	0.059
W + jets		0.040	0.079	0.009
$t\bar{t}$		0.021	0.046	0.029
Single top quark		0.019	0.048	0.015
Diboson		0.033	0.033	0.039
Multi-jet		0.005	0.017	0.005
MC statistical		0.031	0.055	0.038

Heavy Higgs bosons

Searches for Heavy Higgs bosons improve with additional data (reach into tails from high statistics) → LHC Energy limits the ultimate reach in mass scales

YR18





CMS-PAS-HIG-20-016