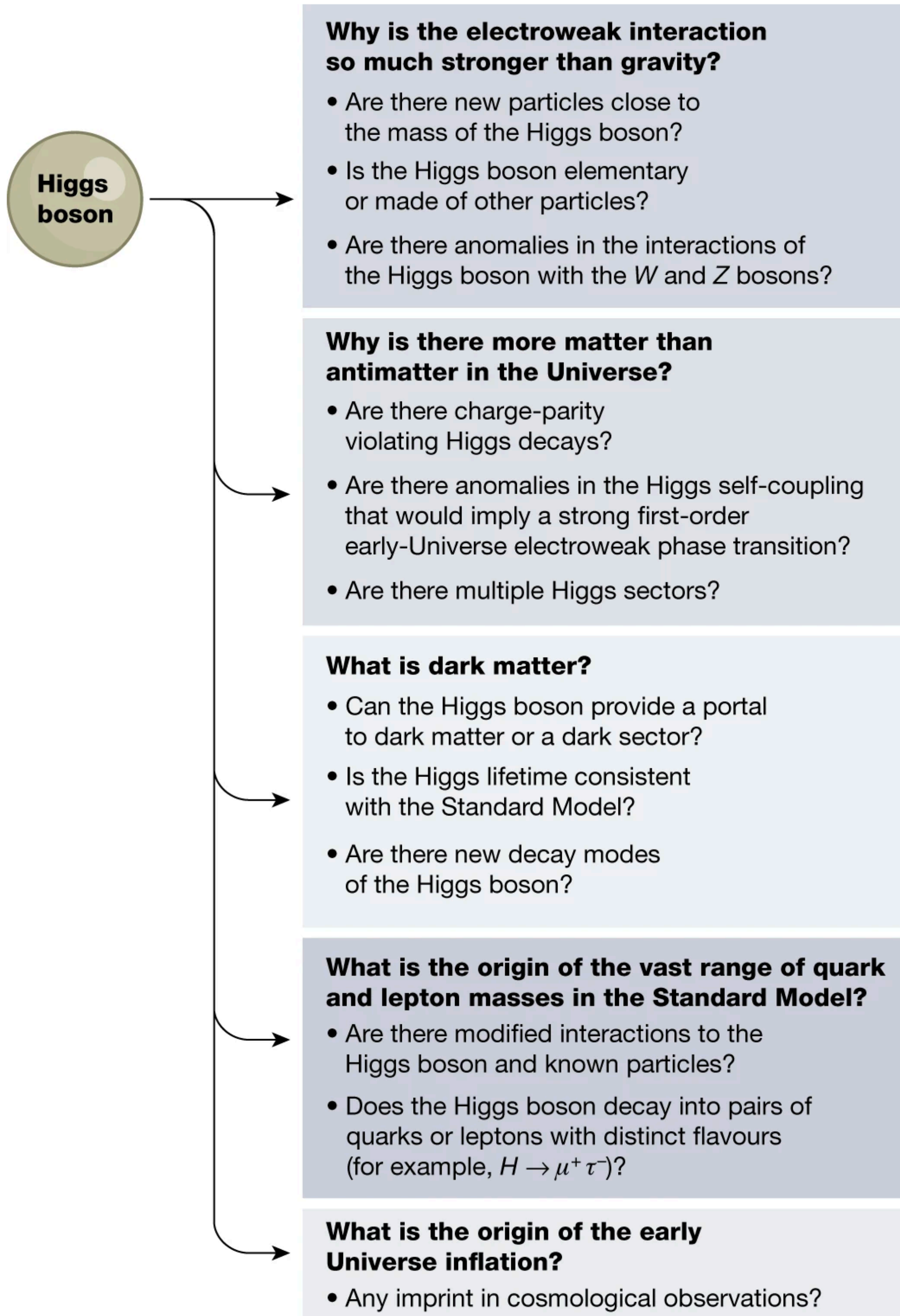
Paolo Meridiani

09/03/2023 - La Thuile 2023 - Les Rencontres de Physique de la Vallée d'Aoste

Higgs couplings and properties

HIGGS: A BROAD PHYSICS PROGRAM



Nature 607, 41-47 (2022)

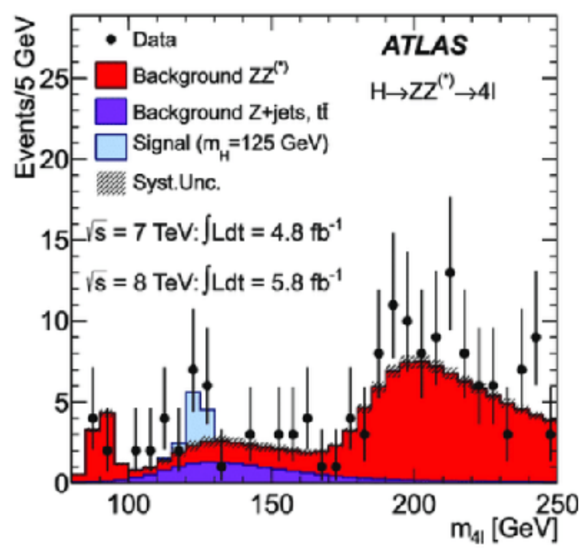
Higgs discovery opened the door to a new sector of fundamental interactions

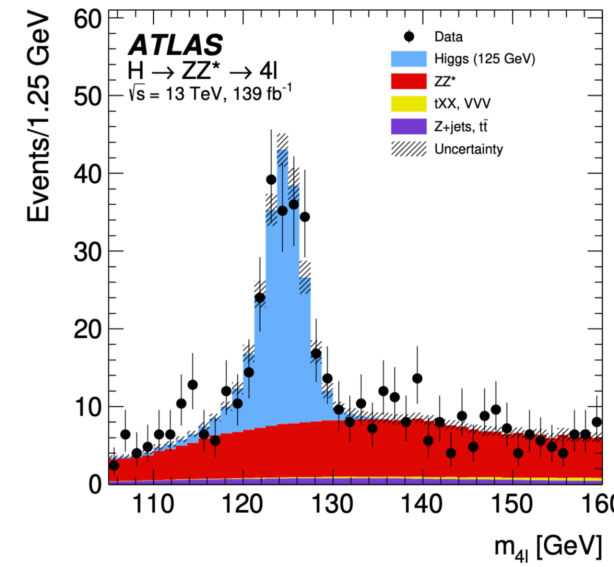
Higgs the only fundamental scalar discovered so far is linked to the most fundamental OPEN questions in particle physics

Studying the Higgs properties could shed light to some of these questions (especially in absence of direct BSM):

- Higgs couplings (including self-coupling, more in G. Palacino's talk tomorrow)
- Higgs total width
- Differential/fiducial cross-sections
- Anomalous couplings (CP-violation)
- Additional scalars
- BSM Higgs decays
- …

A LONG ROAD FOR H(125)





Since discovery stat increased x ~30

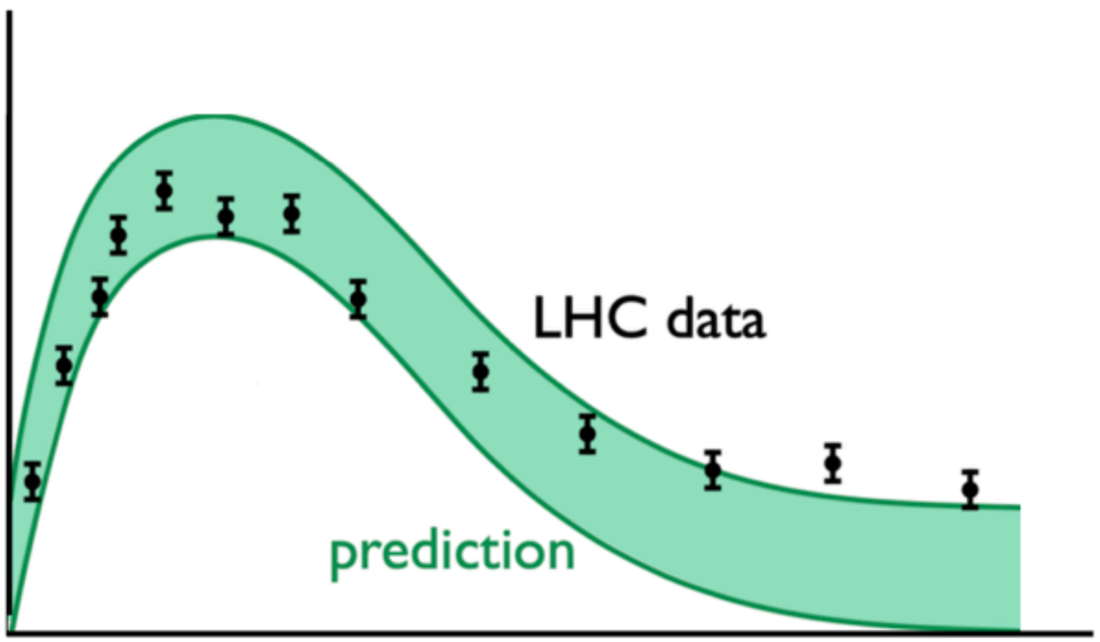
~10M Higgs produced per experiment

ATLAS ~180 papers, CMS ~150 papers published/submitted on Higgs physics after discovery

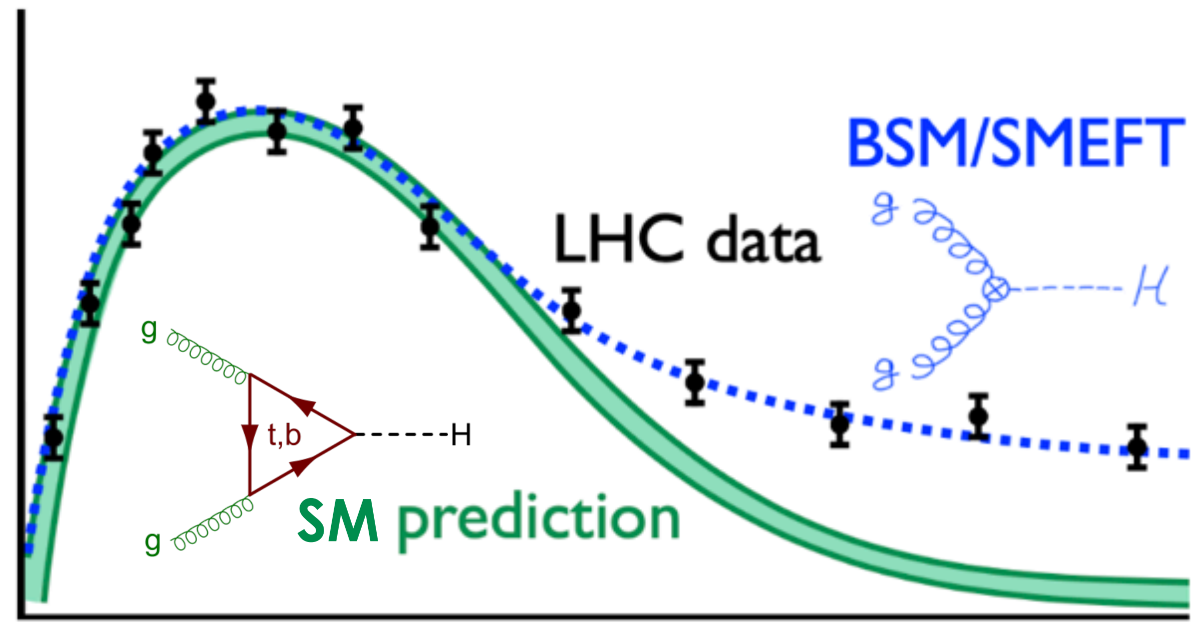
Entered in the Higgs precision physics era

The Role Of Precision

Precision: a "telescope" for BSM physics



Adapted from W. Wiesemann

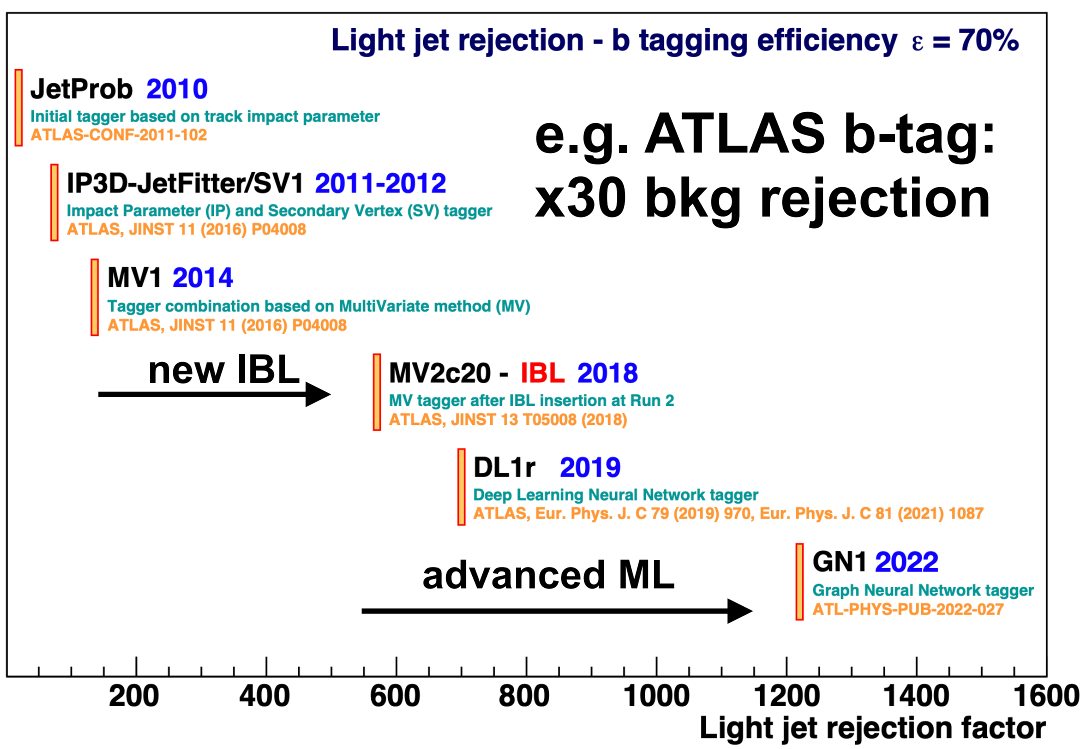


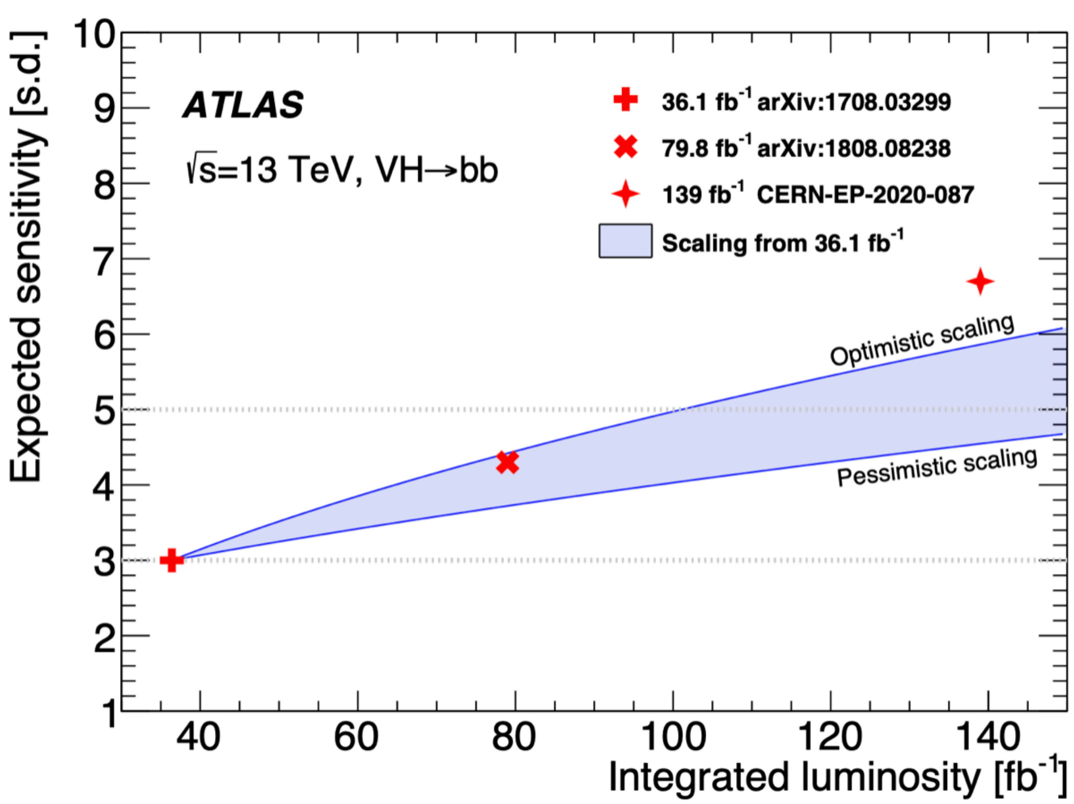
Precision does not come just increasing stat !

THE ROAD TO PRECISION: EXP

Experimental results are improving beyond luminosity scaling, despite more difficult experimental conditions (pile-up)

- Continuous improvements to objects reconstruction and analysis techniques
  - Advanced machine learning making the difference especially when fighting large backgrounds: eg H→bb/cc, H→$\tau\tau$,…
  - Clever use of larger datasets: eg improved event categorisation





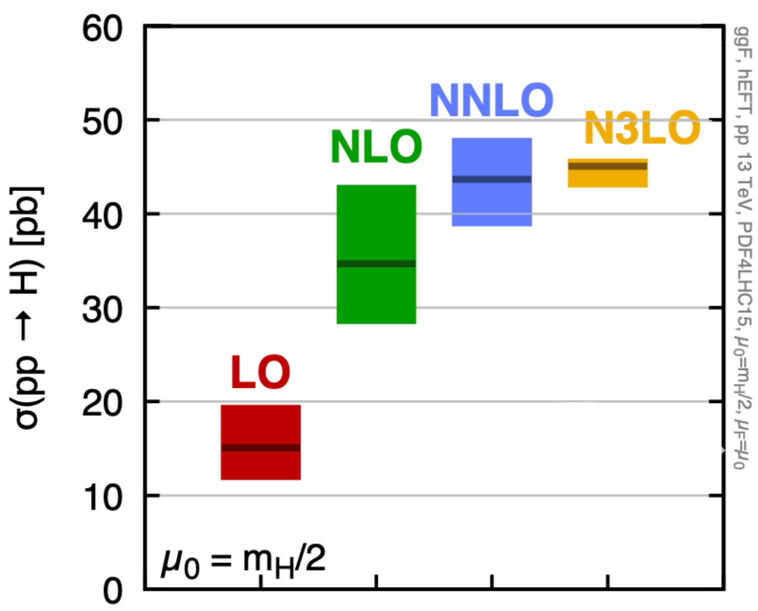
Adapted from F. Gianotti

Not a walk in the park… a lot of effort and ingenuity

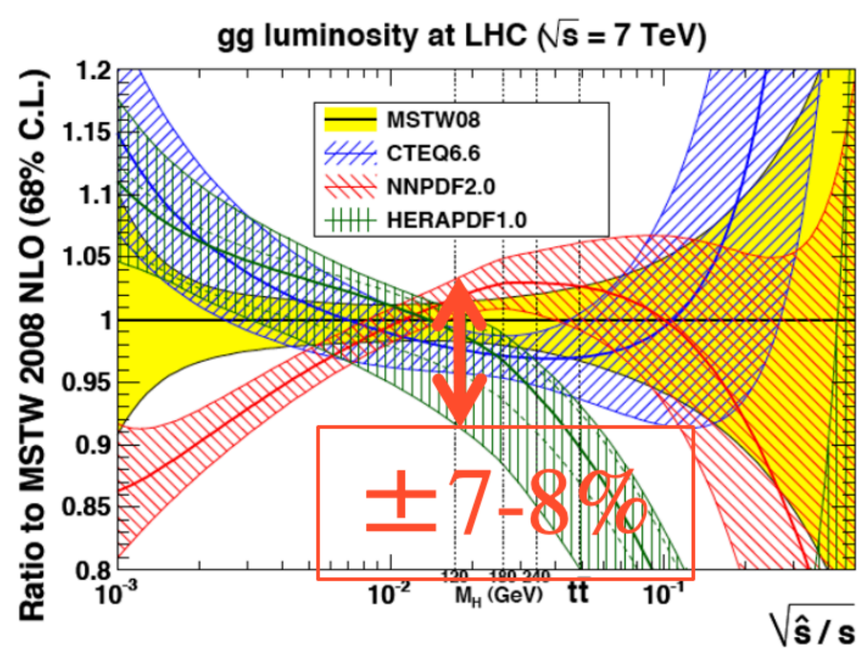
The Road To Precision: Theory

Huge leap in the Higgs theoretical predictions

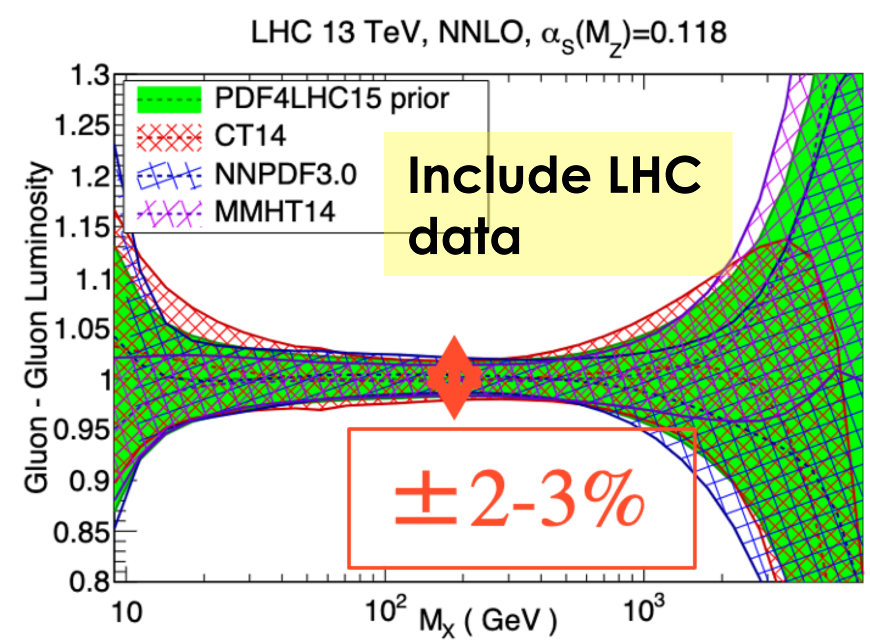
- Most important Higgs production processes calculated at N3LO QCD (ggF, VBF)
- PDFs (also thanks to LHC data)
- Improvements also for critical backgrounds processes: e.g. tt+b(b), VV,…



Adapted from M. Grazzini



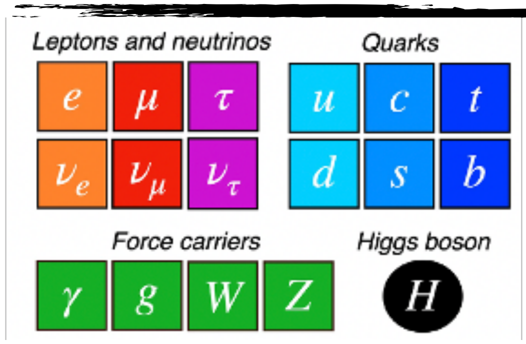
PDF4LHC (2011)



PDF4LHC15 (2015)

Critical role of LHC Higgs XS WG

Higgs in the SM

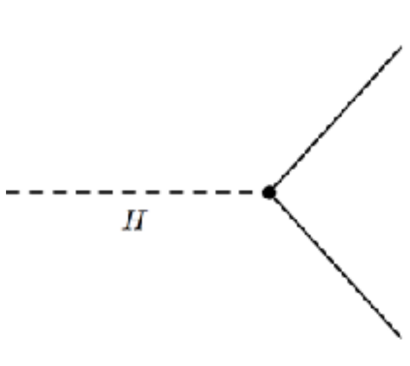


"One scalar to rule them all"

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

15 out of (at least) 19 free SM parameters are related to the Higgs, including the Higgs mass

Yukawa: coupling to fermions

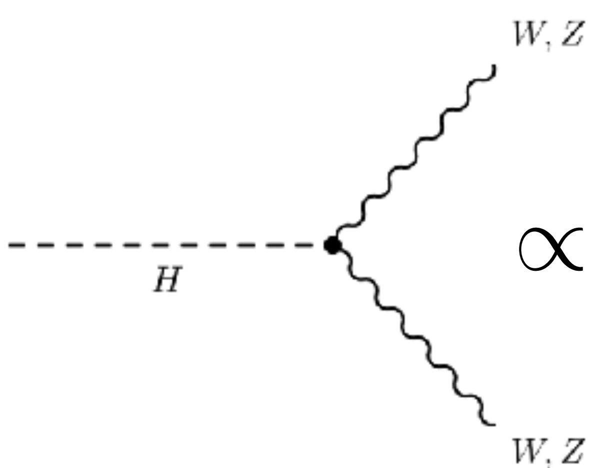


$\propto m_F$

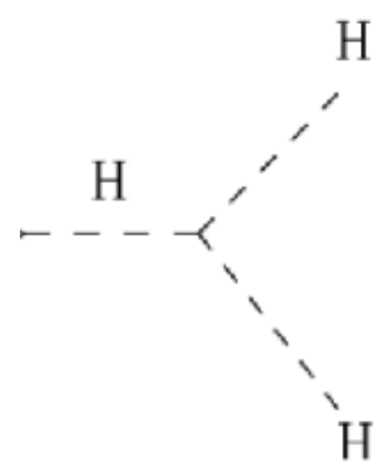
Higgs potential

$$V(\phi) = \mu^2|\phi|^2 + \frac{1}{2}\lambda|\phi|^4$$

Gauge: coupling to vector bosons



$\propto m_V$

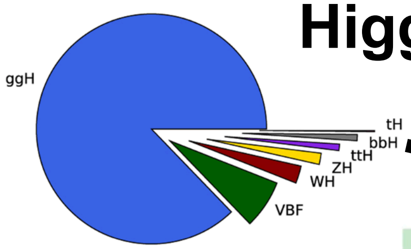


Higgs self-couples in the SM

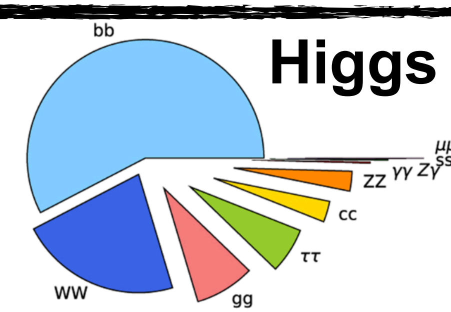
$\propto m_H^2$

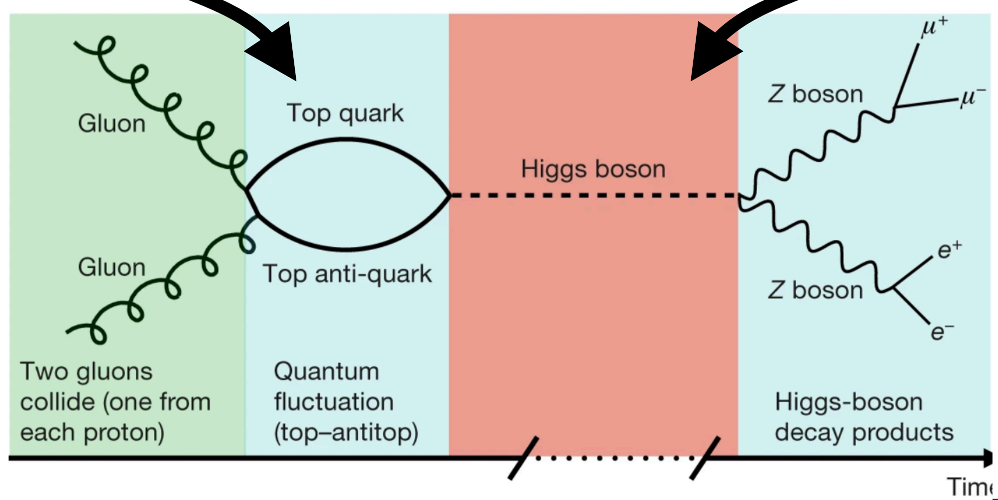
Higgs Physics @ LHC Run2

Higgs production



Higgs decay





LHC Run2: ~9M Higgs produced in ATLAS/CMS

All main production processes experimentally accessible for the main decays

ATLAS →

Nature 607, 52-59 (2022)

CMS

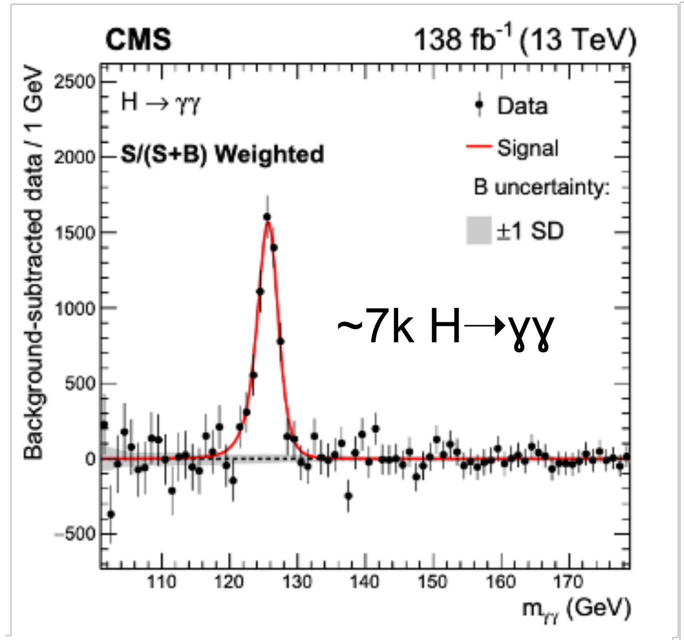
Nature 607, 60-68 (2022)

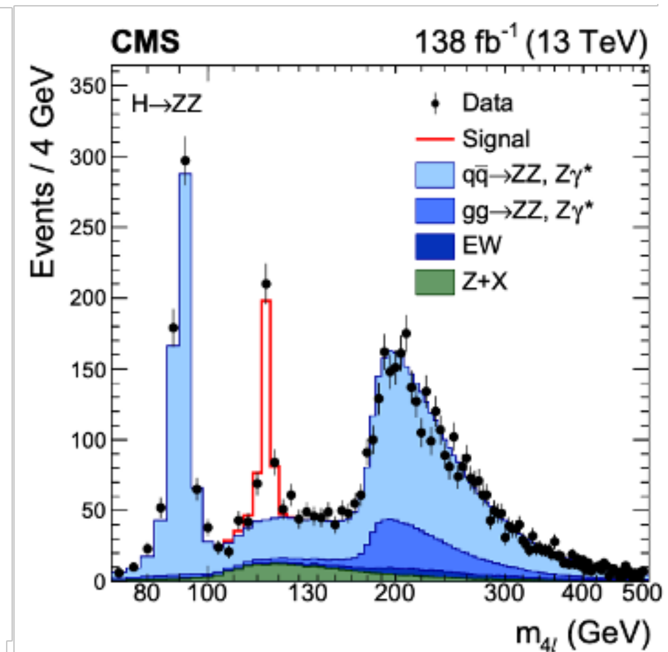
	Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]
H→bosons	$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139
	$H \to ZZ$	ggF, VBF, $WH+ZH$, $t\bar{t}H+tH$	139
		$t\bar{t}H+tH$ (multilepton)	36.1
	$H \to WW$	ggF, VBF	139
		WH, ZH	36.1
		$t\bar{t}H+tH$ (multilepton)	36.1
	$H \to Z\gamma$	inclusive	139
H→fermions	$H \to b\bar{b}$	WH, ZH	139
		VBF	126
		$t\bar{t}H+tH$	139
		inclusive	139
	$H \to \tau\tau$	ggF, VBF, $WH+ZH$, $t\bar{t}H+tH$	139
		$t\bar{t}H+tH$ (multilepton)	36.1
	$H \to \mu\mu$	ggF + $t\bar{t}H+tH$, VBF + $WH+ZH$	139
	$H \to c\bar{c}$	$WH+ZH$	139
H→ν,DM	$H \to$ invisible	VBF	139
		ZH	139

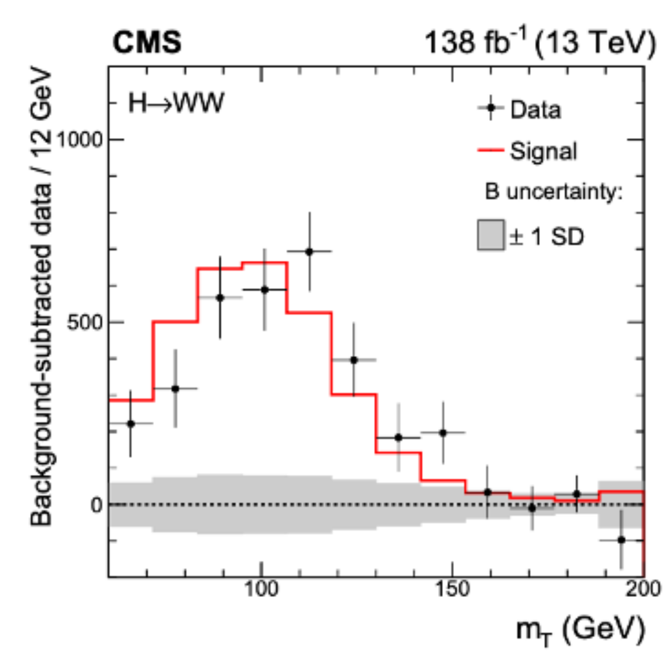
Most of the results discussed in this talk from these 2 papers

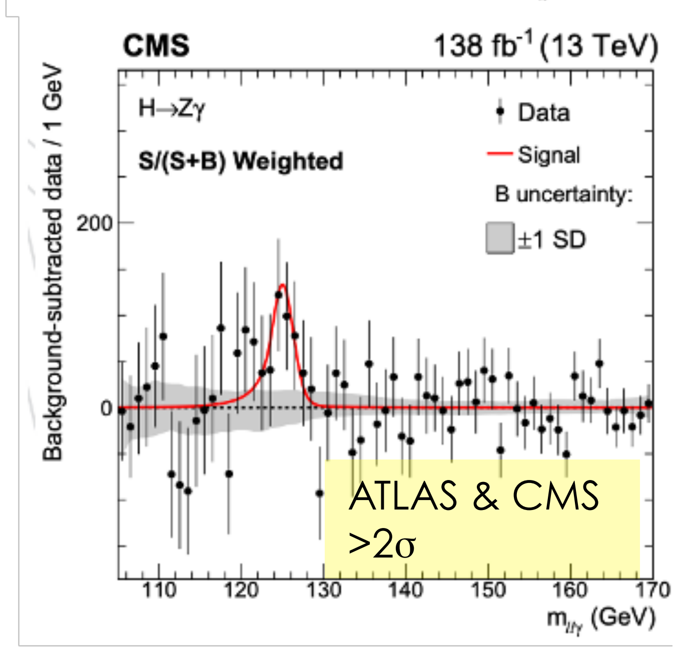
Higgs Pictures From Run2

H→bosons

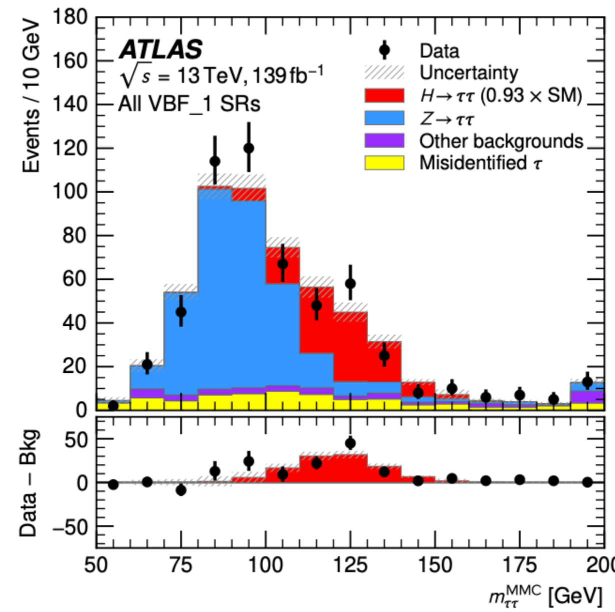


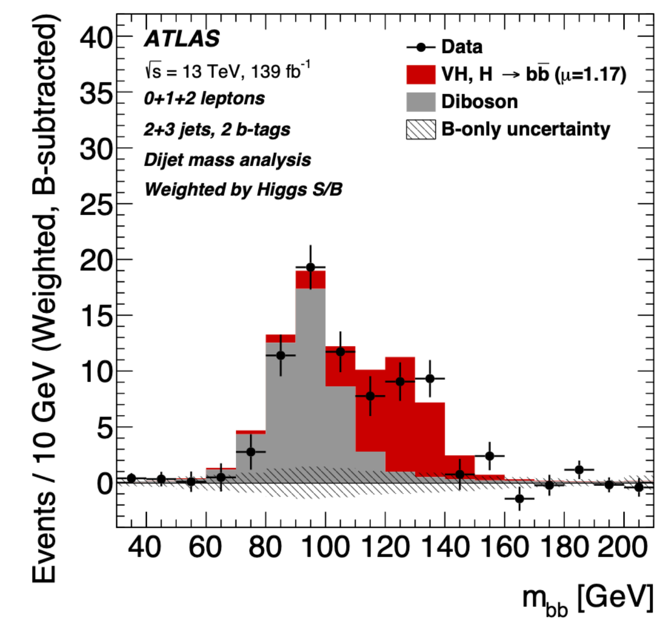


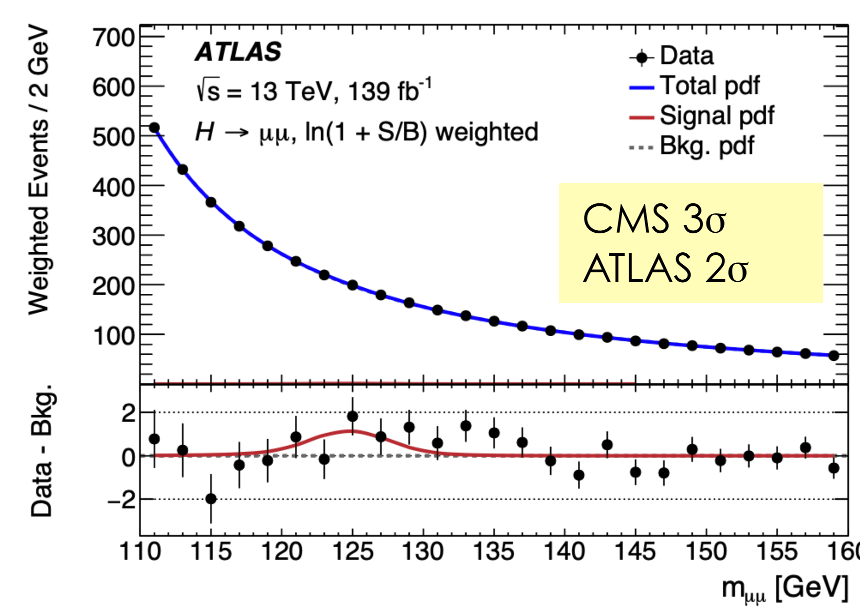




H→fermions



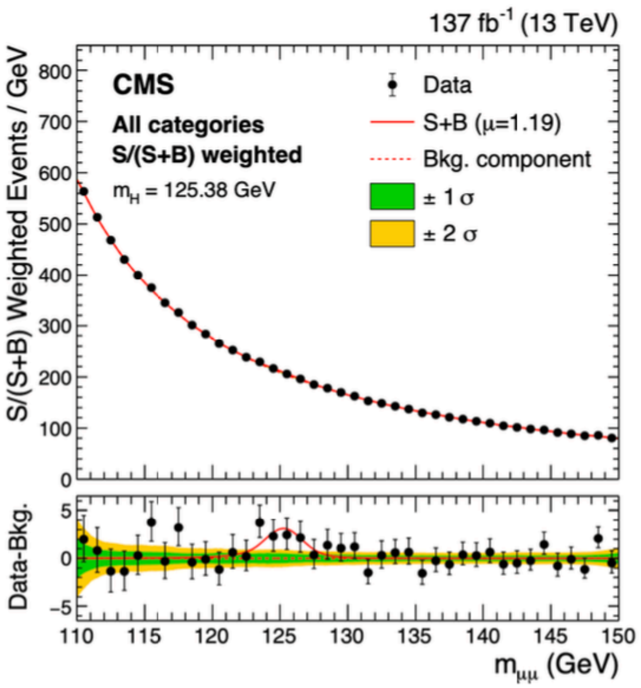


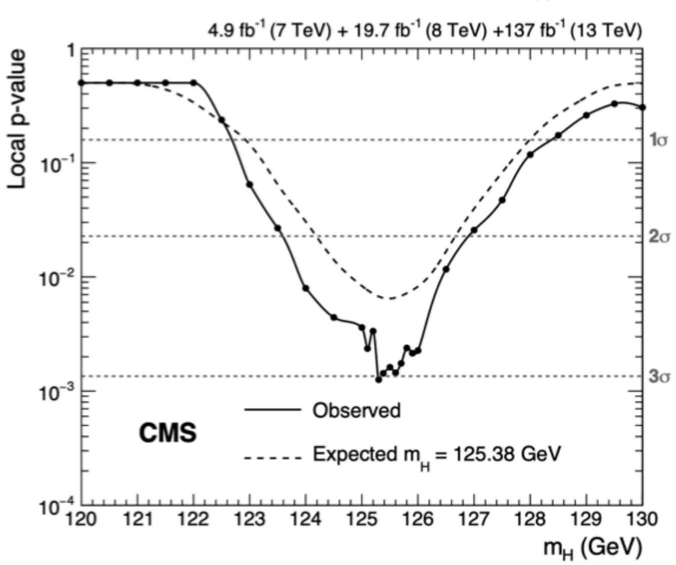


Recent Highlights: 2nd Gen Fermions

H→μμ

ATLAS: PLB 812 (2021) 135980
CMS: JHEP 01 (2021) 148





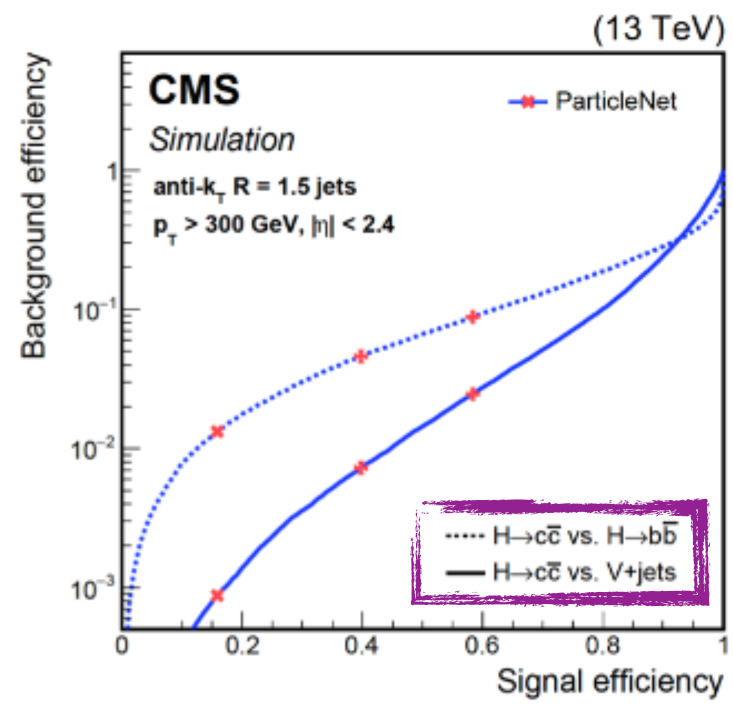
First evidence for coupling with 2nd generation fermions

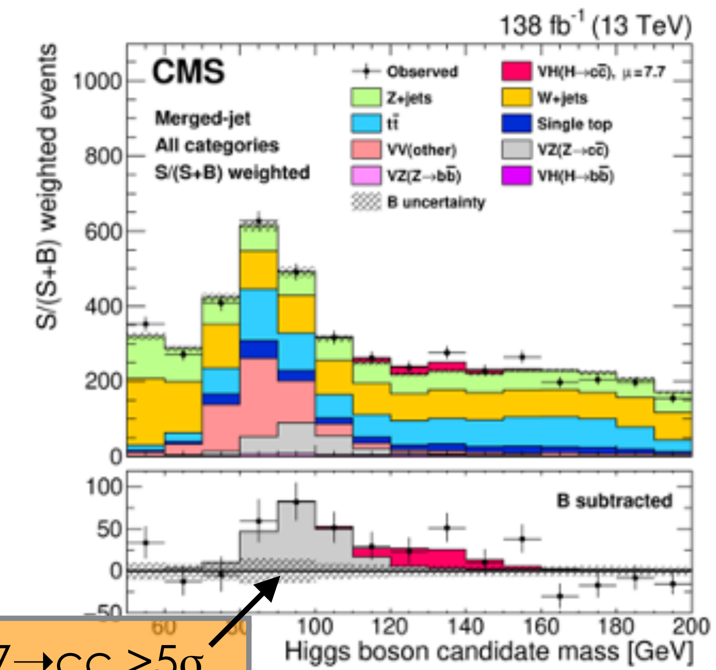
ATLAS: **2.0σ** (1.7 exp) μ=1.2 ± 0.6

CMS: **3.0σ** (2.4 exp) μ=1.19 ± 0.43

H→cc

ATLAS: Eur. Phys. J. C 82 (2022) 717
CMS: arXiv:2205.05550





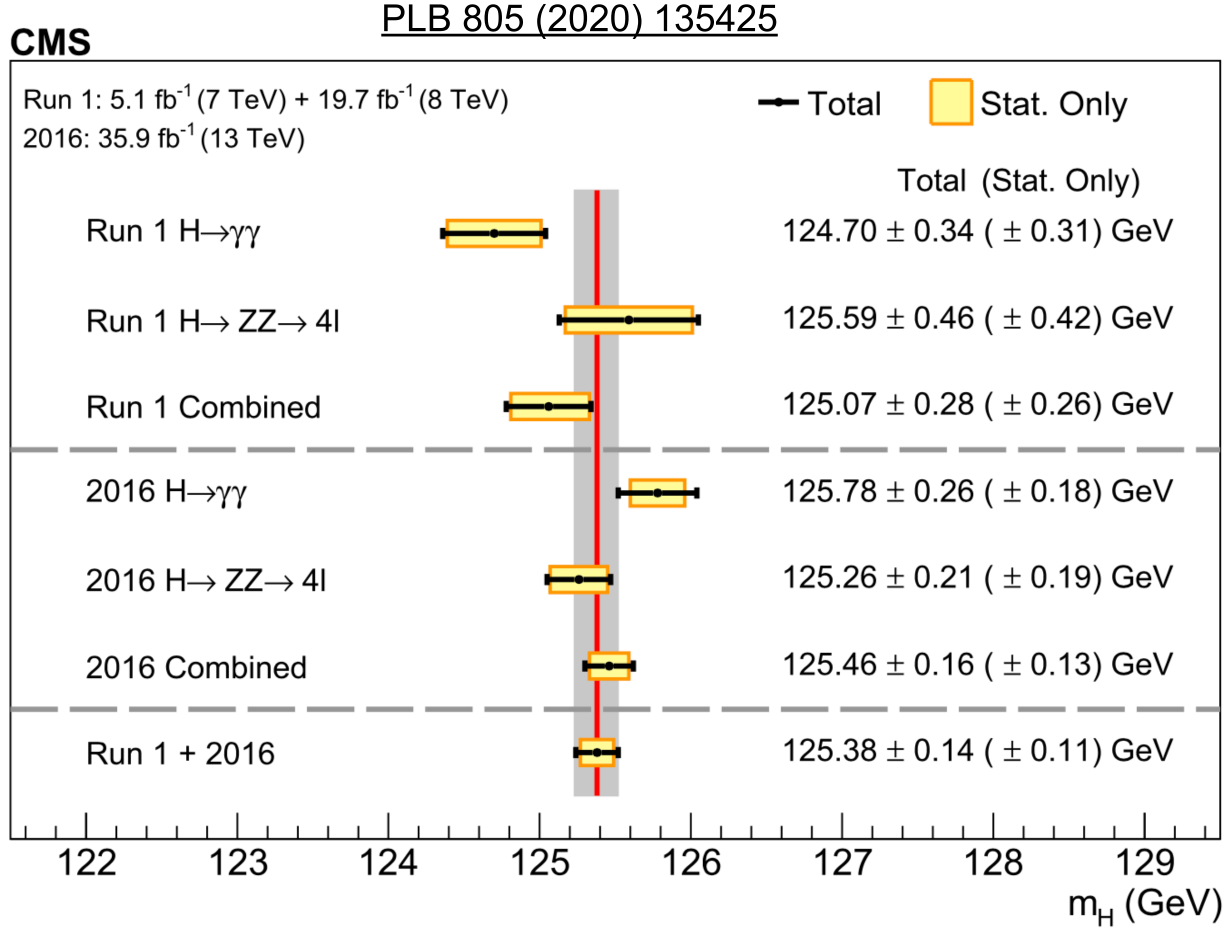
Z→cc >5σ

One of the most striking progress in Run2: **Reached sensitivity to ~ x8 SM** (BR H→cc 0.029)

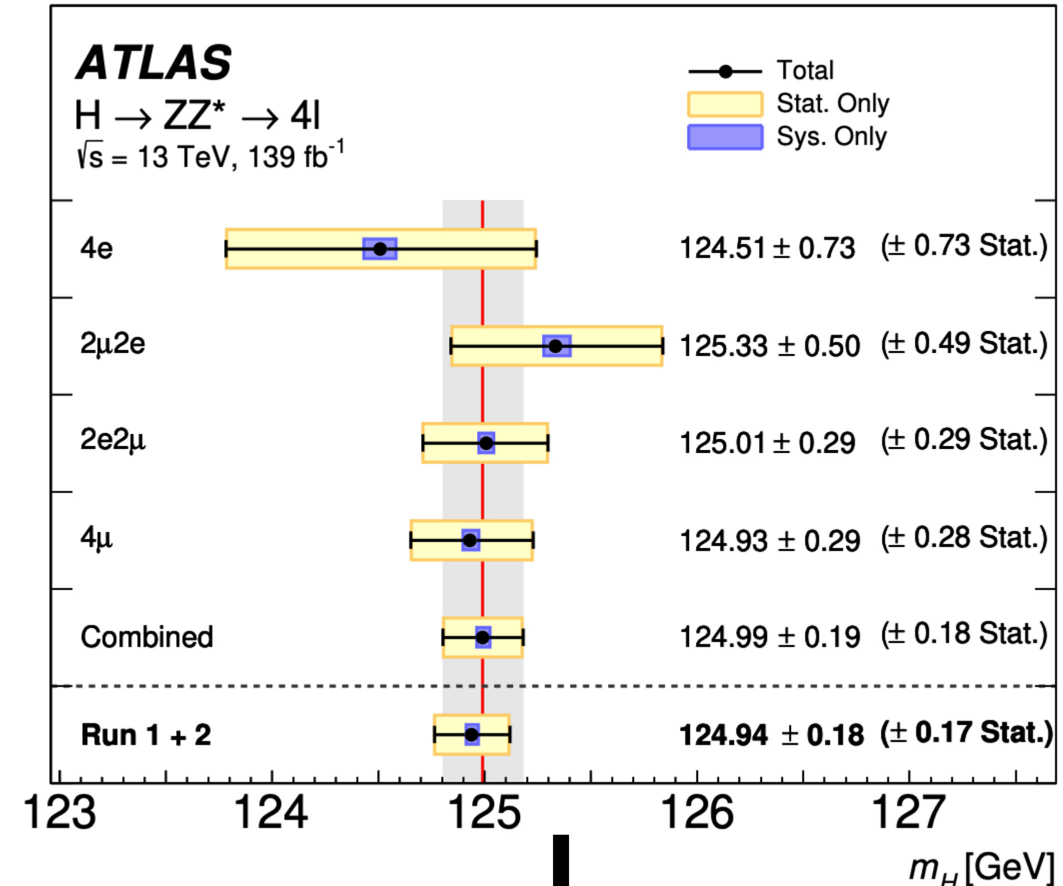
Huge improvement thanks to novel H→cc taggers

Higgs Mass

PLB 805 (2020) 135425



arXiv:2207.00320



Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	±28
Electron energy scale	±19
Signal-process theory	±14

Mass known already at end of Run1 at ~2‰ from ATLAS+CMS (H→γγ,ZZ)

Now ~1‰, still stat limited

Ultimate expected precision (from H→4l) ~50 MeV per experiment

Systematics reduced by ~20% wrt previous Run2 results

HIGGS TOTAL WIDTH

Higgs width from off-shell production: a breakthrough after Higgs discovery

– ~10% of $H \rightarrow ZZ$ off-shell (m_{ZZ}>200 GeV), negative interference with SM continuum

Ratio off-shell to on-shell sensitive to Γ_H

$$\sigma^{\mathrm{on-shell}}_{\mathrm{gg \to H \to VV}} \sim \frac{g^2_{\mathrm{Hgg}} g^2_{\mathrm{HVV}}}{m_{\mathrm{H}} \Gamma_{\mathrm{H}}}$$

Γ_H^{SM} = **4.07 MeV**

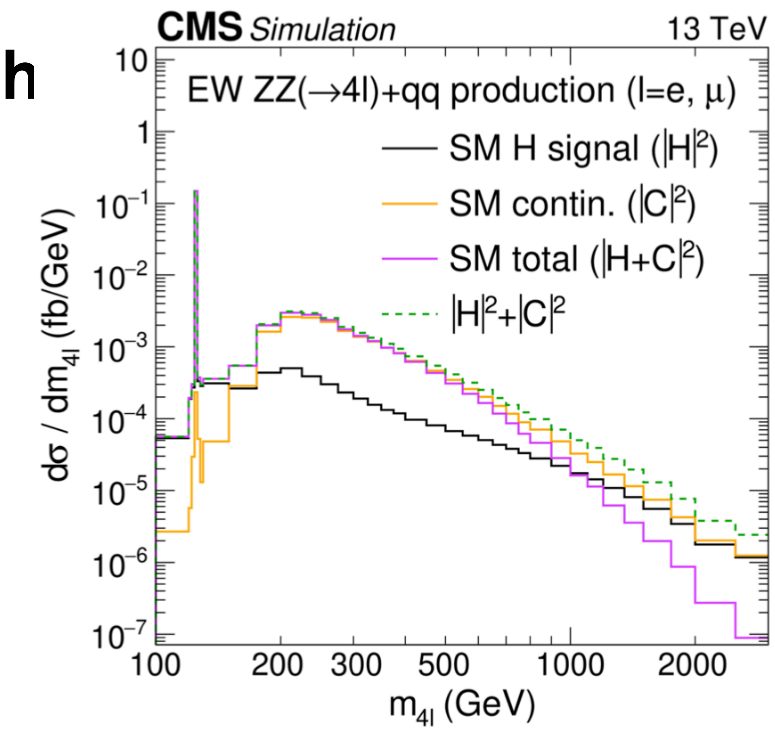
$$\sigma^{\mathrm{off-shell}}_{\mathrm{gg \to H \to VV}} \sim \frac{g^2_{\mathrm{Hgg}} g^2_{\mathrm{HVV}}}{m^2_{\mathrm{VV}}}$$

Main assumption: same on/off-shell couplings

CMS $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

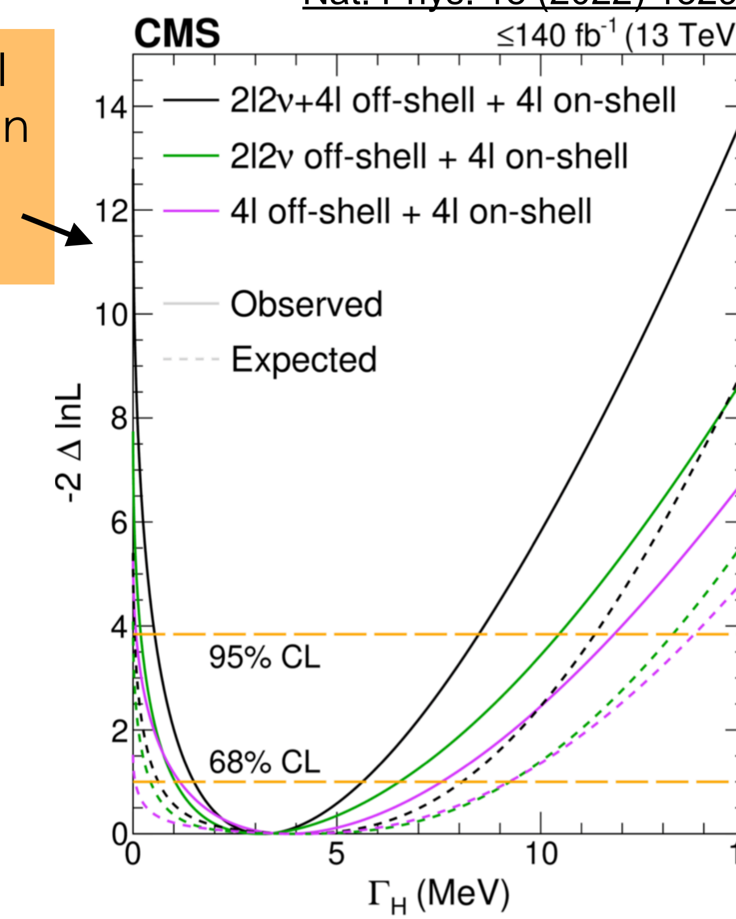
ATLAS $\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV

ATLAS-CONF-2022-068



Nat. Phys. 18 (2022) 1329

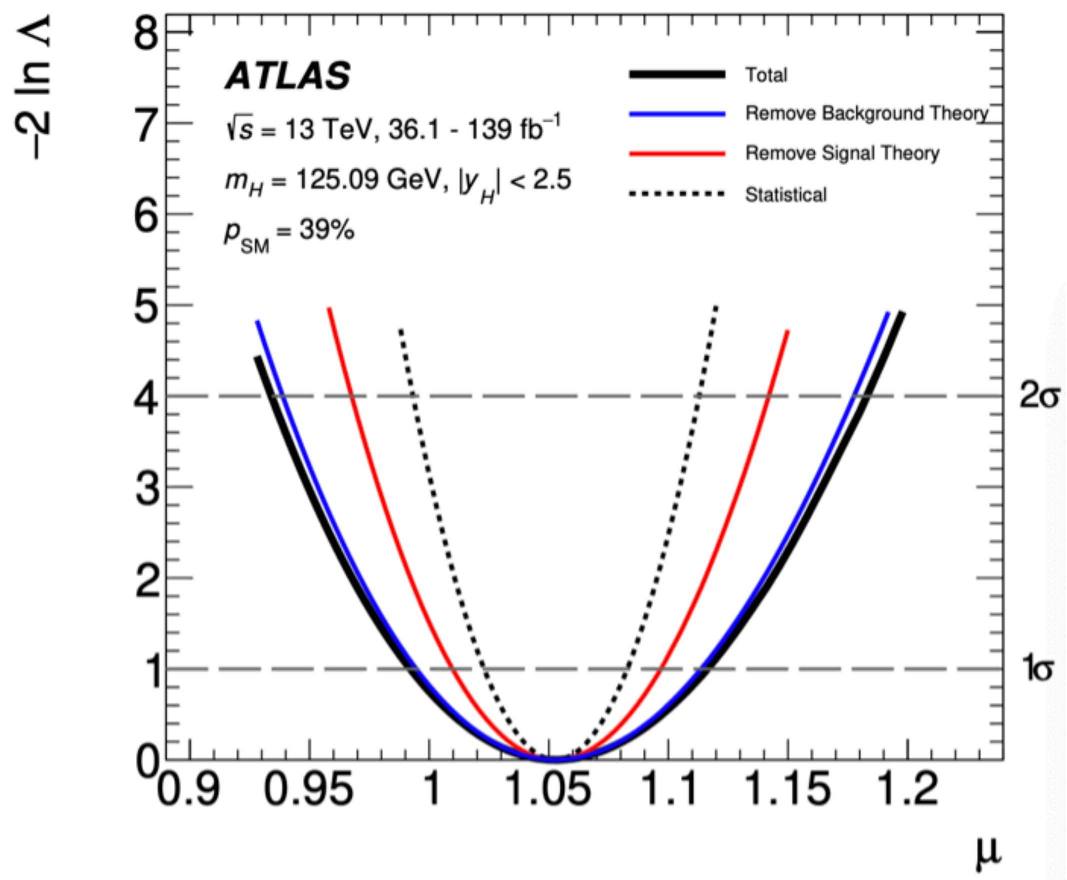
No off-shell contribution excluded at 3.6σ



(Global) Higgs SM Compatibility

Fit data from all production modes and decays with a common signal strength wrt SM

$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$



ATLAS Run2 $\mu = 1.05 \pm 0.04(th) \pm 0.03(exp) \pm 0.03(stat)$

CMS Run2 $\mu = 1.002 \pm 0.036(th) \pm 0.033(exp) \pm 0.029(stat)$

ATLAS+CMS Run1 (20+20 fb^{-1} @ 8 TeV) $\mu = 1.09 \pm 0.07(sig.\ th) \pm 0.03(bkg.\ th) \pm 0.04(exp) \pm 0.07(stat)$

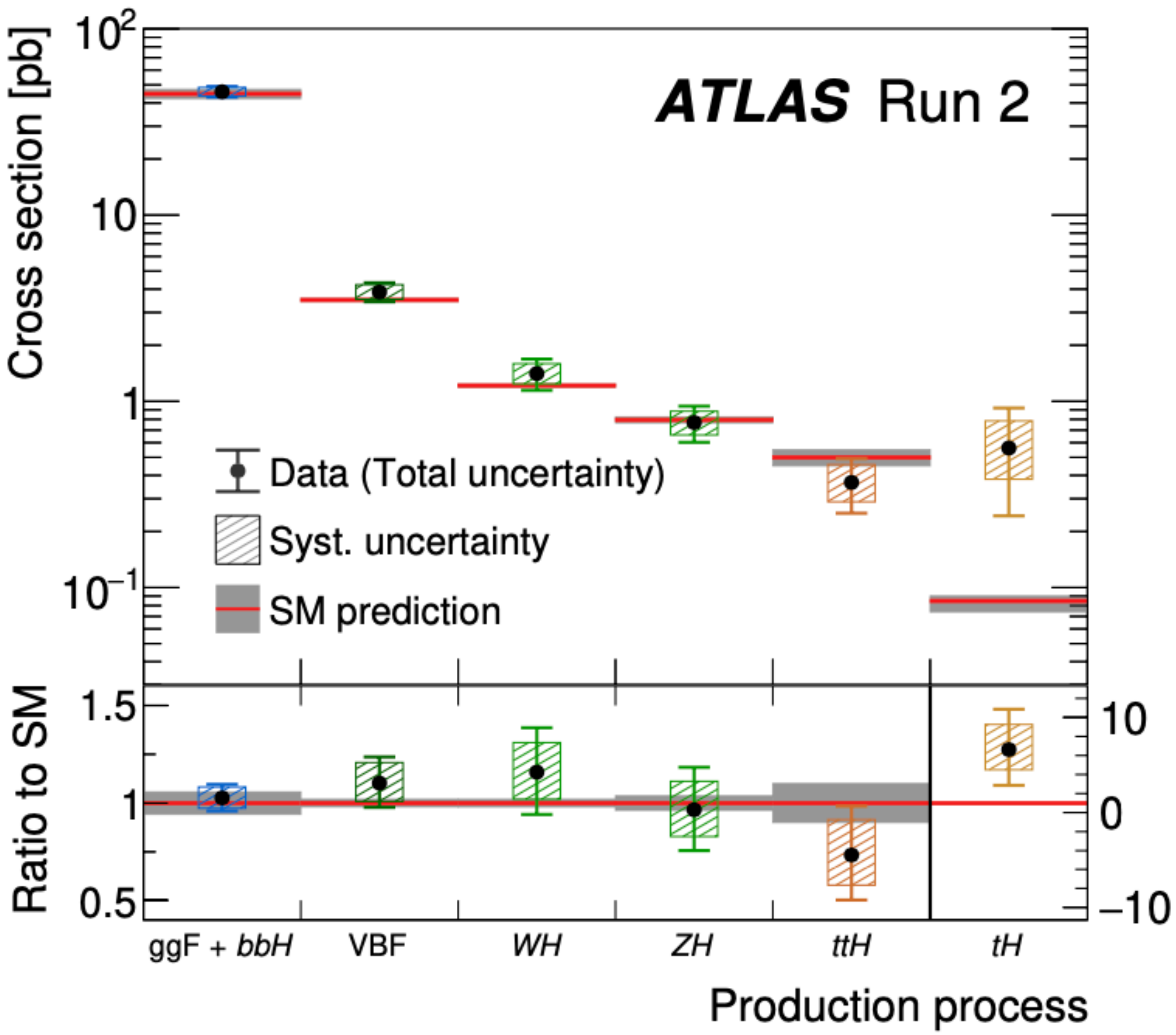
JHEP 2016, 45 (2016)

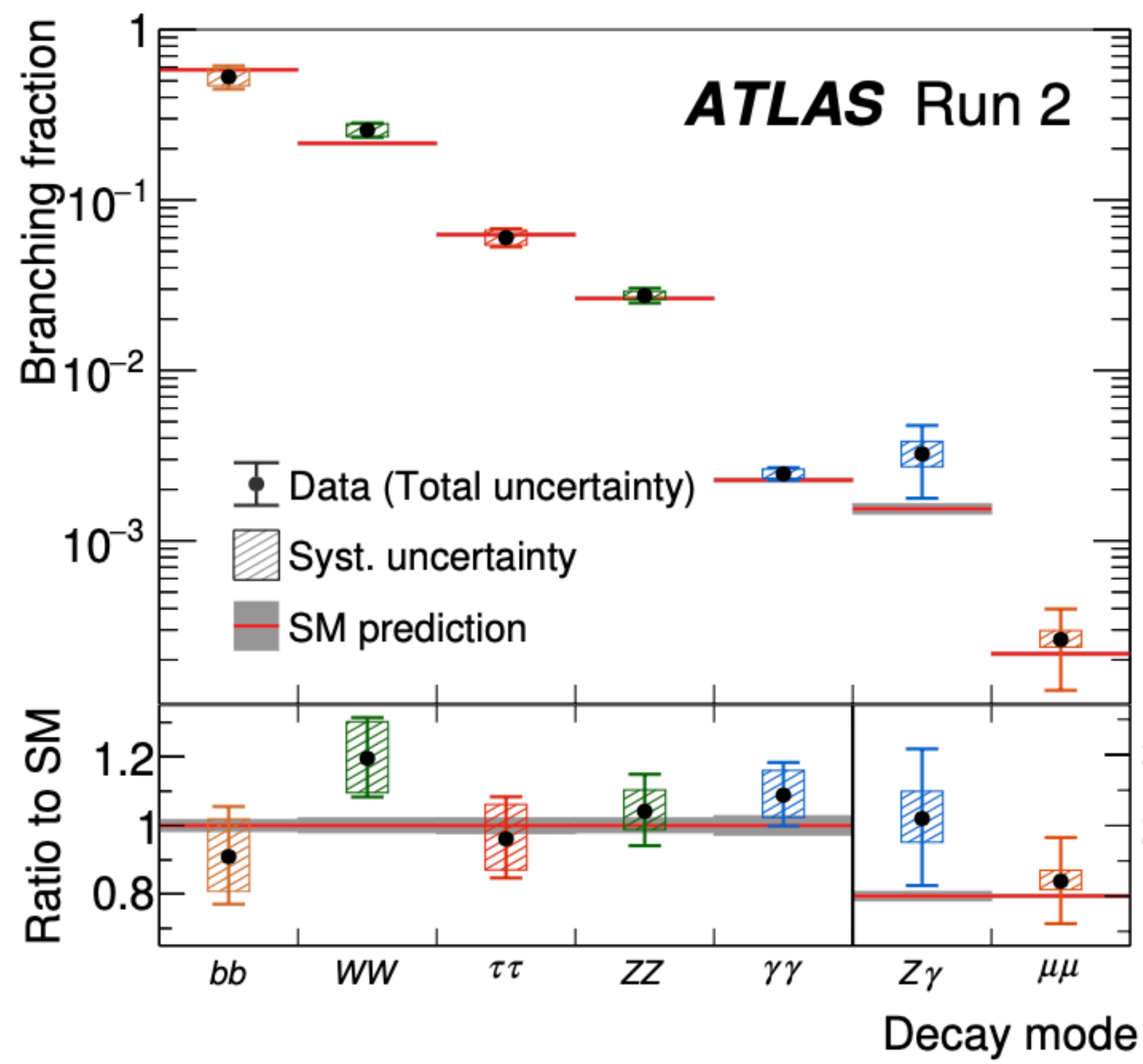
Theory systematics reduced by ~ a factor 2 from Run1

Higgs Production And Decays

All consistent with SM

– uncertainty <=10% for main production modes and decays



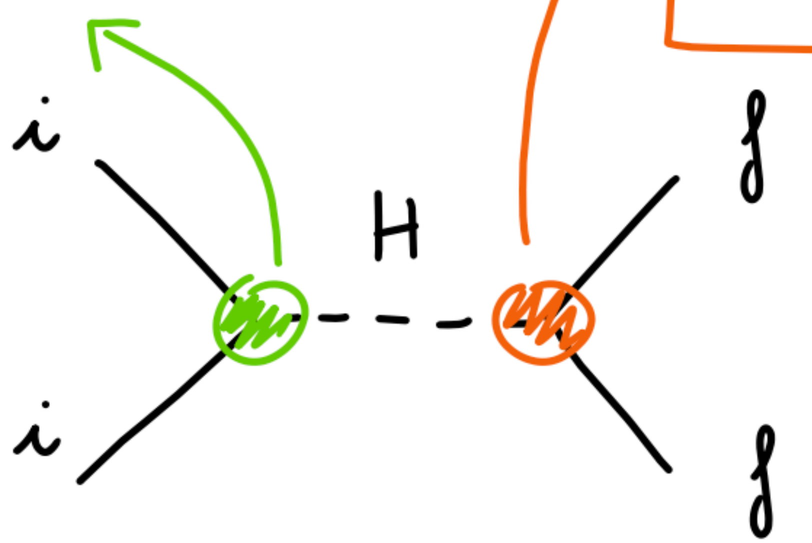


All 5 main production modes and decays >5σ

HIGGS COUPLINGS: K-FRAMEWORK

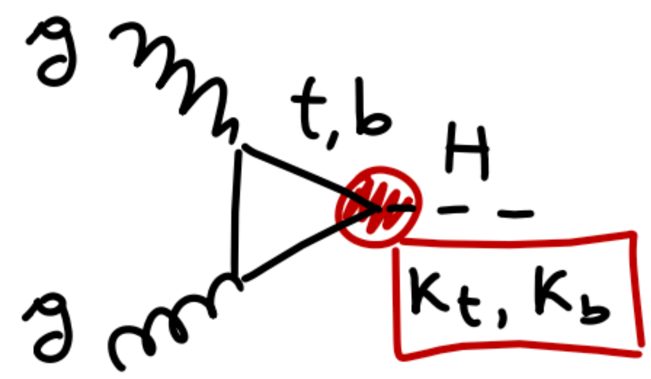
$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

$$\kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}}$$

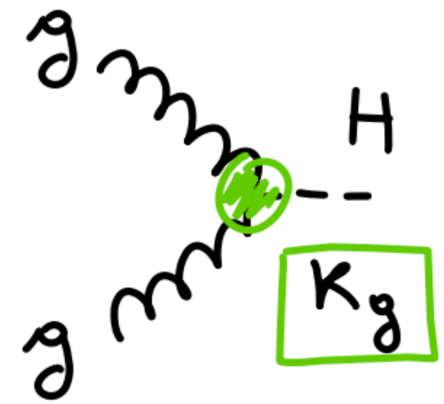


$$\sigma_i \times \mathcal{B}_f = \sigma_i^{SM} \times \mathcal{B}_f^{SM} \times \kappa_i^2 \times \kappa_f^2$$

In case of loops:



Resolved loop



Effective coupling modifier

k-factors: effective Higgs coupling modifiers (no production kinematic variations). Test compatibility with SM

Can also accomodate BSM decays (invisible or undetected) as modification of the total Higgs width

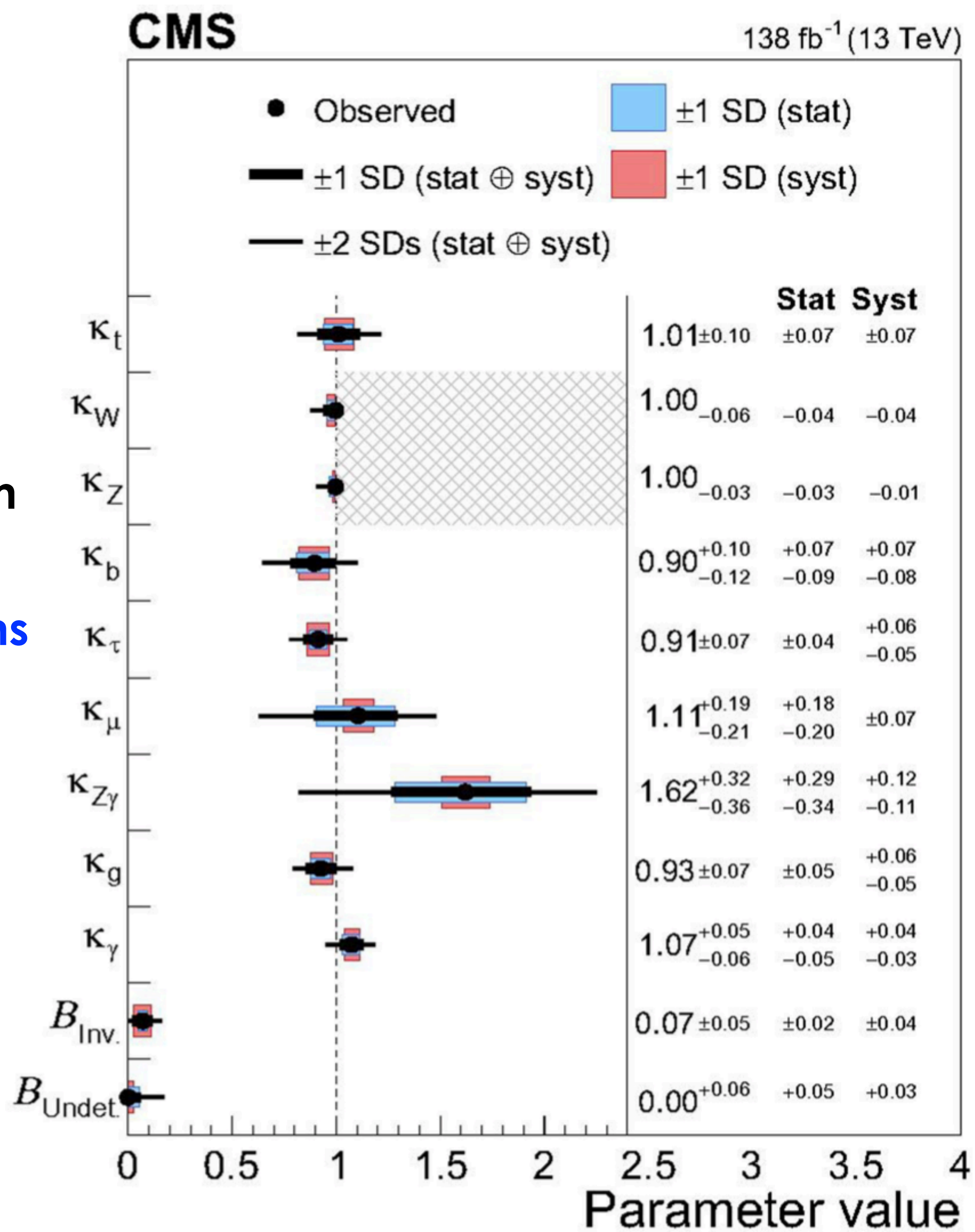
Higgs Couplings

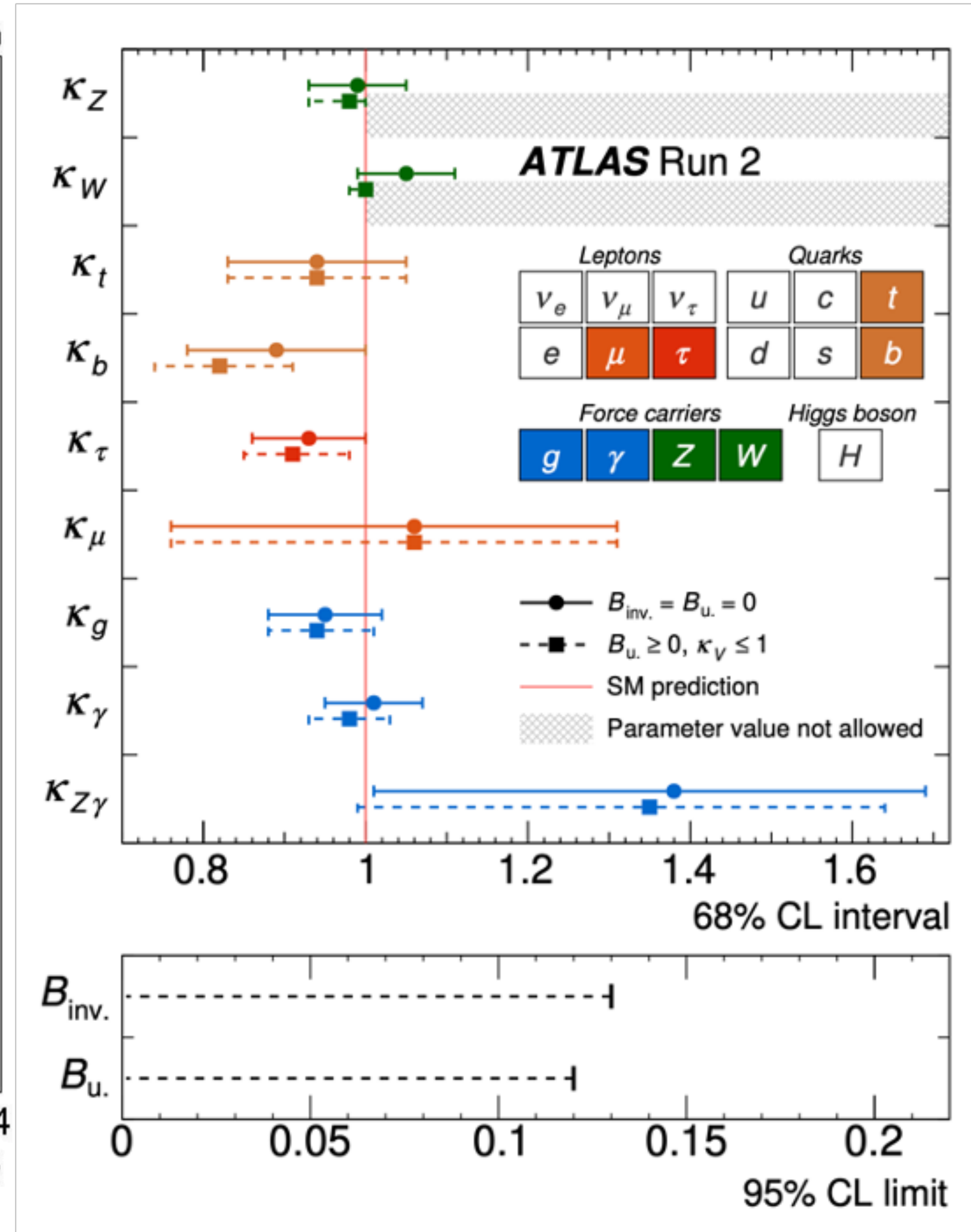
kV<1 when floating Binv,und

W/Z couplings compatible with SM at ~5%

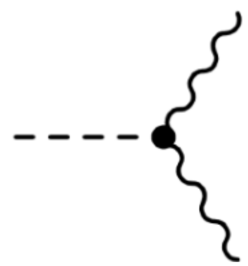
3rd gen fermions at ~10%

Room for BSM decays ~10%

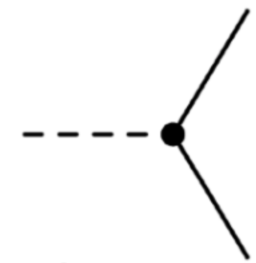




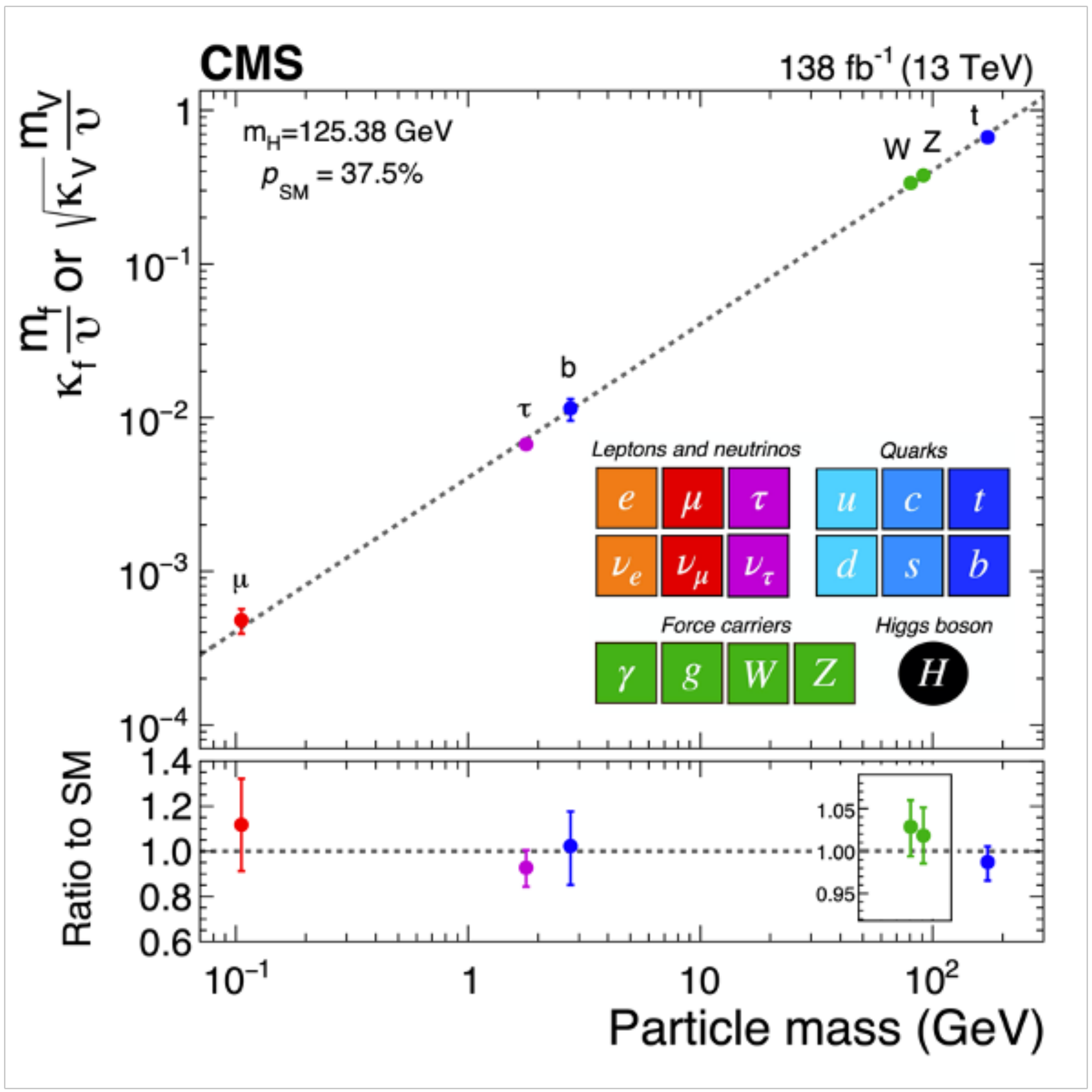
Run2 Legacy: Higgs Couples To Mass

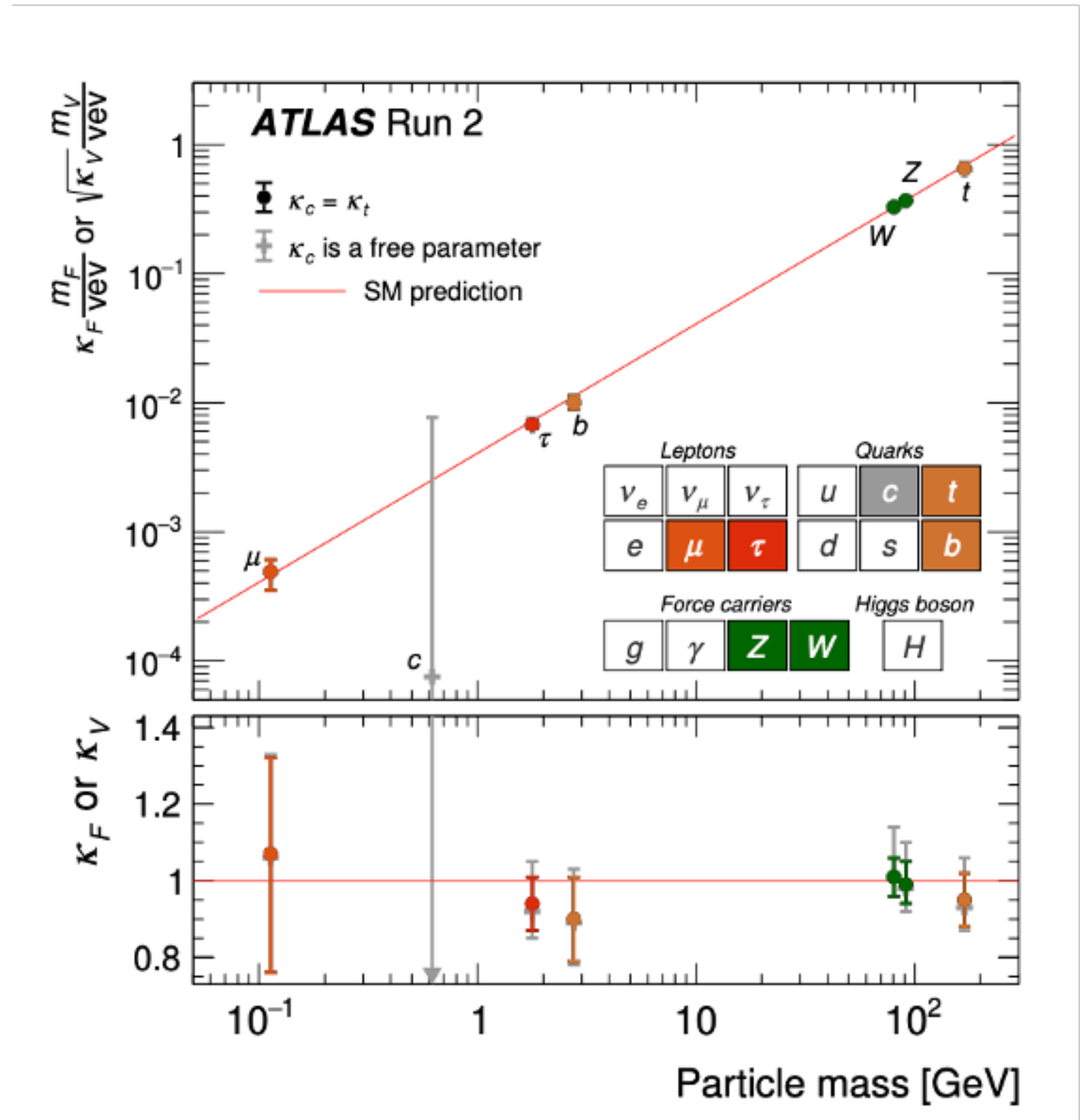


$$g_V = 2\frac{m_V^2}{v}$$



$$g_F = \sqrt{2}\frac{m_f}{v}$$





MORE GRANULARITY: STXS

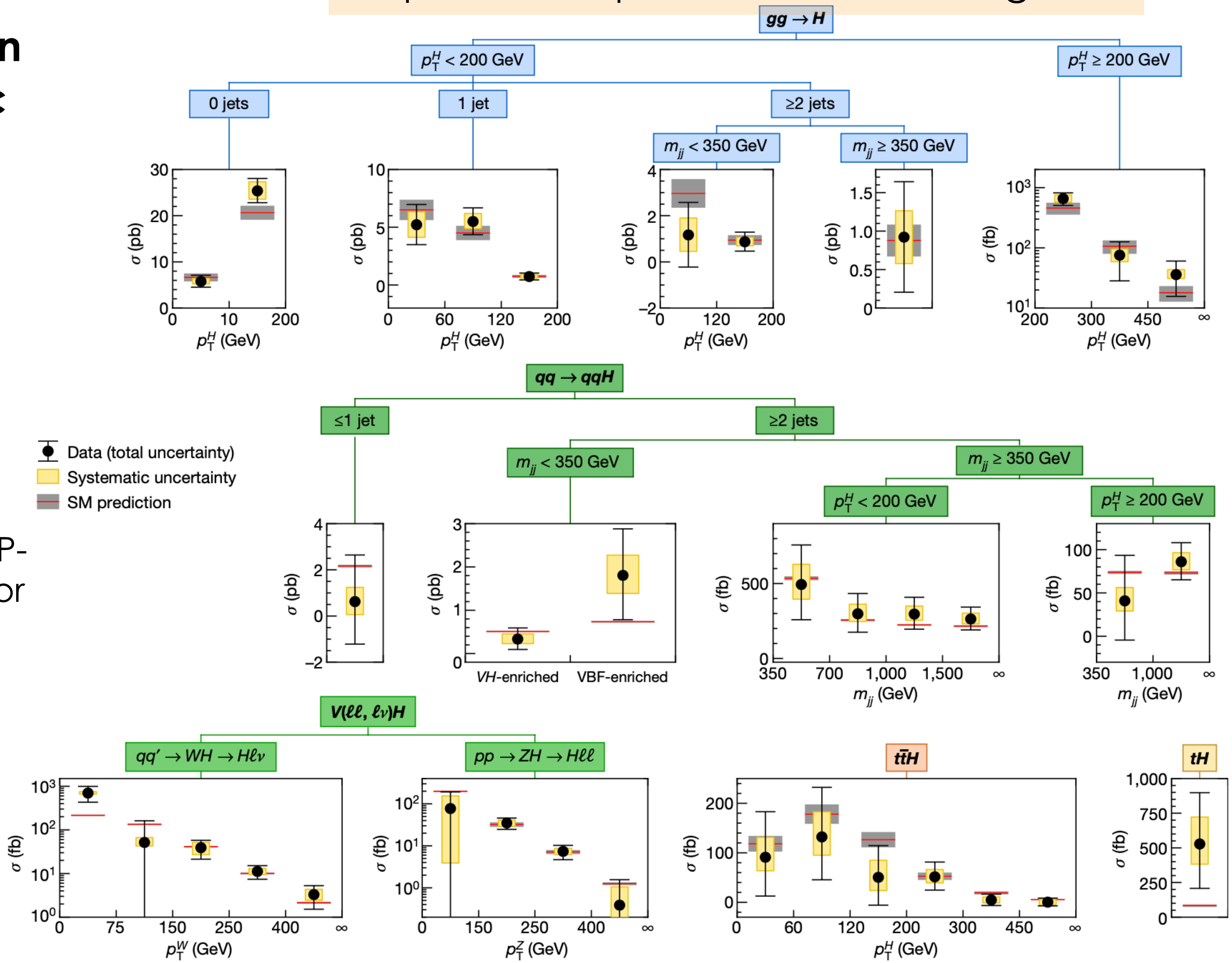
Measure different production modes in exclusive kinematic regions

- combination of multiple decay channels

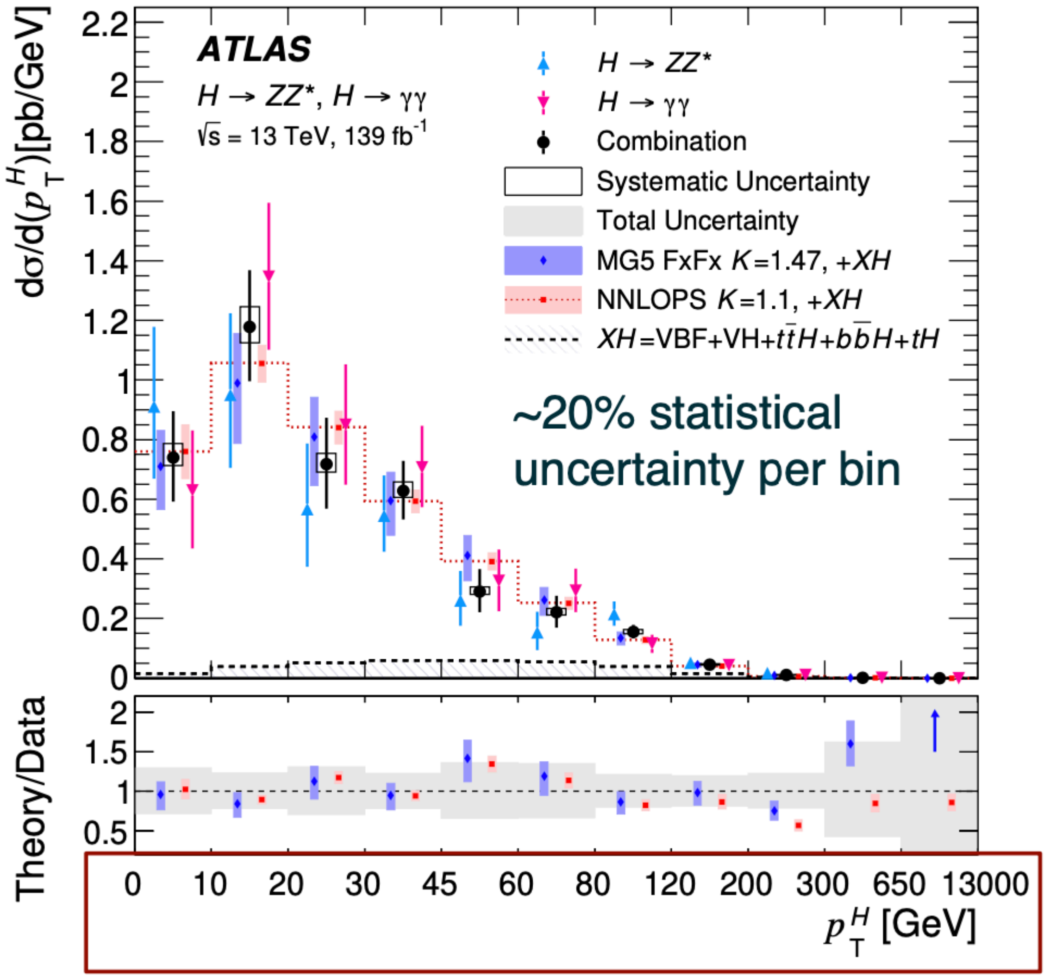
More sensitivity for BSM (eg high pT regions)

- current STXS have limited sensitivity for CP-odd BSM (eg no $\Delta\phi_{jj}$ for qqH)

Simplified **T**emplate **XS**ections: Stage 1.2



MORE GRANULARITY: DIFFERENTIAL



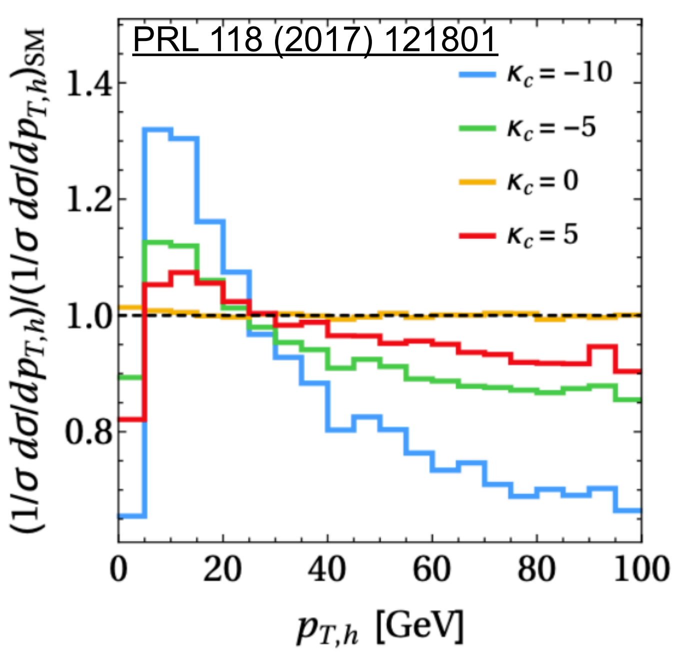
Single and double differential xsec vs p_T^H, η^H, n_{jet}

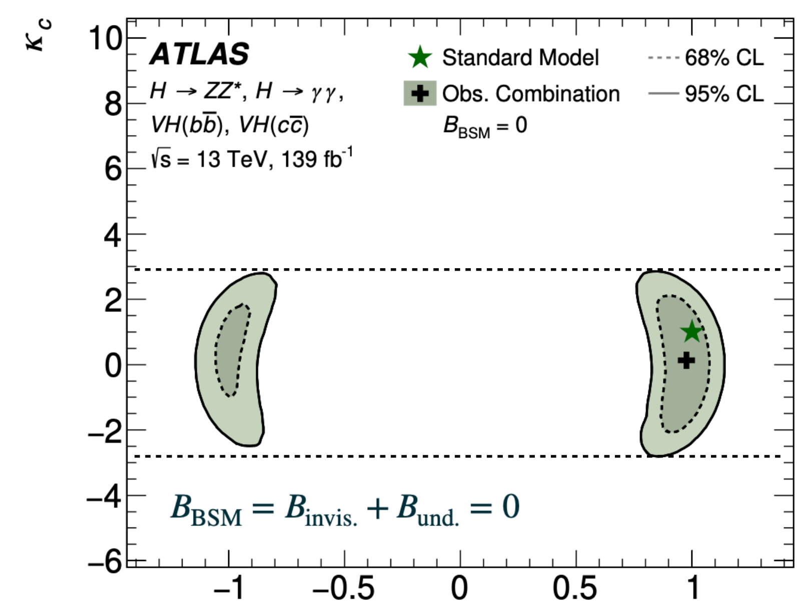
- Best precision for fully reconstructed decays (H→γγ,ZZ)

Higgs p_T: test of perturbative QCD but also sensitivity for BSM couplings

- low p_T: k_c constraints competitive/complementary to direct search for H→cc
- high p_T: probe for higher scale BSM

Combination with direct H→bb,cc constraints: $|k_c|<3$ @95% CL





arXiv:2207.08615

Look For CP Violation

Higgs compatible with $J^P=0^+$ (Run1)

Room for anomalous BSM (possibly CP-violating) couplings

O+ | O- | Tree-level | loop

$$A(H \to ff) = -\frac{m_f}{v}\bar{\psi}_f(\kappa_f + i\tilde{\kappa}_f\gamma_5)\psi_f$$

SM

$$A(H \to VV) \sim (A_1 + A_1^{BSM})m_V^2 + A_2 + A_3$$

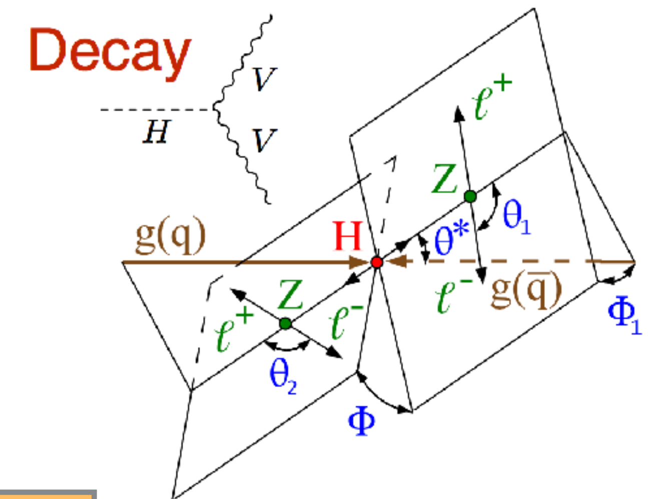
$$f_{a3} = \frac{|A_{0-}|^2}{|A_{0+}|^2 + |A_{0-}|^2}$$

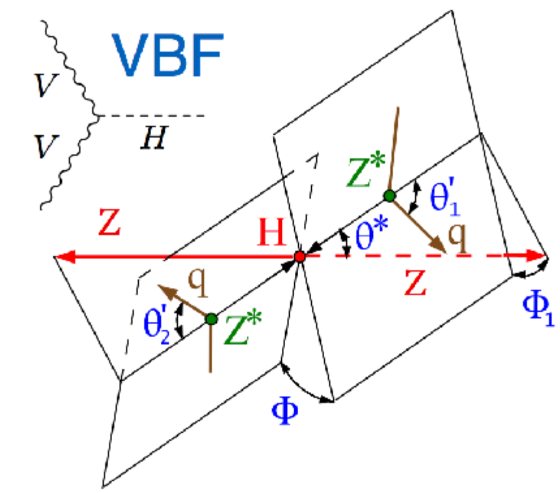
Combination of several decay channels: ZZ,$\tau\tau$,$\gamma\gamma$

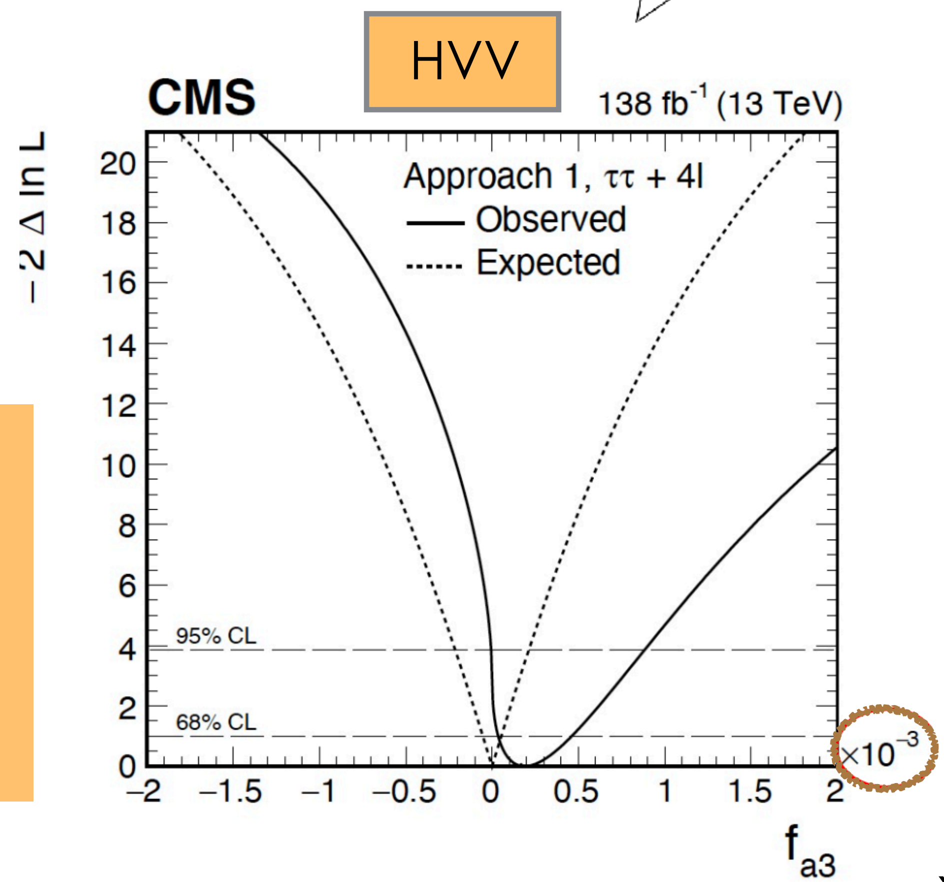
Sensitivity to relative coupling sign from interference

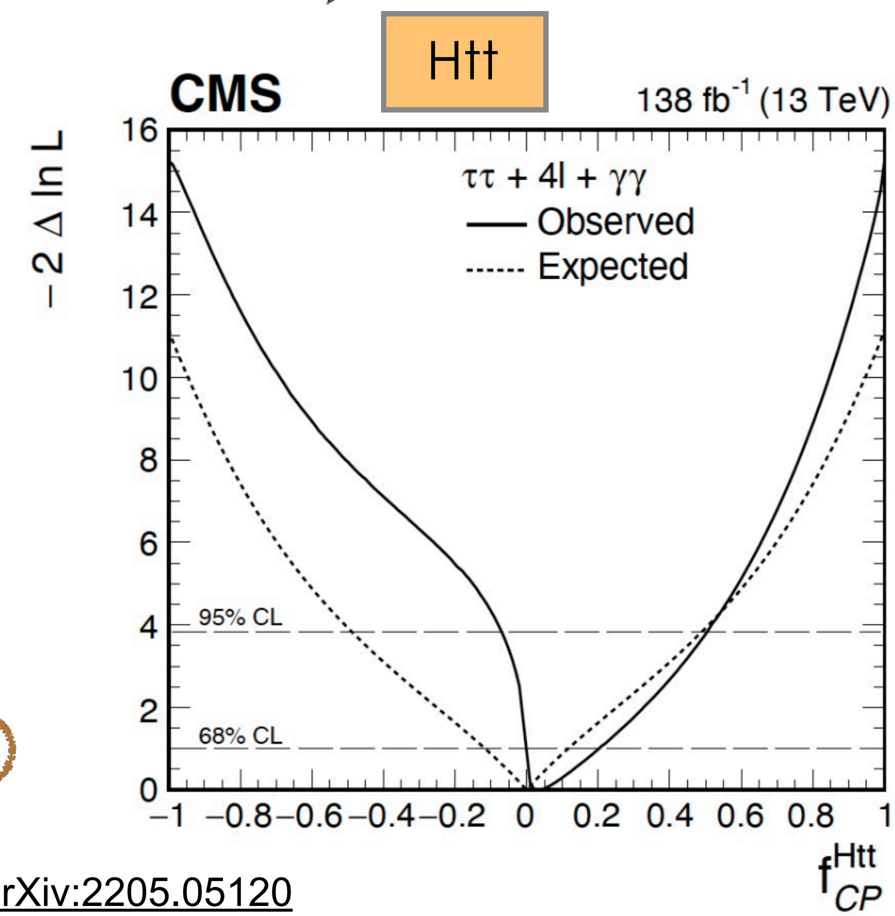
Exploit kinematic correlations among final state objects both in production and decay (ZZ)

– signal extraction including discriminants (MELA) between different couplings hypothesis









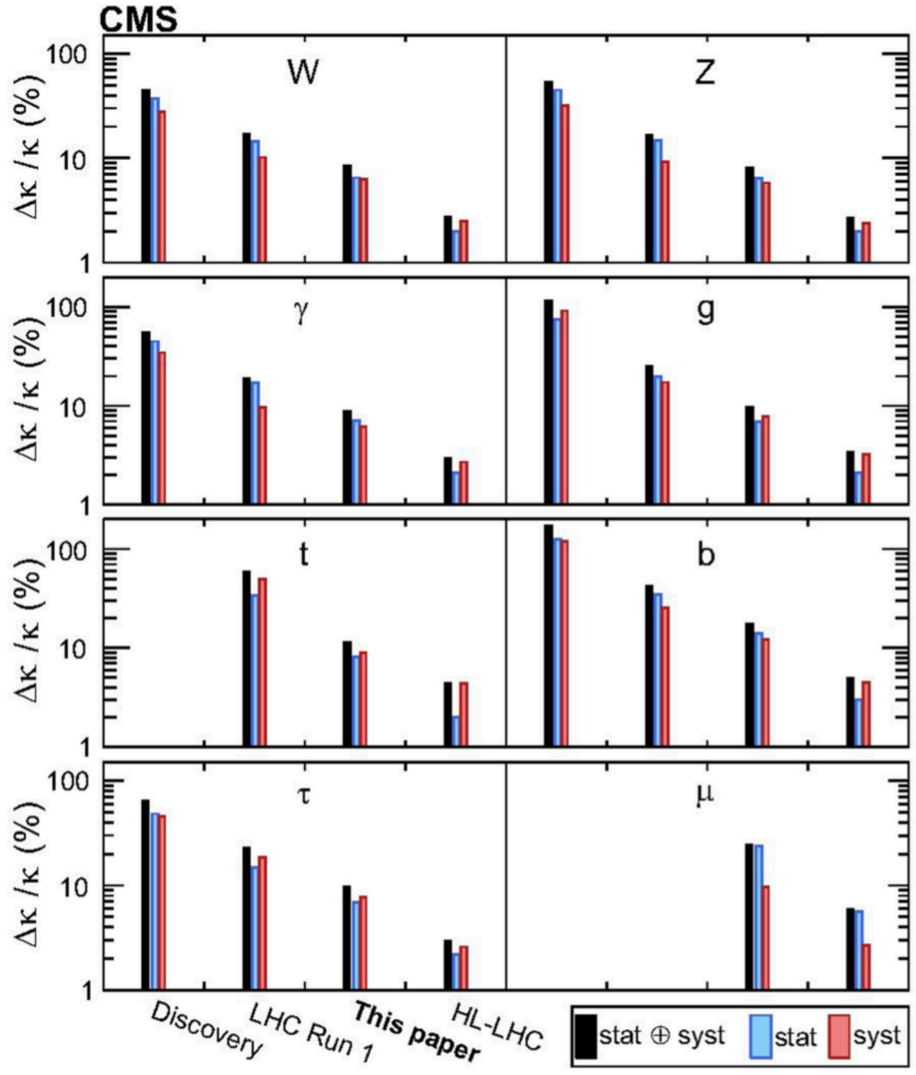
arXiv:2205.05120

SUMMARY

The ATLAS/CMS Higgs Run2 legacy: entered the Higgs precision physics era

- Mass at 0.1%
- Boson couplings known at ~5%, ~10% for heaviest fermions
- Huge progress to look for 2nd generation couplings, self-coupling, anomalous BSM couplings

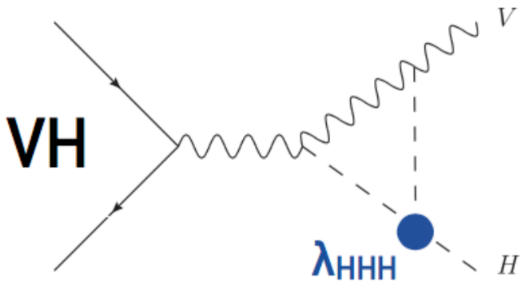
These performance are much better than what expected just 10 years ago: theory & experiment interactions a game changer

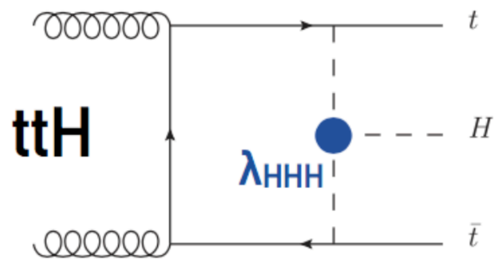


Run3: double Run2 stat, ~300 fb^{-1}@13.6 TeV

From 2029 HL-LHC: up to 4000 fb^{-1}, ATLAS/CMS detector upgrades

- ~180M Higgs/experiment by end of HL-LHC
- Prospects are very high
- Projections keep improving (thanks to better delivered analysis sensitivities)





Single Higgs production modes sensitive to self-coupling through loop corrections

Complementary constraints to direct HH searches