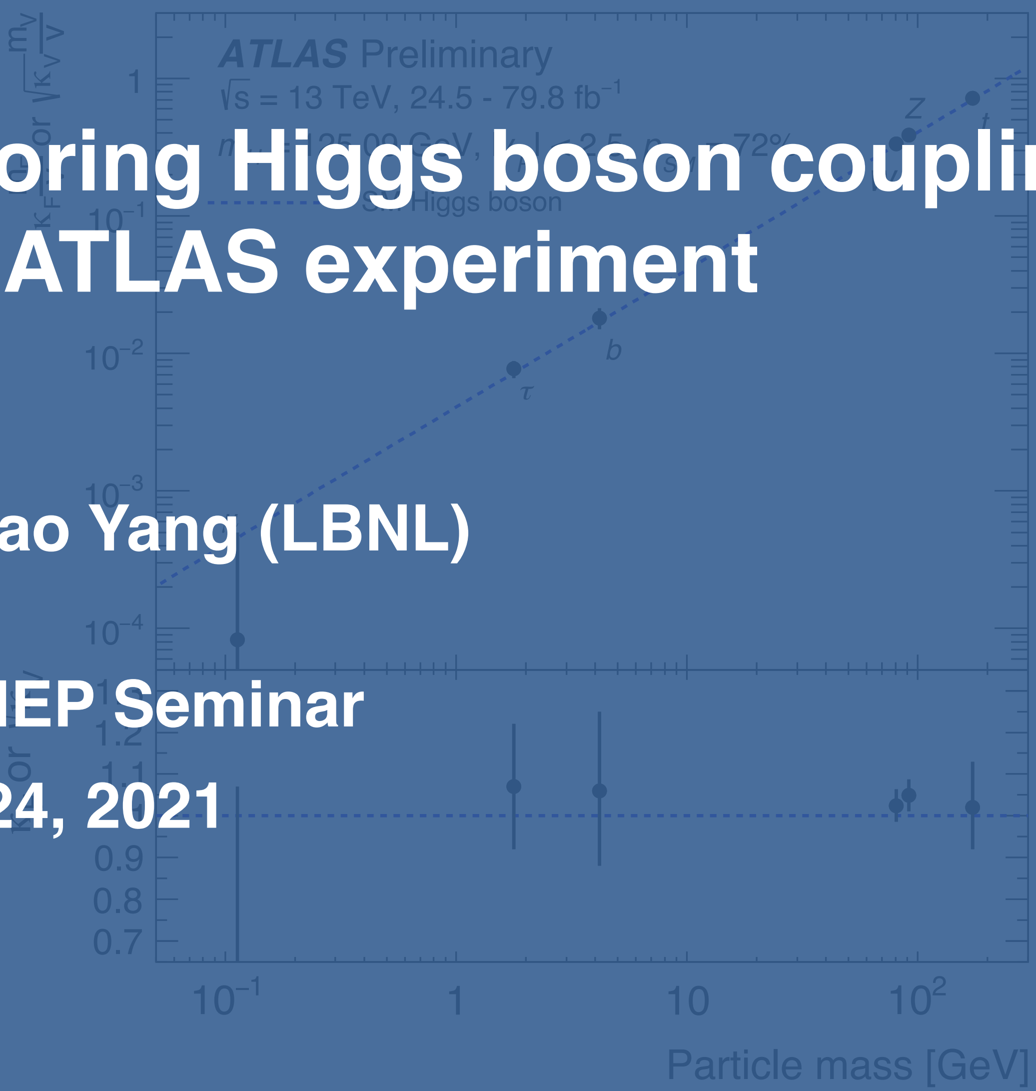


Exploring Higgs boson couplings with ATLAS experiment

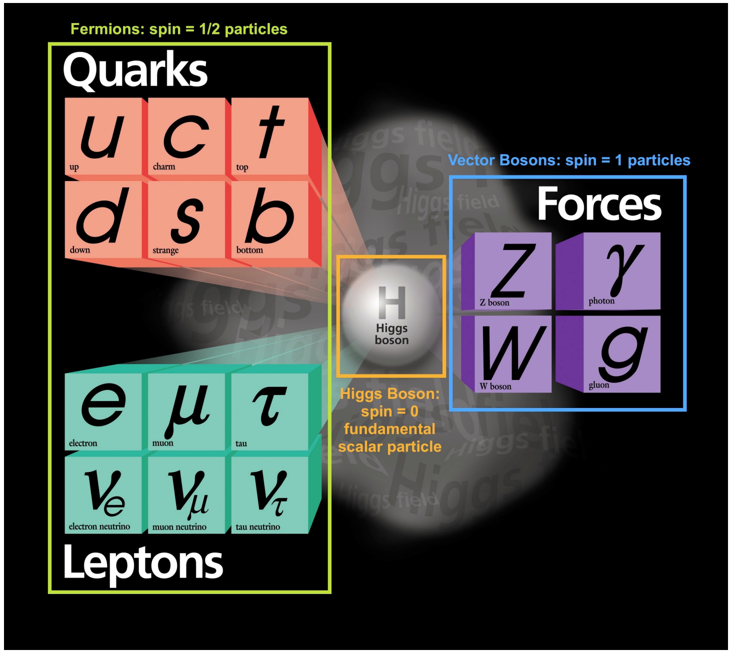
Hongtao Yang (LBNL)

PKU HEP Seminar

June 24, 2021

The Higgs boson

- In the Standard Model (SM), the Brout-Englert-Higgs (BEH) mechanism provides masses to elementary particles
- It predicts a CP-even scalar particle: **the Higgs boson**
- Couplings of fermions (bosons) to Higgs boson proportional to $m_{fermion}$ (m^2_{boson})

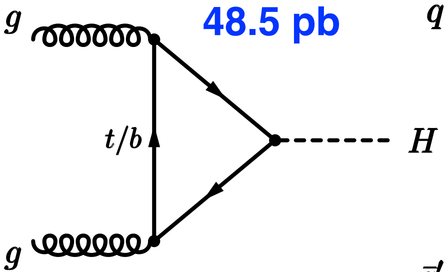


Fish discovered water

F. Wilczek

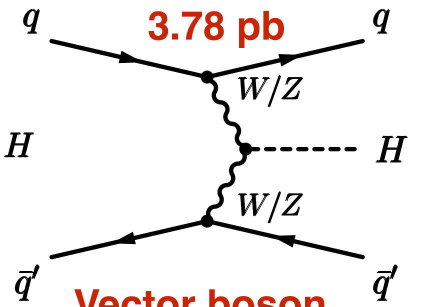
SM Higgs boson production at LHC

Main



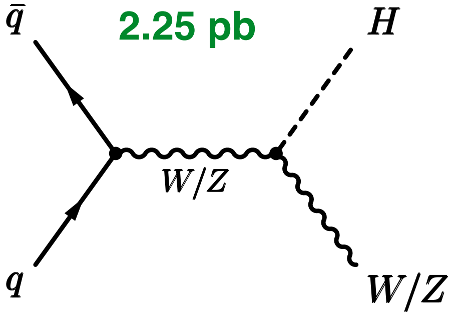
48.5 pb

Gluon-fusion ggF (~87%)



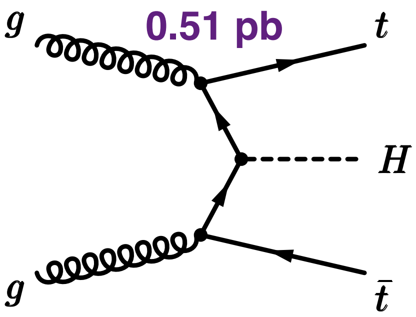
3.78 pb

Vector boson fusion (VBF) (~7%)



2.25 pb

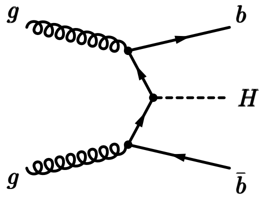
VH (~4%)



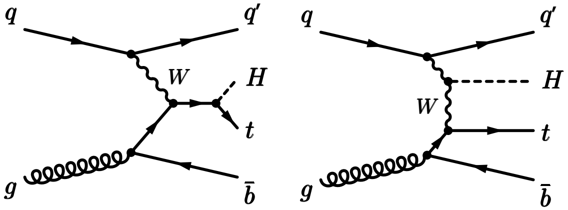
0.51 pb

ttH (~1%)

Rare

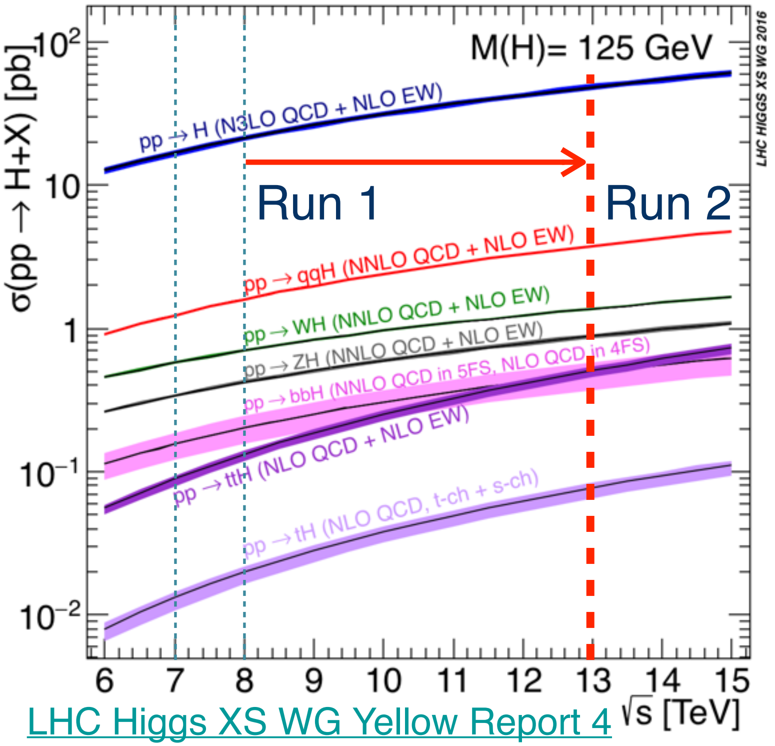


bbH (~1%)
0.49 pb



tH (~0.1%) 0.09 pb

- Distinct topology from each production mode
- Cross section of main production modes calculated with relatively high accuracy
- Rare production modes difficult to probe, but important for beyond the SM (BSM) scenarios

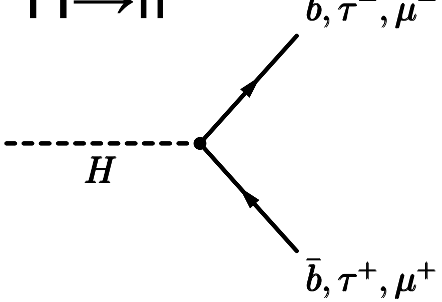


LHC Higgs XS WG Yellow Report 4

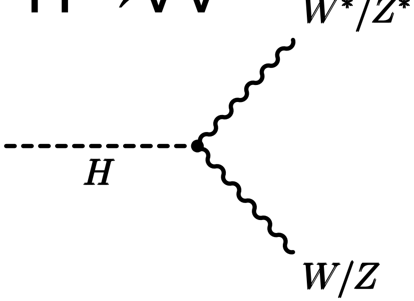
Higgs boson decays

- **“Big five”: γγ, ZZ, WW, ττ, bb**
  - Among them, **γγ** and **ZZ→4l** have best precision due to excellent detector resolution and high S/B
- “Rare” channels: μμ, Zγ, cc, etc. Challenging but also important!

H→ff

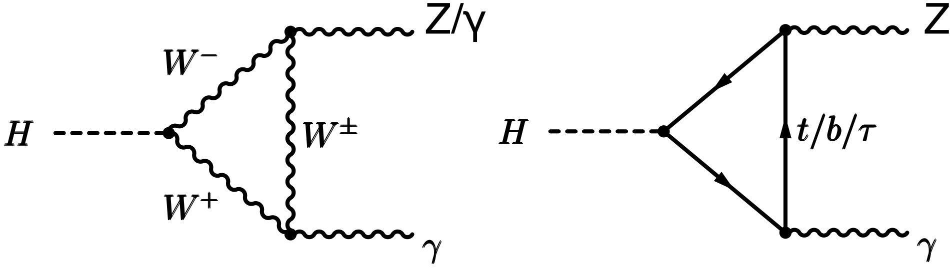


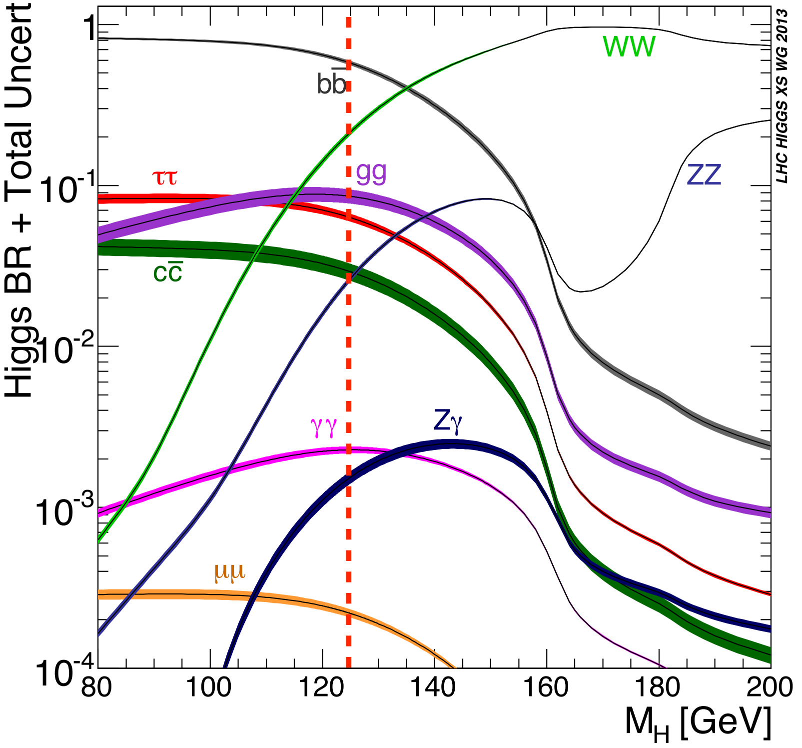
H→VV



H→γγ/Zγ

Yellow Report 4

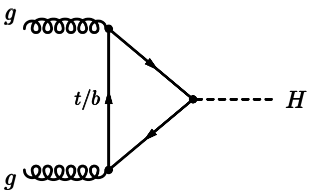




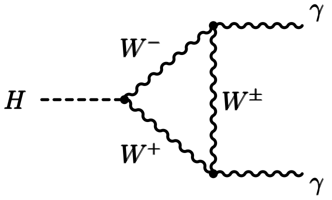
Why do we study Higgs physics?

- Experimental measurements of Higgs boson properties serve as **a test bench for the SM** and **a portal to look for possible new physics**
- New physics could show up in
  - Inclusive production and decay rates, in particular loop induced processes such as ggF and H→γγ
  - Differential distributions, e.g. high $p_T(H)$ sensitive to content of ggF loop
  - Rare processes, e.g. H→μμ, H→inv.

ggF:



H→γγ:

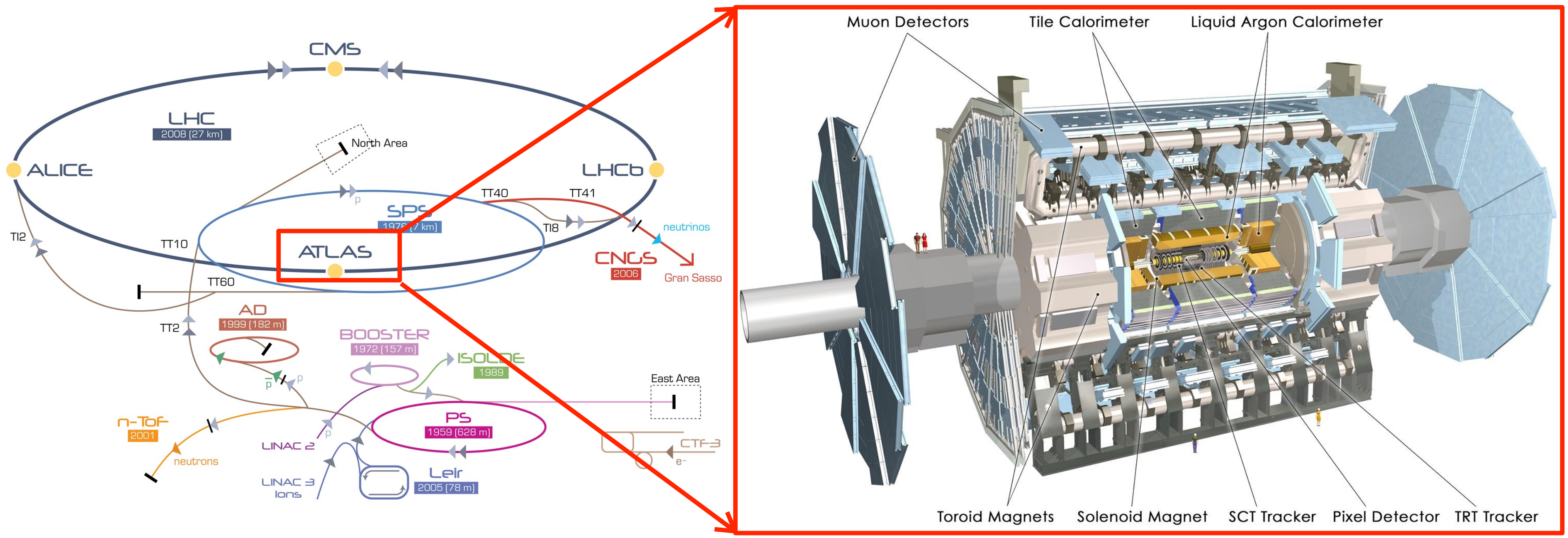


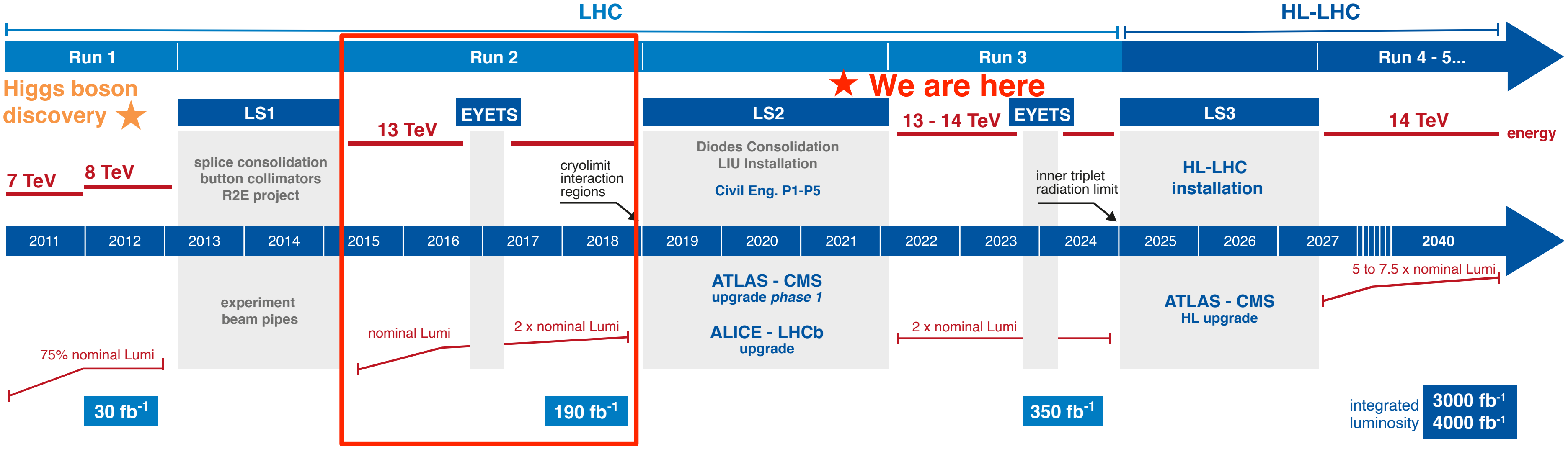
Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

"exploit the Higgs boson as a new tool for discovery"

The ATLAS detector





LHC

HL-LHC

Run 1 | Run 2 | Run 3 | Run 4 - 5...

Higgs boson discovery ★

★ **We are here**

7 TeV | 8 TeV | 13 TeV | 13 - 14 TeV | 14 TeV | energy

LS1: splice consolidation, button collimators, R2E project

EYETS

cryolimit interaction regions

LS2: Diodes Consolidation, LIU Installation, Civil Eng. P1-P5

EYETS

inner triplet radiation limit

LS3: HL-LHC installation

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2040

75% nominal Lumi

experiment beam pipes

nominal Lumi

2 x nominal Lumi

ATLAS - CMS upgrade *phase 1*

ALICE - LHCb upgrade

2 x nominal Lumi

ATLAS - CMS HL upgrade

5 to 7.5 x nominal Lumi

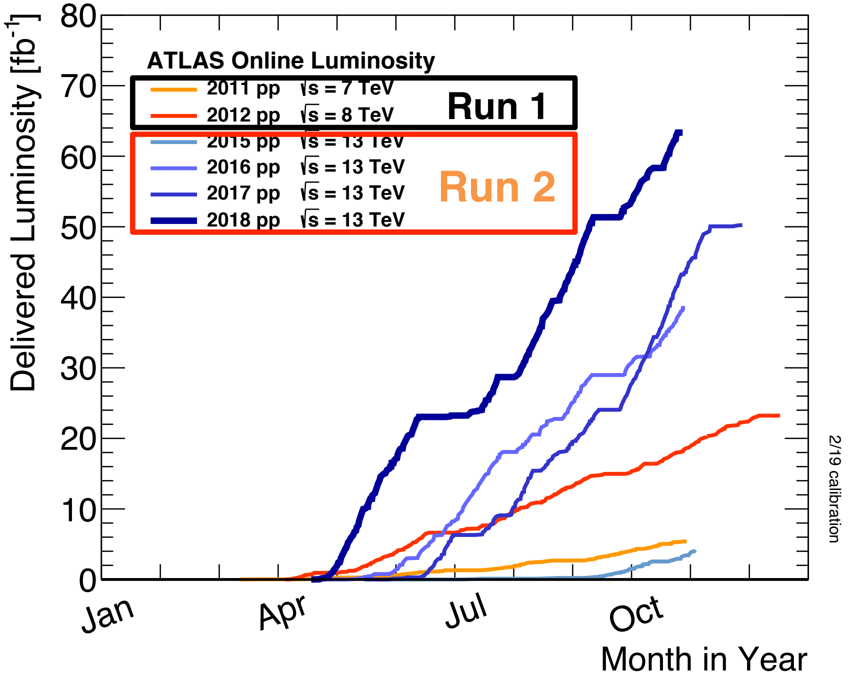
30 fb^{-1}

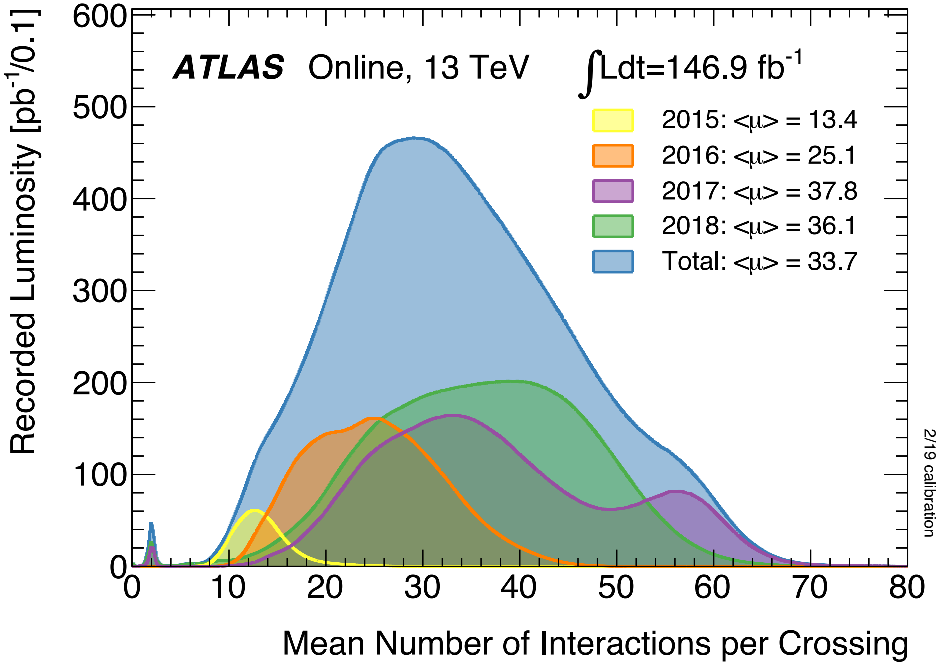
190 fb^{-1}

350 fb^{-1}

integrated luminosity: 3000 fb^{-1}, 4000 fb^{-1}

Run 2 data taking





- **139 fb^{-1}** of **13 TeV** proton-proton collision data collected for physics by ATLAS detector
  - Average 34 interactions per bunch crossing
- Thanks to the excellent LHC performance and smooth operation of ATLAS detector

Combined measurements of Higgs boson couplings

ATLAS-CONF-2020-027

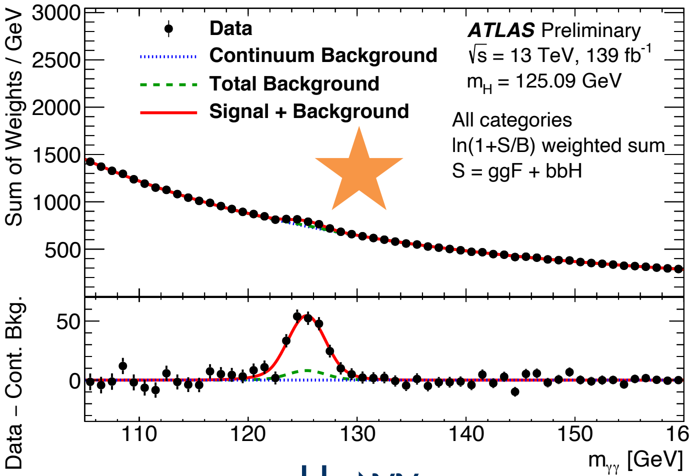
With up to 139 fb^{-1} of 13 TeV data

Channel	ggF	VBF	VH	ttH
$H\to\gamma\gamma$ (139 fb^{-1})	✔	✔	✔	✔
$H\to ZZ$ (139 fb^{-1})	✔	✔	✔	✔
$H\to WW$ (36 fb^{-1})	✔	✔	✓	✔
$H\to\tau\tau$ (36 fb^{-1})	✔	✔	✓	✔
$H\to bb$ (VH 139 fb^{-1}, others 36 fb^{-1})	✓	✔	✔	✔
$H\to\mu\mu$ (139 fb^{-1})	✔	✔	✔	✔
$H\to$inv. (139 fb^{-1})	✓	✔	✓	✓

✔: channel included in the combination

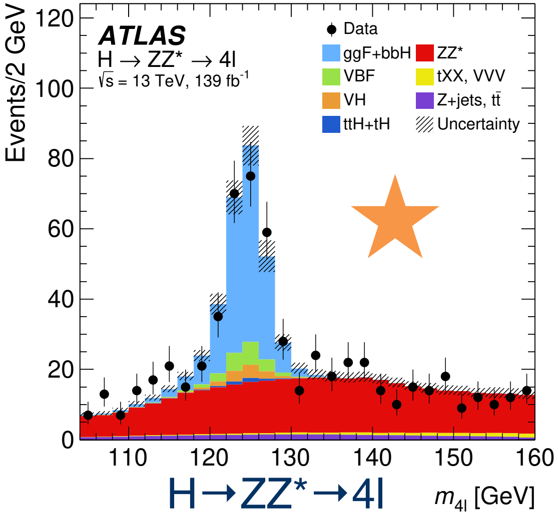
✓: channel available but not included in combination

Invariant mass spectra from input channels



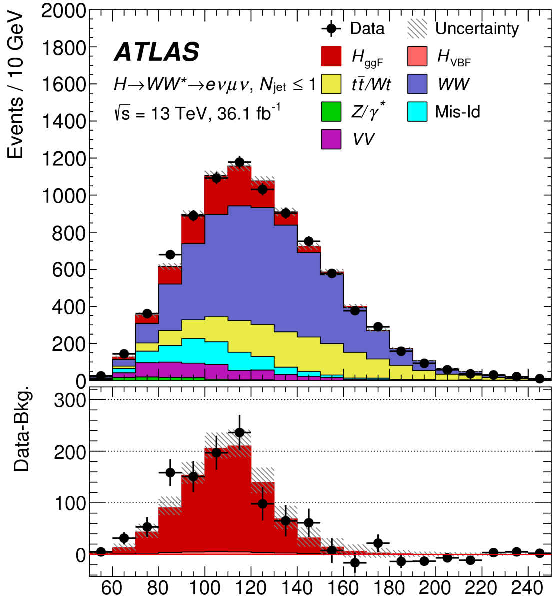
H→γγ

ATLAS-CONF-2020-026



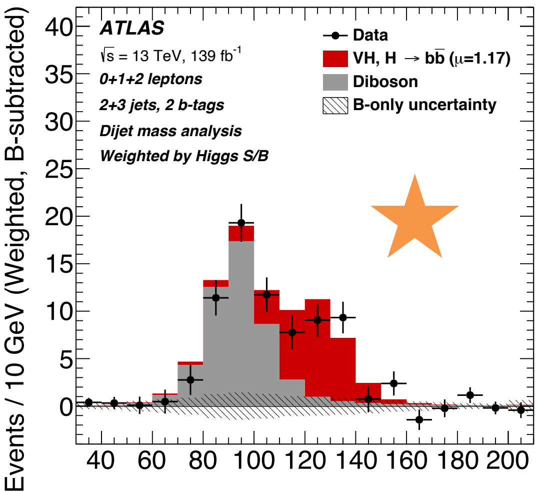
H→ZZ*→4l

EPJC 80 (2020) 957



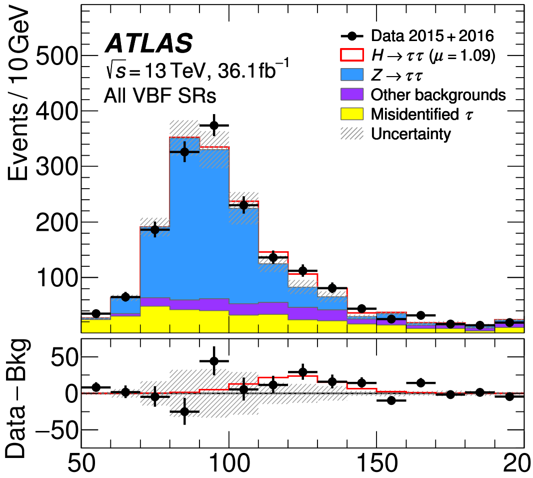
H→WW→eνμν

PLB 789 (2019) 508



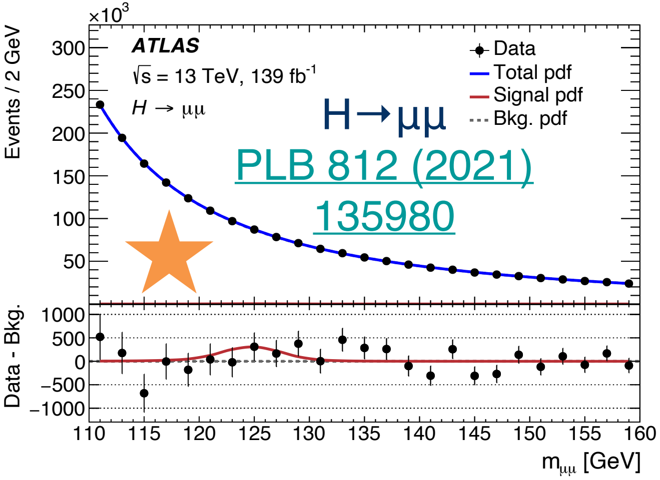
VH, H→bb

EPJC 81 (2021) 178



H→ττ

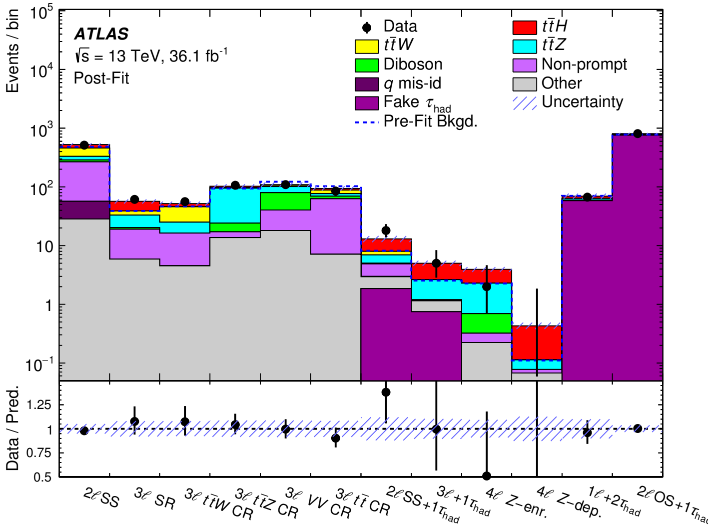
PRD 99 (2019) 072001



H→μμ

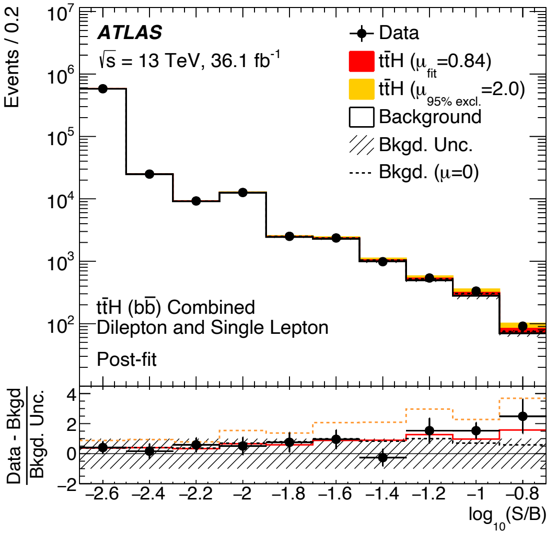
PLB 812 (2021) 135980

Other input channels



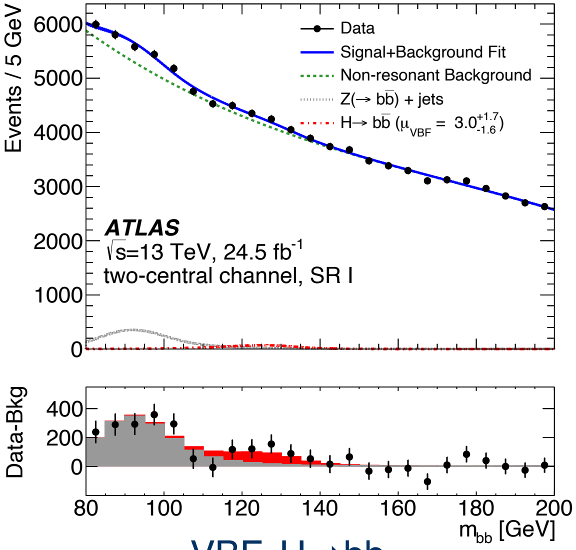
ttH multi-lepton (H→ZZ, WW, ττ)

PRD 97 (2018) 072003



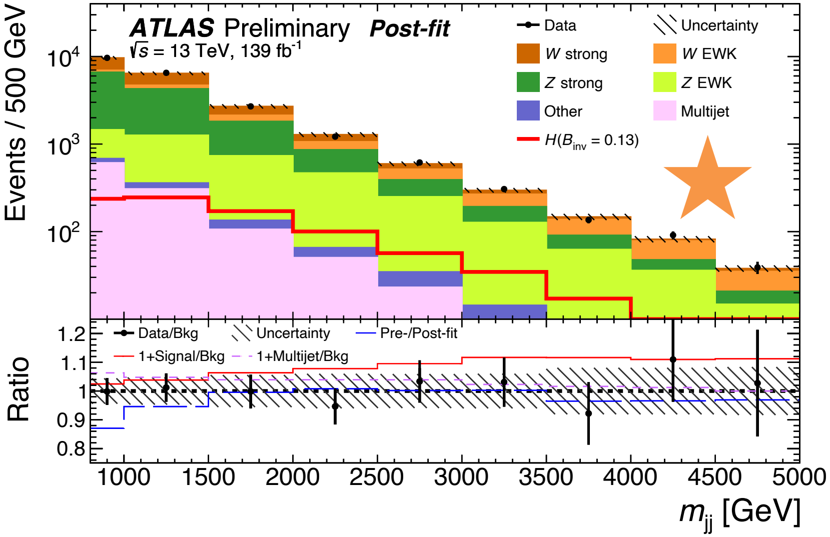
ttH, H→bb

PRD 97 (2018) 072016



VBF, H→bb

PRD 98 (2018) 052003



VBF, H→inv.

ATLAS-CONF-2020-008

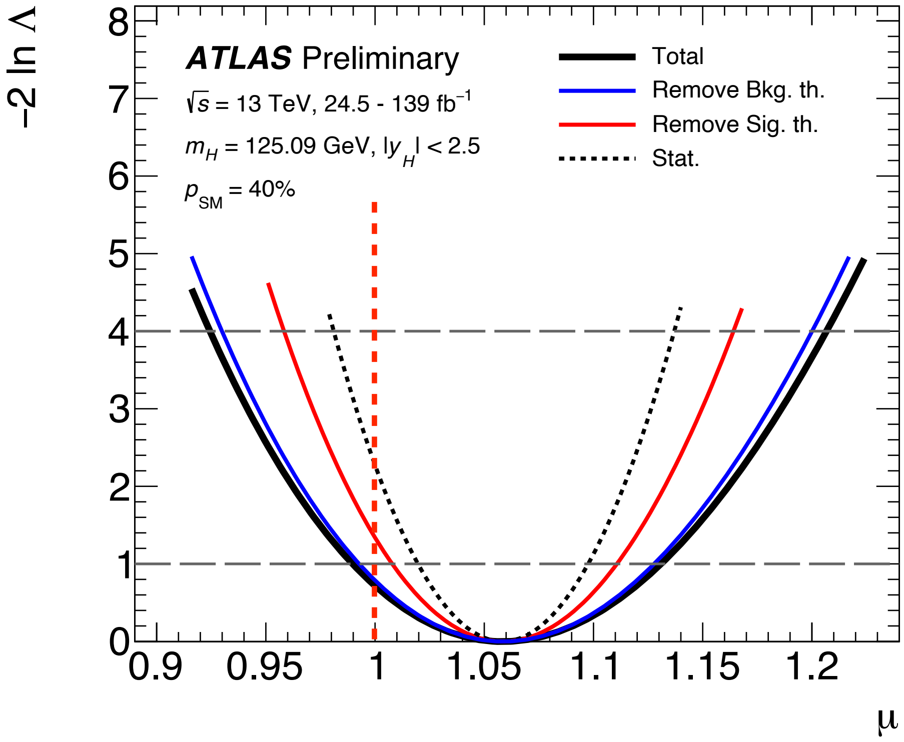
How many Higgs bosons do we have?

Every fb^{-1} of pp collision at 13 TeV	$H\to\gamma\gamma$	$H\to ZZ$	$H\to WW$	$H\to\tau\tau$	$H\to bb$
Produced	130	1,500	12,000	3,500	32,000
Selected	46	1.5	42	17	66
Efficiency [%]	35.4%	0.1%	0.4%	0.5%	0.2%

*Assuming **m_H = 125.09 GeV** from Run 1 ATLAS-CMS combined measurement

- With every fb^{-1} of 13 TeV pp collision data, the SM predicts about **56,000** Higgs bosons produced
- Analyses included in the combination will select about **170** SM Higgs boson candidates **in every fb^{-1}**
  - Large background from proton-proton collisions introduces difficulty in trigger and event selection
  - Number will increase once more analyses are added

Inclusive signal strength



Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, E_T^{miss}	1.4
Flavor tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7

Overall cross-section uncertainty

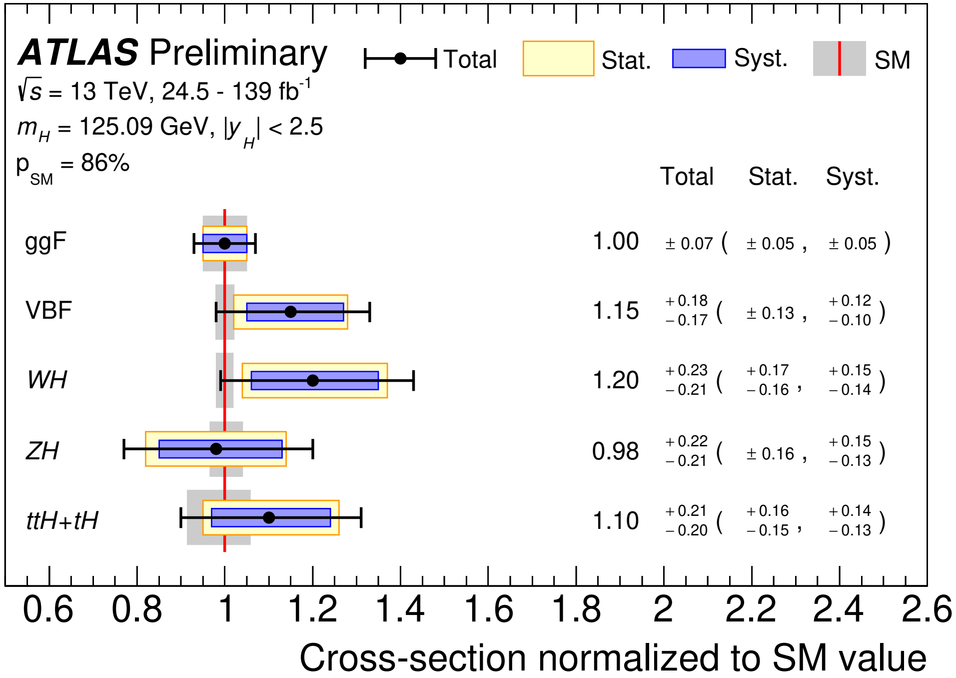
Signal strength: **μ = N$_{signal}$(obs.)/N$_{signal}$(exp.)**

*All numbers are in percentage. Table is obsolete

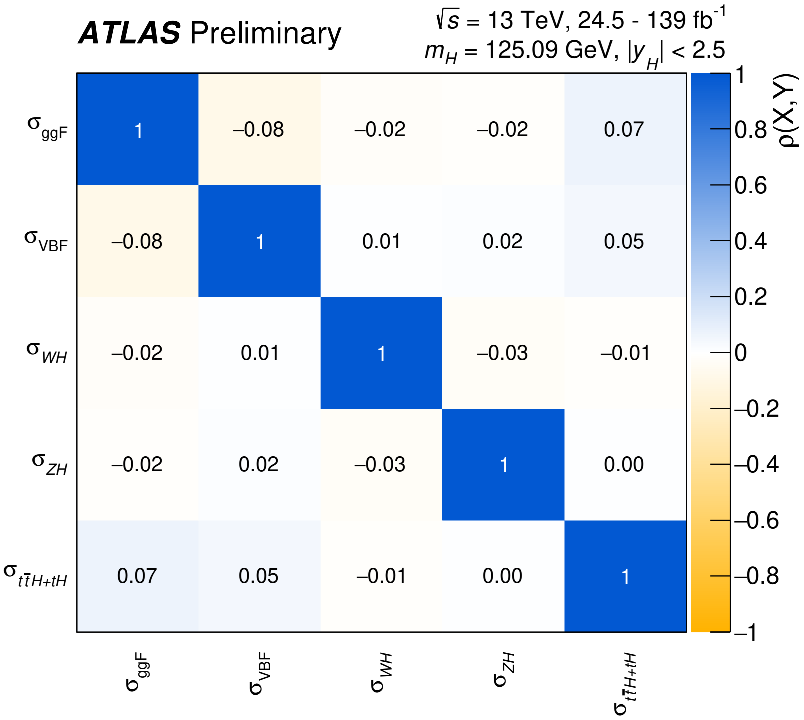
$$\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04(\text{stat.}) \pm 0.03(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$$

- Reaching 8% precision. Good agreement with SM

Production mode cross-sections (assuming the SM BRs)



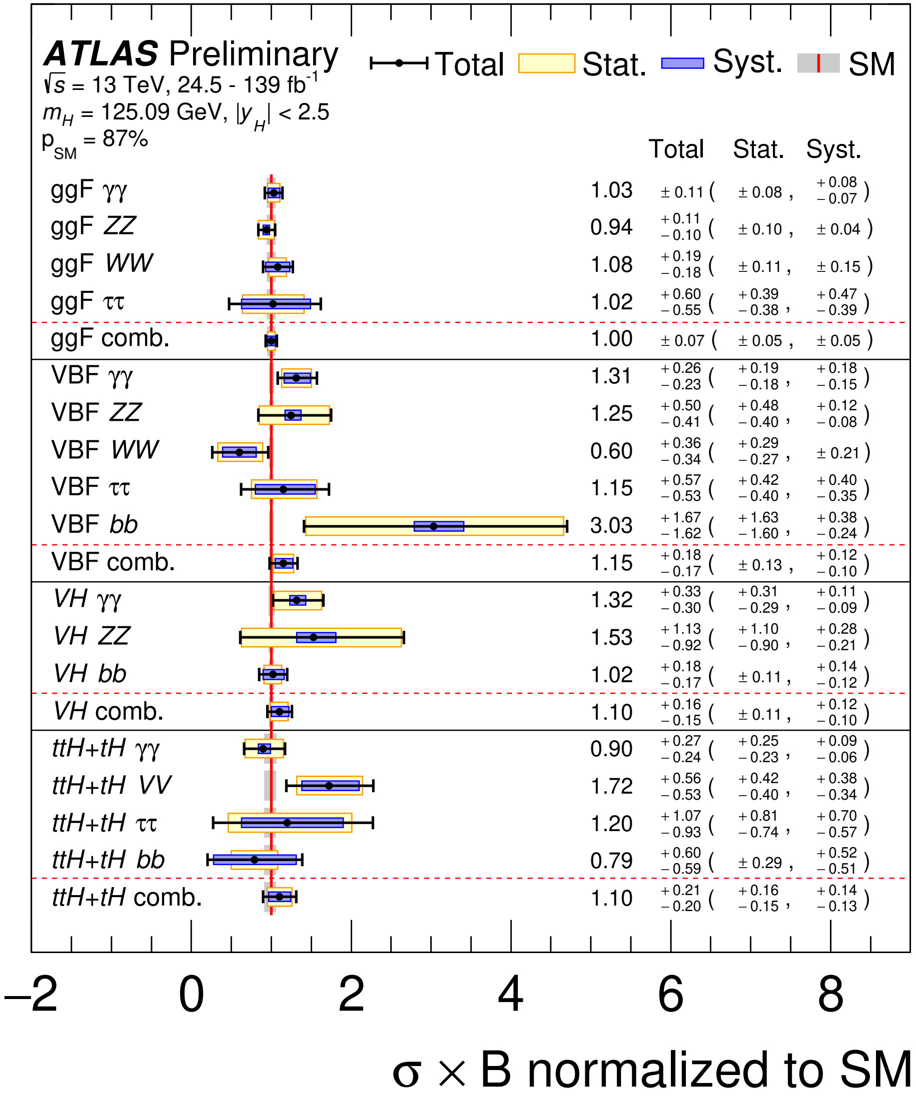
		Total	Stat.	Syst.
ggF	1.00	± 0.07	± 0.05	± 0.05
VBF	1.15	$^{+0.18}_{-0.17}$	± 0.13	$^{+0.12}_{-0.10}$
WH	1.20	$^{+0.23}_{-0.21}$	$^{+0.17}_{-0.16}$	$^{+0.15}_{-0.14}$
ZH	0.98	$^{+0.22}_{-0.21}$	± 0.16	$^{+0.15}_{-0.13}$
ttH+tH	1.10	$^{+0.21}_{-0.20}$	$^{+0.16}_{-0.15}$	$^{+0.14}_{-0.13}$



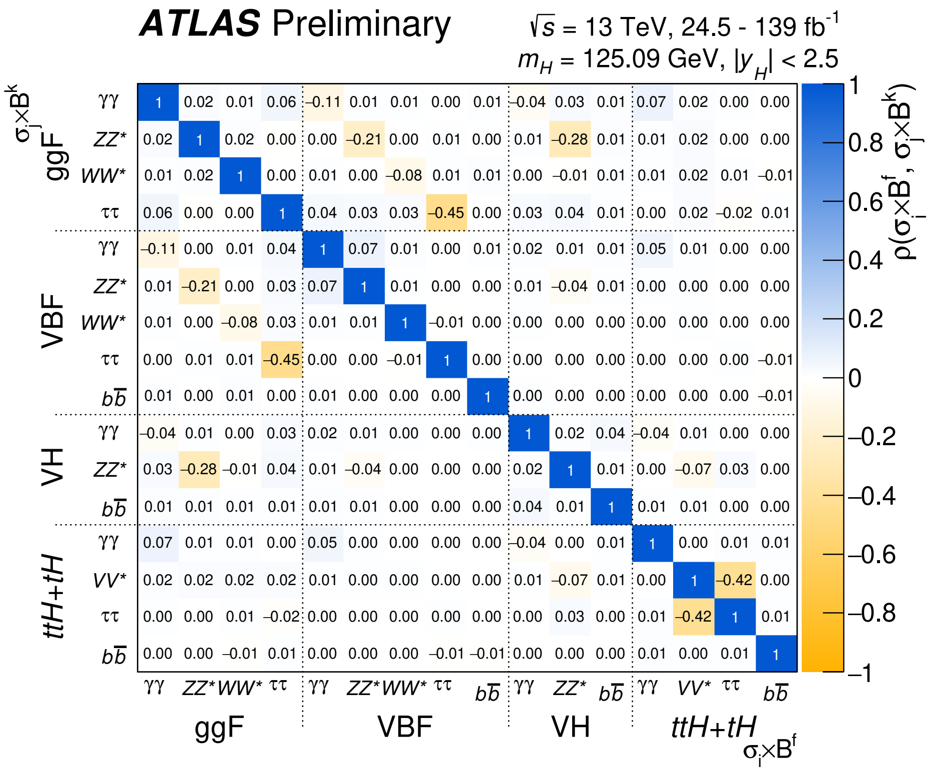
	σ_{ggF}	σ_{VBF}	σ_{WH}	σ_{ZH}	$\sigma_{t\bar{t}H+tH}$
σ_{ggF}	1	−0.08	−0.02	−0.02	0.07
σ_{VBF}	−0.08	1	0.01	0.02	0.05
σ_{WH}	−0.02	0.01	1	−0.03	−0.01
σ_{ZH}	−0.02	0.02	−0.03	1	0.00
$\sigma_{t\bar{t}H+tH}$	0.07	0.05	−0.01	0.00	1

- **ggF cross-section measured with precision of 7%, close to 5% uncertainty on the N^{3}LO cross section prediction**
- **All production modes observed with significance >5σ**
- Small correlations between different production modes

Production cross-section measured in each decay channel



		Total	Stat.	Syst.
ggF γγ	1.03	± 0.11	± 0.08	$^{+0.08}_{-0.07}$
ggF *ZZ*	0.94	$^{+0.11}_{-0.10}$	± 0.10	± 0.04
ggF *WW*	1.08	$^{+0.19}_{-0.18}$	± 0.11	± 0.15
ggF ττ	1.02	$^{+0.60}_{-0.55}$	$^{+0.39}_{-0.38}$	$^{+0.47}_{-0.39}$
ggF comb.	1.00	± 0.07	± 0.05	± 0.05
VBF γγ	1.31	$^{+0.26}_{-0.23}$	$^{+0.19}_{-0.18}$	$^{+0.18}_{-0.15}$
VBF *ZZ*	1.25	$^{+0.50}_{-0.41}$	$^{+0.48}_{-0.40}$	$^{+0.12}_{-0.08}$
VBF *WW*	0.60	$^{+0.36}_{-0.34}$	$^{+0.29}_{-0.27}$	± 0.21
VBF ττ	1.15	$^{+0.57}_{-0.53}$	$^{+0.42}_{-0.40}$	$^{+0.40}_{-0.35}$
VBF *bb*	3.03	$^{+1.67}_{-1.62}$	$^{+1.63}_{-1.60}$	$^{+0.38}_{-0.24}$
VBF comb.	1.15	$^{+0.18}_{-0.17}$	± 0.13	$^{+0.12}_{-0.10}$
VH γγ	1.32	$^{+0.33}_{-0.30}$	$^{+0.31}_{-0.29}$	$^{+0.11}_{-0.09}$
VH ZZ	1.53	$^{+1.13}_{-0.92}$	$^{+1.10}_{-0.90}$	$^{+0.28}_{-0.21}$
VH bb	1.02	$^{+0.18}_{-0.17}$	± 0.11	$^{+0.14}_{-0.12}$
VH comb.	1.10	$^{+0.16}_{-0.15}$	± 0.11	$^{+0.12}_{-0.10}$
ttH+tH γγ	0.90	$^{+0.27}_{-0.24}$	$^{+0.25}_{-0.23}$	$^{+0.09}_{-0.06}$
ttH+tH VV	1.72	$^{+0.56}_{-0.53}$	$^{+0.42}_{-0.40}$	$^{+0.38}_{-0.34}$
ttH+tH ττ	1.20	$^{+1.07}_{-0.93}$	$^{+0.81}_{-0.74}$	$^{+0.70}_{-0.57}$
ttH+tH bb	0.79	$^{+0.60}_{-0.59}$	± 0.29	$^{+0.52}_{-0.51}$
ttH+tH comb.	1.10	$^{+0.21}_{-0.20}$	$^{+0.16}_{-0.15}$	$^{+0.14}_{-0.13}$

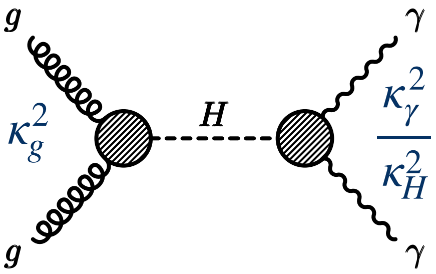


	ggF γγ	ggF *ZZ**	ggF *WW**	ggF ττ	VBF γγ	VBF *ZZ**	VBF *WW**	VBF ττ	VBF $b\bar{b}$	VH γγ	VH *ZZ**	VH $b\bar{b}$	*ttH+tH* γγ	*ttH+tH VV**	*ttH+tH* ττ	*ttH+tH* $b\bar{b}$
ggF γγ	1	0.02	0.01	0.06	–0.11	0.01	0.01	0.00	0.01	–0.04	0.03	0.01	0.07	0.02	0.00	0.00
ggF *ZZ**	0.02	1	0.02	0.00	0.00	–0.21	0.00	0.01	0.00	0.01	–0.28	0.01	0.01	0.02	0.00	0.00
ggF *WW**	0.01	0.02	1	0.00	0.01	0.00	–0.08	0.01	0.01	0.00	–0.01	0.01	0.01	0.02	0.01	–0.01
ggF ττ	0.06	0.00	0.00	1	0.04	0.03	0.03	–0.45	0.00	0.03	0.04	0.01	0.00	0.02	–0.02	0.01
VBF γγ	–0.11	0.00	0.01	0.04	1	0.07	0.01	0.00	0.01	0.02	0.01	0.01	0.05	0.01	0.00	0.00
VBF *ZZ**	0.01	–0.21	0.00	0.03	0.07	1	0.01	0.00	0.00	0.01	–0.04	0.01	0.00	0.00	0.00	0.00
VBF *WW**	0.01	0.00	–0.08	0.03	0.01	0.01	1	–0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
VBF ττ	0.00	0.01	0.01	–0.45	0.00	0.00	–0.01	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–0.01
VBF $b\bar{b}$	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	1	0.00	0.00	0.00	0.00	0.00	0.00	–0.01
VH γγ	–0.04	0.01	0.00	0.03	0.02	0.01	0.00	0.00	0.00	1	0.02	0.04	–0.04	0.01	0.00	0.00
VH *ZZ**	0.03	–0.28	–0.01	0.04	0.01	–0.04	0.00	0.00	0.00	0.02	1	0.01	0.00	–0.07	0.03	0.00
VH $b\bar{b}$	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.04	0.01	1	0.01	0.01	0.00	0.00
ttH+tH γγ	0.07	0.01	0.01	0.00	0.05	0.00	0.00	0.00	0.00	–0.04	0.00	0.01	1	0.00	0.01	0.01
*ttH+tH VV**	0.02	0.02	0.02	0.02	0.01	0.00	0.00	0.00	0.00	0.01	–0.07	0.01	0.00	1	–0.42	0.00
ttH+tH ττ	0.00	0.00	0.01	–0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.01	–0.42	1	0.01
ttH+tH $b\bar{b}$	0.00	0.00	–0.01	0.01	0.00	0.00	0.00	–0.01	–0.01	0.00	0.00	0.00	0.01	0.00	0.01	1

- Good compatibility among decay channels and also with the SM
- Results commonly used for theory interpretations

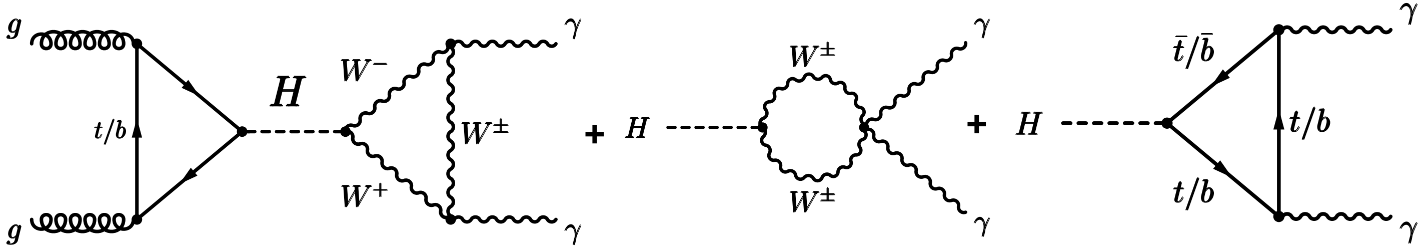
Interpretation using kappa framework

- Leading order motivated framework: assign coupling modifier to each (effective) interaction vertex (e.g. κ_W, κ_Z, κ_t…) and total width (κ_H)



$$\sigma \times BR(gg \to H \to \gamma\gamma) \propto \kappa_g^2 \frac{\kappa_\gamma^2}{\kappa_H^2}$$

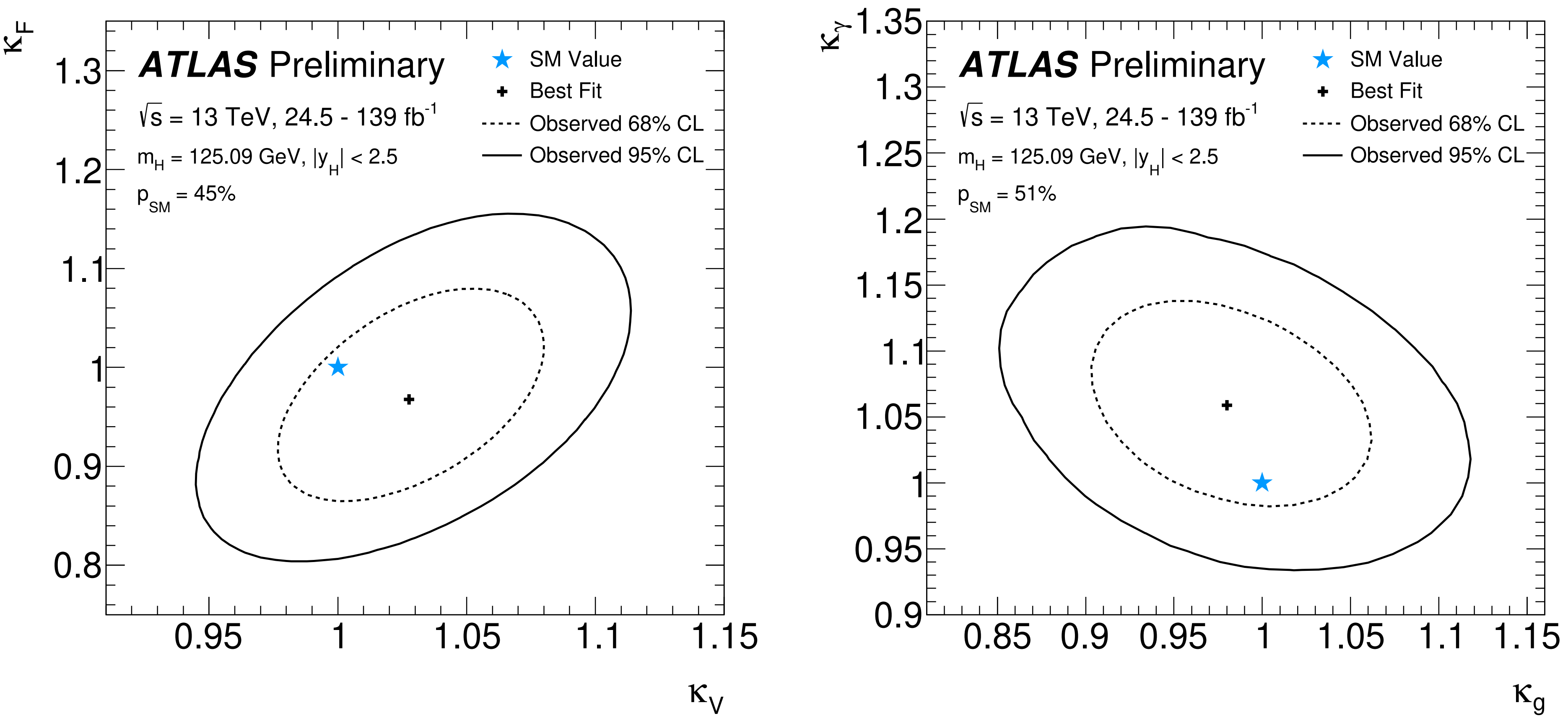
Assume only SM particles → contribute



$$\sigma \times BR(gg \to H \to \gamma\gamma) \propto \underbrace{(1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.04\kappa_t\kappa_b)}_{\kappa_g^2} \underbrace{\frac{1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t}{\kappa_H^2(\kappa_b, \kappa_W, \kappa_\tau, \ldots)}}_{\kappa_\gamma^2/\kappa_H^2}$$

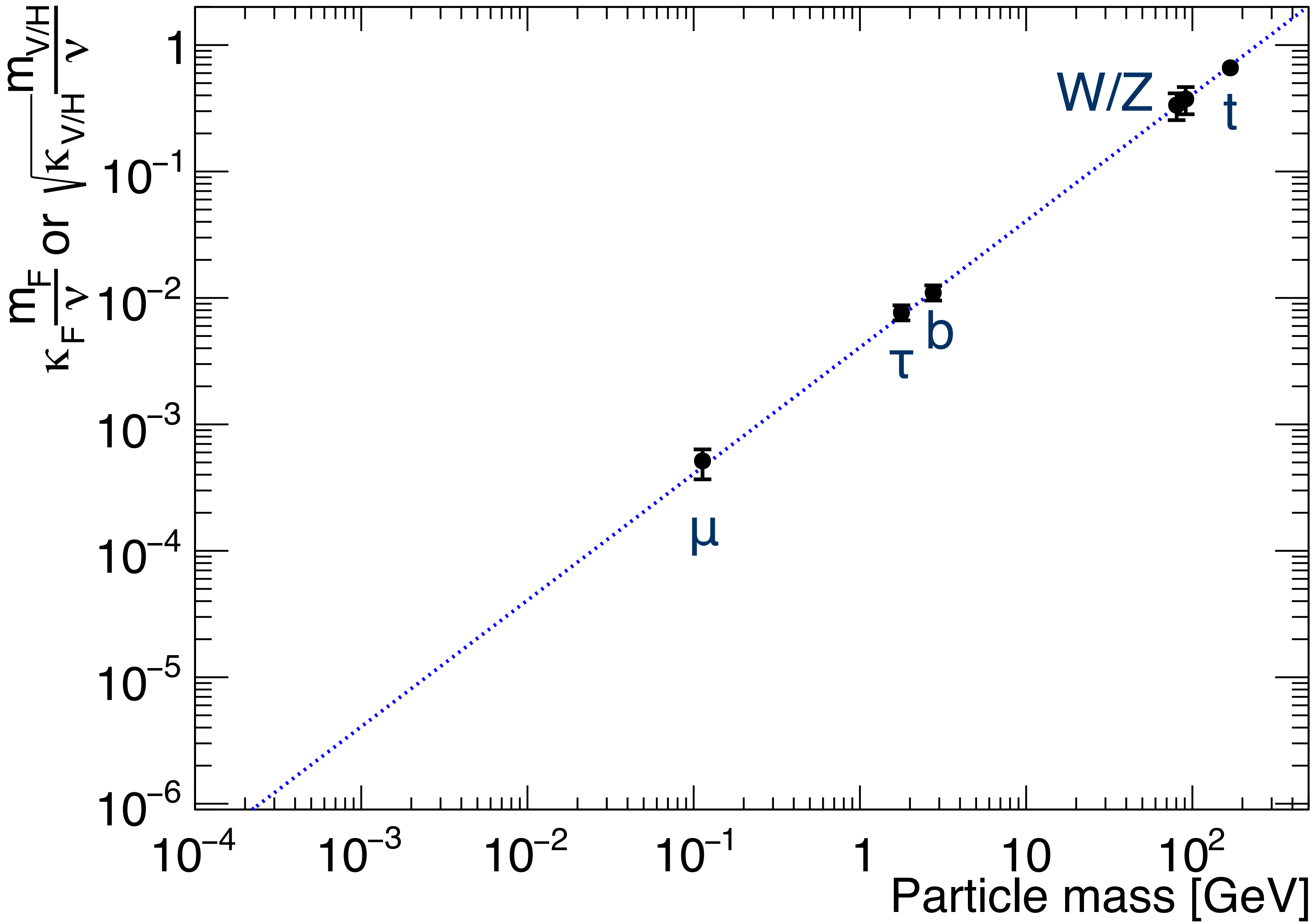
Yellow Report 3

Simple models

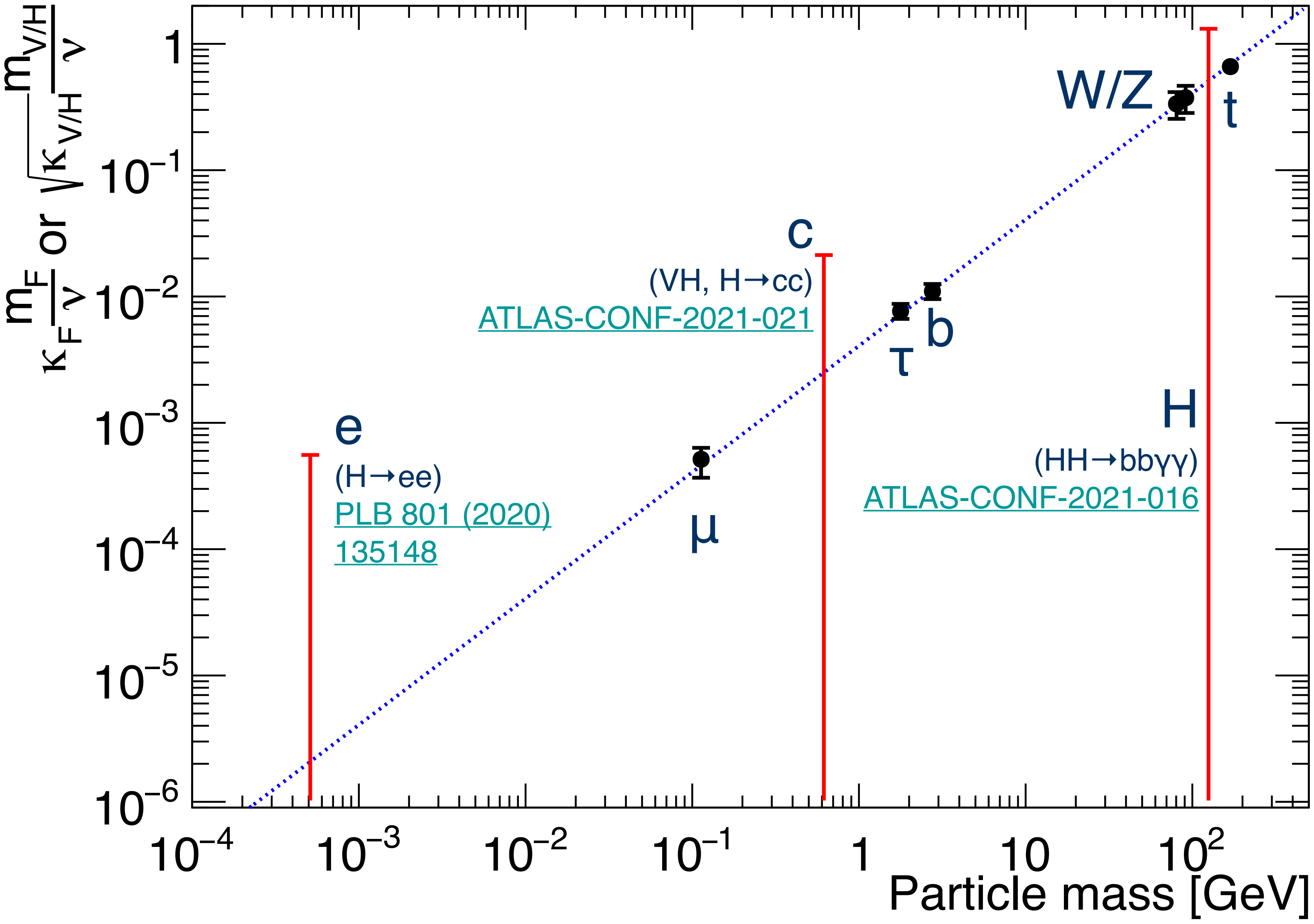


- κ_V vs. κ_F: vector boson vs. fermion coupling
- κ_g vs. κ_γ: focus on loop-induced ggH and Hγγ interactions, with other coupling strengths fixed to SM

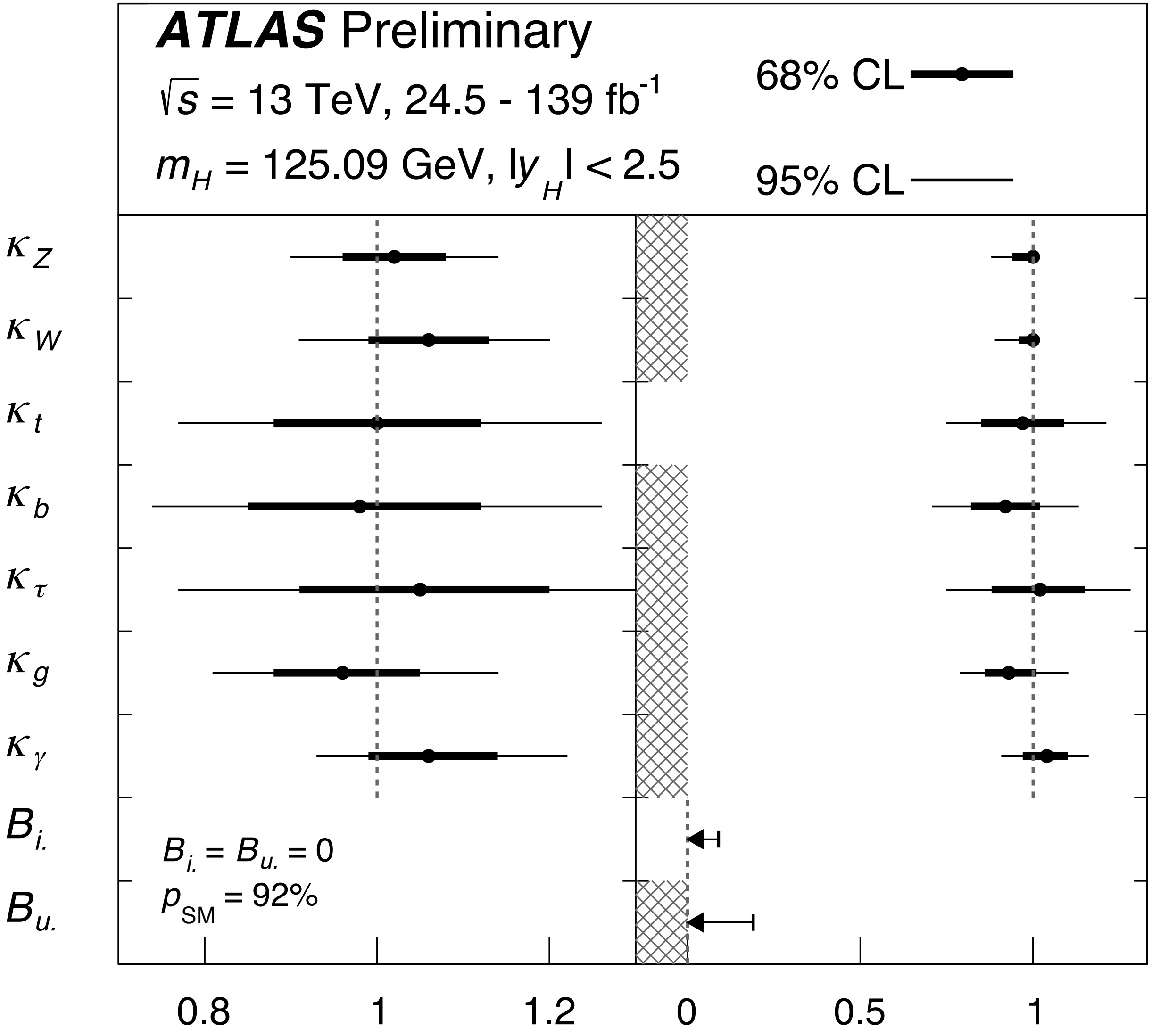
Coupling modifier vs. particle mass



Coupling modifier vs. particle mass

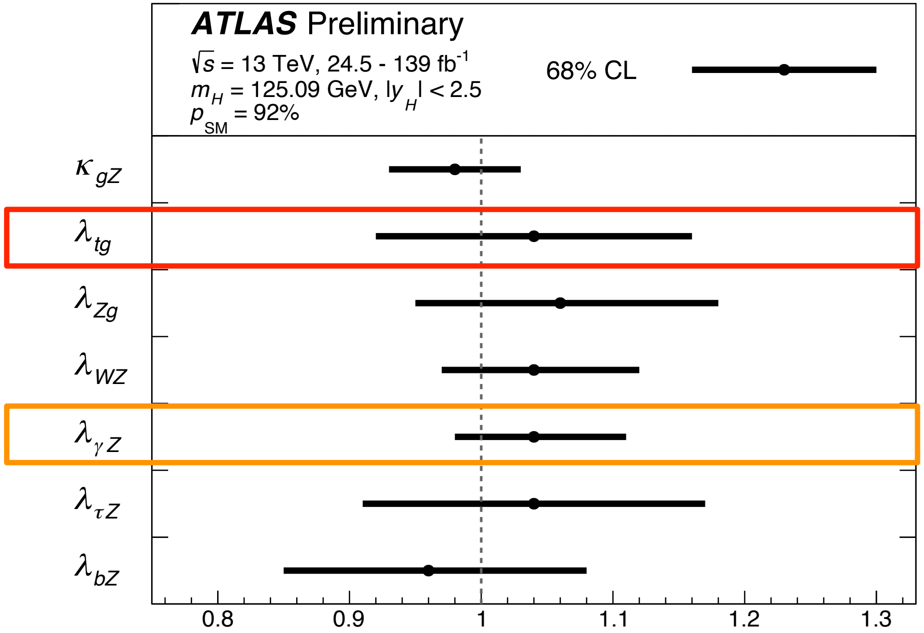


Generic model

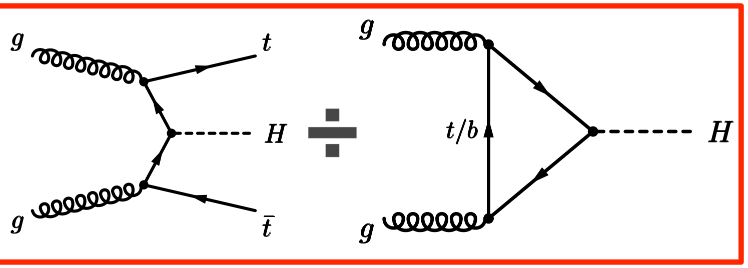


- LHC experiments do not have sensitivity to directly constrain Γ(H) (<< detector resolution)
  - **$B_{\text{inv.}}$ < 9%** @95% CL, mainly constrained by H→inv.
  - **$B_{\text{undet.}}$ < 19%** @95% CL, constrained by inclusive rate + assuming **$|\kappa_V| \leq 1$**

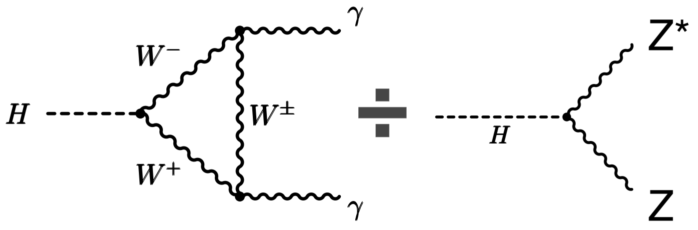
Ratios of coupling strength modifiers



$$\lambda_{tg} = \frac{\kappa_t}{\kappa_g}$$



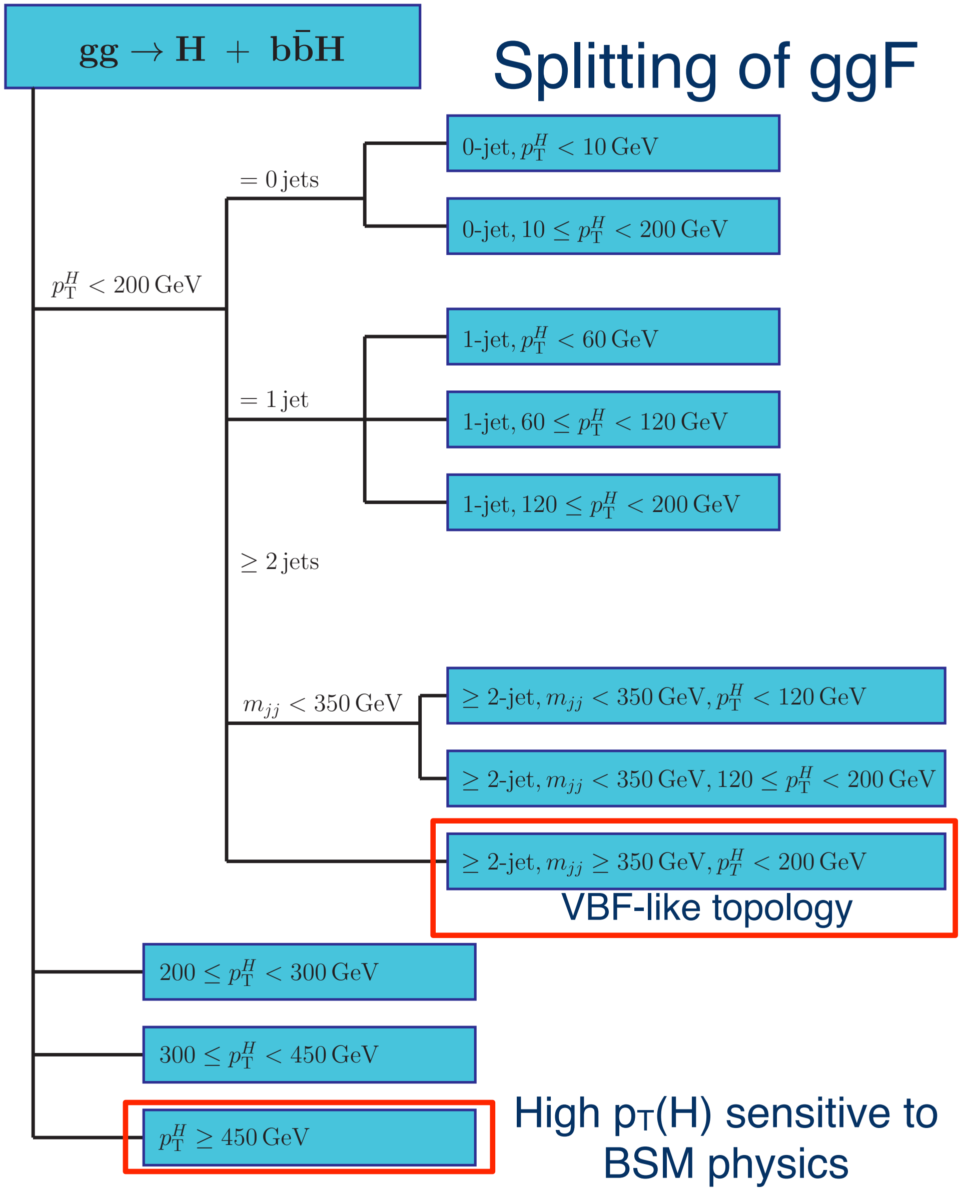
$$\lambda_{\gamma Z} = \frac{\kappa_\gamma}{\kappa_Z}$$



- Ratios are what we can measure best at LHC: less model assumptions; common systematic uncertainties cancel out
  - **λ_{tg}**: compare the direct determination of the top coupling through ttH production (κ_t) to the indirect determination in the ggF loop (κ_g)
  - **$\lambda_{\gamma Z}$**: probe new physics in H→γγ process by comparing with H→ZZ

STXS framework

- **Simplified template cross-section (STXS) framework:** measure cross-section per production mode in different phase-space regions
    - Decay is inclusive so far. No kinematic bins introduced yet
- STXS has several advantages
    - Reduce model dependence while still allow aggressive analysis techniques (e.g. machine learning)
    - Easy to combine multiple production & decay channels
    - Facilitate kinematic-dependent interpretations (e.g. EFT)



Splitting of ggF

$\mathbf{gg \to H \; + \; b\bar{b}H}$

$p_T^H < 200$ GeV

$= 0$ jets

0-jet, $p_T^H < 10$ GeV

0-jet, $10 \leq p_T^H < 200$ GeV

$= 1$ jet

1-jet, $p_T^H < 60$ GeV

1-jet, $60 \leq p_T^H < 120$ GeV

1-jet, $120 \leq p_T^H < 200$ GeV

≥ 2 jets

$m_{jj} < 350$ GeV

$\geq$ 2-jet, $m_{jj} < 350$ GeV, $p_T^H < 120$ GeV

$\geq$ 2-jet, $m_{jj} < 350$ GeV, $120 \leq p_T^H < 200$ GeV

$\geq$ 2-jet, $m_{jj} \geq 350$ GeV, $p_T^H < 200$ GeV

VBF-like topology

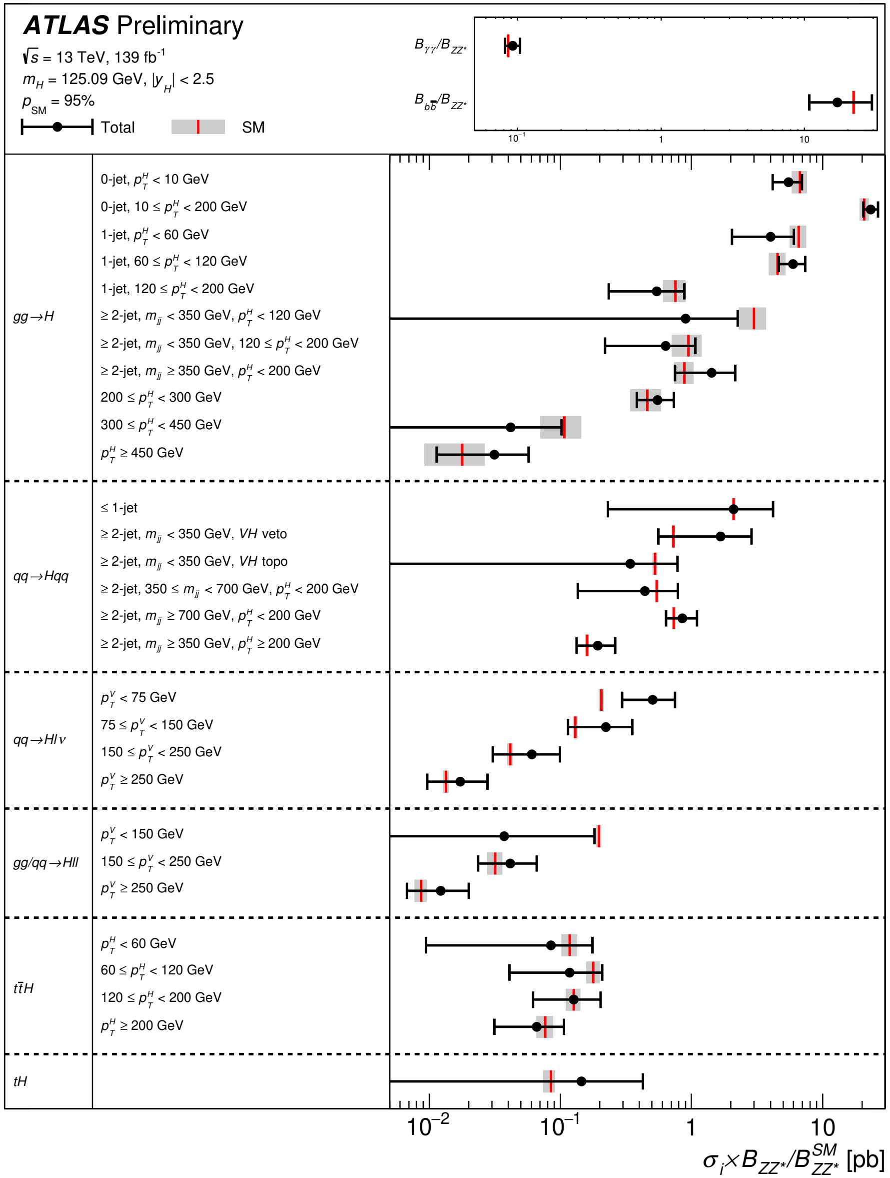
$200 \leq p_T^H < 300$ GeV

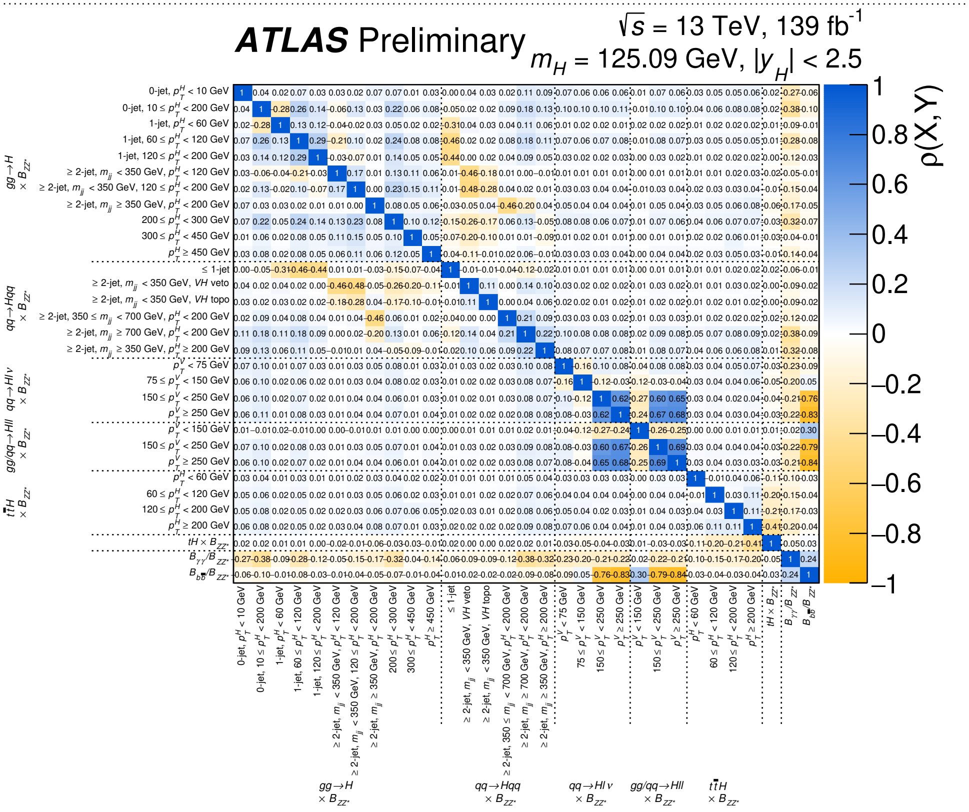
$300 \leq p_T^H < 450$ GeV

$p_T^H \geq 450$ GeV

High $p_T(H)$ sensitive to BSM physics

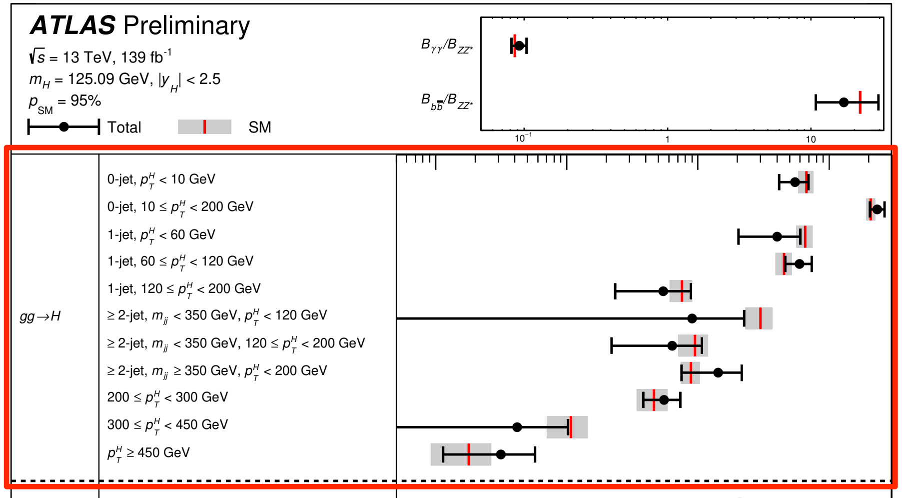
STXS measurements

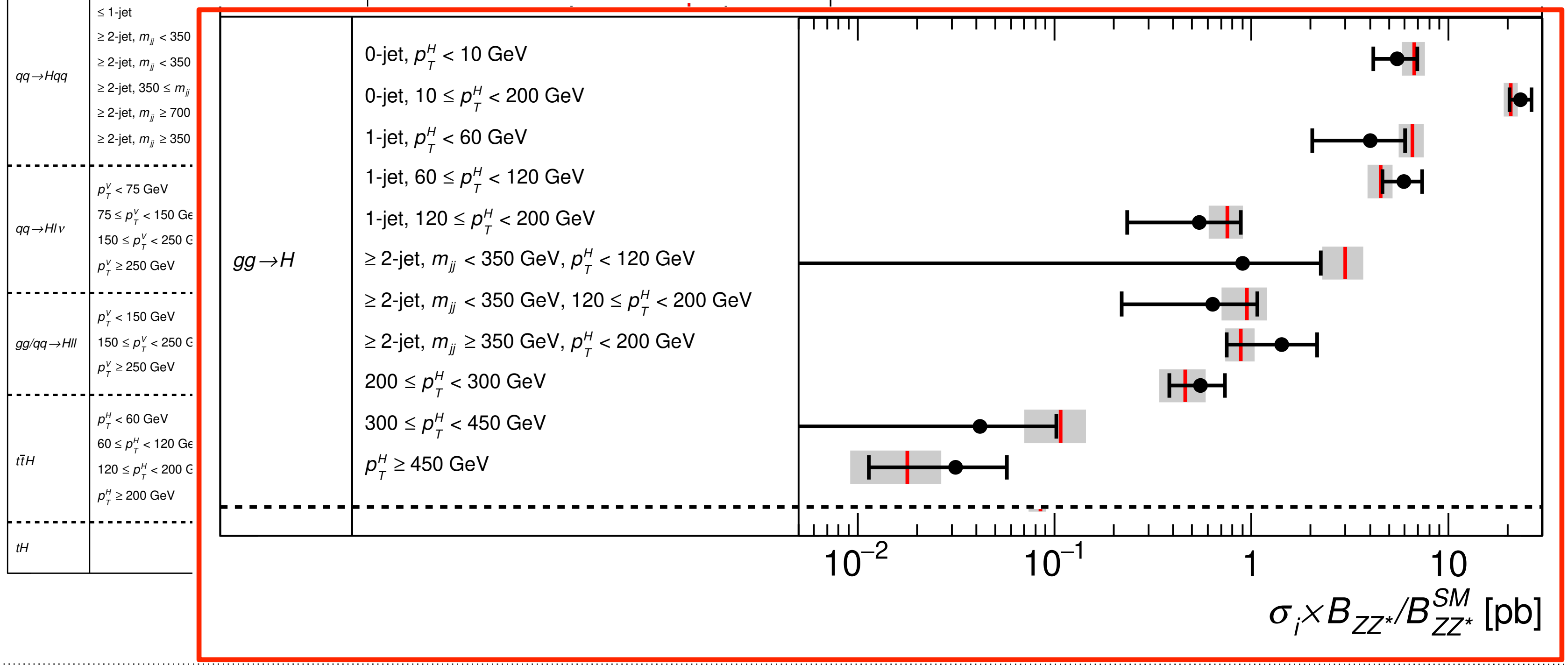




- Including H→γγ, H→ZZ, and VH, H→bb
- Provide differential measurements for all major production modes
- **Nontrivial correlations!**

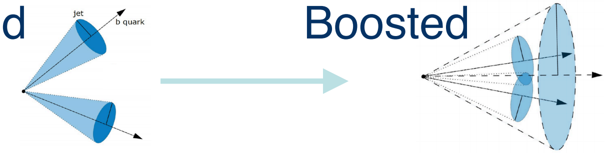
STXS measurements: gg→H



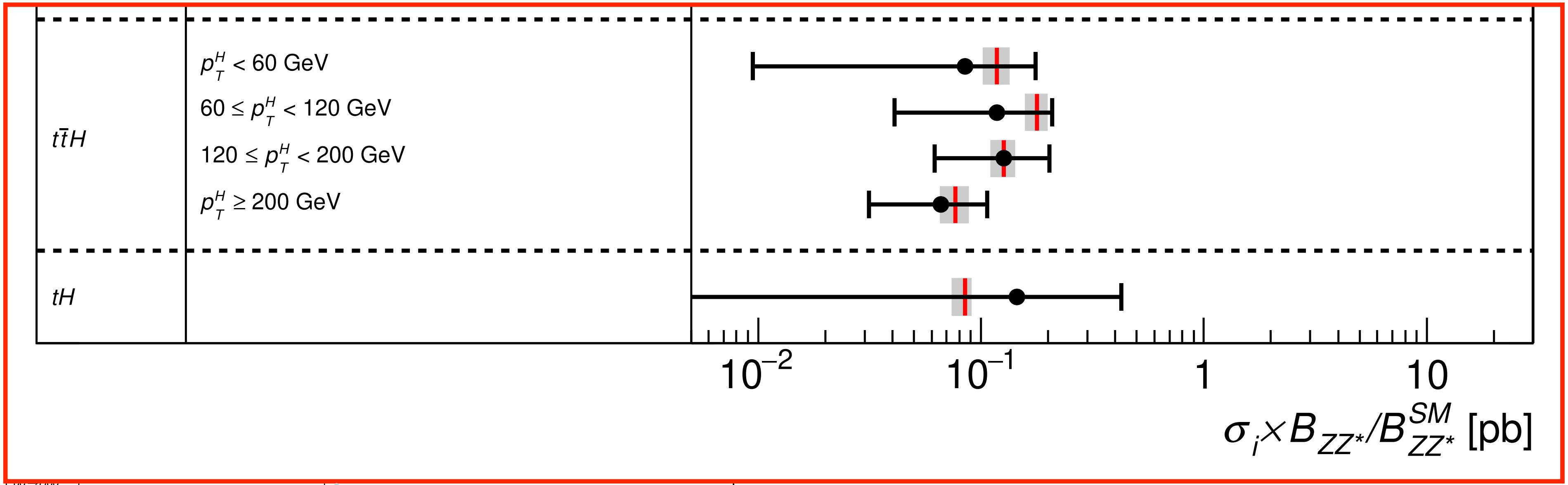


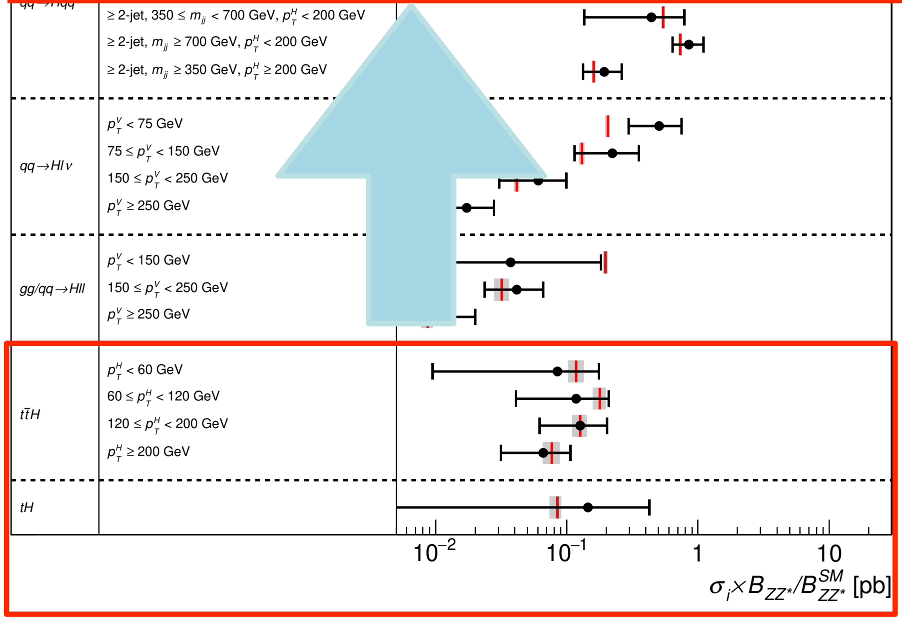
- gg→H = ggF + ggZ(qq)H + bbH
- Can reach even higher $p_T(H)$ when channels like boosted H→bb (ATLAS-CONF-2021-010) are added

Resolved Boosted



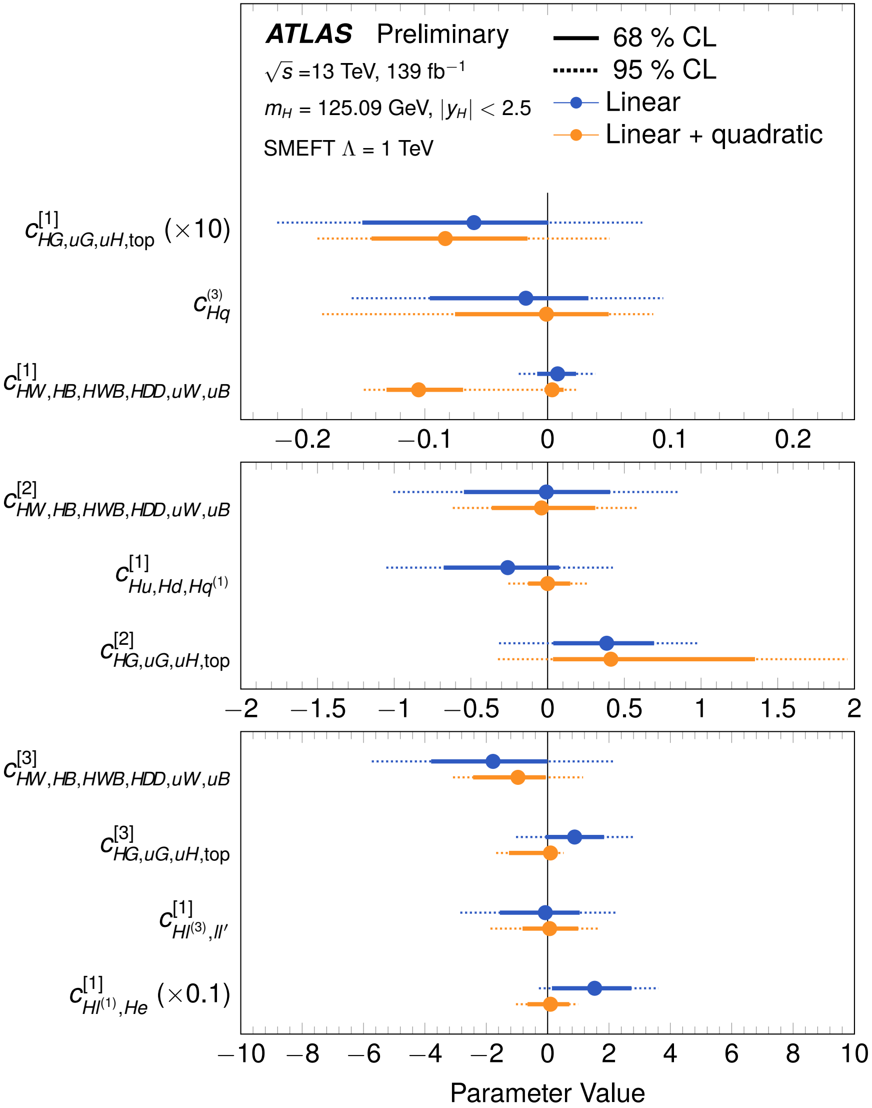
STXS measurements: ttH and tH





- Providing differential measurements in $p_T(H)$ bins for ttH
- Start having sensitivity for tH production

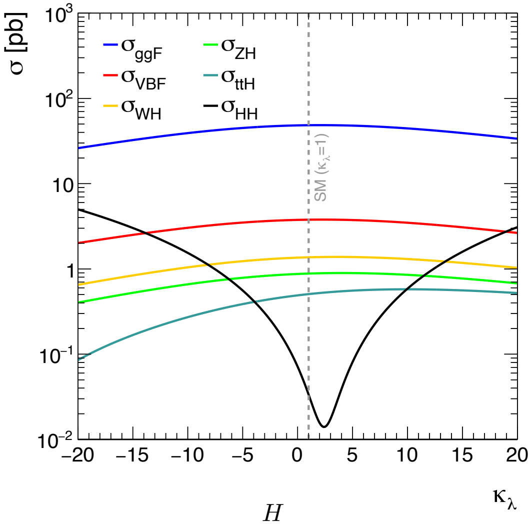
STXS interpretation: EFT

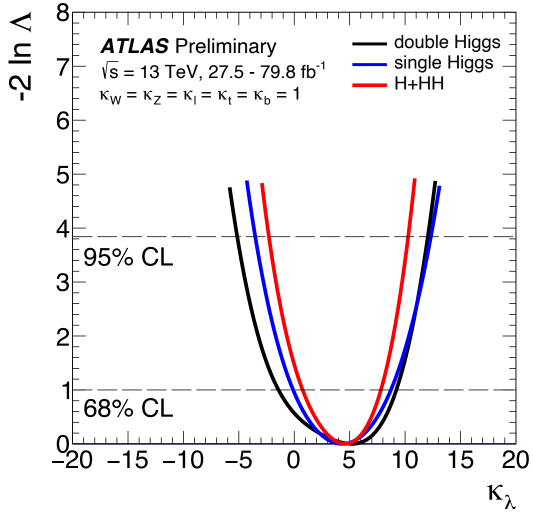


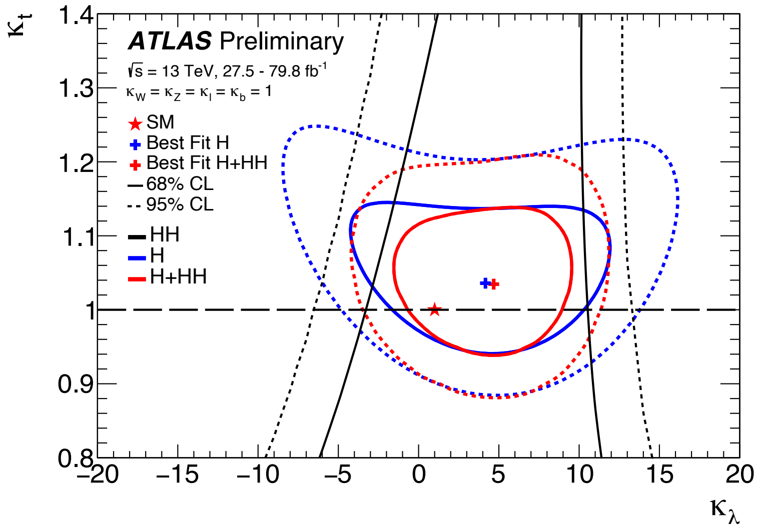
ATLAS-CONF-2020-053

- LHC will not have a major increase of √s in the future. On the other hand, LHC will accumulate very large dataset
- In case new physics is beyond reach of LHC, need to rely on EFT to extract hints of new physics from precision measurements
- EFT operators will introduce nontrivial kinematic-dependent effect: ideal application case for STXS measurements

STXS interpretation: constraining self-coupling (80 fb^{-1})







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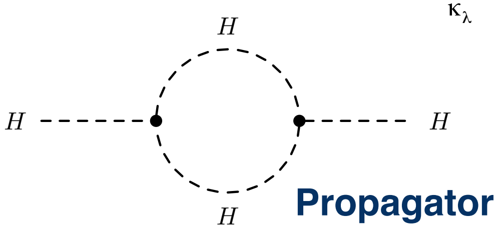

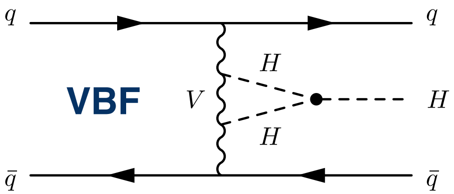

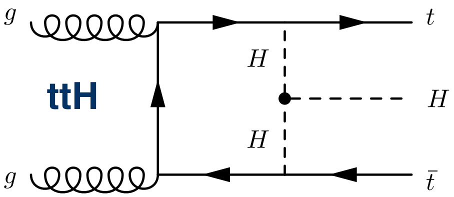

- Single Higgs boson production and Higgs boson decay are sensitive to **self-coupling** κ_λ through NLO EW corrections (kinematic dependent)
- By performing H+HH combination, we can
  - Provide stronger constraint on κ_λ than HH alone
  - Decouple κ_λ from other SM couplings like κ_t

Study of CP properties of top-Higgs interaction in ttH/tH, H→γγ channel

PRL 125 (2020) 061802, CERN news

With full Run 2 (139 fb^{-1} @13 TeV) dataset

CERN
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The detection of this extremely rare association, which was first observed by both @ATLASexperiment and @CMSExperiment in 2018, required the full capacities of the detectors and analysis techniques.

Searching for matter–antimatter asymmetry in the Higgs boson–top quark inte...
Recent years have seen the study of the Higgs boson progress from the discovery age to the measurement age. Among the latest studies of the ...
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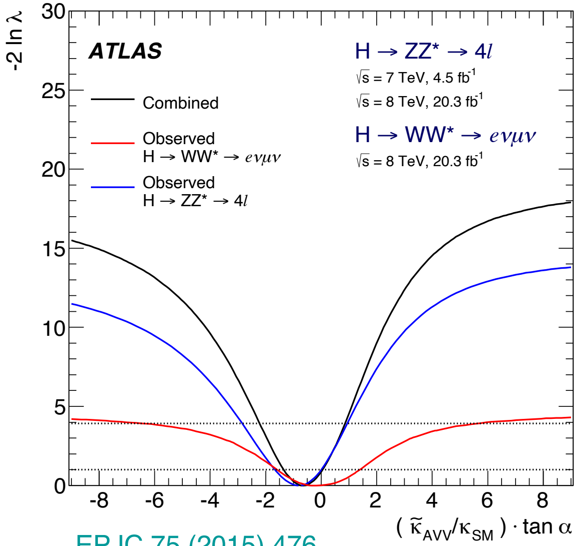
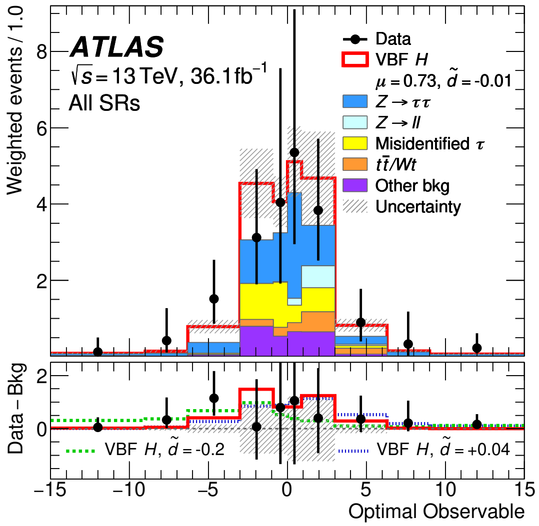
11:58 AM · Apr 29, 2020 · Buffer

CP study in Higgs sector

- Large matter-antimatter asymmetry in Universe cannot be explained by known CP violation mechanism in SM
  - Well motivated to look for additional CP violation sources
- Study of CP properties in Higgs sector started with V-H interactions in VBF production or H→VV decay since Run 1
- CP properties of fermion Yukawa coupling, on the other hand, were not **directly** studied until end of Run 2

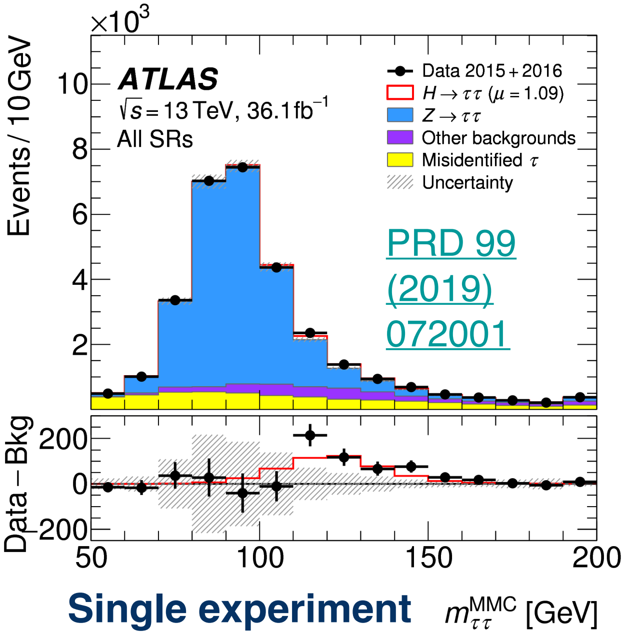


EPJC 75 (2015) 476

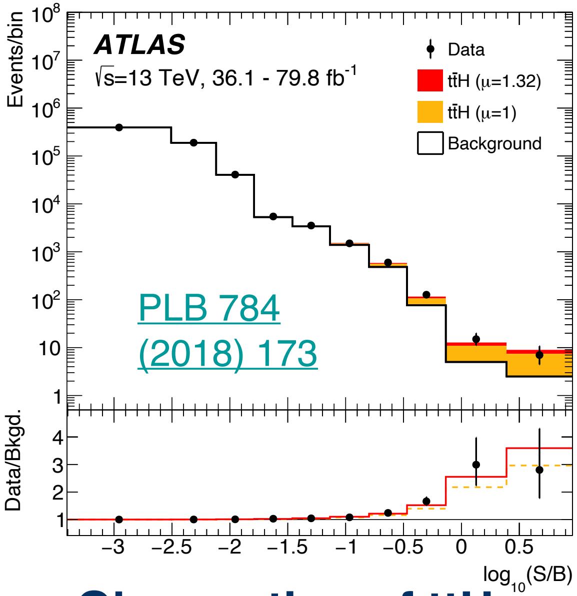


PLB 805 (2020) 135426

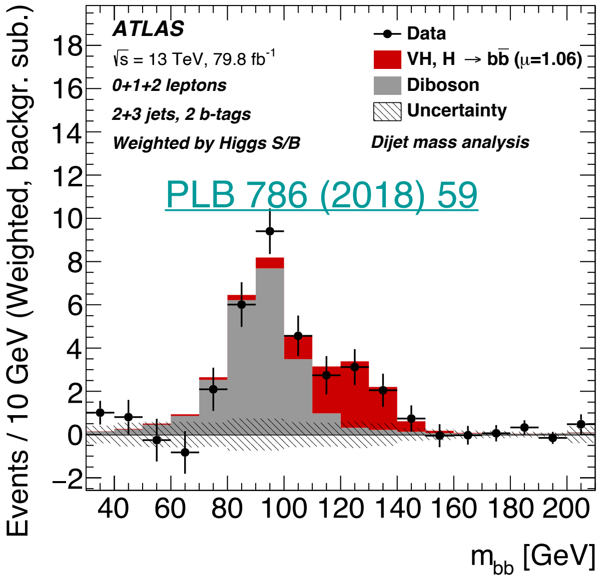
Highlight of Run 2 Higgs physics: Yukawa couplings



Single experiment observation of H→ττ

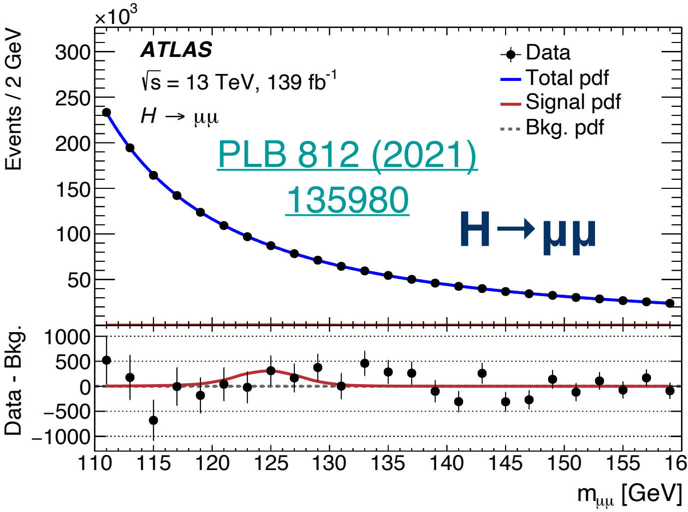


Observation of ttH



Observation of H→bb+VH

- **Direct observation of 3rd generation fermion Yukawa couplings all established**. Among them, **top Yukawa coupling** is particularly interesting
  - Largest (O(1)) Yukawa coupling in SMs
  - Rich phenomenology at LHC
- First evidence of 2nd generation Yukawa coupling

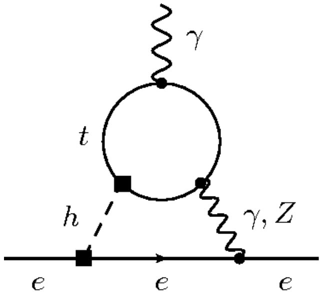


CP properties of top Yukawa coupling

- The Lagrangian for t-H interaction including CP mixing is

$$\mathscr{L}_t = -\frac{m}{v}\kappa_t(\cos(\alpha)\bar{t}t + i\sin(\alpha)\bar{t}\gamma_5 t)H,\ \kappa_t > 0,\ \alpha \in [-\pi, \pi]$$

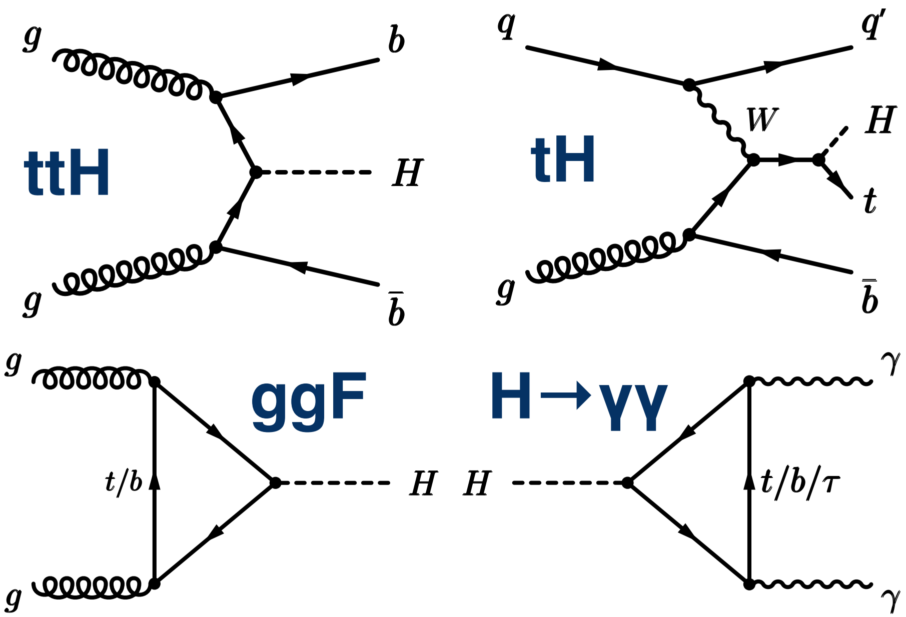
SM corresponds to **α = 0, κ_t = 1**, full CP odd is **α = 90°**

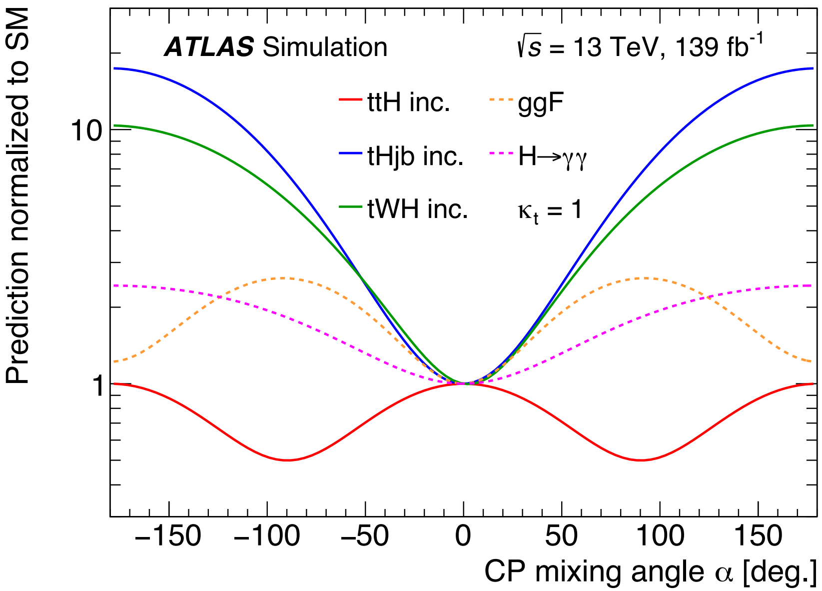


- Only **indirect** constraints on CP mixing in **t-H** interaction existed before ttH observation
  - Stringent limits from **EDMs (e, n, …)**: $\kappa_t \sin(\alpha) < 10^{-3}$
  - Also from loop-induced **H→γγ** and **ggF** rates: $\kappa_t \sin(\alpha) < \sim 0.5$
- **The ttH/tH production mode** opens a new possibility to **probe CP mixing directly in the top Yukawa coupling at tree-level**
- **The H→γγ channel** is ideal for this study due to excellent sensitivity and clean signature

What if there is CP mixing?

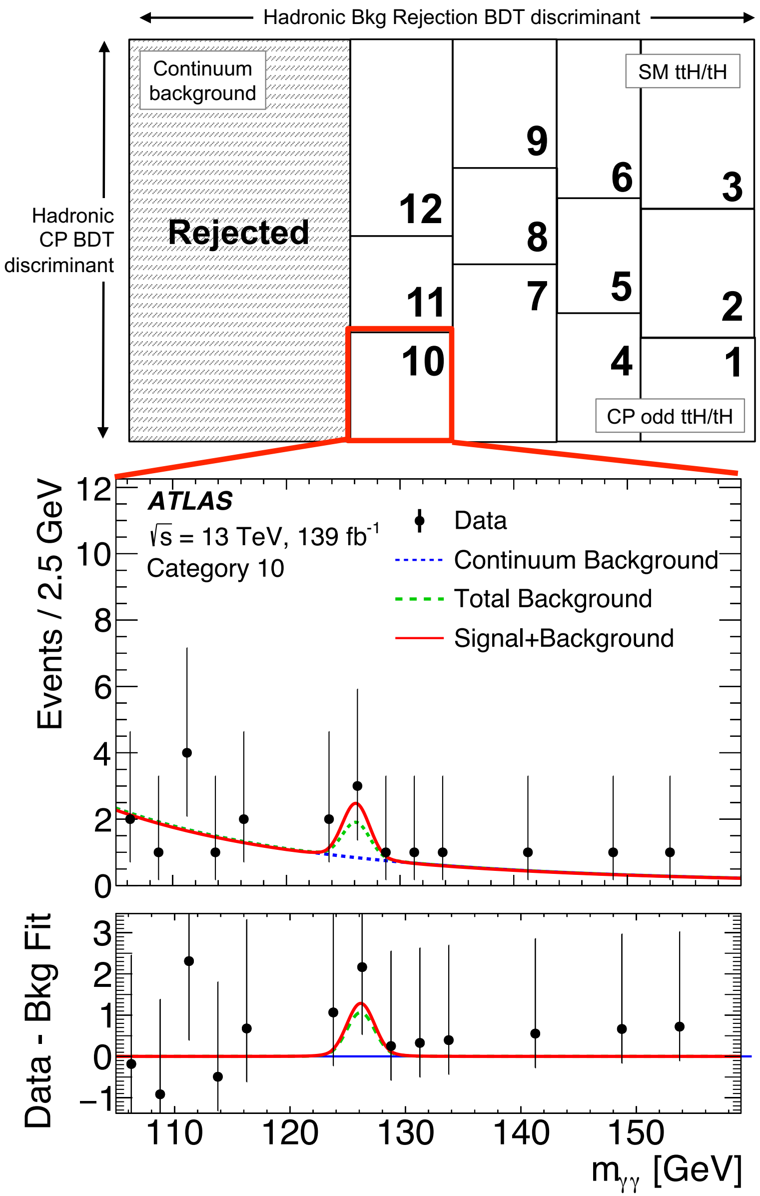
- The presence of a CP odd component in t-H coupling alters:
  - Cross sections as well as kinematics of **ttH & tH processes**: provide **direct constraint** of CP mixing in top Yukawa coupling (focus of this analysis)
  - H→γγ BR and ggF cross-sections: indirect constraint, also sensitive to other new physics scenarios





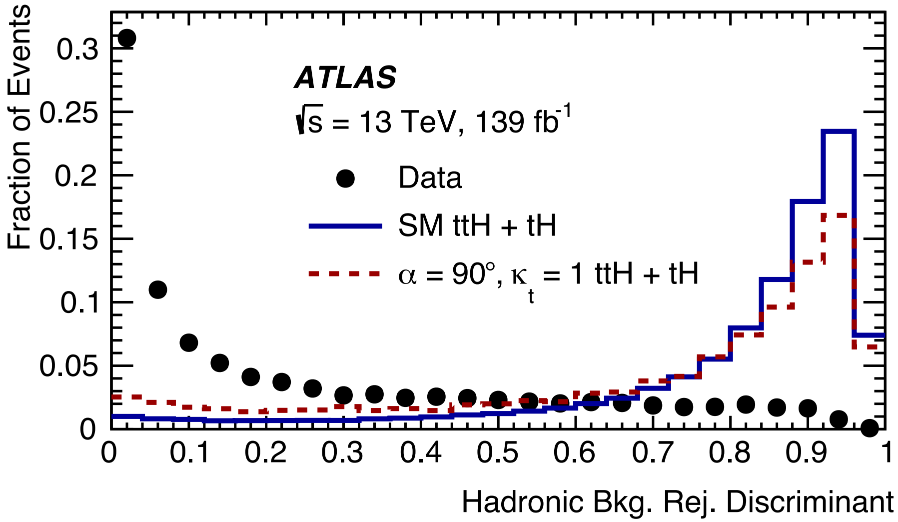
Analysis strategy

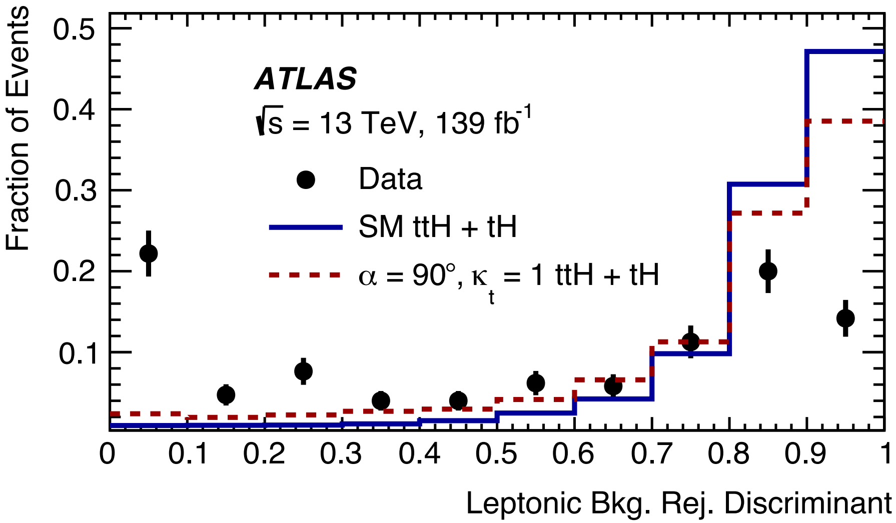
- Divide diphoton sample into two regions
  - **Hadronic** (≥3 jets, ≥1 b-jet, 0 lep)
  - **Leptonic** (≥1 b-jet, ≥1 lep)
- In each region, train following two BDTs (using XGBoost package)
  - **Bkg. rejection BDT**: separate ttH-like events from continuum background
  - **CP BDT**: separate CP-even ttH/tH events from CP-odd
- Divide categories on 2D plane of bkg. rejection vs. CP BDTs
- Fit the $m_{\gamma\gamma}$ spectrum in all categories simultaneously to extract signal



Background rejection BDT

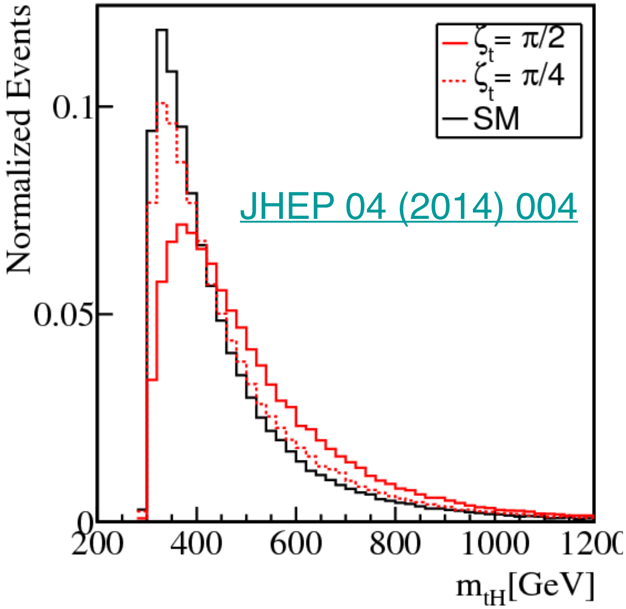
- Use the same BDT discriminant (but not categories!) from ttH search, which is trained using **low-level inputs** such as 4-vec. of γ, j, l, and MET
- Serves the purpose of CP analysis very well
  - Good rejection of background; good acceptance of ttH/tH signal
  - Weak dependence on CP mixing angle



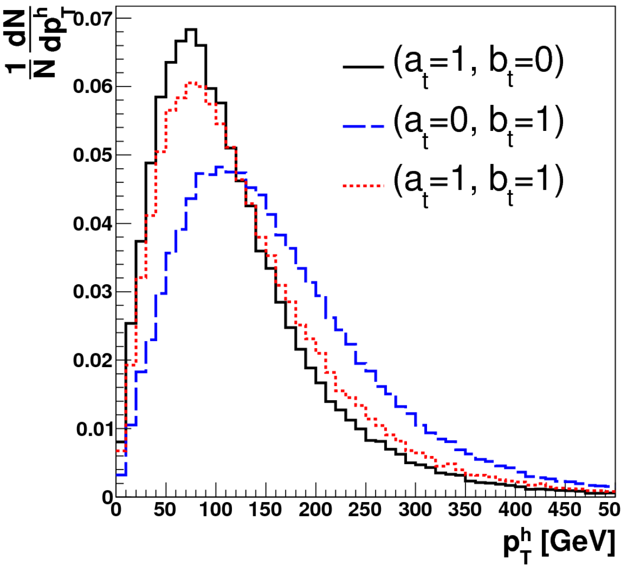


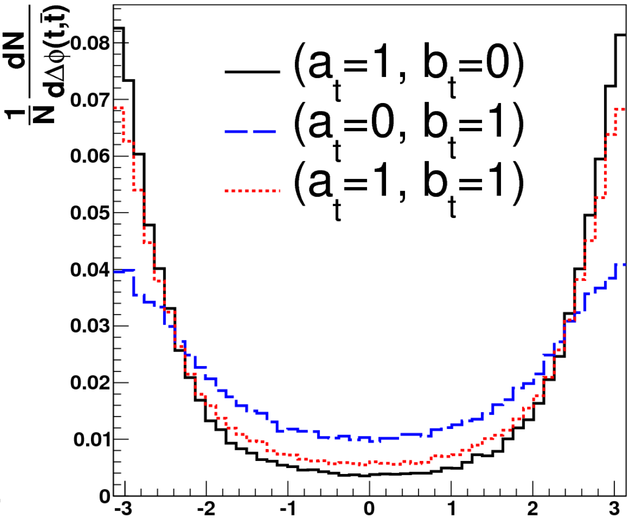
CP sensitive observables

- Compared with SM (CP even), CP odd ttH/tH gives
  - Larger m_{tH} and $m_{t\bar{t}}$; more boosted $p_T(H)$
  - Less back-to-back $\phi(t\bar{t})$; larger opening $\eta(t\bar{t})$
- Exploit shape information in this analysis. Avoid relying on normalization dependence



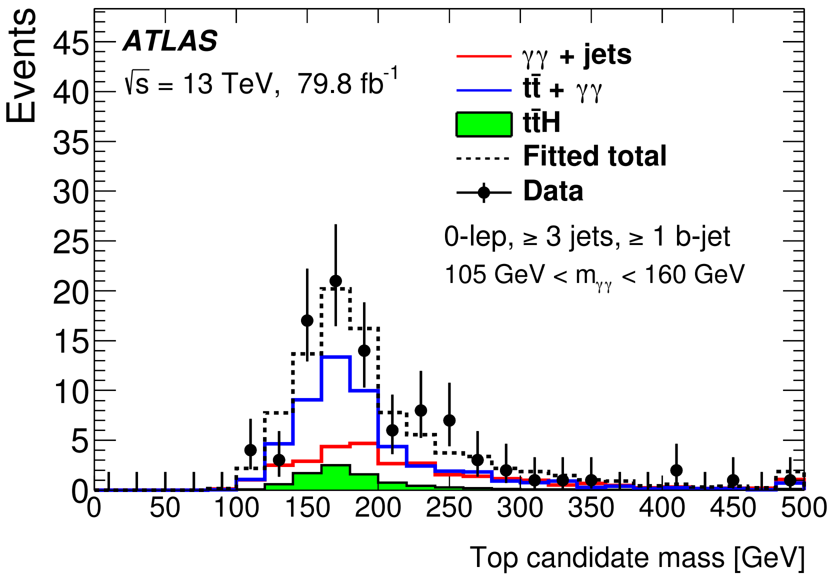
JHEP 04 (2014) 004

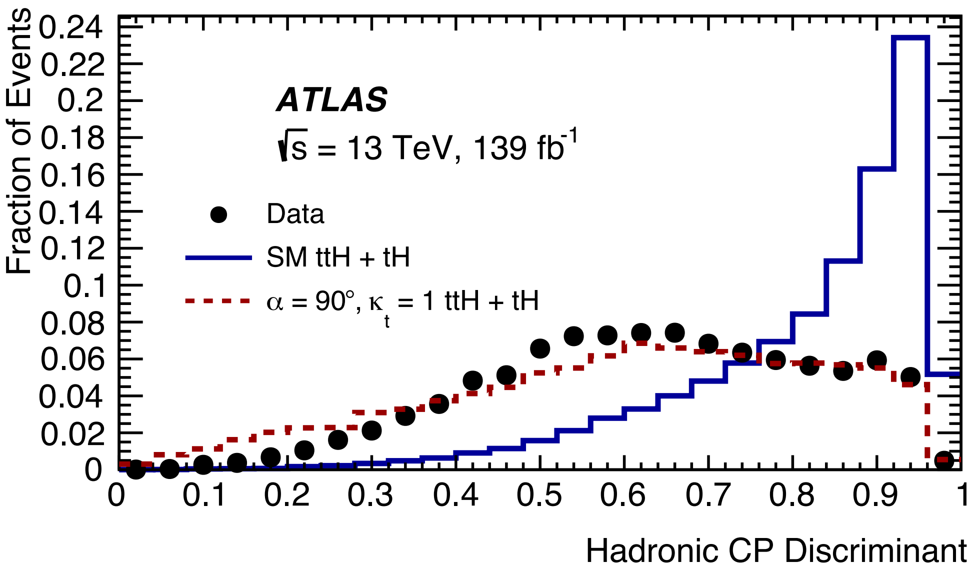




PRD 92, 015019 (2015)

CP BDT

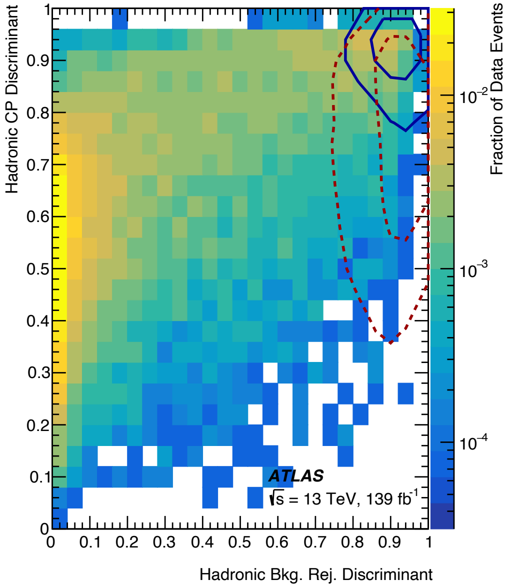


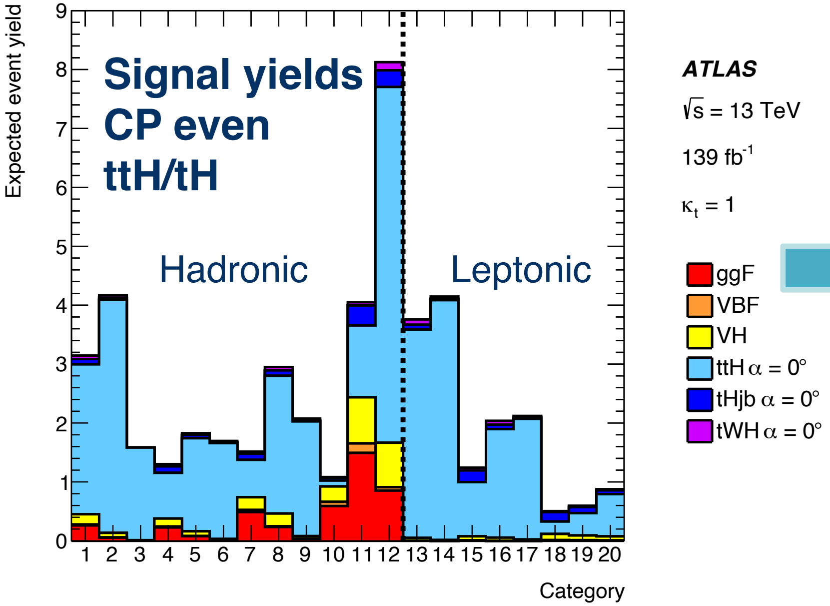


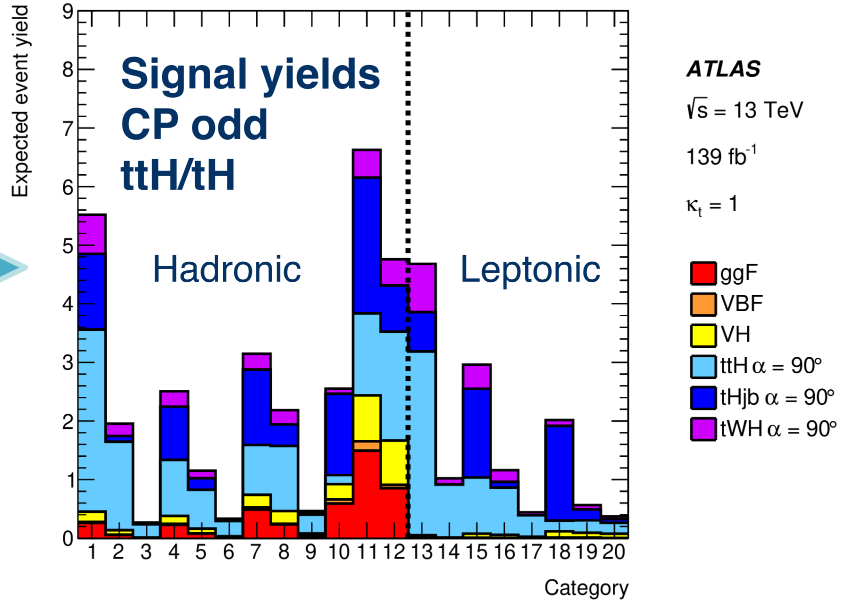
- Train **top reconstruction BDT** to reconstruct two top quarks t_1, t_2
  - Trained using ttH sample: correct pairing vs. wrong paring
  - In case t_2 cannot be built, sum up all remaining objects as t_2
- Train **CP BDT** to separate between **CP even** and **CP odd** ttH+tH
  - p_T / η of diphoton system; H_T, n_{jets}, n_{bjets}, $\Delta R(\gamma, j)$
  - p_T / η / ϕ / **top reco. BDT** score of t_1 and t_2, $m_{t_1 H}$, $m_{t_1 t_2}$, $\phi(t_1 t_2)$, $\eta(t_1 t_2)$

Categorization

- Scan category boundaries on 2D bkg. rejection BDT vs. CP BDT plane to optimize both SM ttH significance and CP separation
- **20 analysis categories** defined in total
  - 12 categories in hadronic region, 8 in leptonic



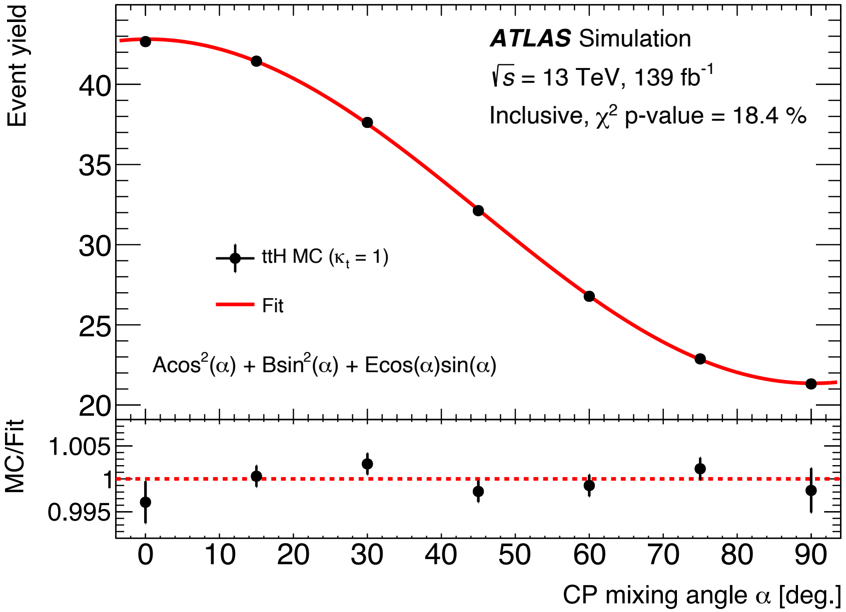




ttH signal yield parameterization

- Parameterize **ttH** and **tH** signal yields in each category as **mixing angle** α and **top Yukawa coupling strength** κ_t
- For ttH process, use

$$\boxed{A\kappa_t^2\cos^2(\alpha) + B\kappa_t^2\sin^2(\alpha) + E\kappa_t^2\sin(\alpha)\cos(\alpha)}$$



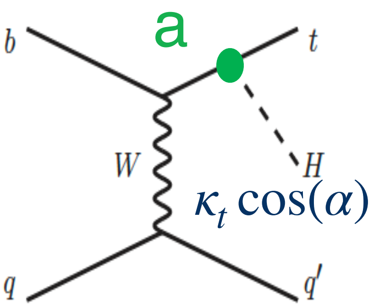
- Parameterization describe MC predictions well in all categories
- Coefficient E for interference term found to be negligible as expected

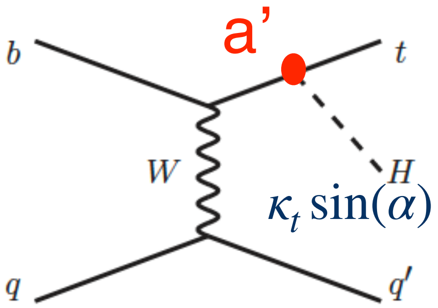
tH signal yield parameterization

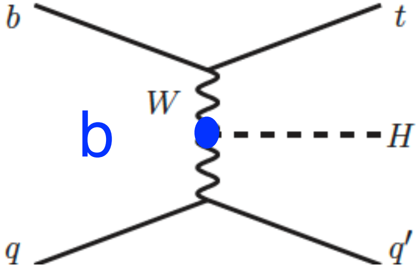
- For tHW and tHjb processes, need to use more complicated parameterizations considering interference between t-H and W-H

$$A\kappa_t^2\cos^2(\alpha) + B\kappa_t^2\sin^2(\alpha) + C\kappa_t\cos(\alpha) + D\kappa_t\sin(\alpha) + E\kappa_t^2\sin(\alpha)\cos(\alpha) + F$$

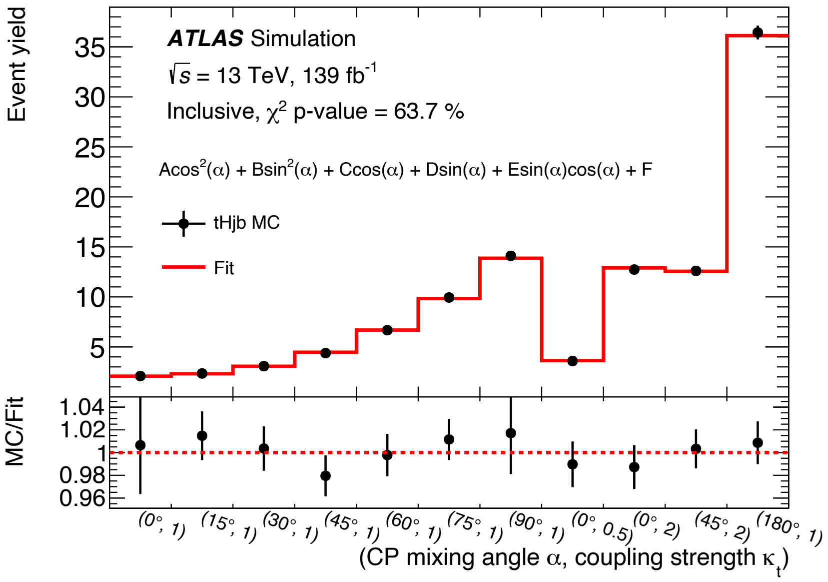
a² **a'²** **2 Re(a b)** **2 Re(a' b)** **2Re(a a')** **b²**







Interference terms between CP even and odd found negligible

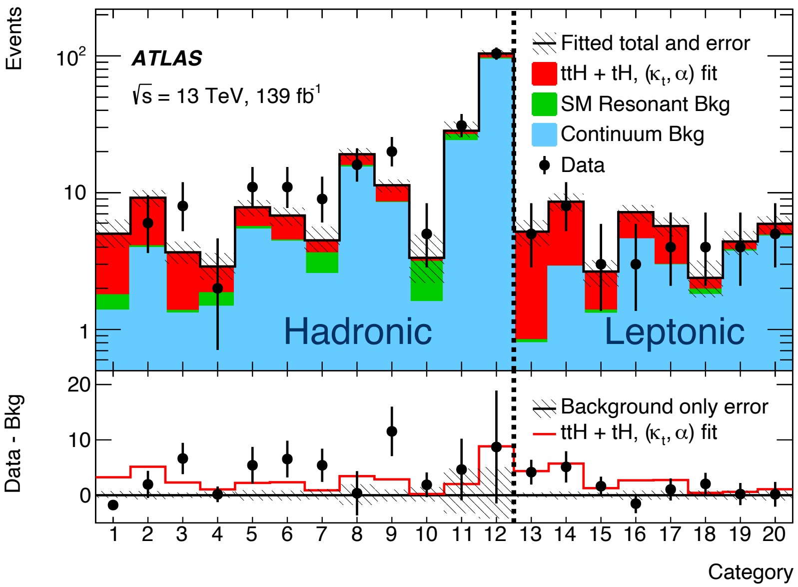


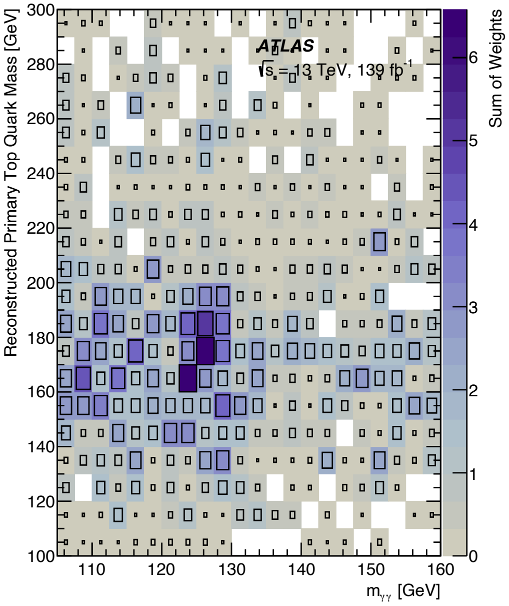
ttH and tH cross-section measurements

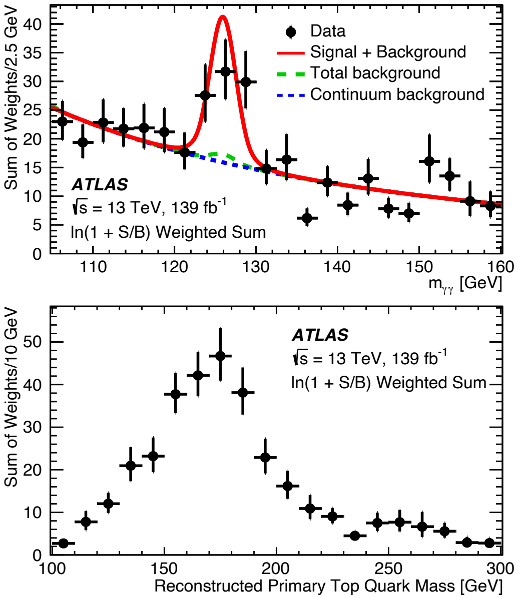
- **Single-channel ttH observation at 5.2σ,** assuming SM for other prod. modes

$$\mu = 1.43^{+0.33}_{-0.31}(\text{stat.})^{+0.21}_{-0.15}(\text{syst.})$$

- tH cross-section < 12×SM @95% CL

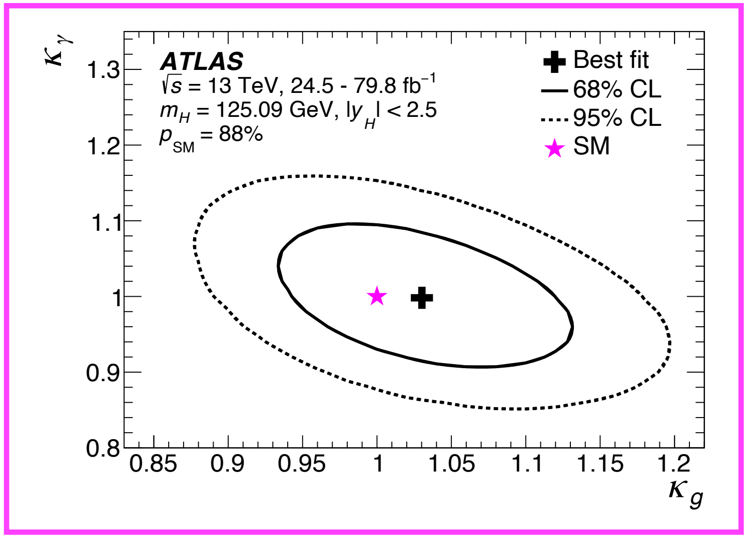


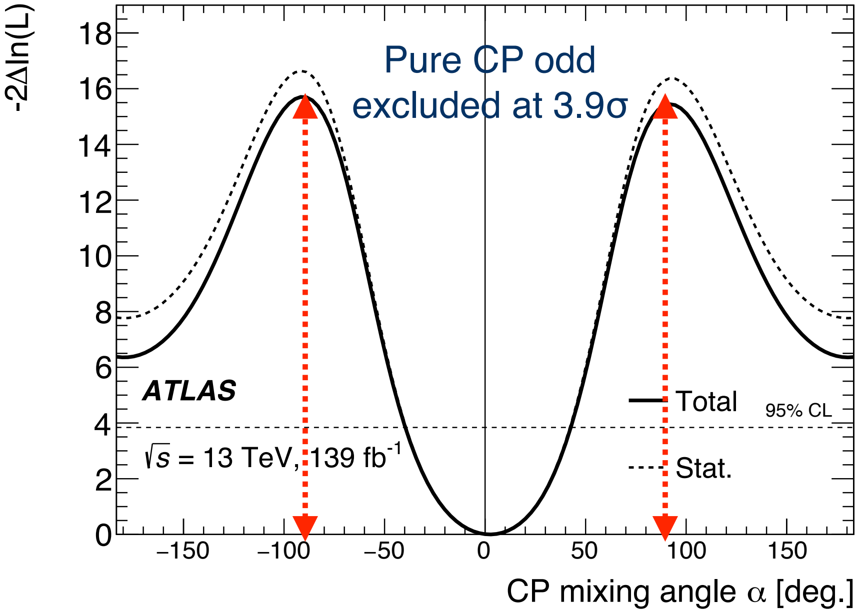


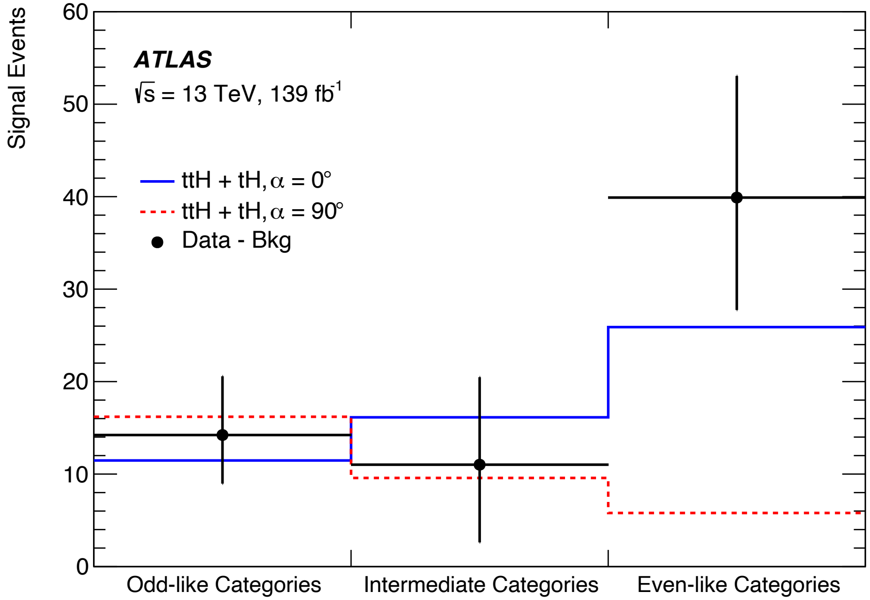


CP constraint: not resolve H→γγ/ggF loops

- Provide **direct** constrain mixing angle α using **only ttH and tH info**
  - Use **κ_γ vs κ_g contour (80 fb^{-1})** to constrain H→γγ and ggF rates
- **$|\alpha| > 43°$** excluded @95% CL **without assumption on κ_t**





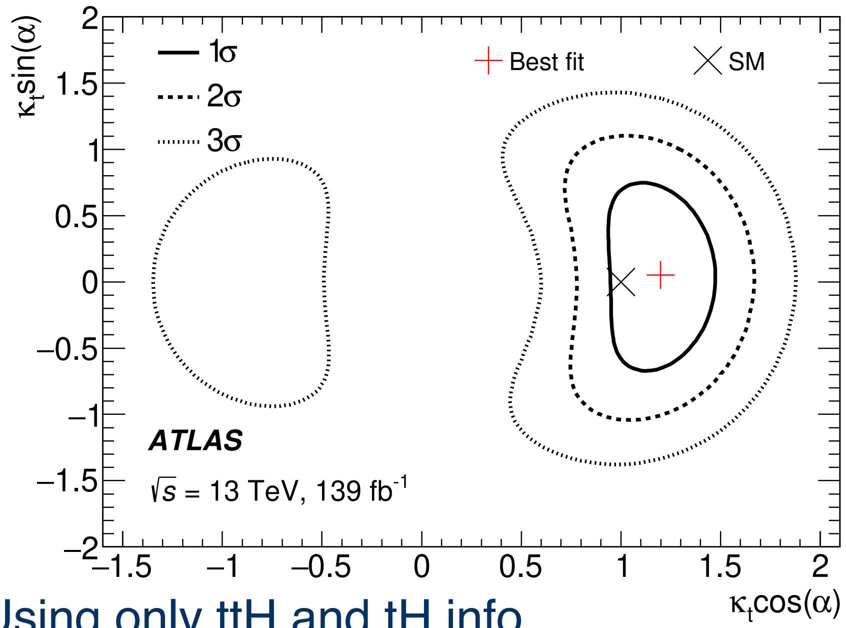


CP constraint: resolve H→γγ/ggF loops

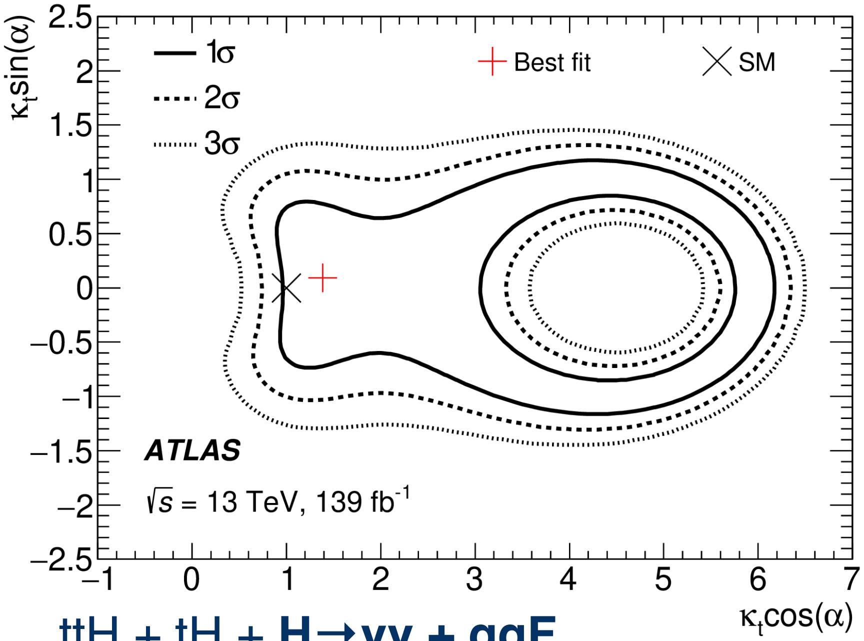
- Assume potential new physics in H→γγ/ggF is only in t-H coupling, and can be parameterized as function of α and κ_t (Ellis et. al. JHEP 04 (2014) 004)

$$\boxed{\begin{gathered}\kappa_g^2 = \kappa_t^2\cos^2(\alpha) + 2.6\kappa_t^2\sin^2(\alpha) + 0.11\kappa_t\cos(\alpha)(\kappa_t\cos(\alpha) - 1) \\ \kappa_\gamma^2 = (1.28 - 0.28\kappa_t\cos(\alpha))^2 + (0.43\kappa_t\sin(\alpha))^2\end{gathered}}$$

- Exclude **$|\alpha| > 43°$ @95% CL without assumption on κ_t**



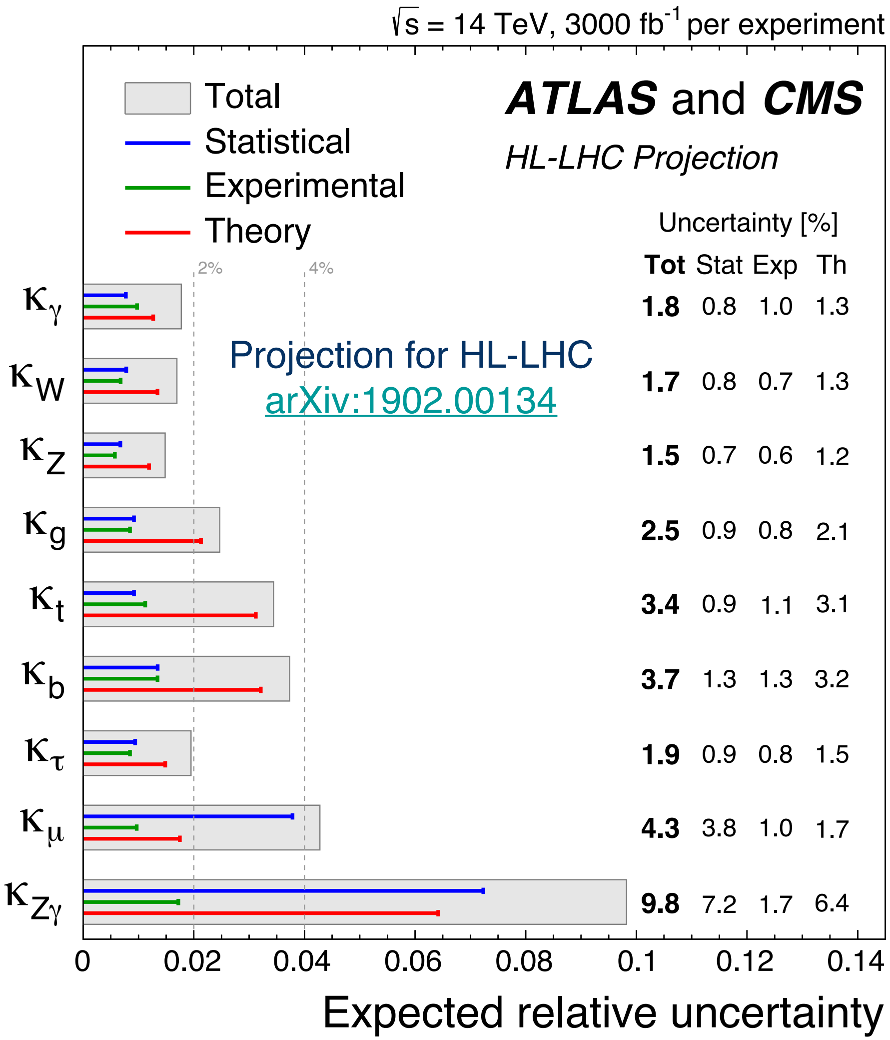
Using only ttH and tH info



ttH + tH + **H→γγ + ggF**

Conclusions

- Measurements of Higgs boson productions and decays now reaching **~10% precision**. Agree with SM so far
- Hints for new physics could be currently covered by uncertainties
  - Combining with CMS: x2 stat
  - HL-LHC could hopefully reduce uncertainty to a couple of percent
  - Higgs Factory can further reduce the uncertainty to sub-percent
- In the meantime, keep trying out innovative ideas on current dataset
  - E.g. using 4-top process to explore CP mixing in top Yukawa coupling proposed by [PRD 99 (2019) 113003 by Q. Cao et. al.]



	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

Projection for HL-LHC
arXiv:1902.00134

Current dataset only 5% of expected LHC total!

Backup

Typical MC generators used for Higgs boson signal

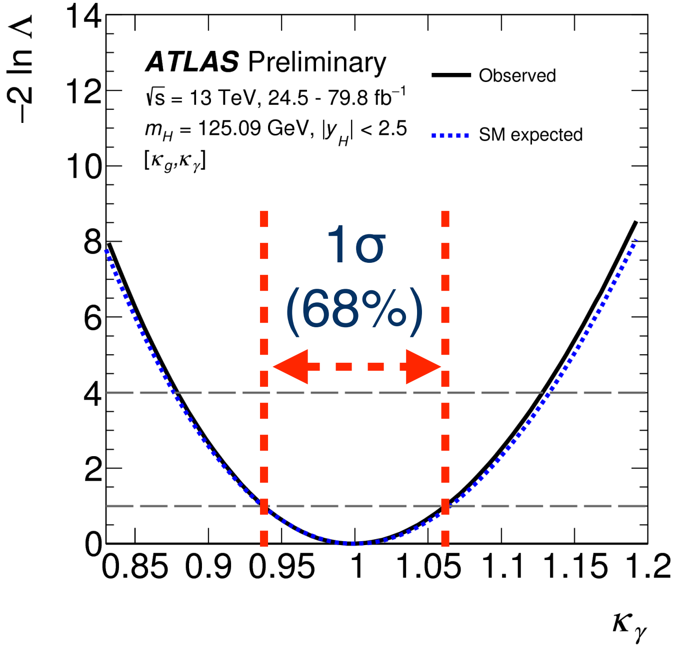
Process	Generator	Showering	PDF set	σ [pb] $\sqrt{s} = 13$ TeV	Order of σ calculation
ggF	Powheg NNLOPS	Pythia 8	PDF4LHC15	48.52	$\mathrm{N^3LO(QCD)+NLO(EW)}$
VBF	Powheg-Box	Pythia 8	PDF4LHC15	3.78	approximate-NNLO(QCD)+NLO(EW)
WH	Powheg-Box	Pythia 8	PDF4LHC15	1.37	NNLO(QCD)+NLO(EW)
$q\bar{q}'\rightarrow ZH$	Powheg-Box	Pythia 8	PDF4LHC15	0.76	NNLO(QCD)+NLO(EW)
$gg\rightarrow ZH$	Powheg-Box	Pythia 8	PDF4LHC15	0.12	NNLO(QCD)+NLO(EW)
$t\bar{t}H$	Powheg-Box	Pythia 8	PDF4LHC15	0.51	NNLO(QCD)+NLO(EW)
$b\bar{b}H$	Powheg-Box	Pythia 8	PDF4LHC15	0.49	NNLO(QCD)+NLO(EW)
tHq	MG5_aMC@NLO	Pythia 8	CT10	0.07	4FS(LO)
tHW	MG5_aMC@NLO	Herwig++	CT10	0.02	5FS(NLO)

Statistical methodology

- Construct combined likelihood model as multiplication of individual channel likelihoods
  - Common parameters, e.g. signal cross-sections and nuisance parameters for the same systematic uncertainties, are shared between likelihood of individual channels
- Use profile likelihood ratio Λ as test statistic:

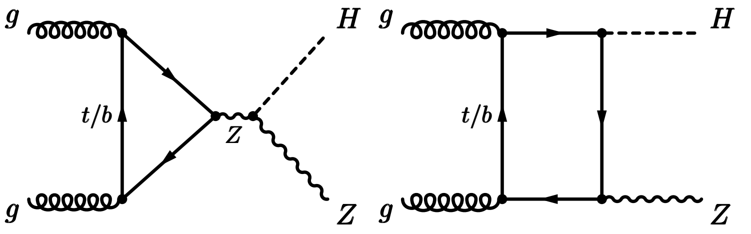
$$\boxed{\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}}$$

- 1-D 68% confidence interval defined by -2lnΛ increasing by 1 (asymptotic limit)
  - Assumption validated with pseudo-experiments in low statistics case

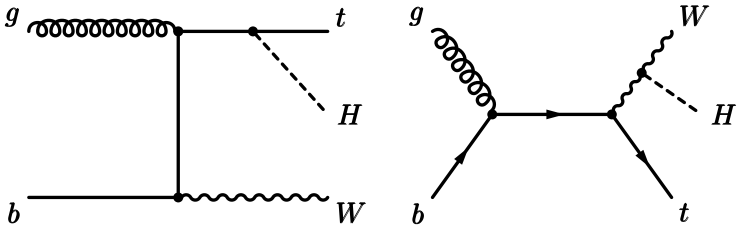


Kappa parameterization

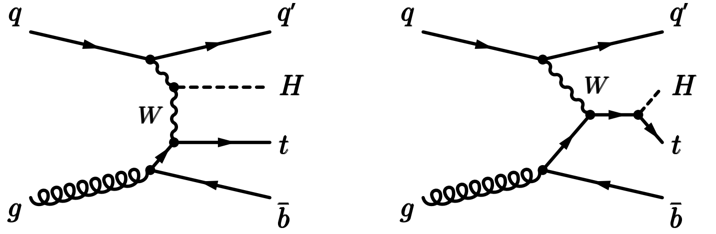
Production	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\text{VBF})$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t - 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t + 0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b - 0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\text{i.}} = B_{\text{u.}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2 + 0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2 + 0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2 + 0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$



gg→ZH

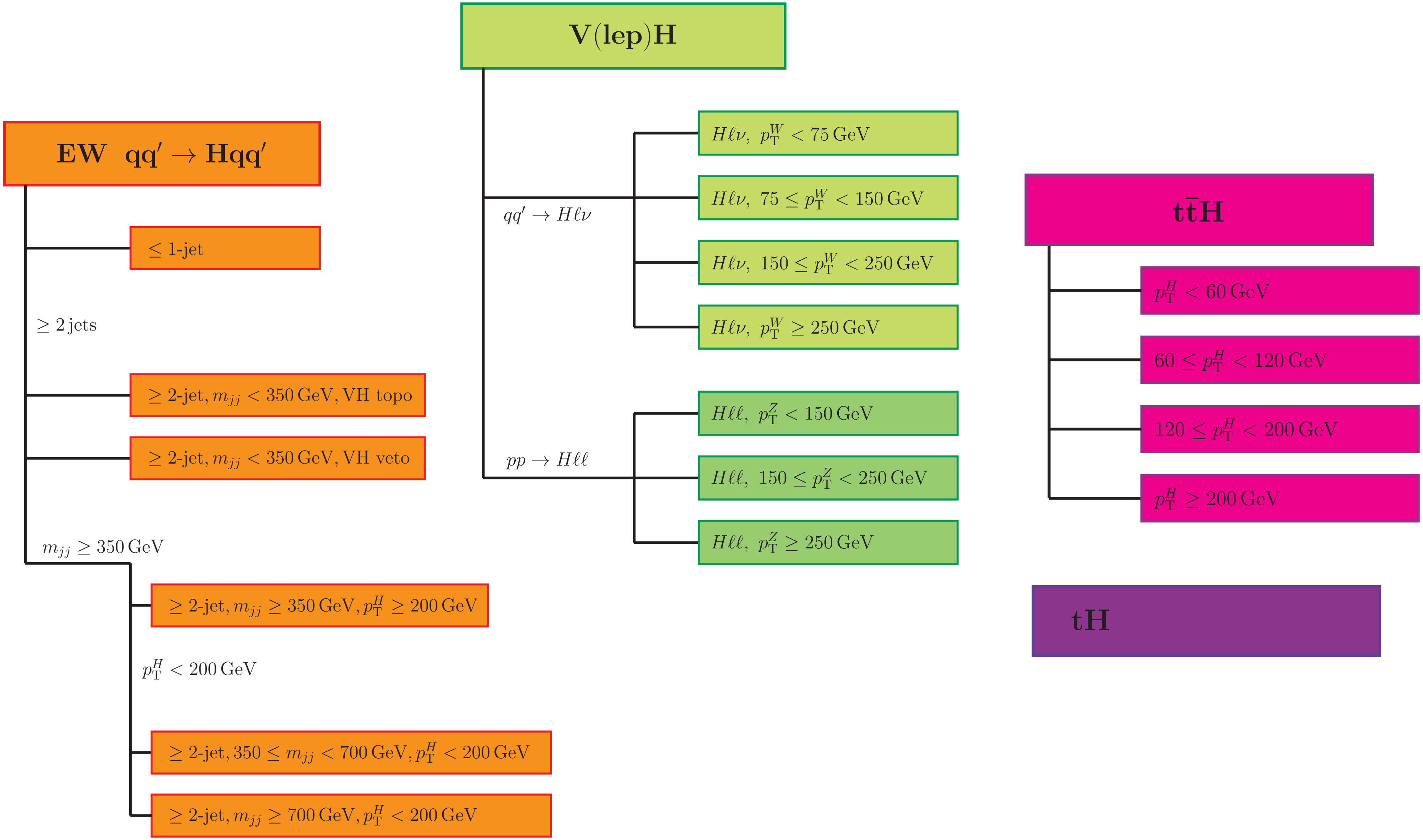


tHW



tHq

STXS framework



EW $qq' \to Hqq'$

$\leq$ 1-jet

$\geq$ 2 jets

$\geq$ 2-jet, $m_{jj} < 350$ GeV, VH topo

$\geq$ 2-jet, $m_{jj} < 350$ GeV, VH veto

$m_{jj} \geq 350$ GeV

$\geq$ 2-jet, $m_{jj} \geq 350$ GeV, $p_T^H \geq 200$ GeV

$p_T^H < 200$ GeV

$\geq$ 2-jet, $350 \leq m_{jj} < 700$ GeV, $p_T^H < 200$ GeV

$\geq$ 2-jet, $m_{jj} \geq 700$ GeV, $p_T^H < 200$ GeV

V(lep)H

$qq' \to H\ell\nu$

$H\ell\nu,\ p_T^W < 75$ GeV

$H\ell\nu,\ 75 \leq p_T^W < 150$ GeV

$H\ell\nu,\ 150 \leq p_T^W < 250$ GeV

$H\ell\nu,\ p_T^W \geq 250$ GeV

$pp \to H\ell\ell$

$H\ell\ell,\ p_T^Z < 150$ GeV

$H\ell\ell,\ 150 \leq p_T^Z < 250$ GeV

$H\ell\ell,\ p_T^Z \geq 250$ GeV

$t\bar{t}H$

$p_T^H < 60$ GeV

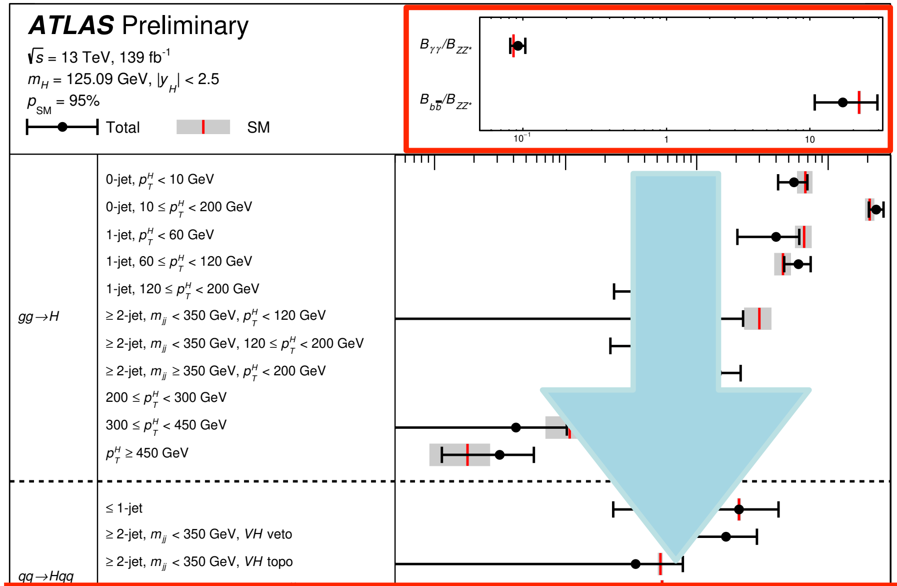
$60 \leq p_T^H < 120$ GeV

$120 \leq p_T^H < 200$ GeV

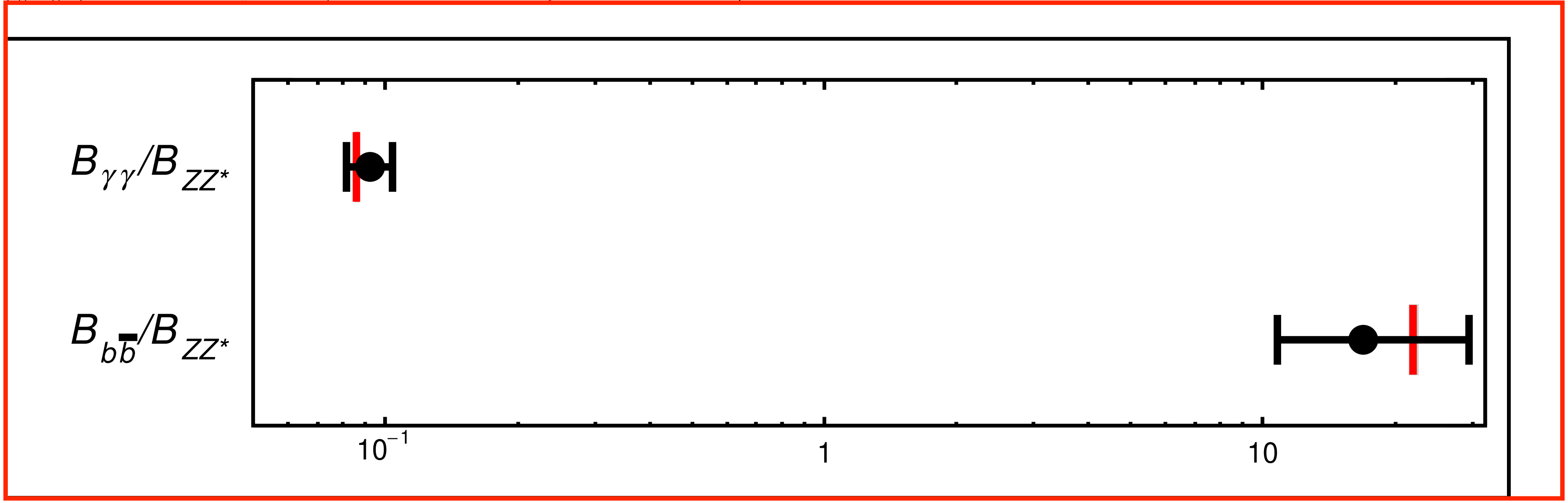
$p_T^H \geq 200$ GeV

tH

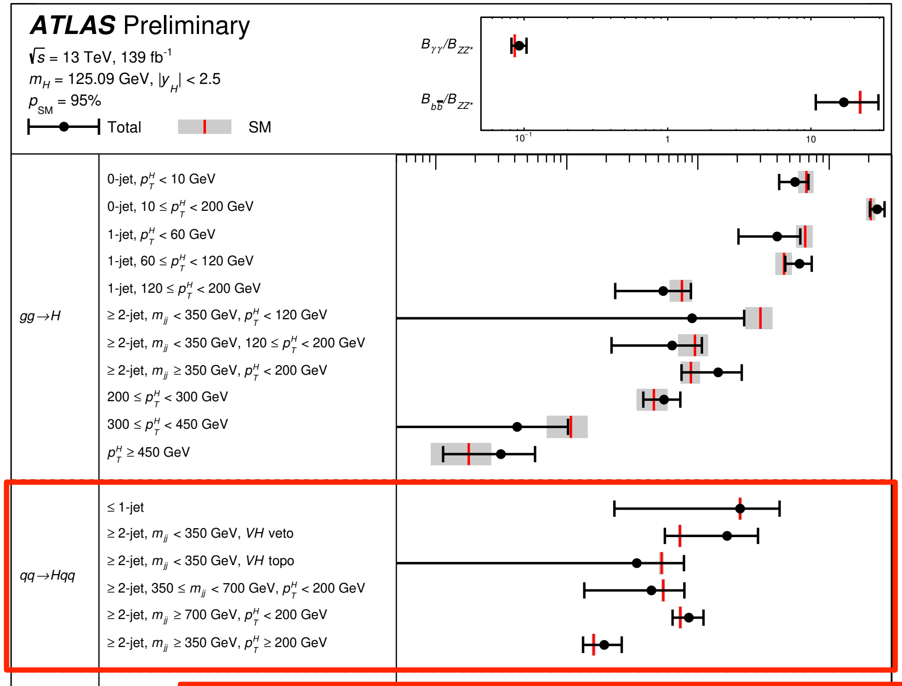
STXS measurements: ratios of BR

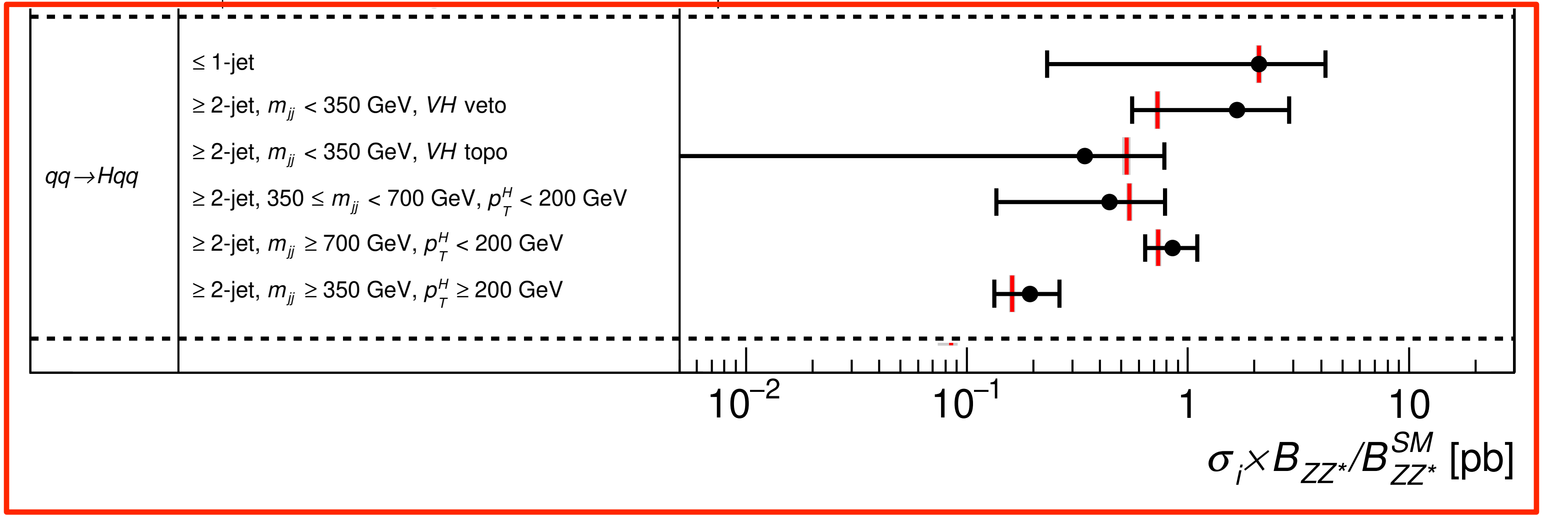


- Ratio of branching ratio is a free parameter determined by data
  - Normalize to **H→ZZ** as it is the cleanest channel at LHC



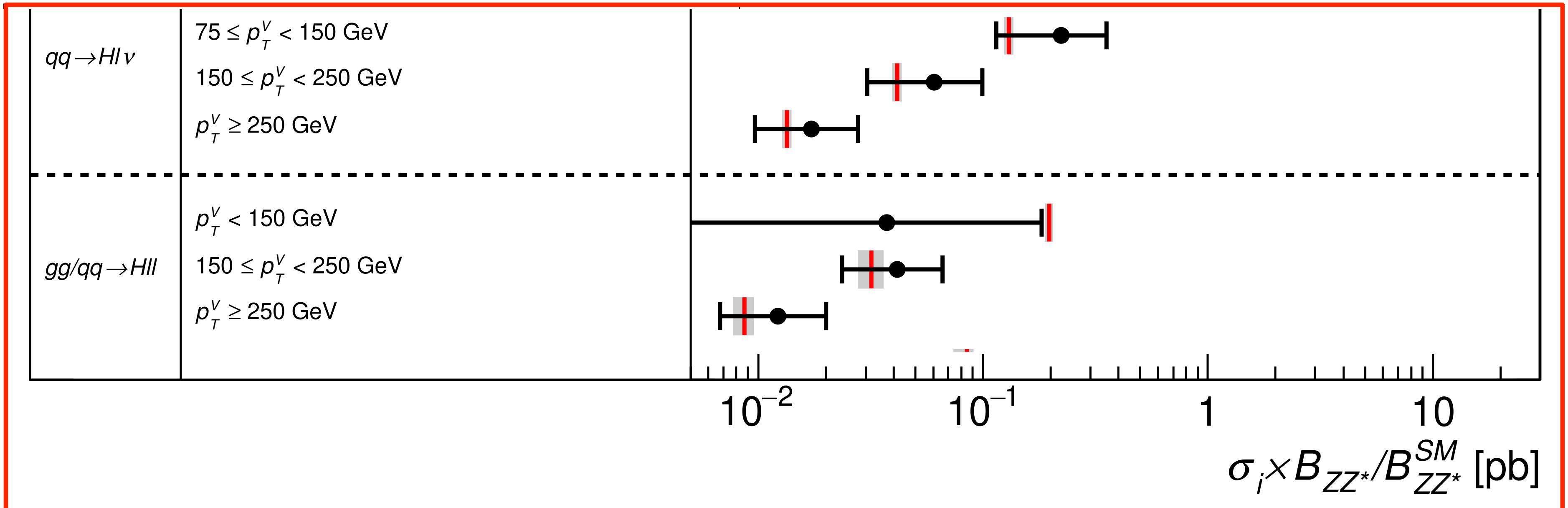
STXS measurements: qq→Hqq

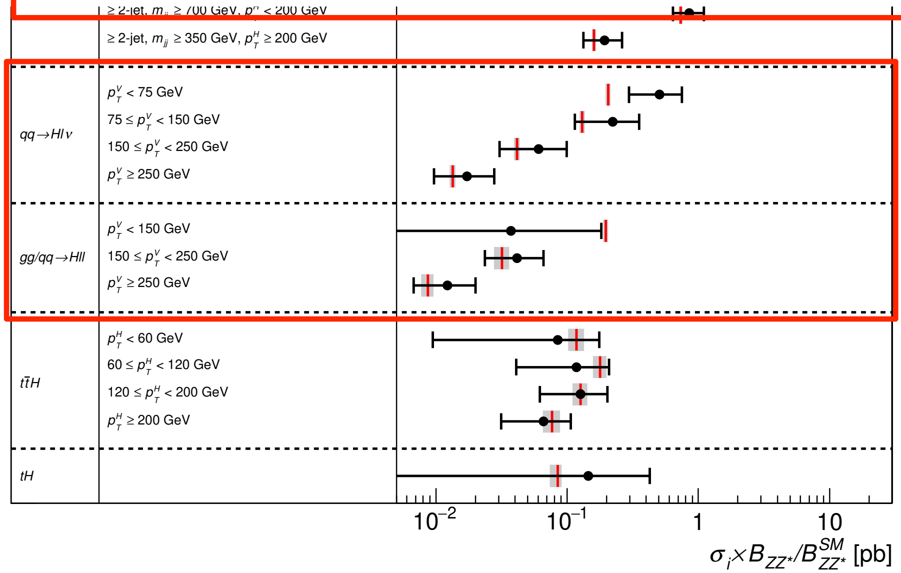




- qq→Hqq = VBF + V(qq)H
- Provide measurements in n_{jet}, m_{jj}, and $p_T(H)$ bins
- Significant improvement expected when H→WW/ττ STXS measurements are added

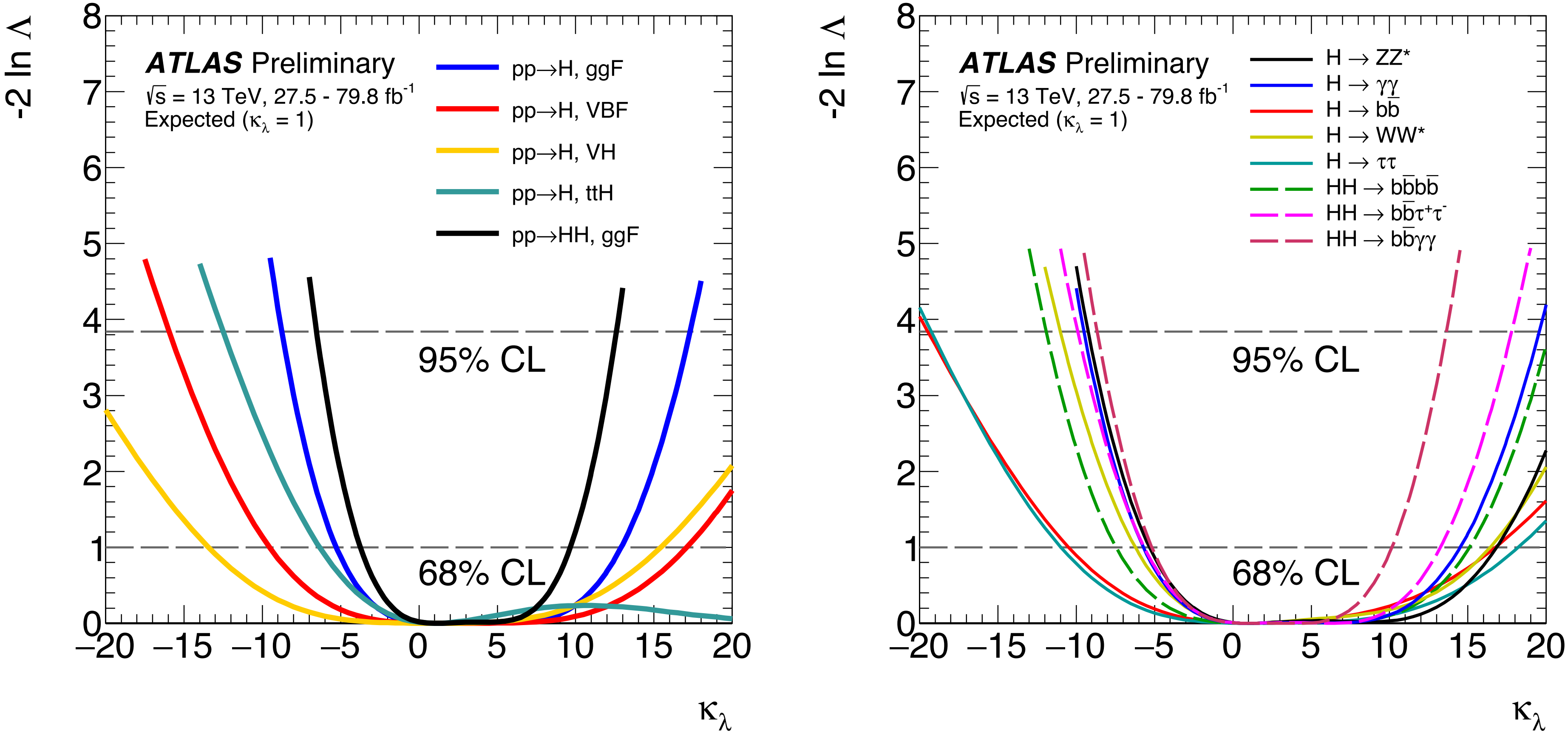
STXS measurements: V(ll)H





- Sensitivity dominated by VH, H→bb
- Split in $p_T(V)$ bins because it has better resolution
- Will extend to higher $p_T(V)$ once boosted channel is included

Self-coupling interpretation: dependence on production/decay



Data & signal MC samples for ttH CP analysis

- **Data**: full Run 2 dataset of 139 fb^{-1}
- **ttH/tH signal**: **NLO MG5_aMC+Pythia8** using **Higgs Characterization (HC) model**
  - ttH: $\boldsymbol{\kappa_t = 1}$, $\alpha = 0°, 15°, 30°, \ldots, 90°$
  - tHjb/tWH: sample generated with both $\boldsymbol{\kappa_t = 1}$ **and ≠ 1** at different mixing angles. $\kappa_W = 1$
- **ggF signal**: PowHeg NNLOPS
  - Kinematic dependence on CP mixing checked to be well-covered by syst. using **MG_aMC HC model ggF+2j** samples
- **Other Higgs production modes**: same as typical ATLAS Run 2 Higgs analyses