10th Anniversary of the Higgs Boson Discovery
-What we learned in a decade-

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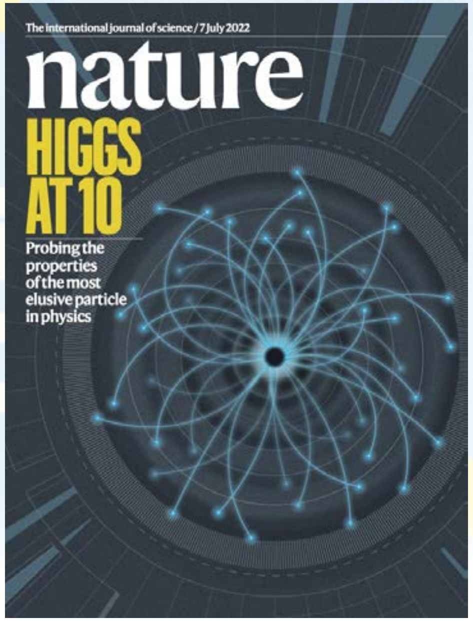
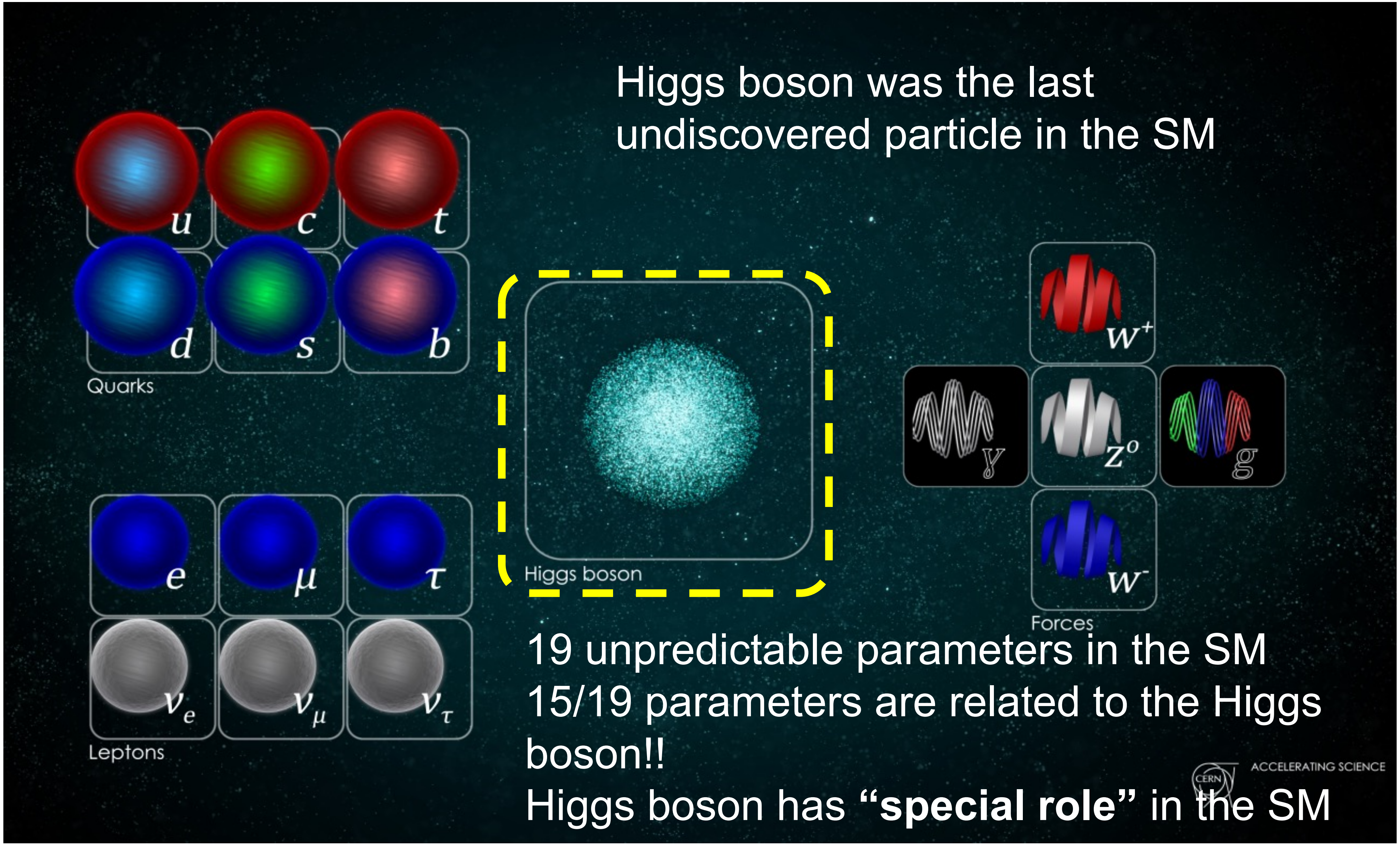
Outline

- The role of the Higgs boson in Standard Model
- Short history of discovery for Higgs boson at LHC
- What we learned in a decade since discovery
  - Mass measurement
  - Coupling and cross section measurement
  - Width measurement
  - Higgs self-coupling measurement
- Summary and Future

Credit: Abigail Malate for *Physics Today*



A Higgs boson and the Standard Model



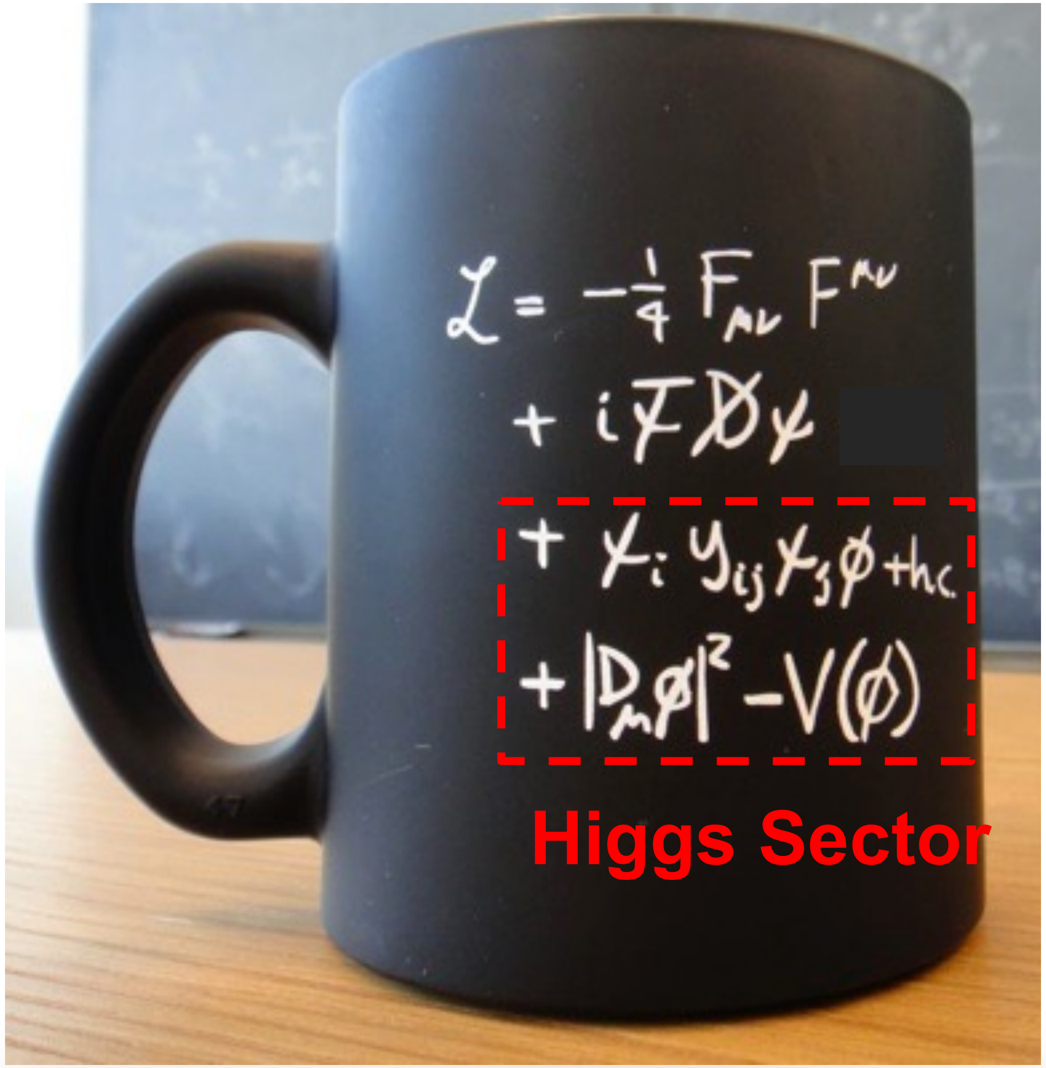
Higgs boson was the last undiscovered particle in the SM

19 unpredictable parameters in the SM

15/19 parameters are related to the Higgs boson!!

Higgs boson has “**special role**” in the SM

SM Lagrangian

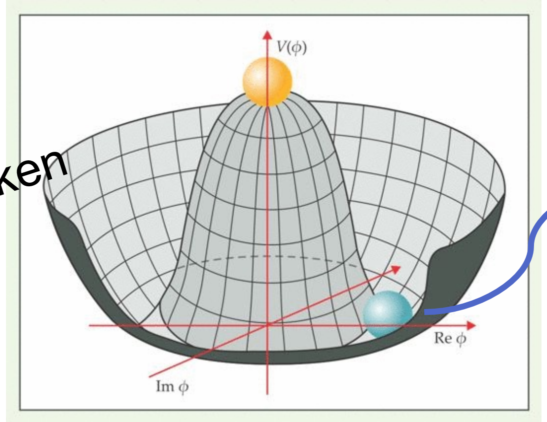


SM Lagrangian

Higgs potential

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + \cdots \quad (\mu^2 < 0, \lambda > 0)$$

Spontaneously symmetry broken



$$\mathrm{v} = \sqrt{-\frac{\mu^2}{2\lambda}}$$

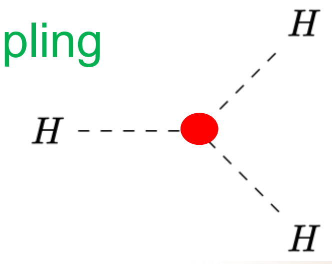
Expand around new vacuum $\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h \end{pmatrix}$

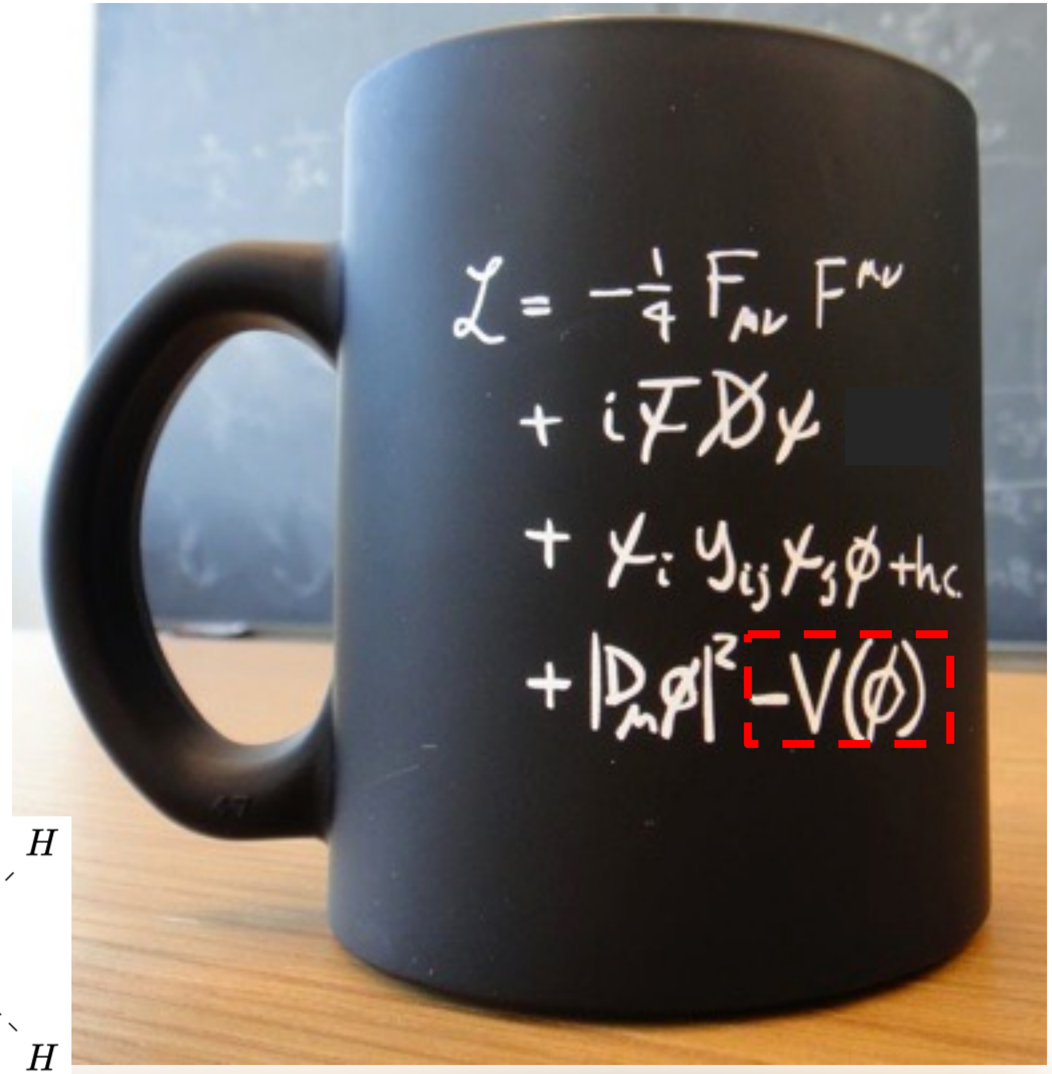
$$V(\phi) = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \cdots$$

Higgs mass term — Higgs self-coupling

$$m_h = \sqrt{2\lambda v^2} = \sqrt{-2\mu^2}$$

Potential parameters are unpredictable
⇔ Higgs mass is unpredictable
➔ Need to measure experimentally!!

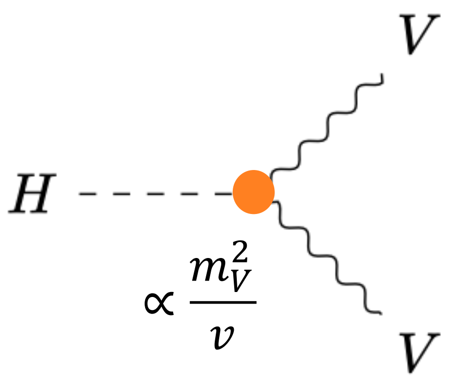




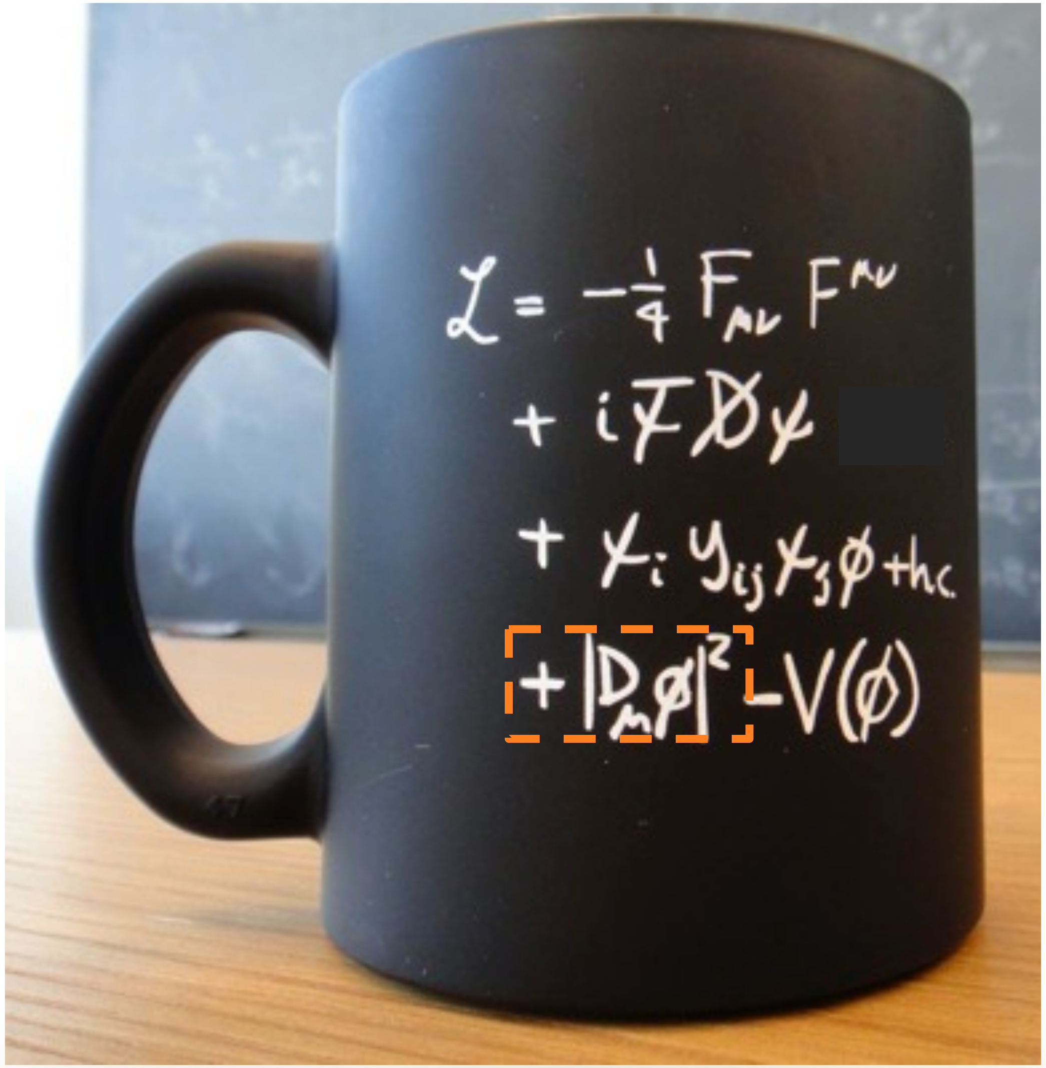
SM Lagrangian

Interaction between Higgs and Gauge bosons

Describe Gauge boson mass term and interactions (Electroweak symmetry breaking)



$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$$



mass term

$$\left|D_\mu \phi\right|^2 = \left(\frac{gv}{2}\right)^2 W_\mu^+ W^{\mu-} + \frac{1}{2}\left(\frac{\sqrt{g^2+g'^2}}{2} v\right)^2 Z_\mu Z^\mu$$

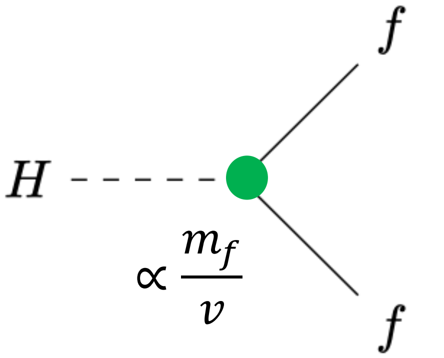
W boson mass Z boson mass

W/Z bosons acquire mass by vacuum shift 0→v
(γ keeps massless)

SM Lagrangian

Interaction between Higgs and Fermions (Yukawa sector)

Describe fermion mass term and Yukawa interactions



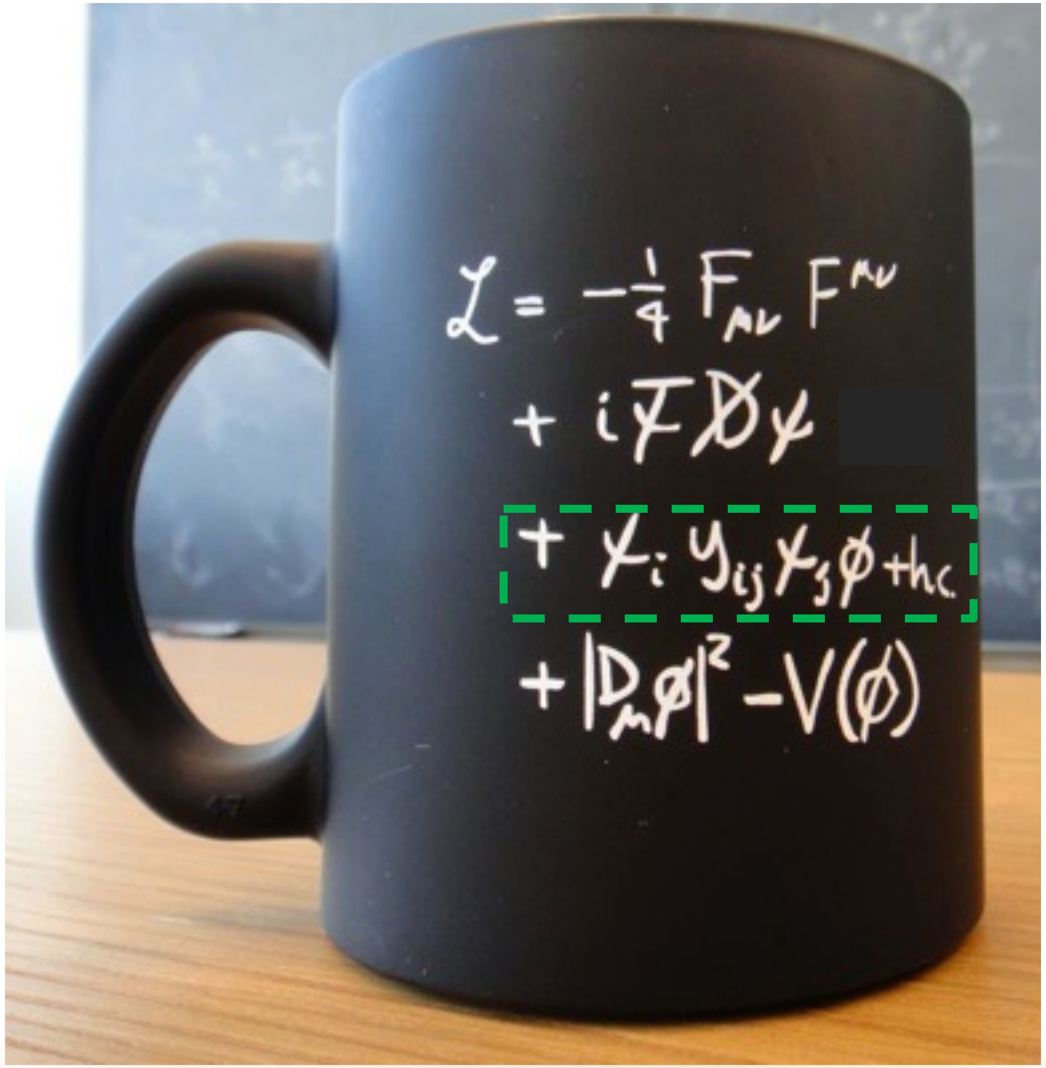
Fermion (charged lepton/quark) mass is given by proportional of Yukawa coupling in the SM

$$m_f = \frac{1}{\sqrt{2}} y_f v$$

However, **Yukawa couplings** are just parameters in SM

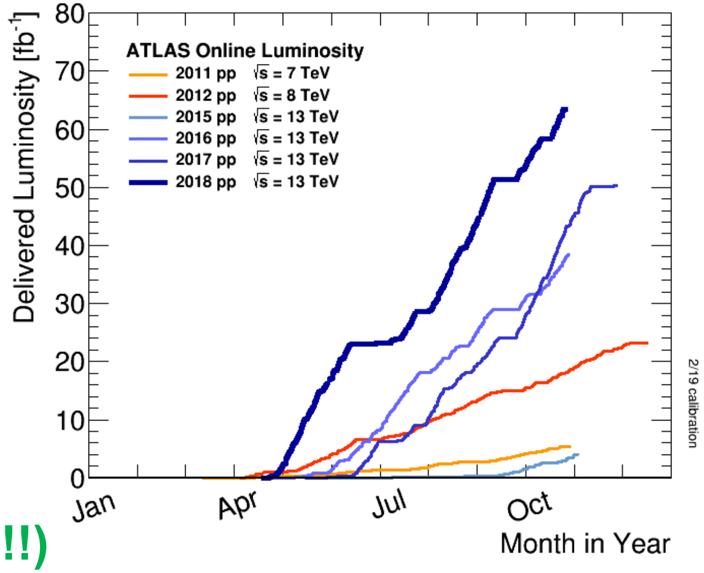
➔ Can't predict fermion mass

➔ Different Yukawa coupling makes "generation" of fermions



LHC-ATLAS experiment

- LHC (Large Hadron Collider) is proton-proton collider located underground in suburban of Geneva

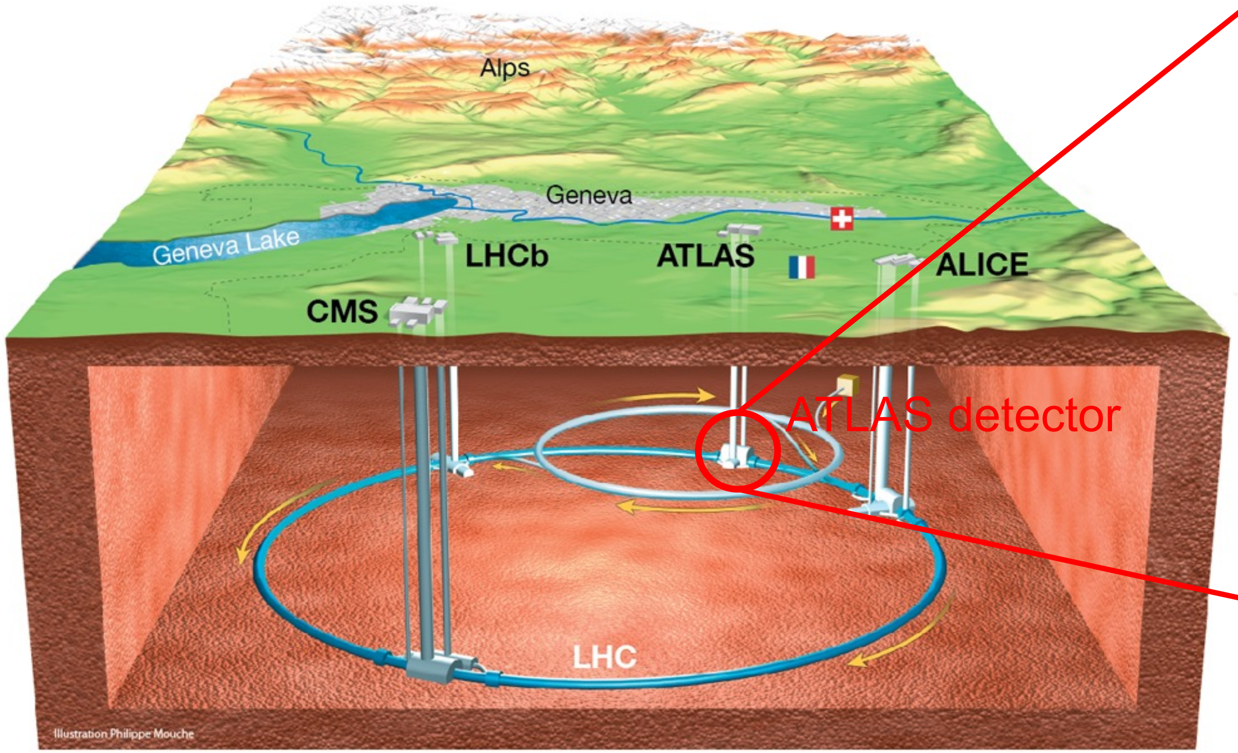


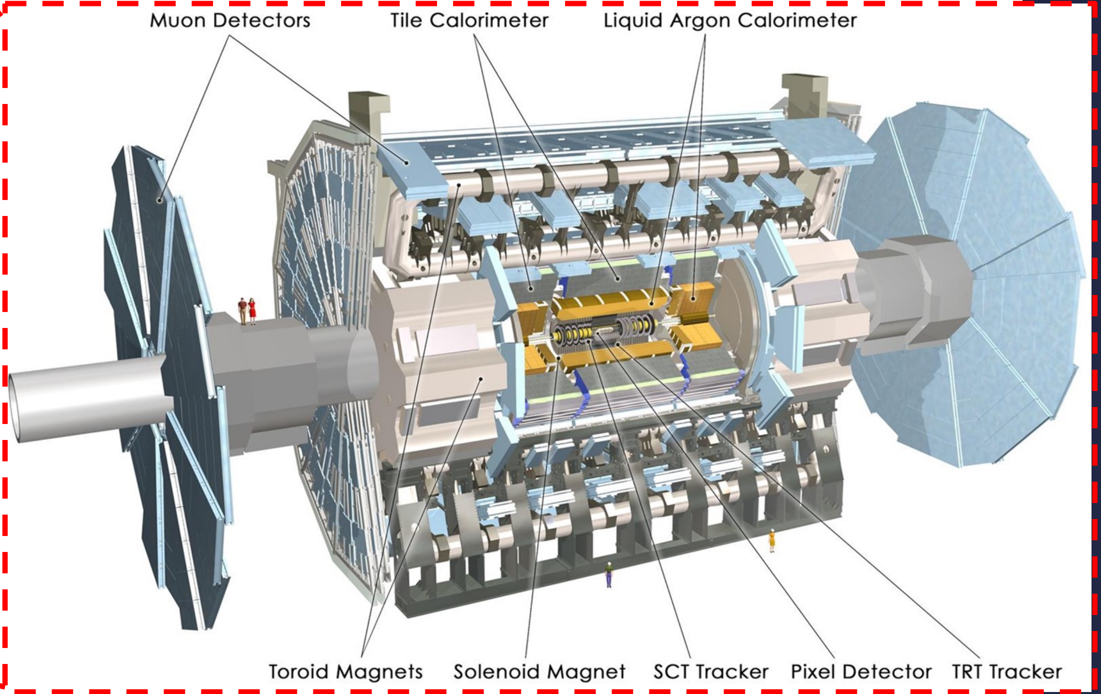
Run 1			LS1		Run 2				LS2			Run 3 ...	
7 TeV	8 TeV				13 TeV							13.6 TeV	
2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023-

~25/fb
➔ ~0.6M Higgs!

~140/fb
➔ ~8M Higgs!!

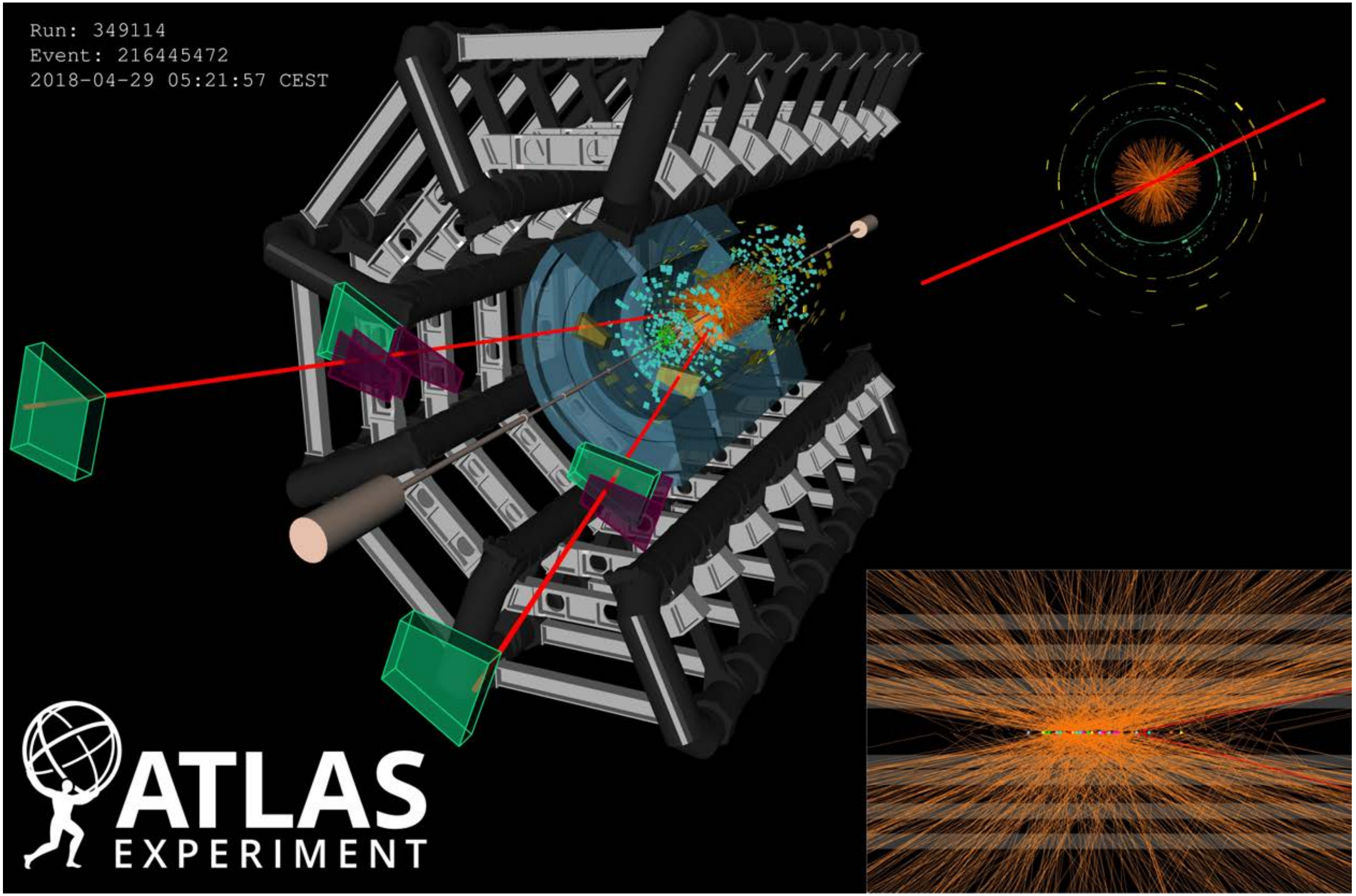
~10/fb (Just started!!)





Multi-purpose 4π detector

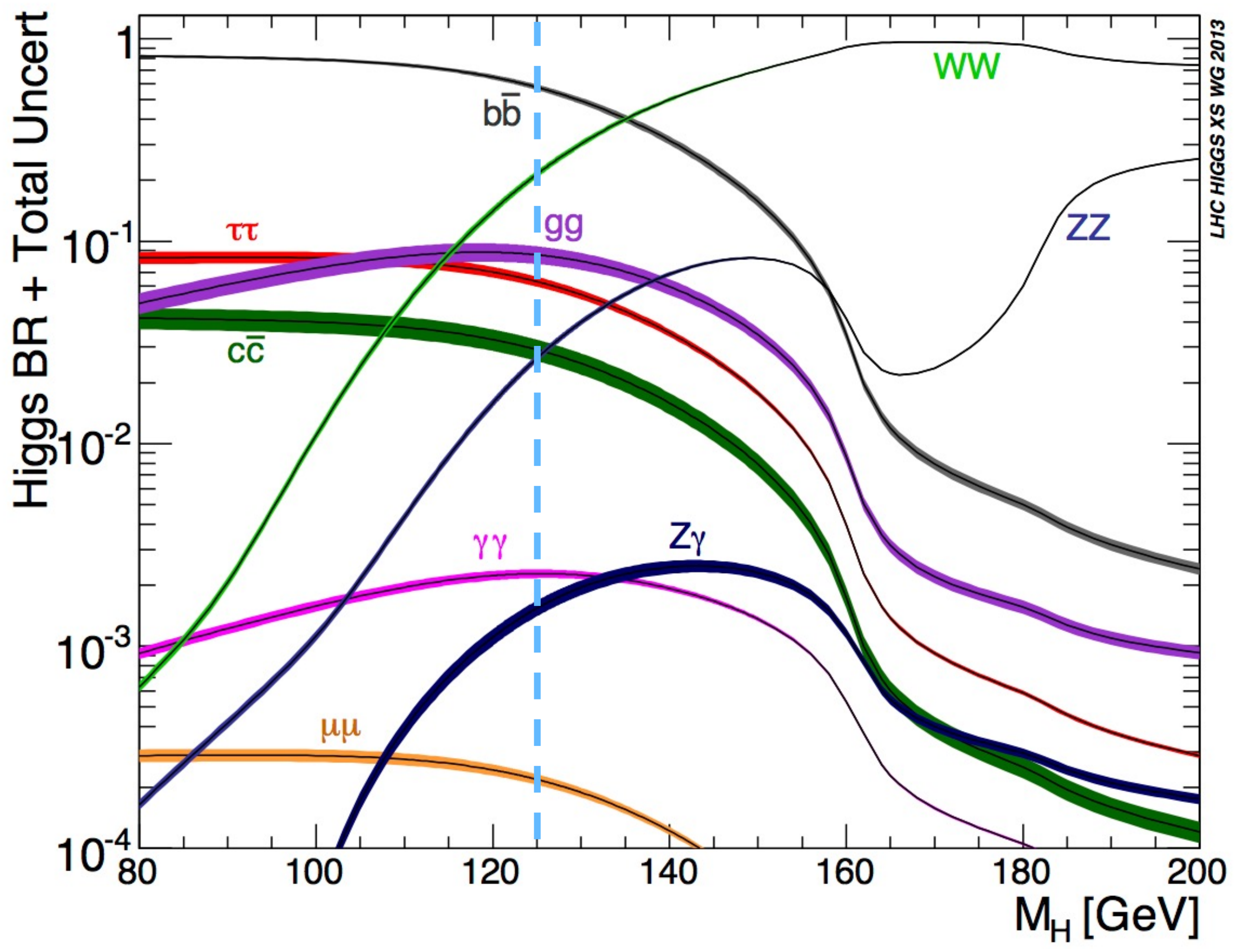
LHC-ATLAS experimental conditions



In Run2 13 TeV condition
~30 Pile-up events on average
➔ Experimentally severe condition to identify interesting events
➔ Many efforts to mitigate pile-up effect

ATLAS Event display in 2018 data
28 pileup on top of $Z \rightarrow \mu\mu$ (red lines) events

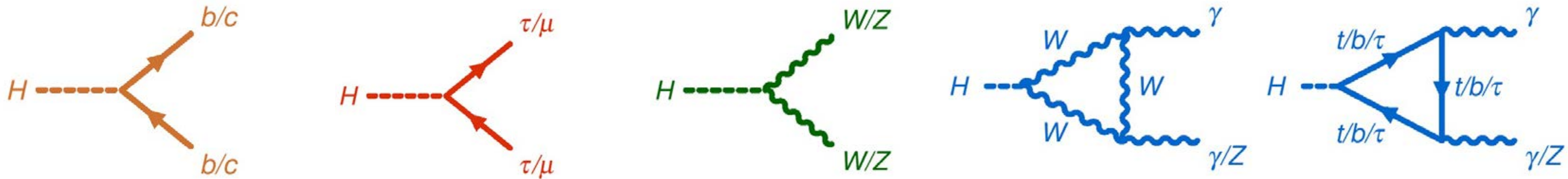
Higgs decay branching ratio



- Higgs boson decays to other SM particles
  - Observed Higgs mass(~125 GeV) is experimentally really good
  - Higgs boson is able to decay various particles
    ➔ Property measurement with different decay modes
  - H→bb decay mode is dominant

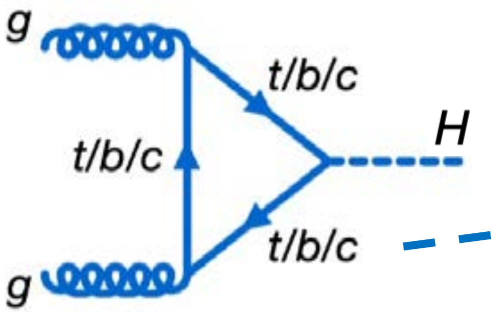
bb	WW	gg	ττ	cc	ZZ
58%	21%	8.2%	6.3%	2.9%	2.6%

γγ	Zγ	μμ
0.23%	0.15%	0.022%

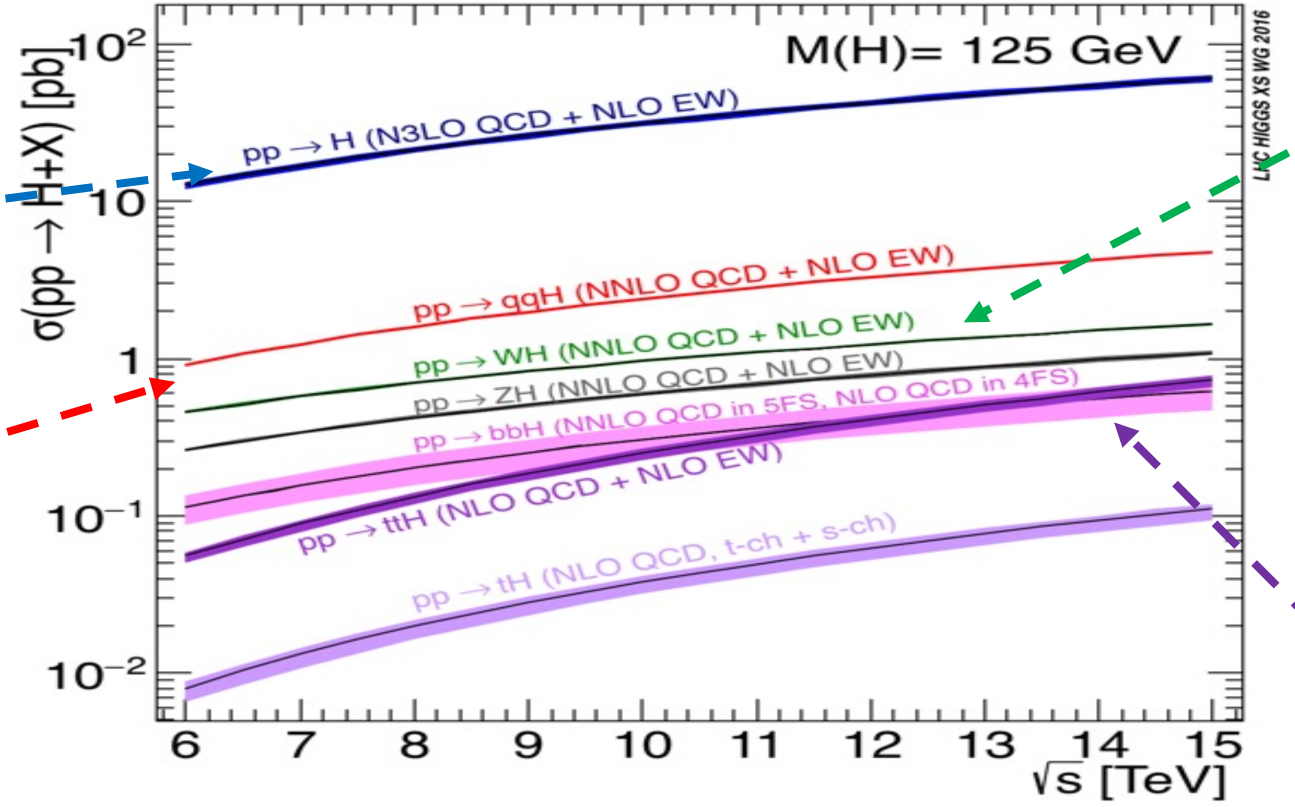


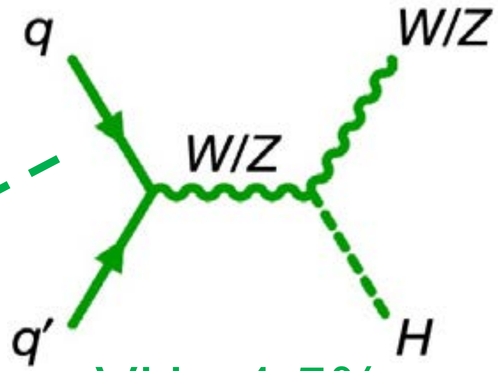
Higgs Production at LHC

- Gluon-fusion process is dominant at LHC (Gluon collider!!)

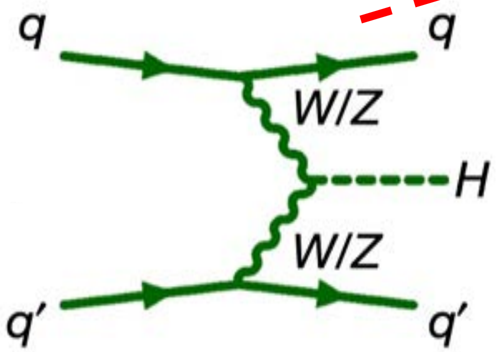


ggF ~88%

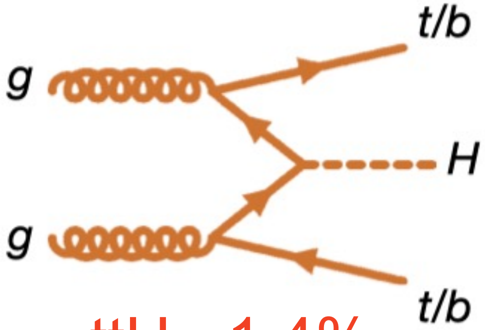




VH ~4.5%



VBF ~7%



ttH ~1.4%

- Higgs physics strategy is built by the combination of production and decay (can not observe all Higgs events experimentally!!)
  - Lots of QCD background, not triggerable, detector coverage...

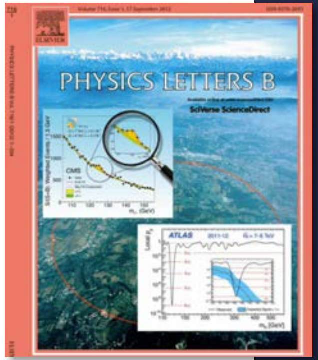
Summary of Higgs physics strategy

- Clean (bosonic decay) modes contributed to the discovery!! (Discovered by ggF process)
  - Contribute to various property measurements as well
  - Fermionic decay modes are particularly important for Yukawa measurement

m_H=125 GeV	H→bb	H→WW→lνlν	H→ZZ→4l	H→γγ	H→ττ	H→μμ	H→cc
ggF	△ y_b measurement	★ Discovery; Cross section, Coupling, Spin/CP, width measurement	★ Discovery; Mass, Cross section, Coupling, Spin/CP, width measurement	★ Discovery; Mass, Cross section, Coupling, Spin/CP measurement	◎ y_{tau} Cross section CP	△ y_{mu}	× y_c
VBF	○	◎	◎	◎	◎	△	×
VH(WH/ZH)	◎	○	△	○	△	△	△
ttH	○ y_t measurement	○ y_t measurement	△	◎	△	△	×
bbH	×	×	×	×	×	×	×
tH	△	△	×	△	×	×	×

For example:
σ(ggF)*BR(H→bb)*Lumi(Run2) = 55.7pb*0.58*139000/pb = ~4.5M event (**not triggerable**)
σ(ggF)*BR(H→γγ)*Lumi(Run2) = 55.7pb*0.0023*139000/pb = ~18K events
σ(ggF)*BR(H→μμ)*Lumi(Run2) = 55.7pb*0.00022*139000/pb = ~1.7K events

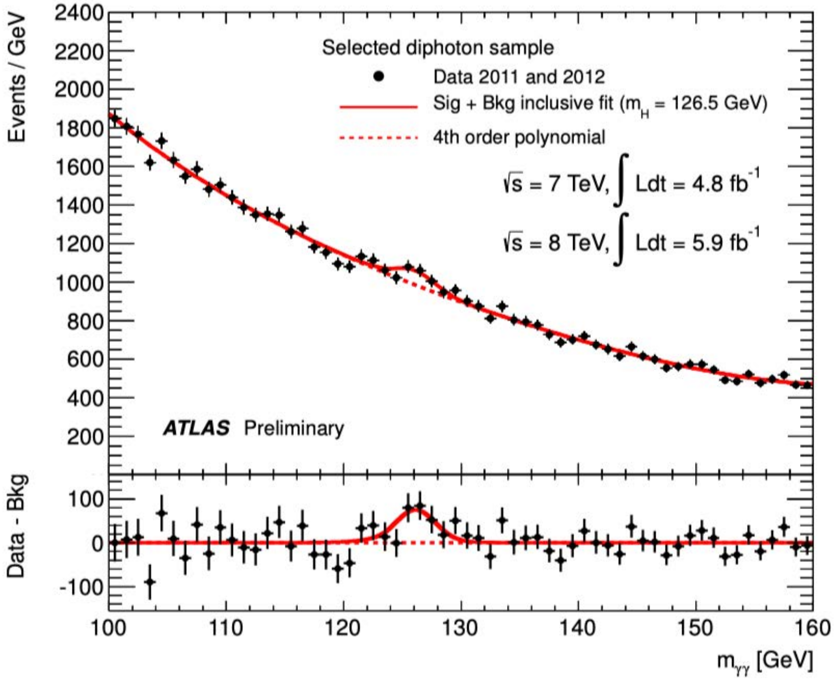
Higgs Discovery at Run1 (2012)



- A Higgs boson was discovered in 2012 in ATLAS and CMS experiments

H→γγ

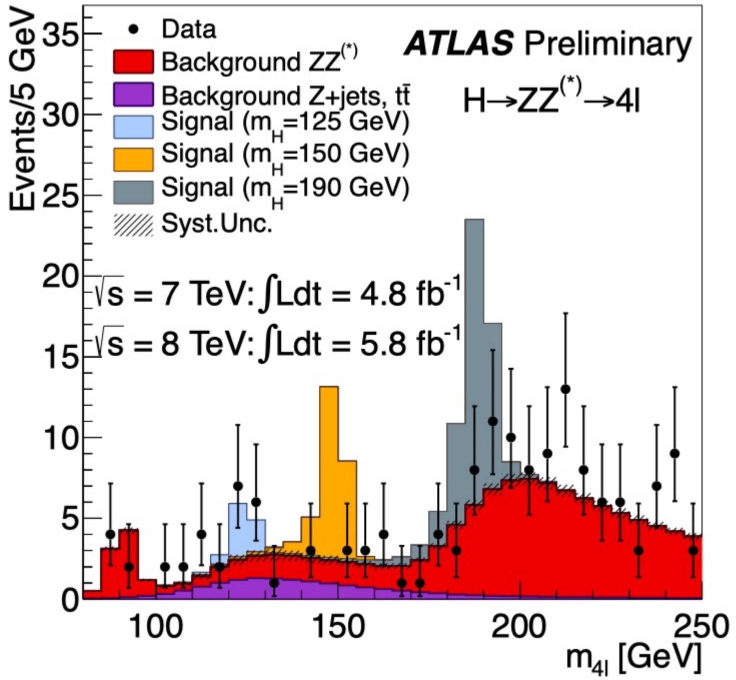
- Excellent mass resolution $\sigma(m_{\gamma\gamma})$~1% ➔ Narrow mass peak can be observed on top of large background



Significance (local) 4.7σ @126.5 GeV

H→ZZ→4l

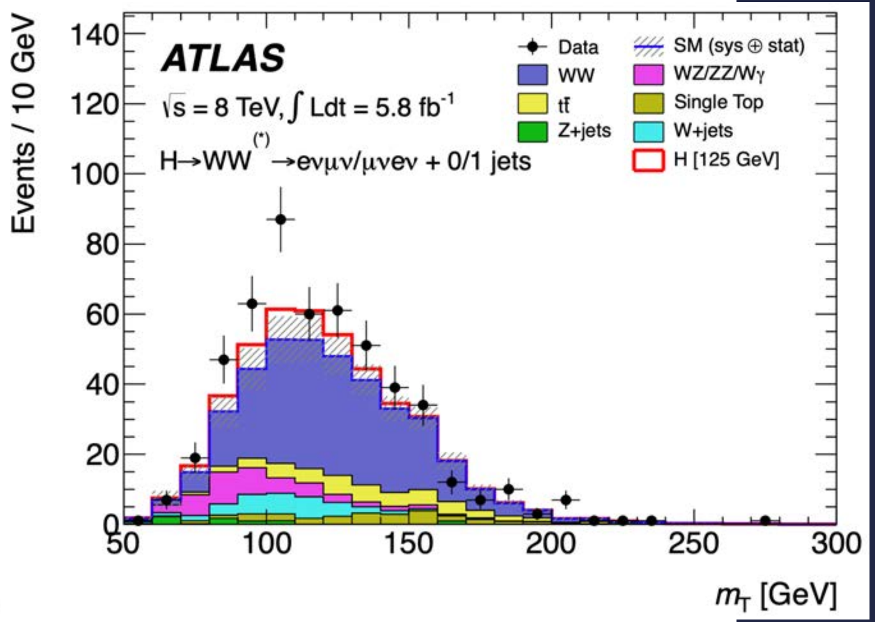
- Excellent mass resolution ~1-2%
- Branching fraction is very low. ~ 0.02%
- Clean background (good S/B)



Significance(local) 3.4σ @125 GeV

H→WW→2l2ν

- Higher event yield but large variety of difficult backgrounds
- mass resolution ~10 GeV due to neutrino in the final state



Significance (local) 2.8σ (2.3σ exp.)@125 GeV

Higgs Discovery at Run1 (2012)

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H→γγ

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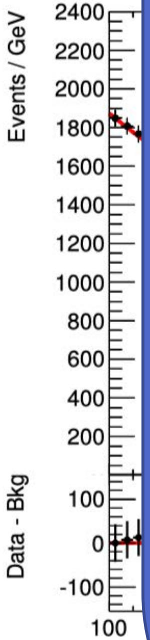
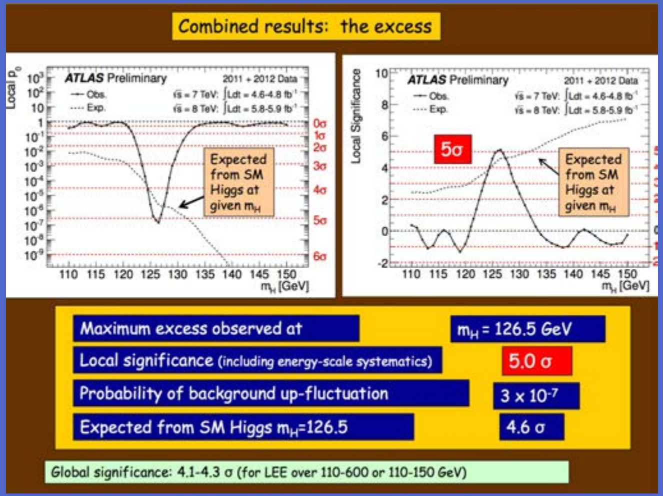
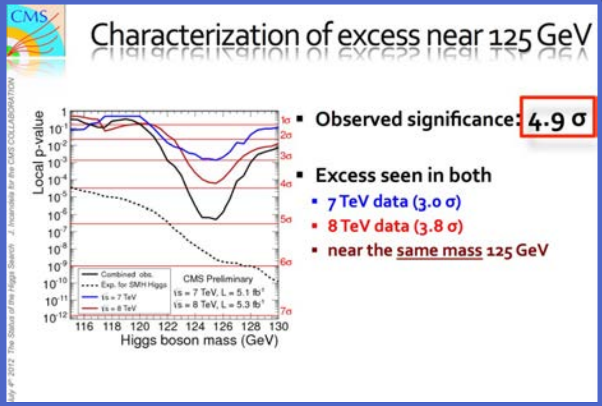
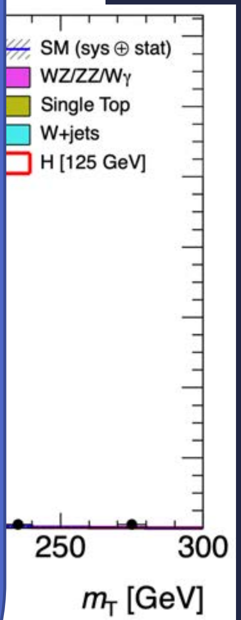


July 4th 2012
Observed ~ 5σ excess around 125 GeV







2013 Nobel Prize

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/

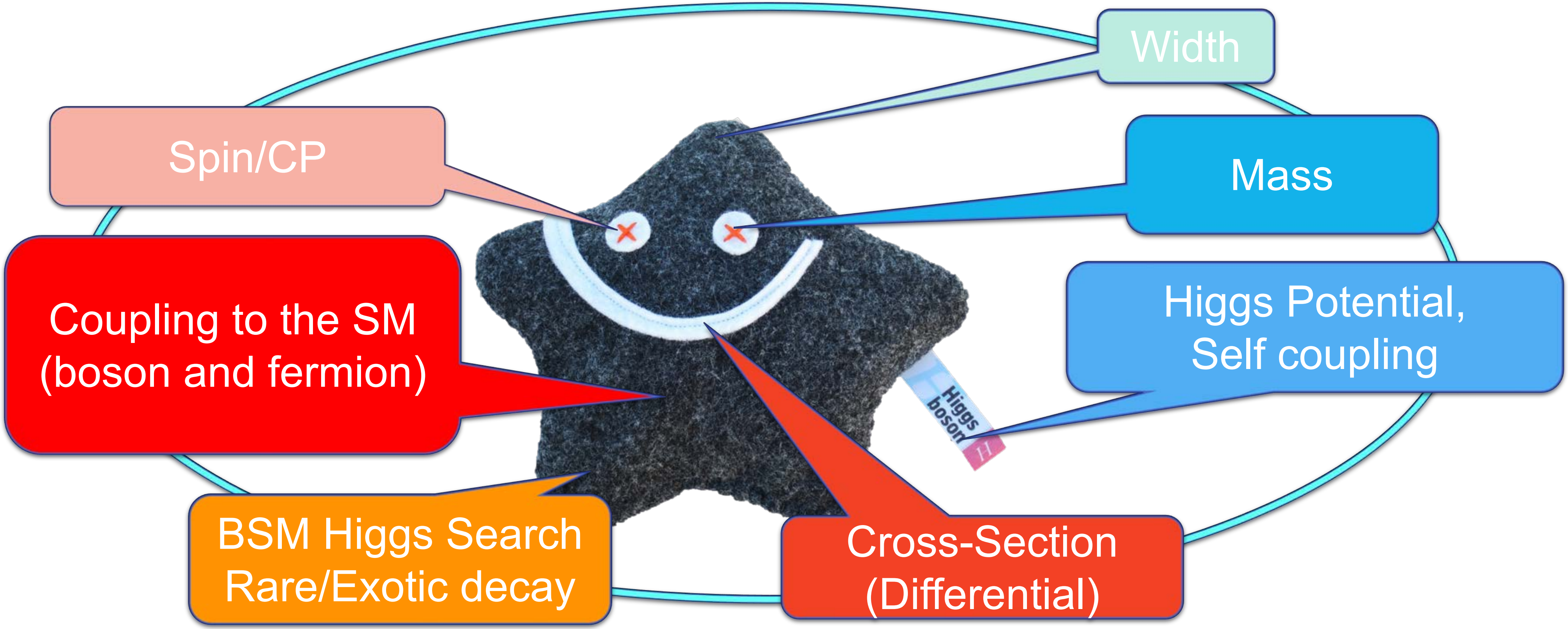
S
@126

@125 GeV

2.8σ
@125 GeV

Higgs Measurements in 10 years

- Higgs discovery provides rich physics topics
- Higgs boson properties have been measured for ~past 10 years
- Show highlights of the resent results up to LHC-Run2



Higgs Mass measurement

- **Higgs mass is one of unpredictable parameters**
- Measure using excellent mass resolution channel ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$)
- ATLAS recently measured mass in 4l channel
  - Use Neutral Network to discriminate signal from background
  - Predict uncertainties (detector region, e or μ, kinematics) event-by-event

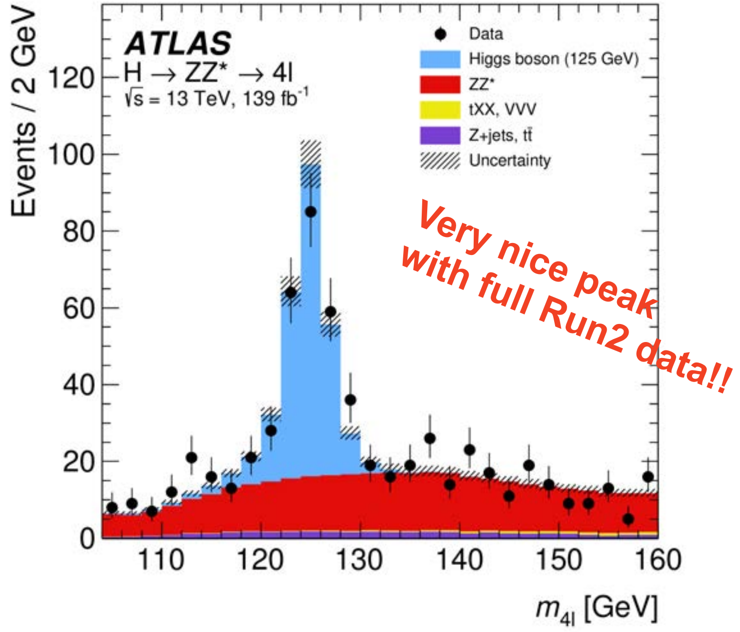
➔ Multi-dimensional fit (m_H vs NN score, uncertainty)

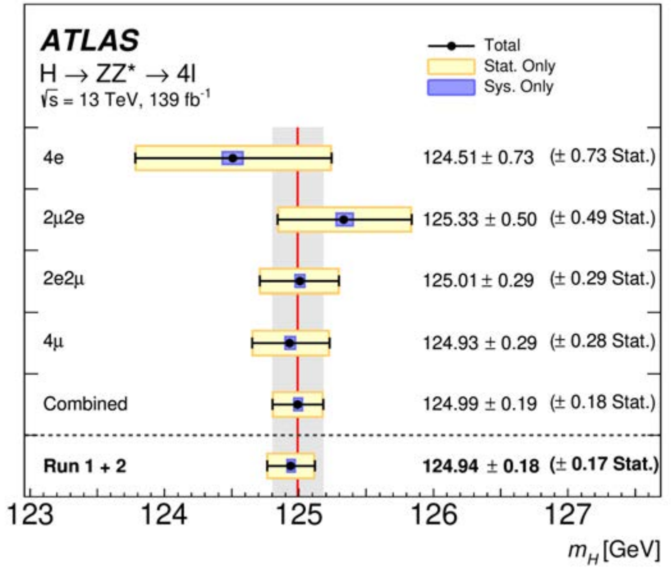
124.99±0.18(stat)±0.04(sys) GeV

0.15% precision!! still statistically dominated

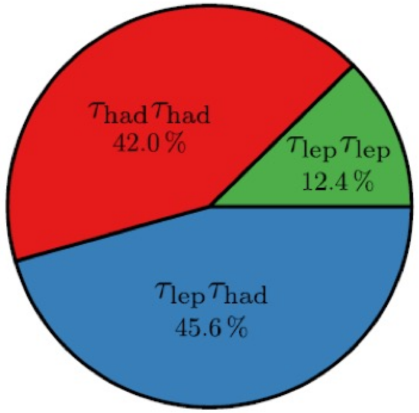
Systematic Uncertainty	Impact (MeV)
Muon momentum scale	±20
Electron energy scale	±16
Theory	±13

c.f. CMS (Run1+partial Run2) 125.38±0.14 GeV





H→ττ measurement



- **Provide an unique opportunity to access tau-Yukawa coupling**
- Observed H→ττ signal b. > 5σ in Run1
- Events are categorized by the tau decay mode and Higgs production channel

Tau decay mode		**Higgs production**
$\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{lep}$	✖	**ggF($p_T^{\tau\tau}$>100 GeV)** **VBF**, VH, ttH

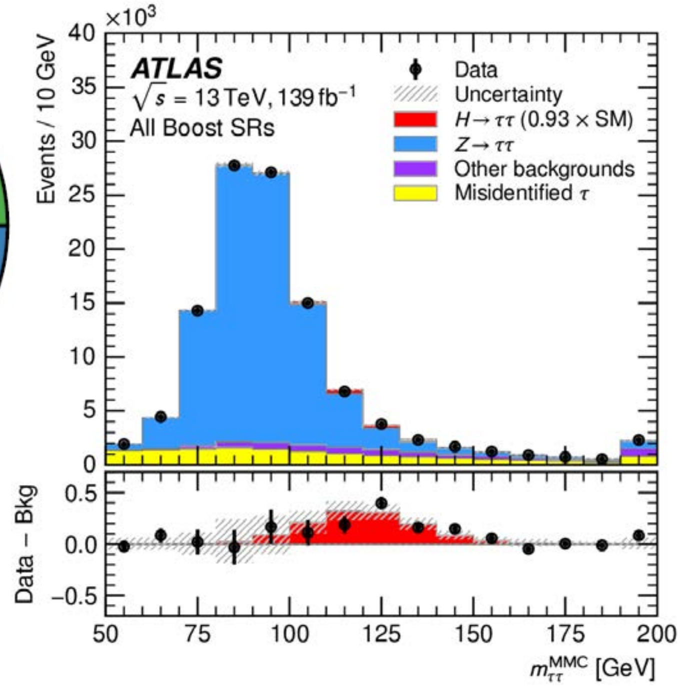
- Measured VBF cross section

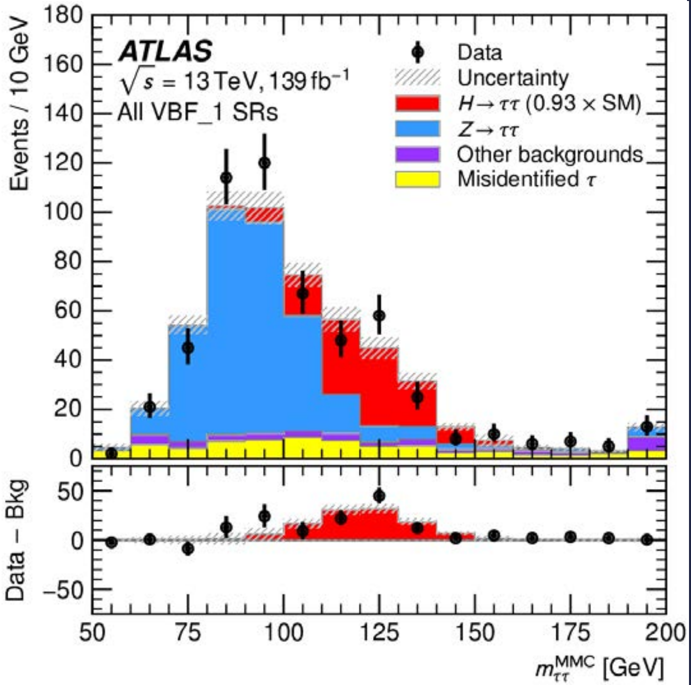
0.197±0.041pb (SM pred. 0.220±0.005pb), 5.3σ (6.2σ exp.)

- Measured ggF cross section

2.65±0.85pb (SM pred. 2.77±0.09pb), 3.9σ (4.6σ exp.)

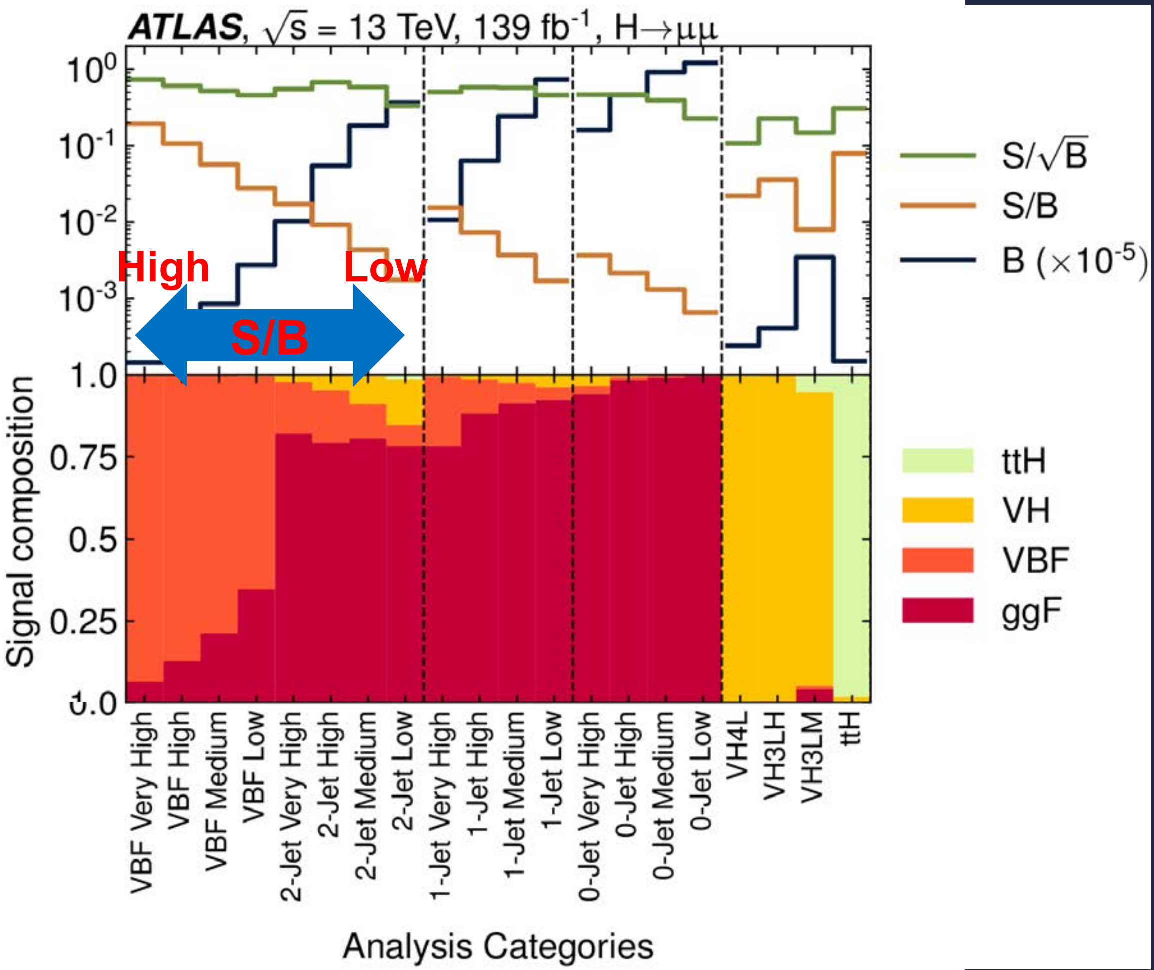
➔ Consistent with SM

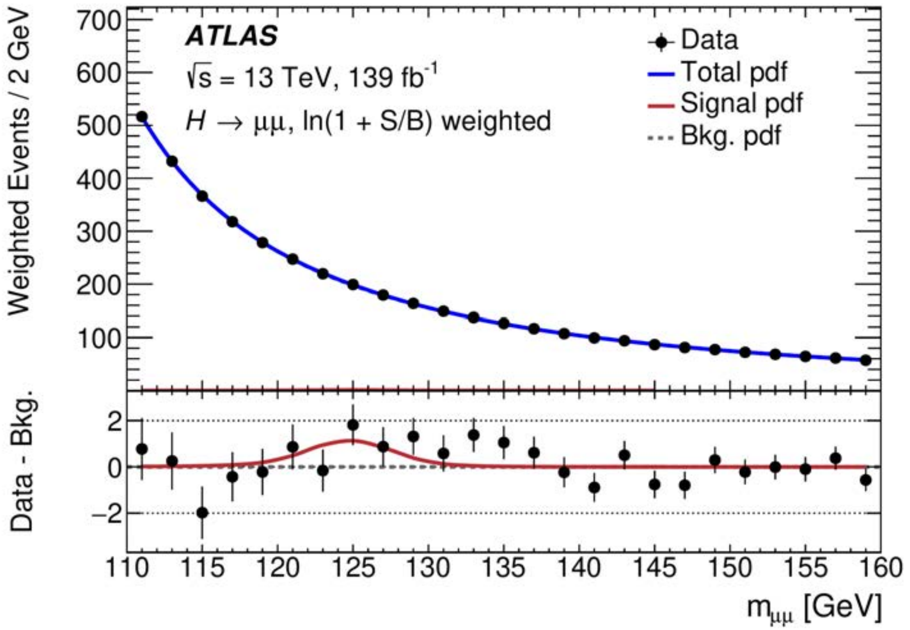




H→μμ measurement

- **H→μμ is an unique opportunity to study 2nd generation lepton Yukawa coupling**
- BR is extremely small (0.022%)
- Mass resolution is good (~3 GeV), but background is huge (DY Z→μμ tail)
- Crucial to extract better S/B region in each production mode using Machine learning technique (BDT)





- **Observed significance**

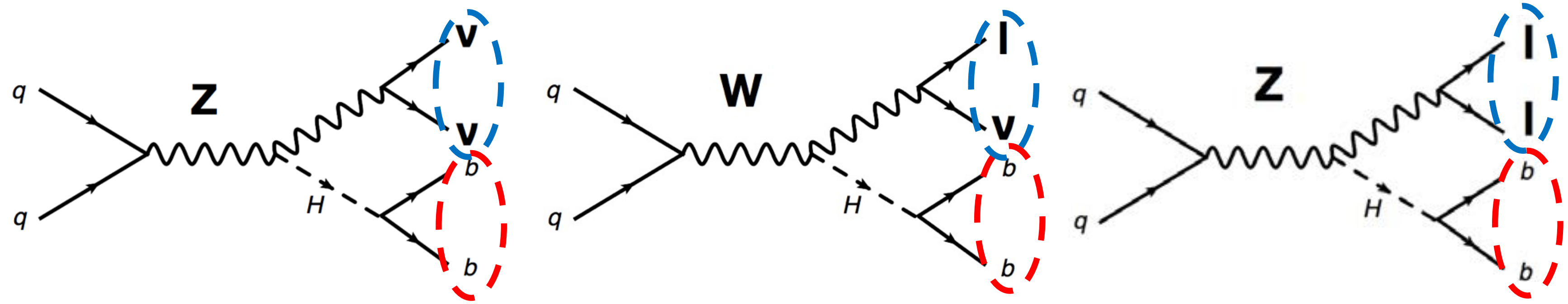
2.0σ (1.7σ exp.)

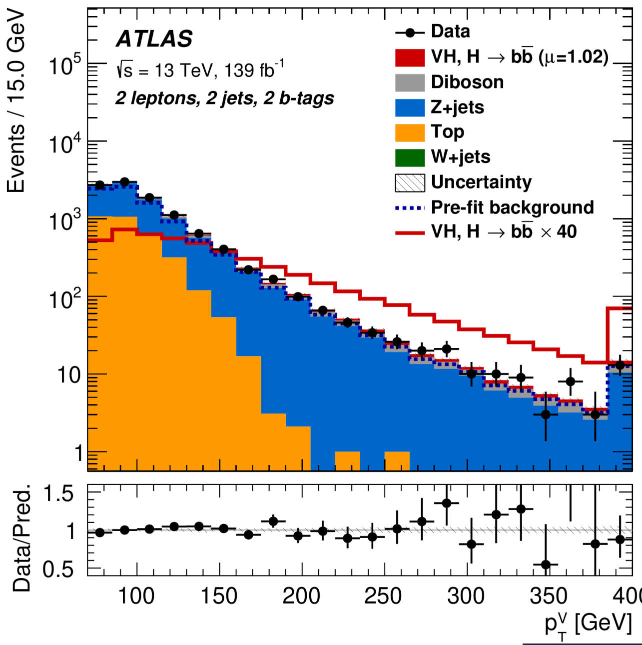
- **Upper limit on BR(H→μμ) < 0.047%**

c.f. CMS: 3.0σ (2.5σ exp.)

H→bb measurement

- **Measurement of bottom Yukawa coupling**
- Dominant branching ratio (58%)
- VH channels are most sensitive (difficult to trigger ggF/VBF and background is huge)





- Triggered by Z→νν(MET), W→lν, Z→ll
- Require 2 b-tagged jets
- Select high p_T^V to enhance S/B

0-lep 1-lep 2-lep	×	2 b-jet 2 b-jet+1jets	×	$75 < p_T^V < 150$ $150 < p_T^V < 250$ $250 < p_T^V$

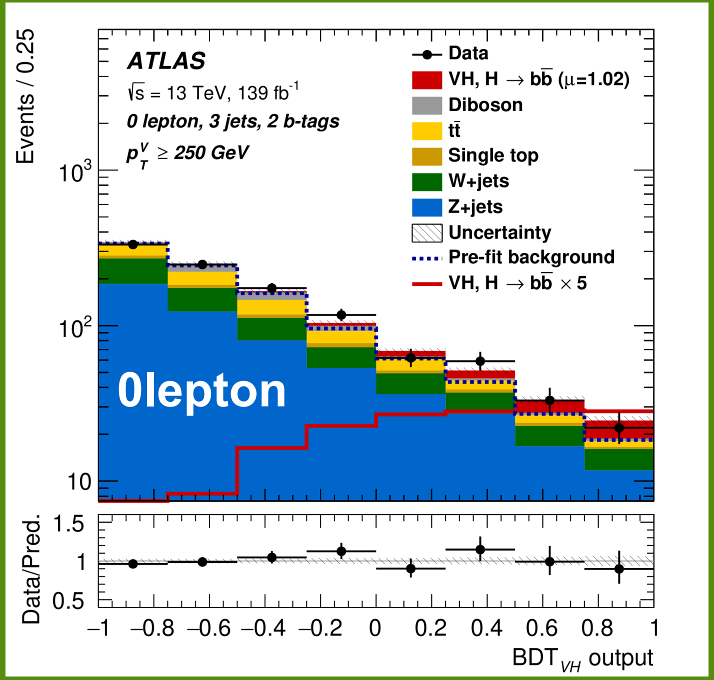
Main background

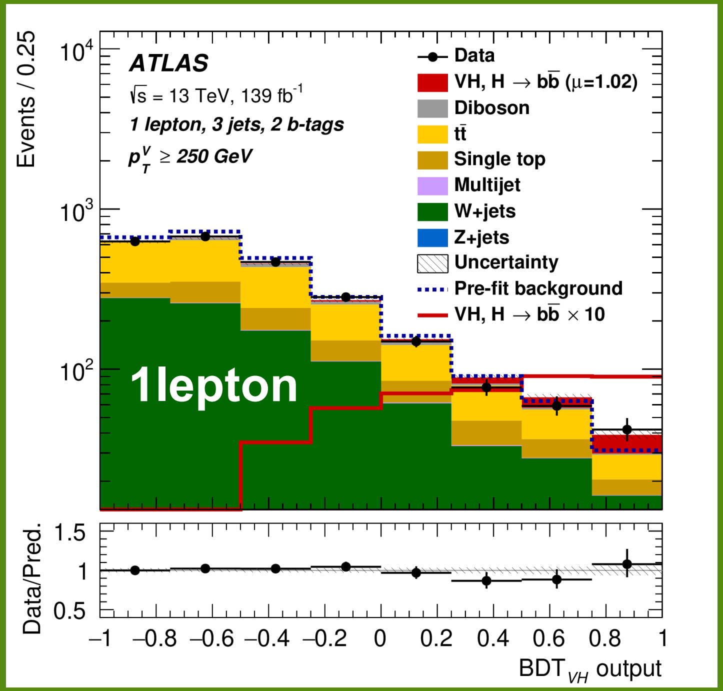
Z+jets(0/2 lep), W+jets(0/1 lep)
ttbar, single top(0/1/2 lep)
diboson(0/1/2 lepton)
➔ Utilize machine leaning to discriminate signal

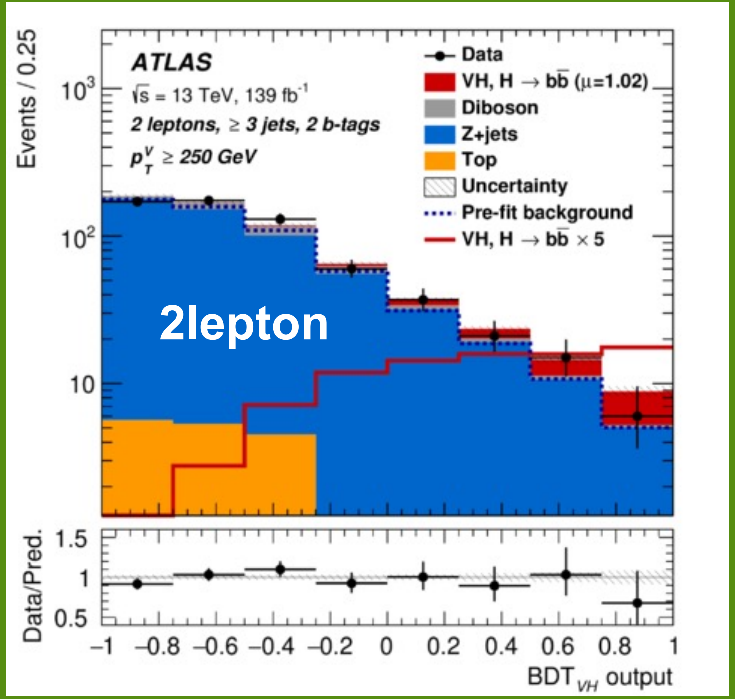
H→bb measurement

- **Measurement of bottom Yukawa coupling**

Final discriminant (BDT output)







Signal can be enhanced in the high BDT output score region
S/B > 1 in 2 lepton highest score bin

1-lep
2-lep

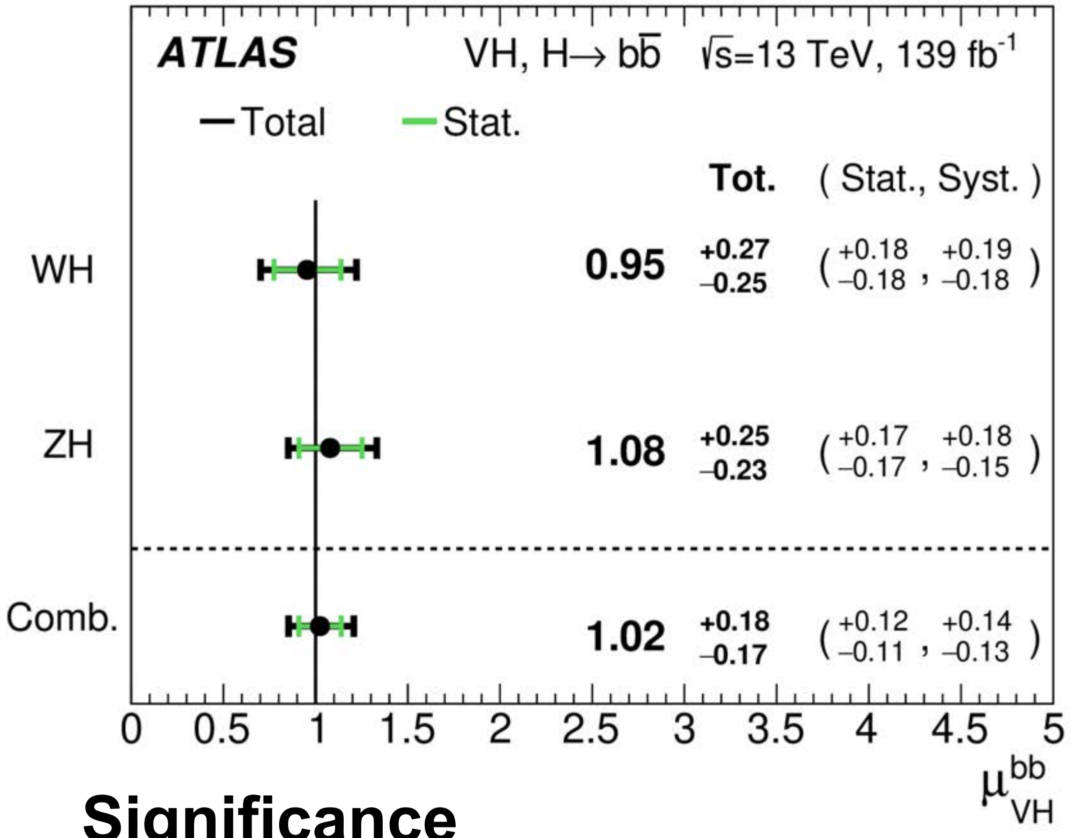
2 b-jet+1jets

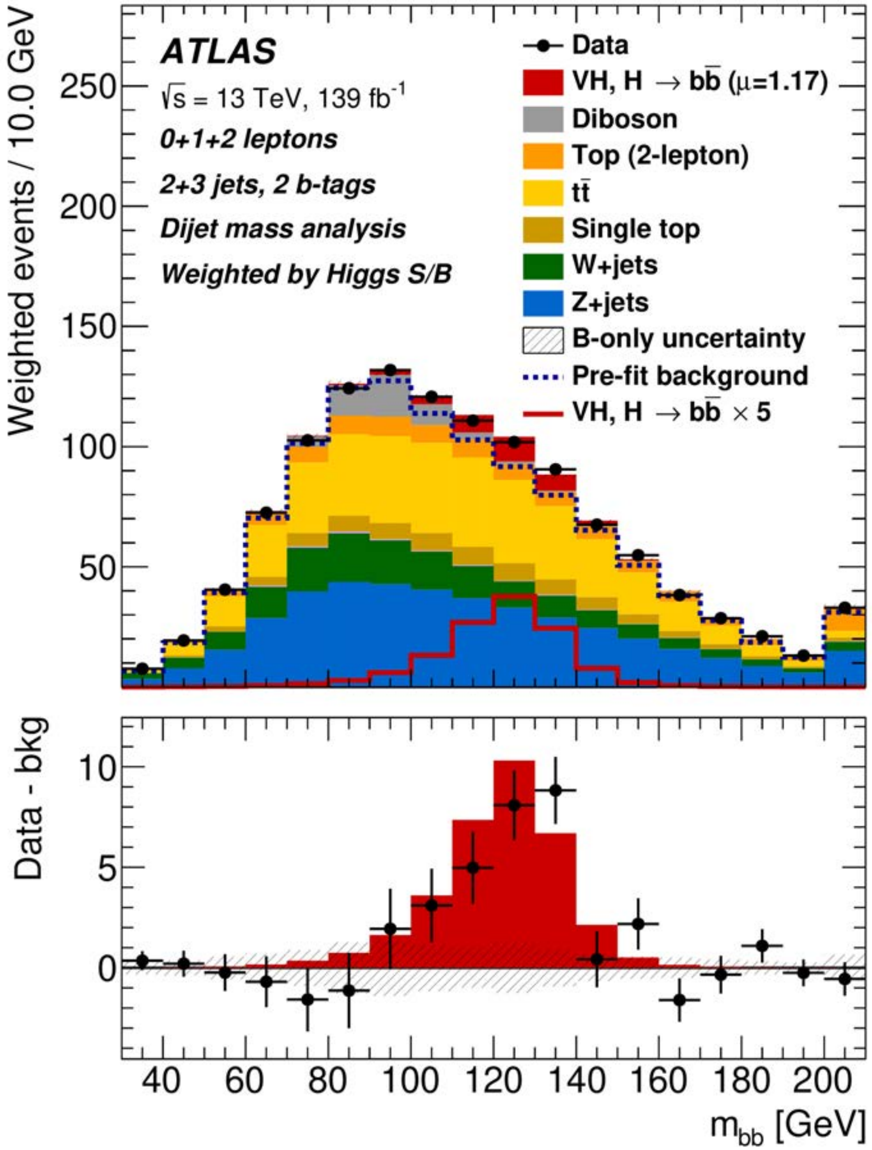
$250 < p_T^V$

➔ Utilize machine leaning to discriminate signal

H→bb measurement

- Signal strength $\mu = (\sigma \times BR)_{measure} / (\sigma \times BR)_{SM}$





Cross-check in m_{bb} fit
5.5σ (4.9σ exp.)

Significance

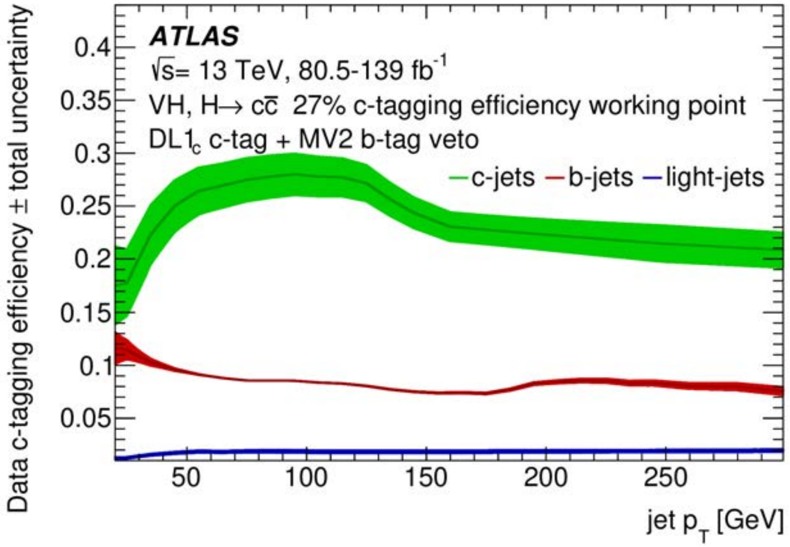
WH: 4.0σ (4.1σ exp.)
ZH: 5.3σ (5.1σ exp.)
VH(WH+ZH): 6.7σ (6.7σ exp.)

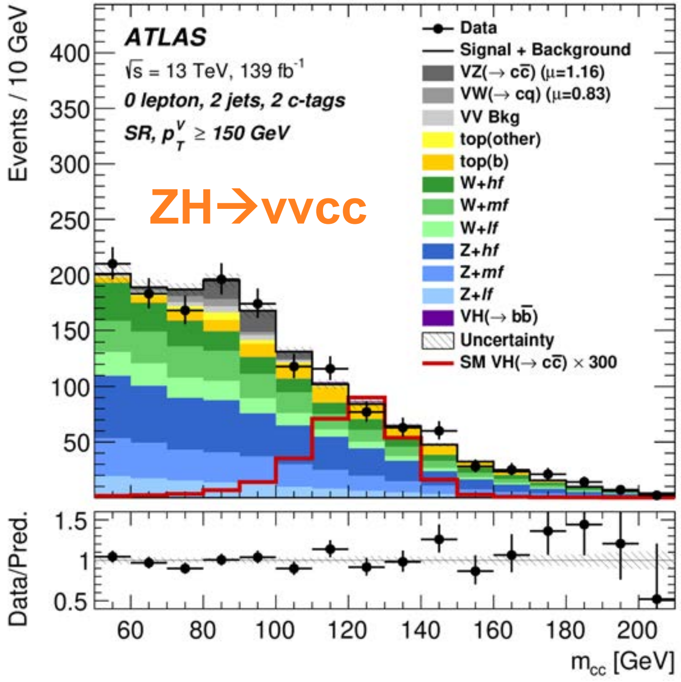
H→cc measurement

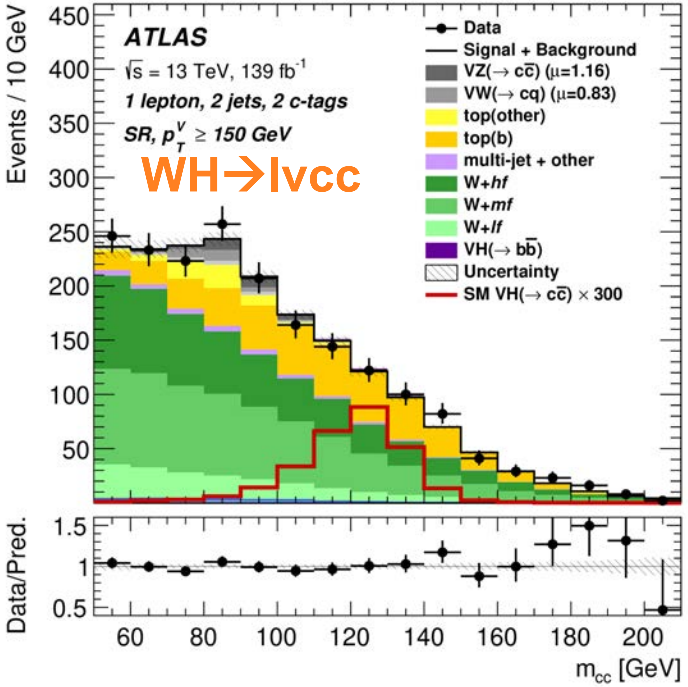
- **Charm Yukawa measurement**
- Small branching ratio (2.9%), huge SM background

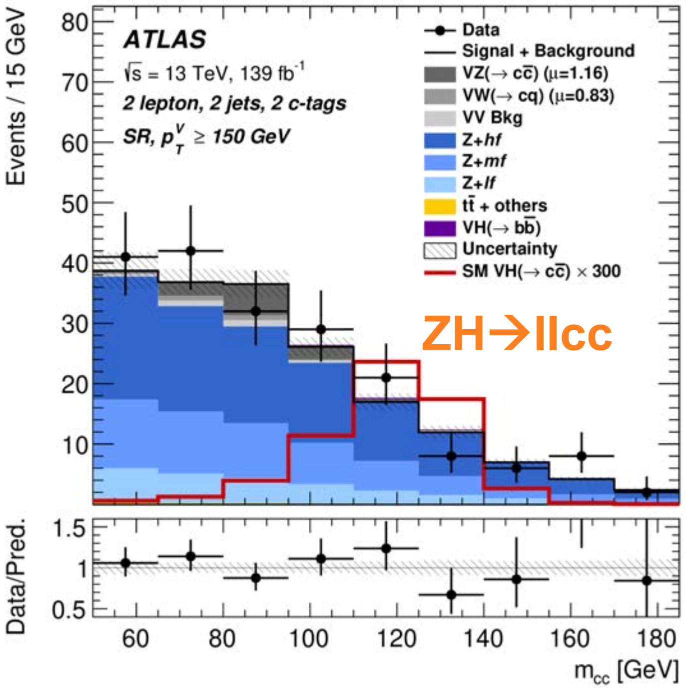
→Super difficult measurement at LHC

→Similar analysis strategy to VH(→bb), but dedicated c-tagging has been developed





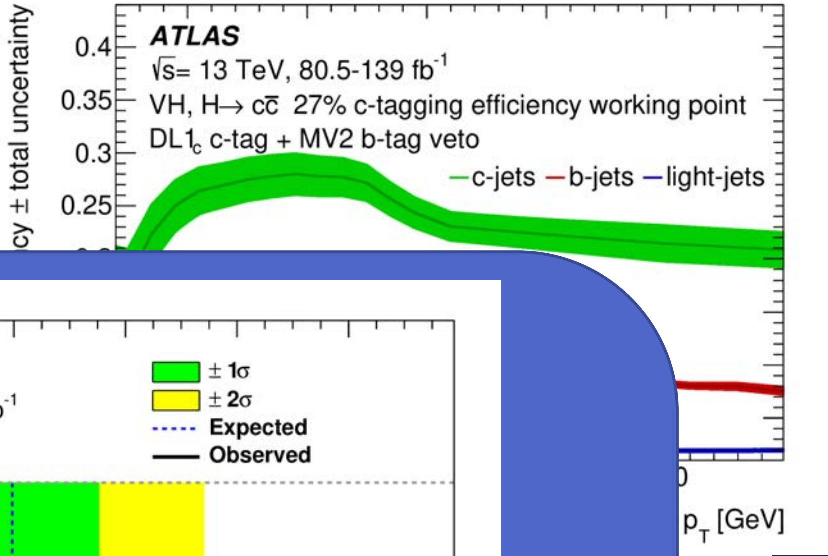


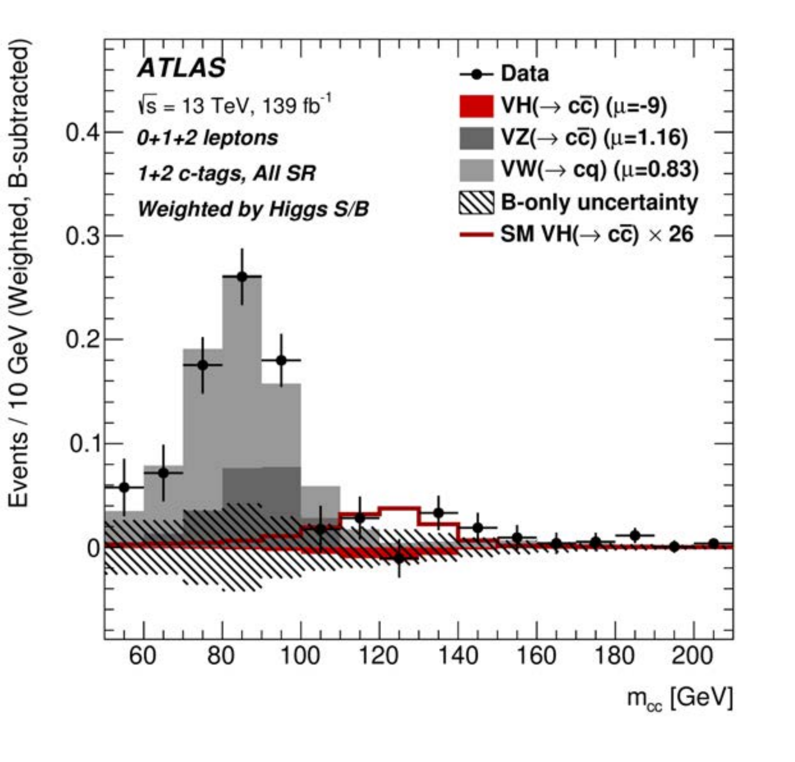


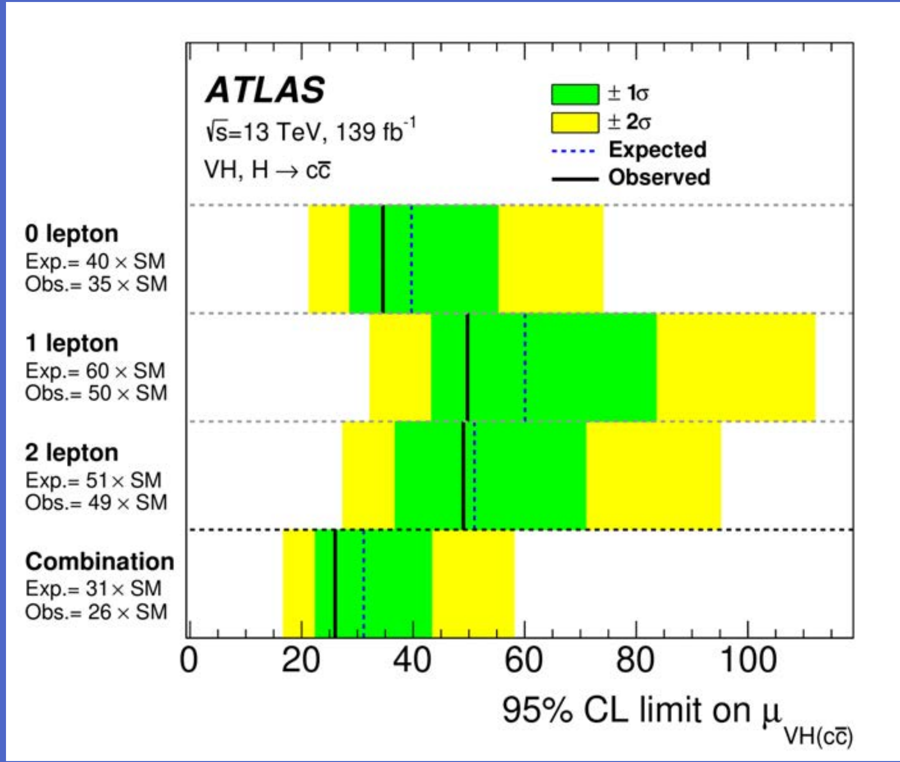
No significant H→cc signal is observed

H→cc measurement

- **Charm Yukawa measurement**
- Sm







Upper limit: 26*SM (31*SM exp.)

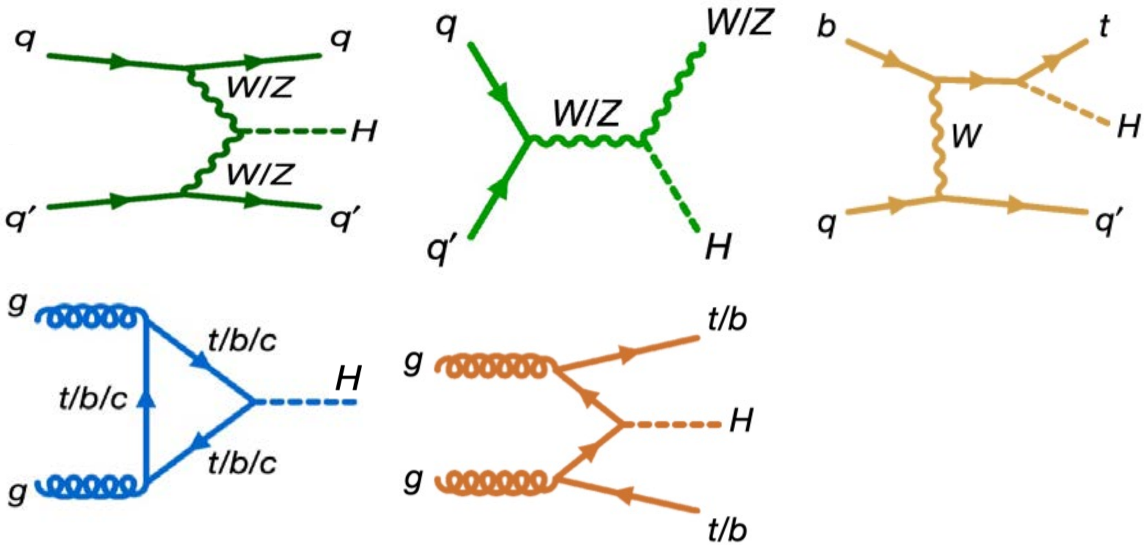
CMS recently developed boosted H→cc tagger: 14.4*SM (7.6*SM)

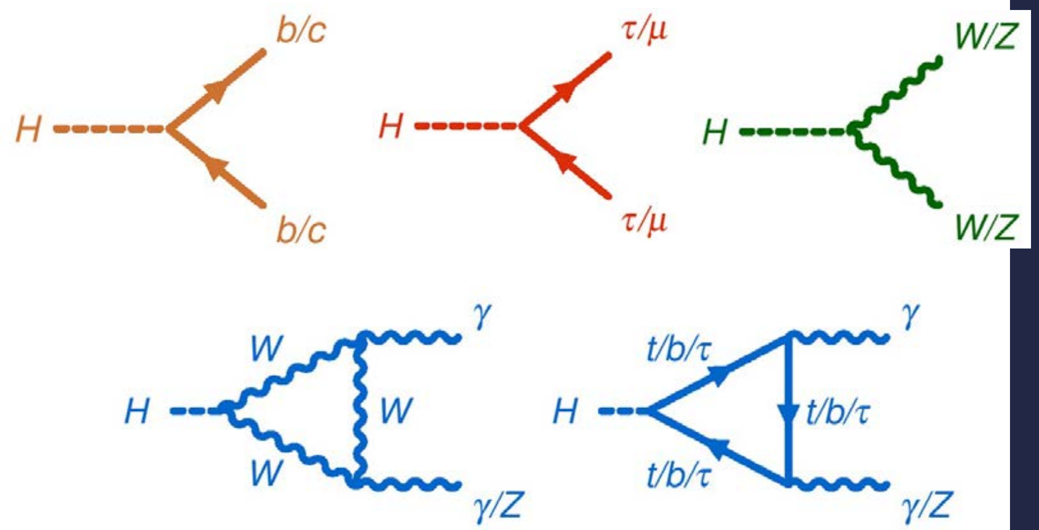
No significant H→cc signal is observed

Higgs Combination

- Analyzed many production and decay modes
  ➔ Statistical combination of all channels to obtain the most precise measurements

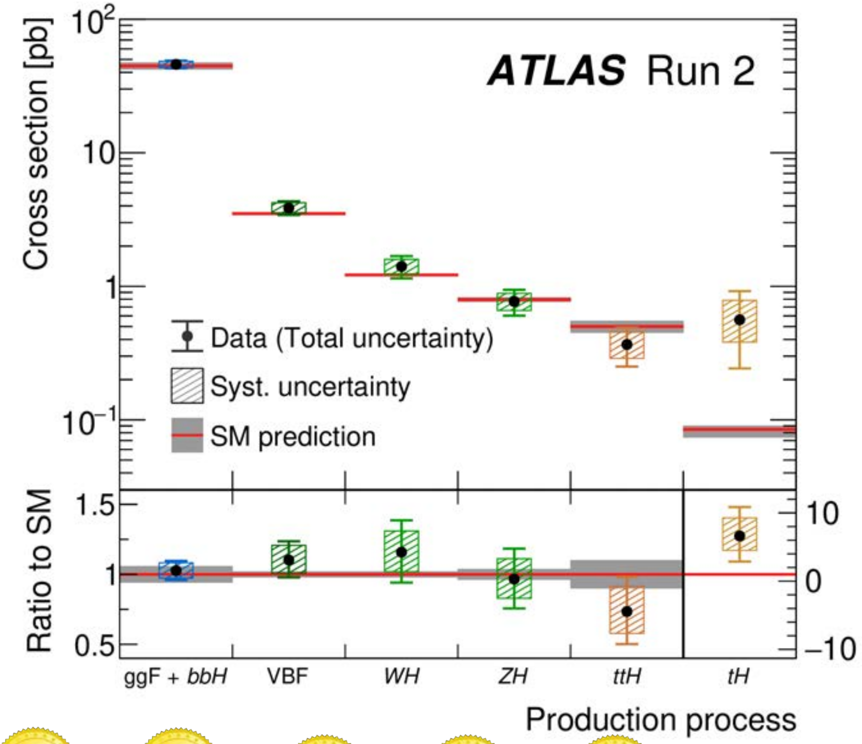
Input channels	H→bb	H→WW	H→ZZ	H→γγ/Zγ	H→ττ	H→μμ	H→cc
ggF	✔	✔	✔	✔	✔	✔	-
VBF	✔	✔	✔	✔	✔	✔	-
VH(WH/ZH)	✔	△(partial data)	✔	✔	✔	-	✔
ttH	✔	△(partial data)	△(partial data)	✔	△(partial data)	-	-
tH	✔	△(partial data)	△(partial data)	✔	△(partial data)	-	-

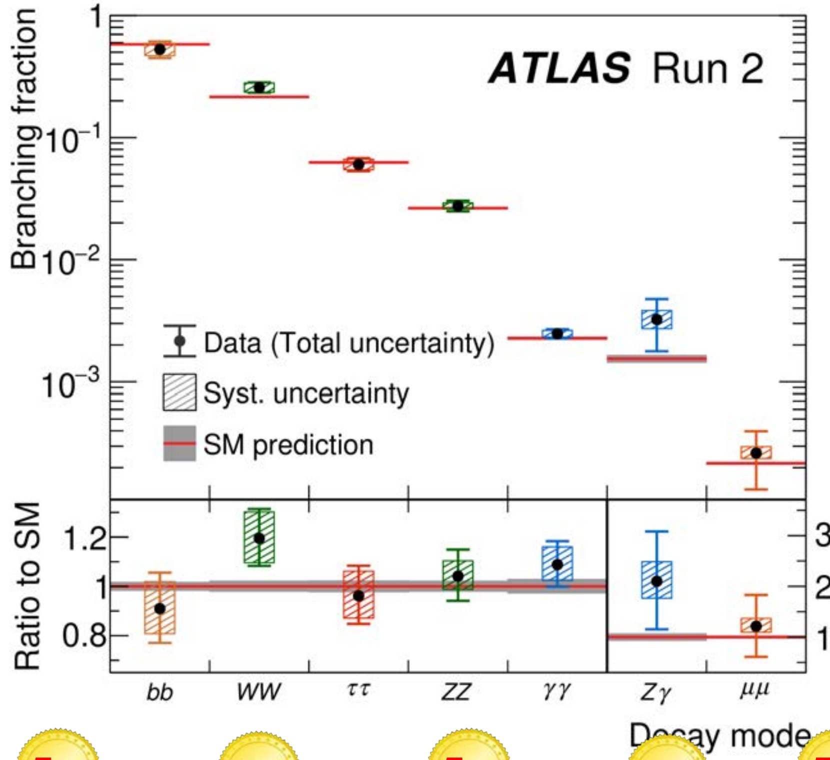




Higgs combined Results ~Production/Decay~

- Main Production channels and decay modes are already observed in Run1 and Run2 data





Start accessing rare production and decay mode

ggF	VBF	WH	ZH	ttH	tH
5σ	5σ	5σ	5σ	5σ	
7%	13%	23%	22%	24%	~70%

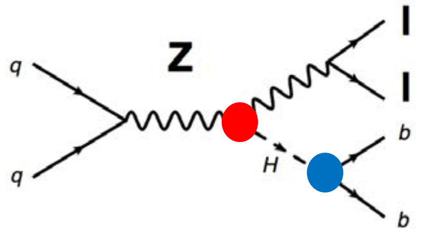
H→bb	H→WW	H→ττ	H→ZZ	H→γγ	H→Zγ	H→μμ
5σ	5σ	5σ	5σ	5σ		
15%	12%	12%	11%	10%	~100%	~60%

No any significant deviation from SM (10-20% precision for main channels)

Higgs combined results ~Coupling~

- Measured couplings between Higgs boson and SM particles

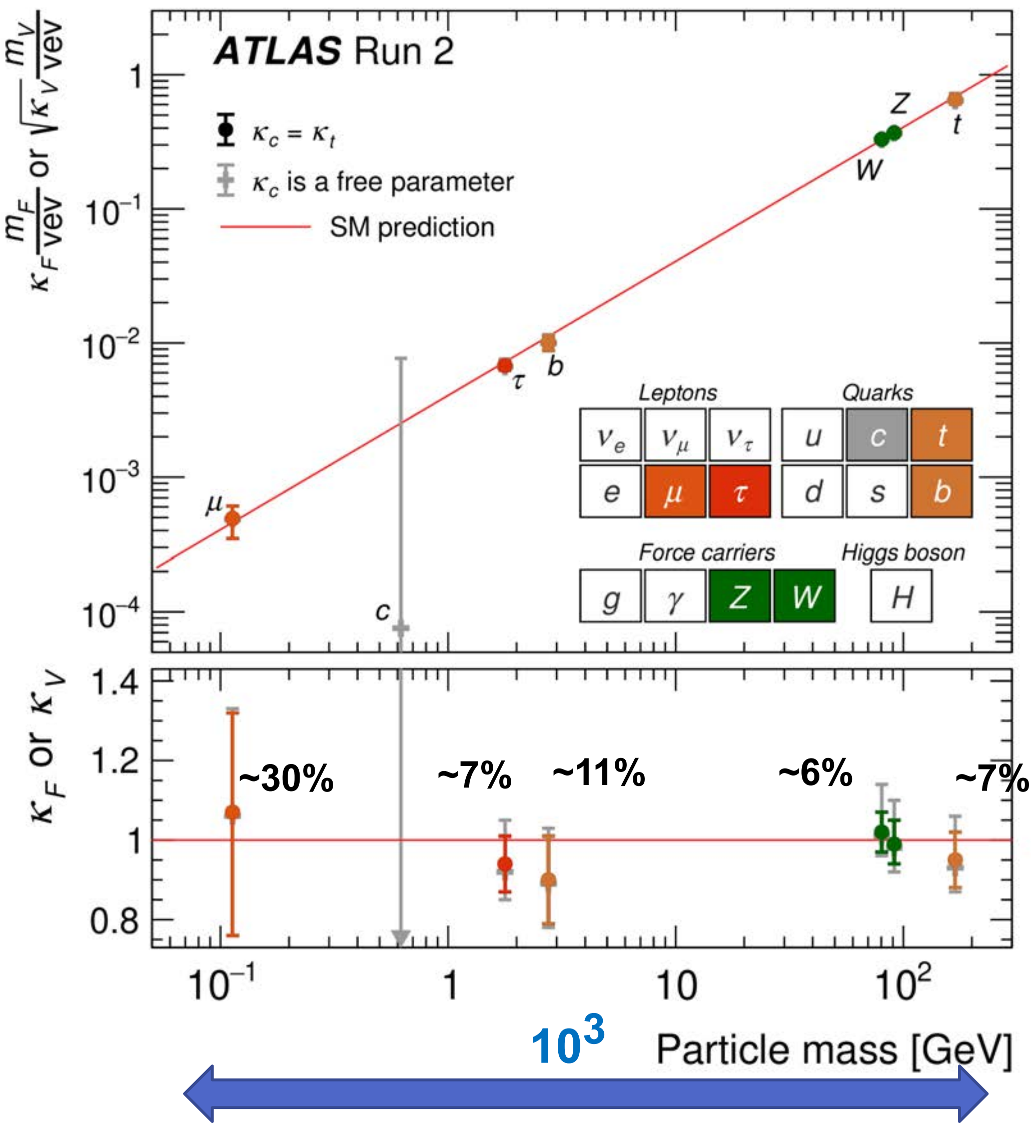
κ-framework: $\kappa = g_x^{measure} / g_x^{SM}$



$$\sigma(pp \to VH) \cdot BR(H \to bb) = \frac{k_V^2 \cdot k_b^2}{k_H^2} \sigma_{SM} \cdot BR_{SM}$$

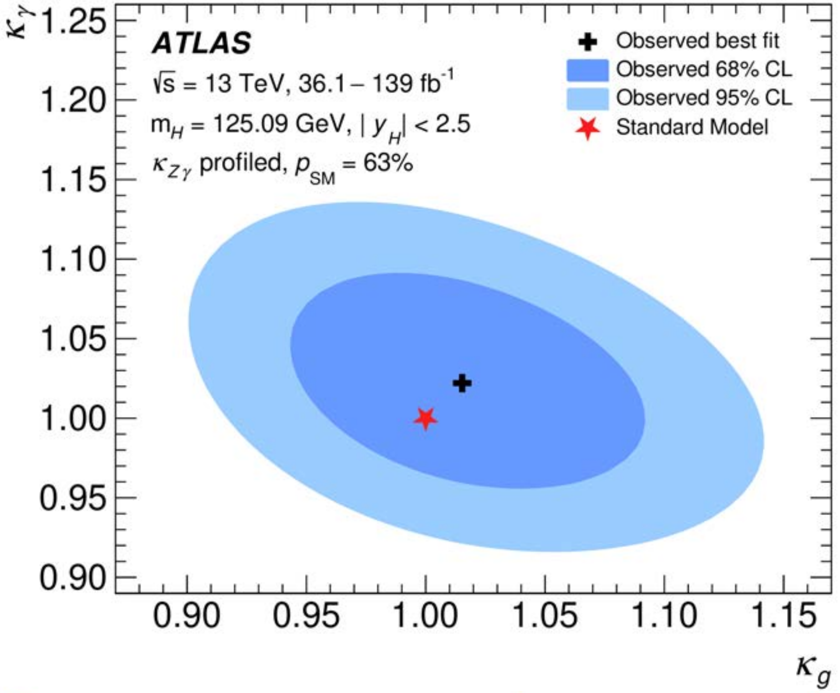
- Coupling modifier κ_t, κ_b, κ_τ, κ_μ, κ_W, κ_Z, (k_c) (measured coupling normalized to SM)
- Precision is 7-11% for top, W/Z, bottom, τ, ~30% for μ
  - Yukawa coupling works well in 10^3 different scale (O(100 MeV) ~ O(100 GeV)!!
  - Higgs boson builds generation of quark and lepton

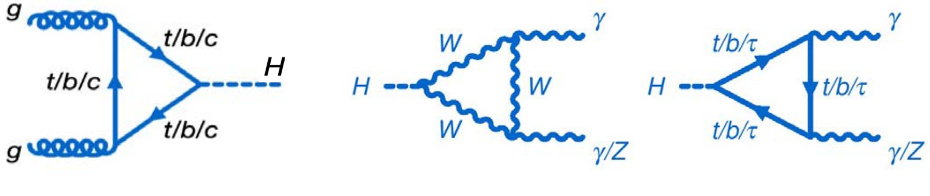
$$Y_\mu \ll Y_\tau, \; Y_c < Y_b \ll Y_t$$

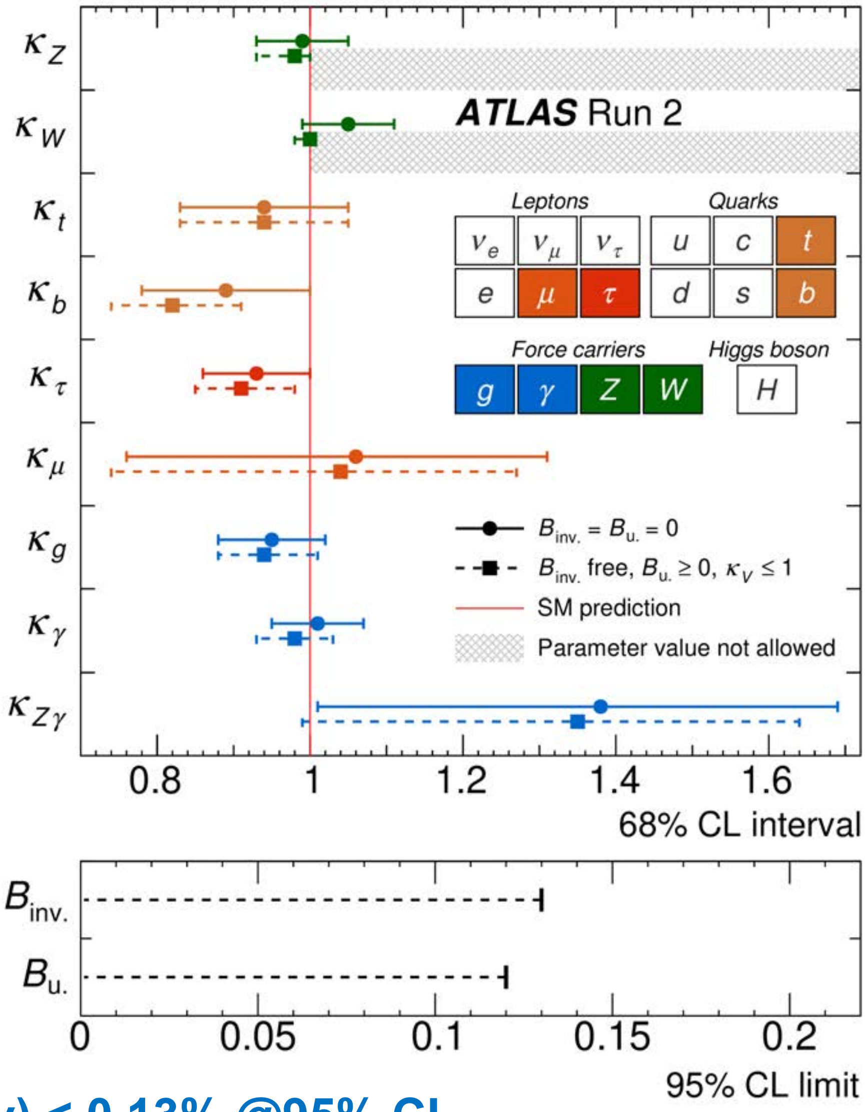


Higgs combined results ~Coupling~

- Measured effective photon, gluon couplings as free parameters (loop diagram)



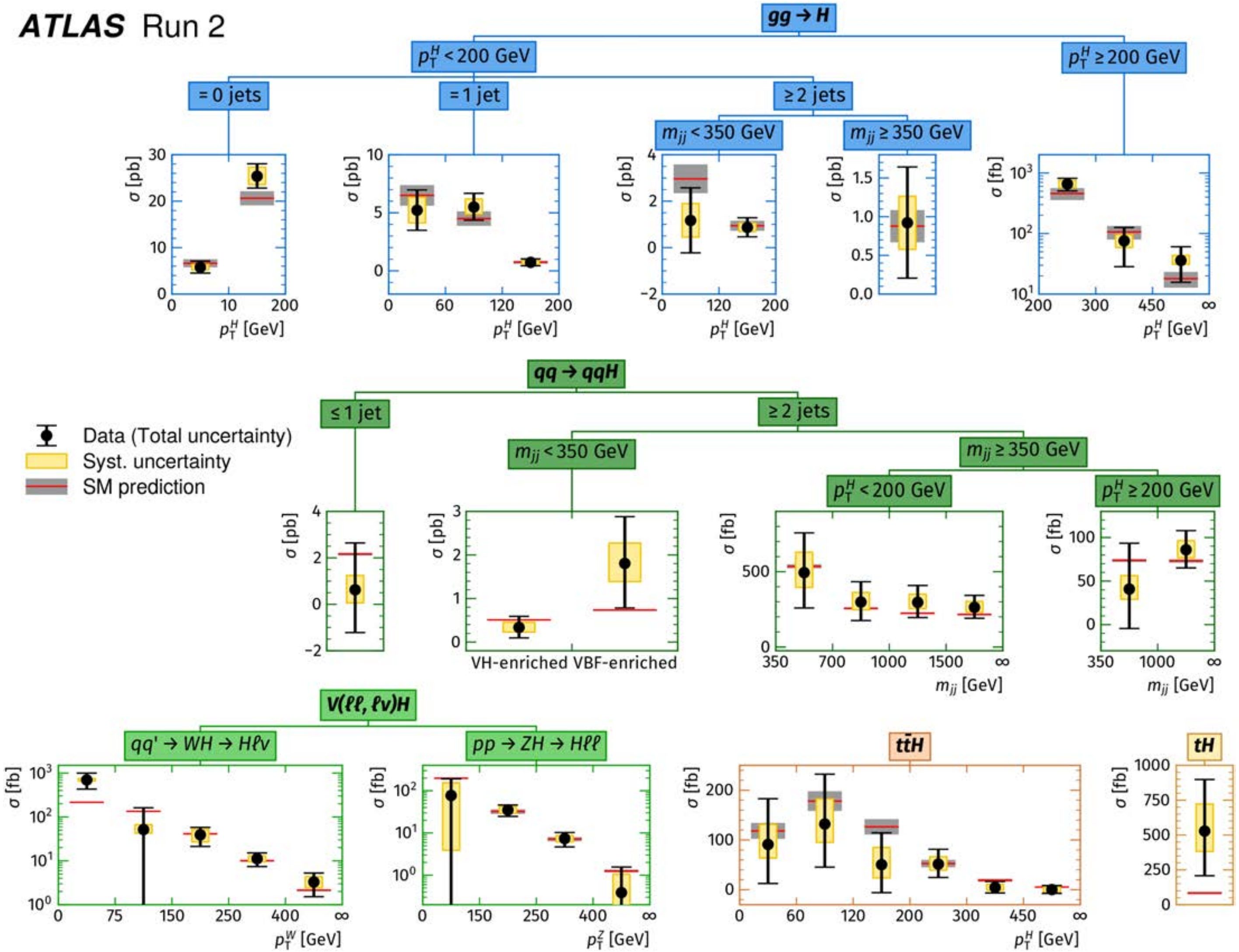


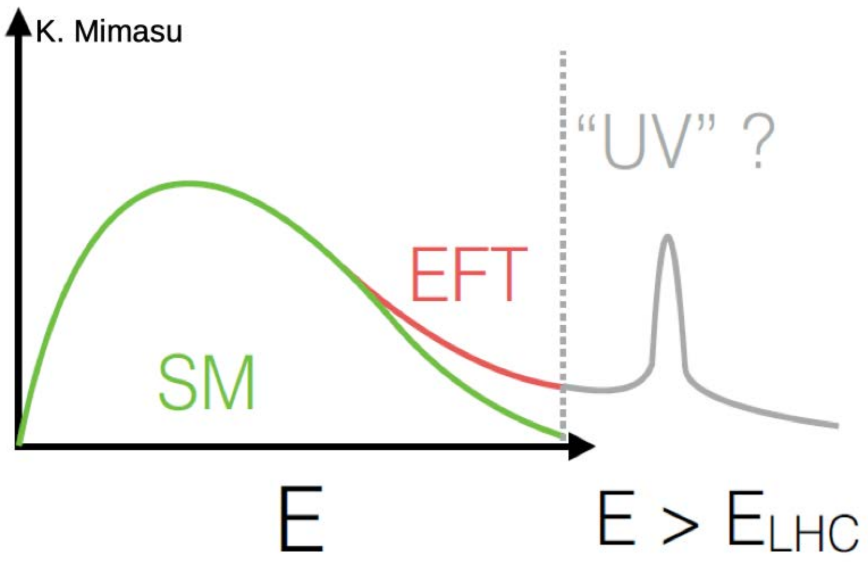


BR(H→inv) < 0.13% @95% CL

Cross Section Measurement

- Inclusive measurement
  → differential measurement





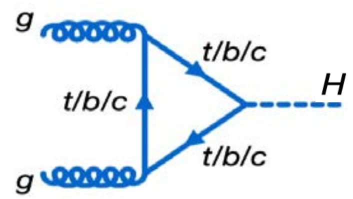
In high statistics Run2 data, Differential cross section corner of phase space (high-p_T^H)

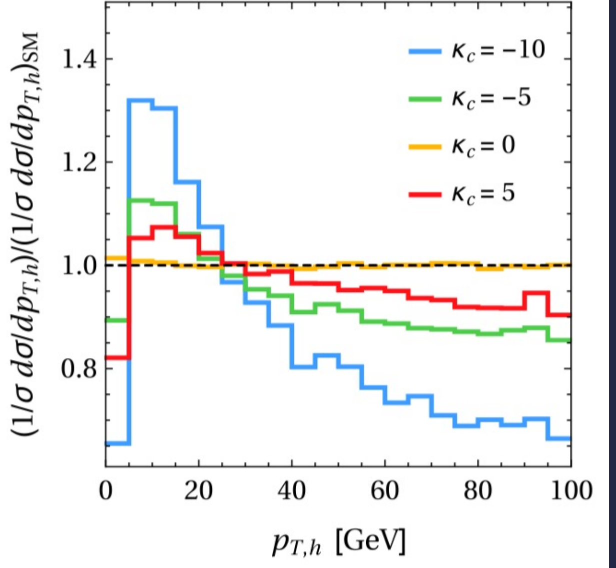
➔ Sensitive to BSM (even higher energy scale than LHC)

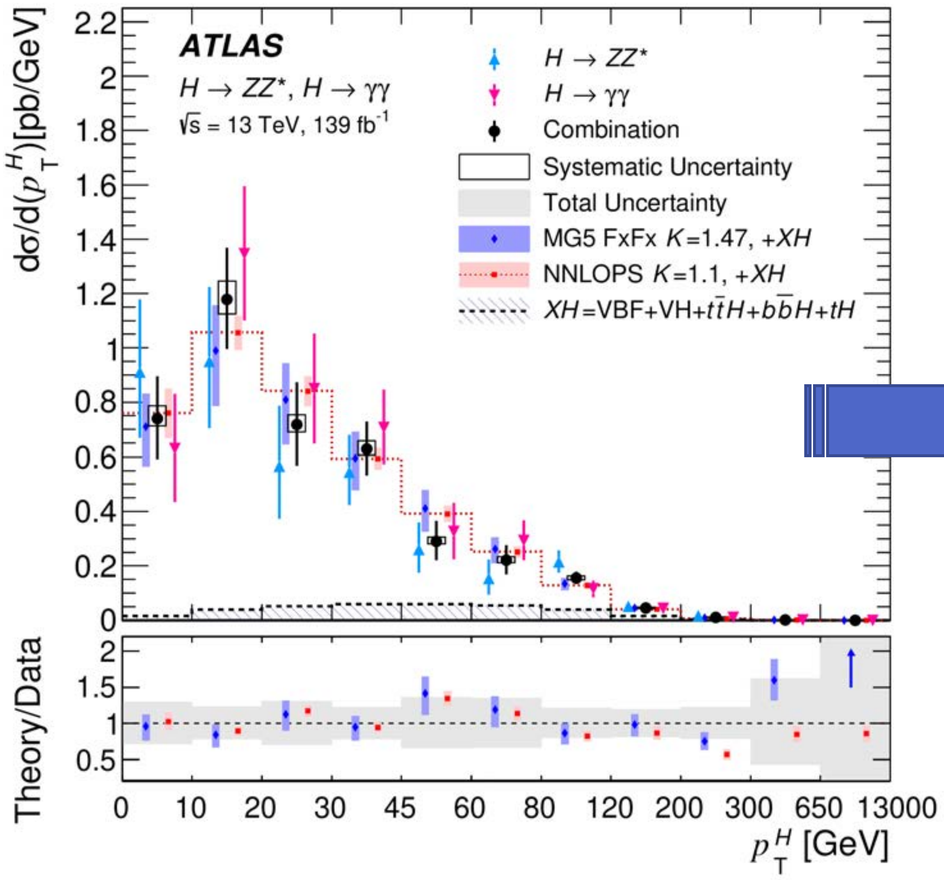
➔ Effective field theory may reveal BSM model if observe deviation from SM

Cross Section Measurement

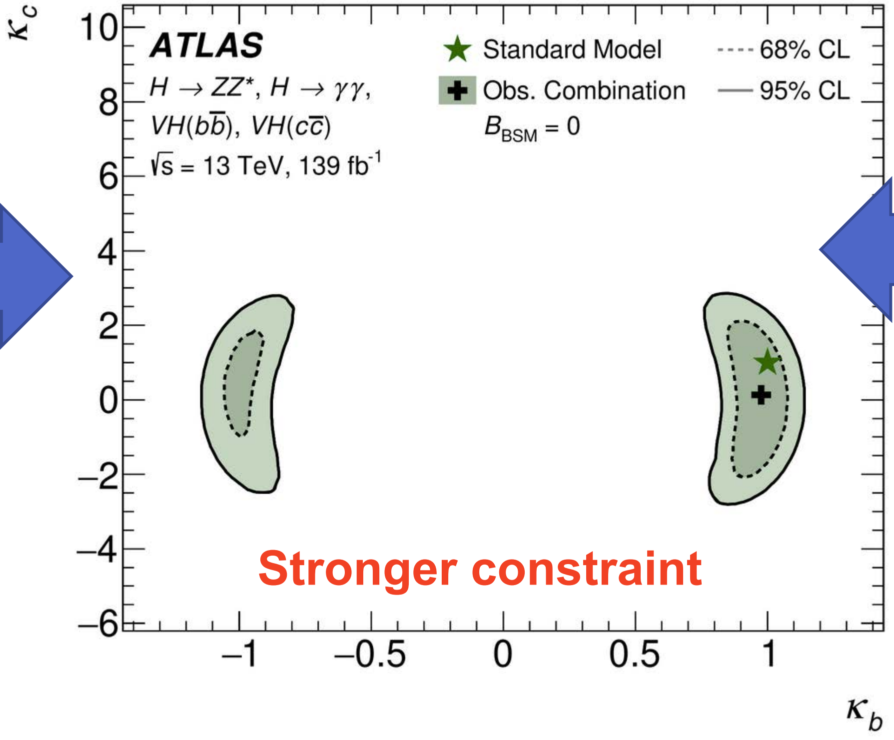
- Differential cross section measurement in H→γγ, H→ZZ→4l
- gluon fusion p_T^H shape is sensitive to κ_c, κ_b
  ➔ Constrain them



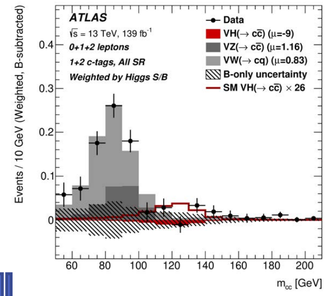


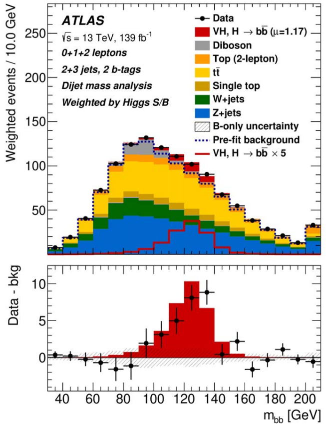


Combine direct VHbb/cc and indirect diff Xsec measurement



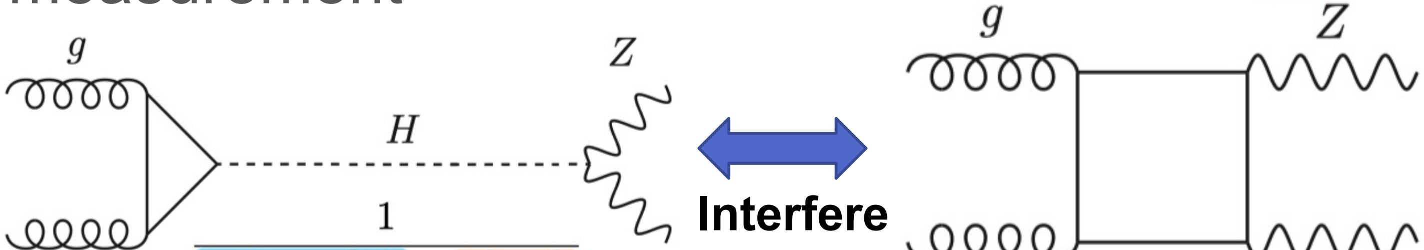
Stronger constraint





Higgs Width measurement

- Higgs boson natural width : Γ_H^{SM} ~4.07 MeV
  - impossible to measure by direct measurement!
- Measure Higgs width indirectly from on-shell/off-shell measurement

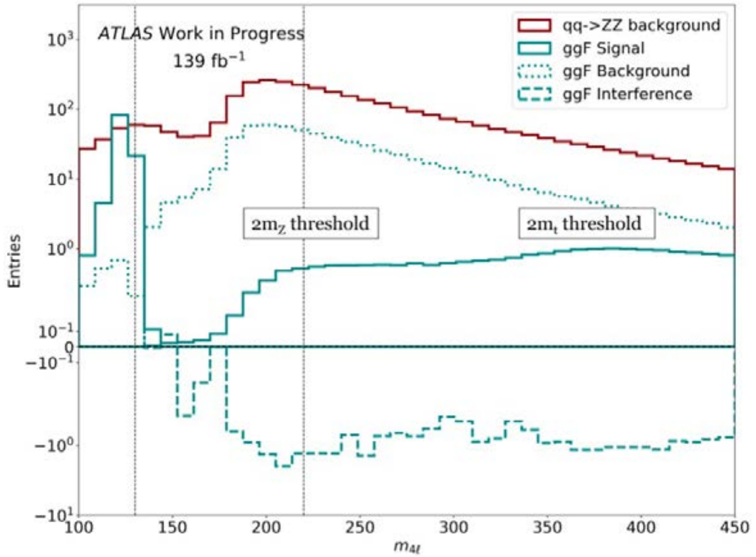


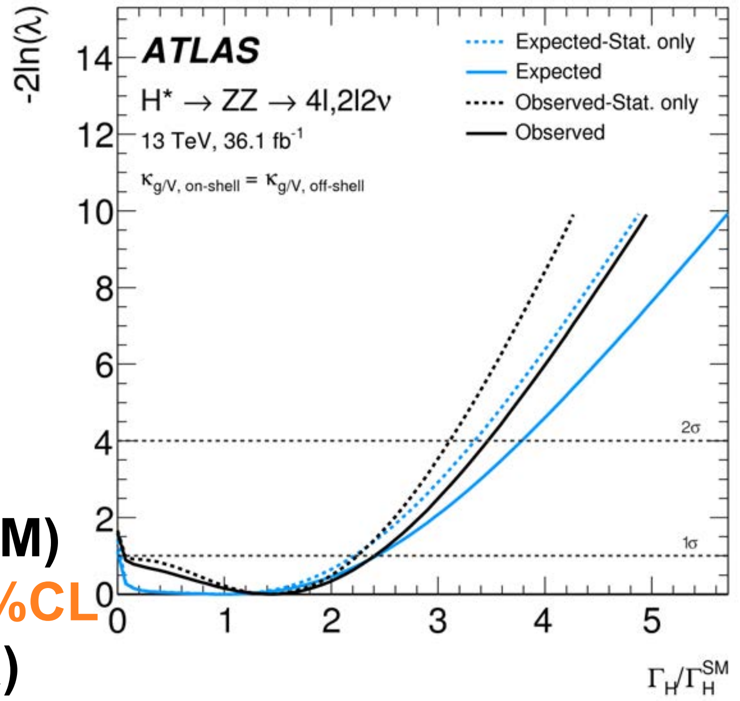
$$\frac{1}{(m^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}$$

$$\mu_{on-shell} = \mu_{gg} \times \frac{BR(H \to ZZ)}{BR_{SM}(H \to ZZ)} = \mu_{gg}\mu_{ZZ}\frac{\Gamma_H^{SM}}{\Gamma_H}$$

$$\mu_{off-shell} = \mu_{gg}\mu_{ZZ}$$

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





off-shell upper limit 3.4×SM(3.8×SM)

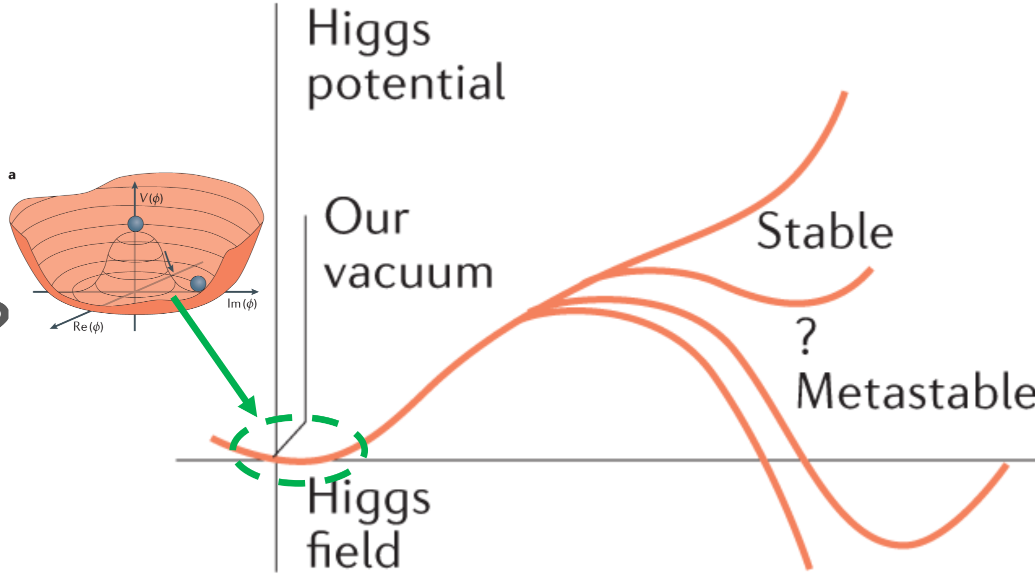
➔ Γ_H < 14.4 (15.2 exp.) MeV @ 95%CL

(to be updated with full Run2 data)

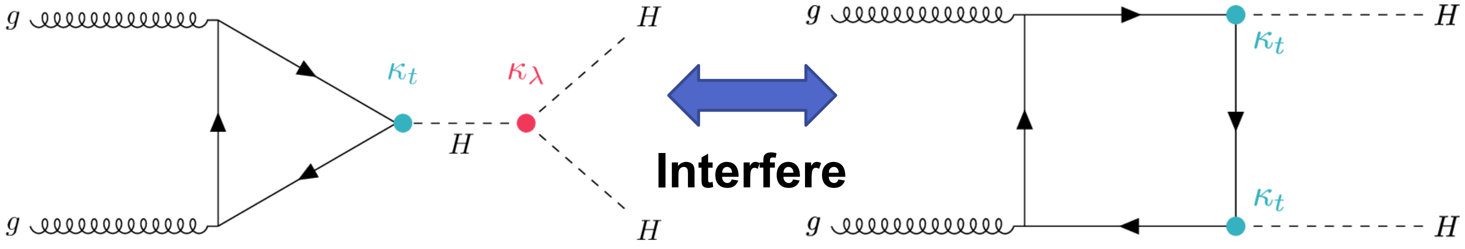
Higgs Self-coupling

- **Is Higgs potential shape really SM-like?**
- **What's the mechanism of EW Phase transition?**

➔ Still remaining mystery in Higgs properties
➔ Anomaly in the Higgs self-coupling?



- Need to observe Higgs pair production to measure Higgs self-coupling(λ) and understand Higgs potential

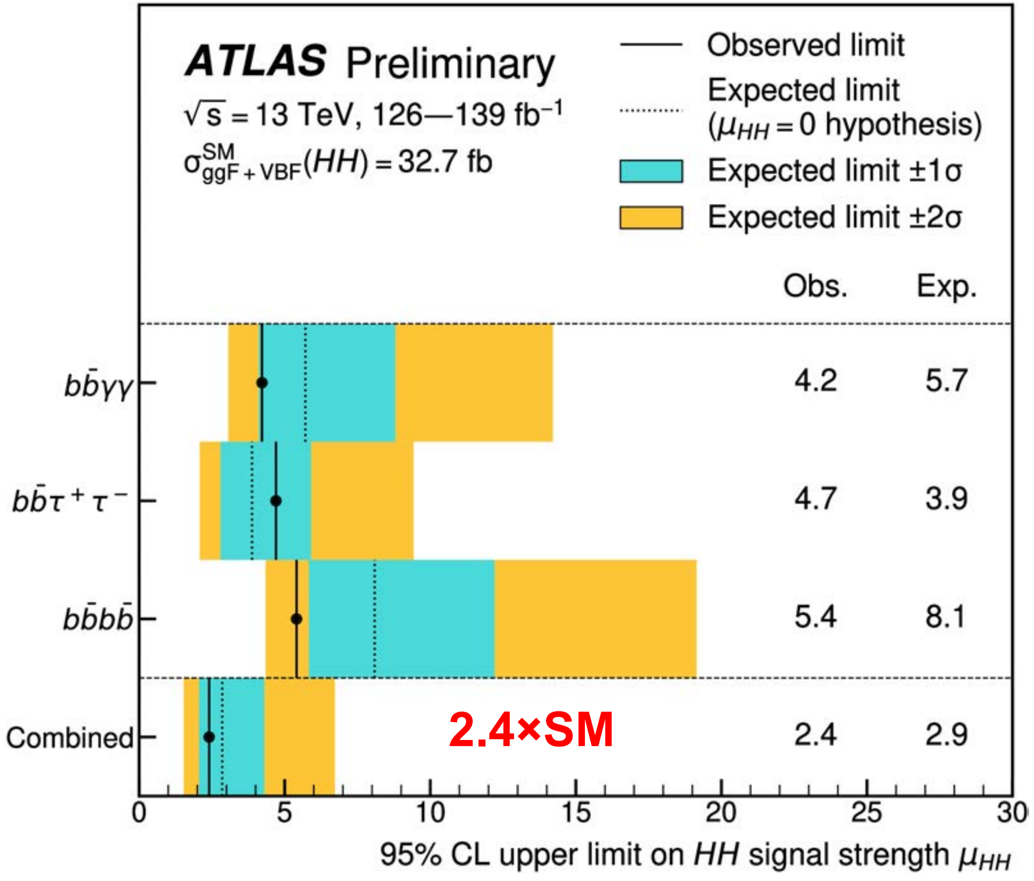


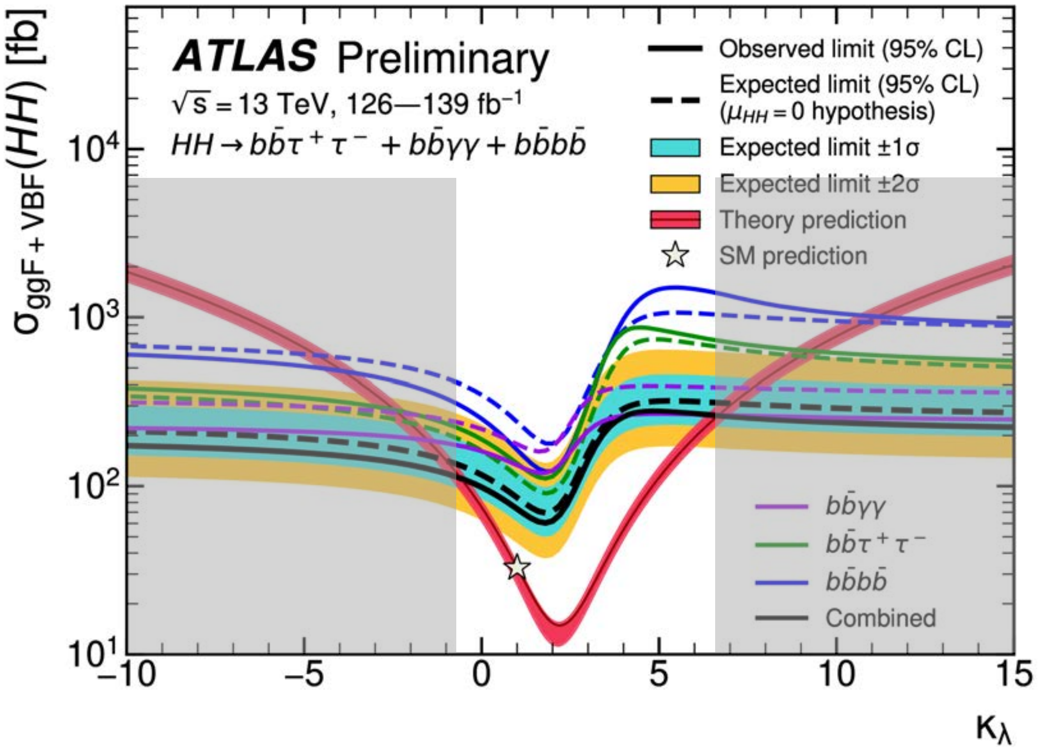
- DiHiggs production cross section is ~31fb at 13 TeV (1000 times smaller than single Higgs production)
- 4b, 2b2τ, 2b2γ final states are sensitive

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Higgs Pair Production Search

- At the beginning of LHC, we thought the observation of Higgs pair production is impossible in LHC (even HL-LHC)
- Many improvements on the analysis (b-tagging algorithm and multi-variate analysis using machine learning) ➔ Not a dream to observe Higgs pair production in Run3!!





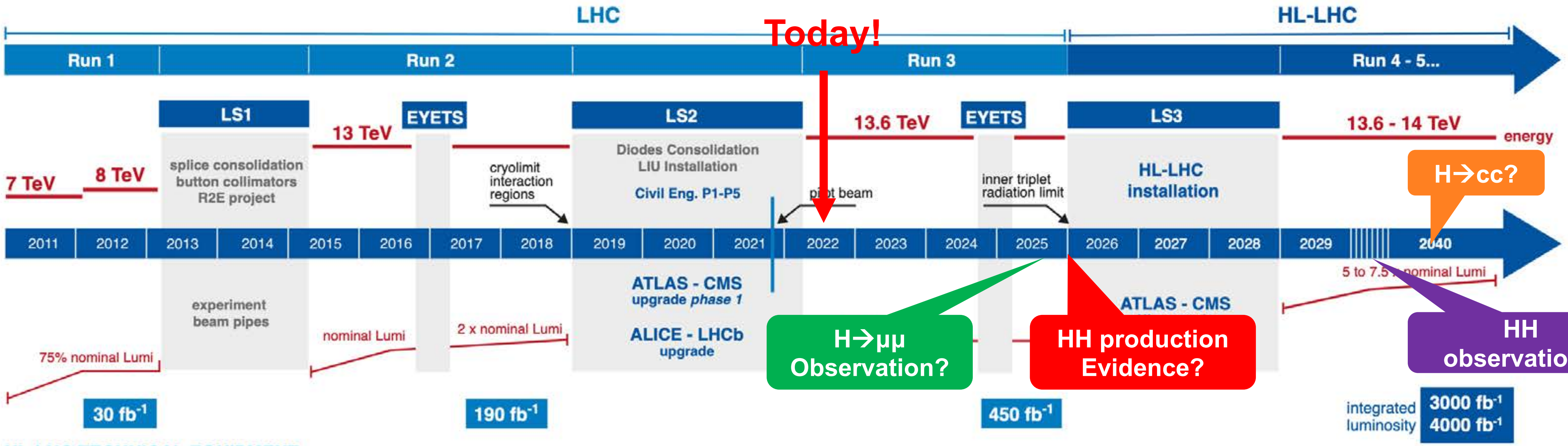
HH combination: $-0.6 < \kappa_\lambda < 6.6$ @ 95% CL

HH+H combination: $-0.4 < \kappa_\lambda < 6.3$ @ 95% CL

Summary and Future

- After Higgs boson discovery in 2012, ATLAS has measured the Higgs boson properties as precisely as possible in various ways
  - **Major production and decay modes are observed in Run1+2 data**
  - **Established the Higgs boson coupling to 3rd generation fermion**
- There are many many interesting Higgs measurements can't show today

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Recent_Results



We analyzed only 5% data of total data!! Higgs physics may open BSM door!!

Backup

Tevatron Flying?

arXiv.org > hep-ex > arXiv:1207.0449

Search or Article-id

High Energy Physics – Experiment

Updated Combination of CDF and D0 Searches for Standard Model Higgs Boson Production with up to 10.0 fb-1 of Data

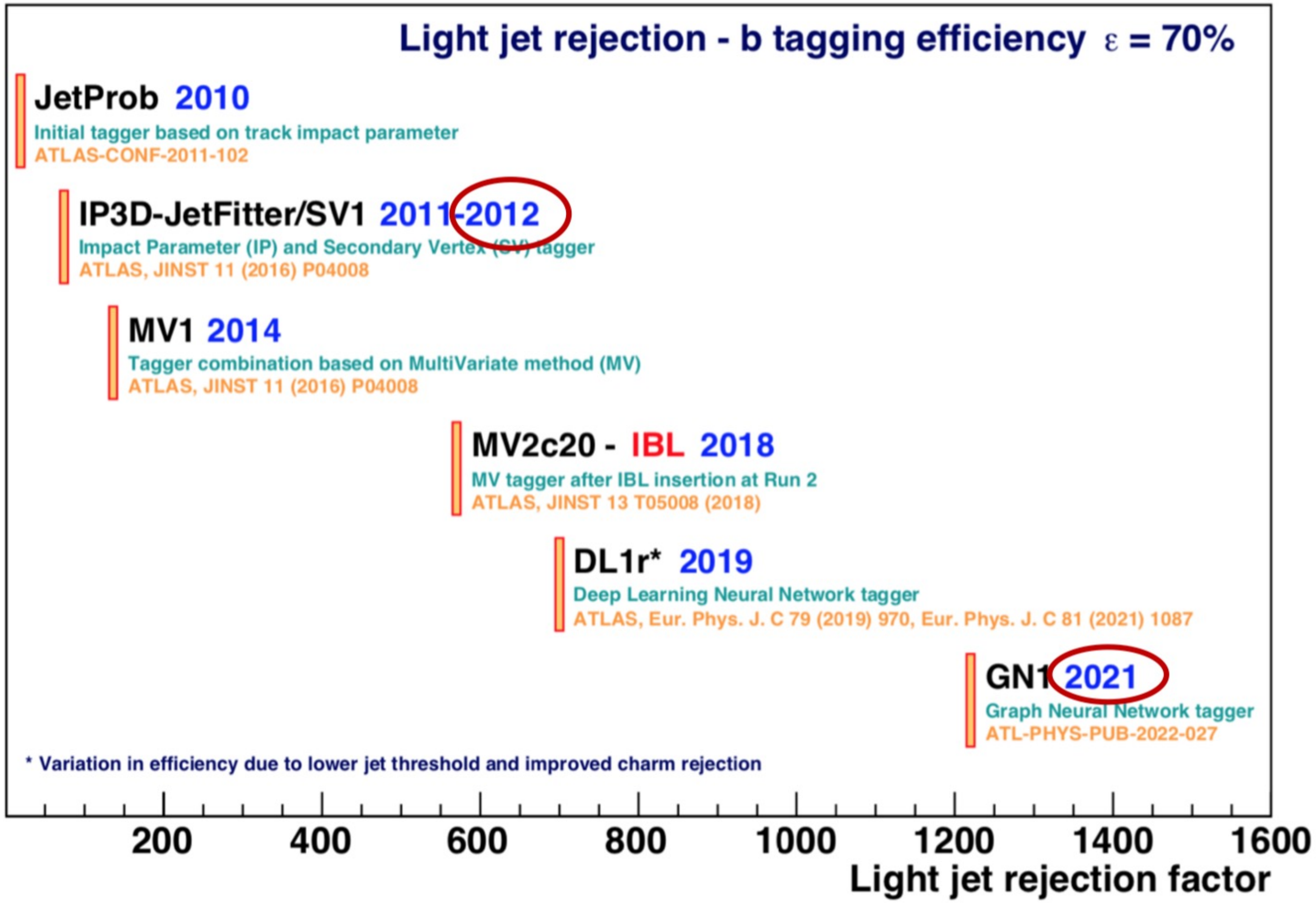
The CDF Collaboration, the D0 Collaboration, the Tevatron New Physics, Higgs Working Group

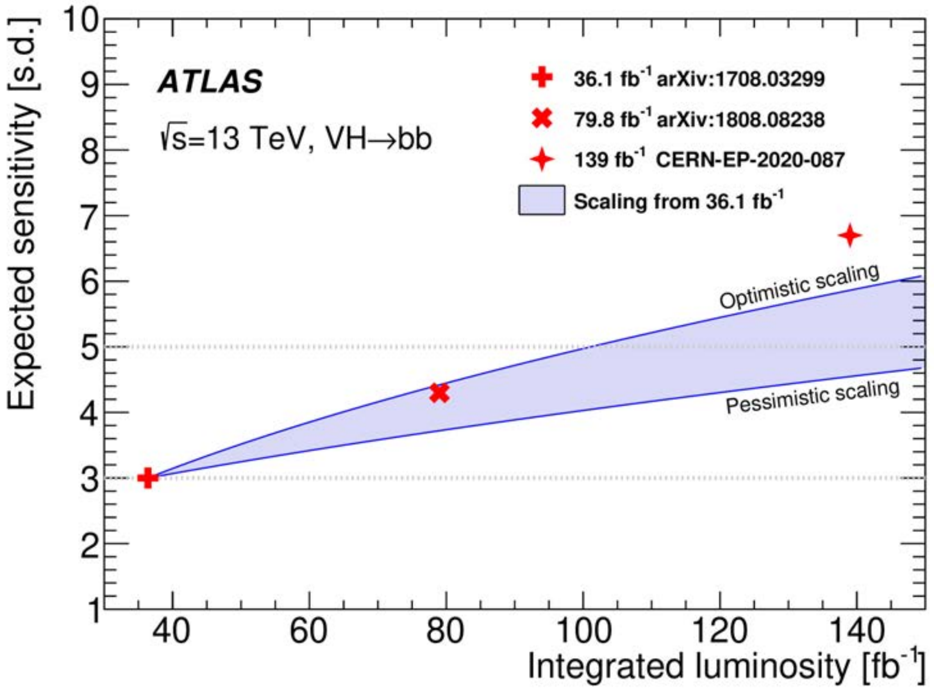
(Submitted on 2 Jul 2012 (v1), last revised 3 Jul 2012 (this version, v2))

We combine results from the CDF and D0 Collaborations on direct searches for the standard model (SM) Higgs boson (H) in ppbar collisions at the Fermilab Tevatron at sqrt(s)=1.96 TeV. Compared to the previous Tevatron Higgs boson search combination, more data have been included, additional channels have been incorporated, and some previously used channels have been reanalyzed to gain sensitivity. Searches are carried out for hypothesized Higgs boson masses between 100 and 200 GeV/c^2. With up to 10 fb-1 of luminosity analyzed, the 95% C.L. median expected upper limits on Higgs boson production are factors of 0.89, 1.08, and 0.48 times the values of the SM cross section for Higgs bosons of mass m_H=115 GeV/c^2, 125 GeV/c^2, and 165 GeV/c^2, respectively. In the absence of signal, we expect to exclude the regions 100<m_{H}<120 GeV/c^2 and 139<m_H<184 GeV/c^2. We exclude, at the 95% CL, two regions: 100<m_H<103 GeV/c^2, and 147<m_H<180 GeV/c^2. There is a significant excess of data events with respect to the background estimation in the mass range 115<m_H<140 GeV/c^2, which causes our observed limits to not be as stringent as expected. At m_H=120 GeV/c^2, the p-value for a background fluctuation to produce this excess is \sim1.5x10^-3, corresponding to a local significance of 3.0 standard deviations. The global significance for such an excess anywhere in the full mass range investigated is approximately 2.5 standard deviations. We also combine separately searches for H to bb and H to WW. We find that the excess is concentrated in the H to bb channel, appearing in the searches over a broad range of m_H. The maximum local significance of 3.2 standard deviations corresponds to a global significance of approximately 2.9 standard deviations. Our results in the H to WW channels are also consistent with the possible presence of a low-mass Higgs boson.

Comments:	Submitted to the Summer 2012 Conferences
Subjects:	**High Energy Physics – Experiment (hep-ex)**
Report number:	FERMILAB-CONF-12-318-E; CDF Note 10884; D0 Note 6348
Cite as:	arXiv:1207.0449 [hep-ex]
	(or arXiv:1207.0449v2 [hep-ex] for this version)

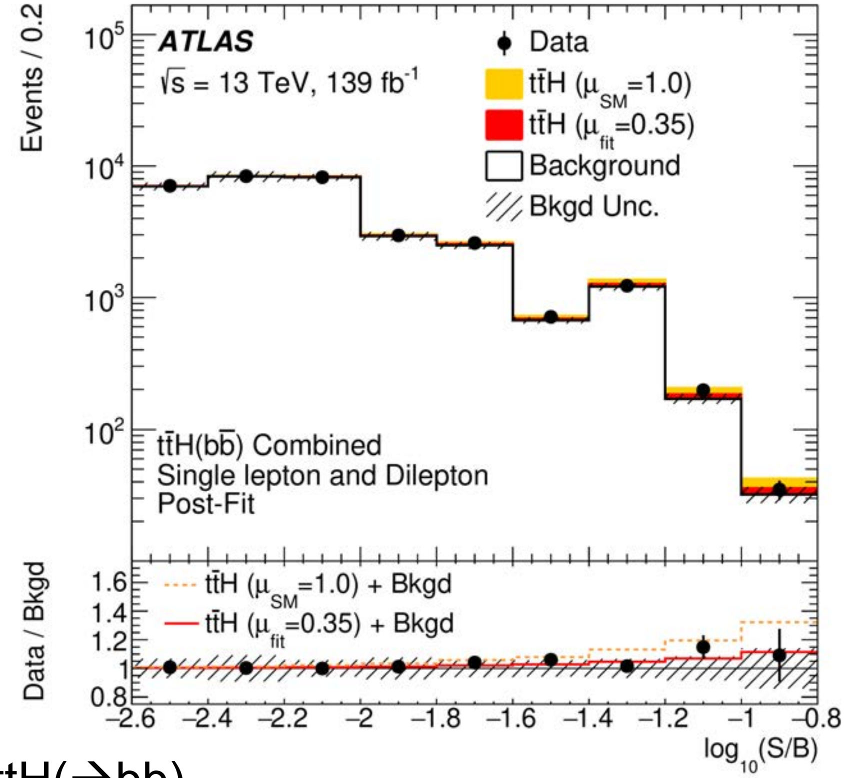
Improvement of analysis



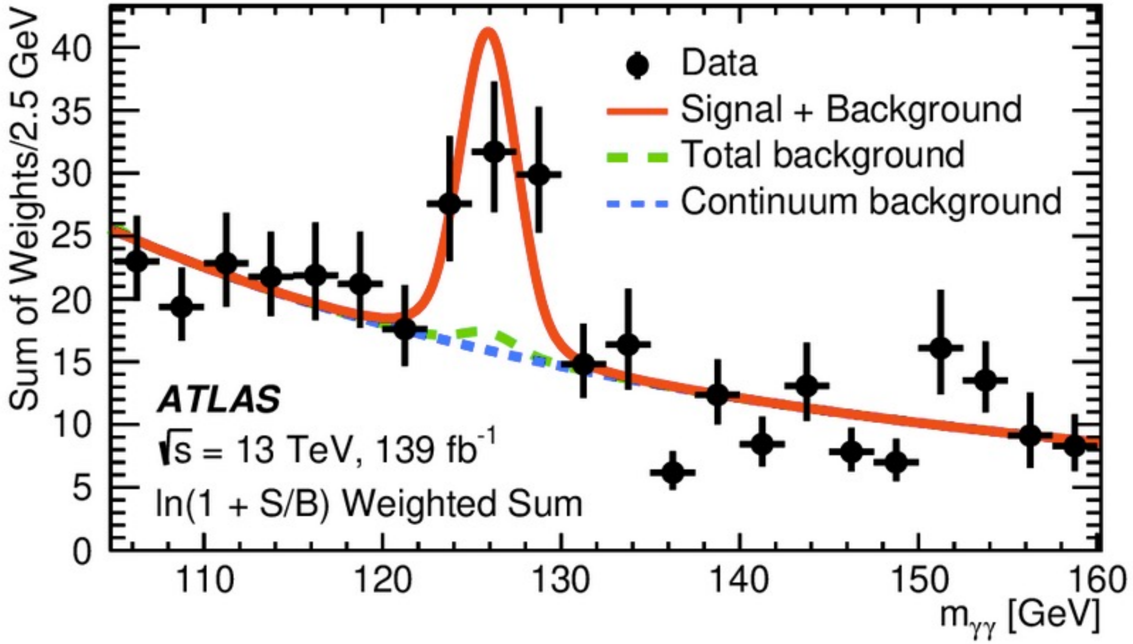


ttH Production

- Direct measurement of Higgs interaction with top quark
- ttH→γγ (cleanest channel)
- ttH→bb(High yield but difficult tt+bb background)
- ttH→WW/ZZ/ττ (relatively clean, but complicated final states)

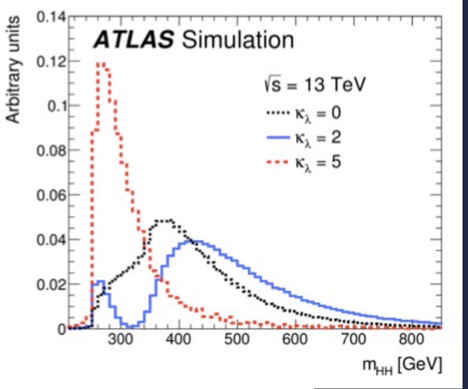


ttH(→bb)
Observed significance: 1.0σ(2.7σ exp.)
Signal strength $\mu = 0.35^{+0.36}_{-0.34}$

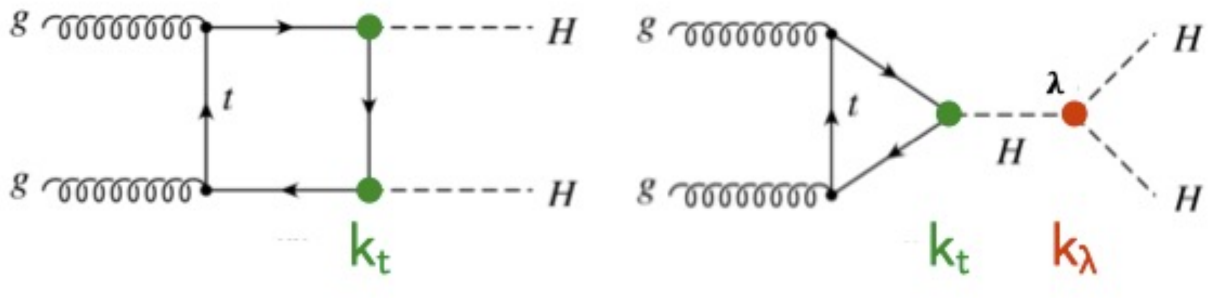


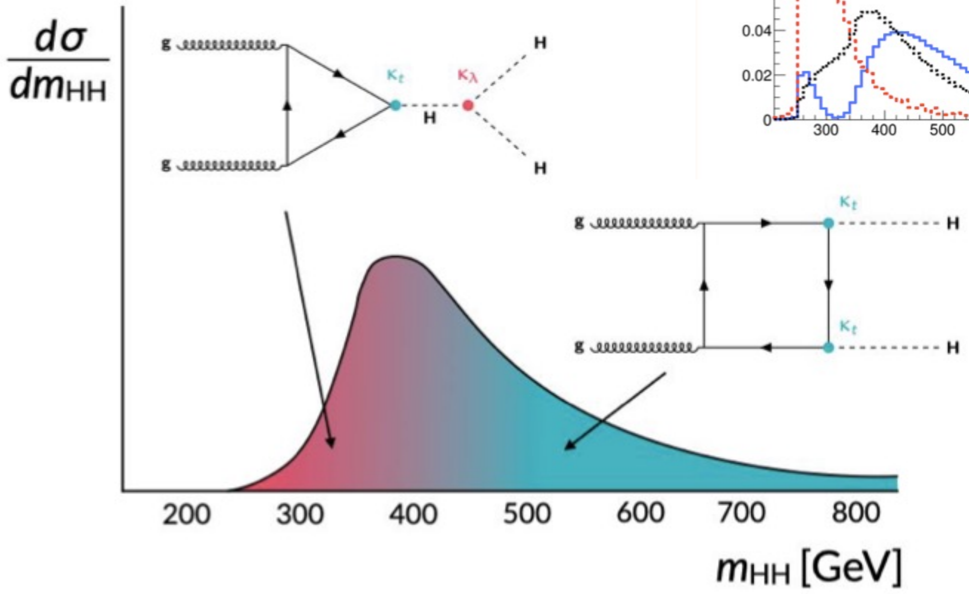
ttH(→γγ)
Observed significance: 5.2σ(4.4σ exp.)
Measured Cross-section
μ_{ttH}=1.43±0.33(stat)±0.21(syst)

Higgs pair production

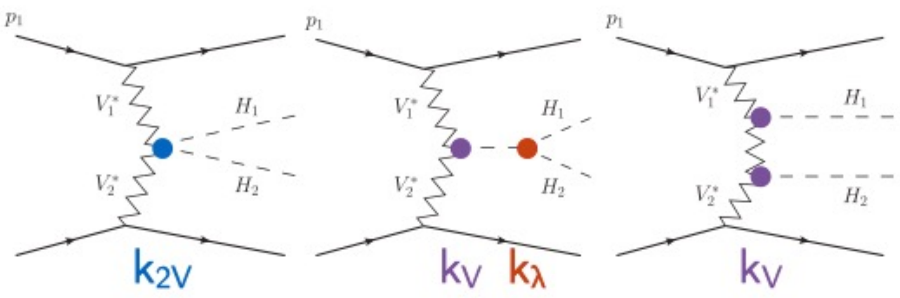


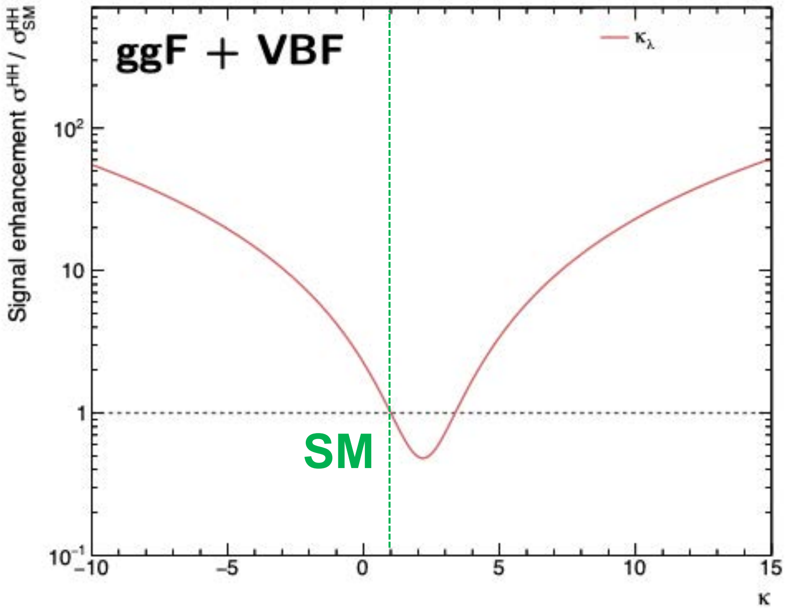
- σ(ggF→HH): 31.05fb





- σ(VBF→HH): 1.73fb



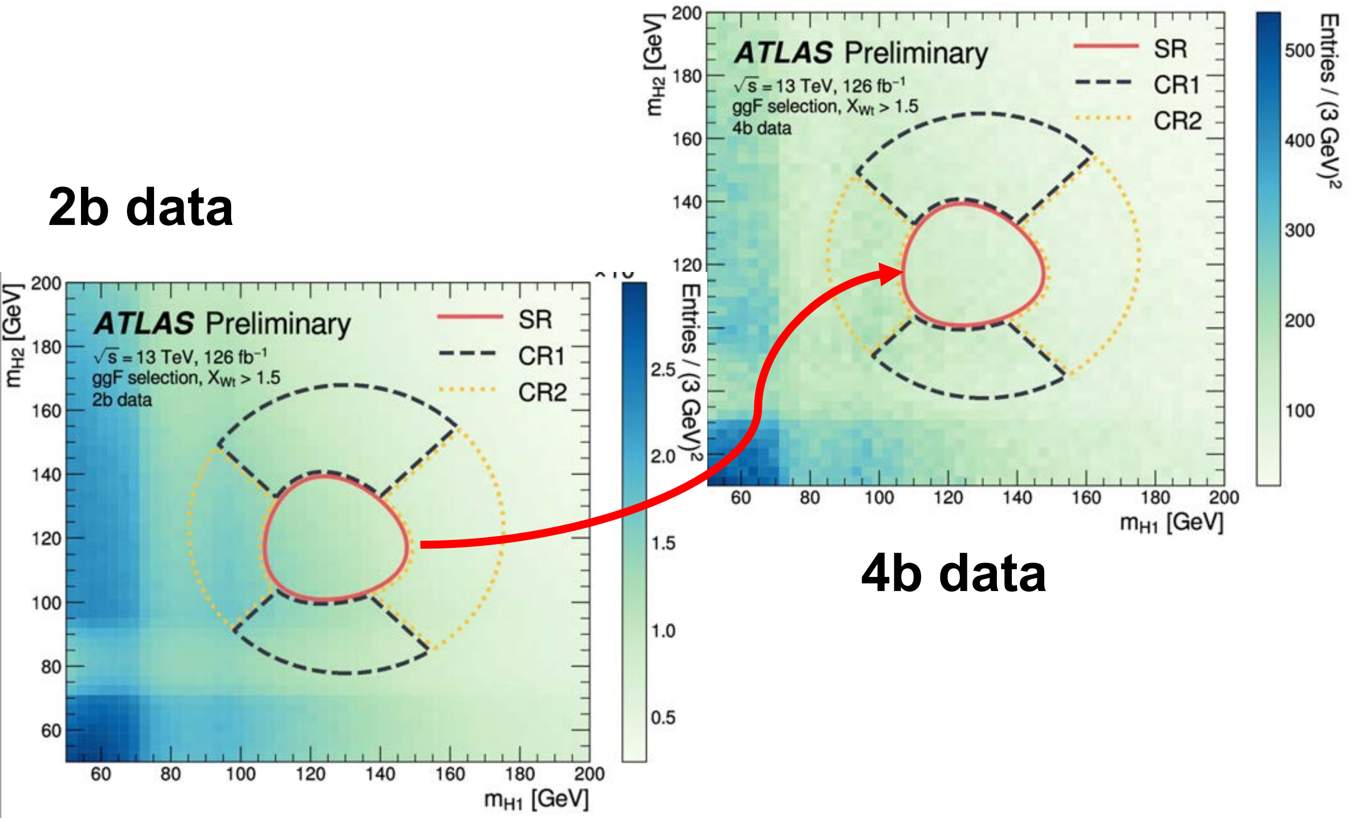


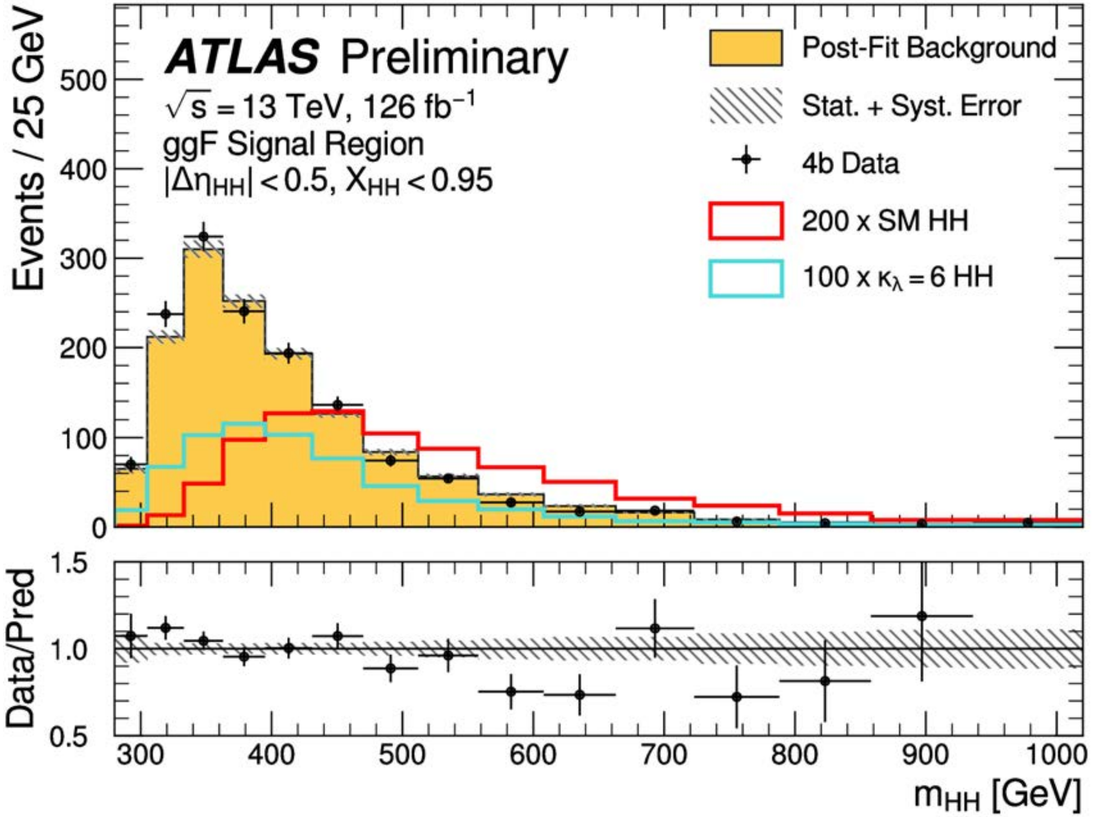
Cross section enhancement depends on κ_λ

Minimum at k_λ=2.45

HH→4b analysis

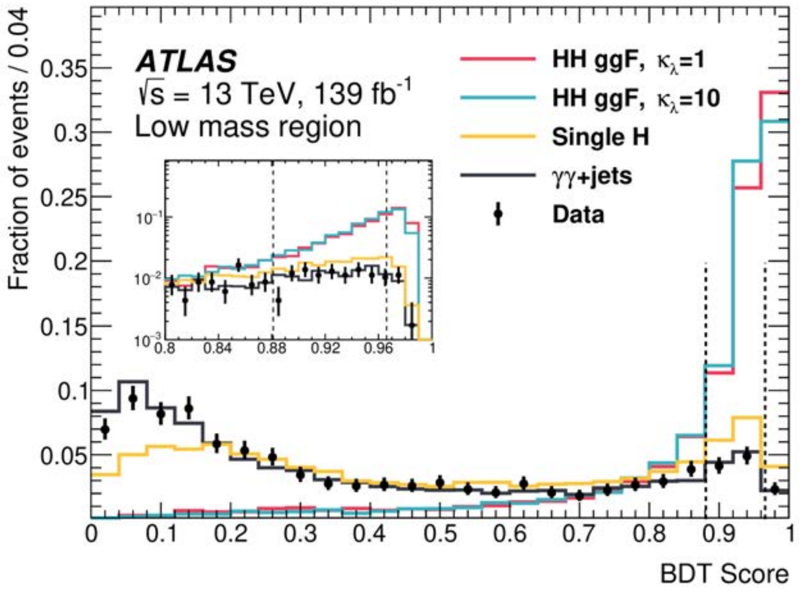
- Highest branching ratio BR(HH→4l) ~34%
- Background is QCD multi b-jets ➔ difficult to model in MC
- Extrapolate from 2b+2jet CR to 4b SR using reweighting factor estimated from NN in data-driven way

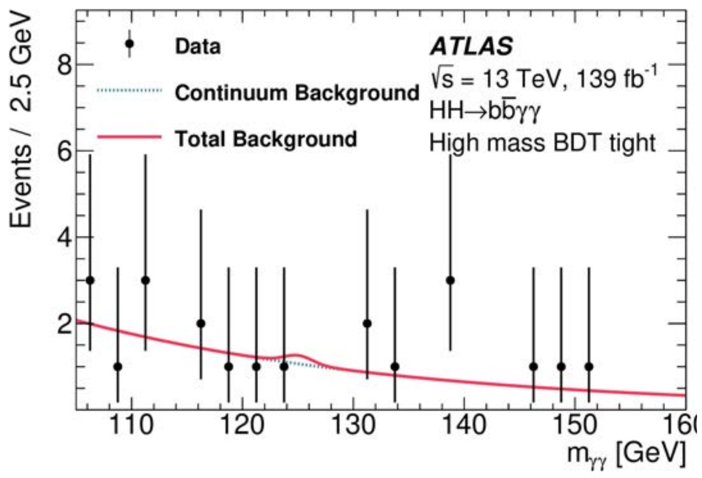


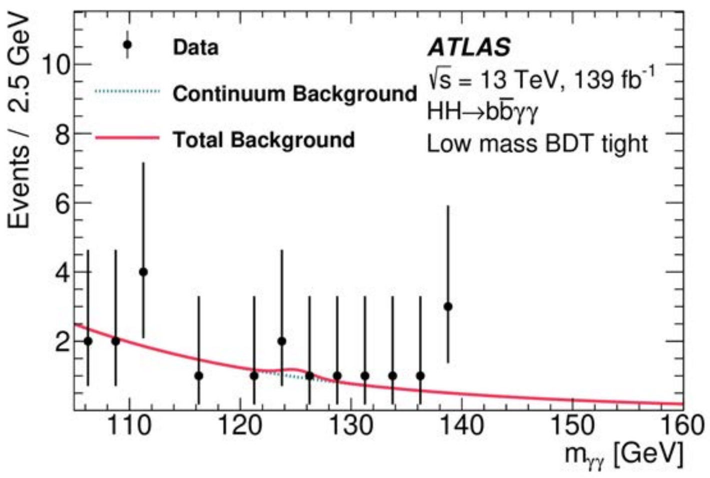


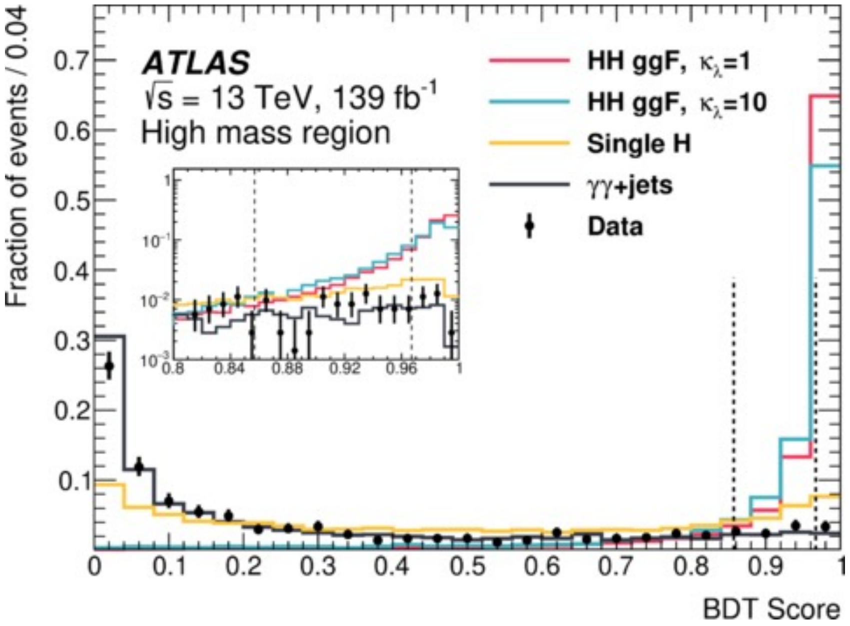
HH→2b2γ analysis

- Select diphoton and 2 b-jets
- Event categorization based on $m_{bb\gamma\gamma}^*$ and BDT score
  - $m_{bb\gamma\gamma}^* = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV
- $m_{\gamma\gamma}$ distribution is used as final discriminant







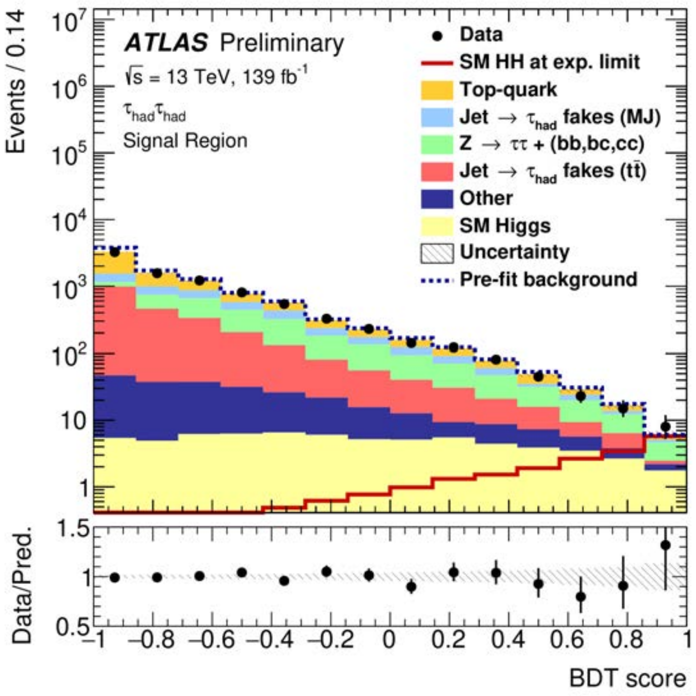


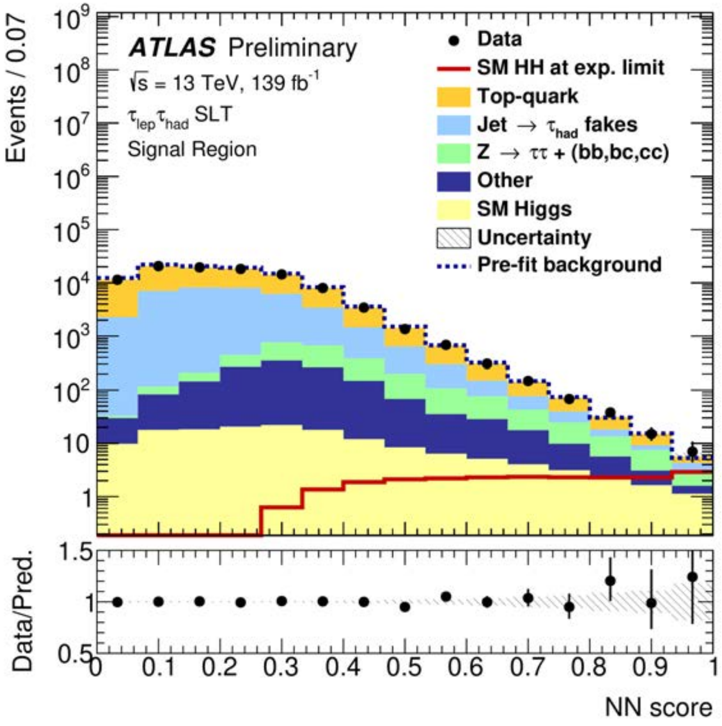
HH→2b2τ analysis

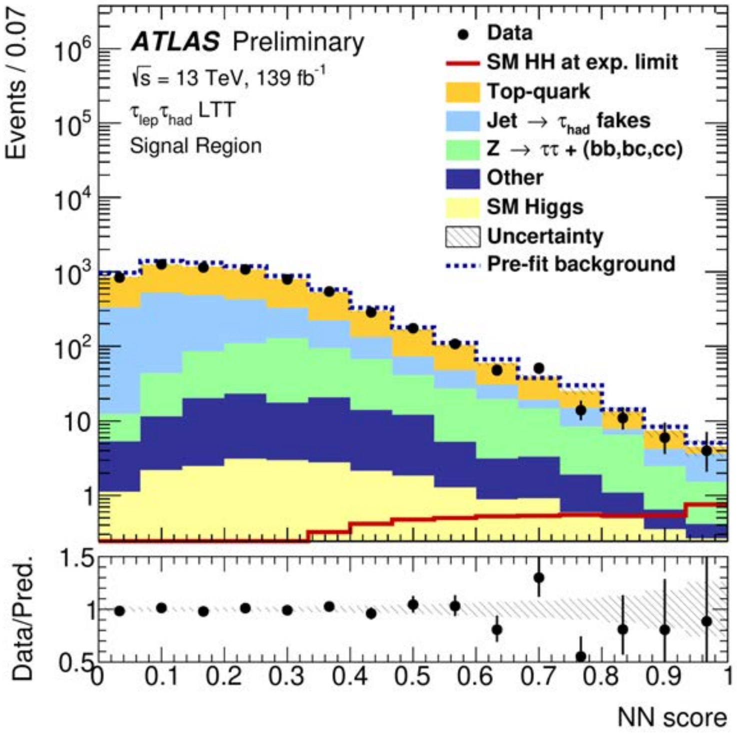
- Require 2τ and 2 b-jets
- $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channels are used
- Further subdivided by the trigger
- MVA scores are used as final discriminant

Category	$\tau_{had}\tau_{had}$		$\tau_{lep}\tau_{had}$	
Trigger	single τ_{had} triggers (STTs)	di-τ_{had} triggers (DTTs)	single-lepton triggers (SLTs)	lepton-plus-τ_{had} triggers (LTTs)
Region	$\tau_{had}\tau_{had}$		$\tau_{lep}\tau_{had}$ - SLT	$\tau_{lep}\tau_{had}$ - LTT

Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_T(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet p_T		✓	
m_T^W		✓	
E_T^{miss}		✓	
$\mathbf{p}_T^{miss}$ ϕ centrality		✓	
$\Delta\phi(\ell\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_T^{miss})$			✓
$\Delta\phi(\ell\tau, \mathbf{p}_T^{miss})$			✓
S_T			✓

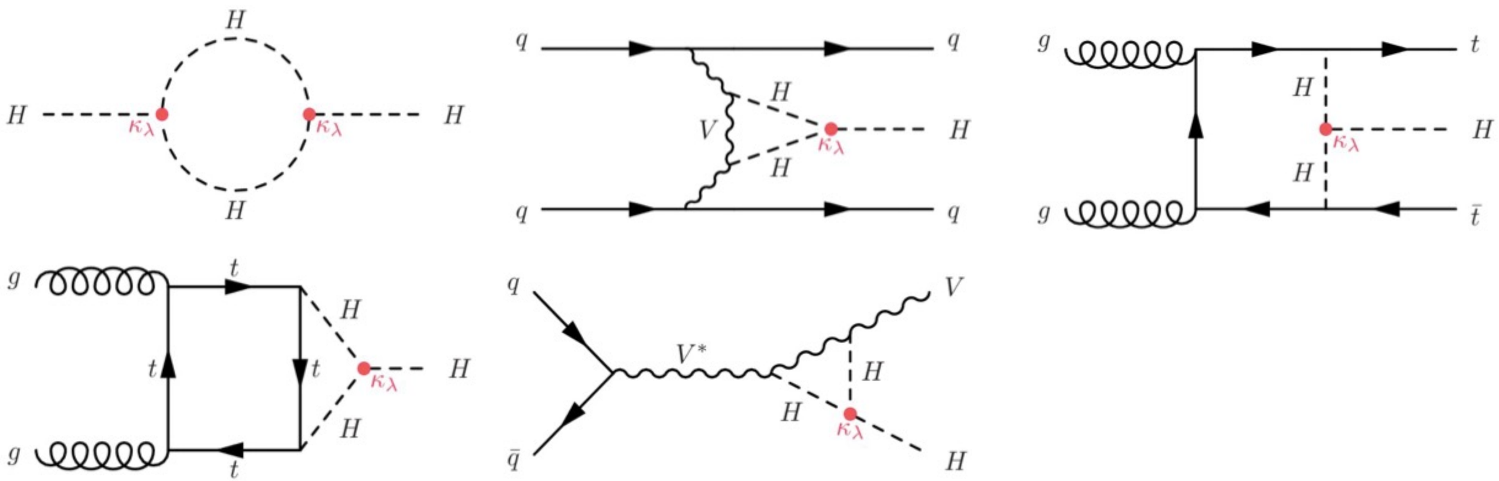


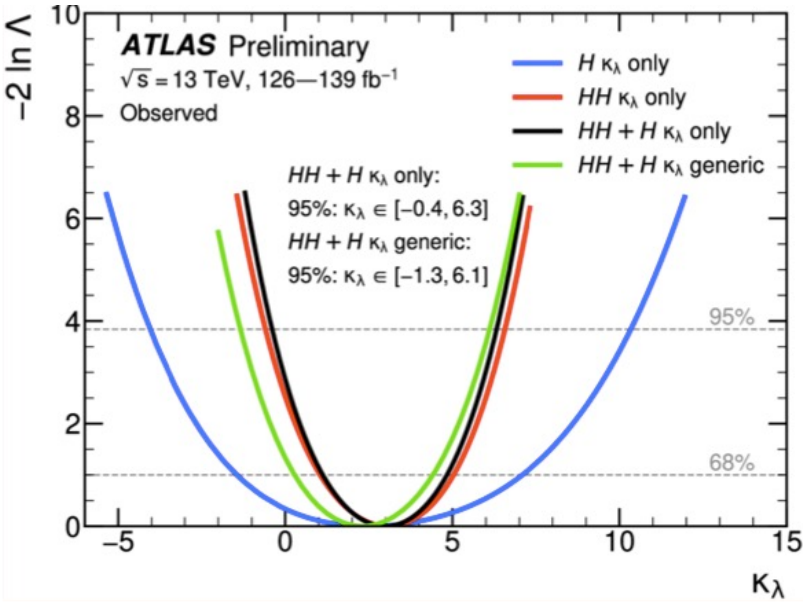


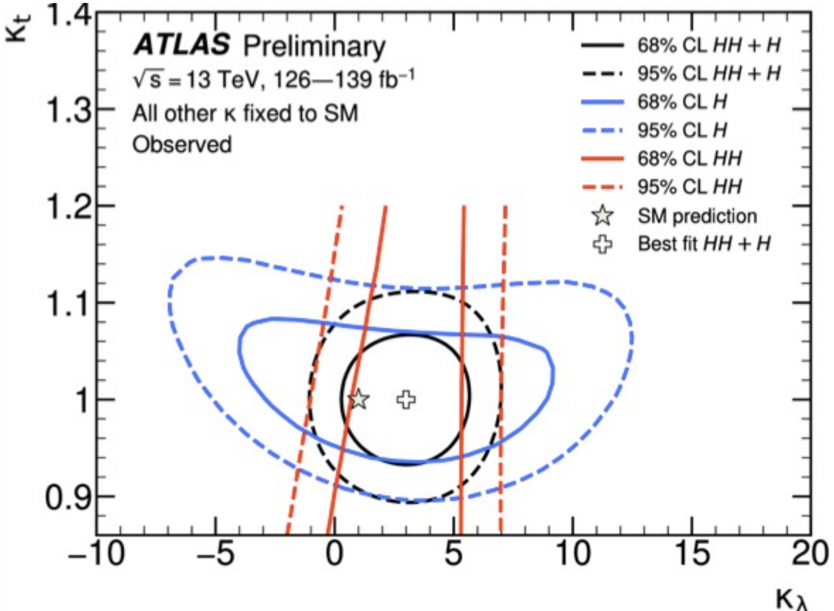


Single Higgs contribution

- Single Higgs production modes also have self-coupling contribution via NLO EW correction
- κ_λ dependence by a function of Higgs p_T
  - ttH has highest dependence
- Perform combined fit with single Higgs and HH analysis ➔ Possible to constrain other coupling parameters (κ_t) simultaneously







Comparison with CMS

- **ATLAS upper limit at 95% CL**
  - Observed < 2.4*SM
  - Expected < 2.9*SM
- **CMS upper limit at 95% CL**
  - Observed < 3.4*SM
  - Expected < 2.5*SM