The Precision Higgs Era and Beyond…

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PULVERTURM

My wife Betty

Our nephew:

Nagsen Chao (born Sept 2017)

In 2012, the Higgs Boson was like…..

……a newborn child

The world celebrated its arrival

- predicted in 1964
- serious experimental searches since 1998
- discovery in 2012

.....and now its 7 years old

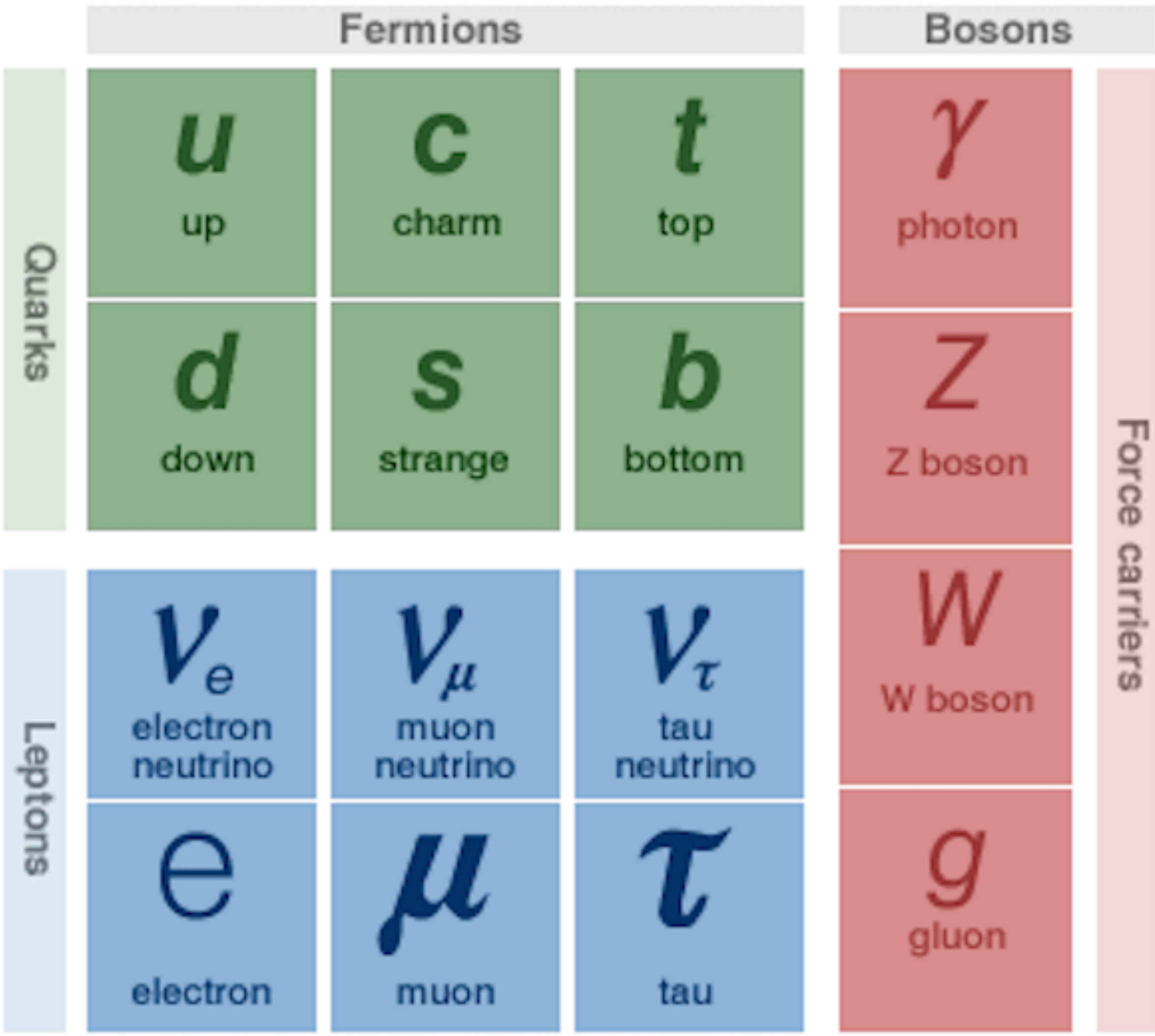
we know much more about the Higgs boson

- a "personality" has developed
- we know more and can do more with the Higgs boson than in 2012

We have already reached the ***"precision era"*** of Higgs physics

- precision mass measurements
- extensive coupling measurements
- quantum numbers (spin, CP)
- searches for rare decays
- measuring the self-coupling

The Standard Model of Particle Physics



Describes physics at the fundamental level

Matter particles

- quarks and leptons (3 generations)

Force carriers

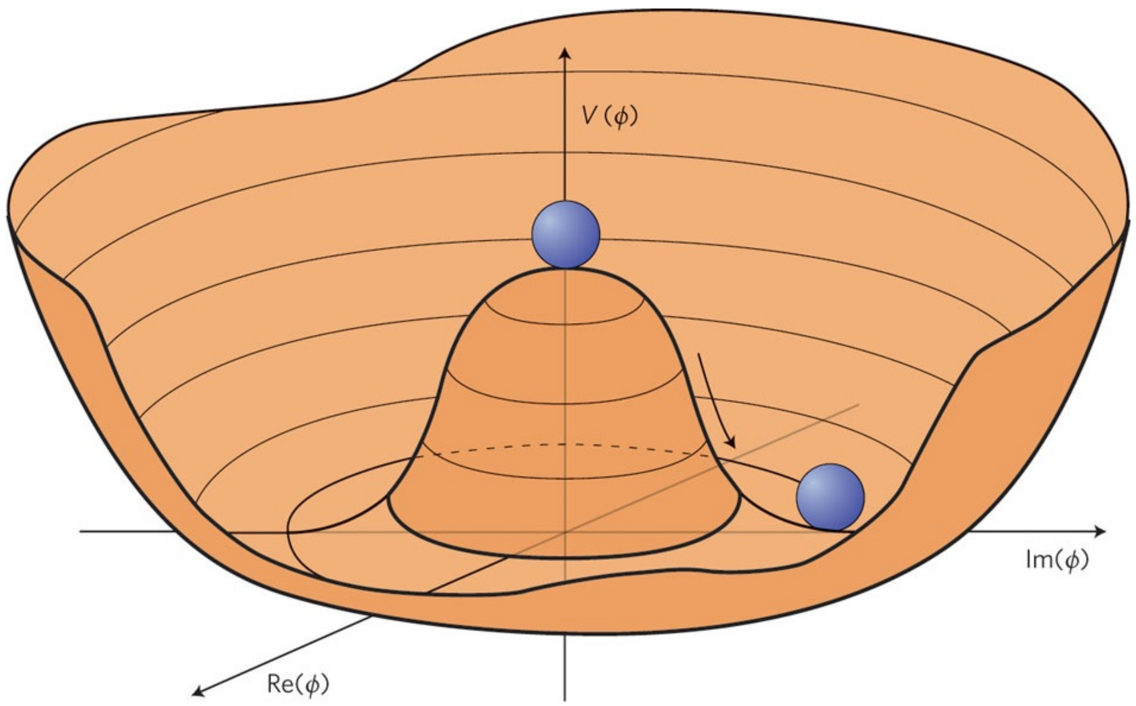
- Forces mediated via vector bosons (except gravity)

All particles and forces described in a ***unified, symmetric*** theory
$\Rightarrow$ but all particles must be ***massless***

But particles ***DO*** possess mass

A ***Higgs field*** is necessary to explain masses for fundamental particles

The Brout-Englert-Higgs Mechanism (1964)



Higgs field: scalar field Φ with potential:

$V(\Phi) = \mu^2 \Phi^*\Phi + \lambda|\Phi^*\Phi|^2$ (Higgs-field)

For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

Field Φ has a non-zero value in the vacuum:

$v = (-\mu^2/\lambda)^{1/2} \sim 246$ GeV (from G_F)

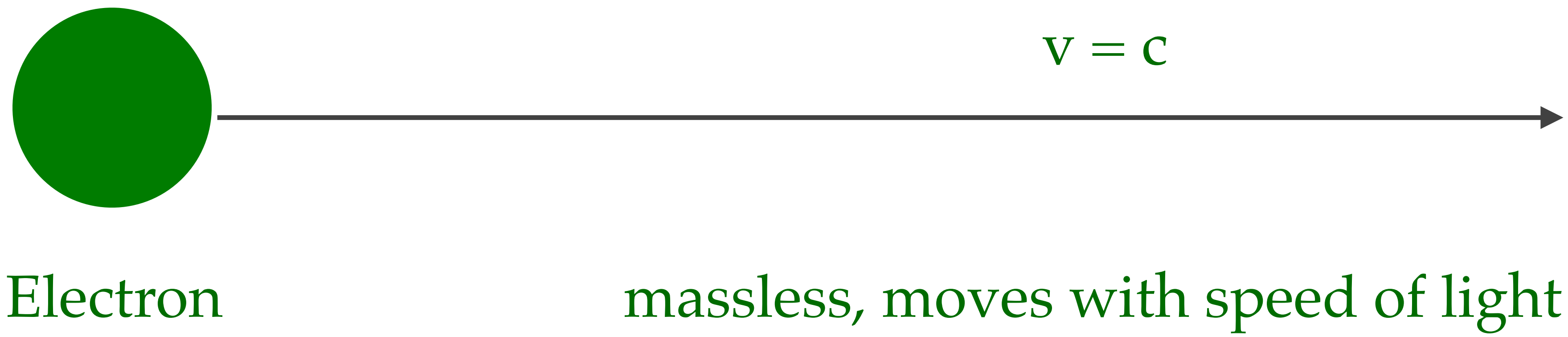
Particles acquire mass through coupling to the Higgs field: $m \sim v$
(masses need not be introduced in ad-hoc way)

Quantum excitation of the Higgs field: The Higgs Boson

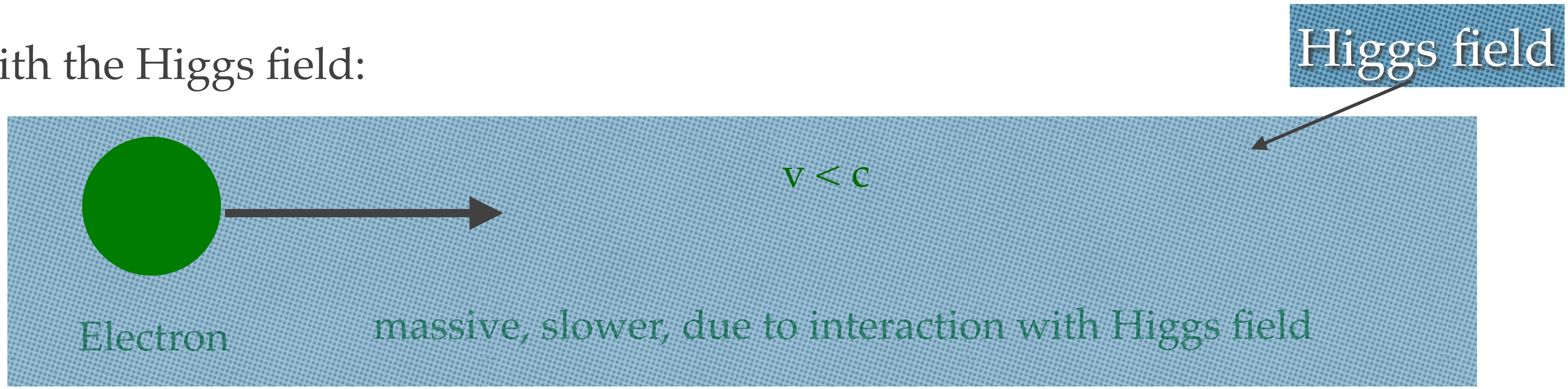
- mass of Higgs boson: free parameter in the Standard Model ($m_H^2 = 2v^2\lambda$)

The Higgs Field and Particle Masses

Without the Higgs field:



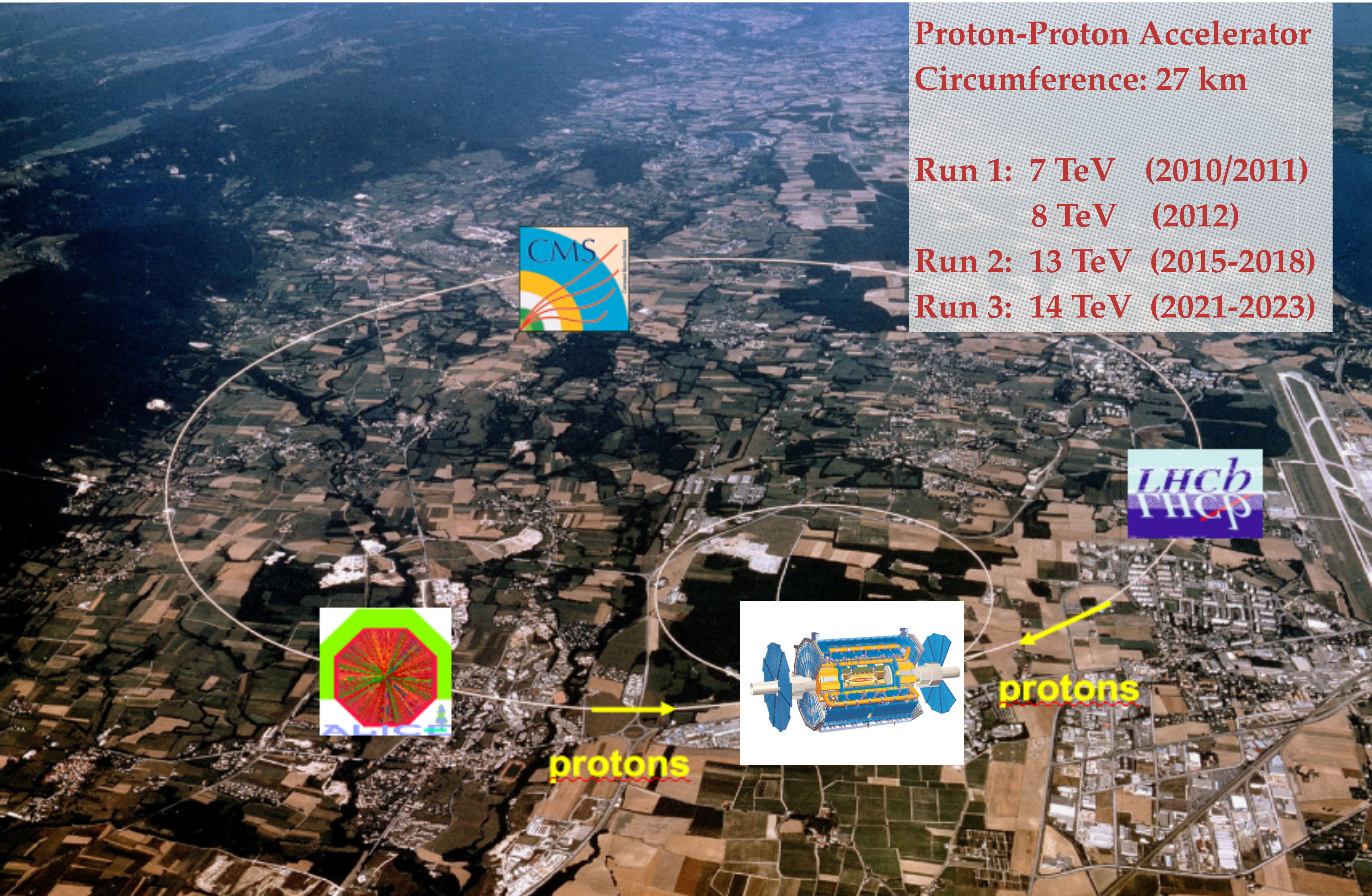
With the Higgs field:



The Higgs field explains why particles can possess mass

The more a particle directly interacts with the Higgs field, the heavier it is

Large Hadron Collider (LHC)

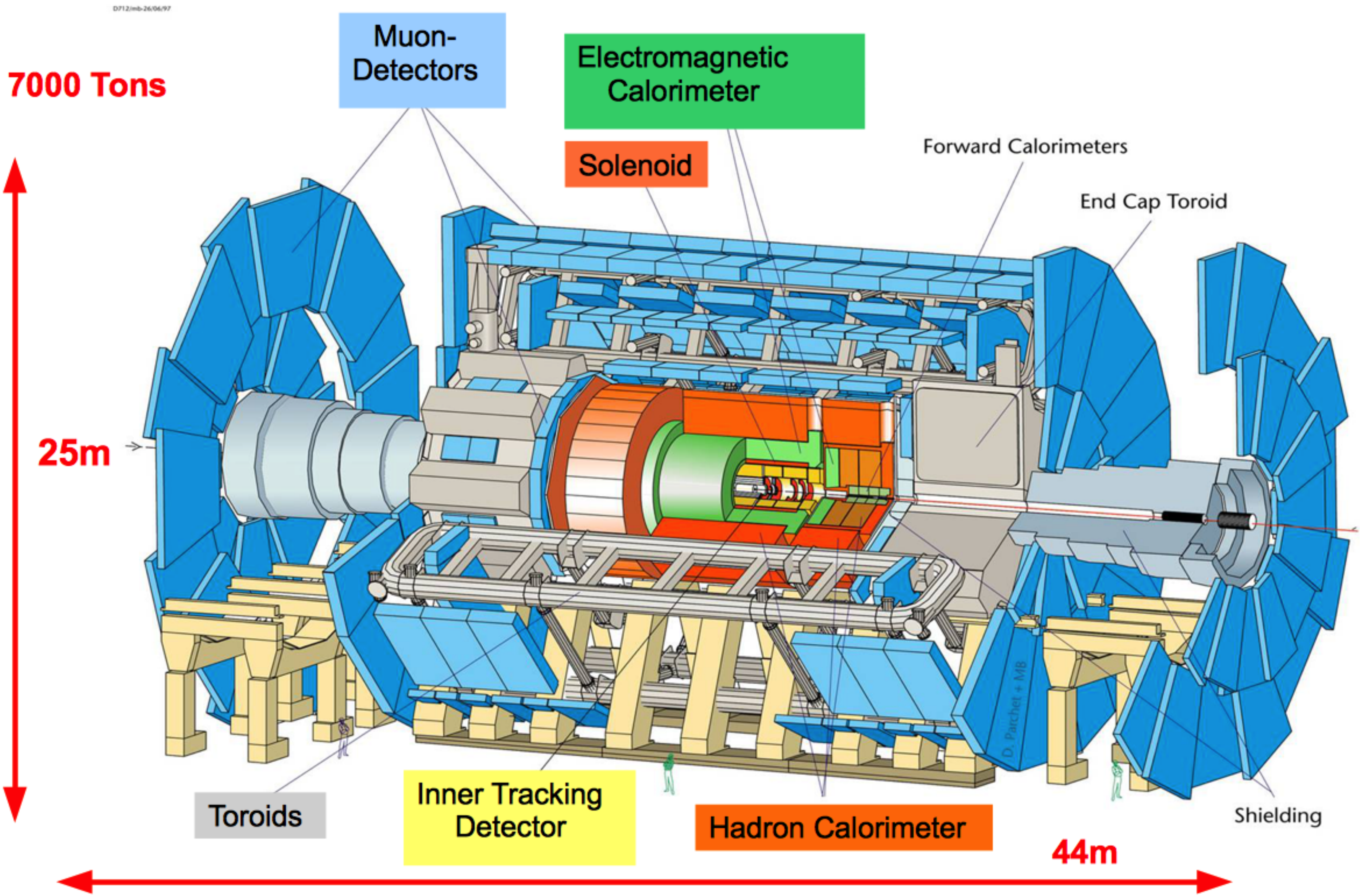


Proton-Proton Accelerator

Circumference: 27 km

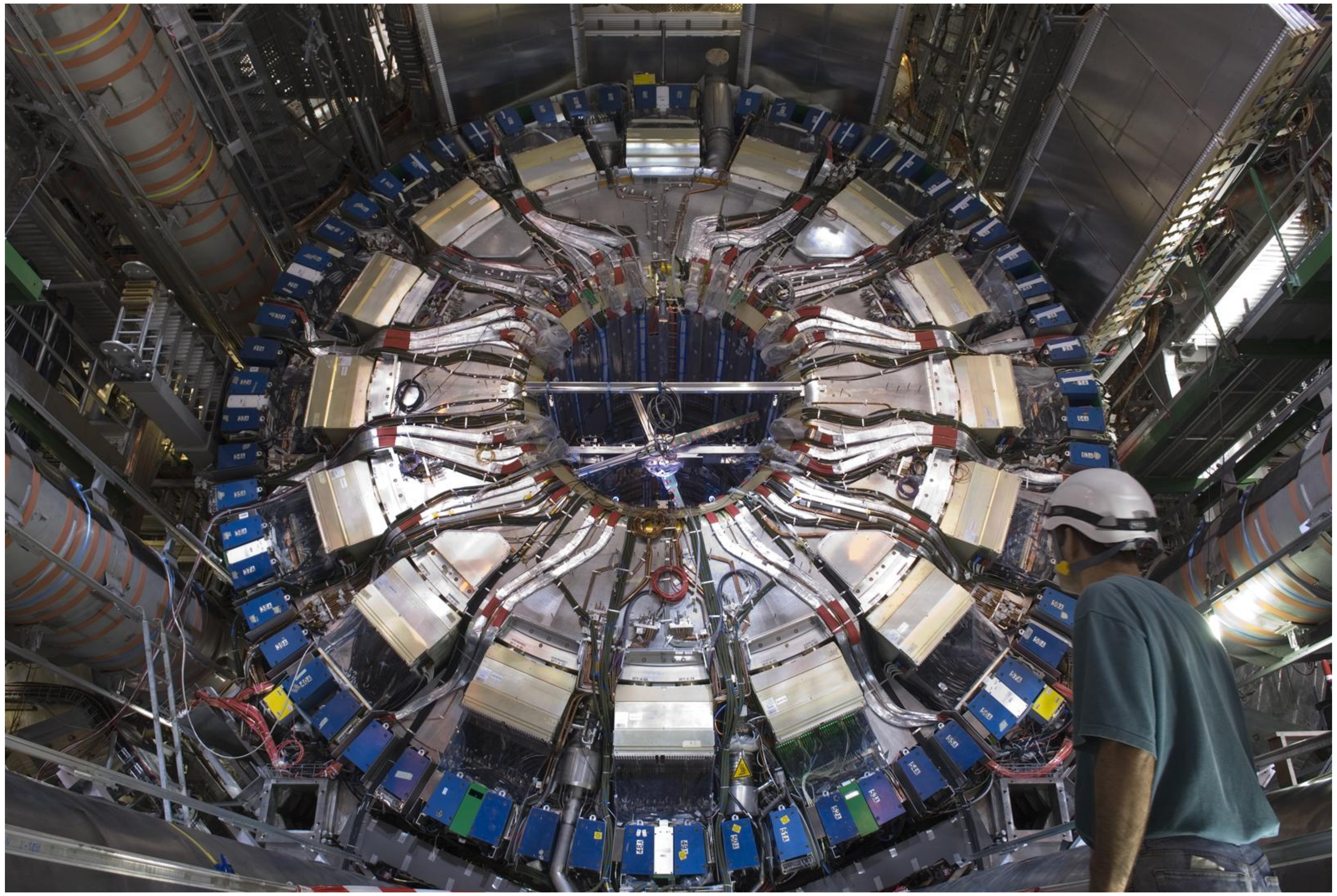
Run 1:	7 TeV	(2010/2011)
	8 TeV	(2012)
Run 2:	13 TeV	(2015-2018)
Run 3:	14 TeV	(2021-2023)

The ATLAS Detector



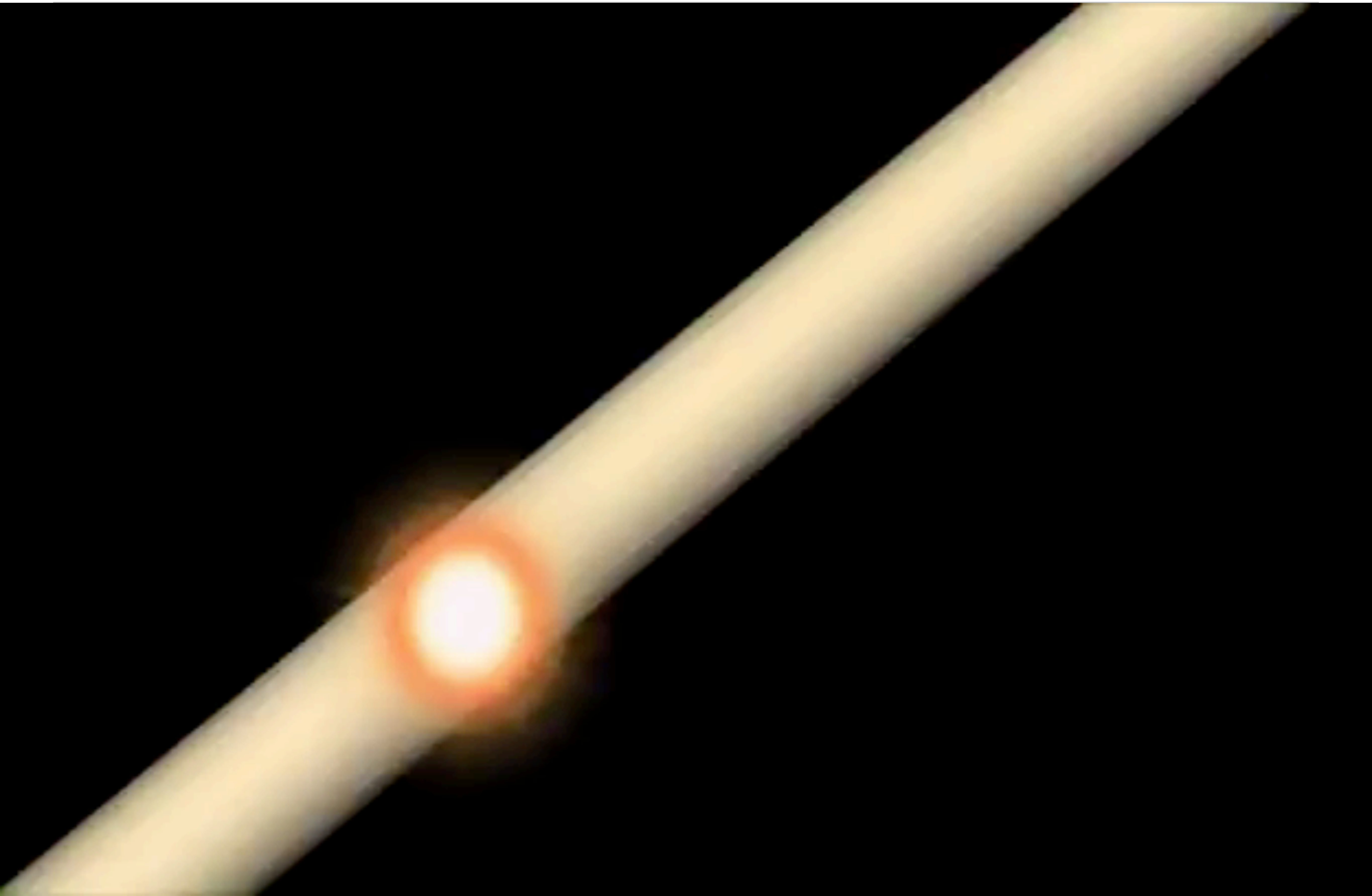
The ATLAS Collaboration

Particle Physics in Germany



installation of the ATLAS calorimeter

LHC Collisions



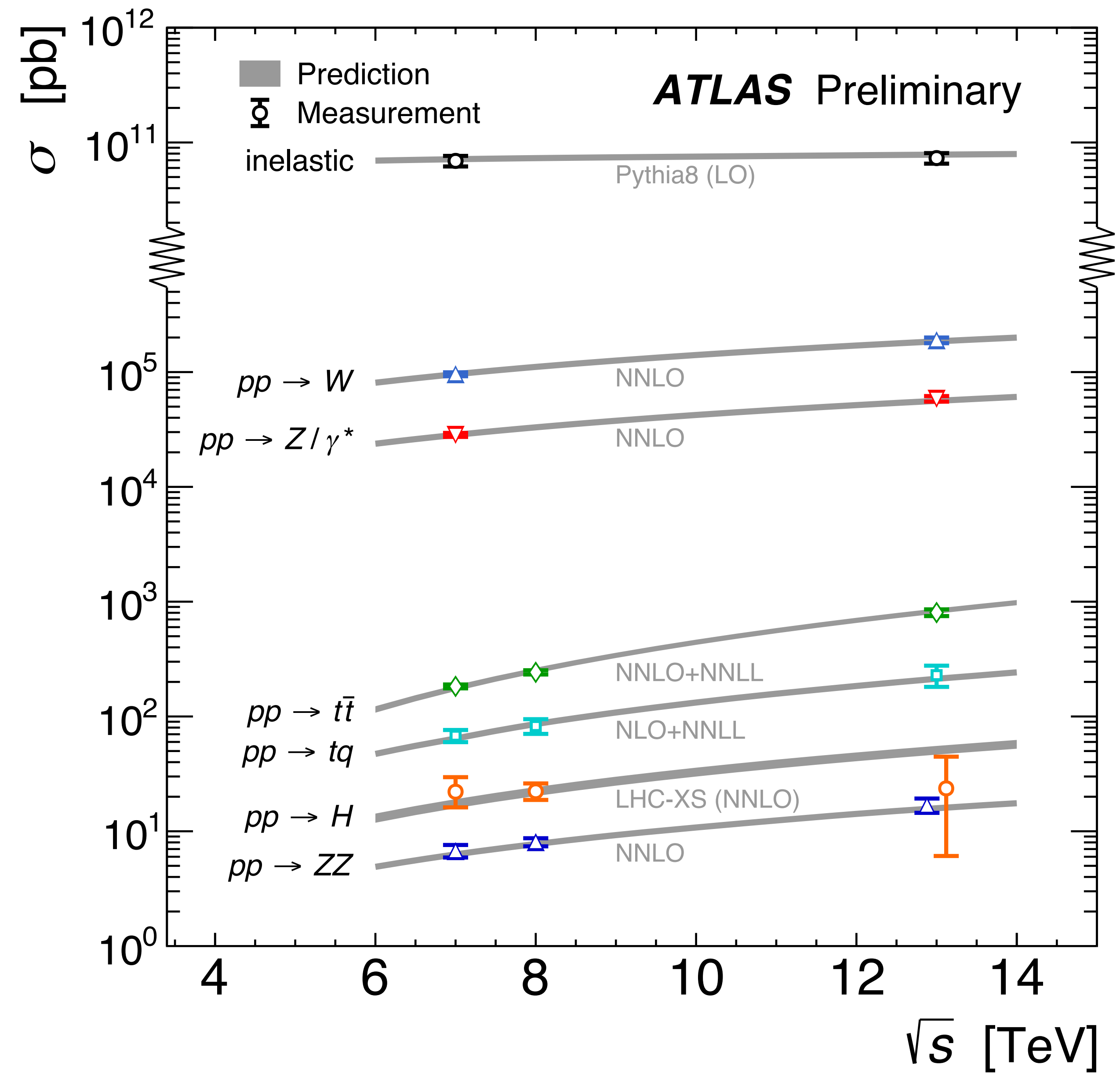
Higgs Production Cross Sections

Tiny probability to produce Higgs bosons:
1 Higgs boson per 10^{12} collisions

$\sigma_{inelastic} \sim \sigma_{Higgs} \times 10^{10}$

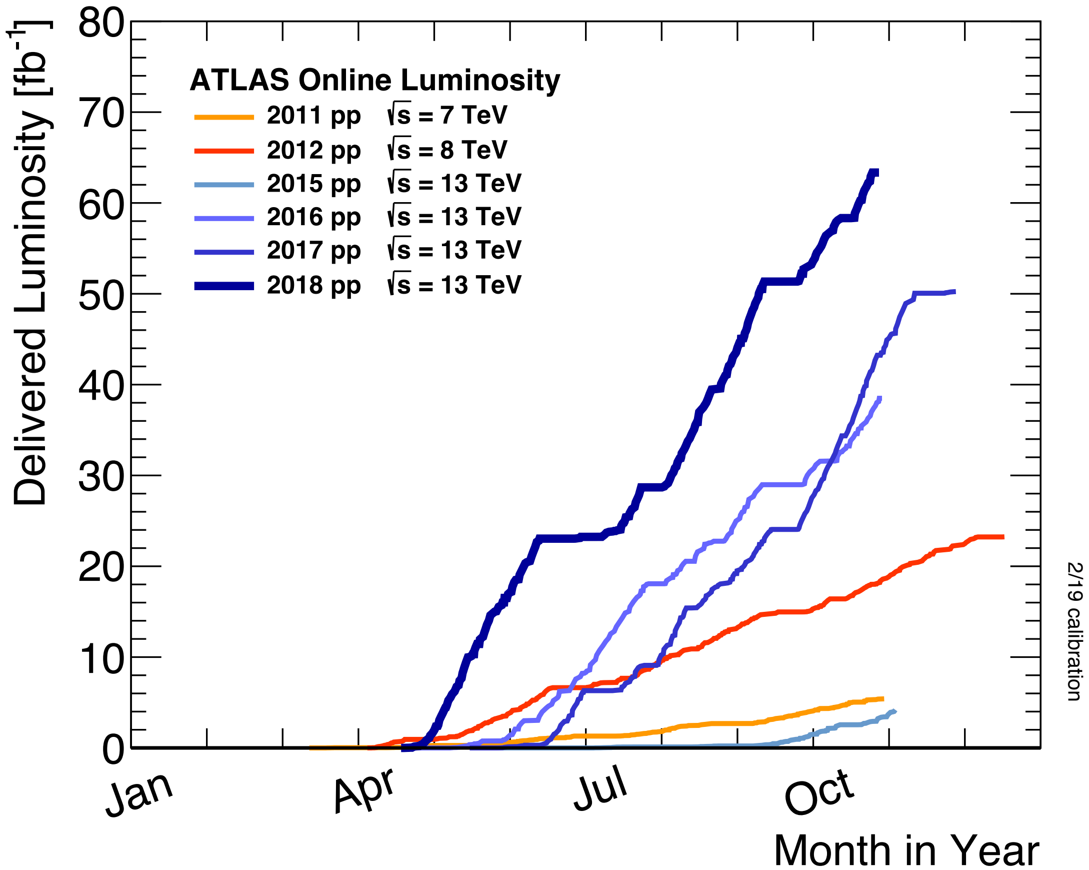
$\sigma_{W} \sim \sigma_{Higgs} \times 10^{4}$

$\sigma_{top} \sim \sigma_{Higgs} \times 10$



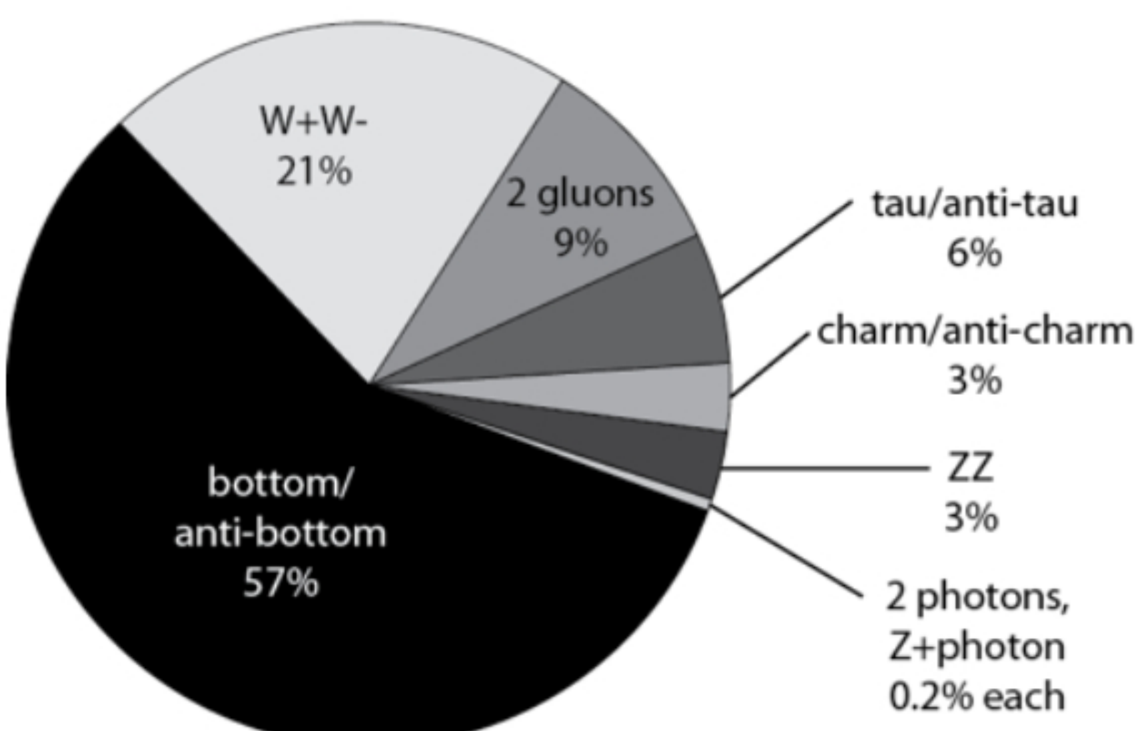
Challenge: separating the Higgs boson signal from background processes

Higgs Boson Decays



Year	produced Higgs bosons
2011	83 000
2012	440 000
2015	190 000
2016	1 700 000
2017	2 200 000
2018	2 900 000

Decays of a 125 GeV Standard-Model Higgs boson



The Higgs boson decays with $\tau \sim 10^{-22}$ s

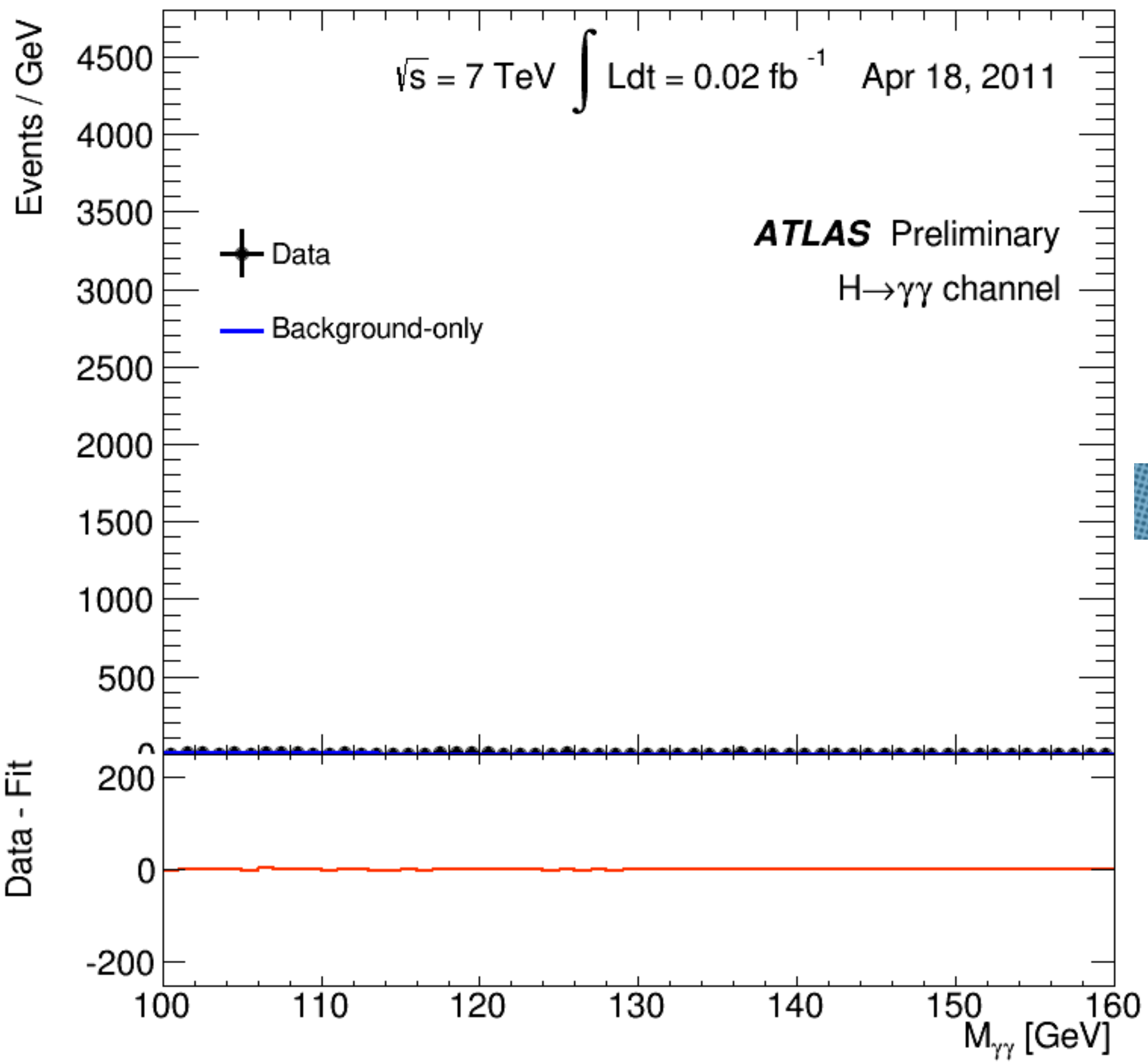
- only detectable through decay products

Most sensitive channels:

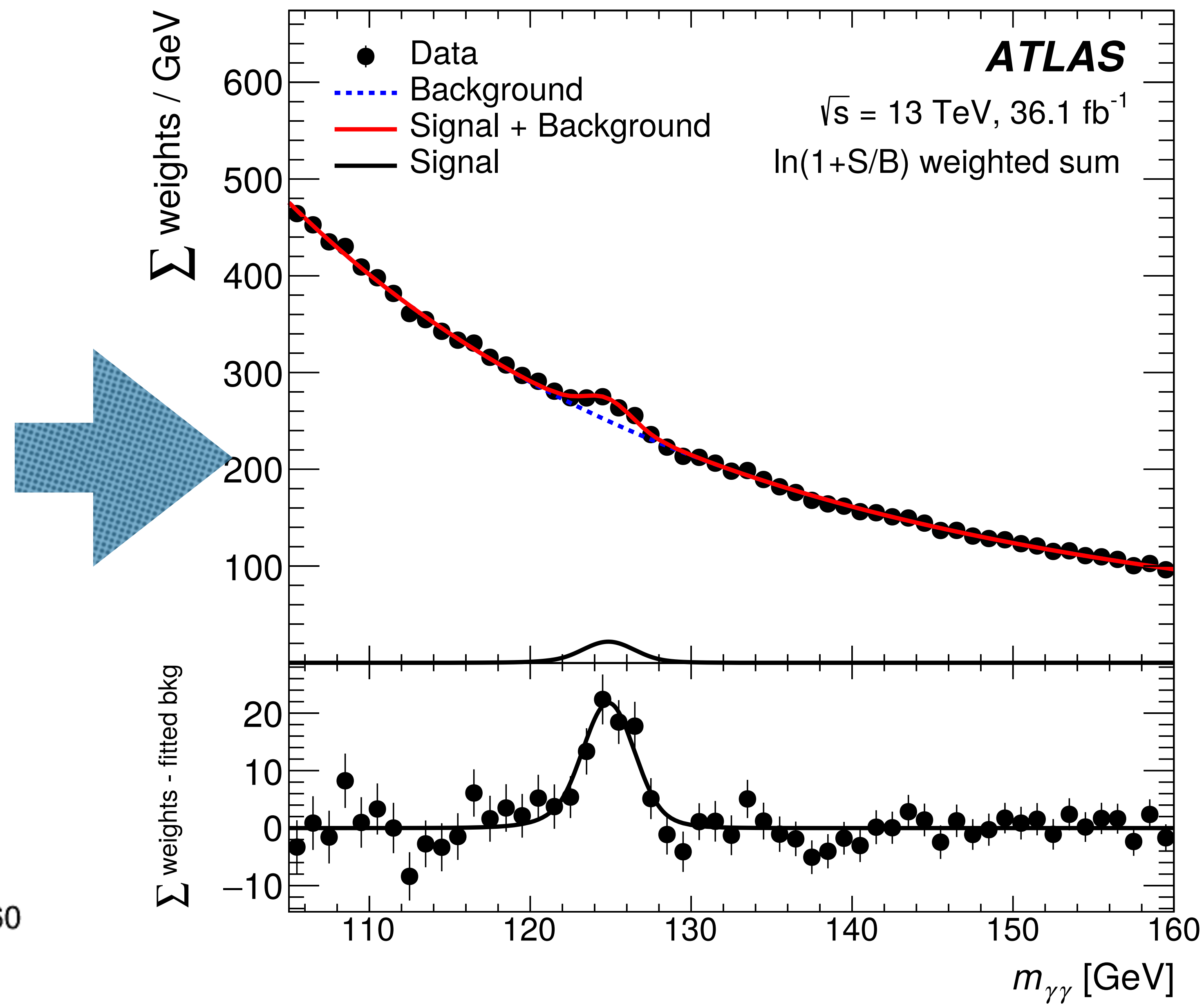
- $H \rightarrow \gamma\gamma$ 0.23%
- $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ 0.028%

Searching for H→γγ

Run-1



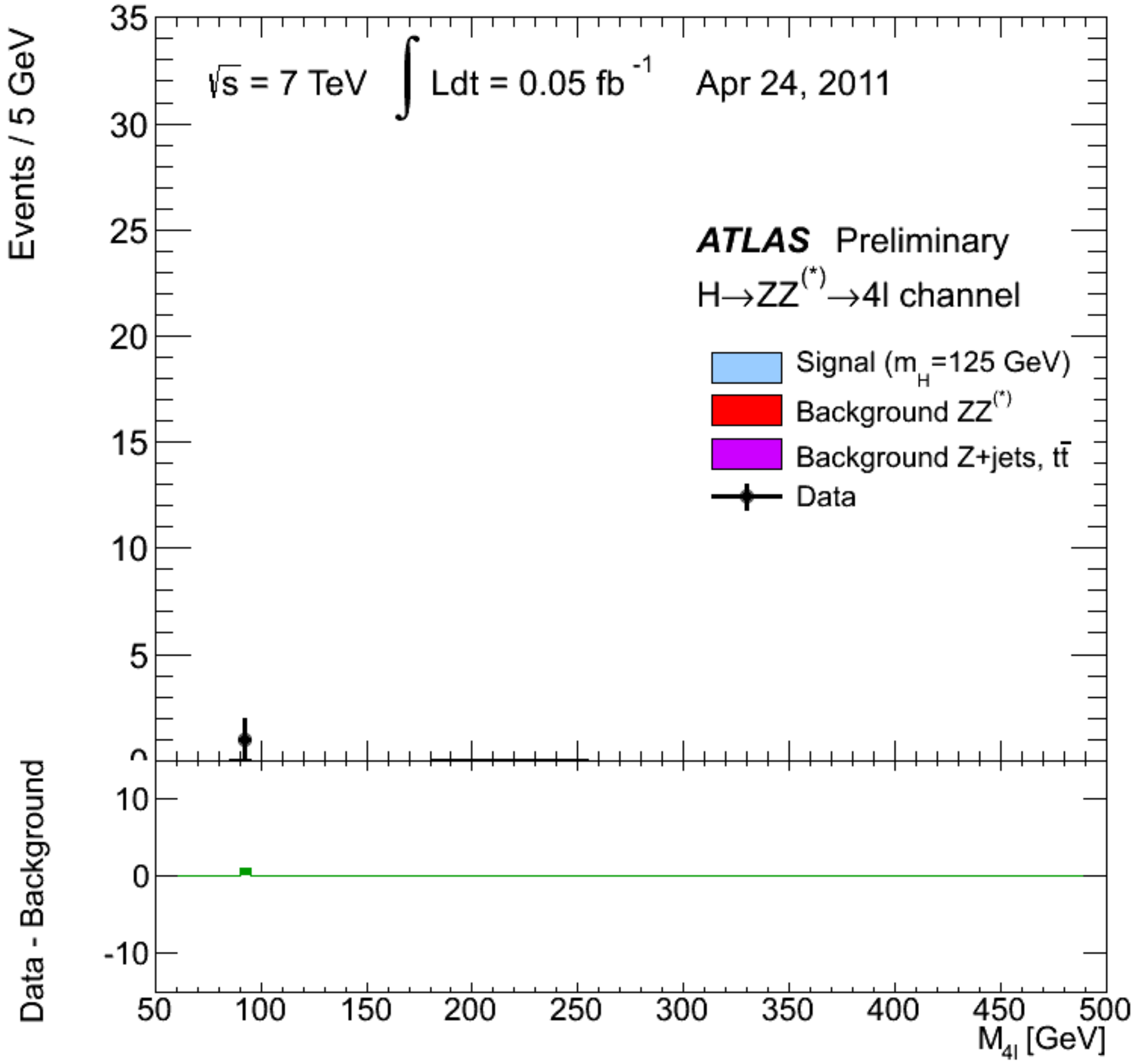
Run-2



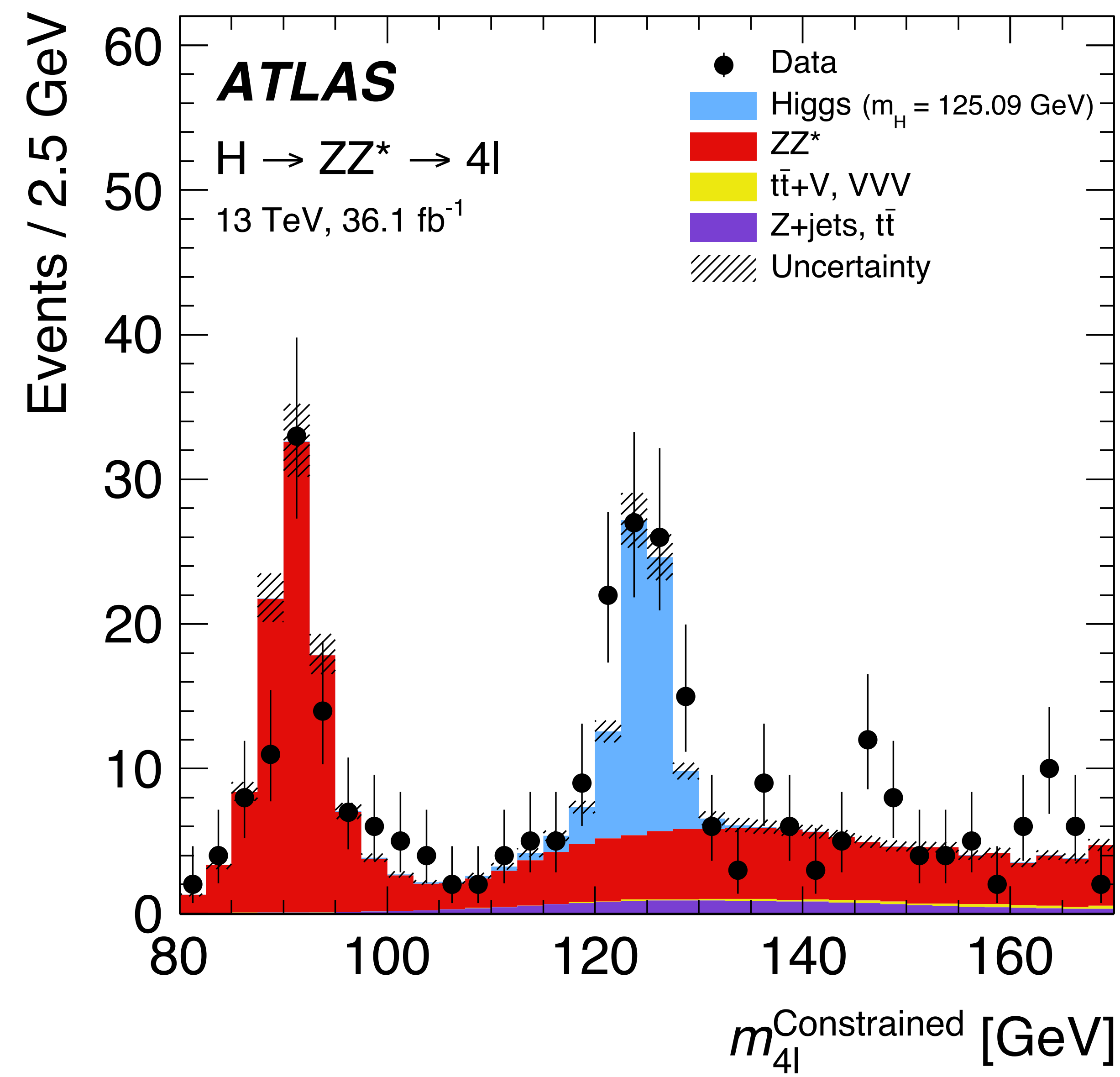
Similar results from the CMS experiment

Searching for H→ZZ→ℓℓℓℓ

Run-1

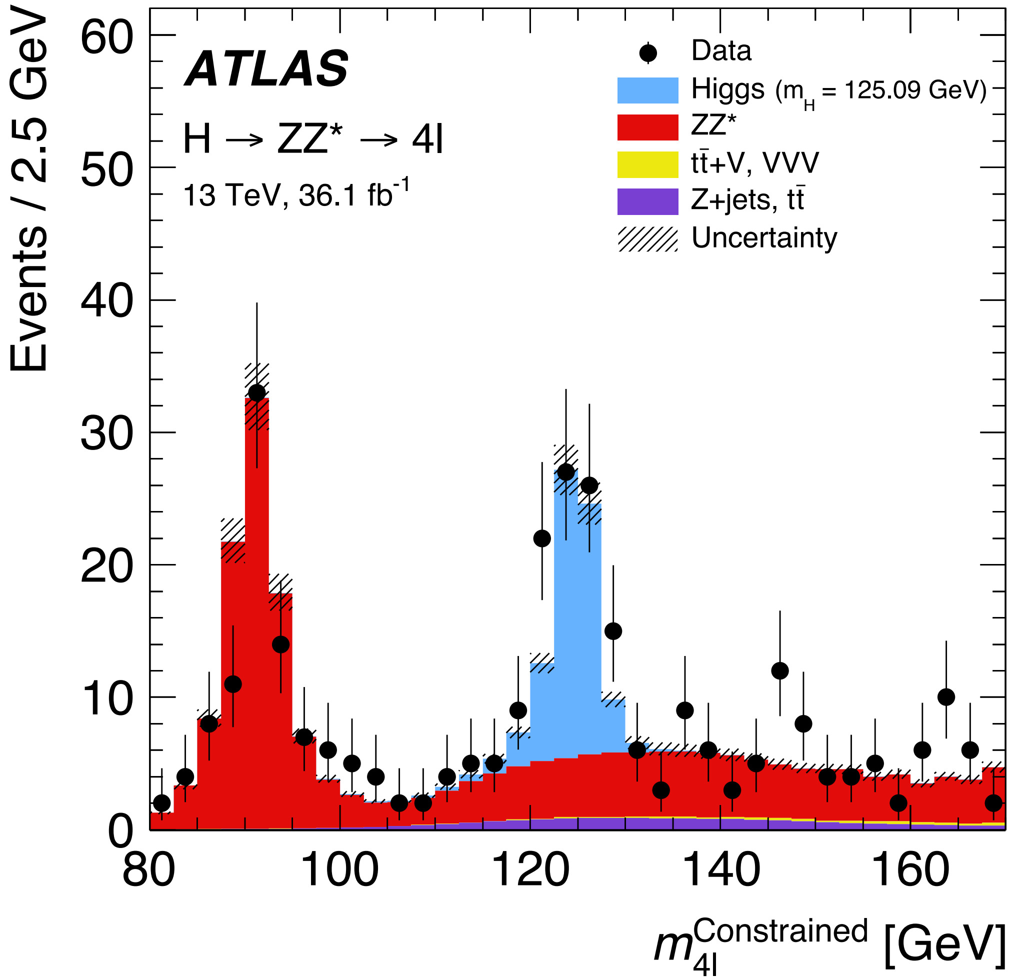


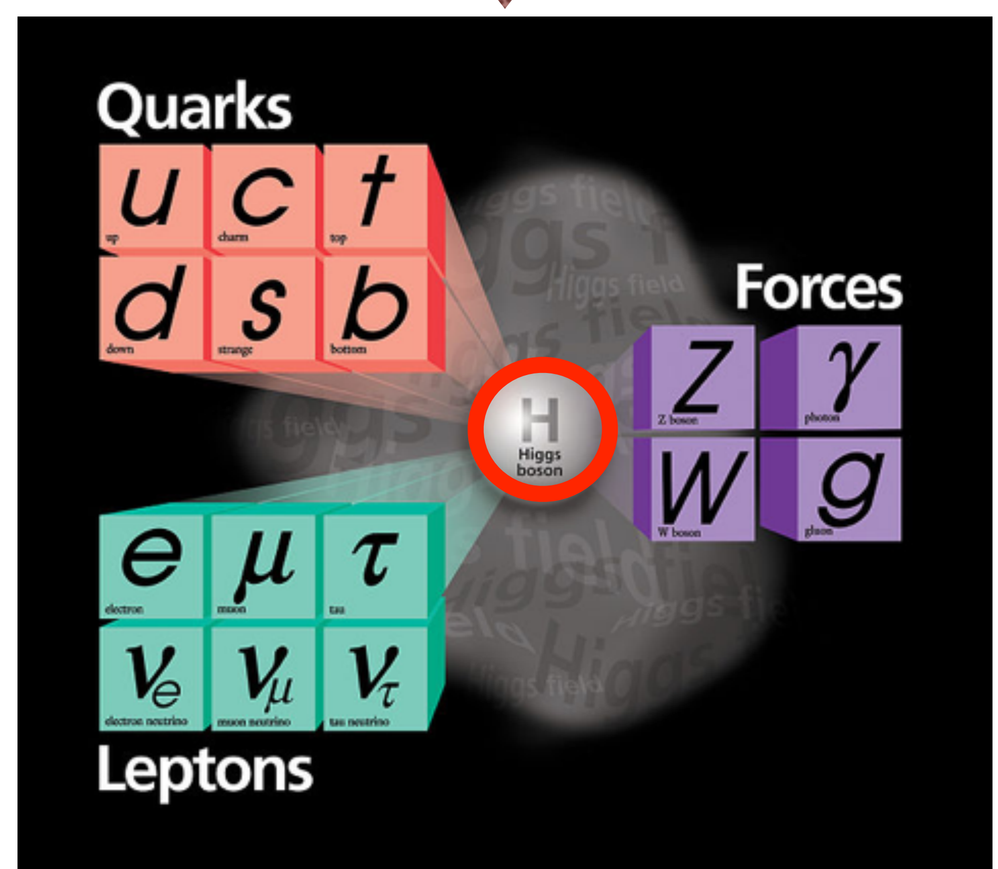
Run-2



Similar results from the CMS experiment

Reminder: Why do we care so much?





We finally can say how fundamental particles acquire their mass

The Precision Era

Year	produced Higgs bosons
2011	83 000
2012	440 000
2015	190 000
2016	1 700 000
2017	2 200 000
2018	2 900 000

} **the discovery era** (2011–2012)

} **the precision era** (2015–2018)

With the dataset in Run-2, what do we know about the Higgs boson?

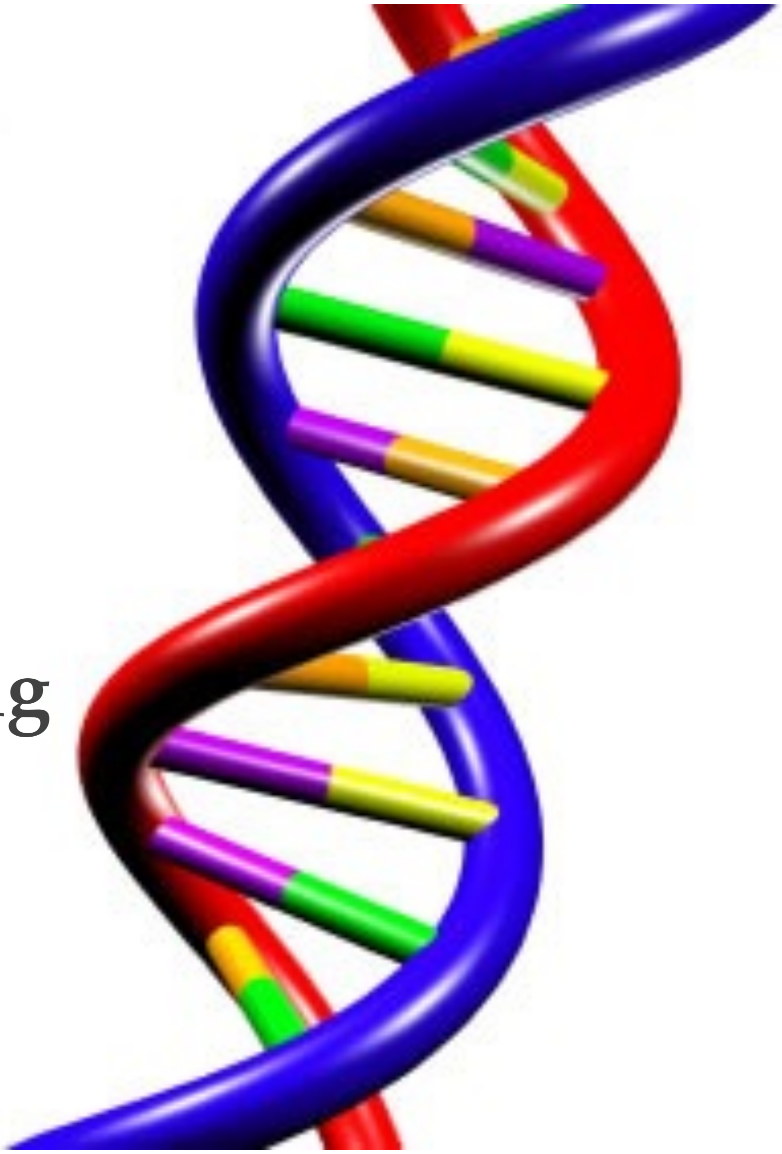
- precision mass measurements
- extensive coupling measurements
- quantum numbers (spin, CP)
- searches for rare decays
- measuring the self-coupling

Higgs Boson Mass Measurement

Fundamental property of any particle (invariant)

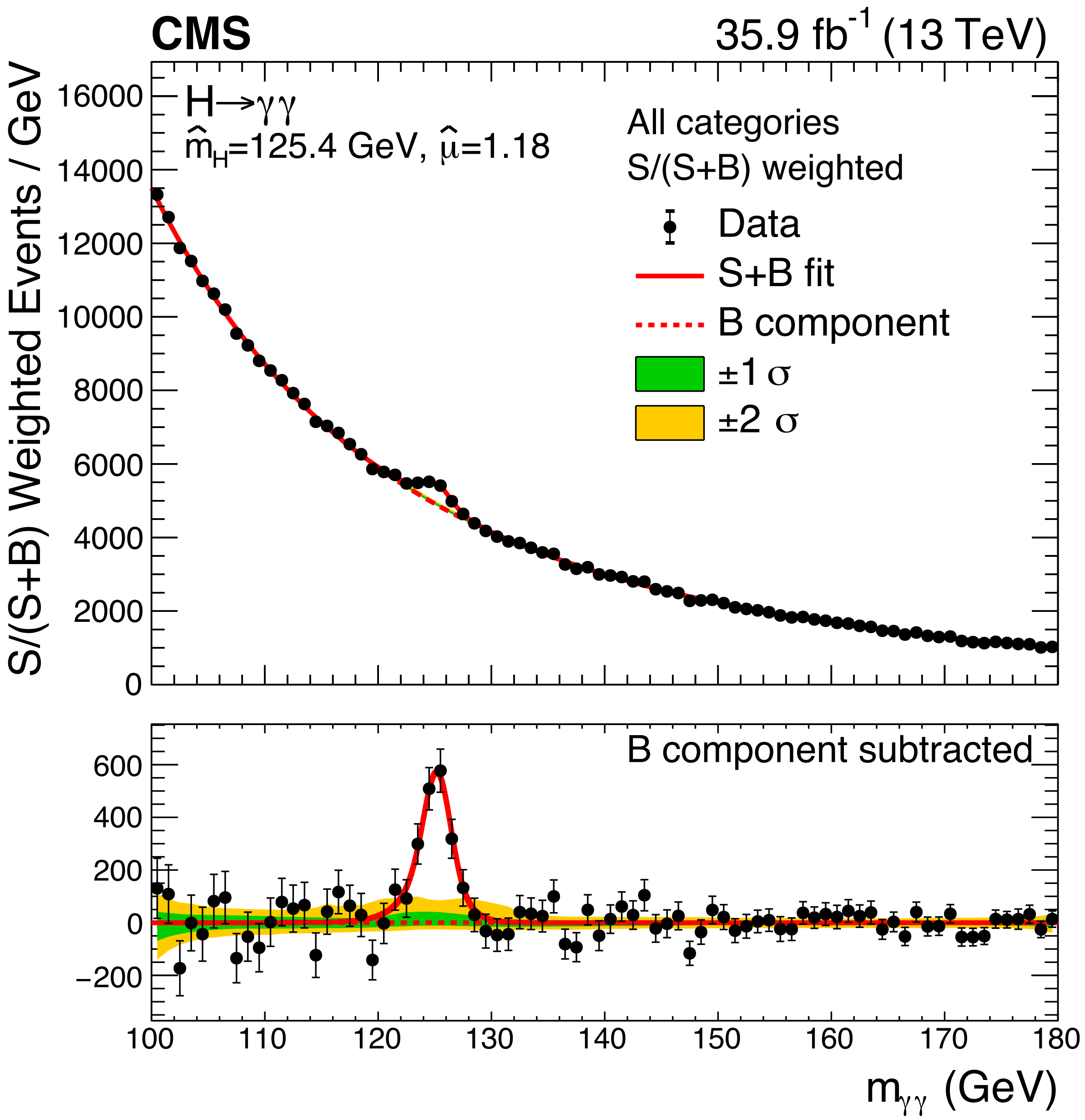
The free parameter of the SM Higgs sector

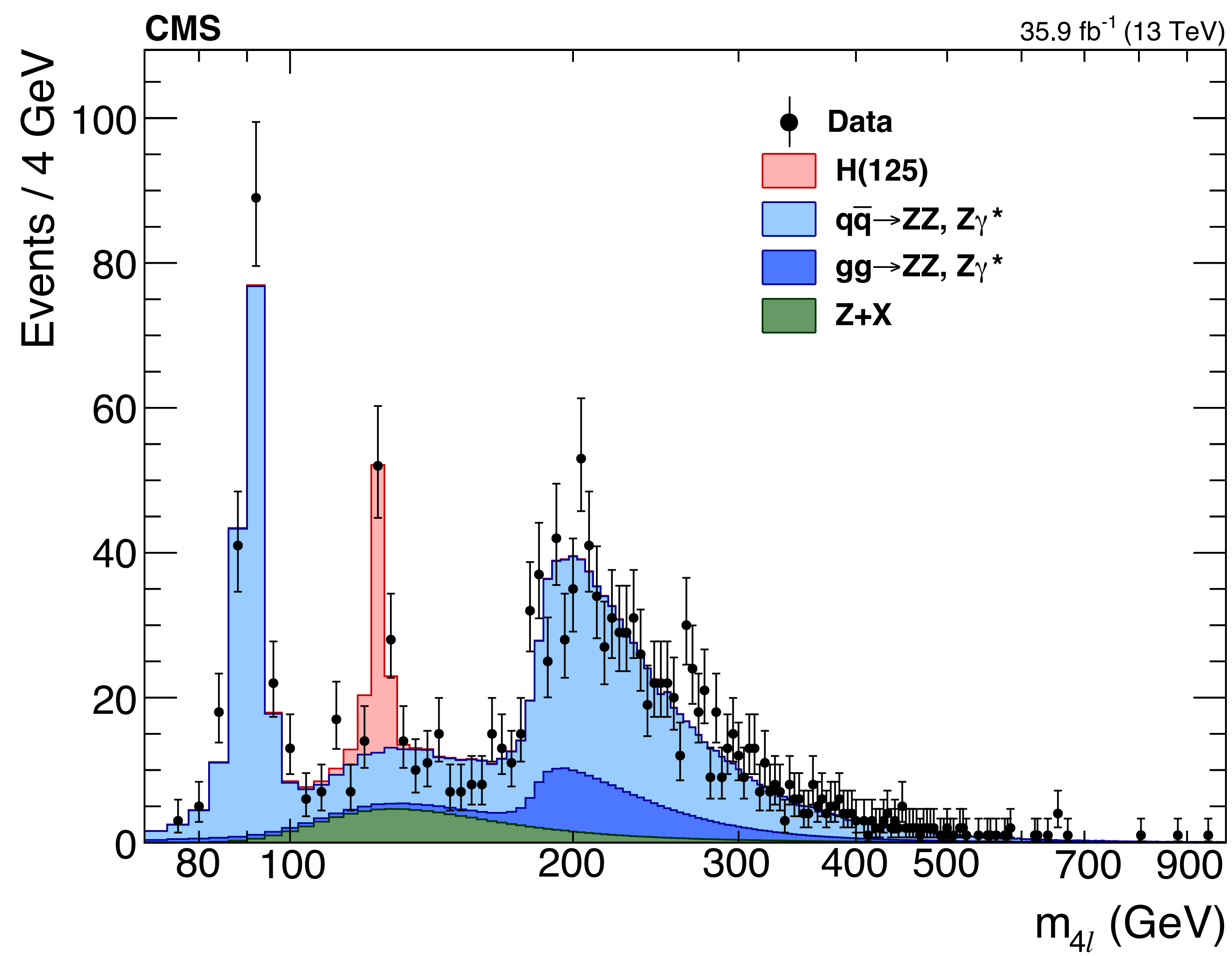
Linked to Higgs potential and Higgs-self-coupling



Higgs Boson Mass Measurement

High Mass Resolution channels: γγ and ZZ→ℓℓℓℓ



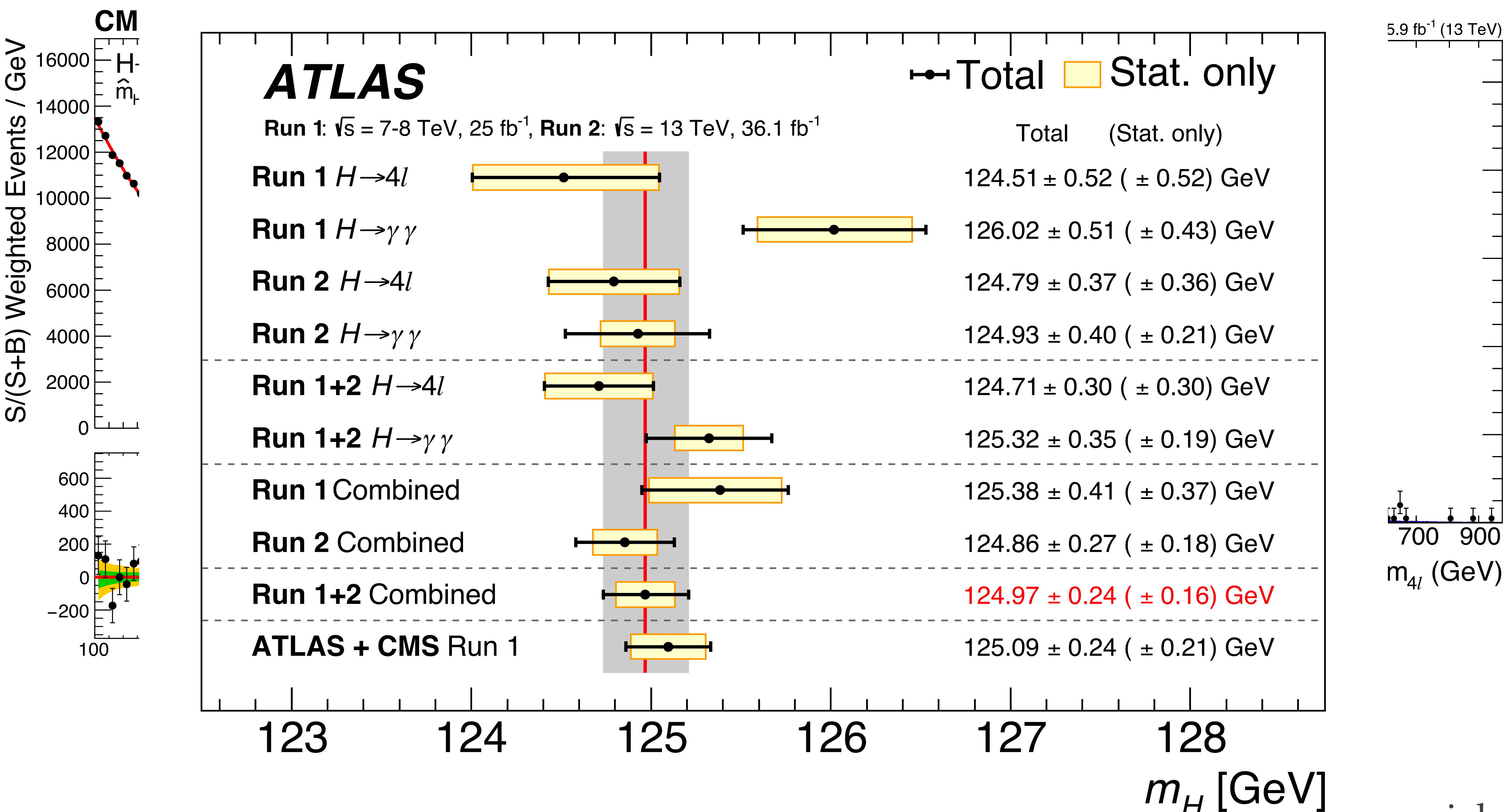


Maximum likelihood fit on invariant mass spectrum

Precise energy scale calibration crucial

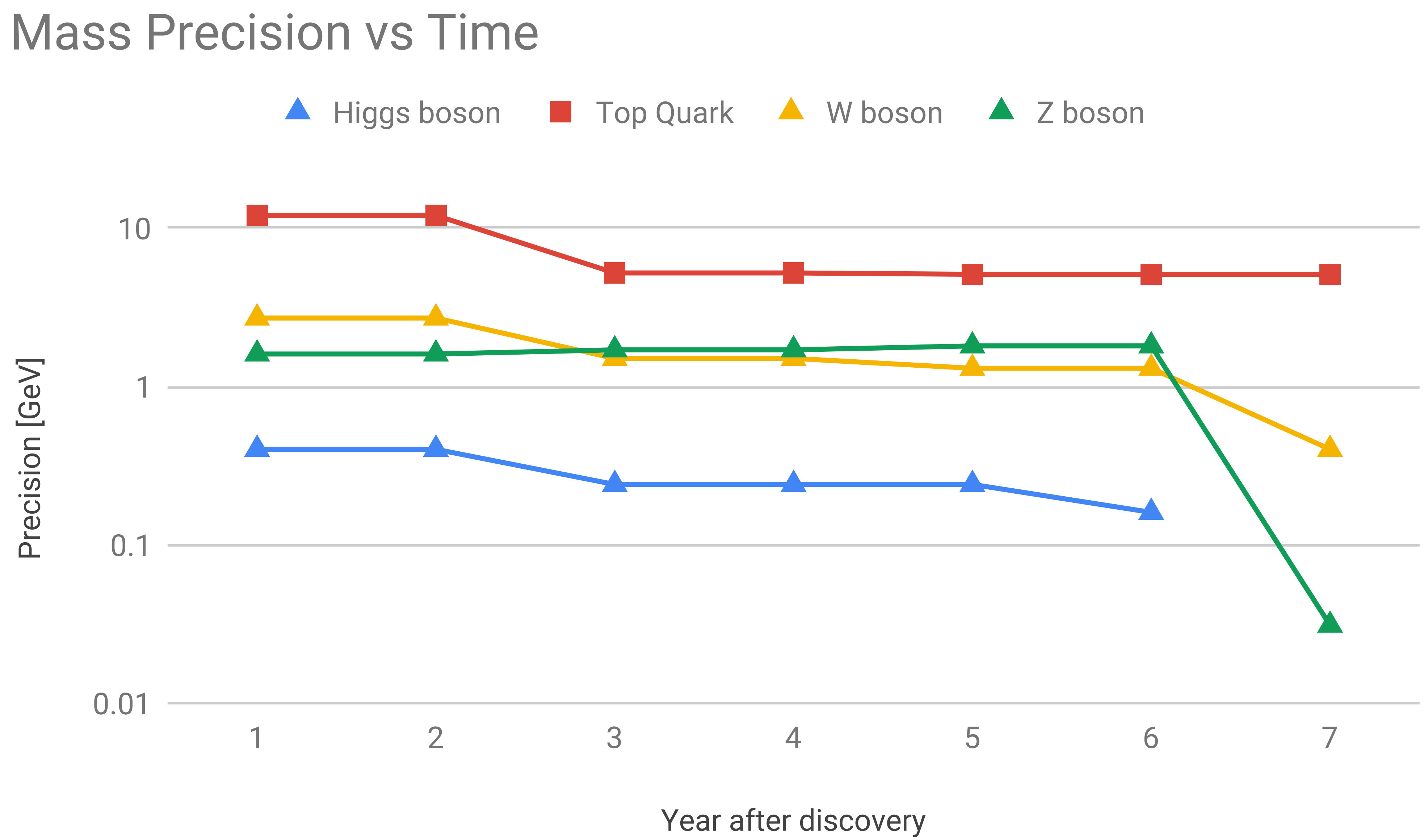
Higgs Boson Mass Measurement

High Mass Resolution channels: $\gamma\gamma$ and $ZZ \rightarrow \ell\ell\ell\ell$



rucial

Precision of Mass Measurements



Current Precision	W	Z	top	Higgs
Δm/m (%)	0.014	0.002	0.23	0.13

Higgs Boson Couplings

Predicted for all SM particles for a given m_H

Determine Higgs Boson Phenomenology & Experimental Signatures

Sensitive to Beyond-Standard-Model Phenomena coupling to Higgs Sector

Does the Higgs boson couple to fermions?

ATLAS/CMS claimed observation of new particle decaying to $\gamma\gamma$, ZZ, WW (all bosons)

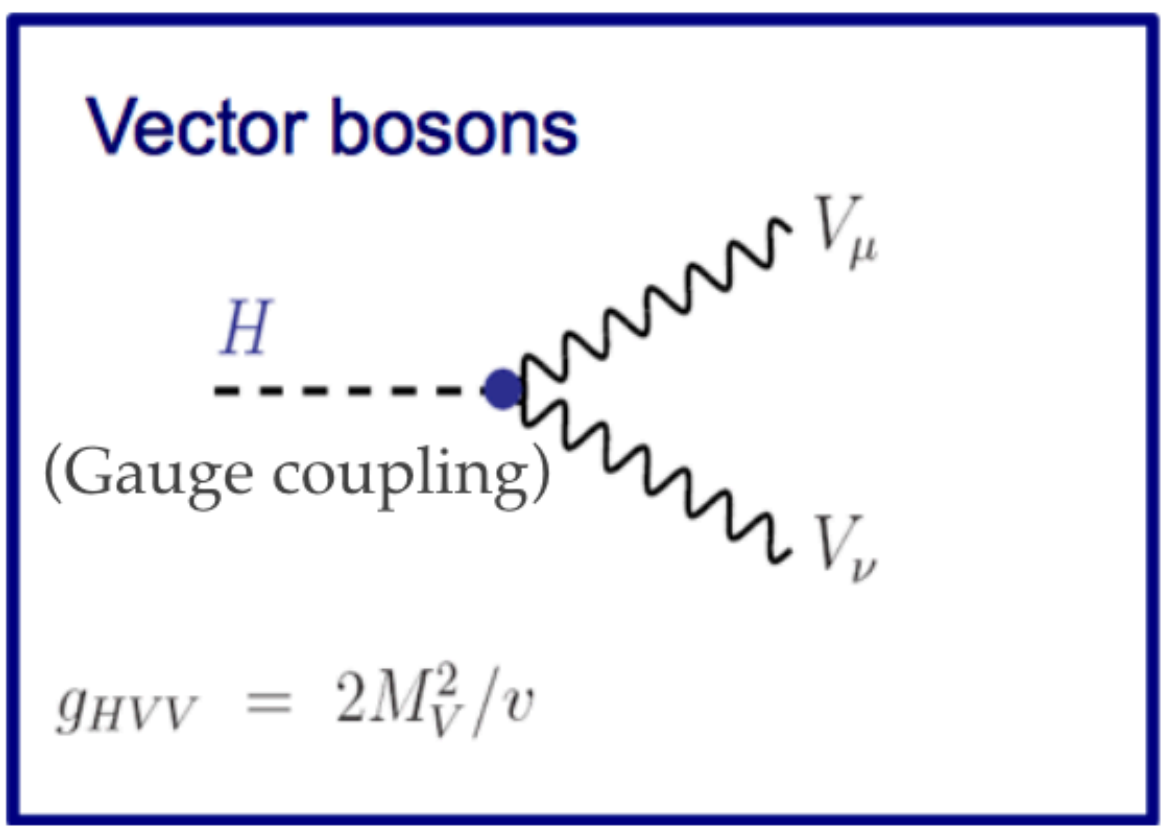
- particle is a boson
- particle couples to vector bosons

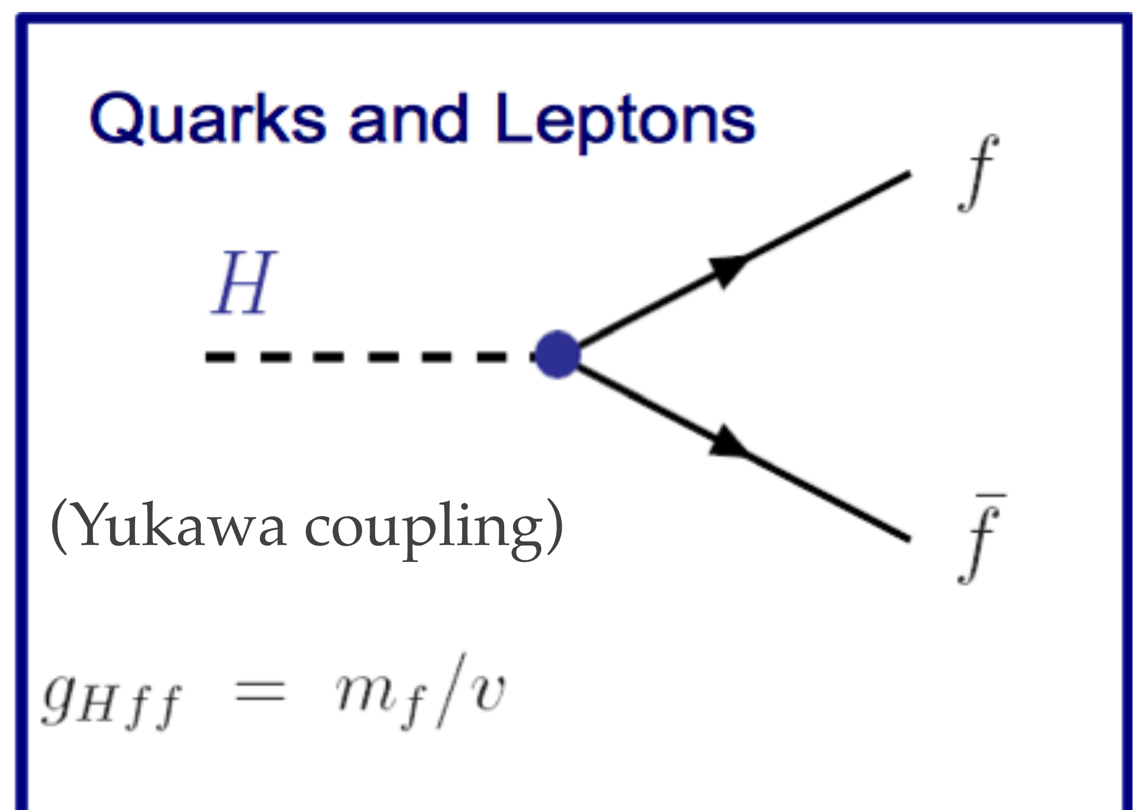
Does particle couple to fermions? (quarks and leptons)

$$\mathcal{L}_{\text{bosonic}} = (D_\mu\phi)(D^\mu\phi)$$

$$D_\mu = \partial_\mu + ig_W \mathbf{T}\cdot\mathbf{W}_\mu + ig'YB_\mu/2$$

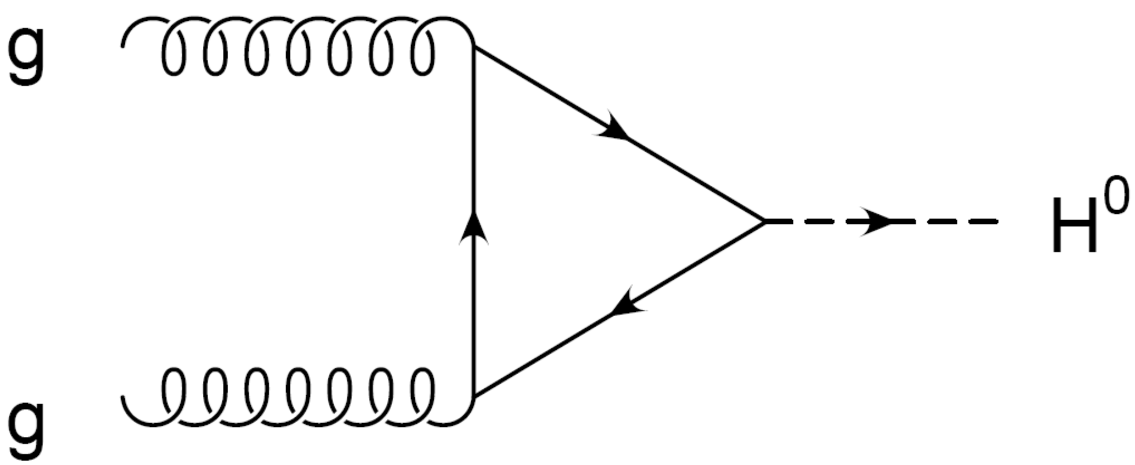
$$\mathcal{L}_{\text{fermionic}} = -g_f\,[\bar{L}\phi R + (\bar{L}\phi R)^\dagger]$$

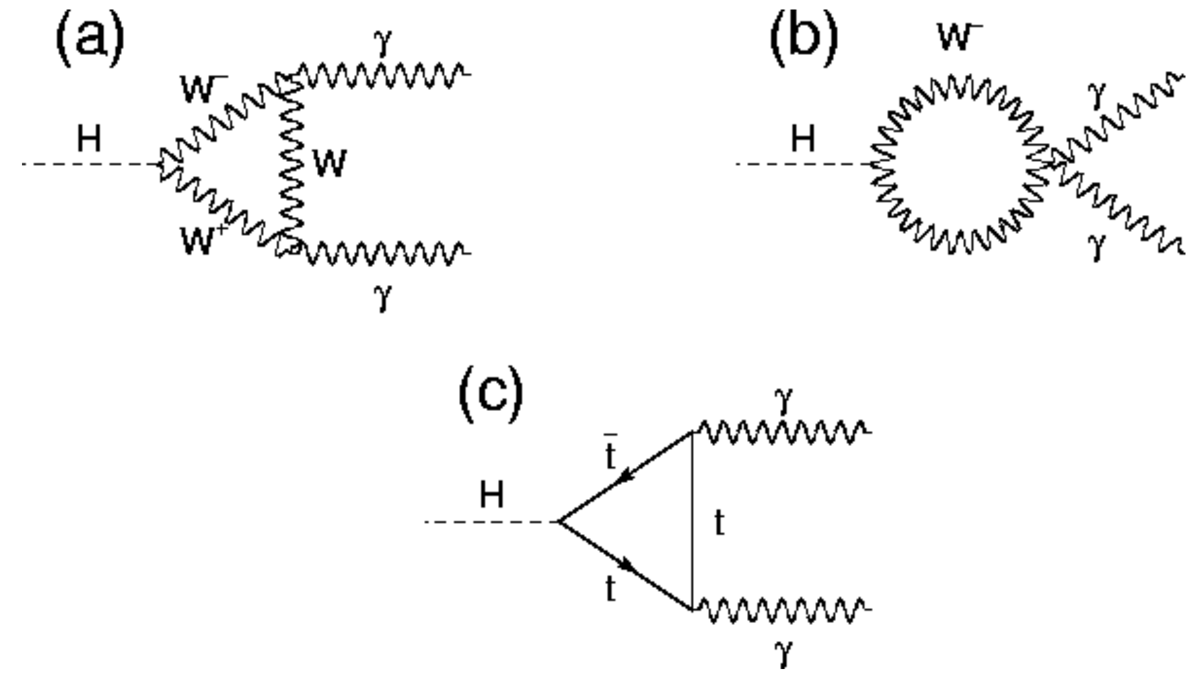




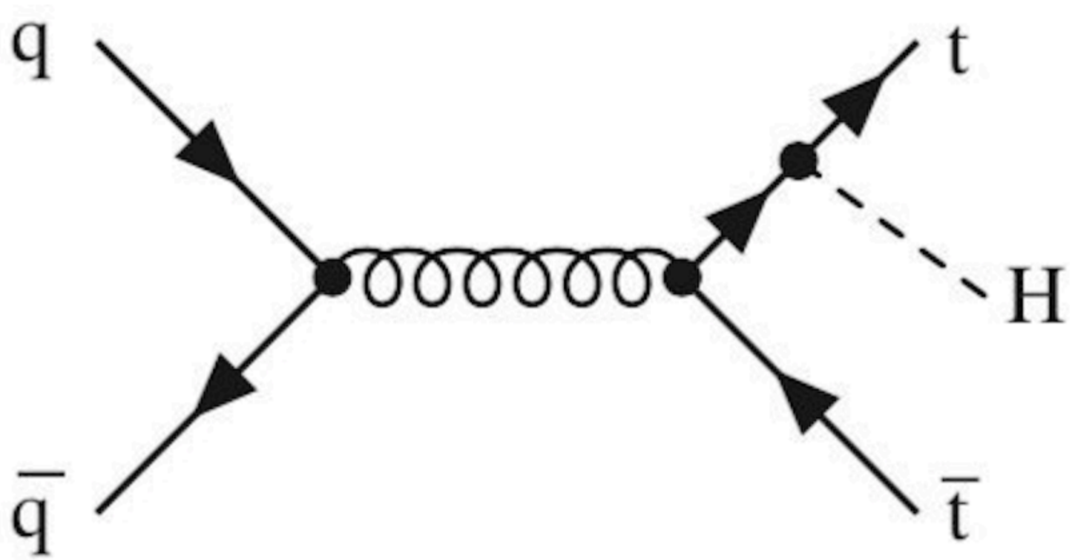
How to prove fermion couplings?

Suspect Higgs-quark couplings due to indirect evidence

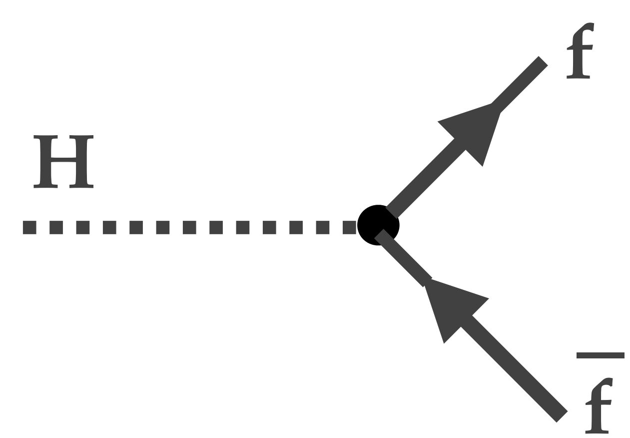




Direct evidence requires verifying Higgs-fermion couplings through real (non-virtual) particles



Search for ttH production



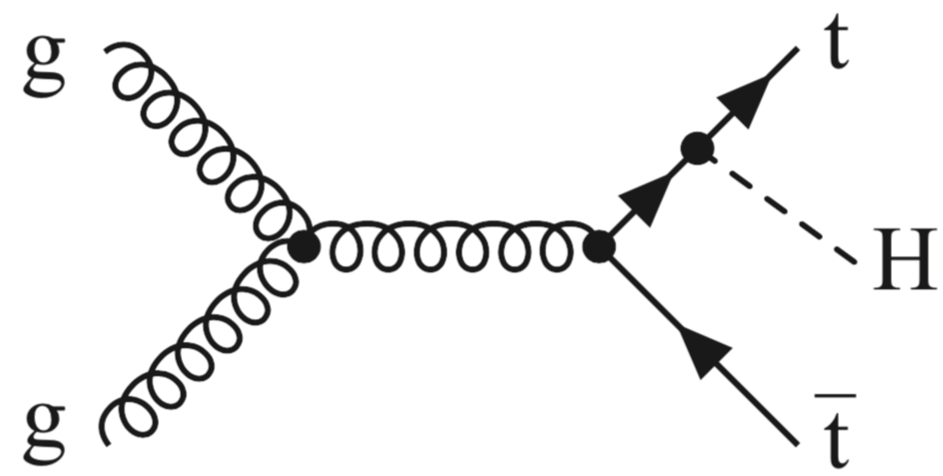
Search for H→bb and H→ττ decays

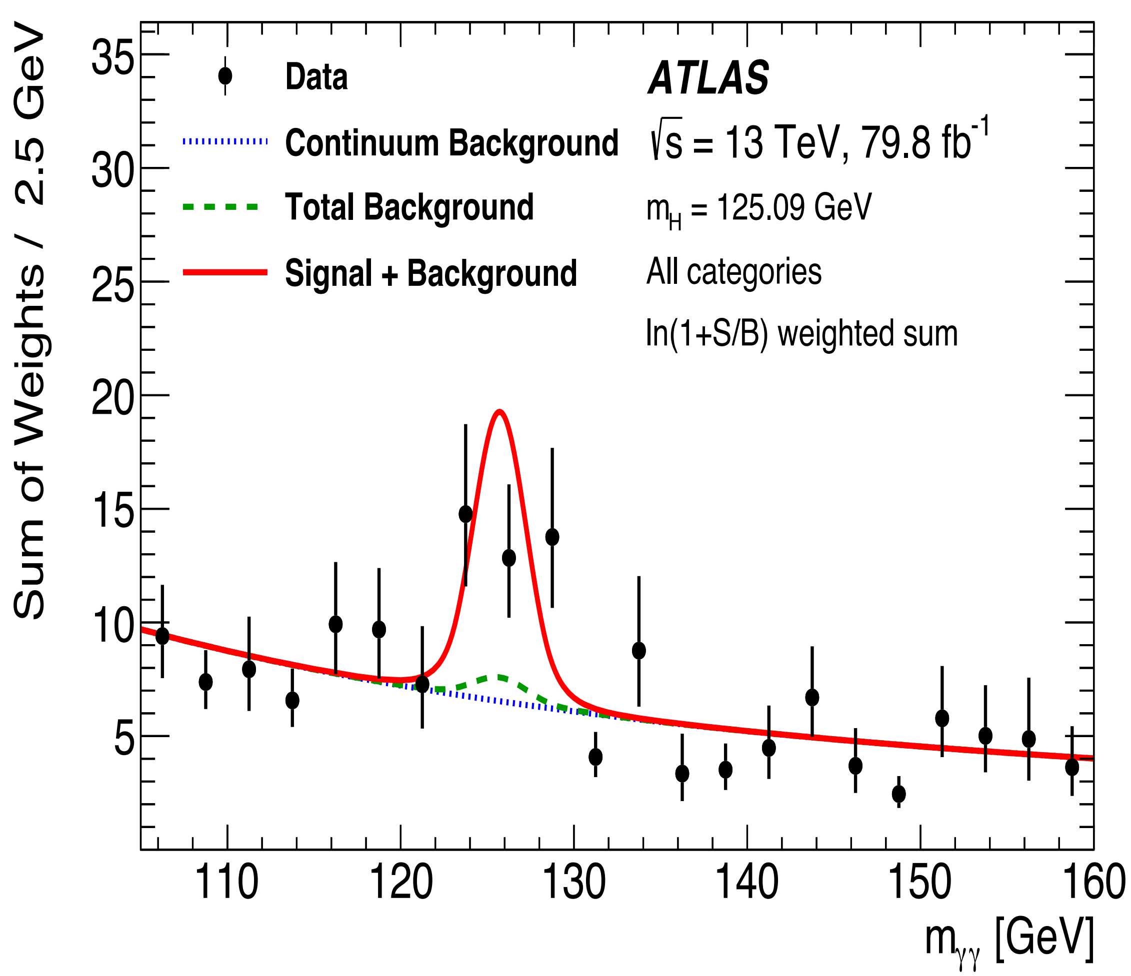
ttH production

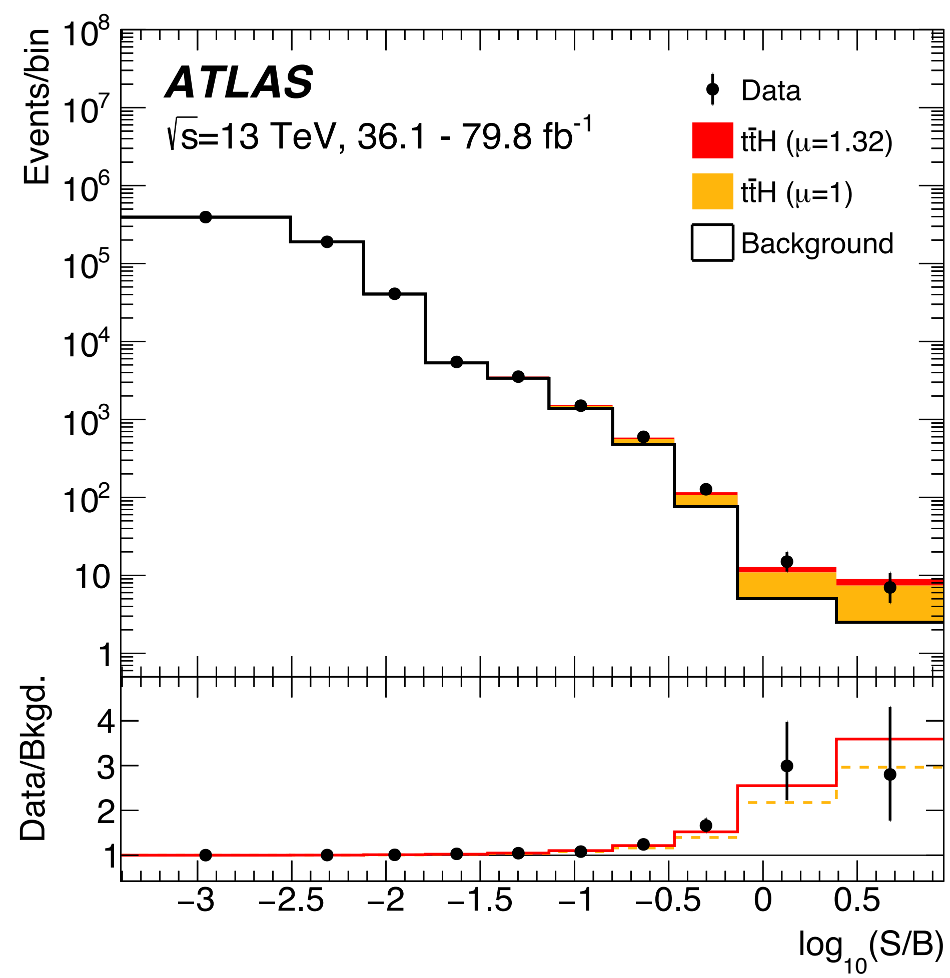
Extremely low cross-section

Combine different decay channels:

- diphoton final state + $t\bar{t}$
- multi-lepton final state + $t\bar{t}$
- $b\bar{b}$ final state+ $t\bar{t}$







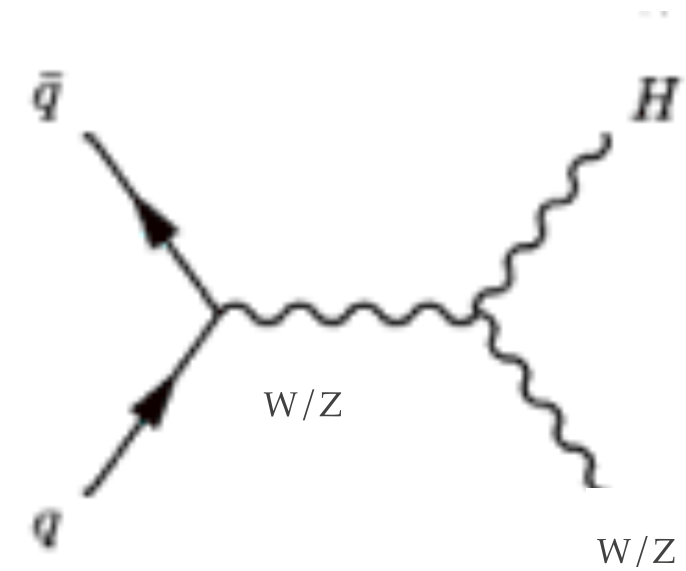
ATLAS: **5.8σ** (4.9σ)

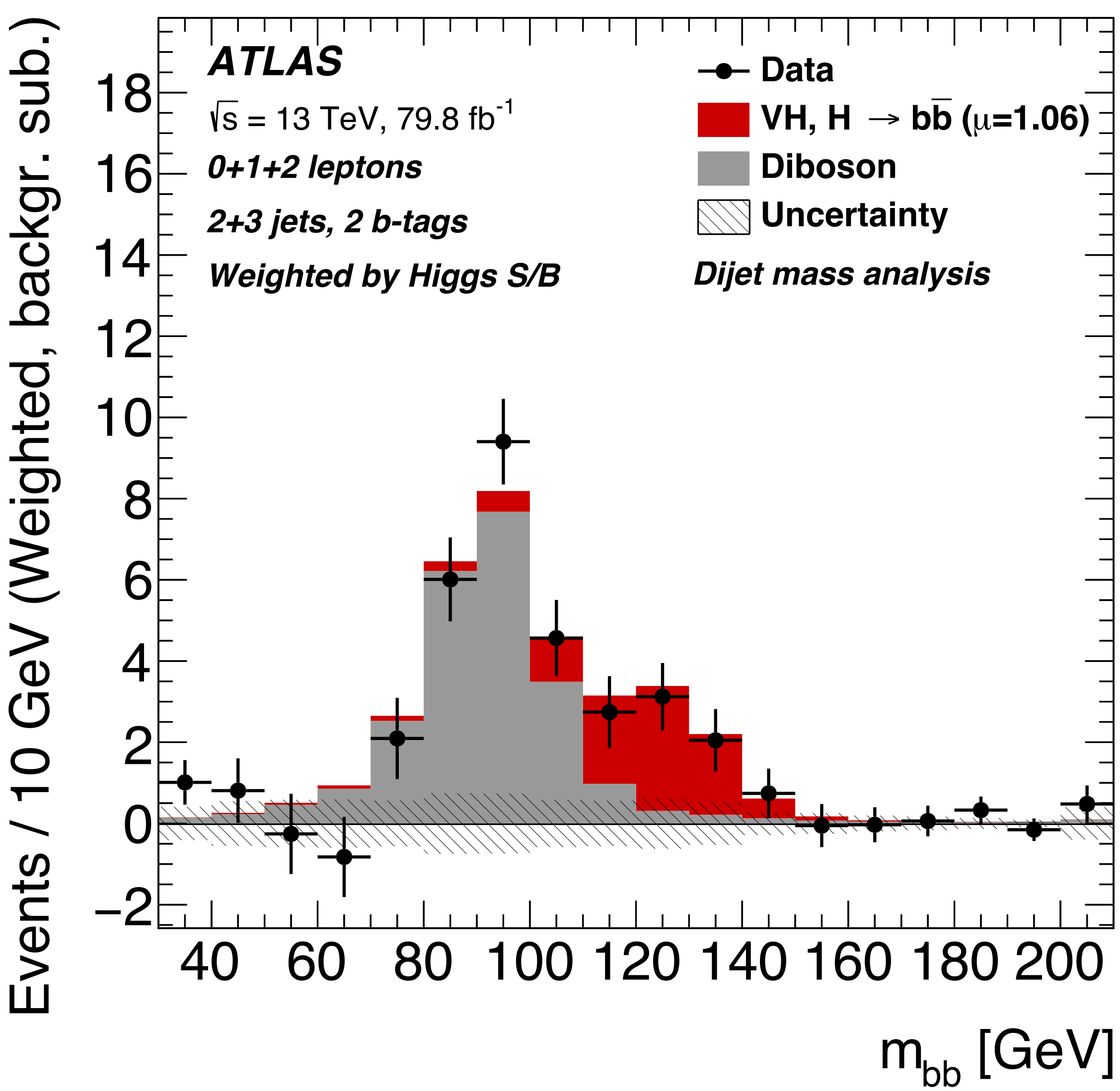
CMS: **5.2σ** (4.2σ)

H→bb decays (BR ~ 58%)

Analysis strategy

- need excellent b-jet tagging
- target VH production to reduce background
- categorization / multi-variate discriminants used
- special techniques to improve m_{bb} resolution





Combine VH production mode with results from VBF and ttH production

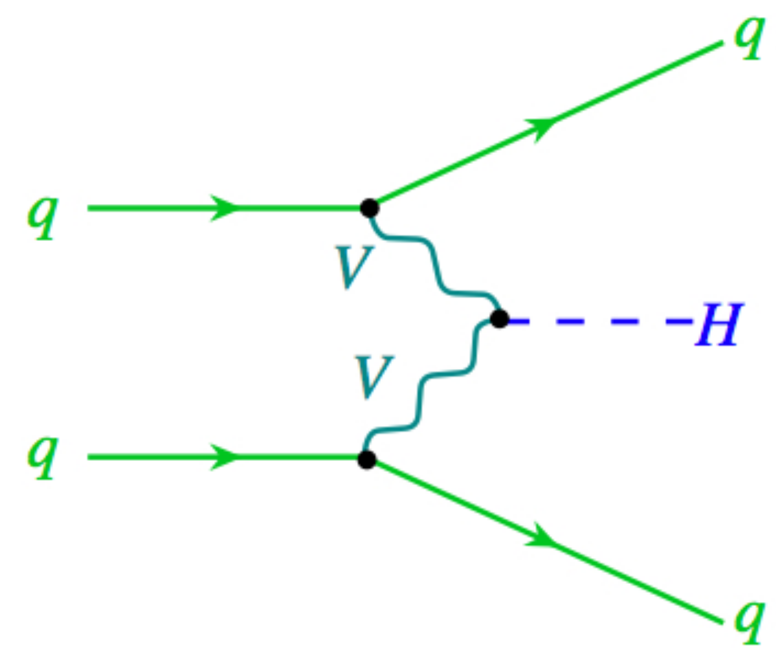
ATLAS: **5.5σ** (5.4σ)

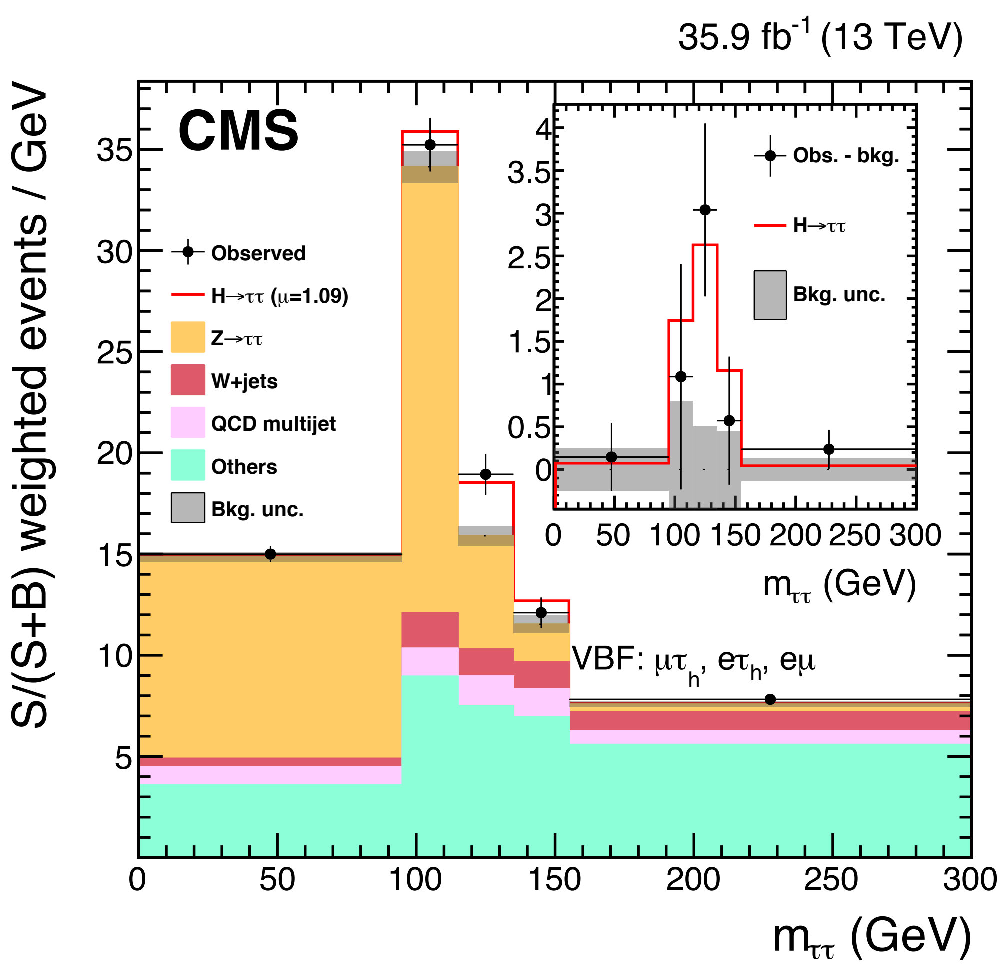
CMS: **5.6σ** (5.5σ)

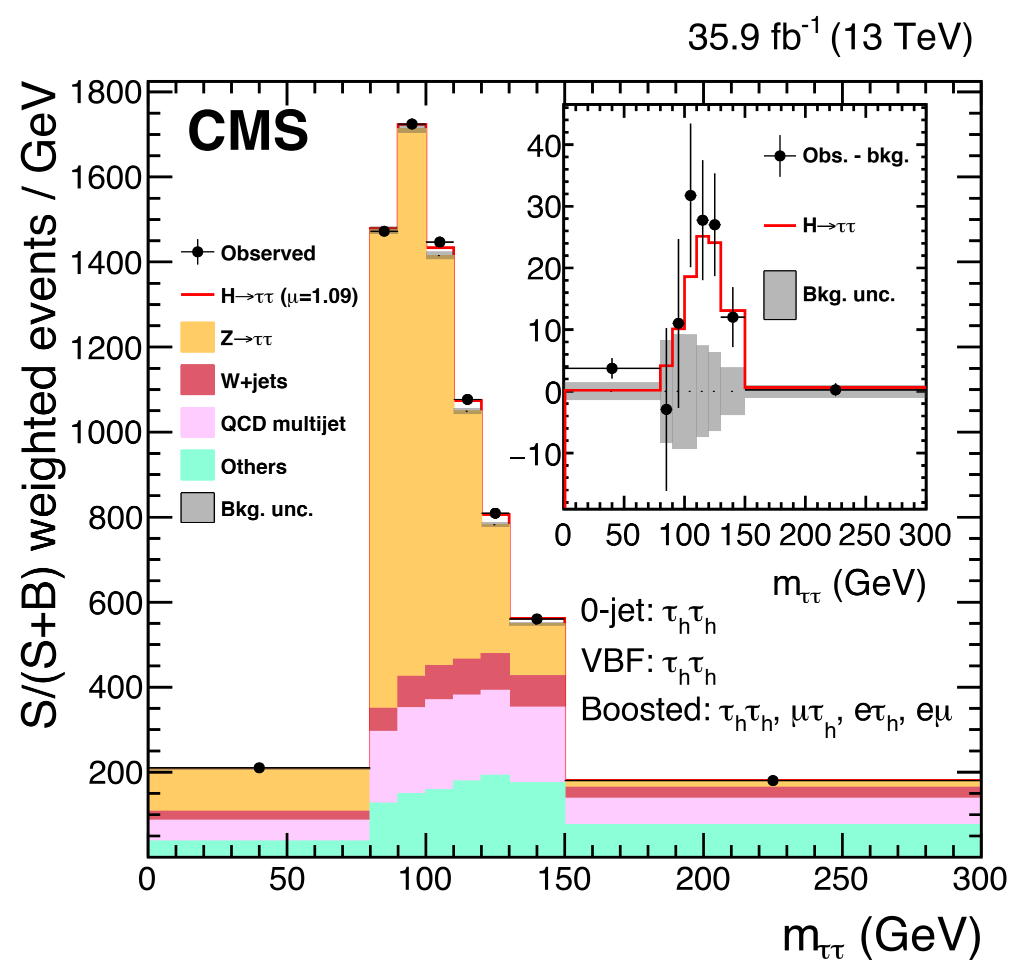
H→ττ decays (BR ~ 6%)

Analysis strategy

- need excellent τ lepton identification
- target VBF production to reduce background
- categorization / multi-variate discriminants used
- missing energy from neutrinos taken into account in invariant mass reconstruction



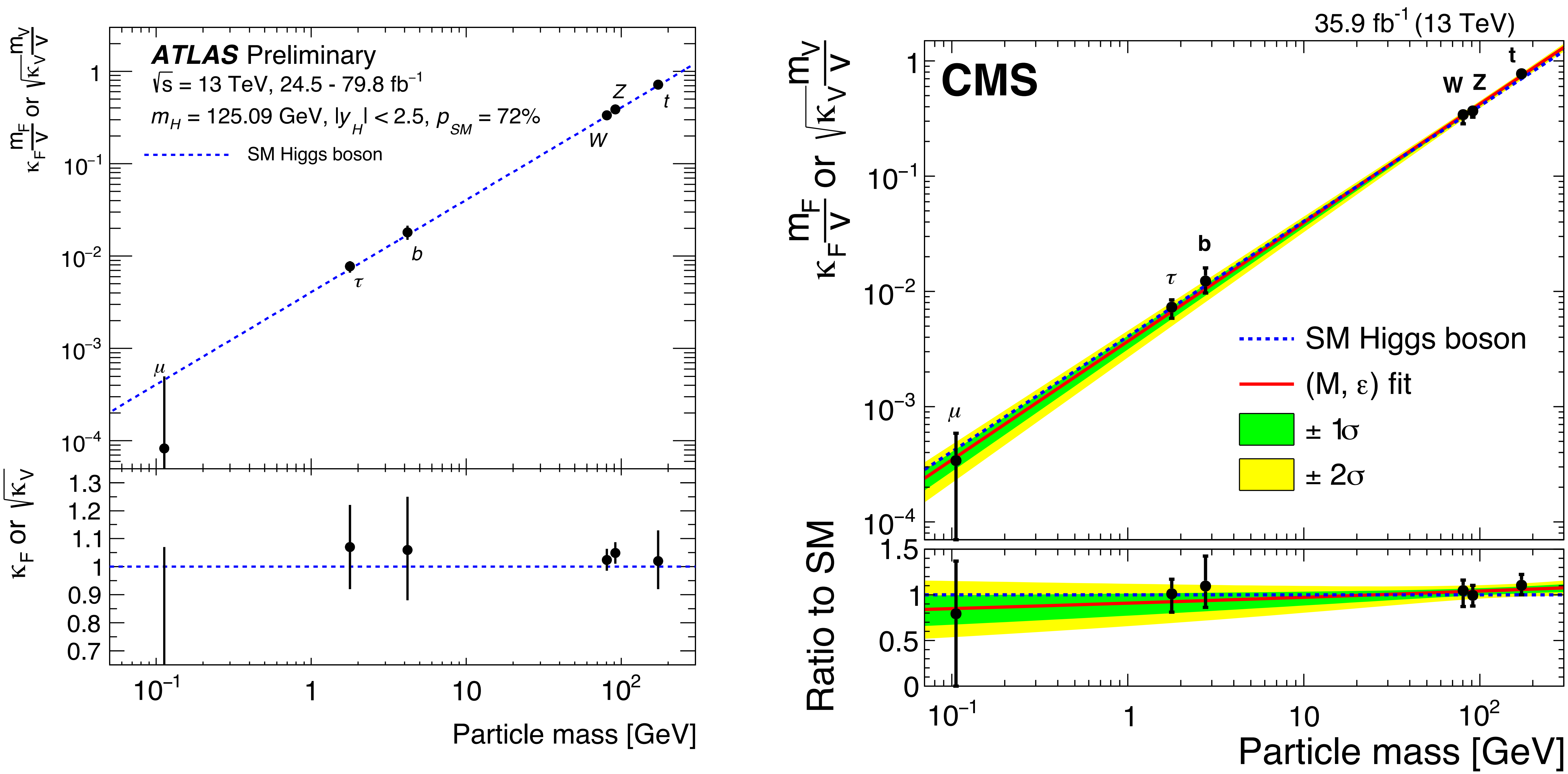




ATLAS: **6.4σ** (5.4σ)

CMS: **5.9σ** (5.9σ)

Summary of Higgs Couplings

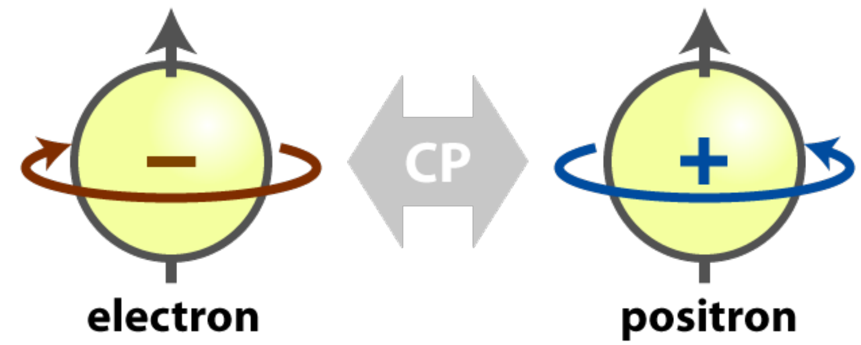


This particle seems consistent with all predicted Standard Model couplings

Main Run-2 achievement: direct observation of Higgs-fermion couplings

Higgs Boson Quantum Numbers

Clear SM prediction for Higgs boson quantum numbers: $J^{CP} = 0^+$

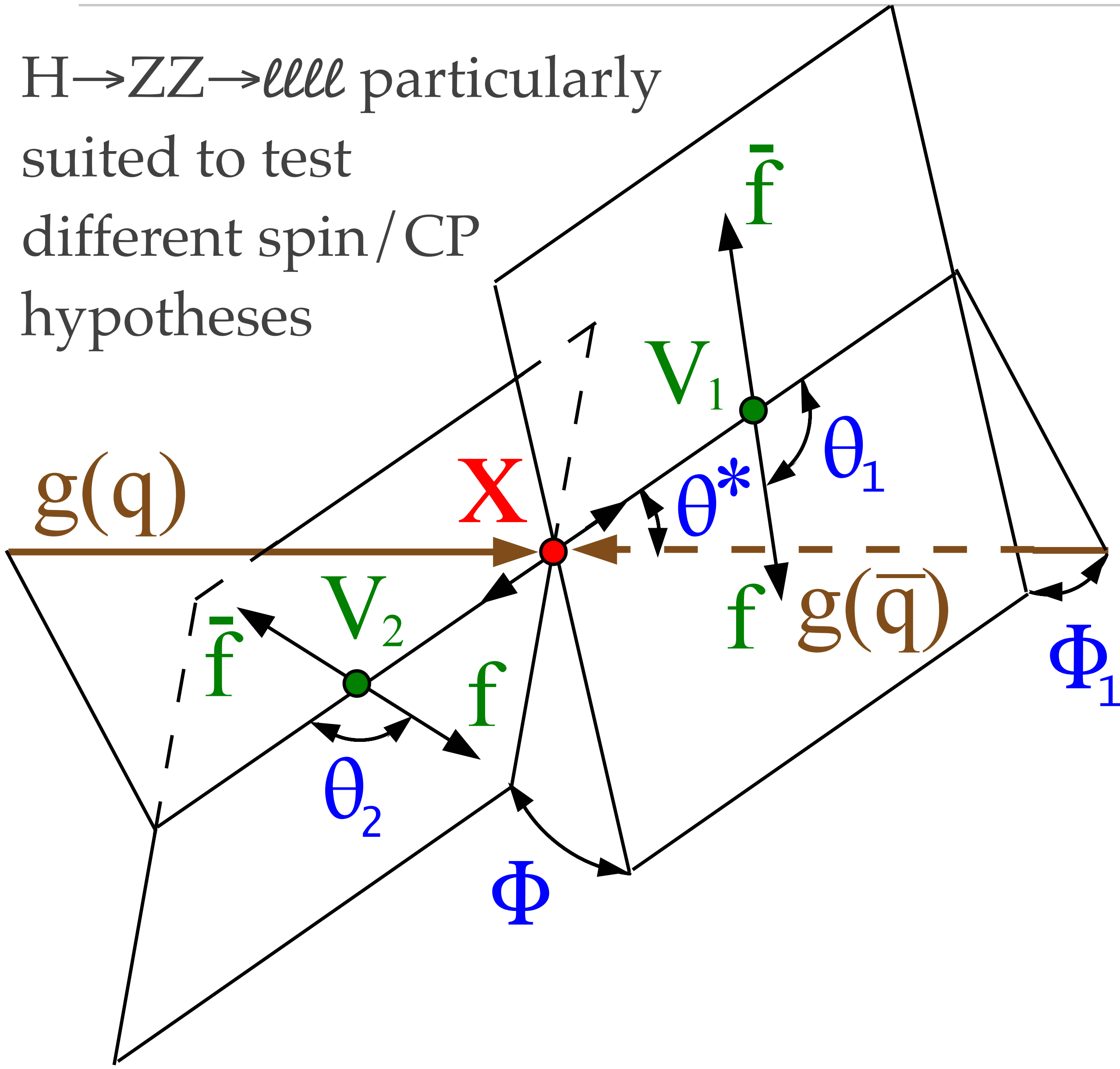


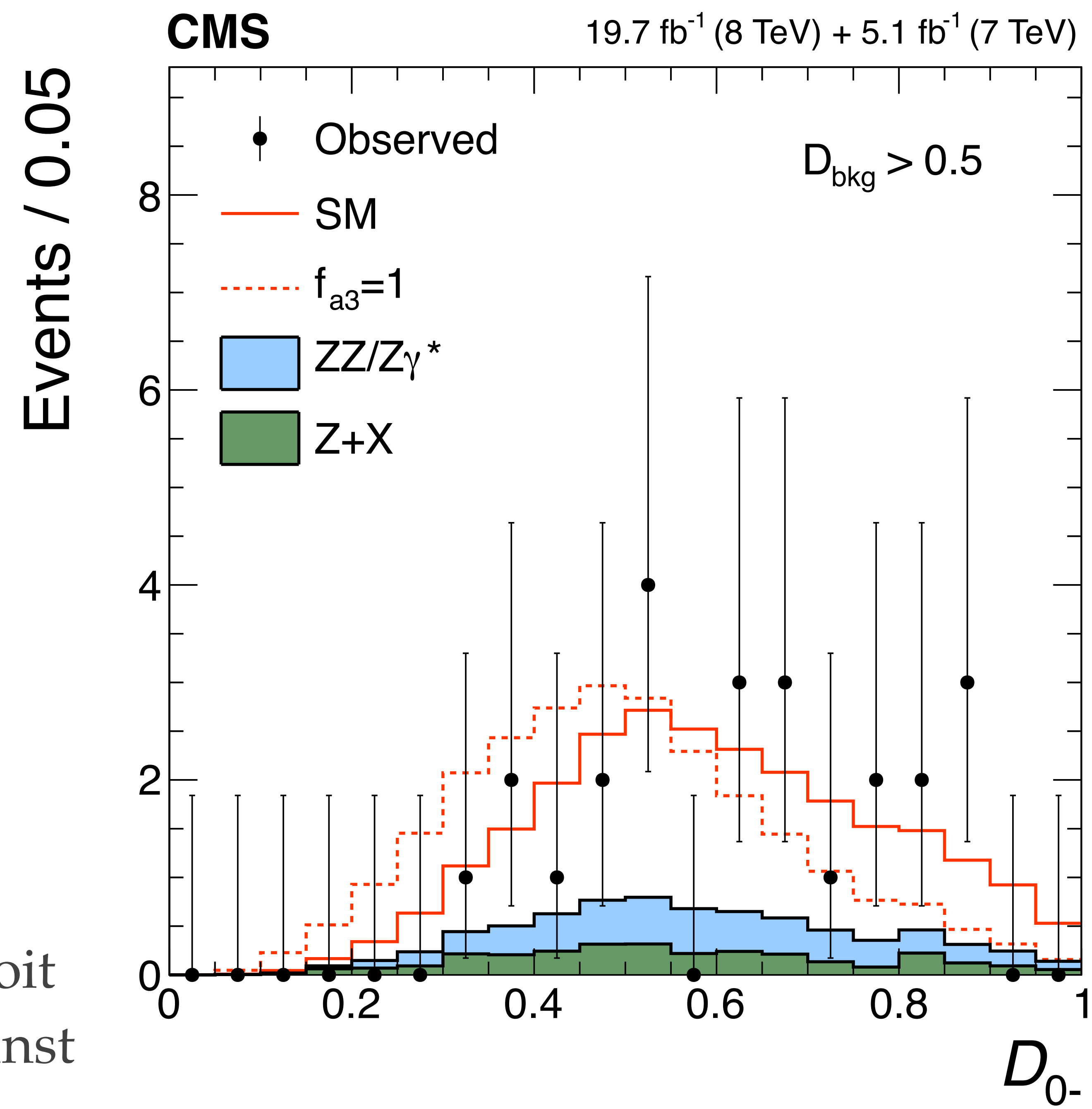
Spin/CP quantum numbers sensitive to angular correlations of Higgs boson production and decay products

Can use hypothesis testing to test SM prediction against alternatives

Determining Quantum Numbers: Angular Correlations

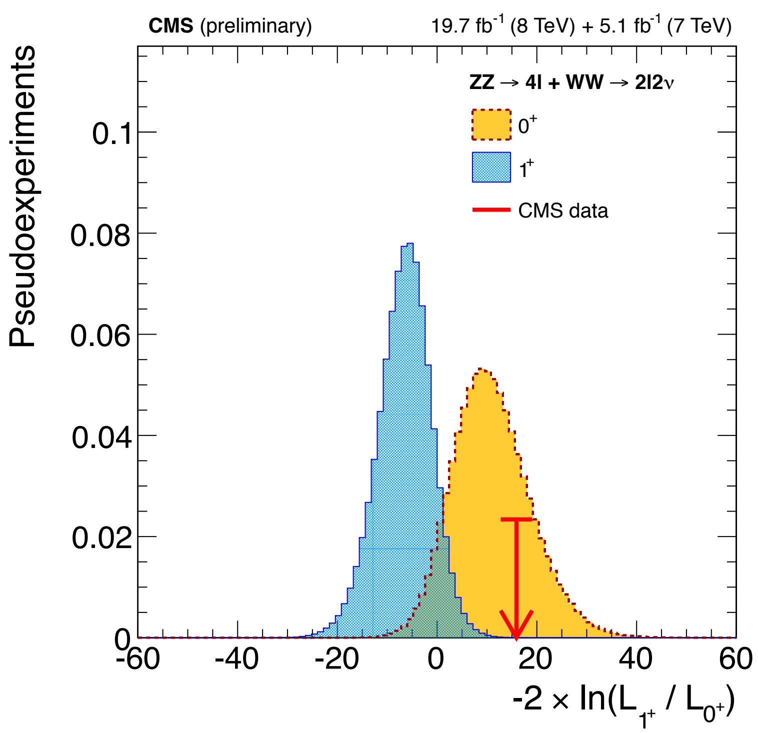
H→ZZ→ℓℓℓℓ particularly suited to test different spin/CP hypotheses

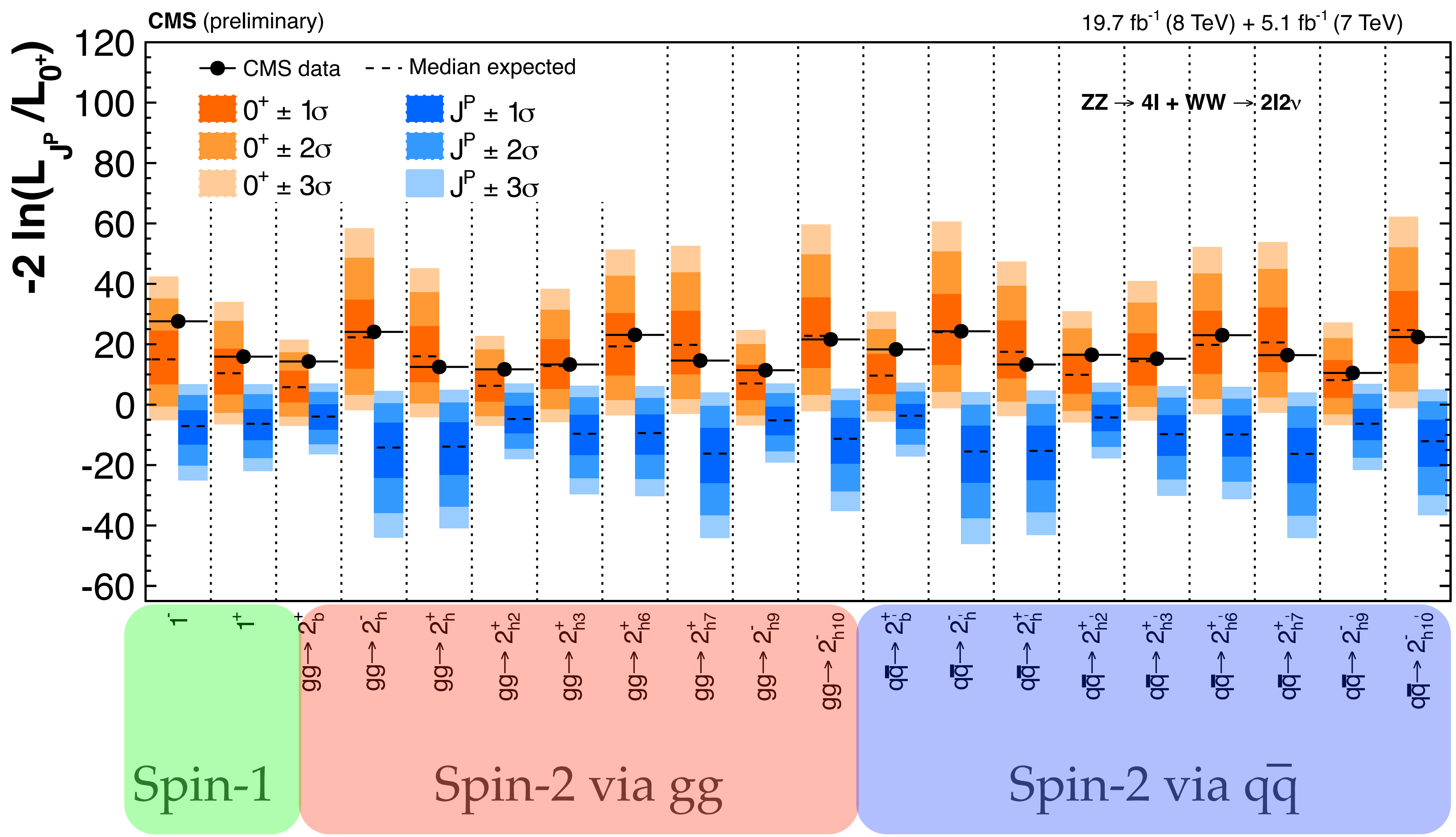




Form discriminants which exploit angular information to test against different spin/CP hypotheses

Spin/CP Results





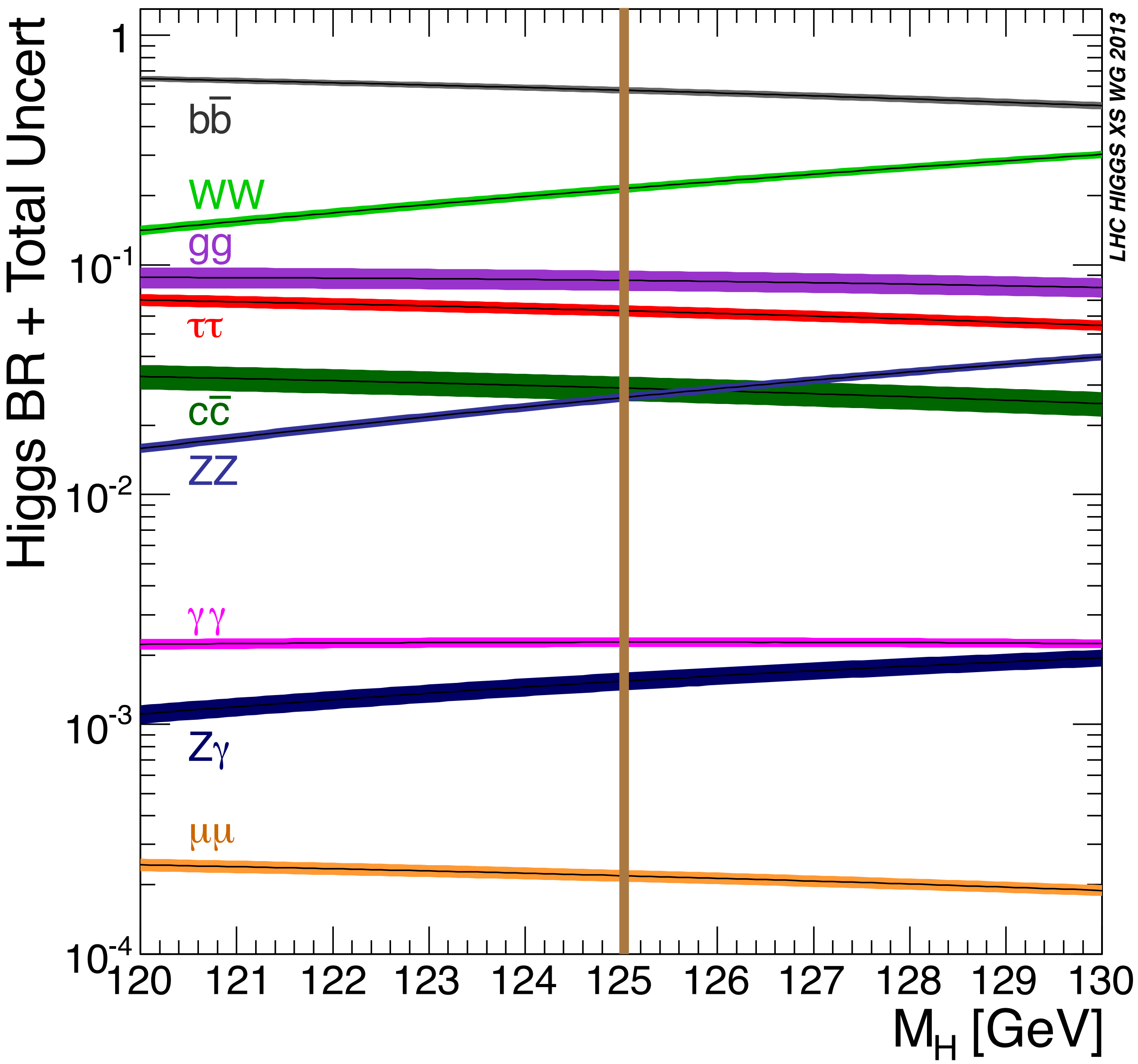
All alternative hypotheses excluded to more than 99.9% CL

Higgs boson very SM-like: small non-SM admixture not yet excluded

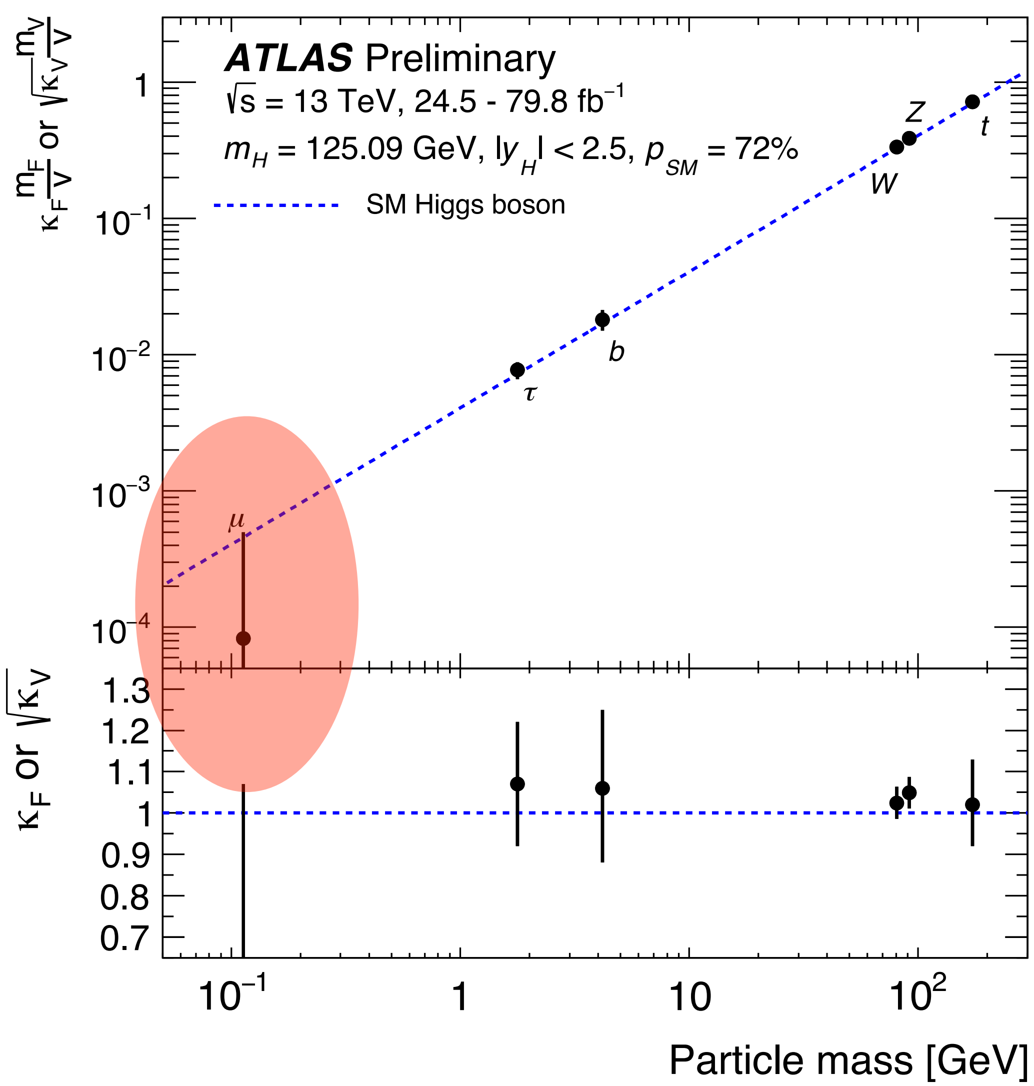
Searches for Rare Higgs Boson Production & Decays

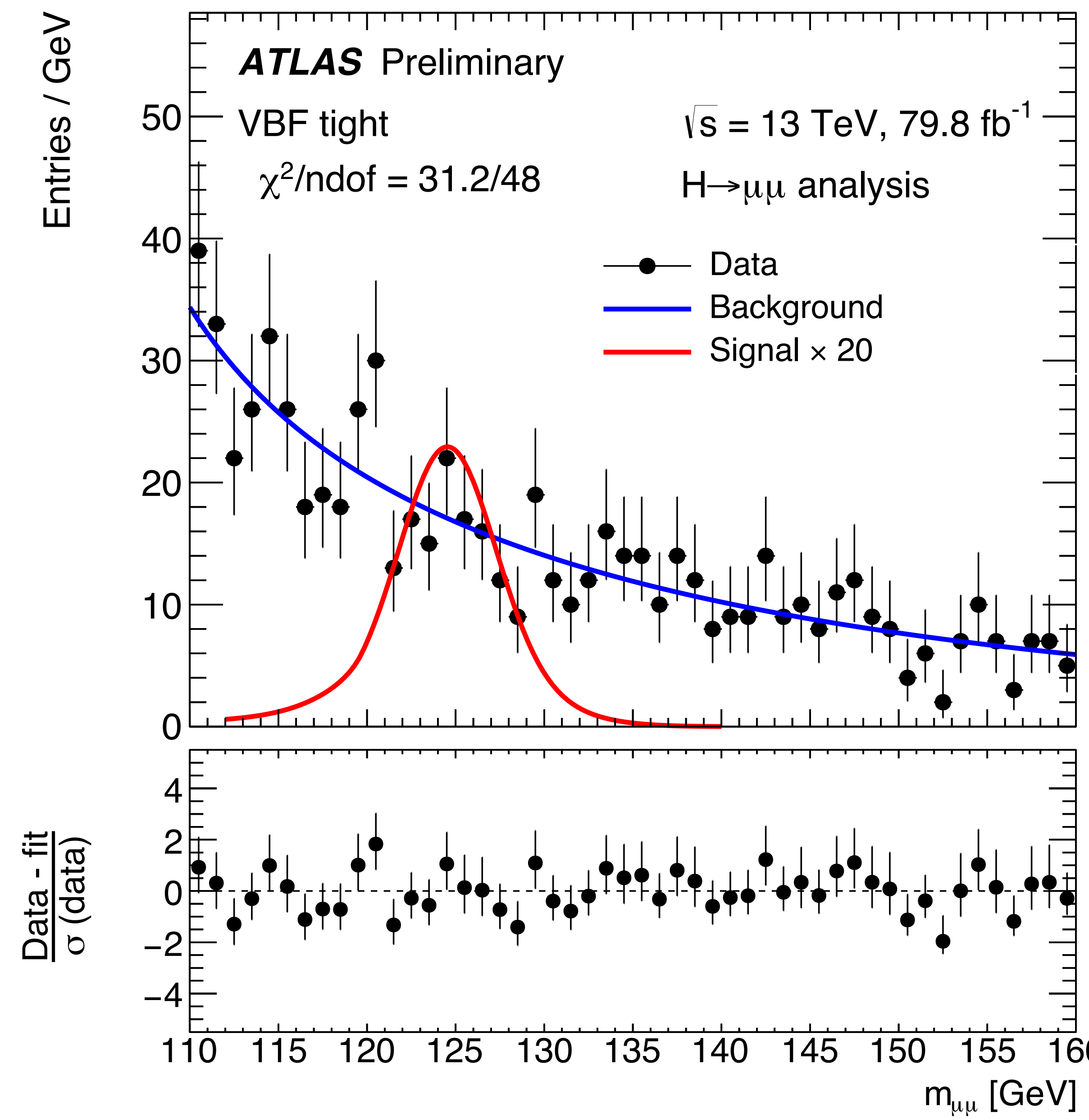
Searches for rare SM decays

- **H→μμ (probe 2nd generation lepton coupling)**
- **H→Zγ (probe loop decay)**



Searching for H→μμ





Best chance to establish Higgs couplings to 2nd generation fermions

ATLAS: $BR_{H\to\mu\mu}$ < **2.0** x BR_{SM} (95% CL)

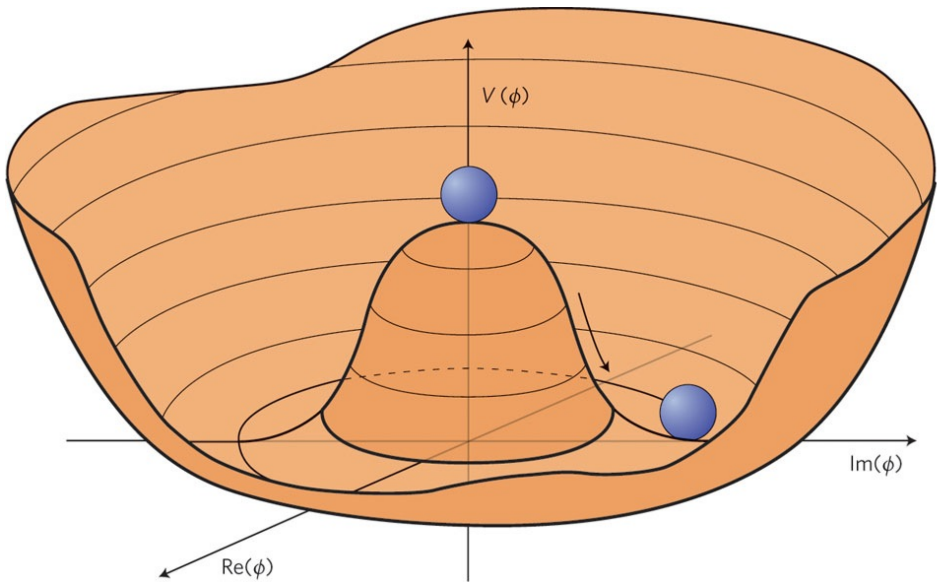
CMS: $BR_{H\to\mu\mu}$ < **2.9** x BR_{SM} (95% CL)

The channel to watch in **Run-3**

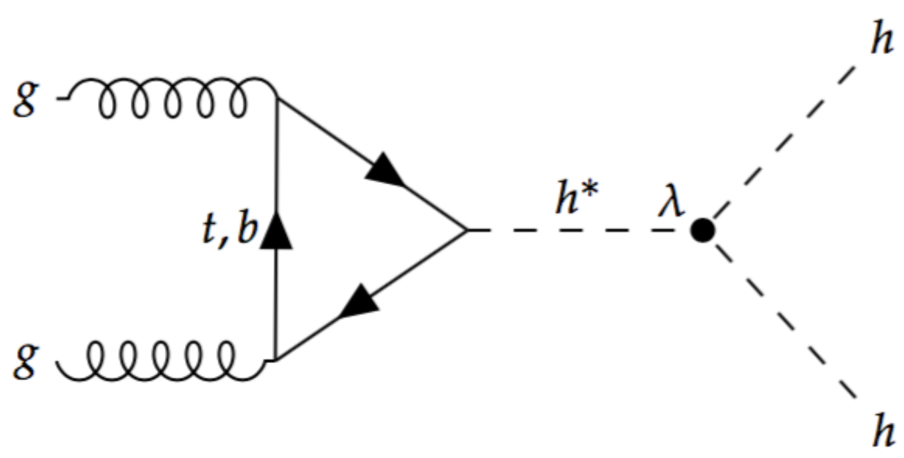
The Higgs Self-Coupling & Higgs-Pair Production

The "holy grail" of Higgs physics

Direct measurement of the Higgs potential

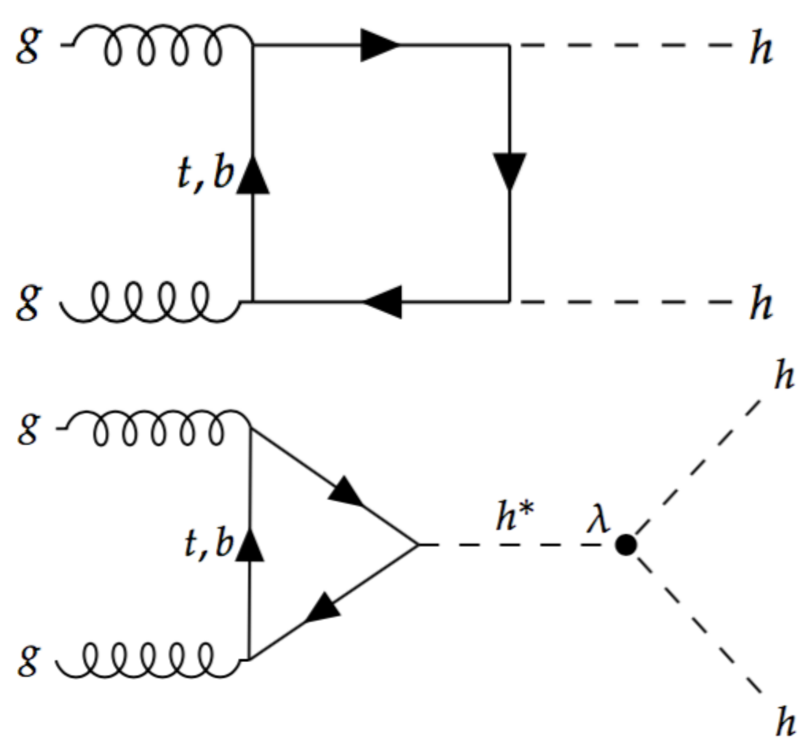


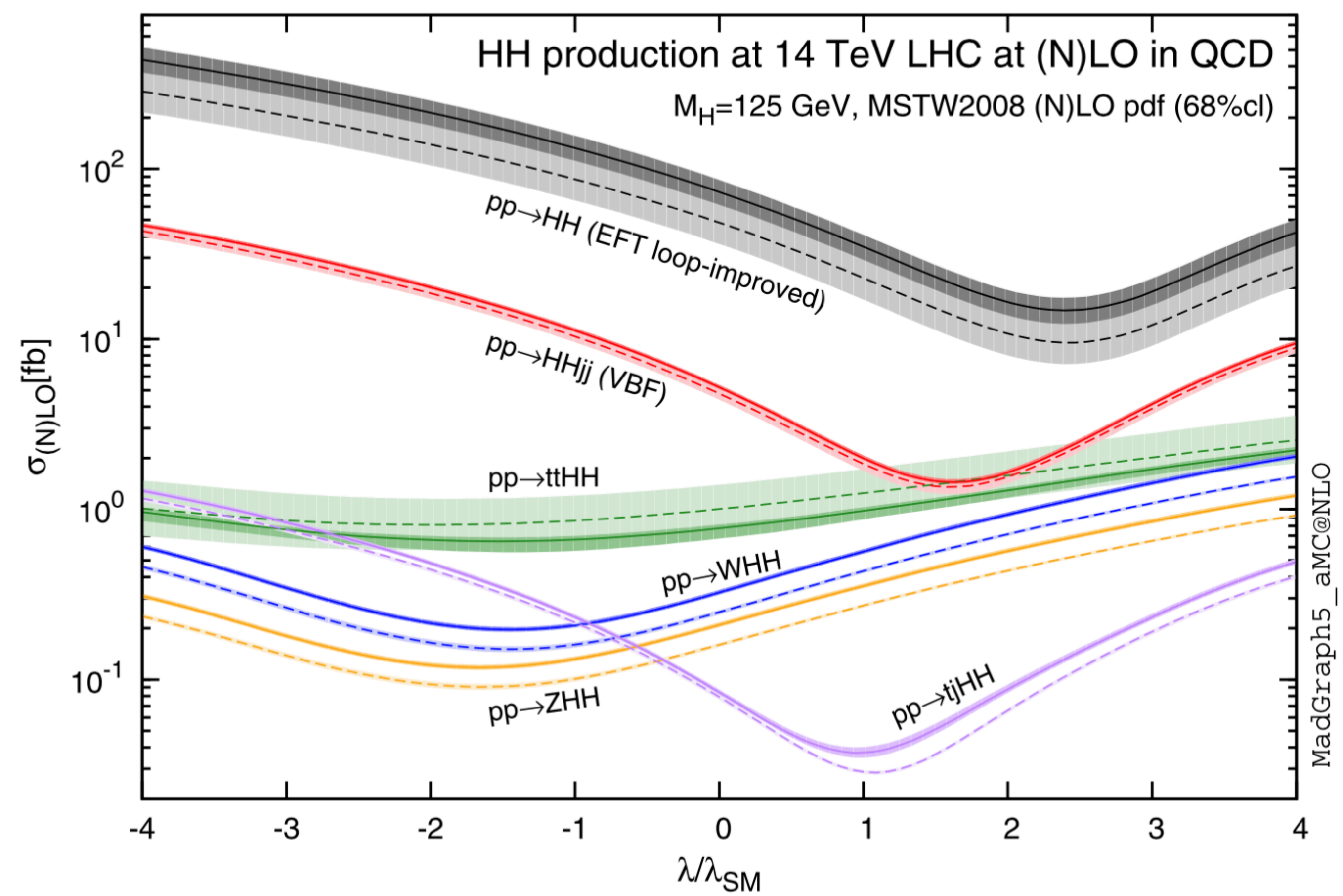
$$V(\Phi) = \mu^2 \Phi^*\Phi + \lambda |\Phi^*\Phi|^2$$



Searches for Higgs-Pair Production

negative interference between diagrams





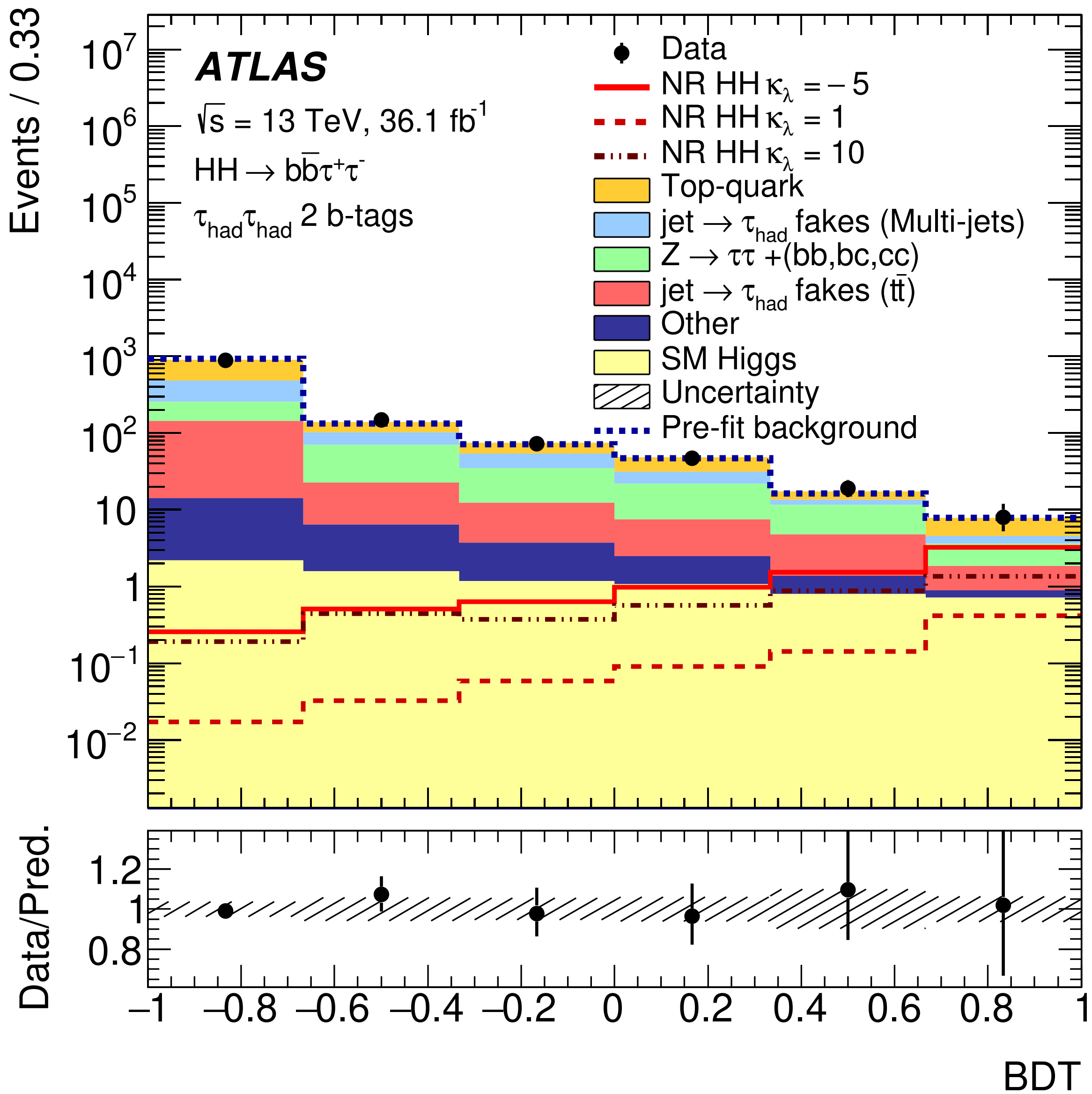
interference at maximum when $\lambda \sim 2 \times \lambda_{SM}$

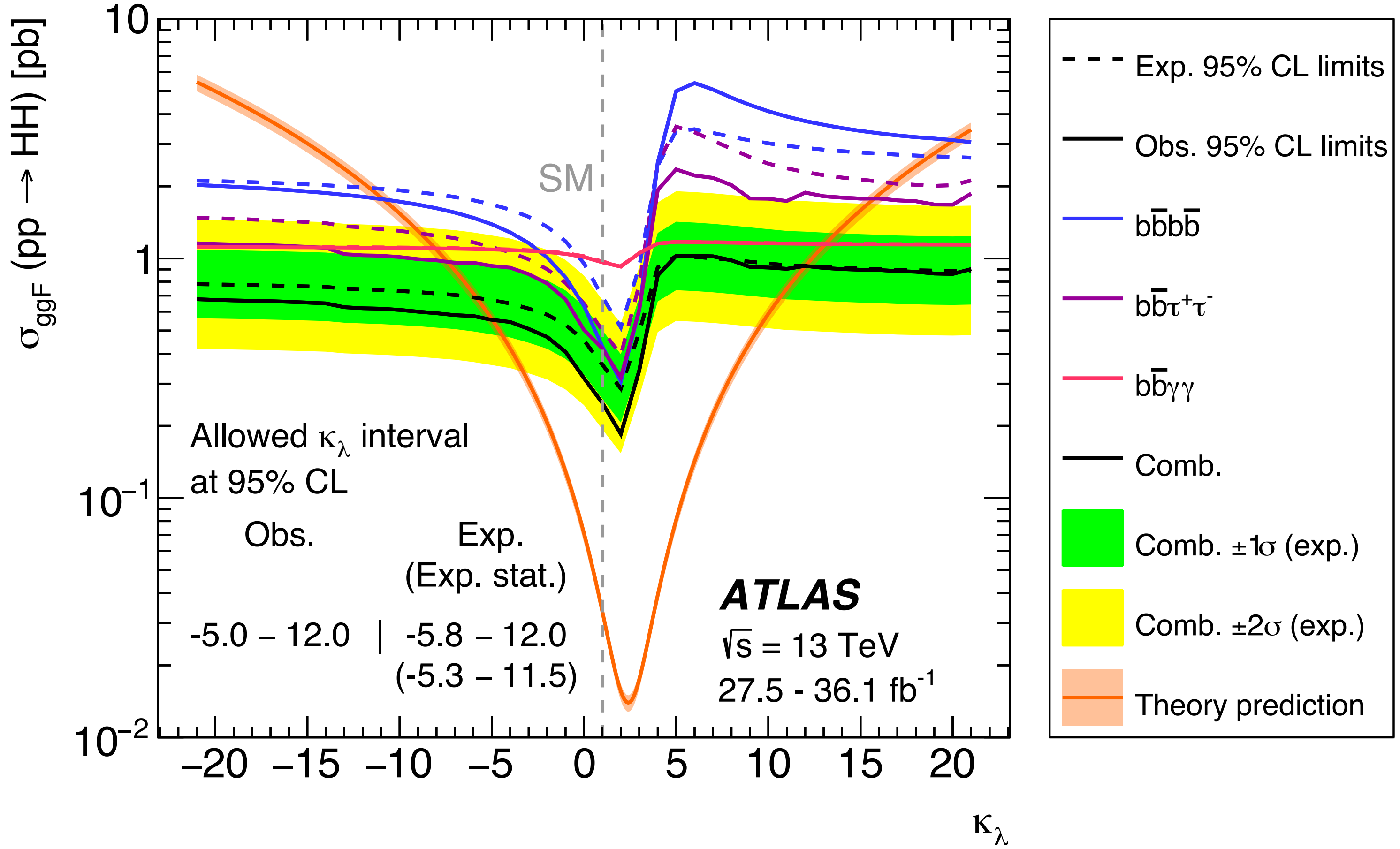
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Search for Higgs-pair production across many channels

Most sensitive: bbbb, $bb\tau\tau$, $bb\gamma\gamma$

Higgs-Pair Production Searches





ATLAS: $-5.0 \times \lambda_{SM} < \boldsymbol{\lambda} < 12.0 \times \lambda_{SM}$ (95% CL)

CMS: $-11.8 \times \lambda_{SM} < \boldsymbol{\lambda} < 18.8 \times \lambda_{SM}$ (95% CL)

Searches are statistics limited: more data will constrain λ even more!

The Precision Higgs Era has clearly started….

In this talk we saw that with Run-2:

- Higgs mass measured to unprecedented precision
- Higgs couplings to the fermion sector confirmed
- Exclusion of alternative spin and CP hypotheses for the Higgs boson
- Approaching sensitivity to Higgs couplings with 2nd generation fermions
- Excluding large values of the Higgs self-coupling

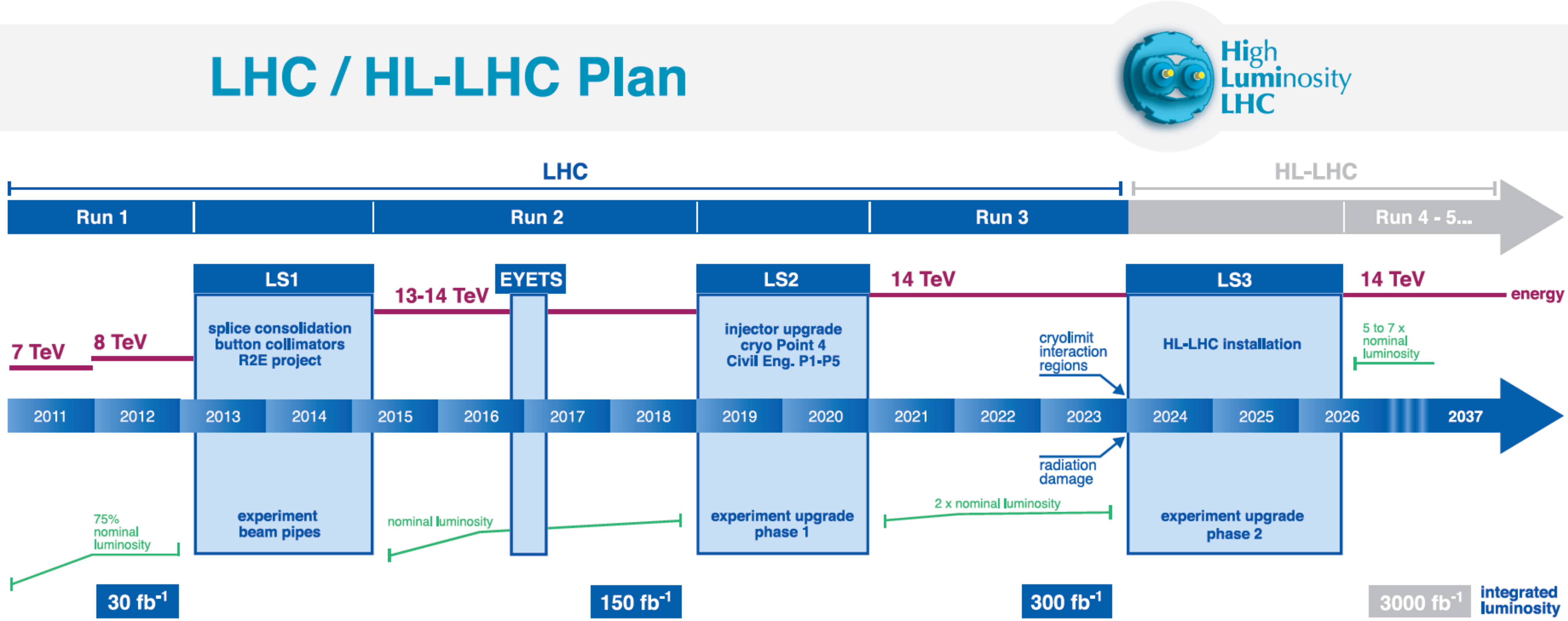
In addition:

- differential cross-sections measured
- exclusions of large anomalous couplings
- increasing sensitivity to CP-admixture scenarios
- inference of limits on Higgs width from off-shell measurements

We have learned much about the "personality" of the Higgs boson at the end of Run-2

Run-3 and the HL-LHC

…but the precision era will continue

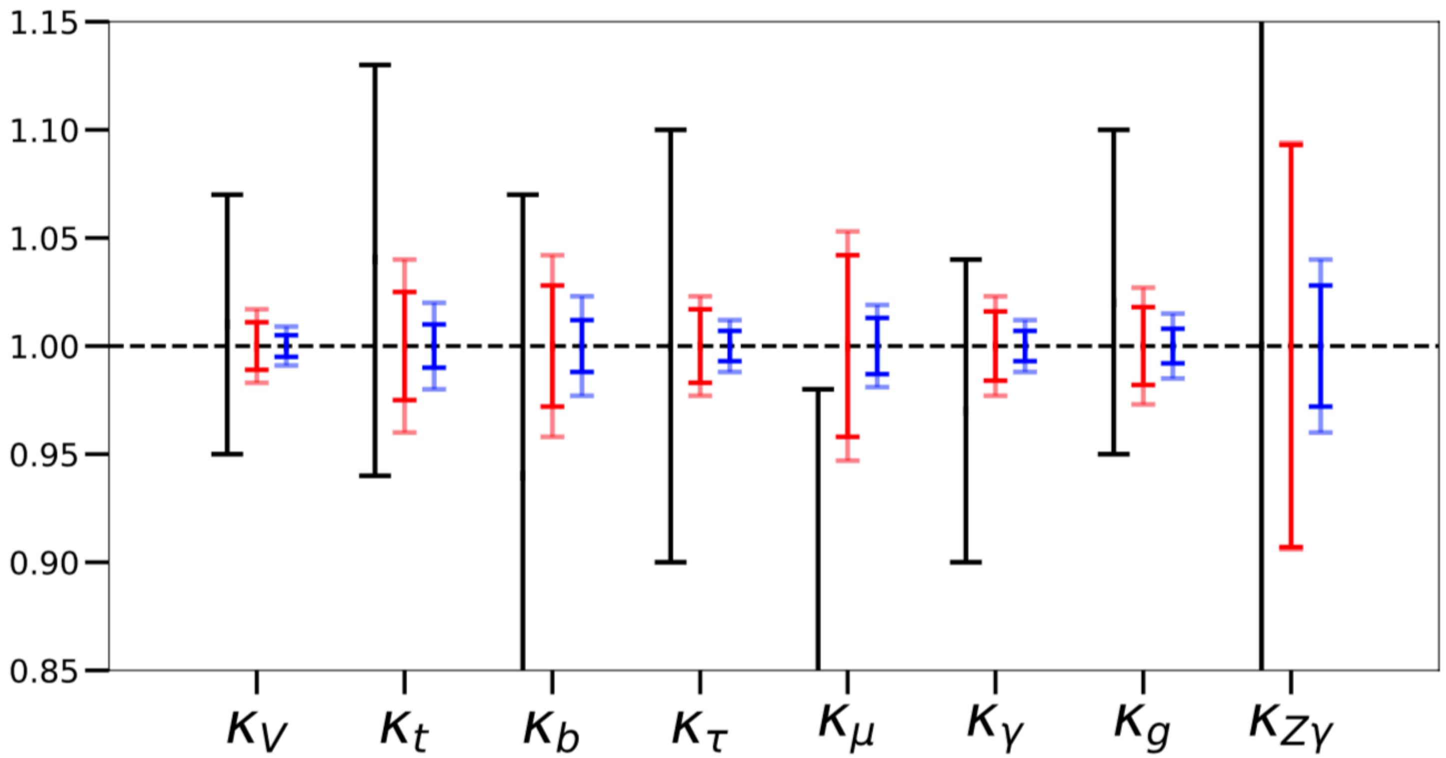


increase in data by ~2 orders of magnitude to 3000 fb^{-1}

increase in energy to 14 TeV

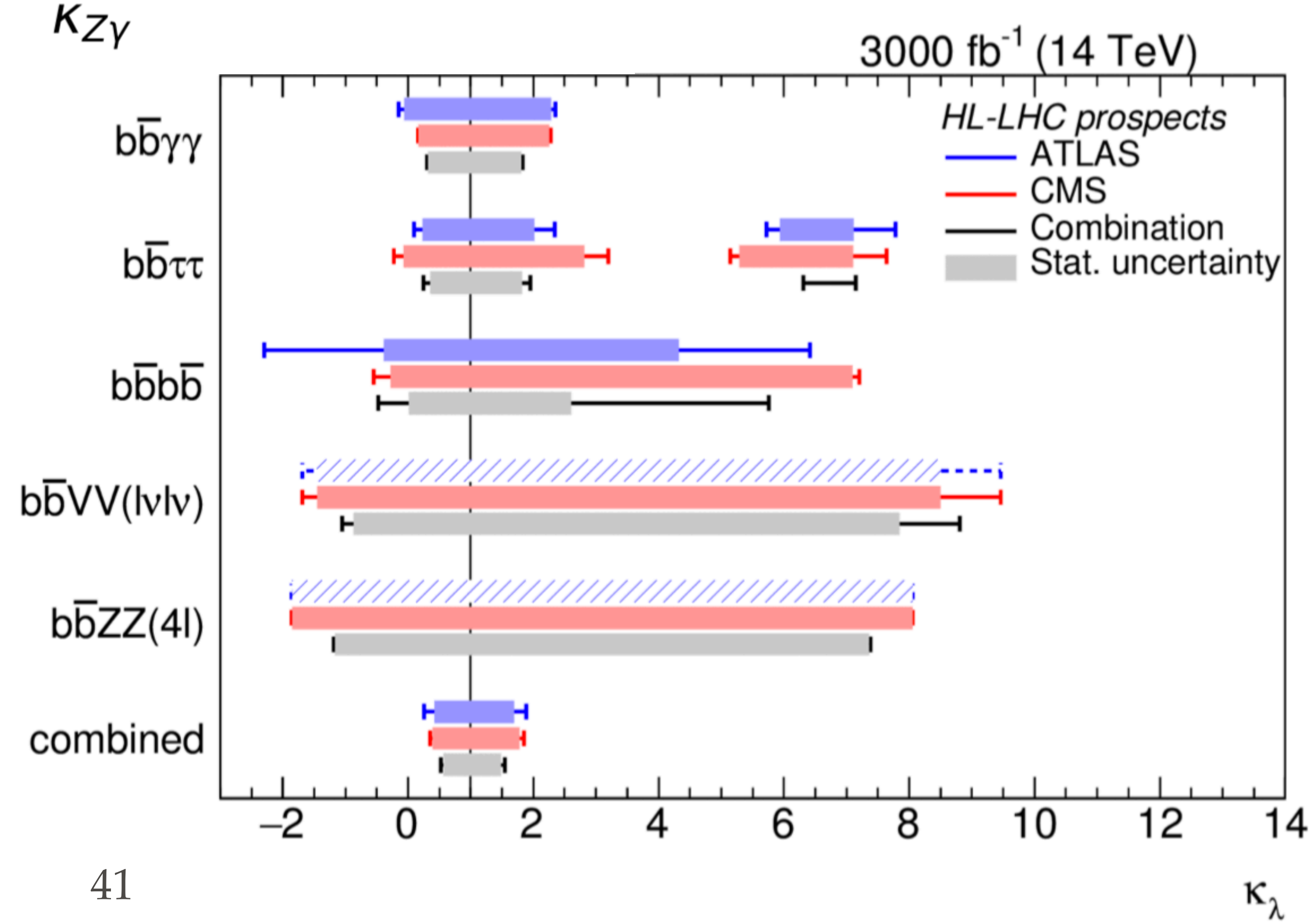
Significant upgrades to accelerator complex and LHC detectors

Sensitivity Estimates



Projections on the Higgs coupling scale factors

Projection on sensitivity to Higgs-self-coupling



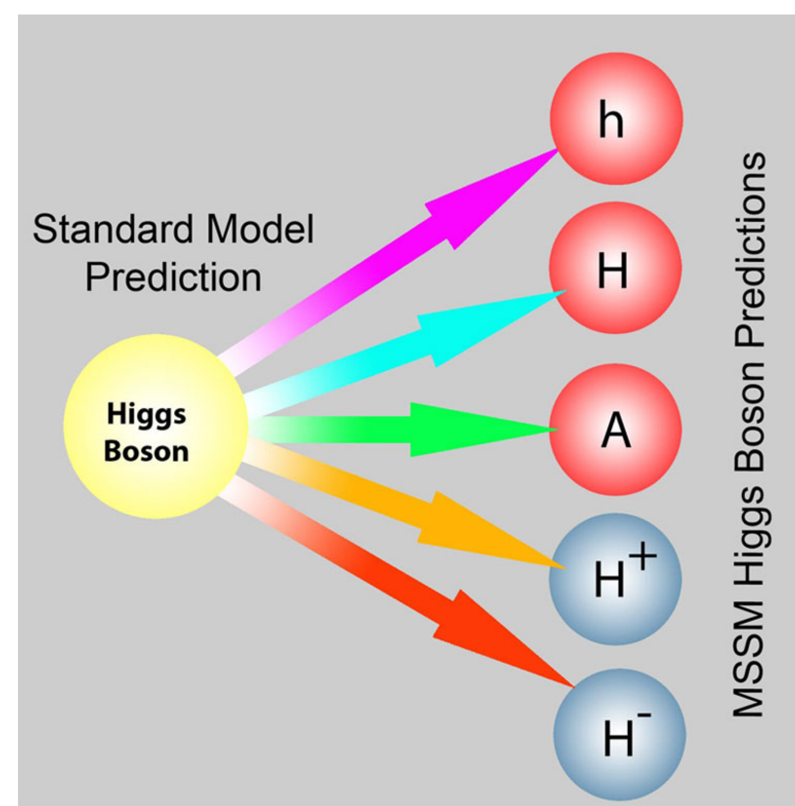
Summary & Outlook

We have come to know much more about the Higgs boson in the last 7 years

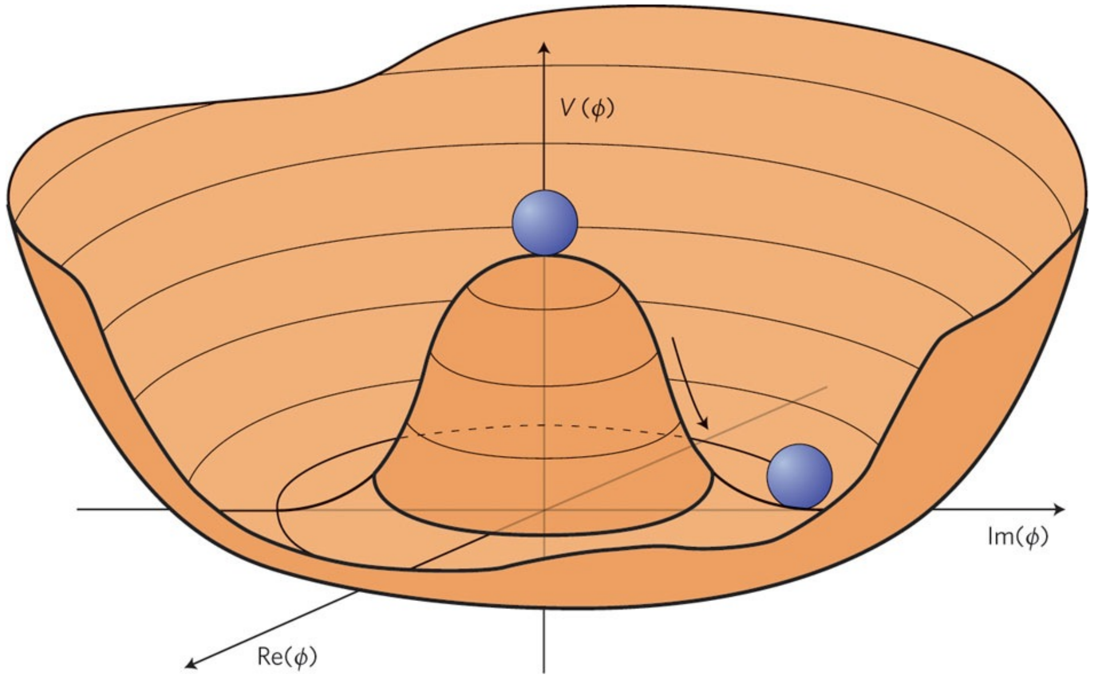
Its personality thus far is very "standard"

But the teenage years are still to come ;)

Maybe it has siblings we don't know about ;)

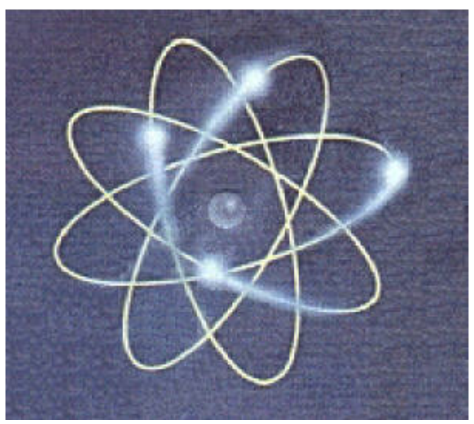
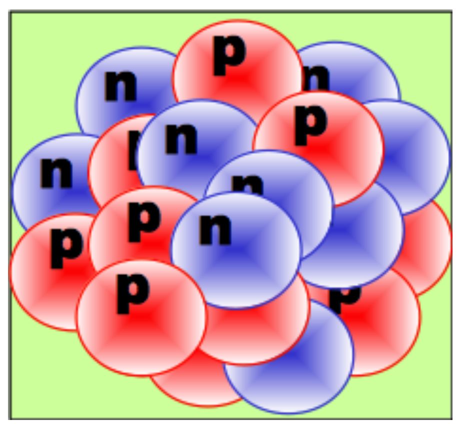
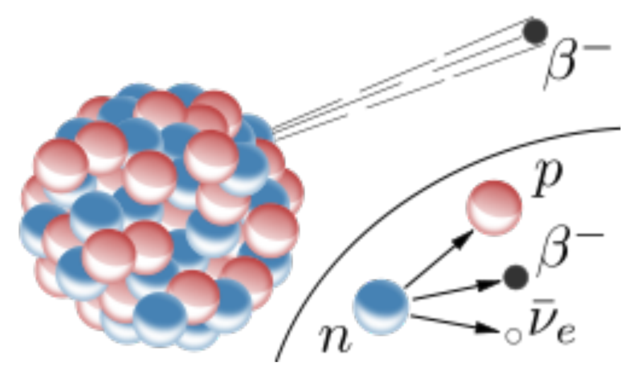


Thanks for your attention!!



Fundamental Forces/Interactions

Four fundamental forces/interactions that we know about

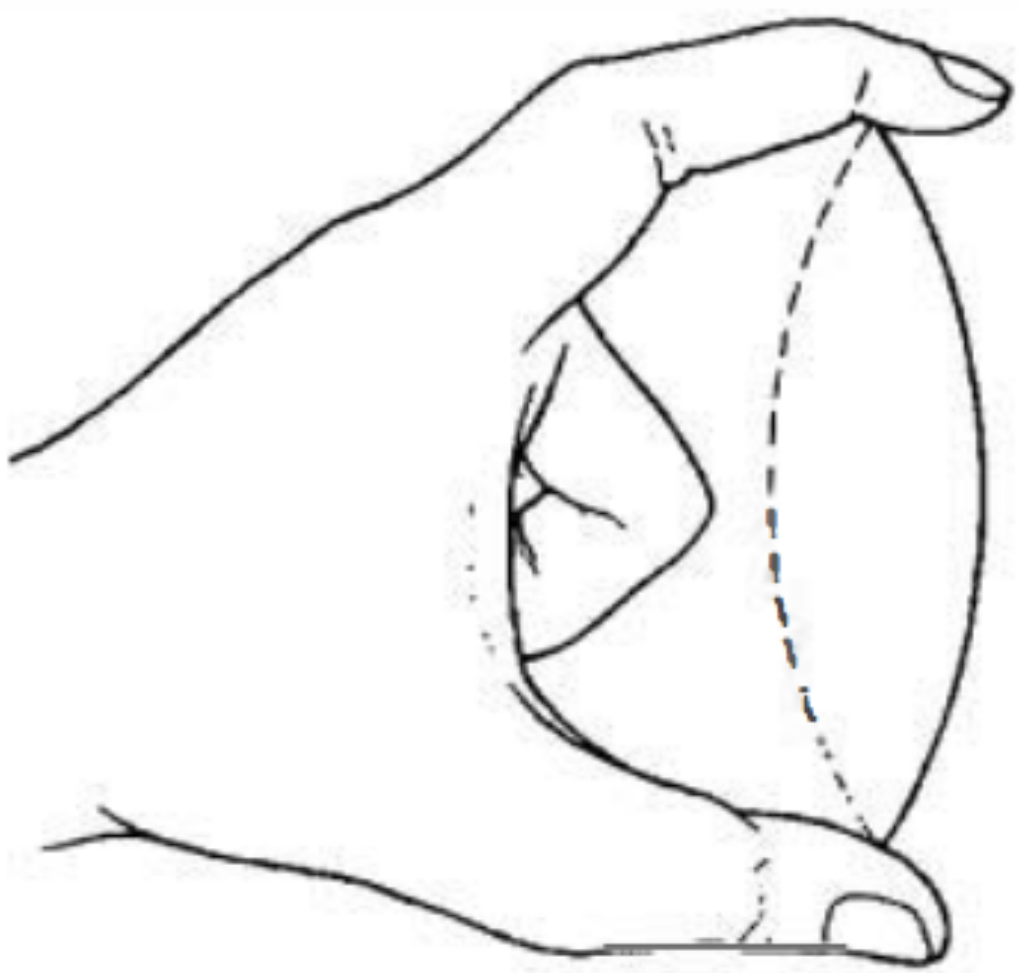
Electromagnetic	Strong Nuclear	Weak Nuclear	Gravity (very weak!)
			
photons	gluons	W/Z bosons	graviton???

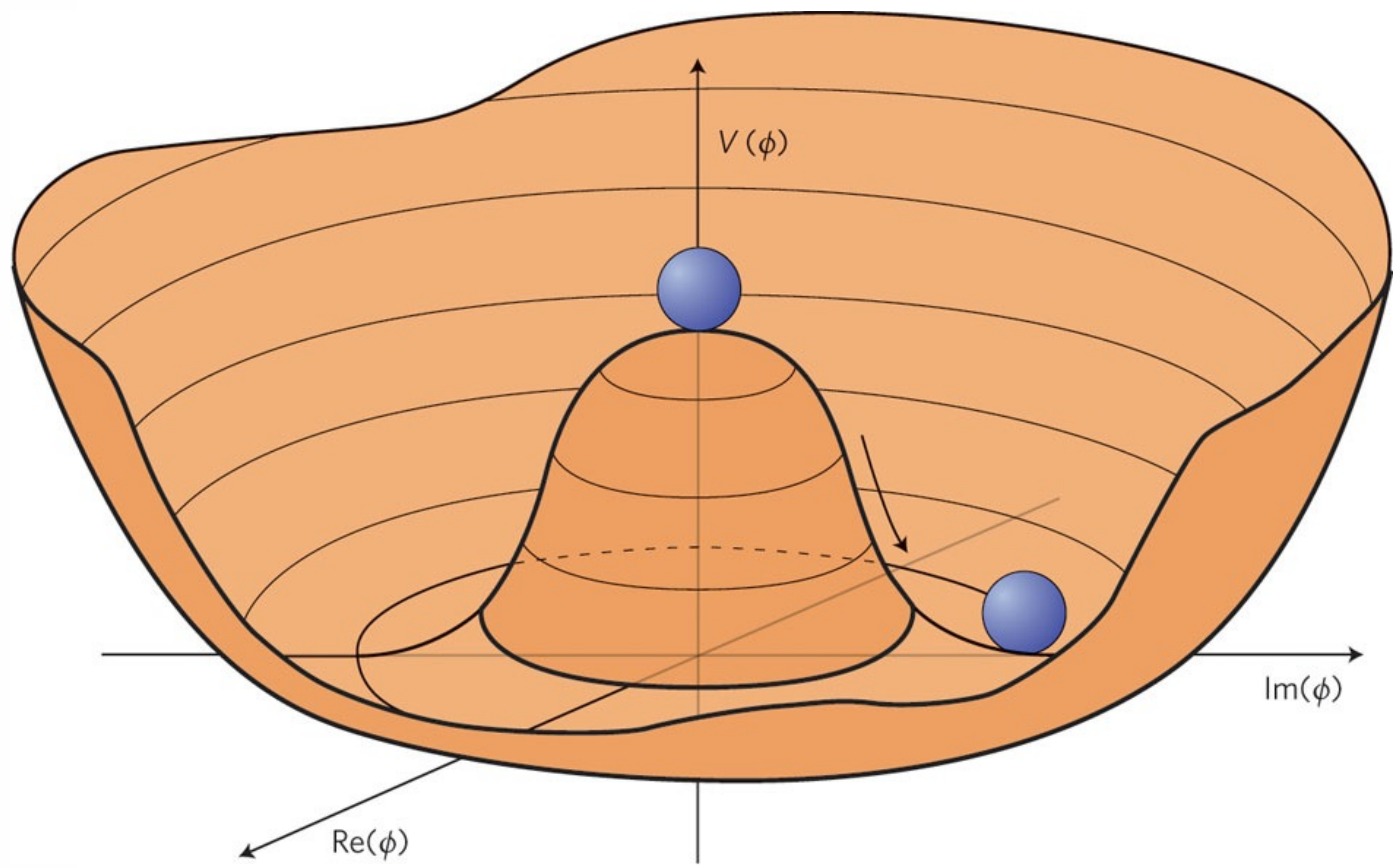
At the quantum mechanical level, forces transmitted by particles (force carriers)

- all interactions we know of can be described by these forces (and particles of the Standard Model)

Symmetry Breaking

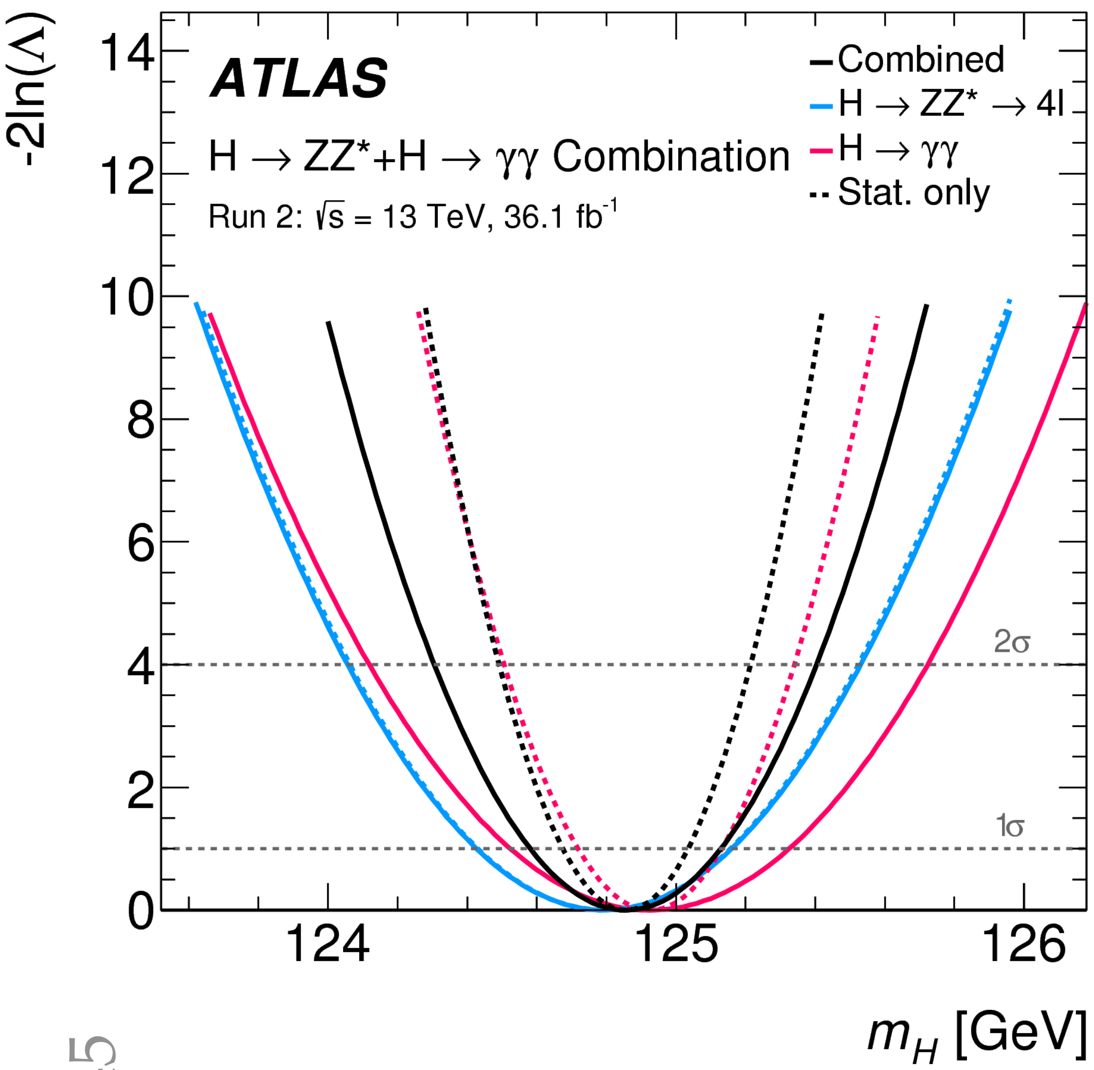
Examples of symmetry breaking





The vacuum state hides the symmetry of the system

Higgs Mass: ATLAS results & systematics



Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20
$H \to \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10

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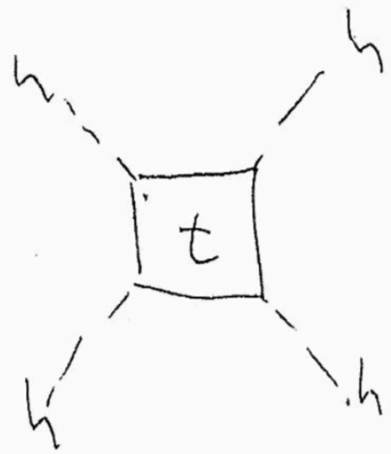
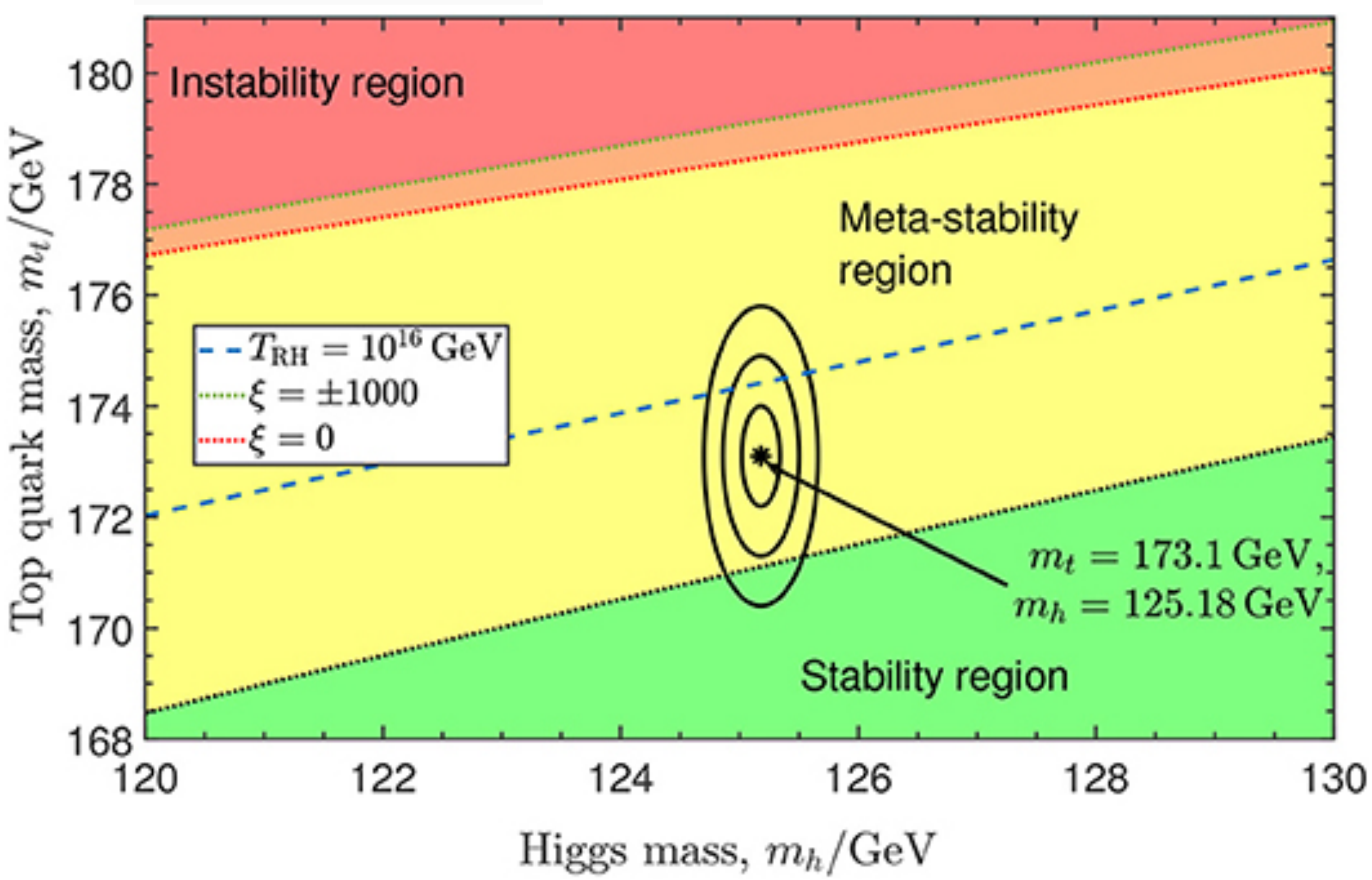
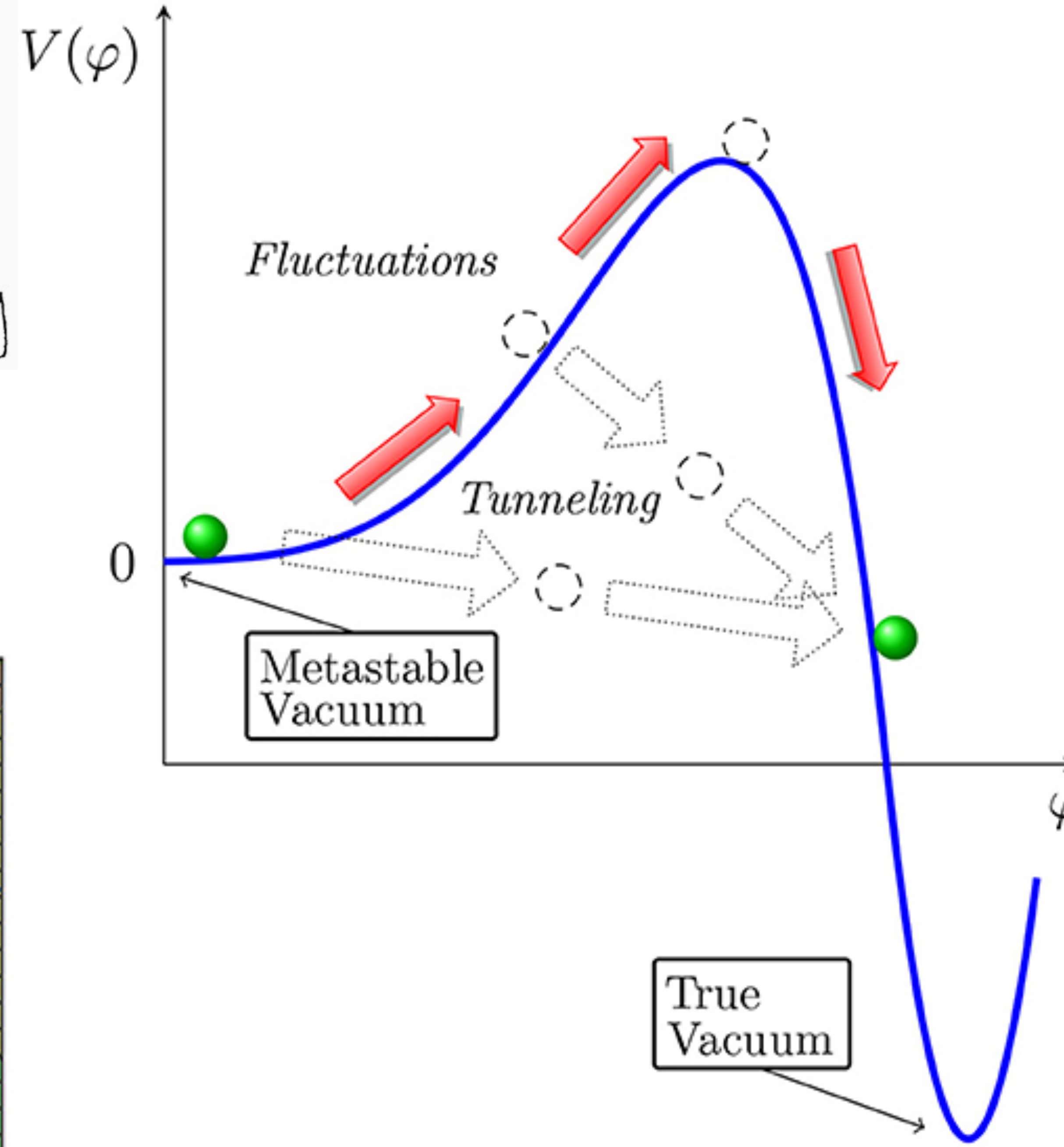
The Higgs Mass and the Fate of the Universe

$$\frac{d\lambda(Q^2)}{d(\ln Q^2)} = \frac{3}{4\pi^2}\left[\lambda^2 + \lambda g_t^2 - g_t^4/4 \ldots\right]$$

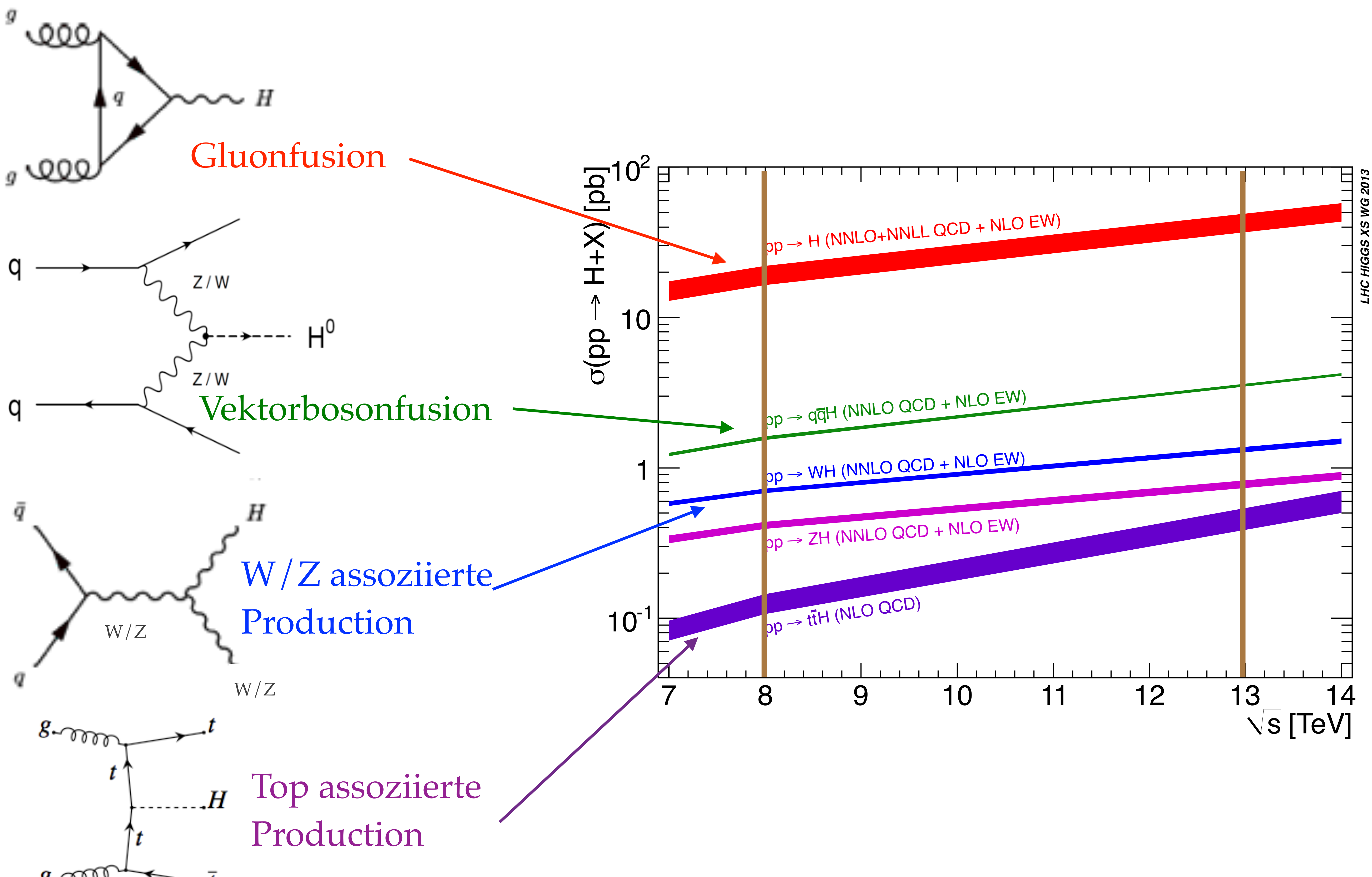
g_t: top Yukawa coupling



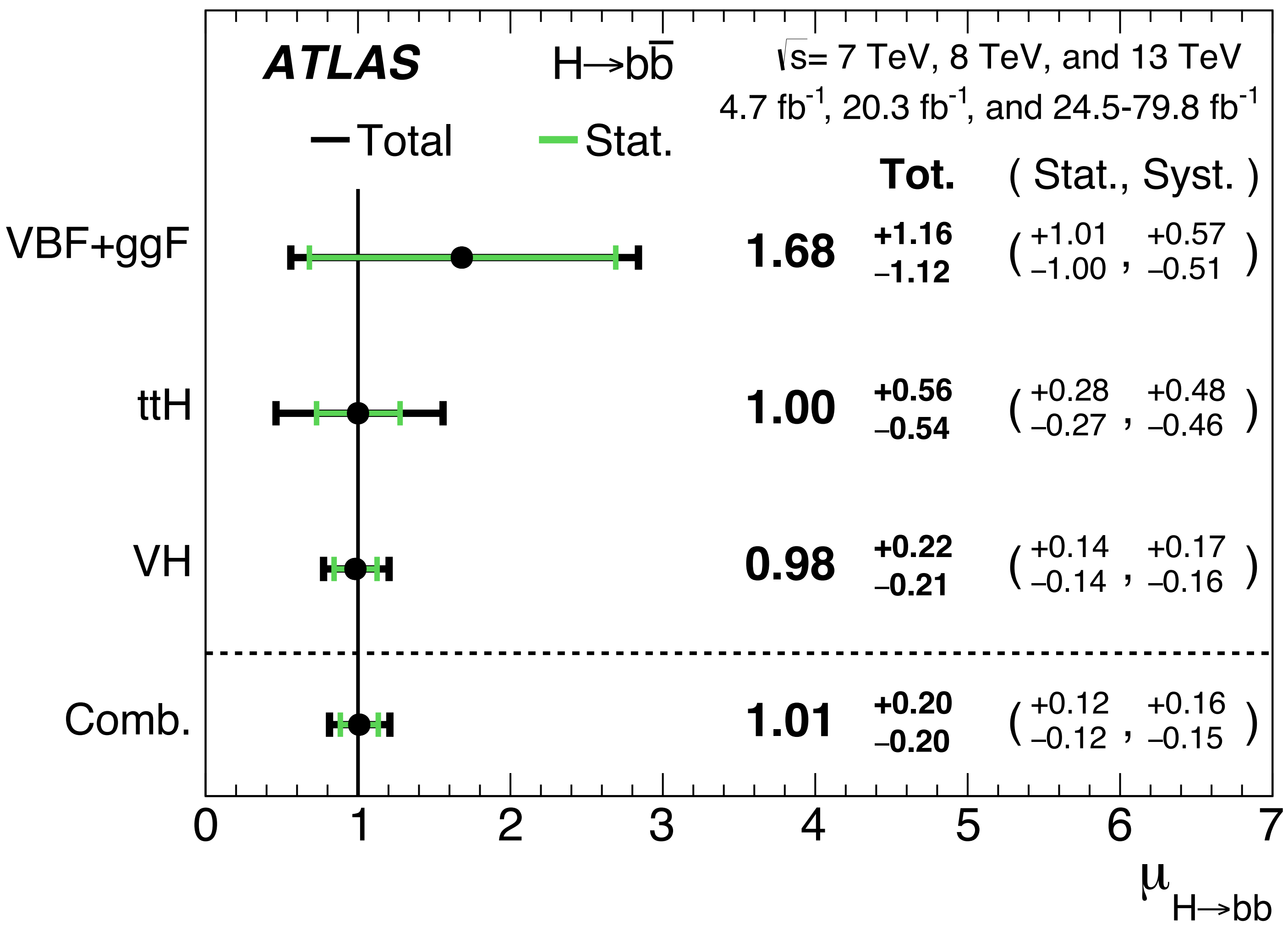




Erzeugung von Higgs-Bosonen am LHC



ATLAS H→bb Results (13 TeV)



Channel	Significance	
	Exp.	Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \to b\bar{b}$ combination	5.5	5.4

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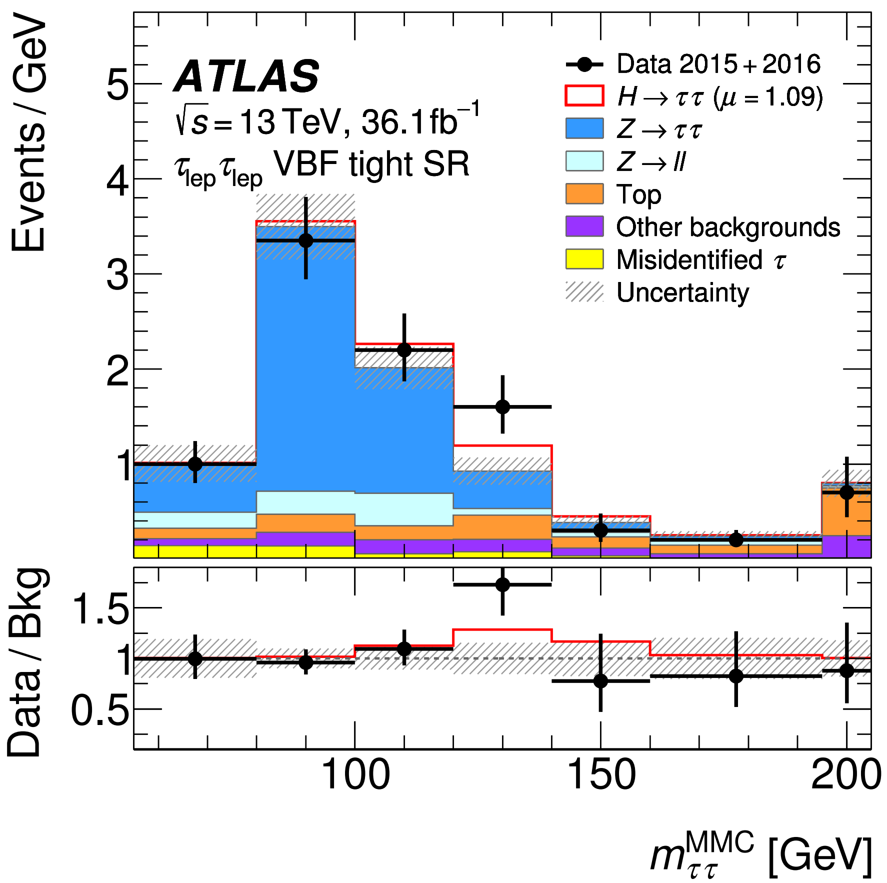
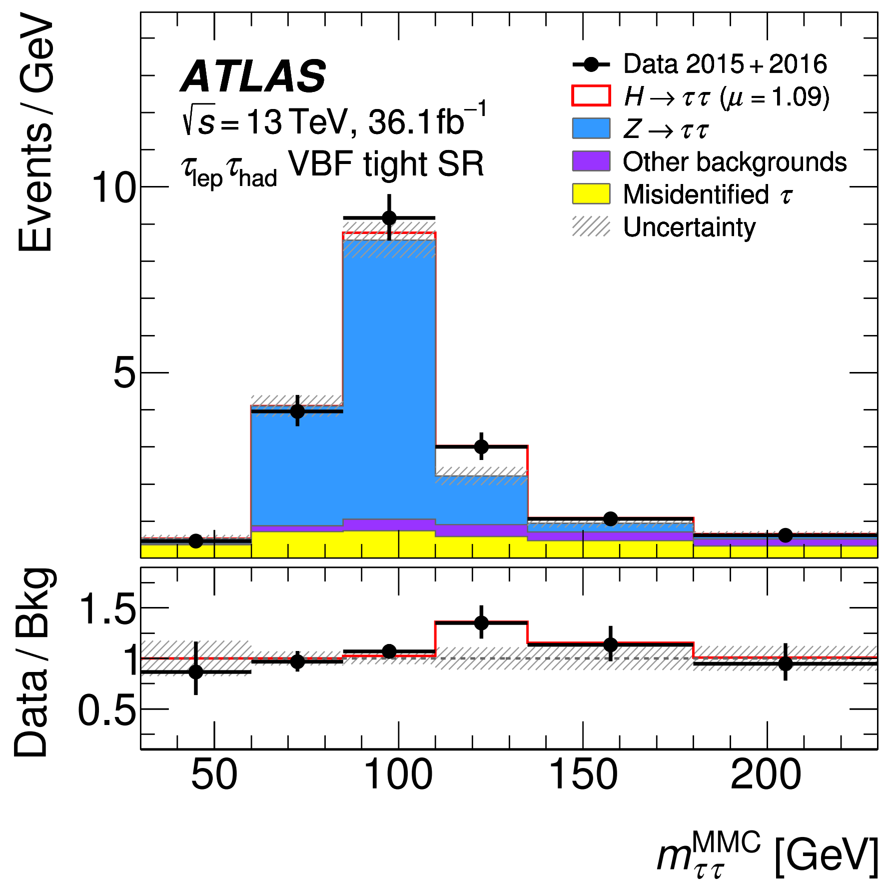
CMS Results: 5.6σ observed, 5.5σ expected

ATLAS H→ττ

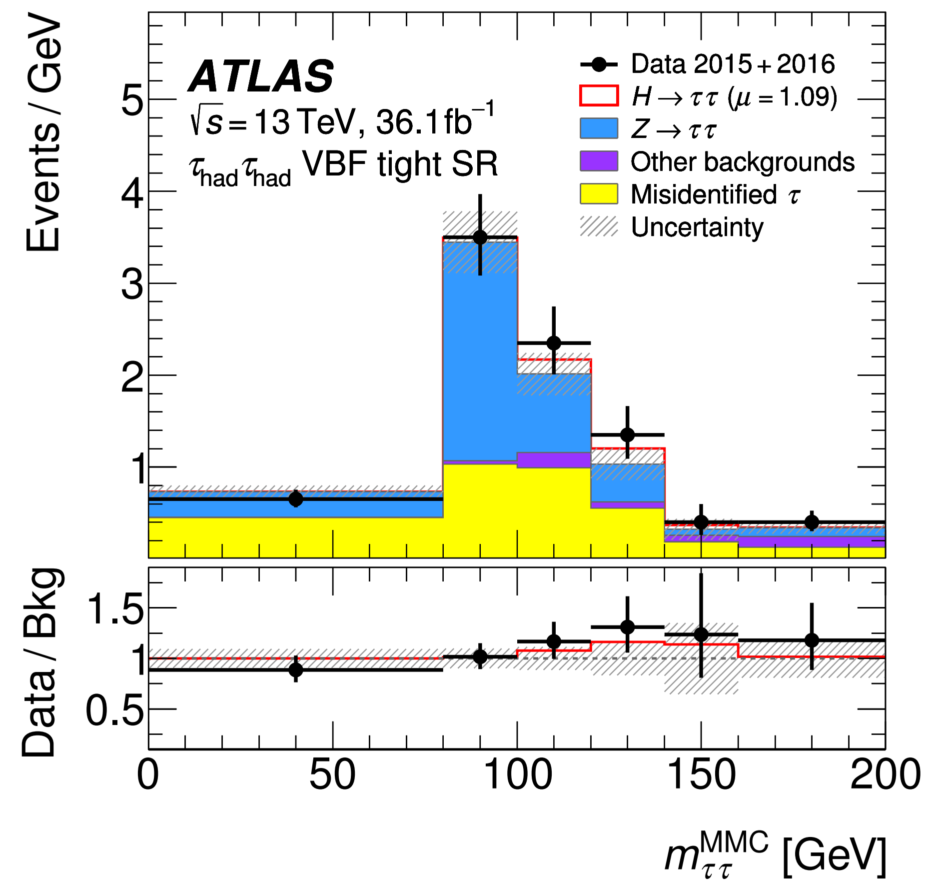
lep-lep



lep-had



had-had



Clear excess of data above background prediction

Excess consistent with SM Higgs boson prediction

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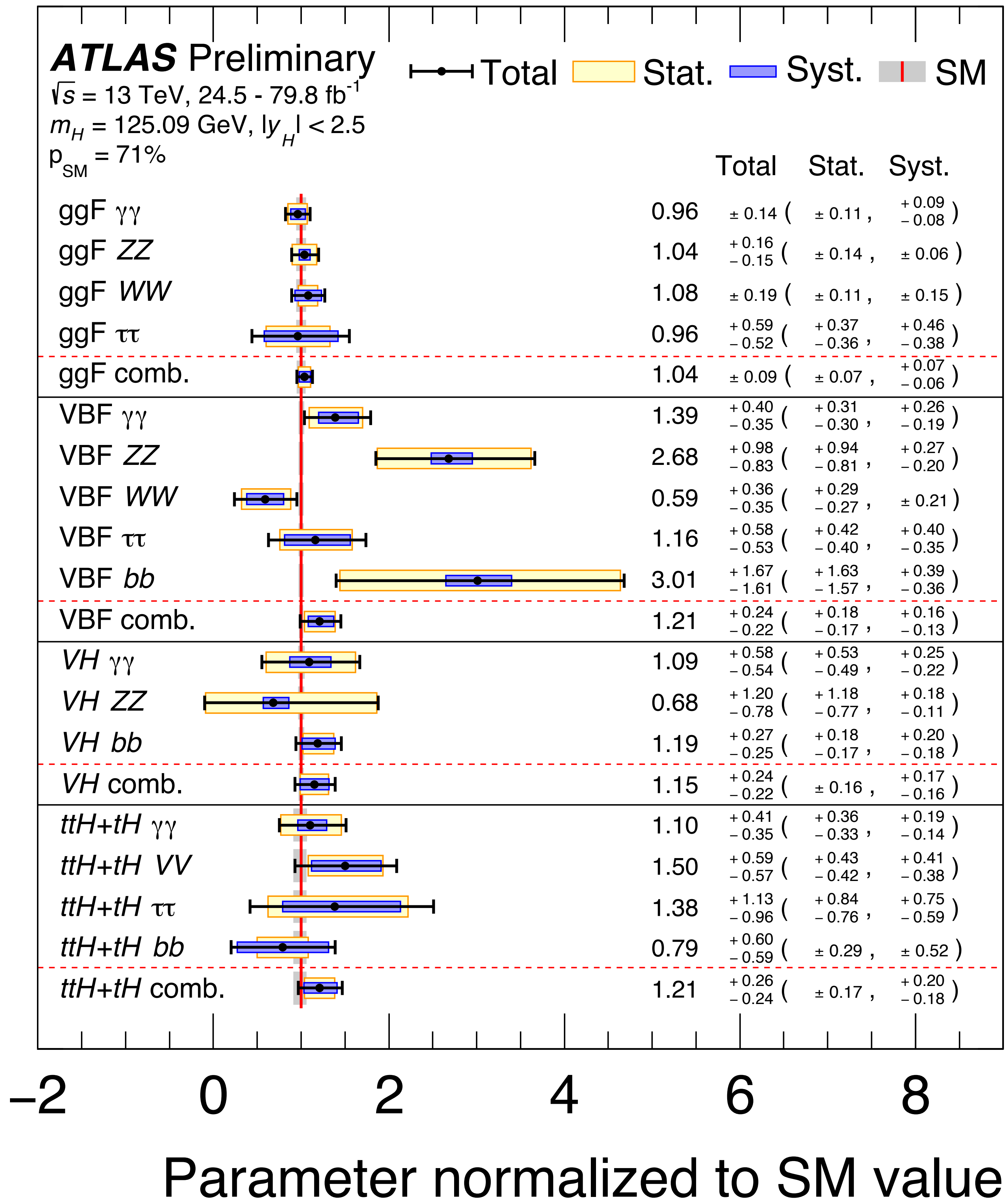
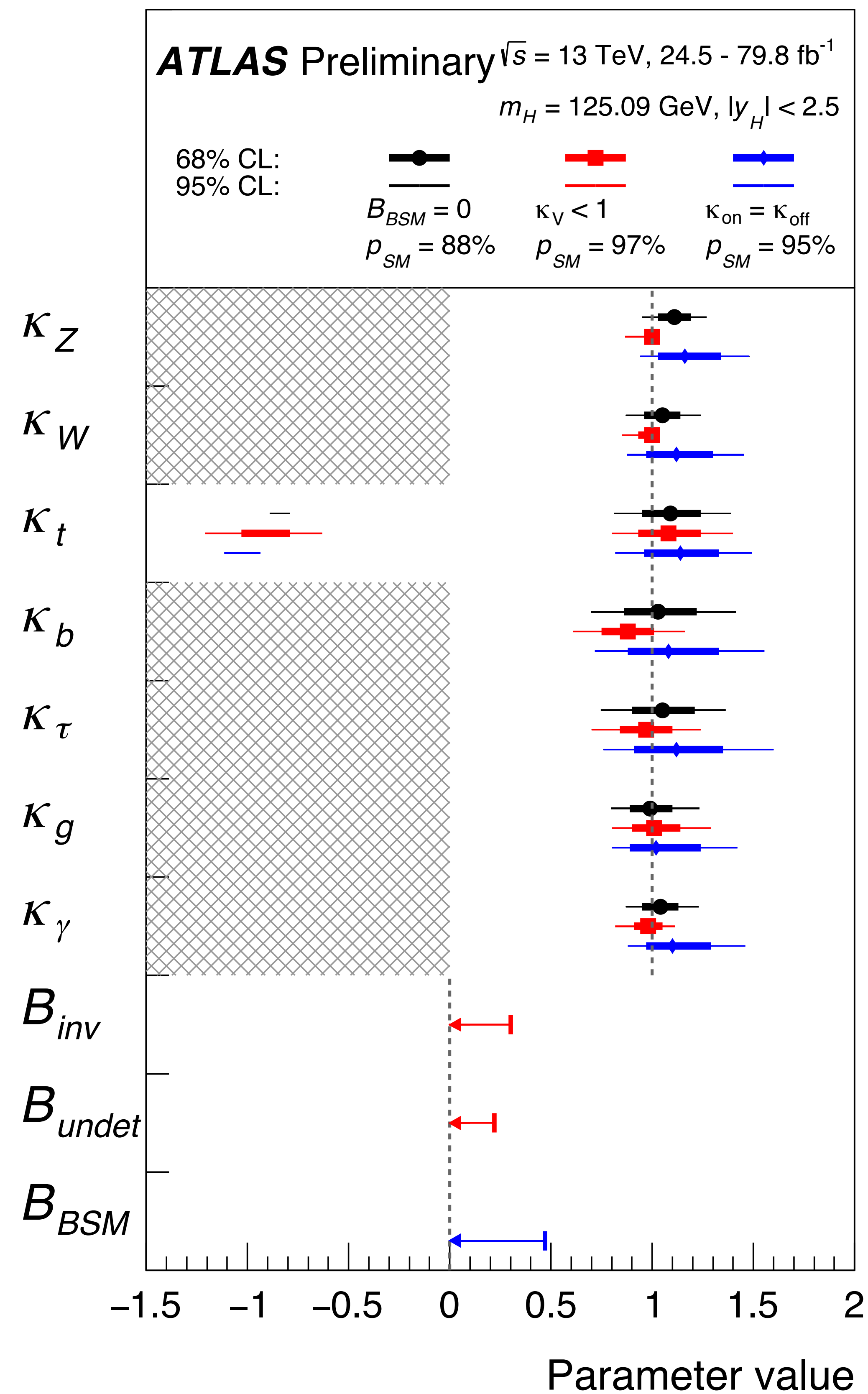
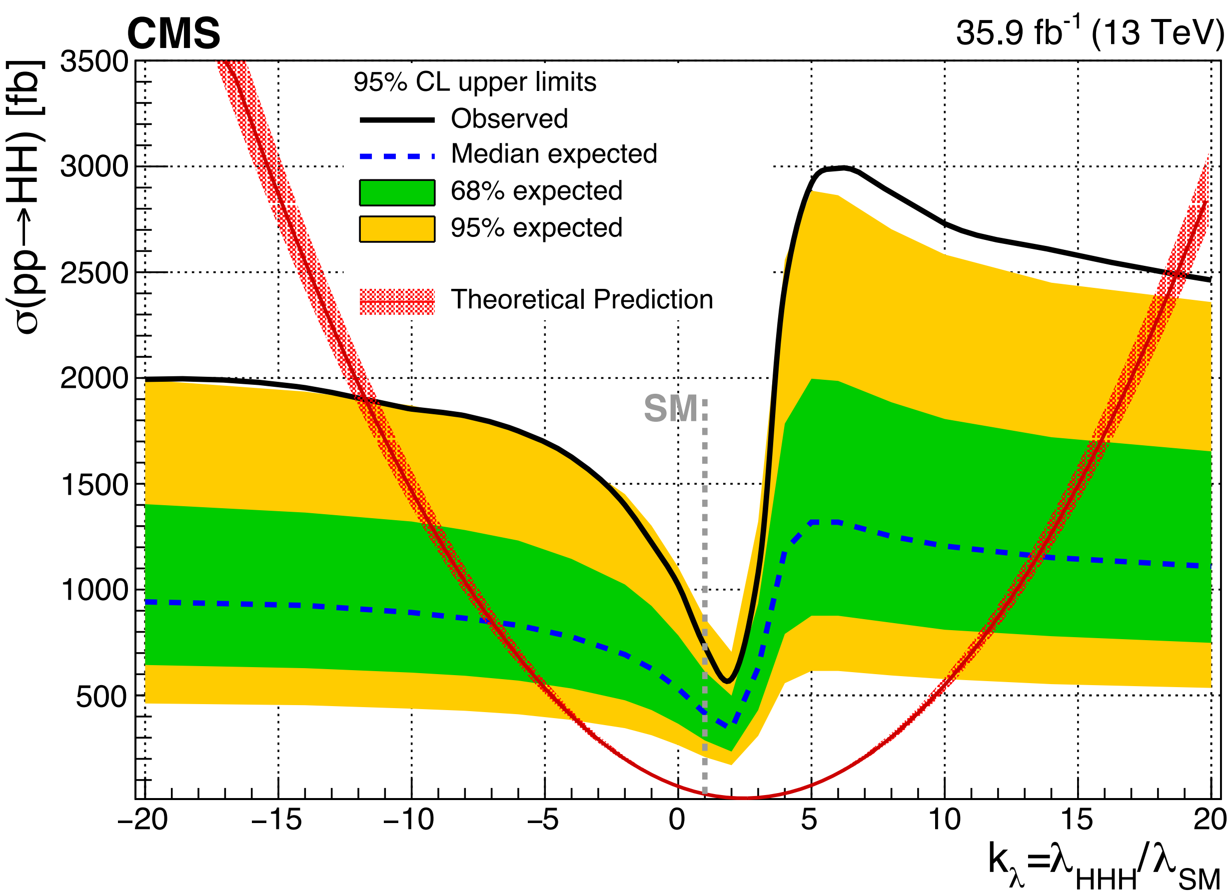
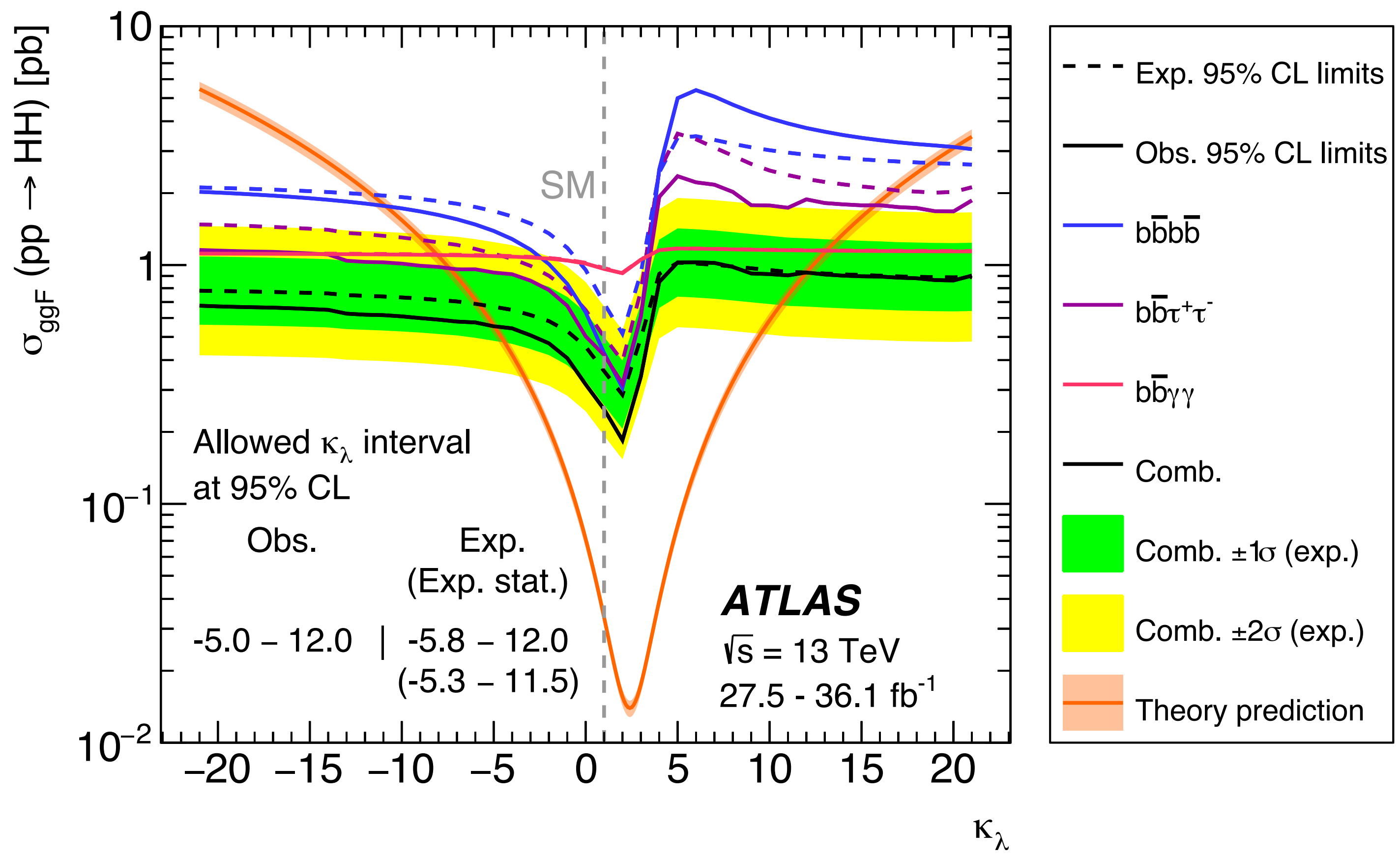
ATLAS Coupling Combination





Higgs-Pair Production Searches





ATLAS: $-5.0 \times \lambda_{SM} < \lambda < 12.0 \times \lambda_{SM}$ (95% CL)

CMS: $-11.8 \times \lambda_{SM} < \lambda < 18.8 \times \lambda_{SM}$ (95% CL)