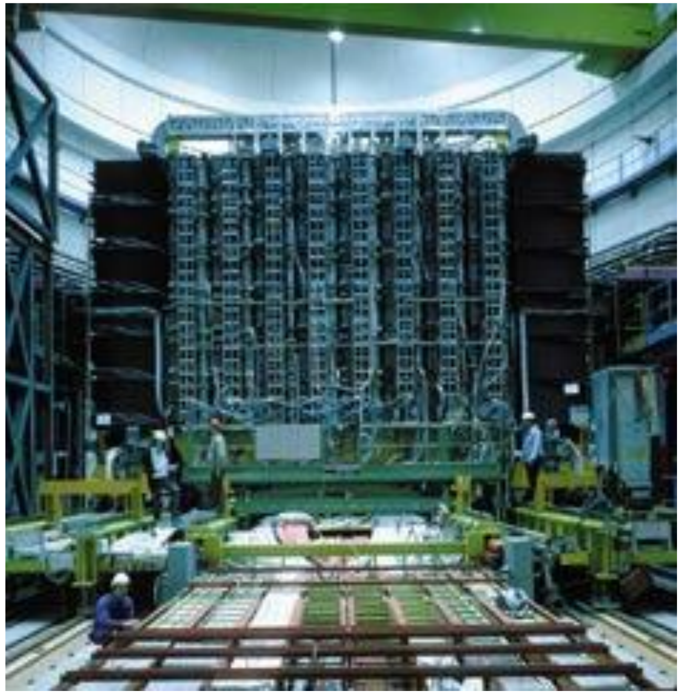
Physics at Energy Frontier

A.Myagkov (NRC KI -IHEP)

UA1 and UA2 Experiments



Two experiments : UA1, UA2(Underground Area 1 and 2)
large “multipurpose detectors”(discussed later)
Each a collaboration of ~150 physicists
Capable of tracking charged particles and identifying electrons and   muons

UA1 and UA2 Experiments

- The experimental challenge
- Find a handful of W bosons produced in approx. 1 billion interactions
- Look for clear signatures of a W-boson
- 10 % of time the W boson decays: W-> e ν

- Signal:
- • isolated electron
- • missing “transverse energy” from ν the W bosons are massive

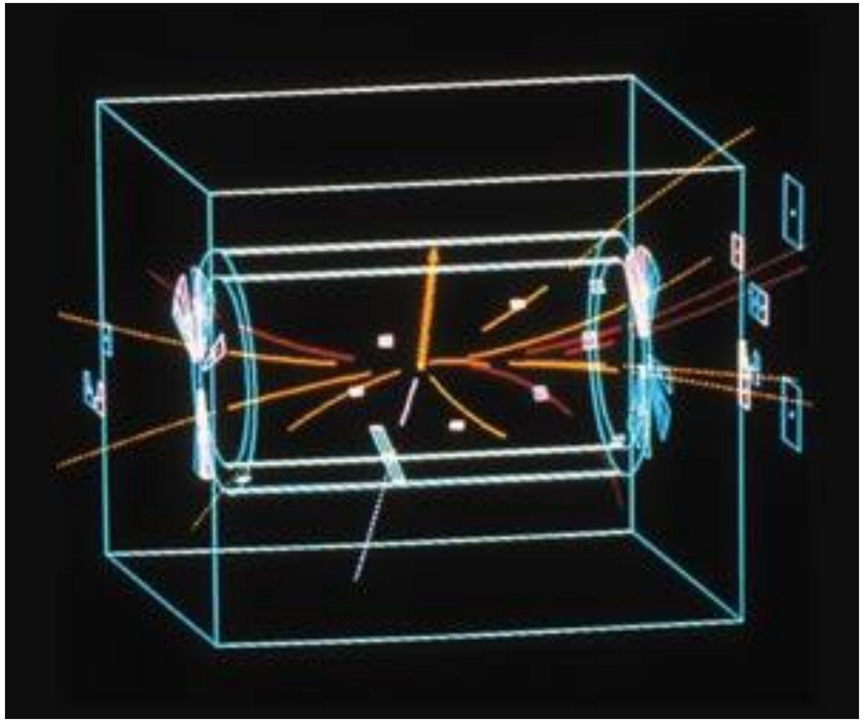
Discovery of the W and Z !

- W bosons produced in the collisions leave very clear signature
- Just run the machine…

- •Nov/Dec 1982:109interactions
- •9 events (5 for UA1 and 4 for UA1)

consistent with from W-> e v were observed

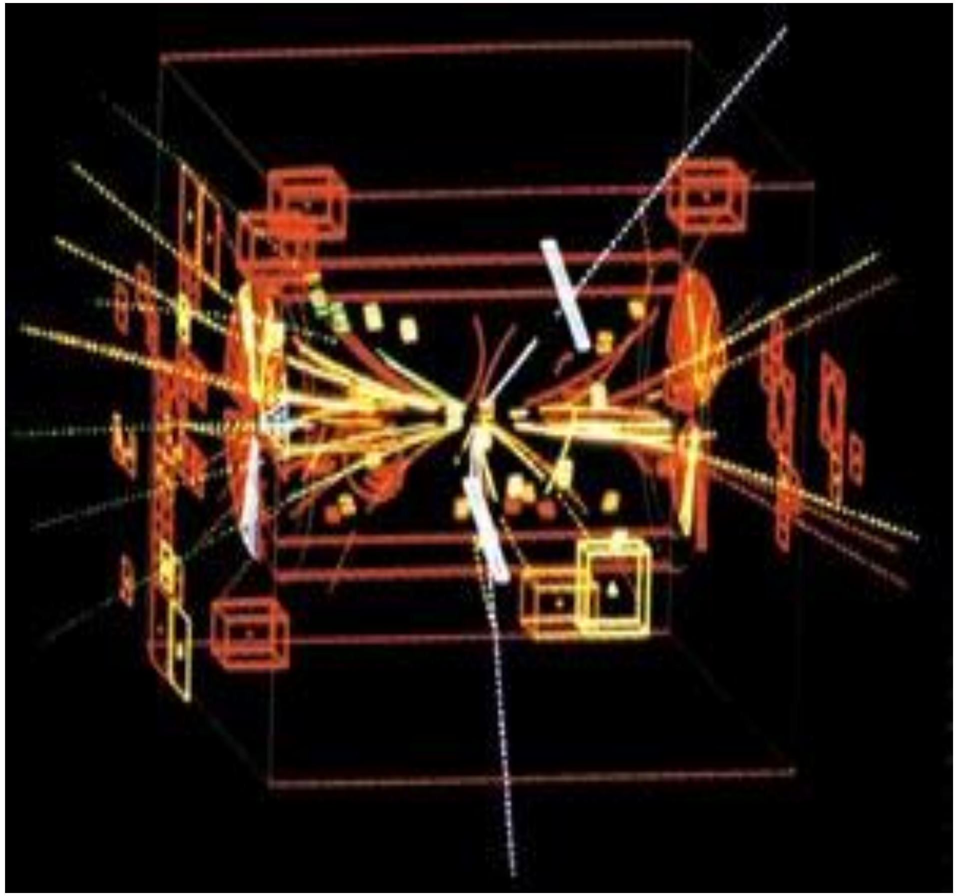
- First Results
- Discovery of the W-boson !



Discovery of the W and Z !

- Second Run
- April/May 1983•
- More W-bosons…e.g. UA1 saw 54
- Four events consistent

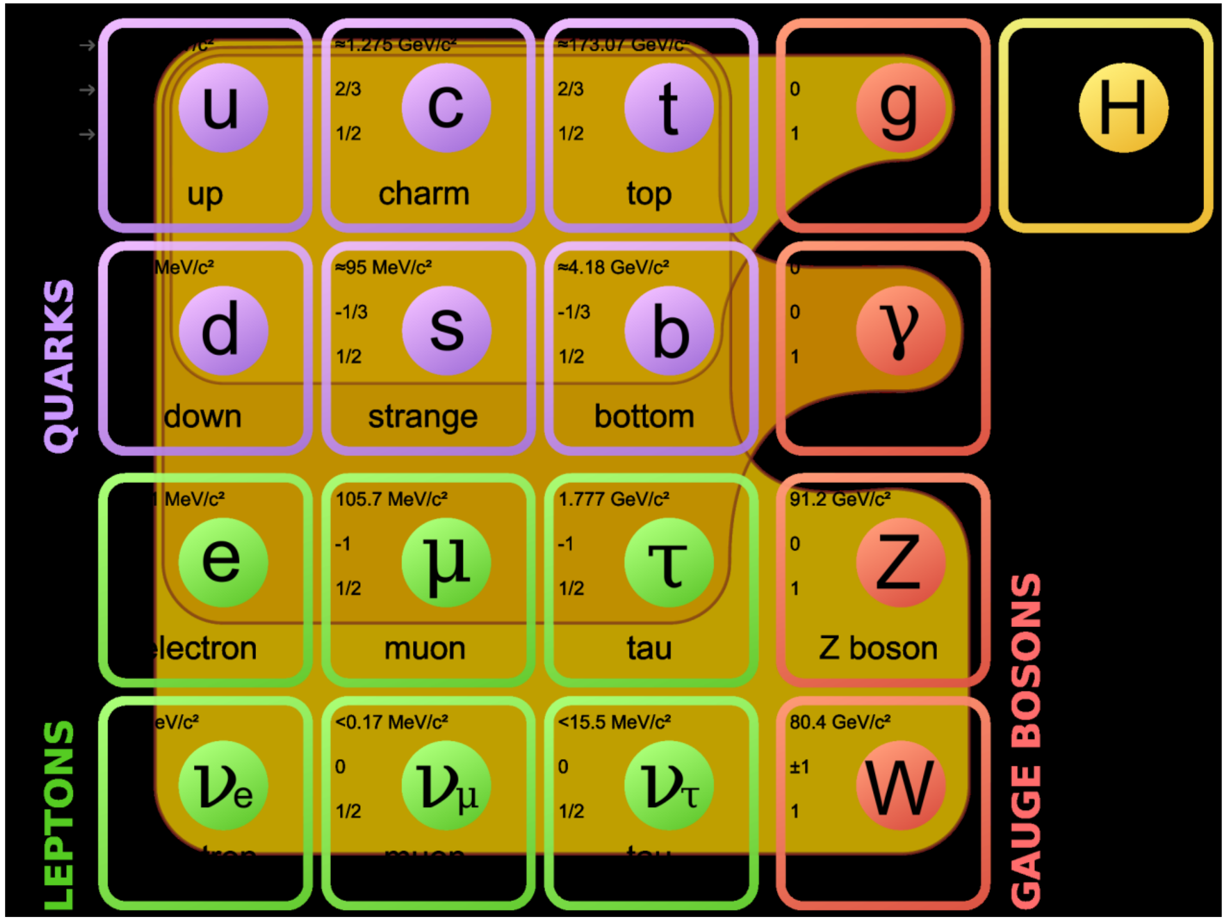
with Z->ee and one with Z->mm



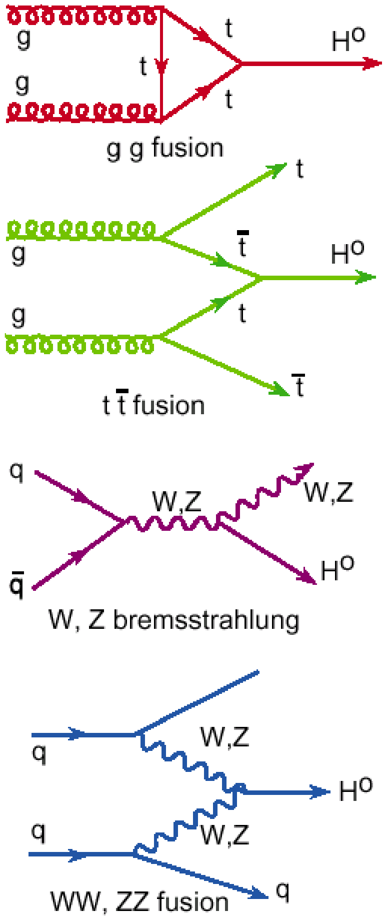
Higgs in Standard Model

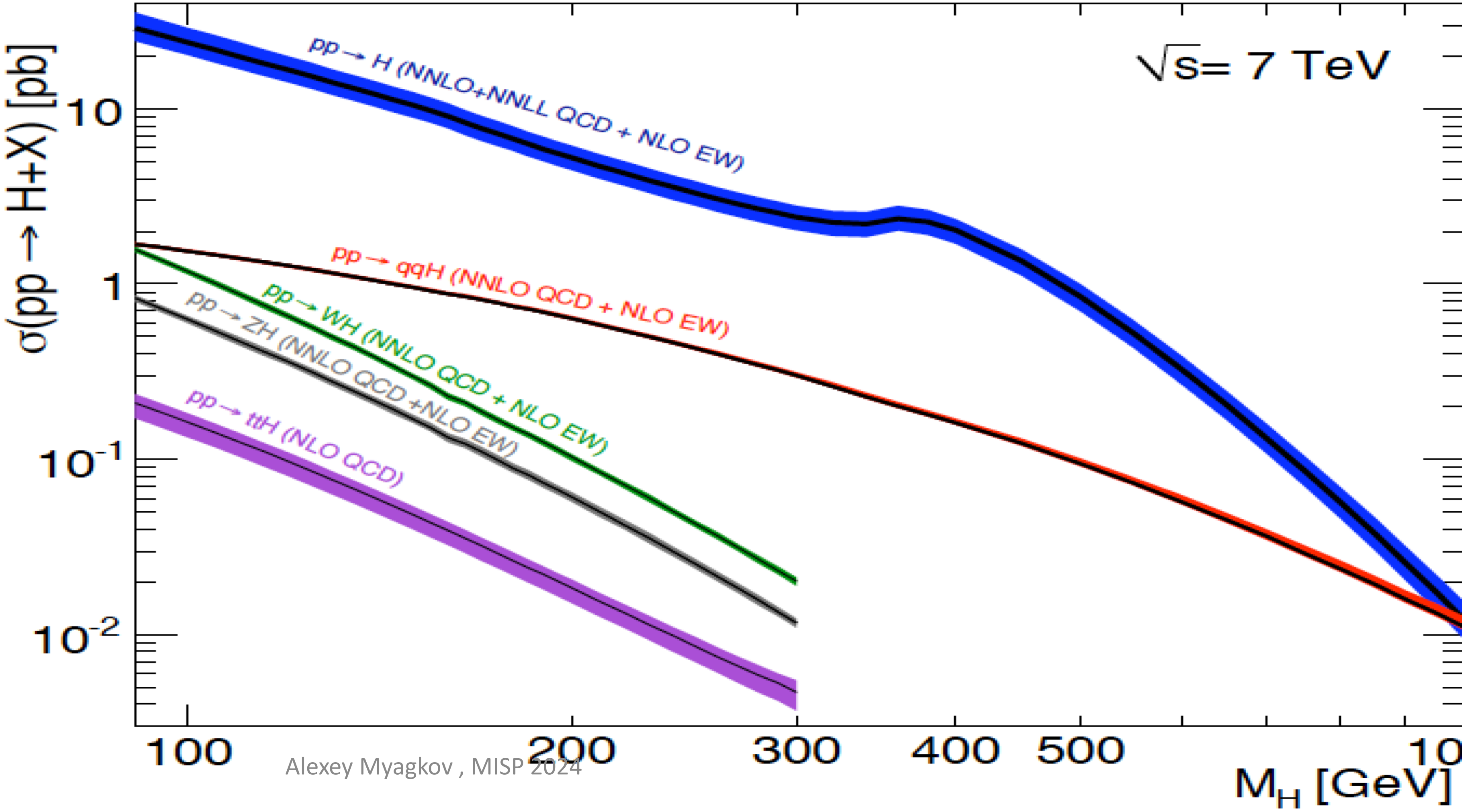
The only scalar in fundamental particles

- Responsible for EWSB and explain the origin of mass
- Its mass is at EW scale O(100GeV)

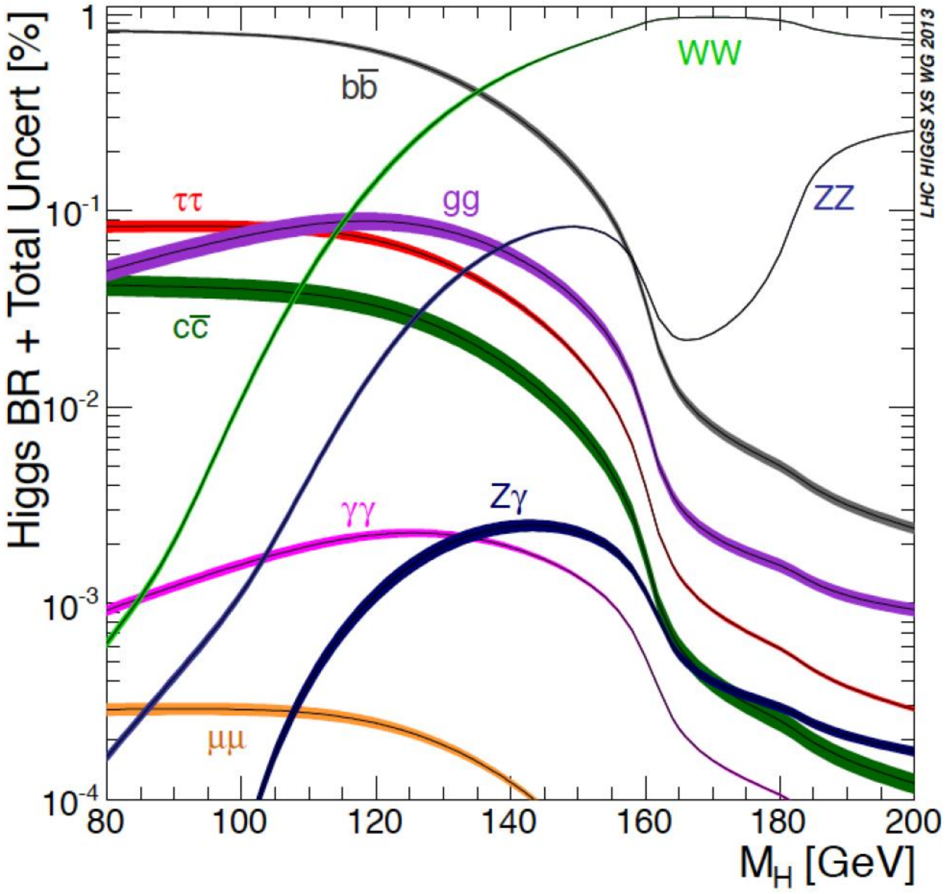


Higgs Production





Decay Branchings



How many Higgs Bosons @ 125 GeV?

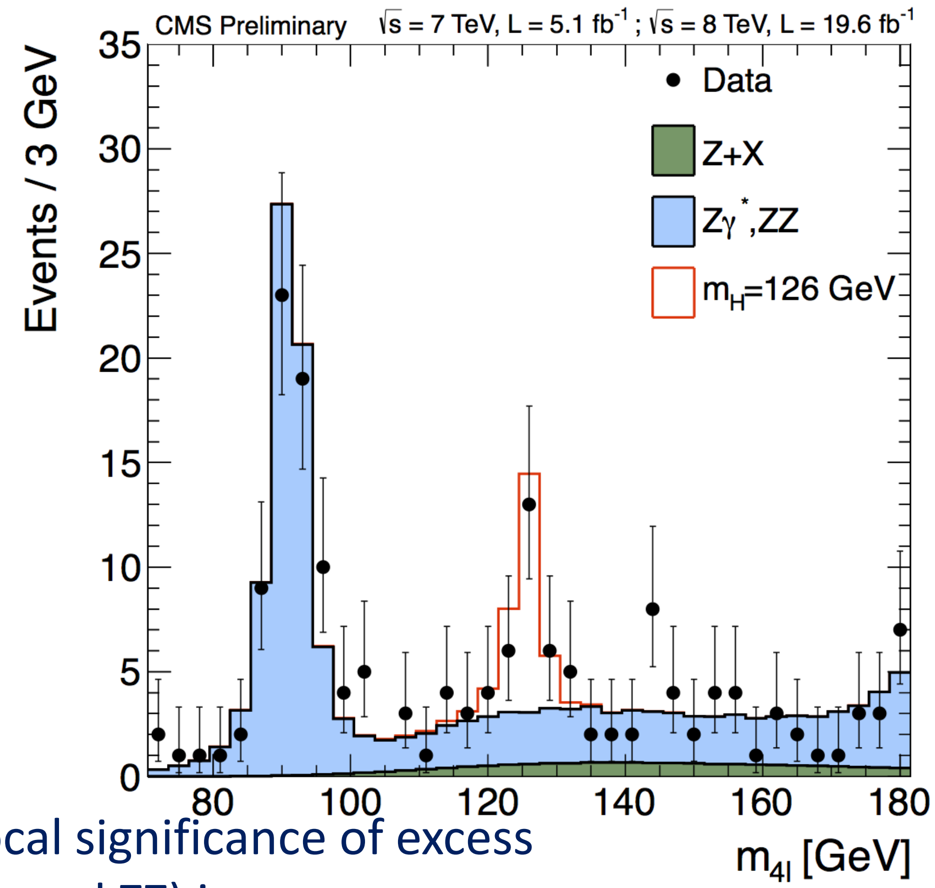
- cross section ≈ 20 pb
- collected luminosity ≈ 25 fb-1 500 000 events
- Dominant Decays:
- H-> bb : 285 000
- H->WW : 105 000 H
- H->ZZ : 13 000

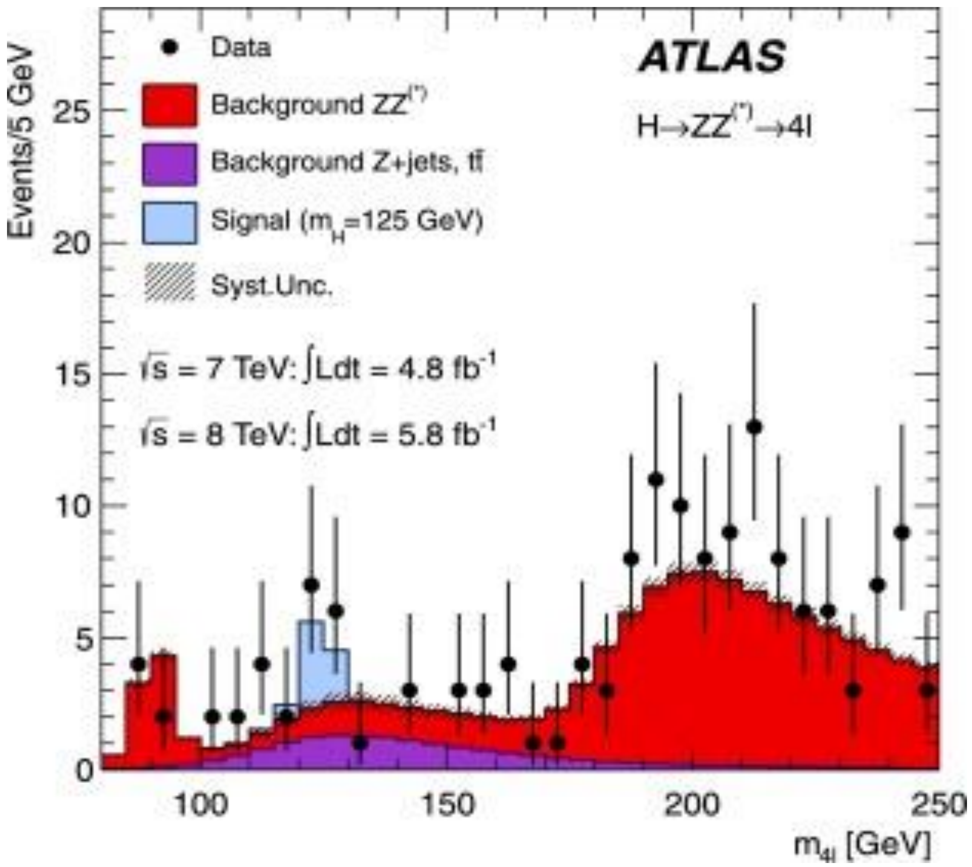
How to find the Higgs @ 125 GeV?

- channel selection reduction width background
- bb identify bottom 0.5 15 GeV huge
- WW electrons, muons 0.05 25 GeV large
- ZZ electrons, muons 0.001 2.5 GeV small
- gg 1 1.7 GeV large

Decay channel	Mass resolution
$H \to \gamma\gamma$	1–2%
$H \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	1–2%
$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$	20%
$H \to b\bar{b}$	10%
$H \to \tau^+\tau^-$	15%

Discovery of a New Boson:



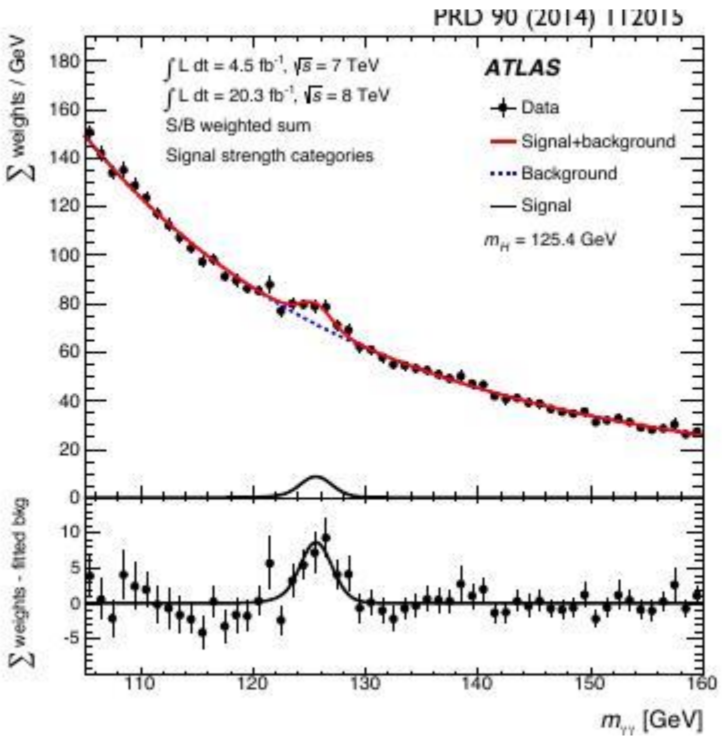


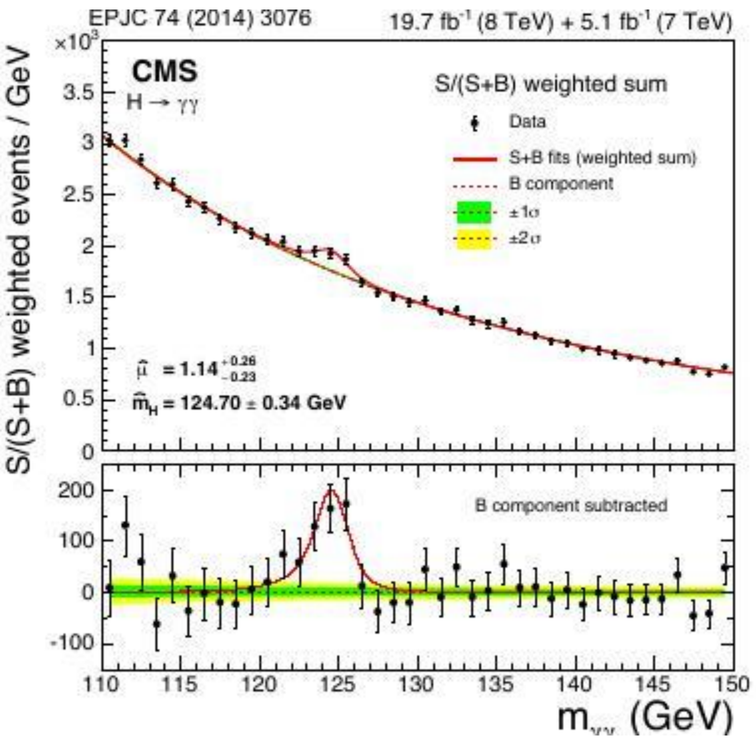
Local significance of excess ($\gamma\gamma$ and ZZ) is

5.9 σ for Atlas and

5.0 σ for CMS

Two photon decay





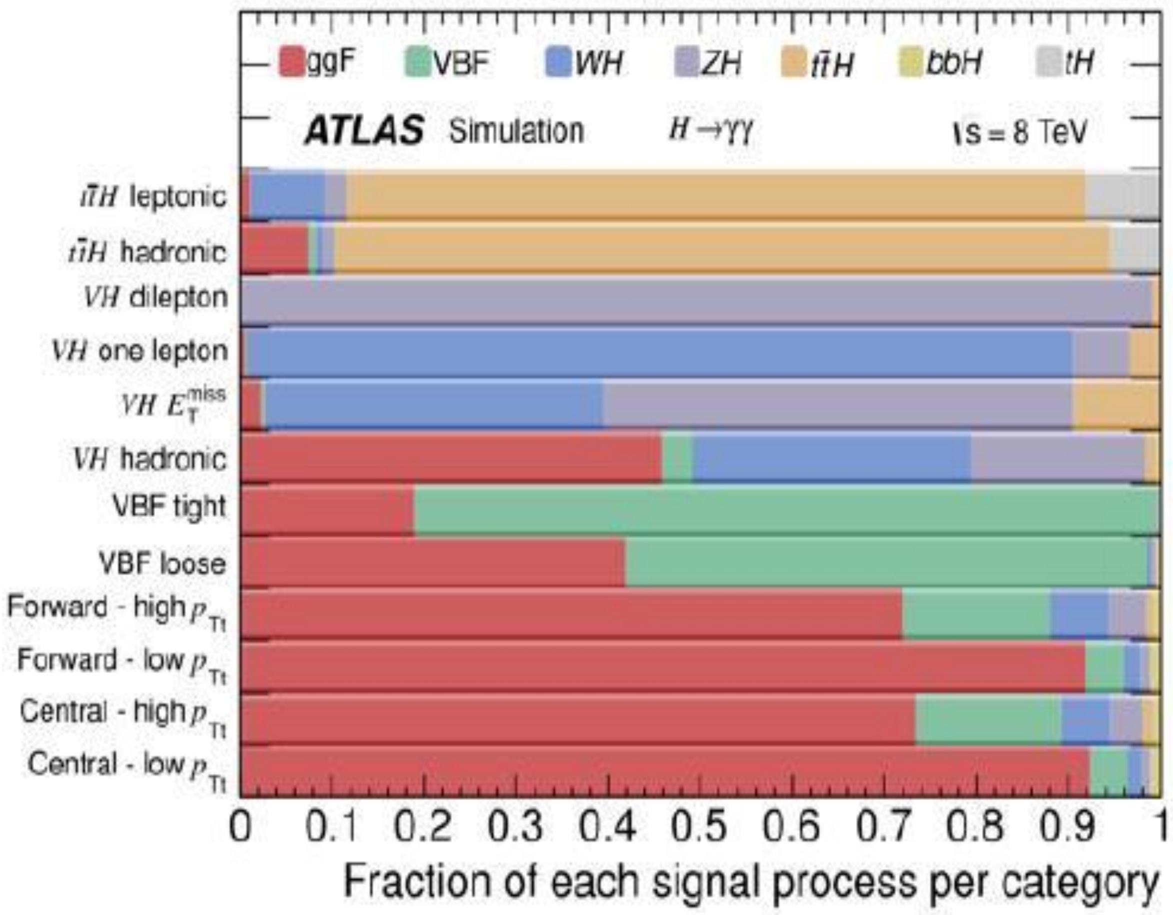
Significance
Observed 5.2 Sig
Expected 4.6

Significance
observed 5.7
expected 5.2

M_H =126.02 +- 0.43 (stat) +- 0.26 (syst) GeV

M_H= 124.70+- 0.31(stat)+- 0.15(syst) Gex

Two photon - categorization

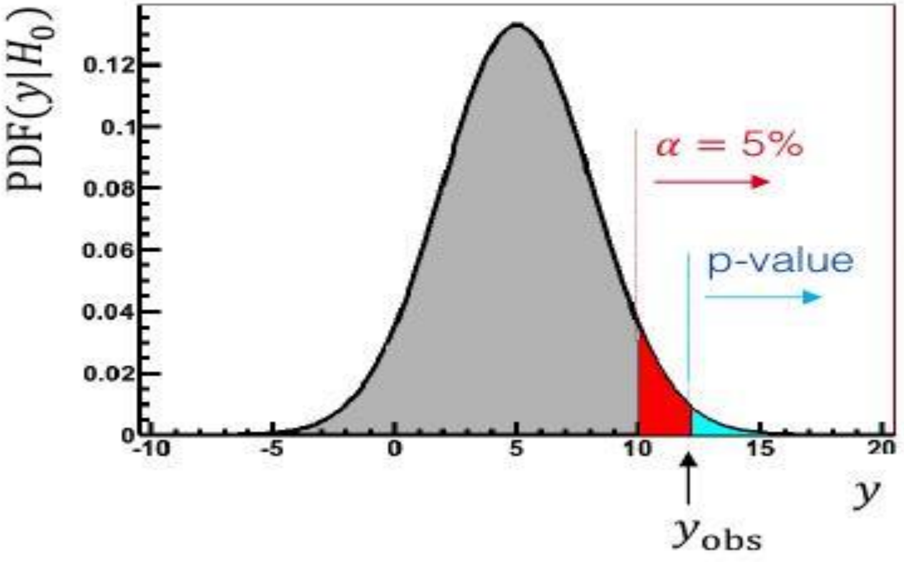


Categorization to increase the overall sensitivity to different production modes

p-value probability of stat. fluctuation

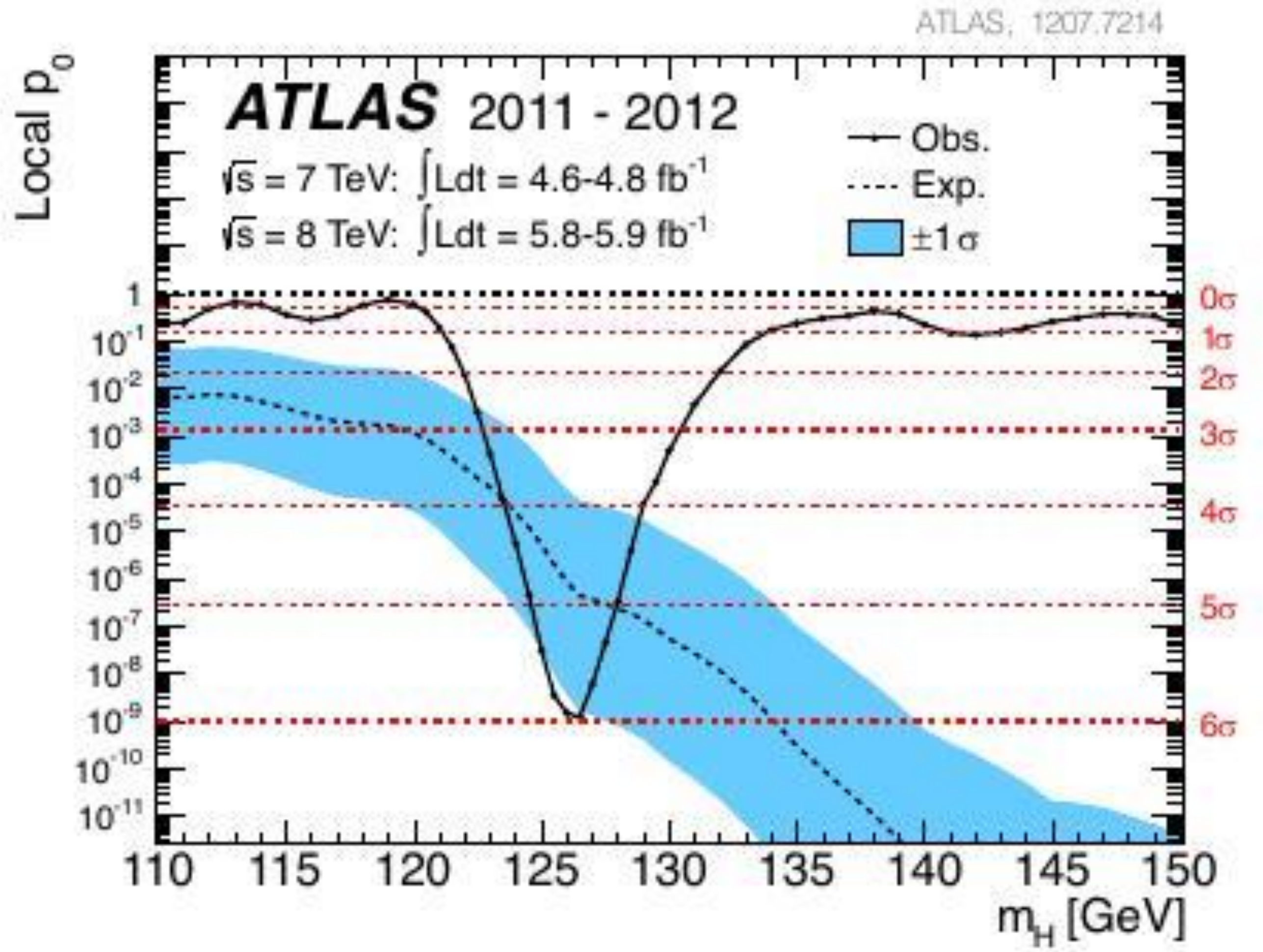
P-value -: how likely is that at a certain mass M_H

- The expected background fluctuates upward
- to produce at least the number of observed events

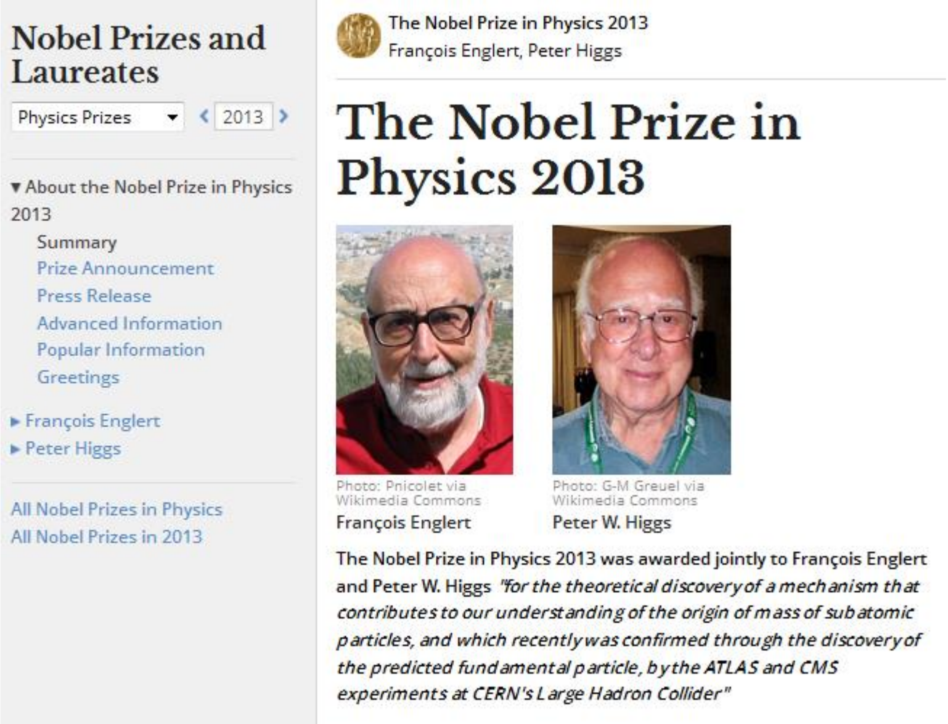


$$= \int_{y_{obs}}^{\infty} \mathrm{PDF}(y|H_0)\, dy$$

Measured p-value distribution



F.Englert and P.Higgs on the presentation of Higgs boson discovery



Nobel Prizes and Laureates

Physics Prizes 2013

▾ About the Nobel Prize in Physics 2013
- Summary
- Prize Announcement
- Press Release
- Advanced Information
- Popular Information
- Greetings

▸ François Englert
▸ Peter Higgs

All Nobel Prizes in Physics
All Nobel Prizes in 2013

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

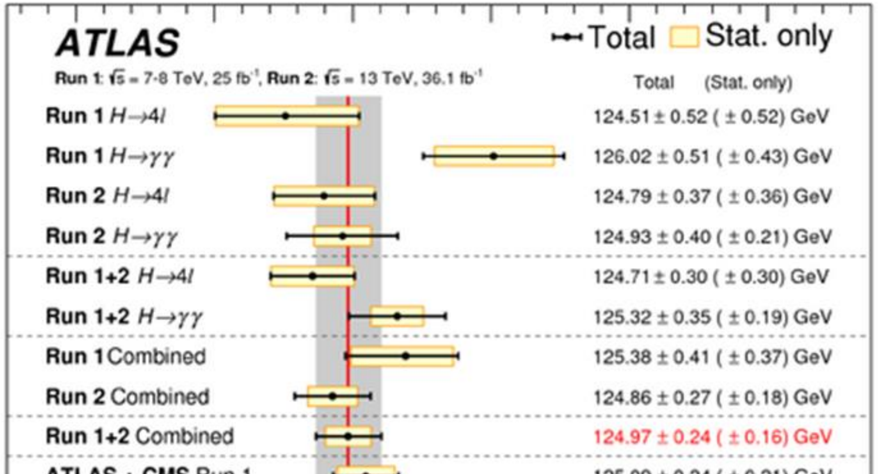
Photo: Pnicolet via Wikimedia Commons
François Englert

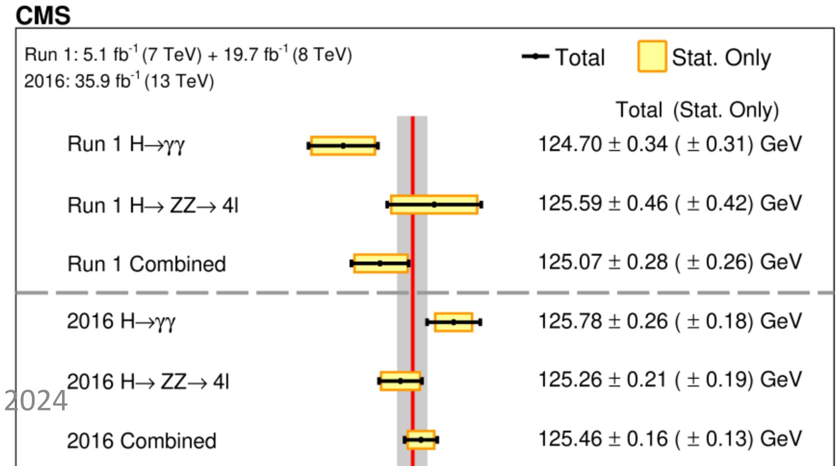
Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

The Higgs Boson Mass

- H→ZZ*→4l and H→$\gamma\gamma$ are the most sensitive channels
- • Clear signature final states
- • High mass resolution 1-2 %
- • Main uncertainties: Electron/photon energy scale and muon momentum scale
- • ATLAS: results @ 139 fb-1 in the H→ZZ*→4l channel (+Run1)
- • CMS: results @ 35.9 fb-1 combined results H→ZZ* + H→$\gamma\gamma$ (+Run 1)





Higgs boson

Monday 4 Jul 2022, CERN

2207.00043 A portrait of the Higgs boson by the CMS experiment ten years after the discovery

Nature volume 607,pages 60-68 (2022)

2207.00092 A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

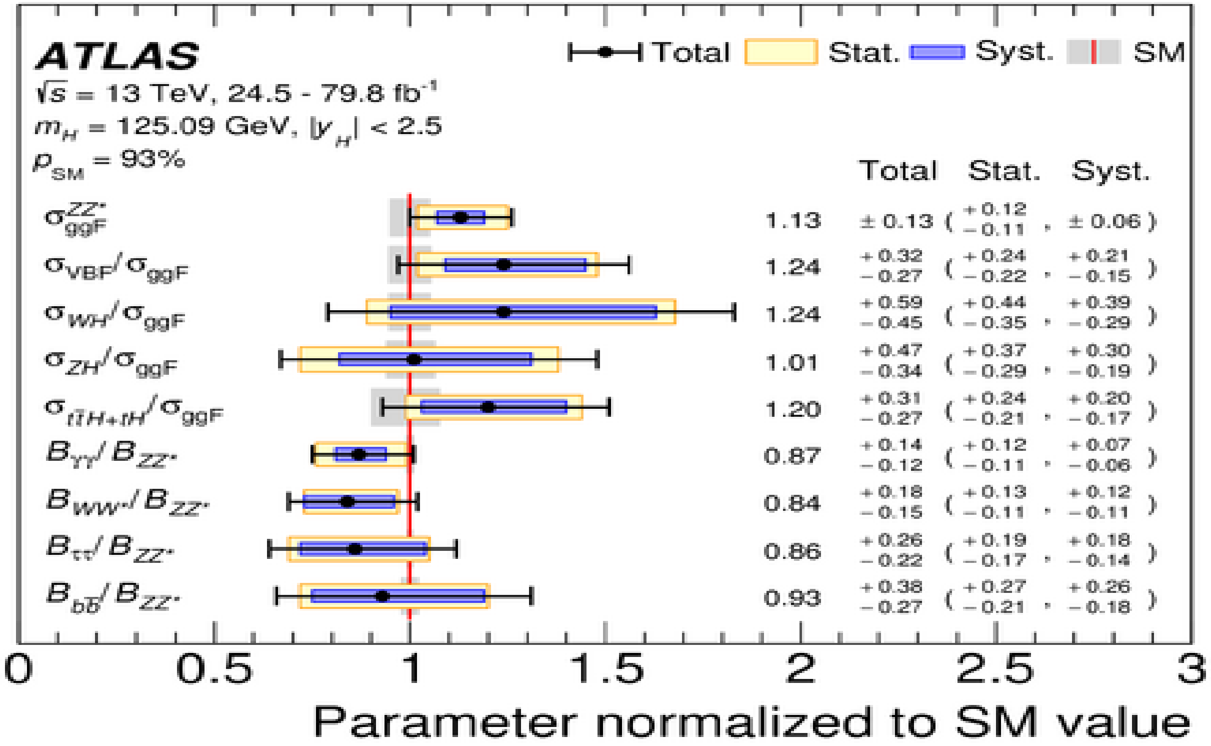
Nature volume 607,pages 52-59 (2022)

A new particle! A Higgs boson?

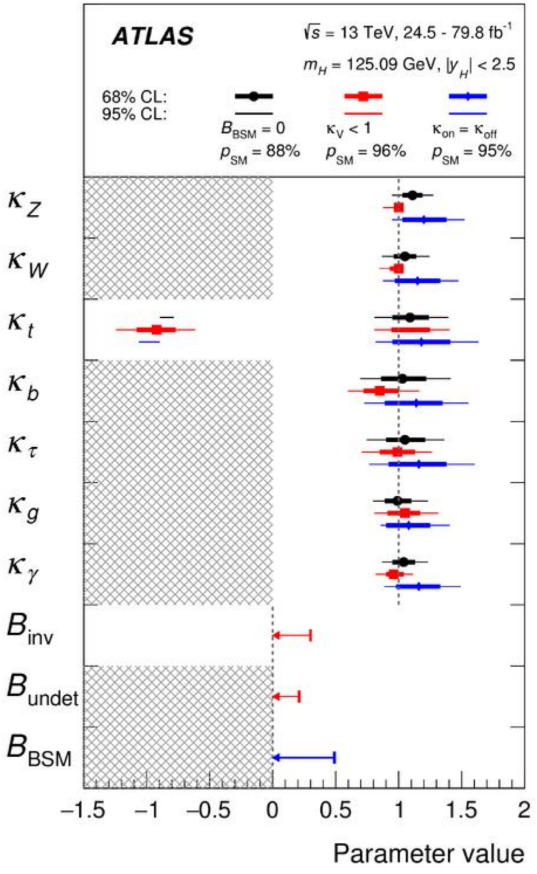
- Qualitative: ‘Higgs’ suggestive!
- Mass accords with expectation
- It is a boson (NOT spin 1!)
- Found in expected decay channel

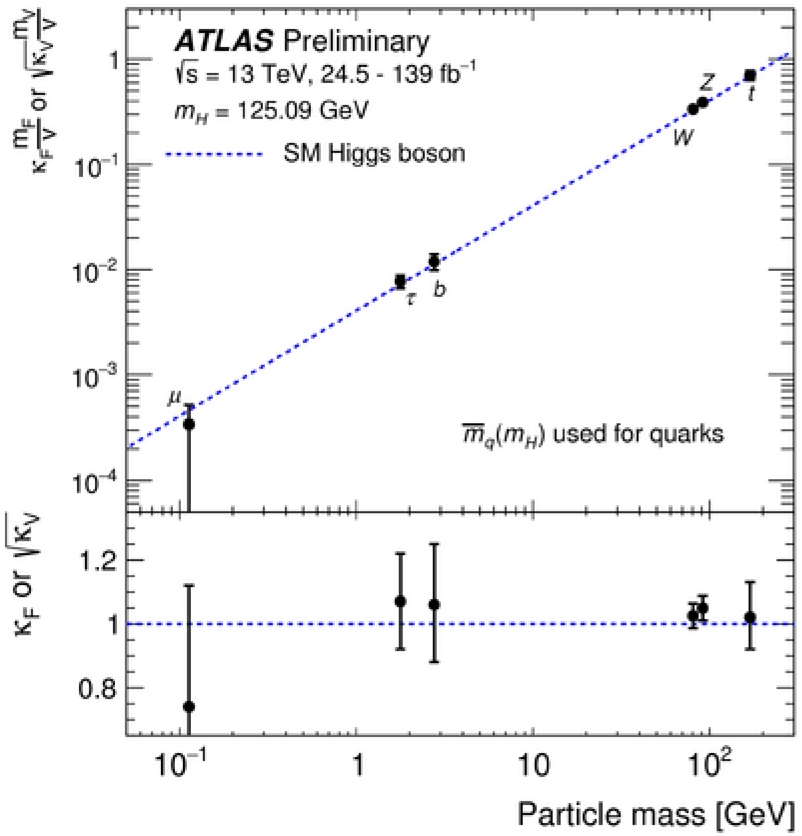
- Production mechanisms
- Branching ratios into bosons and fermions
- Width of Higgs boson
- Spin and parity
- Higgs self coupling (Higgs potential) Significant progress since discovery

Run 2 cross section and partial decay width ratios

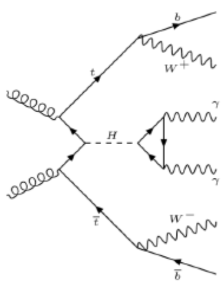


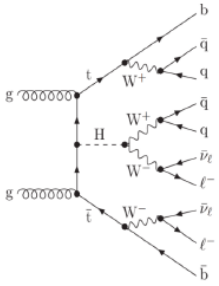
Run 2 coupling strength

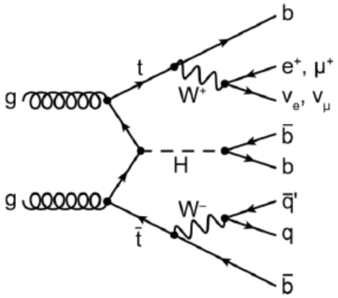




Higgs coupling to top quark





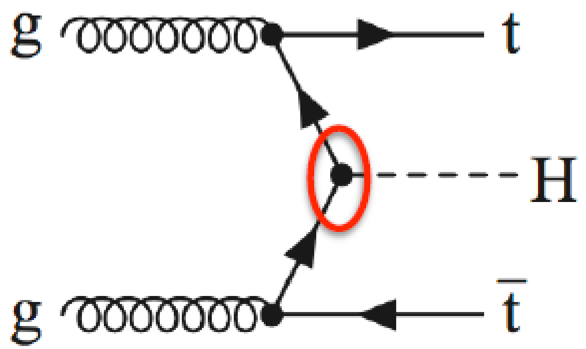


$H \to ZZ^* \to 4\ell$
$H \to \gamma\gamma$

$H \to WW^* \to \ell\nu\ell\nu$
$H \to \tau\tau$
(multi-leptons)

$H \to b\bar{b}$

ttH production



Yukawa coupling proportional to fermion mass → largest couplings to t-quark

CMS
Run-1+Run-2: **5.2σ** (4.2σ exp.)

PRD 97 (2018) 072003, PRL 120 (2018) 231801, PRL 125 (2020) 061802

ATLAS 6.3 (5.1) sig
Higgs boson decays into $b\bar{b}$, WW^*, ττ, γγ, and ZZ^*
Phys. Lett. B 784 (2018) 173

H->2nd Generation (H->ccbar)

Hμμ: CMS 3.0σ (2.5σ), ATLAS 2.0σ (1.7σ)

Hcc:

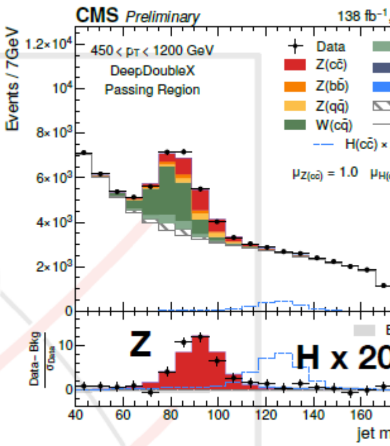
- $\sigma\mathcal{B} < 14.4\ (7.6) \times$ SM **CMS**
- $\sigma\mathcal{B} < 31\ (26) \times$ SM **ATLAS**

ggH Analysis

- Boosted cc system in the final state

$$\mu_{\rm H} = 8.6^{+19.9}_{-19.4},$$

45 (38) at the 95% CL.

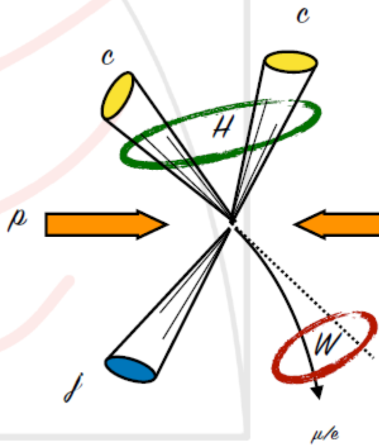


VH Analysis of the Run 2 datasets

- Higgs to charm reconstructed both in the **boosted** (p_T>300 GeV) and **resolved** regimes

Resolved regime:

- Using deep neural network to improve rejection of light quarks vs b jets (DeepJet)
- Dedicated energy regression
- 3 Categories: 0 lepton, 1 lepton, and 2 lepton targeting Z→νν, W→ℓν, and Z→ℓℓ



Reduced coupling strength modifiers κFmFv
 for fermions (F=t, b, τ, μ) and κV−−−√mVv for weak gauge bosons (V=W, Z) as a function of their masses mF and mV

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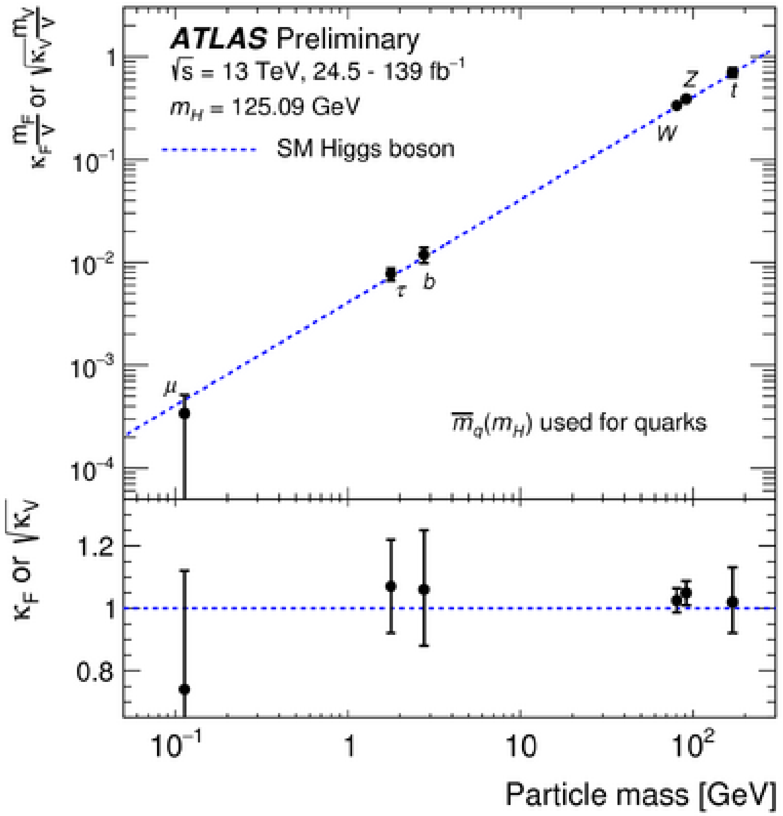
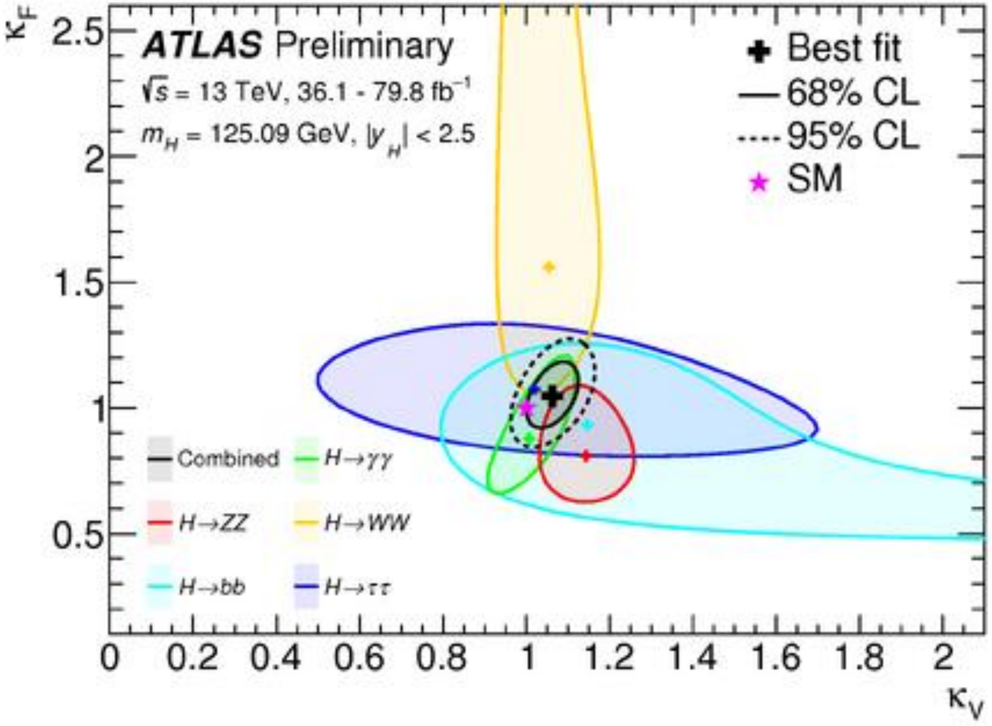


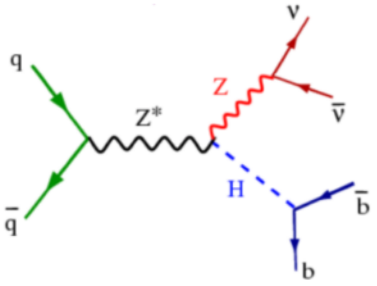
Observed contours at 68% and 95% CL in the (κF, κV) plane, defined in the asymptotic approximation by -2logΛ = 2.28 and 5.99, respectively, for individual channels and the combined fit.

•

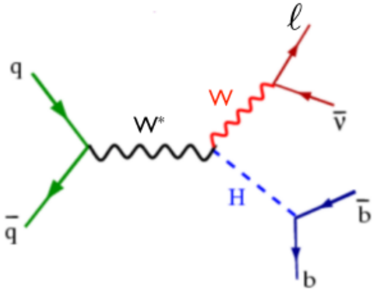


VH production and H->bbar

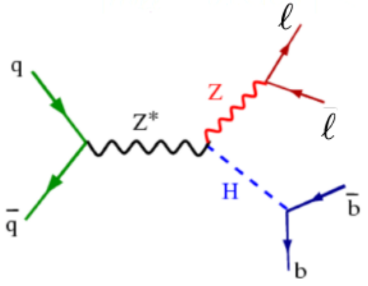
0-lepton



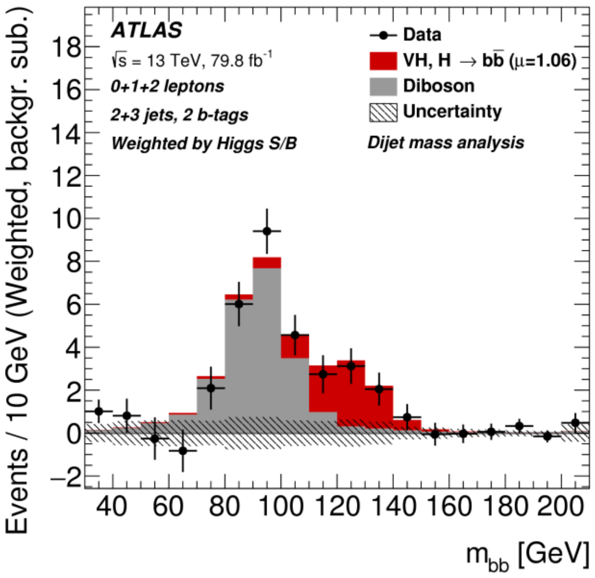
1-lepton



2-lepton



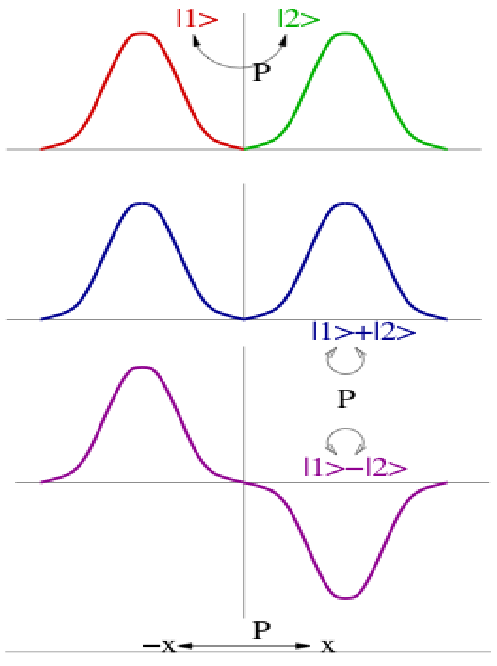
	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.22



Spin + parity measurements

- Predicted Higgs Spin/Parity: 0+
- Spin: angular momentum ‘of a point’
- Measured from angular distribution of Higgs decay products

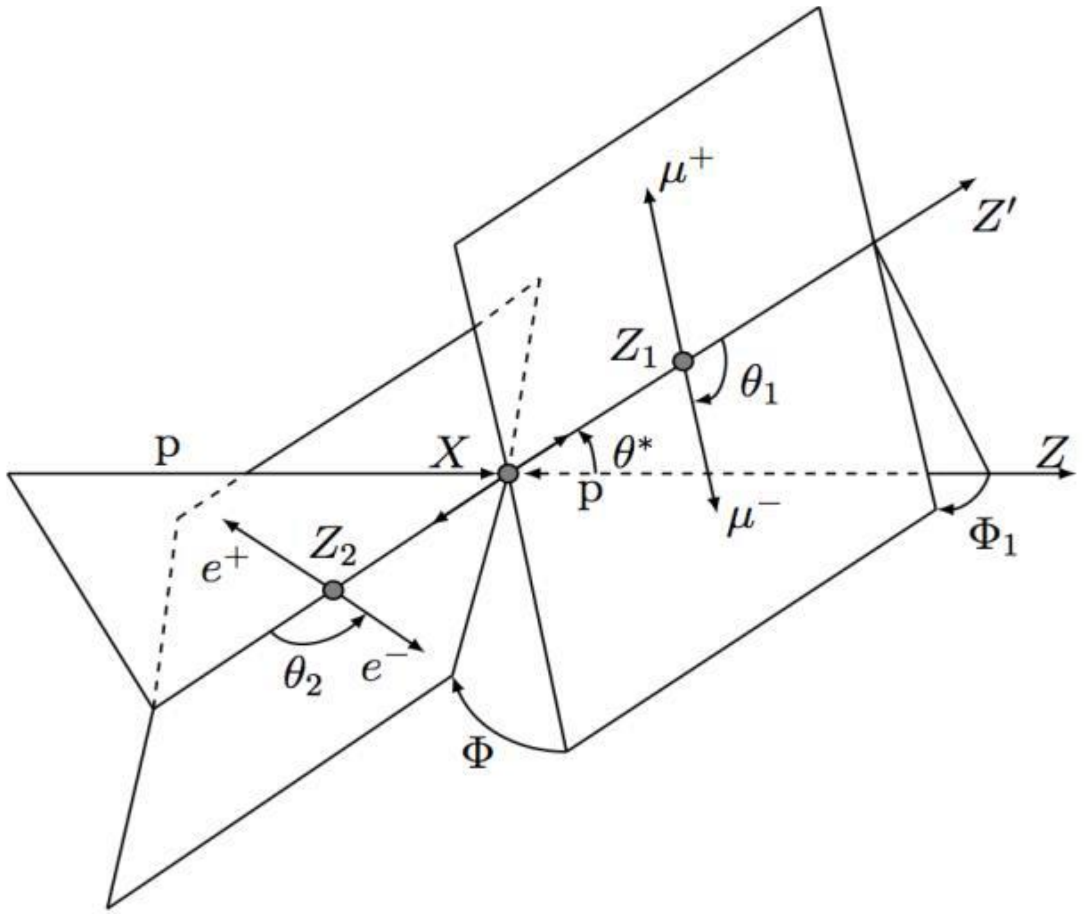
- Parity: how does a particle look in the mirror?
- parity transformation (x, y, z, t) ⃞ (-x, -y, -z, t)
- wave function either symmetric (+) or
- antisymmetric (-)
- Measured by sequential decay



Parity of the Higgs

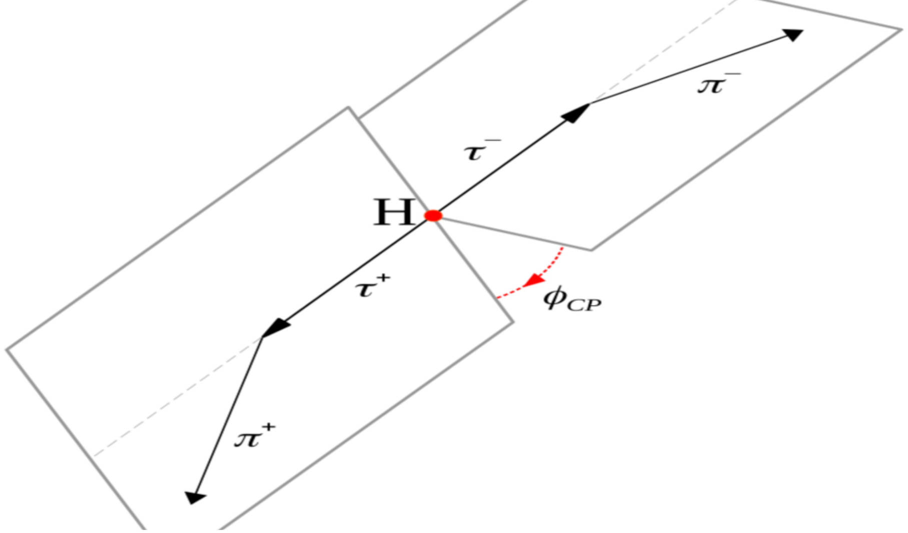
Example: h -> W+W- Spin 0   Spins of W's opposite m's aligned

E.g. angle between decay planes
Use several observables to find optimal discrimination



Probe CP violation in Hττ

- **Lagrangian for τ Yukawa coupling parameterized with**
- **• Use observable Φ_CP to probe the effective mixing angle**



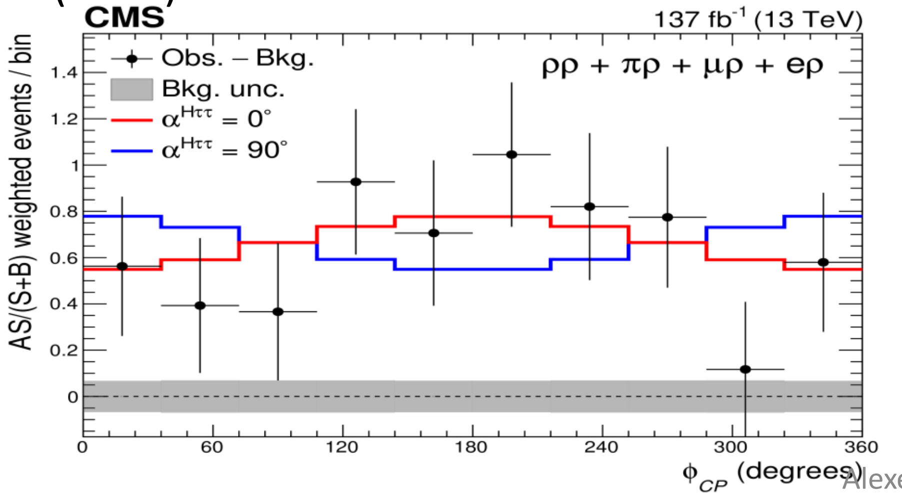
$$\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$

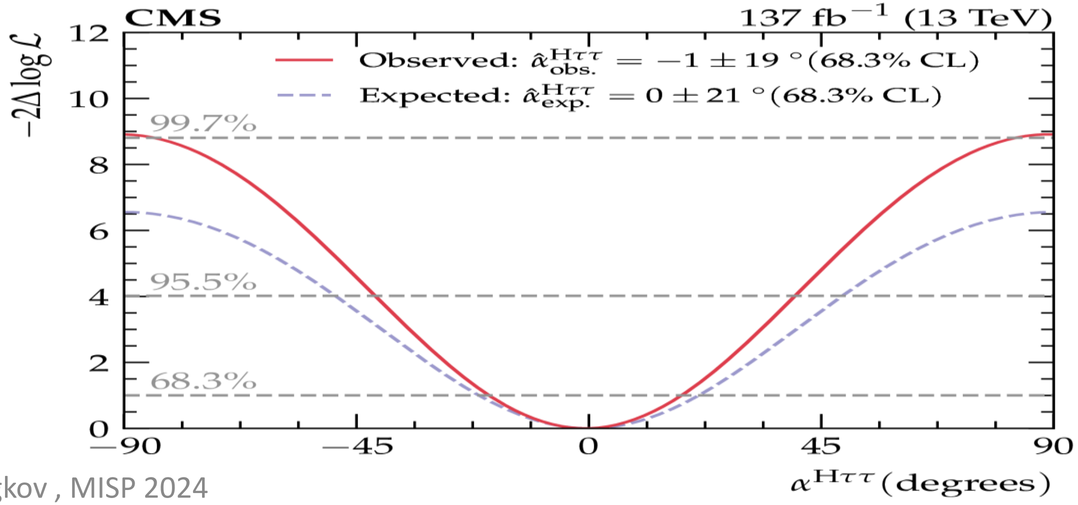
$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

Use observable Φ_{CP} to probe the effective mixing angle

$a_{H\tau\tau}$ **Observed -1±19 ° (68% CL) Expected 0±21°**

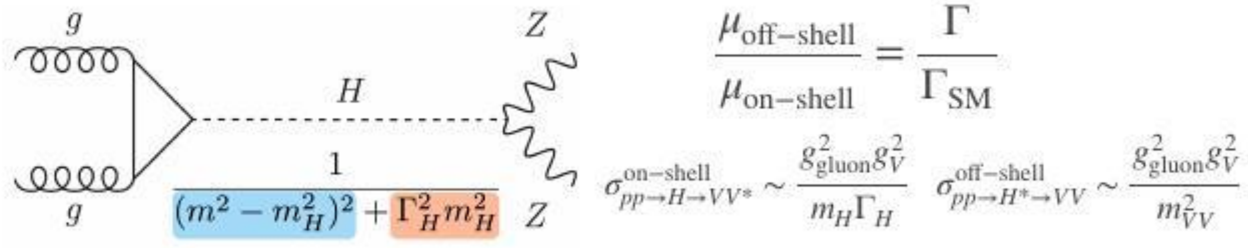
JHEP 06(2022)012





Higgs Boson Width

- Predicted width in SM ΓH: **4.07MeV**
- Direct measurements : measuring Higgs lifetime or on-shell width.
- mass resolution limited by **detector resolution 1-2GeV.**



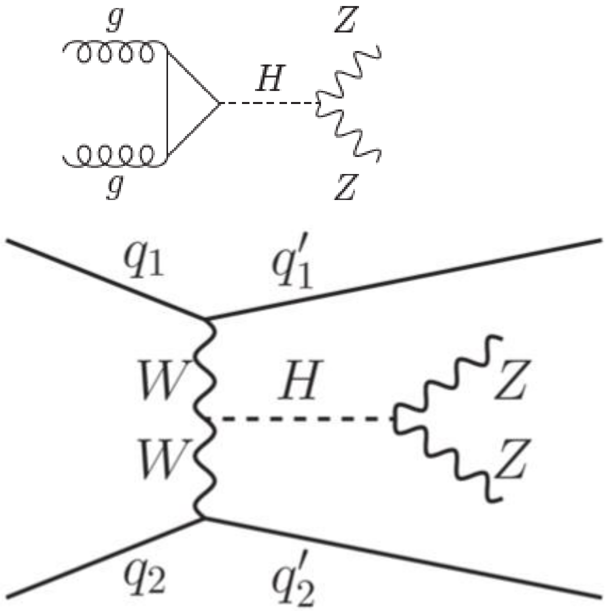
- Indirect measurement: measuring the signal
- strengths in on-shell and off-shell separately, and
- take their ratio: ZZ is the ideal channel

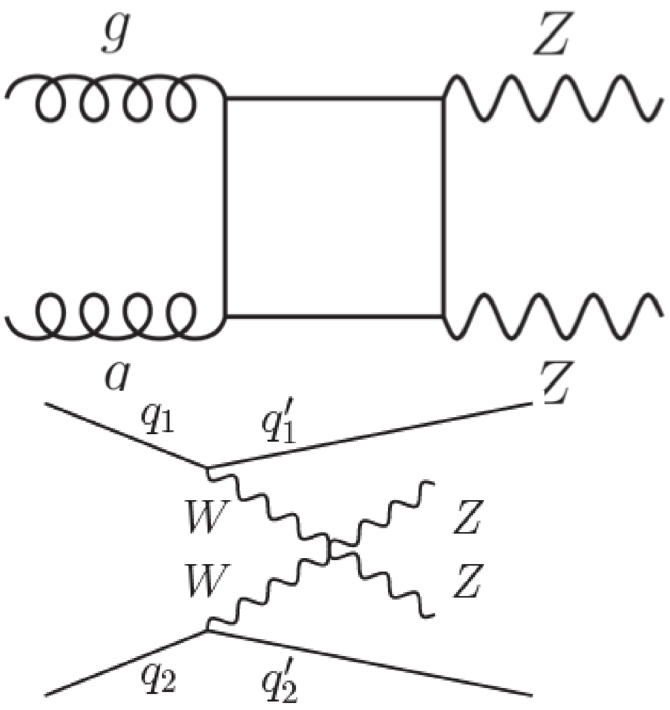
Off-shell Higgs in ZZ channel

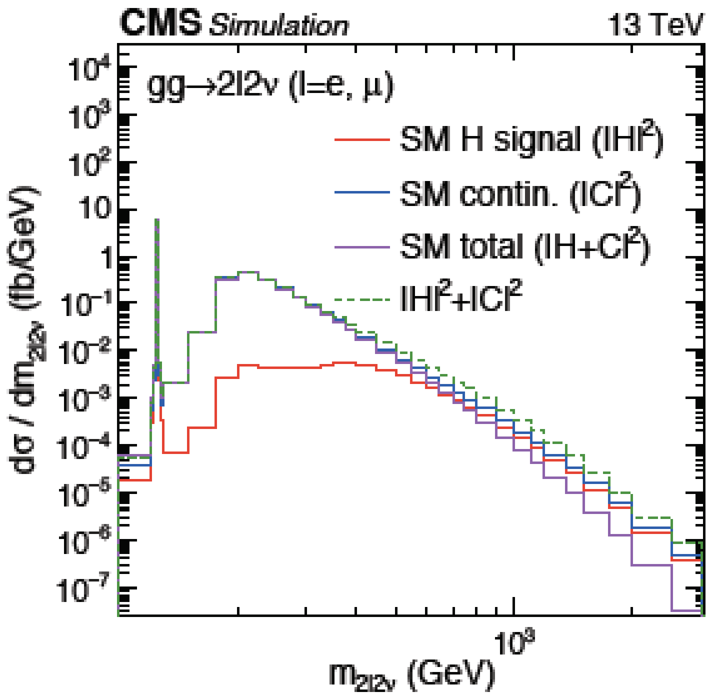
Nature Phys. 18(2022)1329

- Difficulties for probing off-shell Higgs:
- • low production rate: ~10% of total xs
- • large destructive interference with continuum

Background







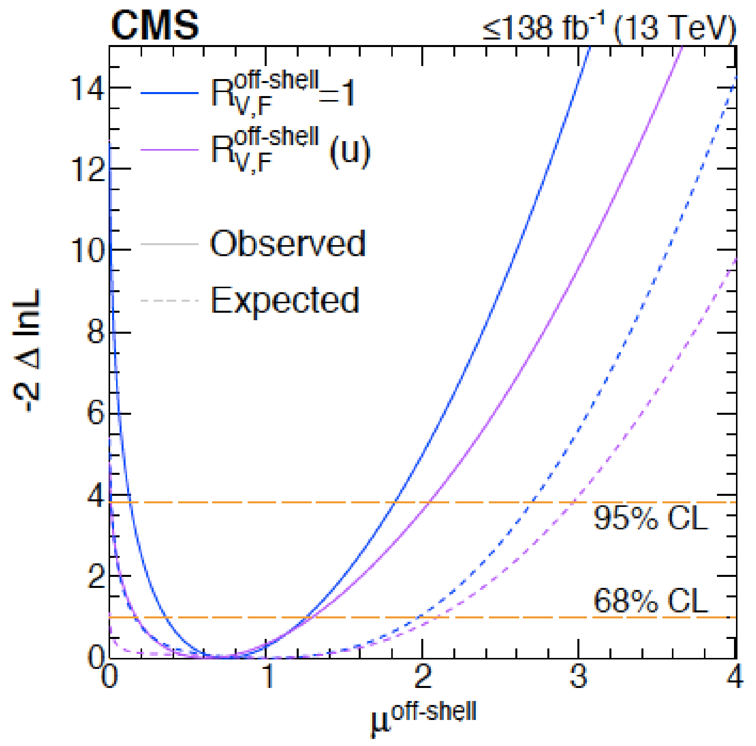
Higgs Boson Width

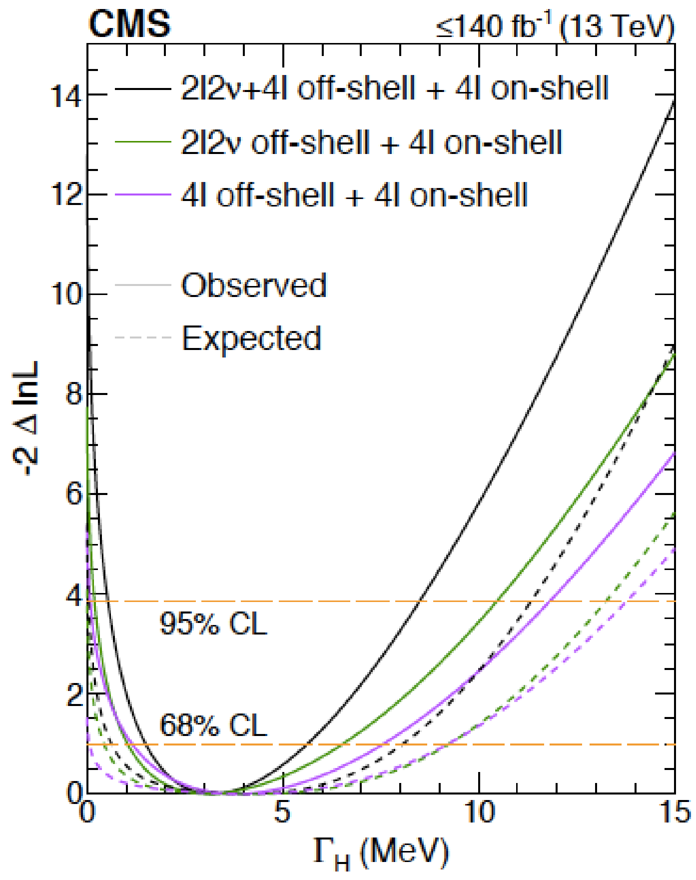
- Off-shell data 2l2v, on-shell 4l
- 117 multidimensional distributions were used in the fit
- H→ ZZ(*) → 4ℓ 2ℓ2ν
- From a combined measurement of on-shell and

off-shell production CMS finds evidence for off-shell Higgs production, scenario with no off-shell production is excluded with 3.6 σ

- ΓH= 3.2−1.7+2.4MeV [arXiv:2202.06923]

Evidence for off-shell Higgs and Measured Width

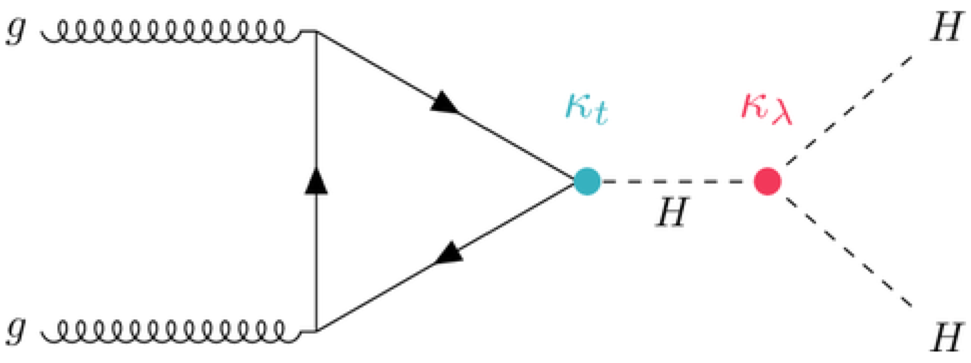


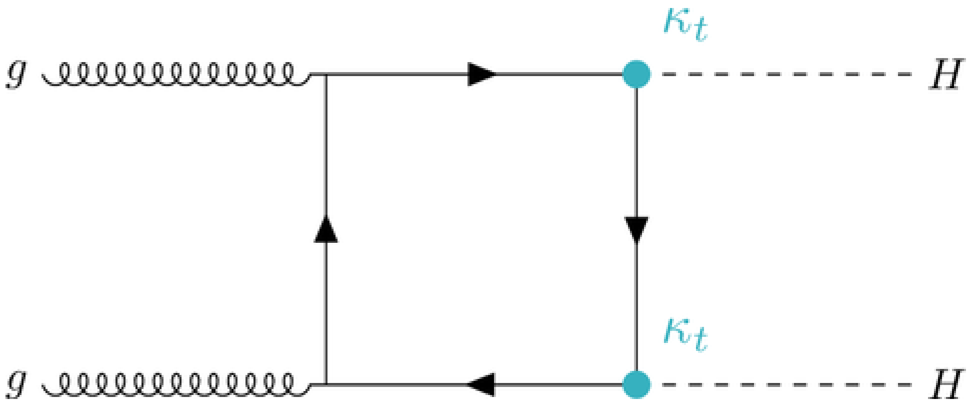


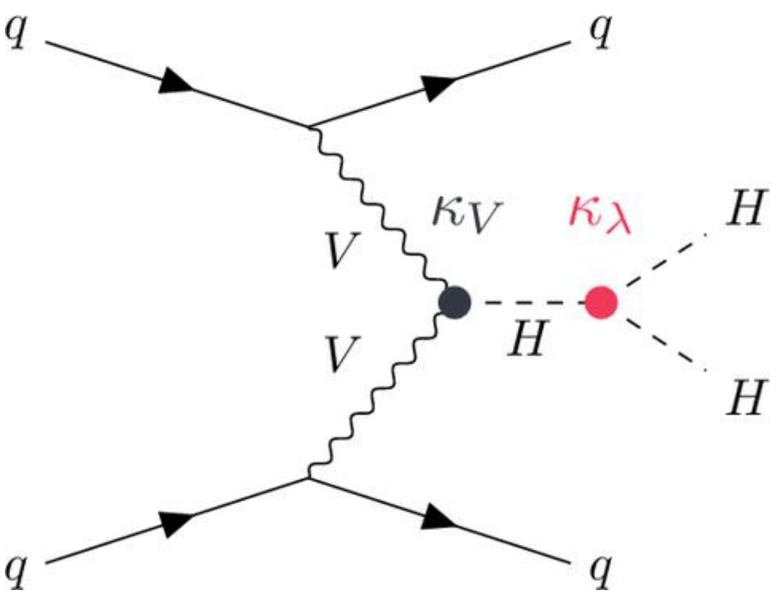
off-shell Higgs evidence: 3.6σ

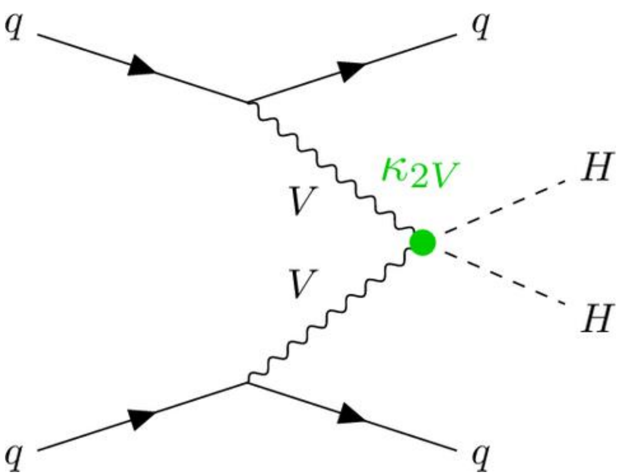
Observed $\Gamma_H = 3.2^{+2.4}_{-1.7}\,\mathrm{MeV}$

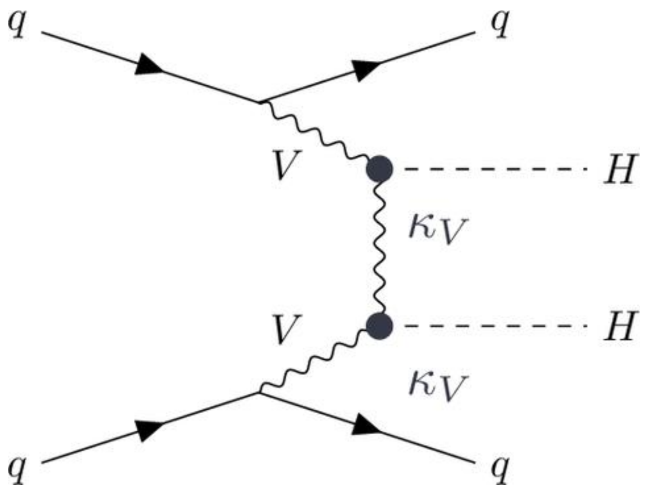
The LO Feynman diagrams for HH production



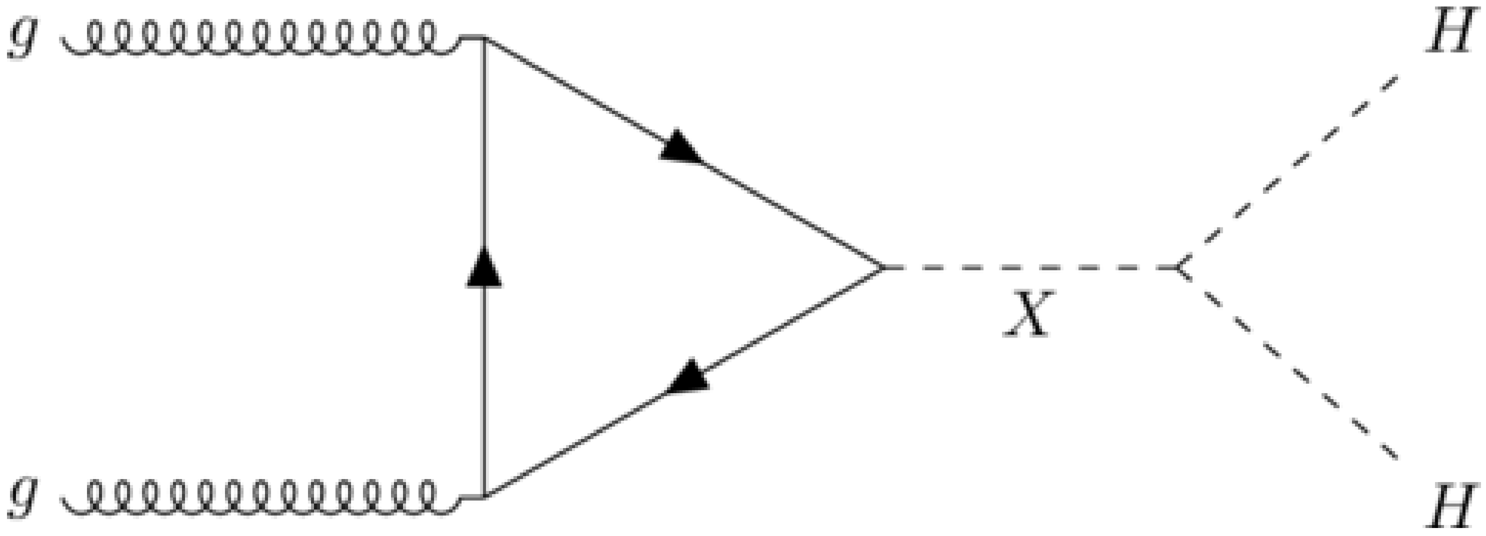




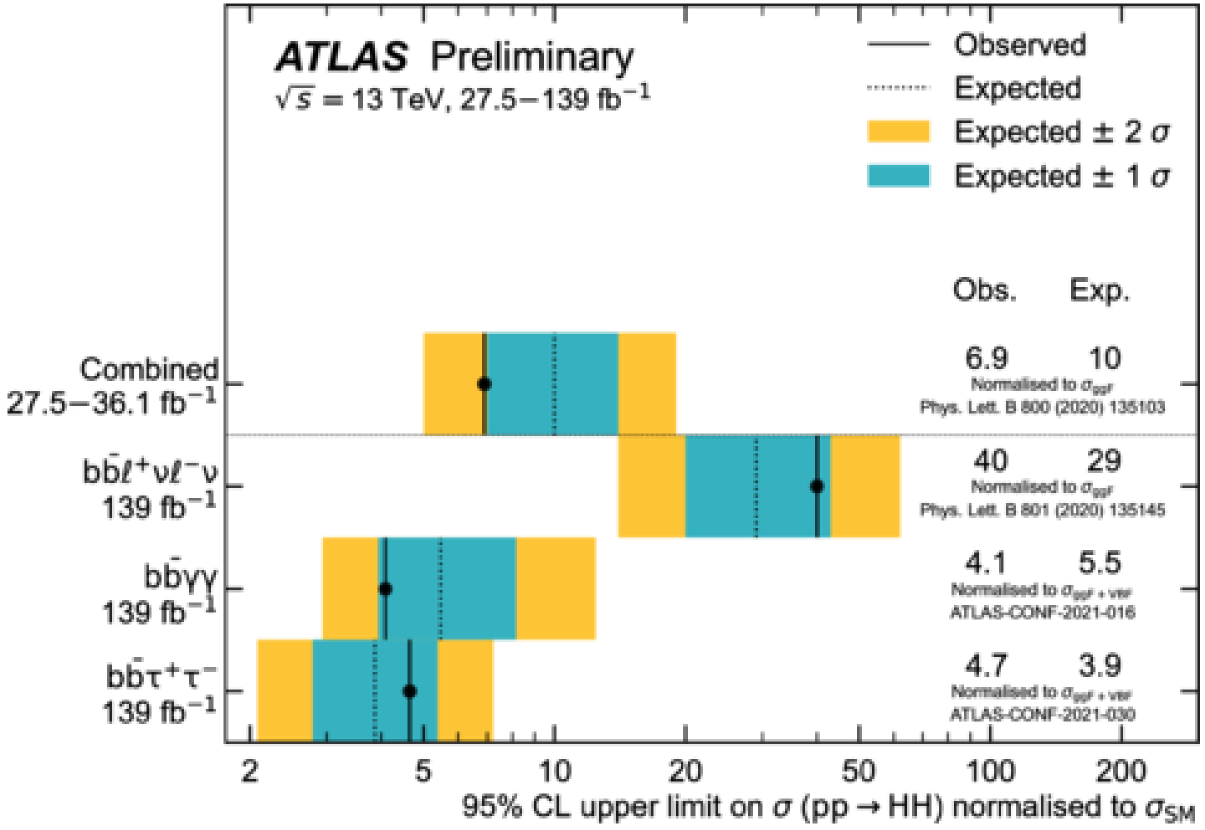




The LO Feynman diagram for gluon-gluon fusion production of a heavy scalar resonance decaying into a Higgs boson pair



Upper limits at 95% confidence level (CL) on the ratio of non-resonant HH production cross-section to the Standard Model prediction, obtained over an expected hypothesis assuming the absence of the SM HH signal.

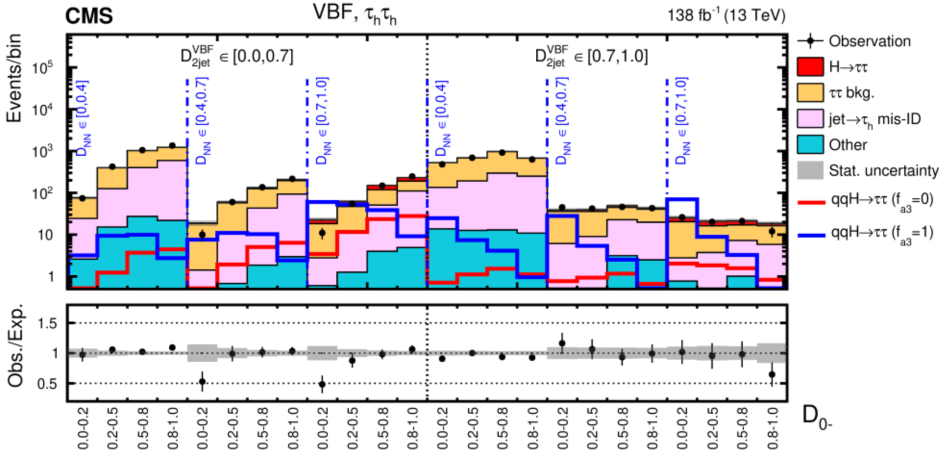


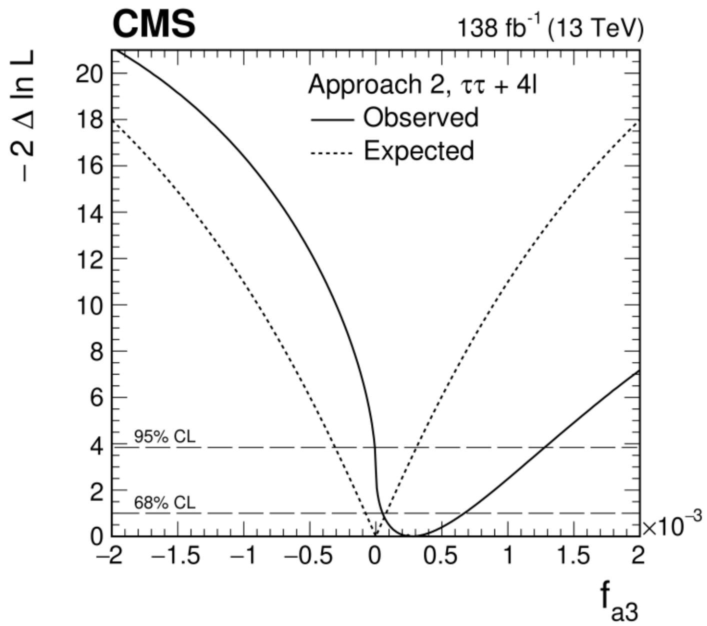
HVV Anomalous Couplings

Interaction amplitude of H and VV(ZZ, WW, Zγ, $\gamma\gamma$ and gg) are parameterized as:

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

arXiv:2205.05120, accepted by PRD

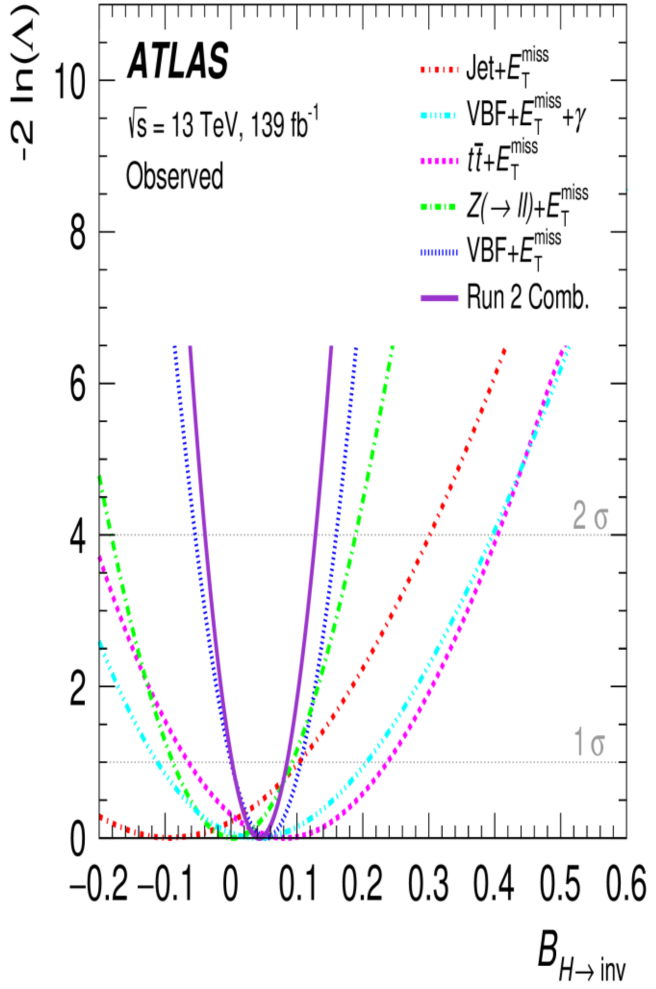




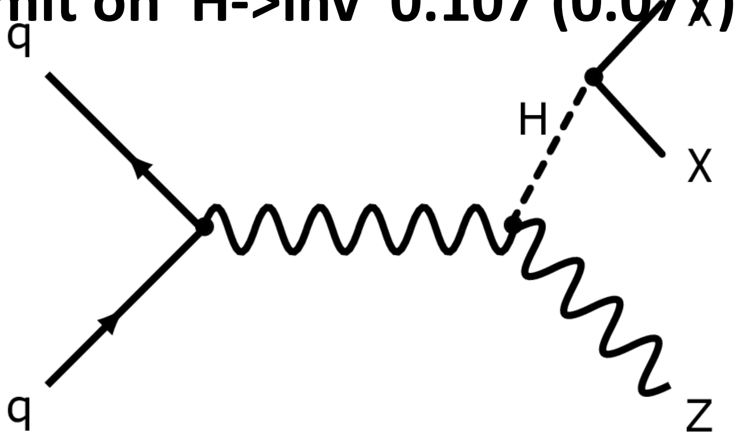
ATLAS H → Invisible arXiv:2301.10731v1

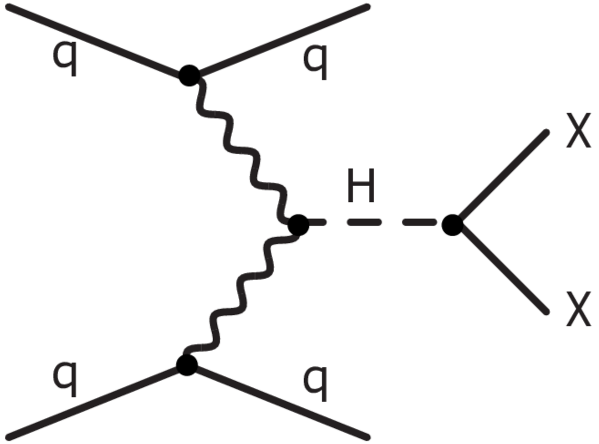
Higgs → Dark Matter! Invisible (→ MET), so measure and interpret accompanying visible particles

- New combination of results:
- VBF + MET
- Z + MET
- tt + MET
- VBF + MET + γ
- Jet + MET



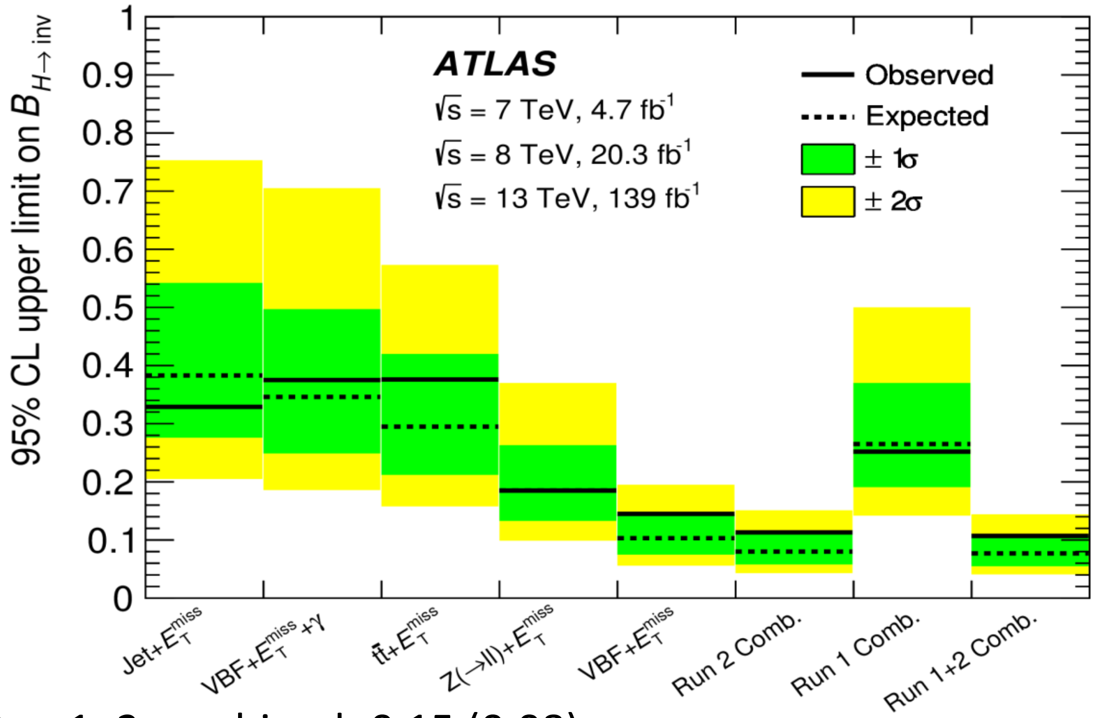
Upper limit on H->inv 0.107 (0.077)



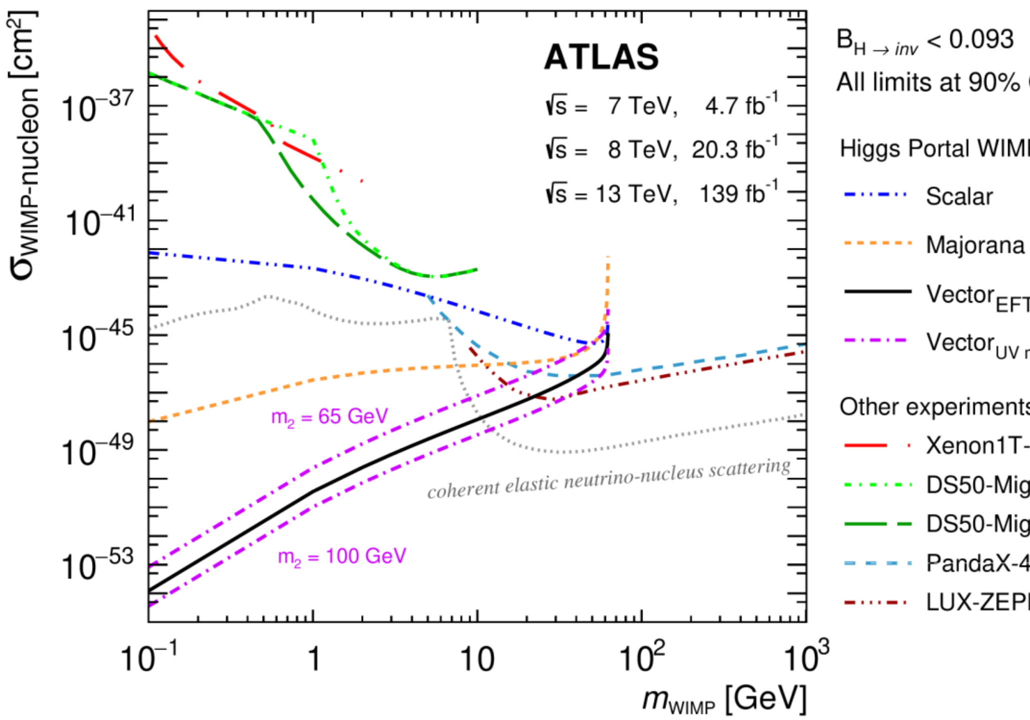


ATLAS H → Invisible arXiv:2301.10731v1

- VBF+MET most sensitive channel. Slight excess
- observed: Br @ 95% CL < 0.145(0.103) obs(exp)



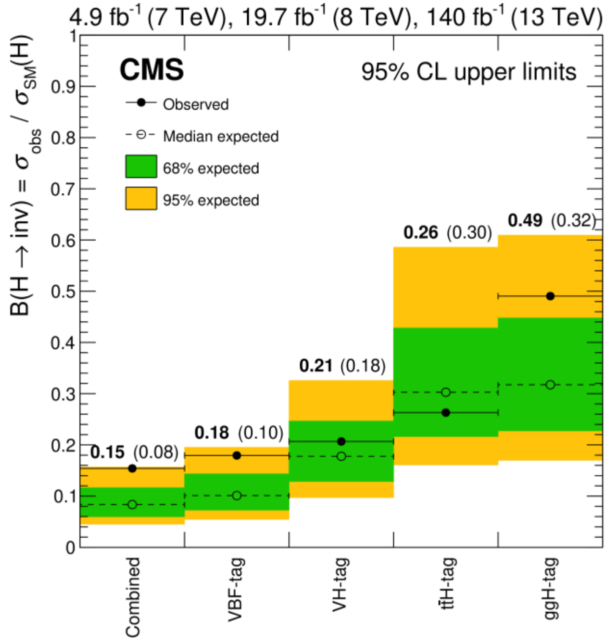
Run 1+2 combined: 0.15 (0.08)

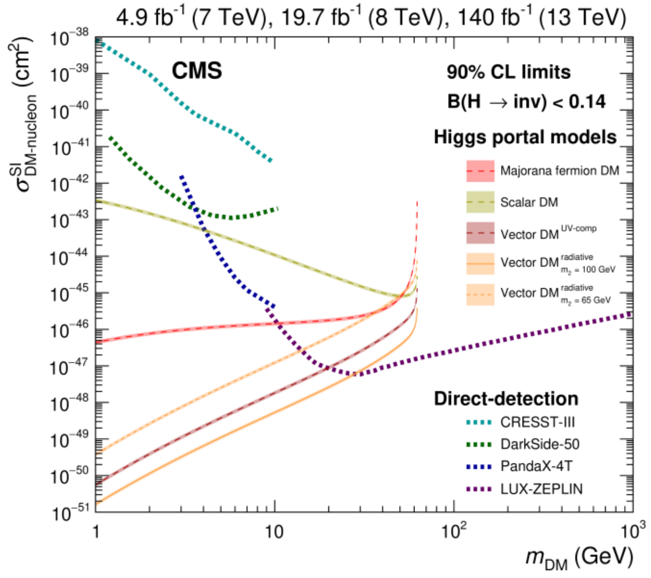


Higgs portal: m2 = dark Higgs mass

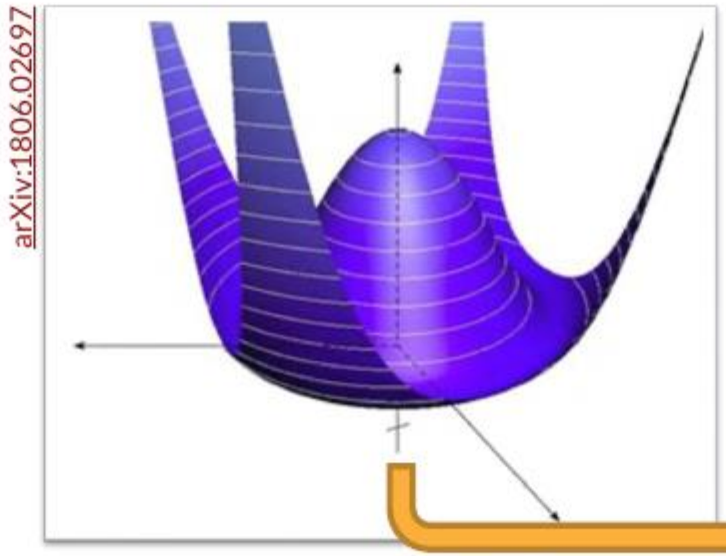
CMS H → Invisible arXiv:2303.01214v1

- New: ttH+MET, combine with previous (VH production)
- ‣ BGs: Z→ inv, EWK → lost leptons
- ‣ AK8 Jet mass (PUPPI PF with SD plus Deep AK8) separates high-pT t or V decays from q/g fragmentation
- ‣ @ pT > 400 GeV, t quark tag eff ~ 28% with 1% QCD mistag rate

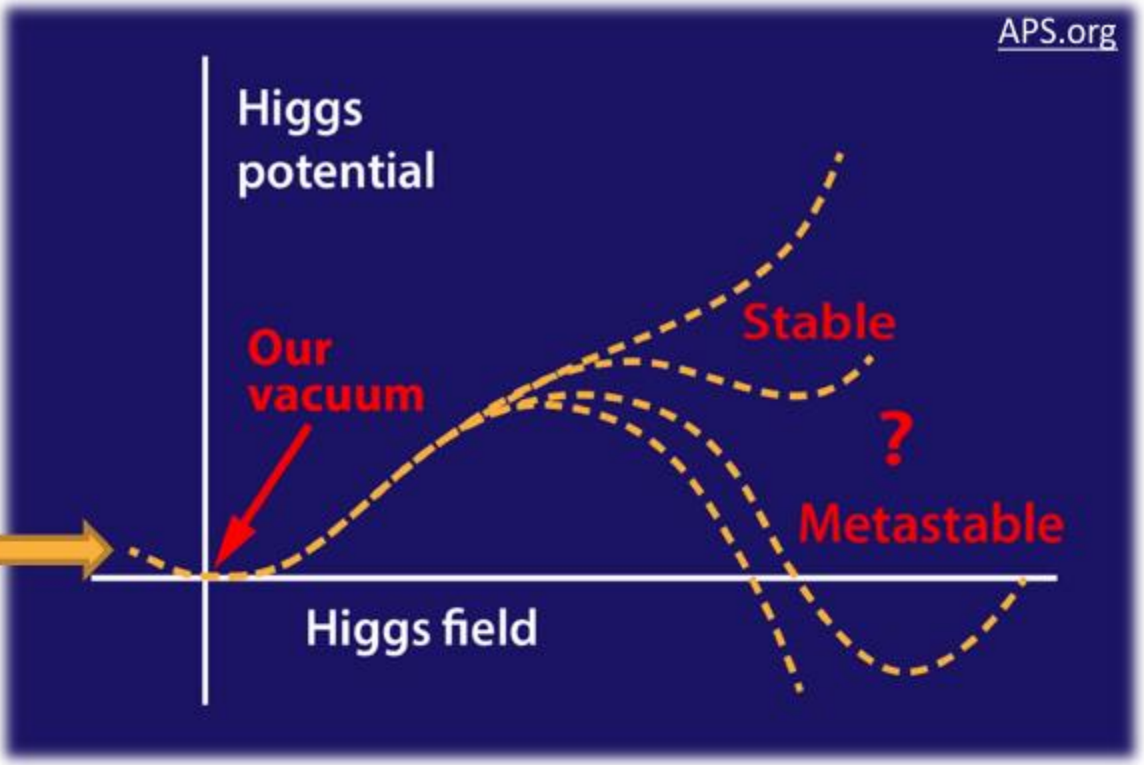




The Higgs Potential



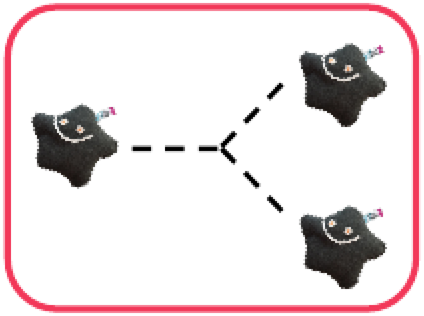
$$V(h) \sim \lambda v h^3 + \frac{1}{4}\lambda h^4$$

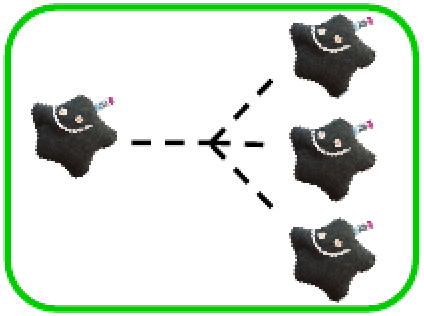


How do we measure the Higgs potential

"Non-resonant"
Production

$$V(h) \sim \lambda v h^3 + \frac{1}{4}\lambda h^4$$





Higgs Pair Production and Decay Modes

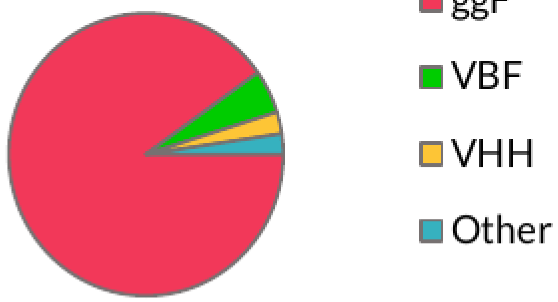
gluon-gluon Fusion (ggF)
$\sigma \sim 31.0$ fb — $\sim \kappa_\lambda$

Vector Boson Fusion (VBF)
$\sigma \sim 1.72$ fb — $\sim \kappa_\lambda, \kappa_{2V}$

Vector Boson Associated (VHH)
$\sigma \sim 0.86$ fb — $\sim \kappa_\lambda, \kappa_{2V}$

$$\kappa_\lambda = c_{HHH}/c_{HHH}^{SM}$$
$$\kappa_{2V} = c_{VVHH}/c_{VVHH}^{SM}$$

Cross Section (13 TeV)



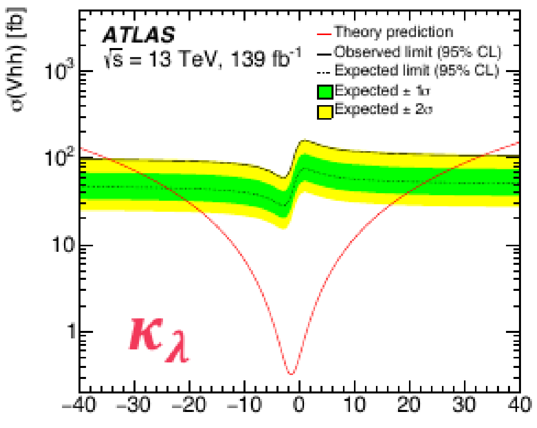
HH Decay Modes

	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%

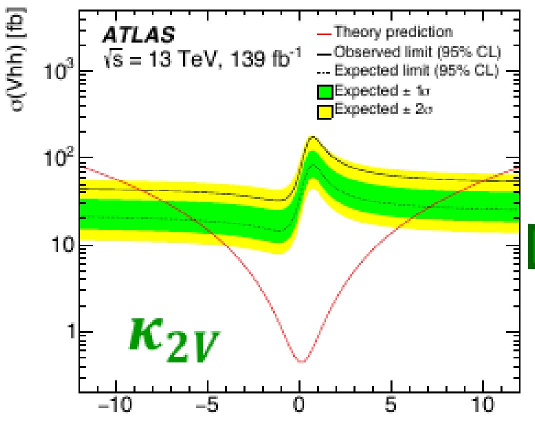
VHH limits

$VHH \to (\ell\ell, \ell\nu, \nu\nu) + b\bar{b}b\bar{b}$

arXiv:2210.05415



$-34.4 < \kappa_\lambda < 33.3$
(Exp: $-24.1 < \kappa_\lambda < 22.9$)



$-8.6 < \kappa_{2V} < 10.0$
(Exp: $-5.7 < \kappa_{2V} < 7.1$)

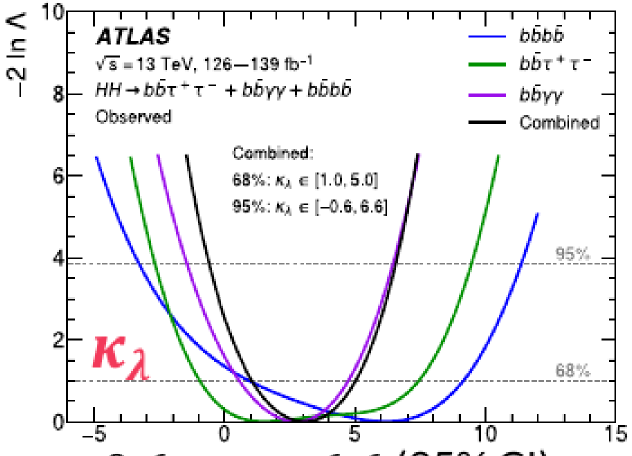
VHH production allows separation of $ZZHH$ and $WWHH$

→ $\mathbf{-9.9} < \kappa_{2Z} < \mathbf{11.3}$ ($-7.1 < \kappa_{2Z} < 8.5$ Exp.) $\mathbf{-12.3} < \kappa_{2W} < \mathbf{13.5}$ ($-8.6 < \kappa_{2W} < 9.8$ Exp.)

HH Combination

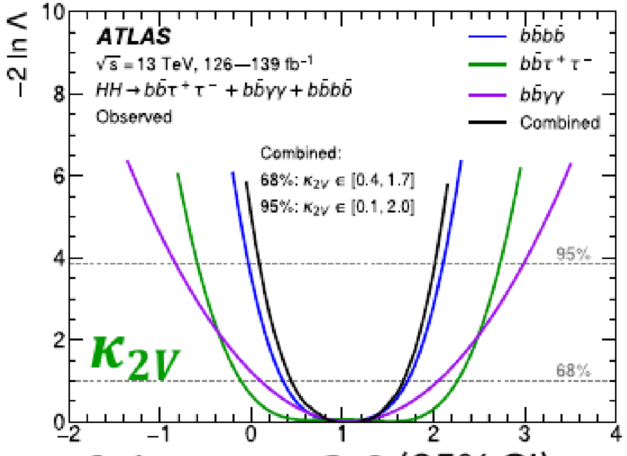
Combination: $HH \rightarrow b\bar{b}b\bar{b}, b\bar{b}\tau\tau, b\bar{b}\gamma\gamma$

arXiv:2211.01216



$-0.6 < \kappa_\lambda < 6.6$ (95% CI)

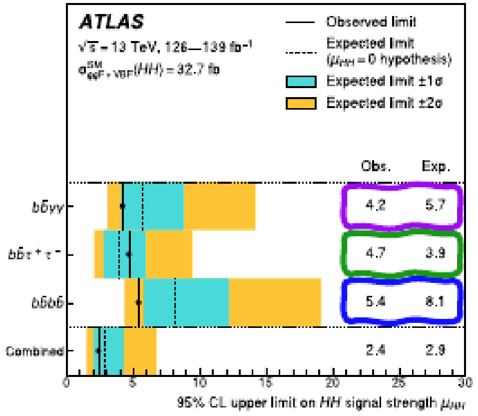
$(-2.1 < \kappa_\lambda < 7.8)$ (Exp.)



$0.1 < \kappa_{2V} < 2.0$ (95% CI)

$(0.0 < \kappa_{2V} < 2.1)$ (Exp.)

	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%

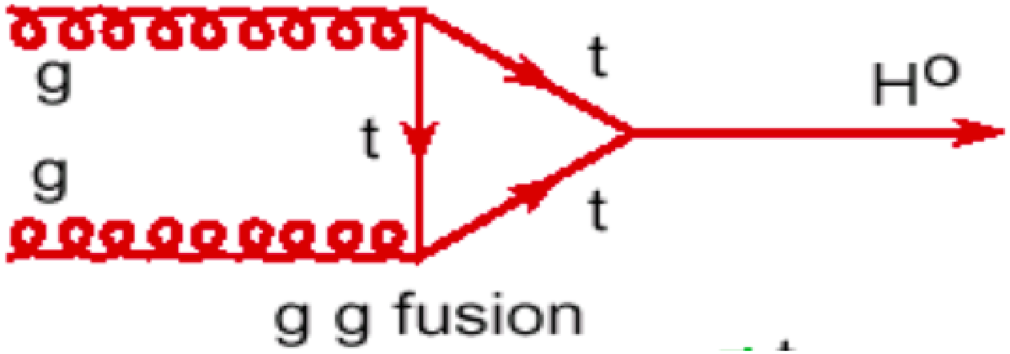


Combined upper-limit on SM HH Cross-Section:

$2.4 \times \sigma_{SM}$ (2.9 Exp.)

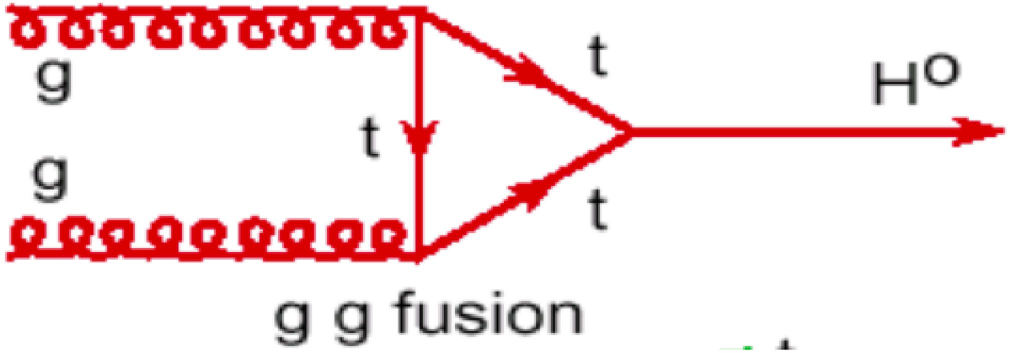
☆ "Log Likelihood Scan" limits utilize different assumptions

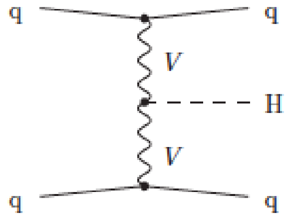
- THANK YOU FOR YOUR ATTENTION!



б ~ $|g_{Htt}*g_{HZZ}|_{2}$

Fermion vs. Boson Couplings





Discrimate gg→h from WW/ZZ→ h by jets in fwd direction

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masses of bosons and fermions break gauge symmetry
massive gauge – bosons:
cross sections WLWL⍰ WLWL outside theoretical bound at ~ 1.2 TeV

Way out: introduce new scalar (spin 0) particle ‘Higgs boson’
Theory devised in 1964 by Brout & Englert; Higgs