The scalar sector – story so far from the ATLAS perspective

Seminarium środowiskowe “Białasówka”

Kraków, 22.03.2024

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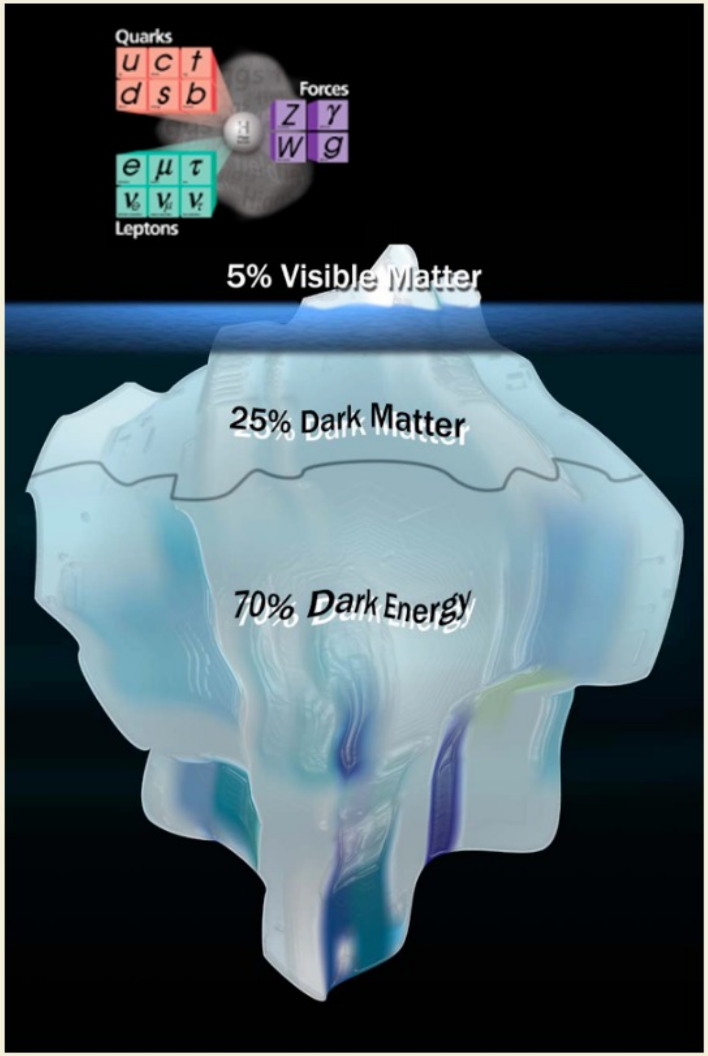
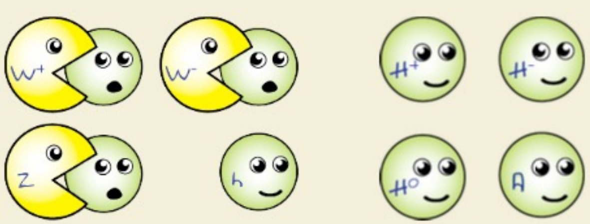
BSM physics in the scalar sector?



Sketches adapted from www.quantumdiaries.com

There are already many (indirect) hints of new physics beyond the SM! And its Higgs sector has serious short-comings:

- Why so many orders of magnitude across the fermion couplings to the Higgs field?
- m_H is driven to a very large scale by loop corrections, why such a precise cancellation against the bare mass?
- It is possible that our Universe leaves in a metastable vacuum state.
- Why should the Higgs potential have a minimal form, and could there be an extended Higgs sector?



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The BEH mechanism – must have a massive scalar interacting with SU2 gauge bosons

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Is it the whole story? – the above do not preclude existence of a non-minimal scalar sector - 125 GeV Higgs **properties** $\oplus$ direct **searches** for additional scalars

Plan for today:

- I'll summarise the fundamental properties confirming the BEH mechanism
- I did talk about the Yukawa interactions. Today only some less well-known examples

- Where do we stand in terms of direct searches for the extended phenomena? Today just a summary

A topic for a separate seminar, perhaps...

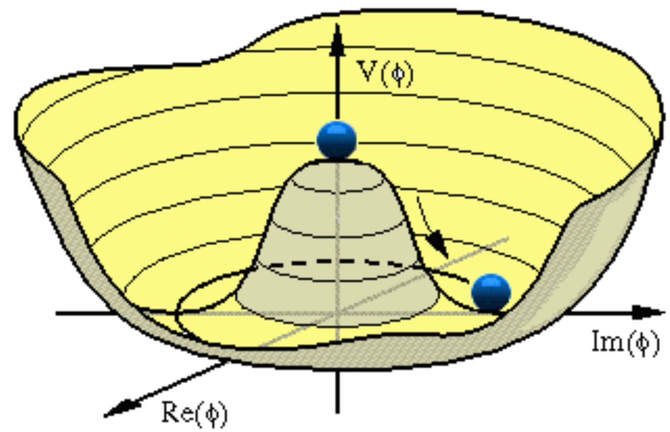
Brout-Englert-Higgs-Hagen-Guralnik-Kibble field and… the Higgs boson (1964)

T.Kibble G.Guralnik R.C.Hagen F.Englert R.Brout & P.Higgs

$$\mathcal{L}_{Higgs} = D_\mu \phi^\dagger D^\mu \phi - V_{Higgs}$$

$$V_{Higgs} = \frac{1}{2}\mu^2 \left(\phi^\dagger \phi\right) + |\lambda| \left(\phi^\dagger \phi\right)^2$$

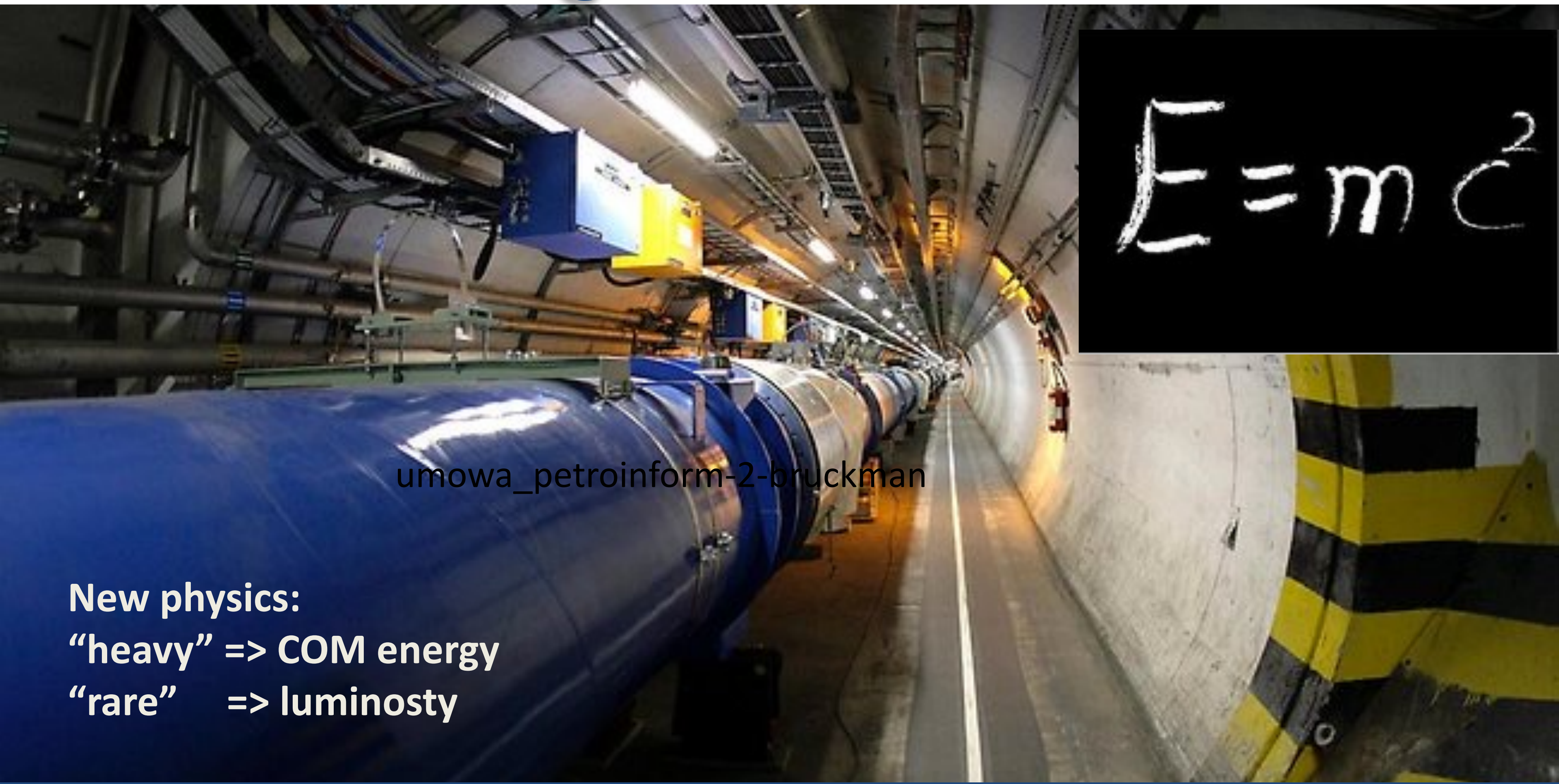
$$\mathbf{\Phi} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \mathbf{\Phi_0} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \upsilon + h(x) \end{pmatrix}$$



$$v = \sqrt{-\mu^2 / |\lambda|} \sim 246 \text{ GeV}$$

vacuum state (174 GeV) the Higgs particle

The Large Hadron Collider

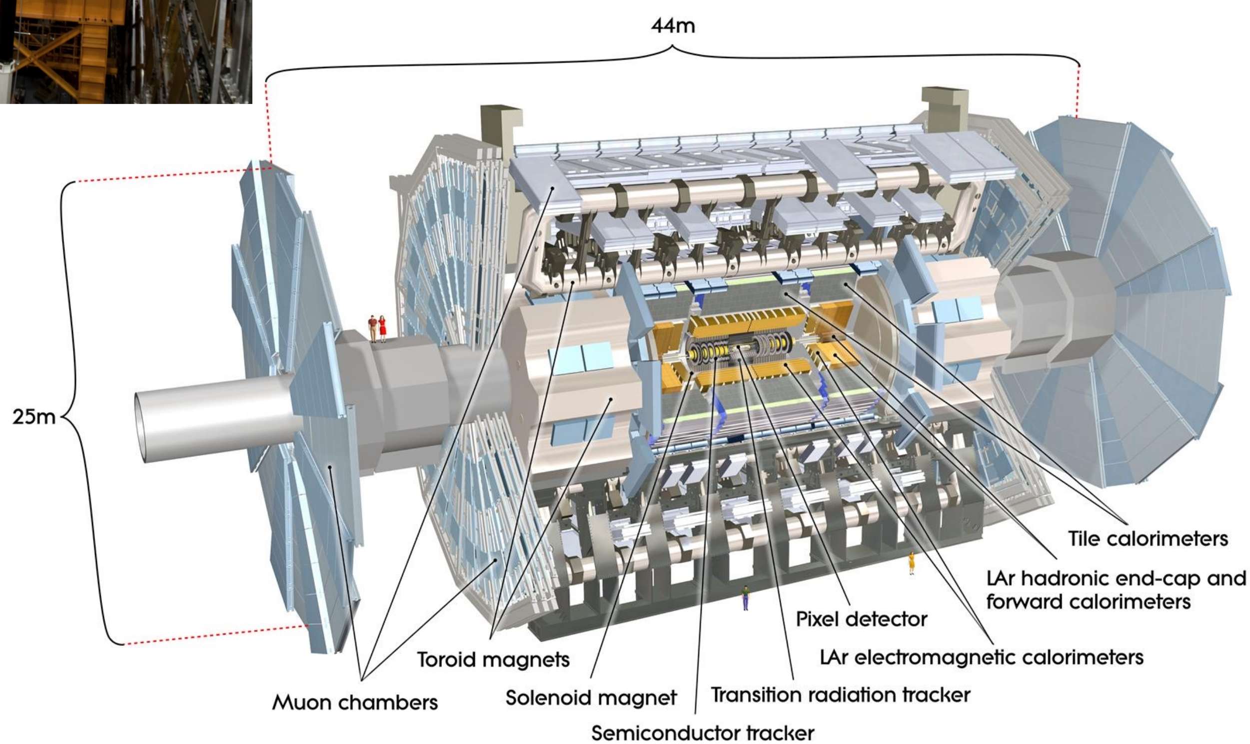


- pp collisions at the world-highest ever energy (currently **13.6 TeV**)
- Intensity: ~**60 interactions every 25 ns** (40 MHz)
- E.g.: The Higgs Boson is produced ~**once per second**!

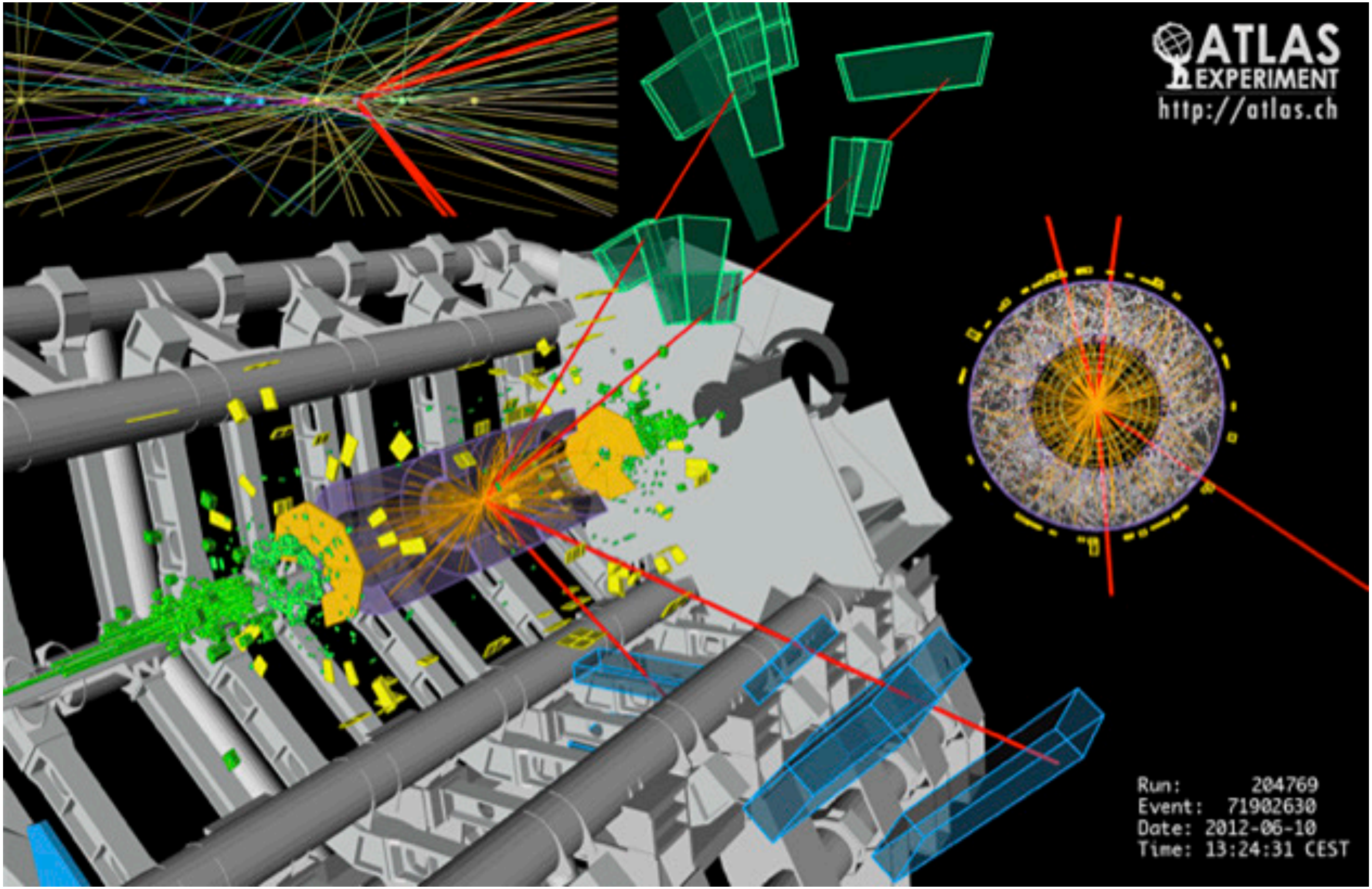
ATLAS Detector

	ATLAS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)

ATLAS Collaboration
38 Countries
175 Institutions
3000 Scientific Authors total



$H \rightarrow ZZ^* \rightarrow 4l$ candidate

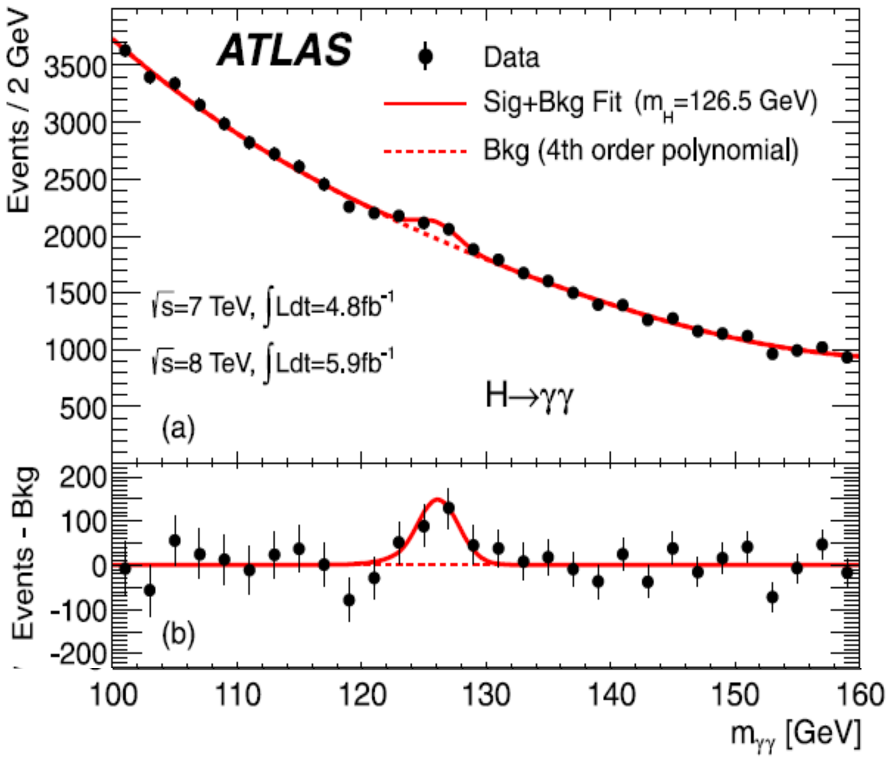



2012
CERN, 4 July 2012
Ladies and gentlemen,
I think we've got it!
Discovery of a Higgs-like particle
decaying to gauge bosons

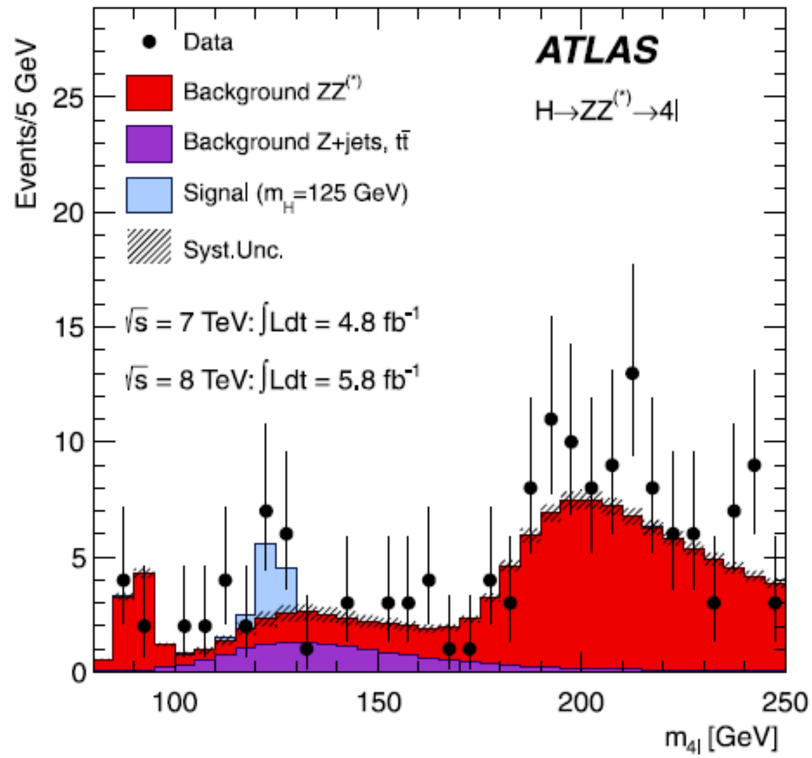

2012
CERN, 4 July 2012
2013 NOBEL PRIZE IN PHYSICS
François Englert
Peter W. Higgs

… what was observed

H → γγ



H → ZZ* →4l



m_H=126.0±0.4 (stat)±0.4 (sys) GeV **GS = 5.1σ**

[Phys. Lett. B 716 (2012) 1-29]

How did we know what was actually observed?

QM assures us that:

1. H → 2 bosons ($\gamma\gamma$) -> must be a **boson**

2. H → 2 photons implies it cannot be a vector boson (S=1). Options left: 0, 2.

3. Analysis of angular distributions in H → 4l and others excluded S=2 @99% CL, fully confirming the S=0 hypothesis (**scalar**!)

4. **Couplings** to SM particles are key features of the Higgs boson – they depend on the particle mass!

J^P of the 125 GeV Higgs

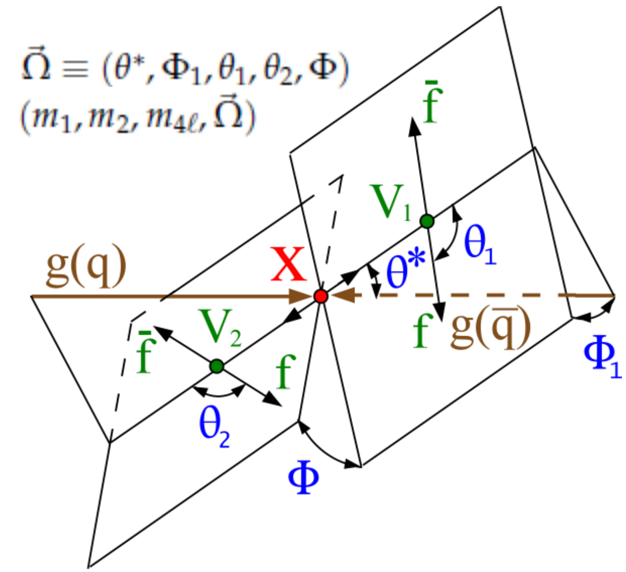
Eur. Phys. J. C75 (2015) 476

Testing for alternative J^{CP} scenarios using decay kinematics.

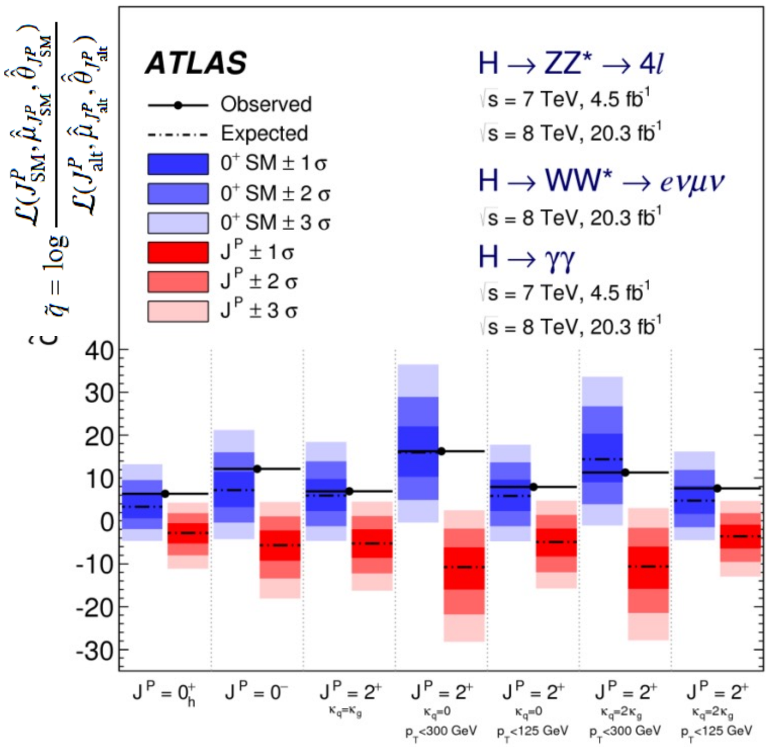
ZZ: full kinematics available

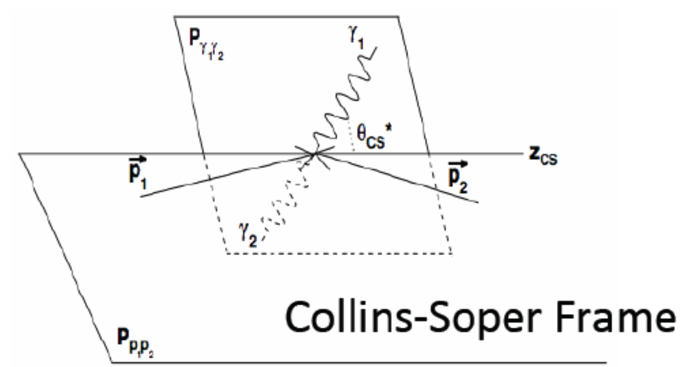
WW: $m^{\ell\ell}$, $p_T^{\ell\ell}$, $\Delta\phi^{\ell\ell}$ and m_T

$\gamma\gamma$: $\cos(\Theta_{CS}^*)$, $p_T^{\gamma\gamma}$



Exclusions @ 99% CL or better



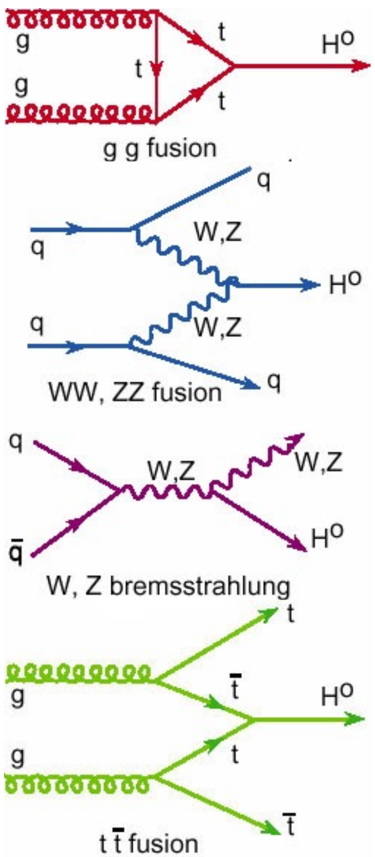


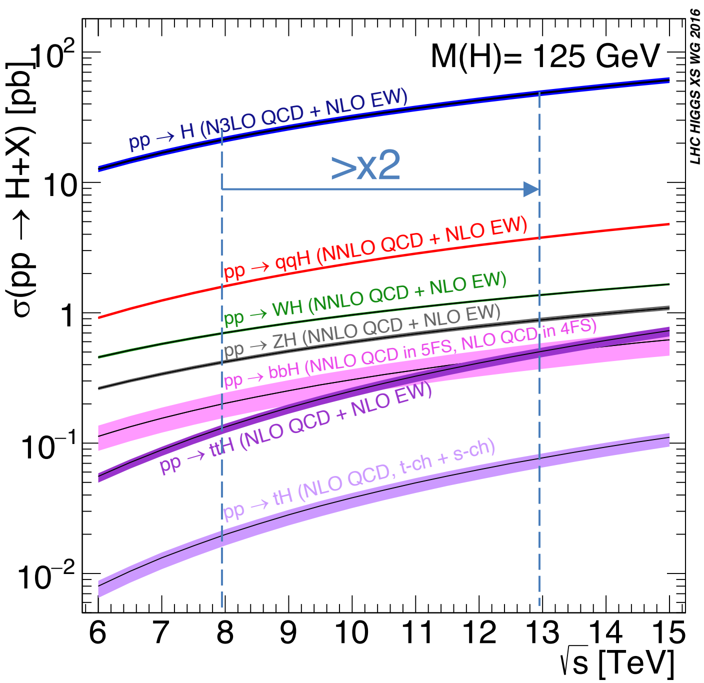
Note: Landau-Yang theorem precludes J=1 hypothesis in the presence of H->$\gamma\gamma$

Production and Decay of the SM Higgs Boson at the LHC

Production (gg Fusion dominant)

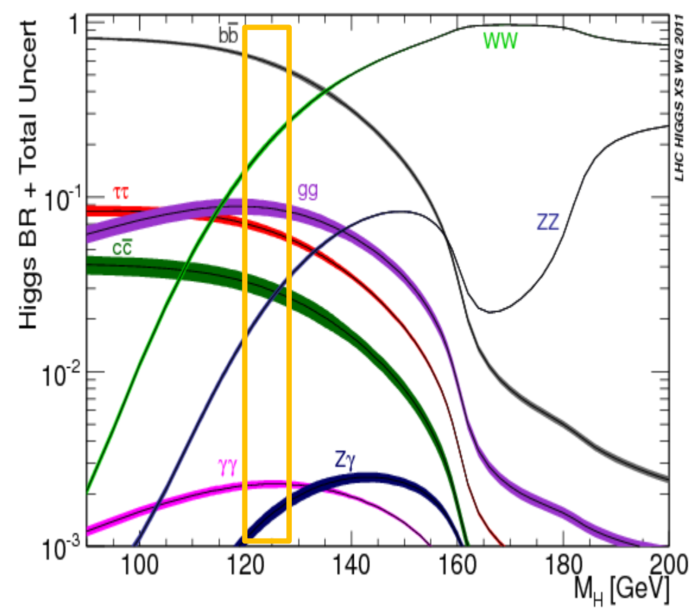
Higgs coupling proportional to mass ⇒ Higgs generaly decays to heaviest particles possible





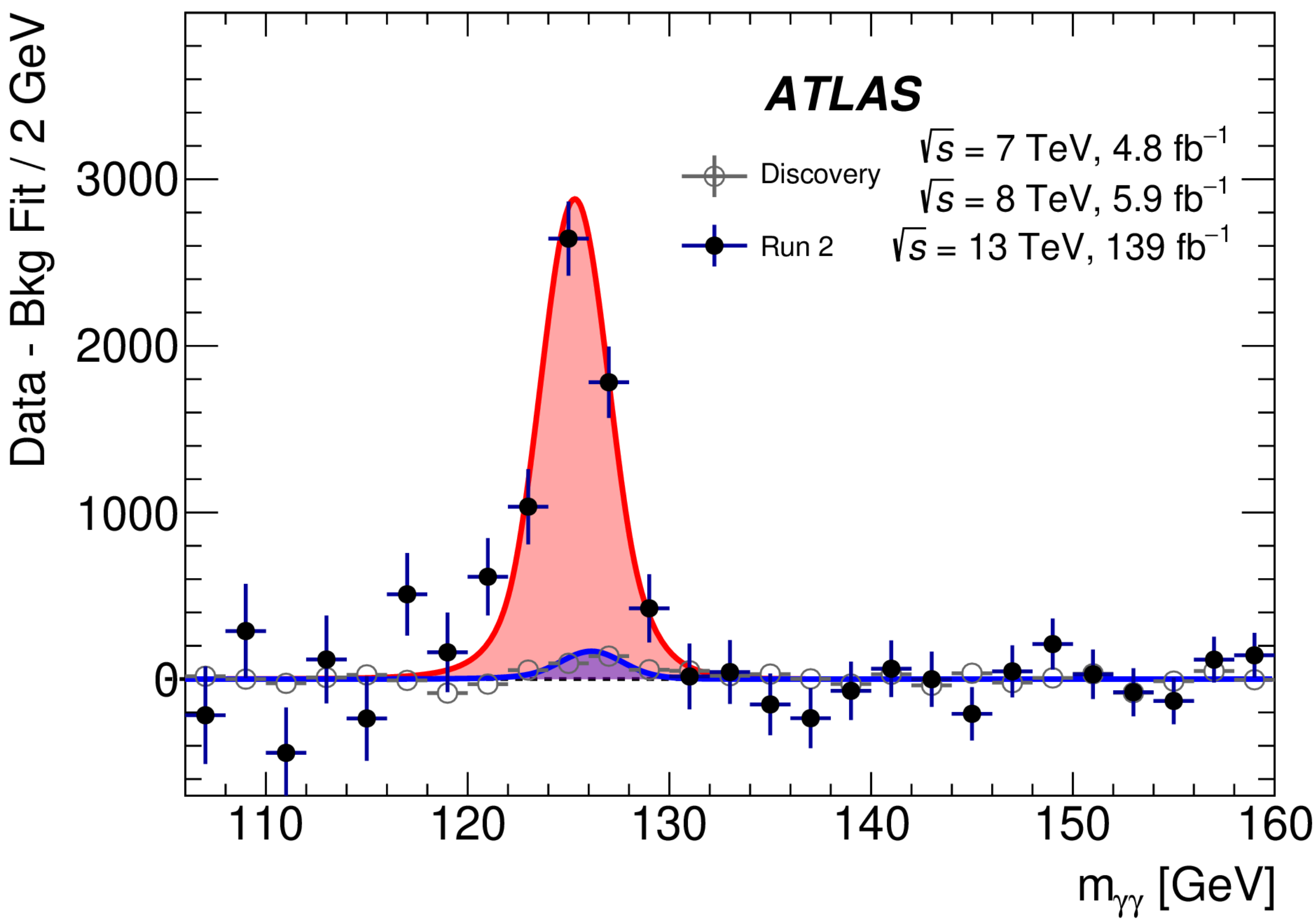
← production @ LHC

Higgs decay branching →



Getting to know the 125 GeV scalar

10 years HIGGS boson discovery



Run 2

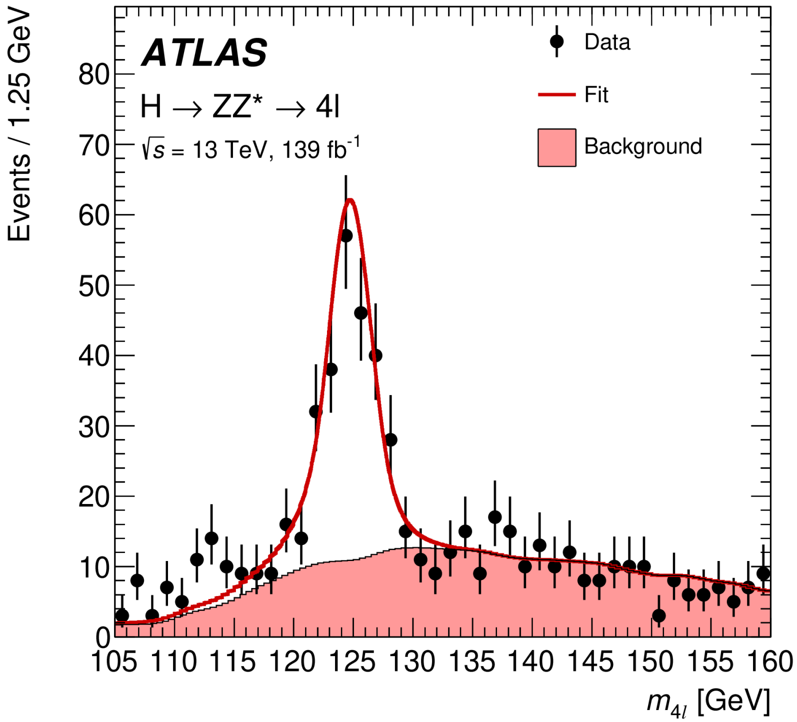
x30

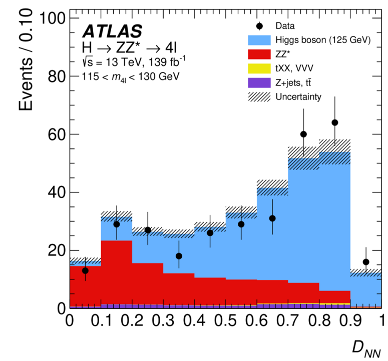
Discovery

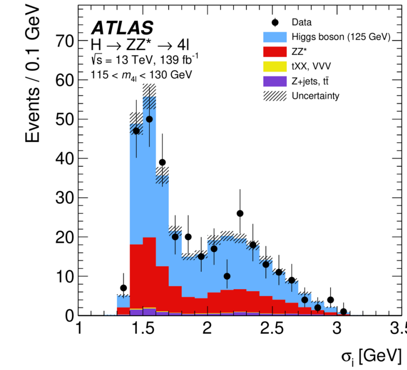
Higgs mass measurement

HIGG-2020-07

$H \rightarrow ZZ^* \rightarrow 4l$

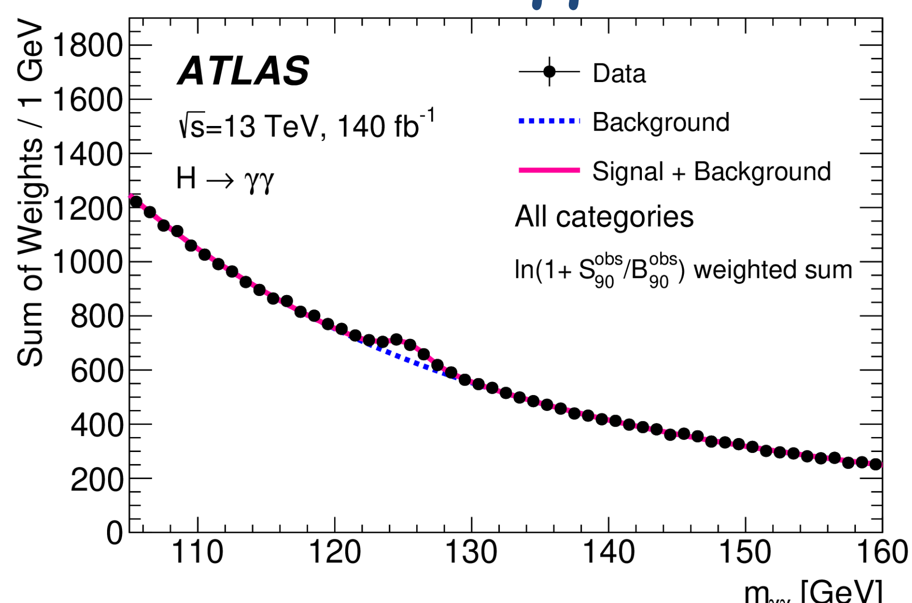






NN output to parameterise per-event resolution and composition

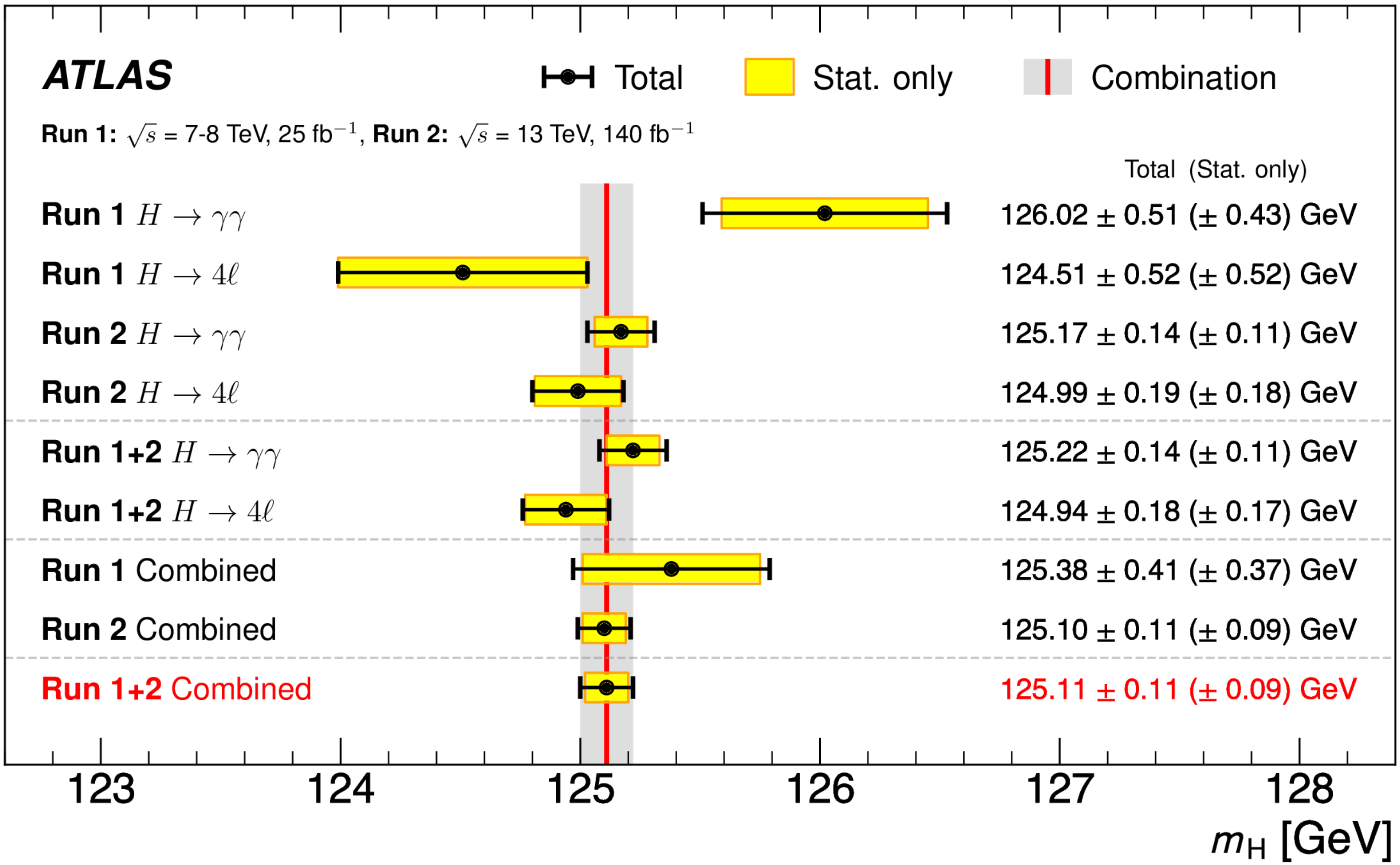
$H \rightarrow \gamma\gamma$



- The result is statistically dominated!
- Largest systematics come from muon momentum scale and electron energy scale

Higgs mass measurement

HIGG-2020-07

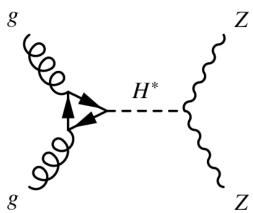


Legacy Run2 Higgs mass (4l+$\gamma\gamma$ combined) currently @ 0.14GeV (approaching 10^{-3} precision!). We know top mass to 2×10^{-3}, W mass to 2×10^{-4}

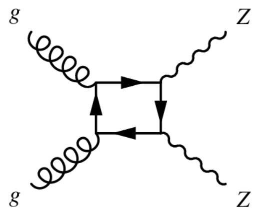
Higgs total width – the smart way

[Phys. Lett. B 846 (2023) 138223]

Explore the off-shell Higgs decays...



$\oplus$

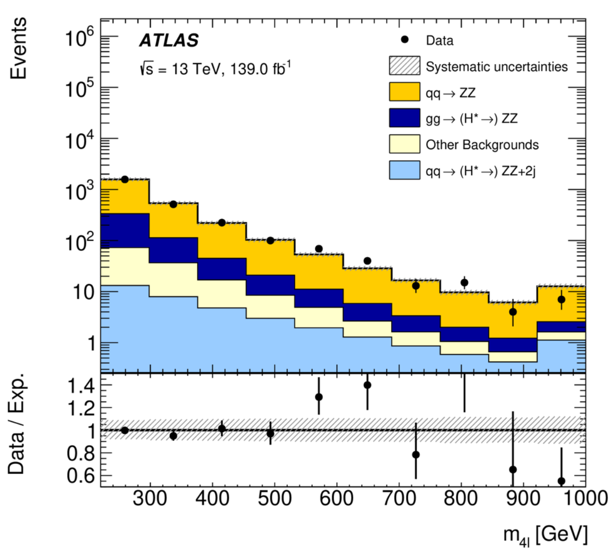


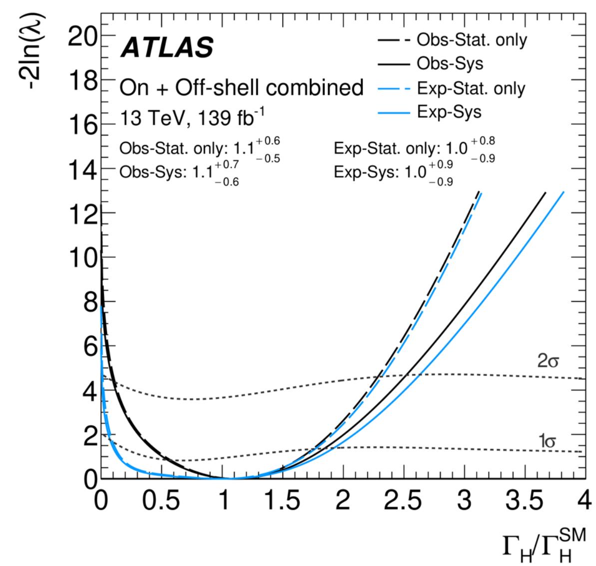
$\oplus$ the interference term

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m_H \Gamma_H},$$

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m^2_{ZZ}}.$$

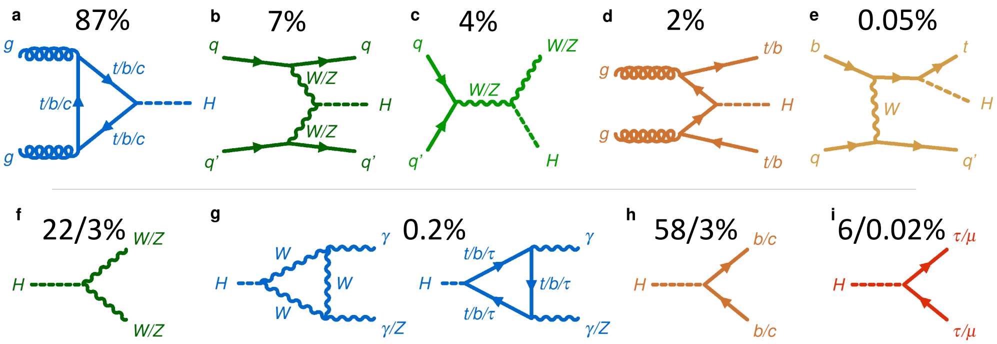
...into two on-shell Z bosons decaying leptonically (4l or 2l2ν)





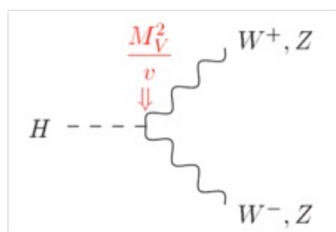
The measured total width of the Higgs boson is $4.5^{+3.3}_{-2.5}$ MeV (Γ_{SM}(125 GeV) = 4.1 MeV)
95% CL observed (expected) limits on the Higgs width: 0.5(0.1) < Γ_H < 10.5(10.9) MeV

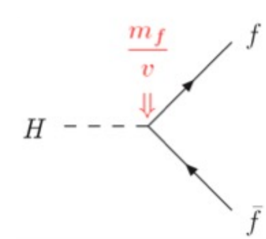
Higgs couplings combination

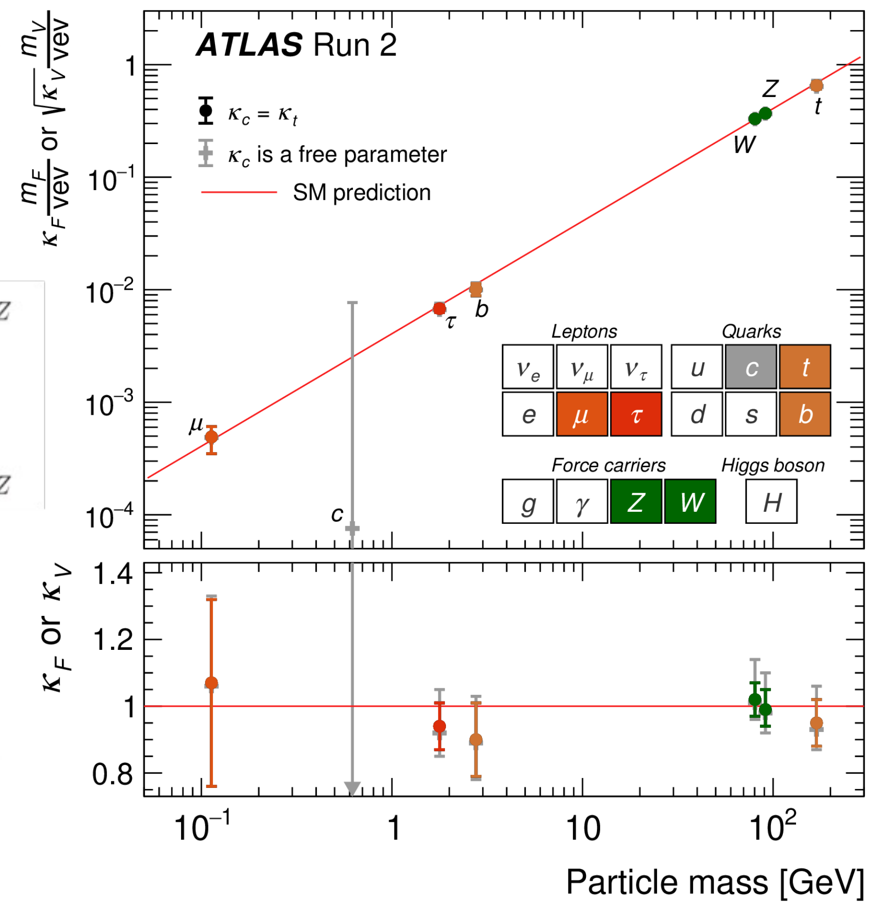


[Nature 607, pages 52-59 (2022)](#)

- $H \to ZZ^* \to l^+l^-l^+l^-$
- $H \to W^\pm W^\mp \to l^\pm \nu_l l^\mp \nu_l$
- $H \to \gamma\gamma$
- $H \to Z\gamma$ (limit, incl.)
- $H \to b\bar{b}$ (all but ggF)
- $H \to \tau^+\tau^-$
- $H \to \mu^+\mu^-$
- $H \to c\bar{c}$ (VBF, ZH)
- $H \to$ invisible (VBF, ZH)







Excellent agreement of couplings across three orders of magnitude of particle mass!

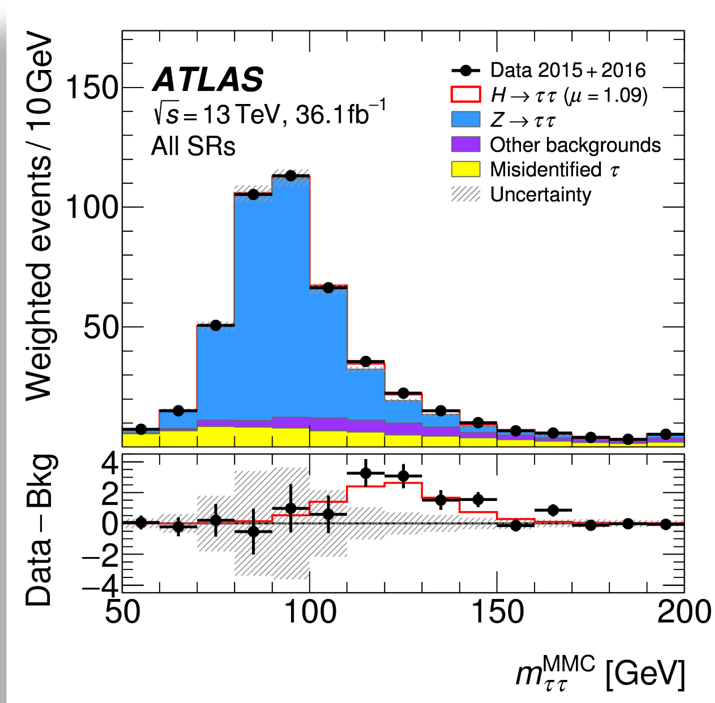
Assuming m(H) = 125.09 GeV

[PRL **114** (2015) 191803](#)

2018

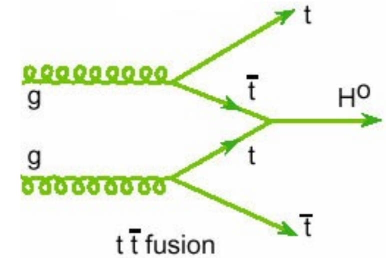
Run 2 (36 fb^{-1} & 80 fb^{-1})

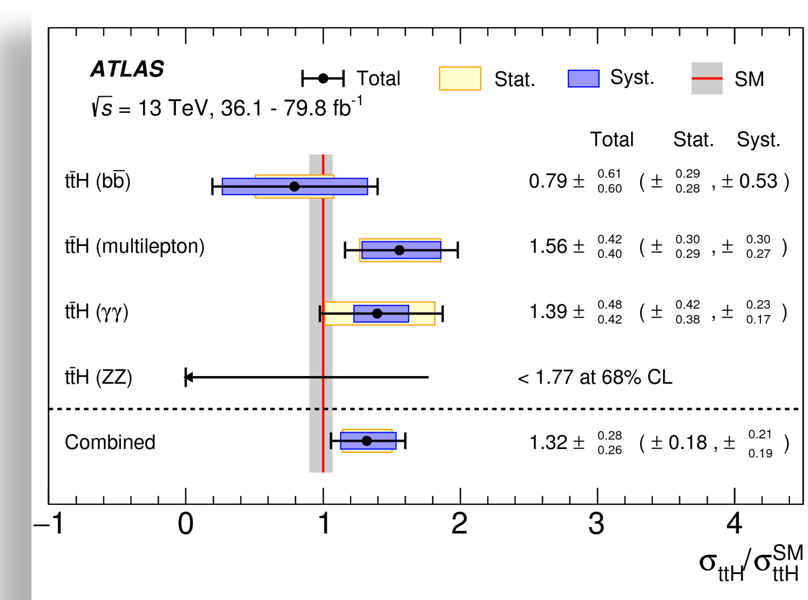
H->ττ



MMC: Nucl. Instrum. Meth. A 654 (2011) 481

ttH





Higgs decays to WW*, ZZ*, $\gamma\gamma$, $\tau\tau$, *bb* considered

Signal strength:	**μ**=1.09 +0.35-0.30
Significance:	S=4.4(4.1 exp.)σ
⊕ Run 1:	
Significance:	S=6.4(5.4 exp.)σ

Signal strength:	**μ**=1.32 +0.28-0.26
Significance:	S=5.8(4.9 exp.)σ
⊕ Run 1:	
Significance:	S=6.3(5.1 exp.)σ

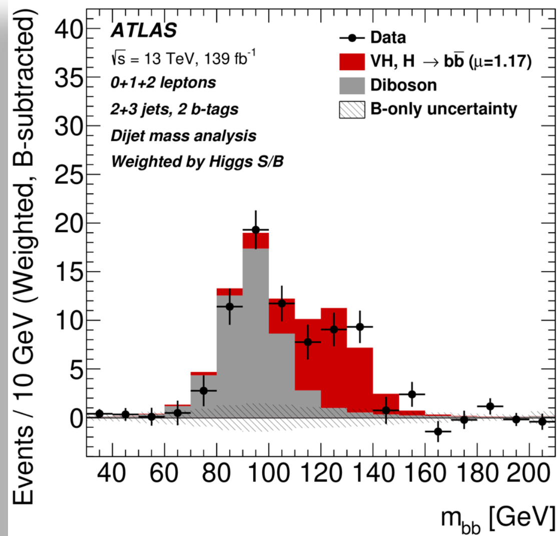
2020

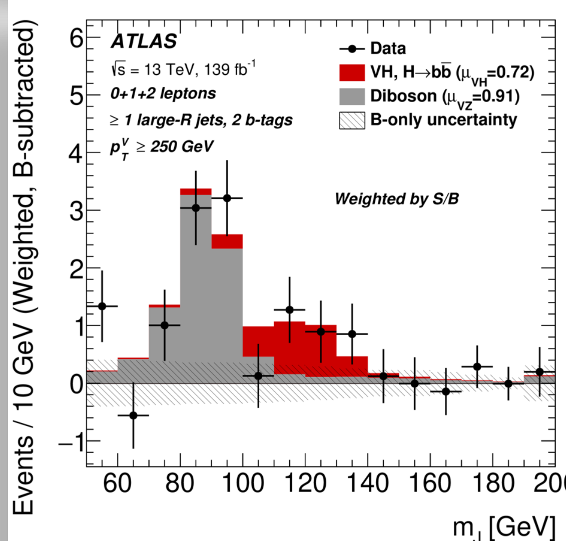
Run 2 (139 fb^{-1}) VH, H->bb

Resolved VH->bb arXiv:2007.02873 (2020)
Boosted VH->bb arXiv:2008.02508 (2020)

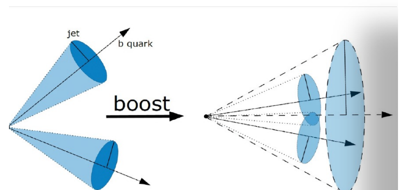
Signal strength: **μ**=1.02 ±0.12 ±0.14
Significance: **S**=6.7(6.7 exp.)σ
Significance (ZH): **S**=5.3(5.1 exp.)σ

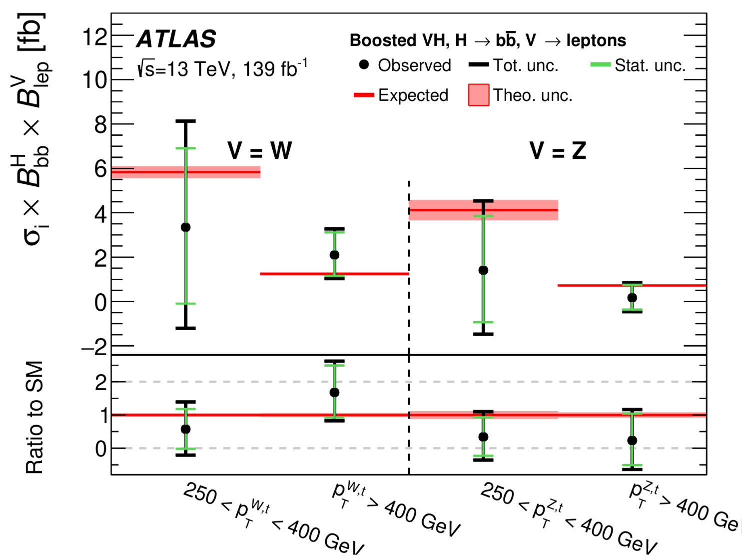
All backgrounds except VZ subtracted





Boosted analysis: measurement at high p$_T$ - increased sensitivity to BSM physics



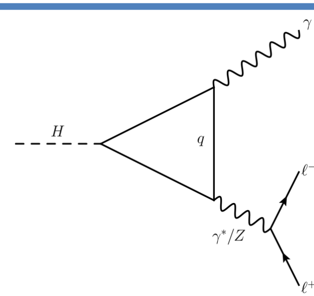


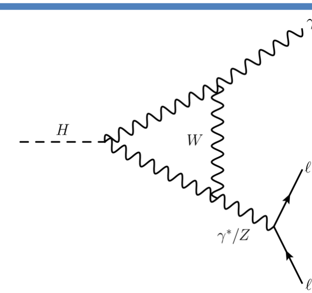
Search for rare loop-induced or Yukawa-suppressed decays (with a prompt photon)

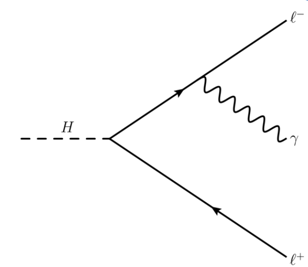
- Extra contributions to the fermionic/bosonic loops?
- Modified fermion couplings?

$H \rightarrow Z\gamma$ $(Z \rightarrow ll)$

$H \rightarrow \gamma\gamma^*$ $(\gamma^* \rightarrow ll)$

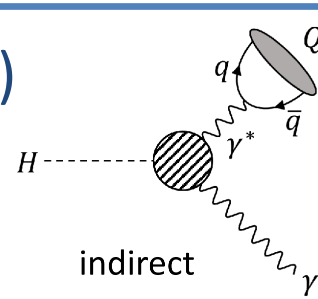




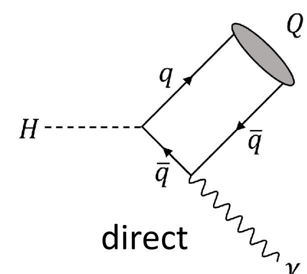


$H \rightarrow J/\psi\gamma$, $\psi(2S)\gamma$ or $\Upsilon\gamma$ $(Q \rightarrow \mu\mu)$

$H \rightarrow \omega\gamma$, $K^*\gamma$ (exclusive!)



indirect



direct

$H\rightarrow Z\gamma$ ($Z\rightarrow ll$, $l=e,\mu$)

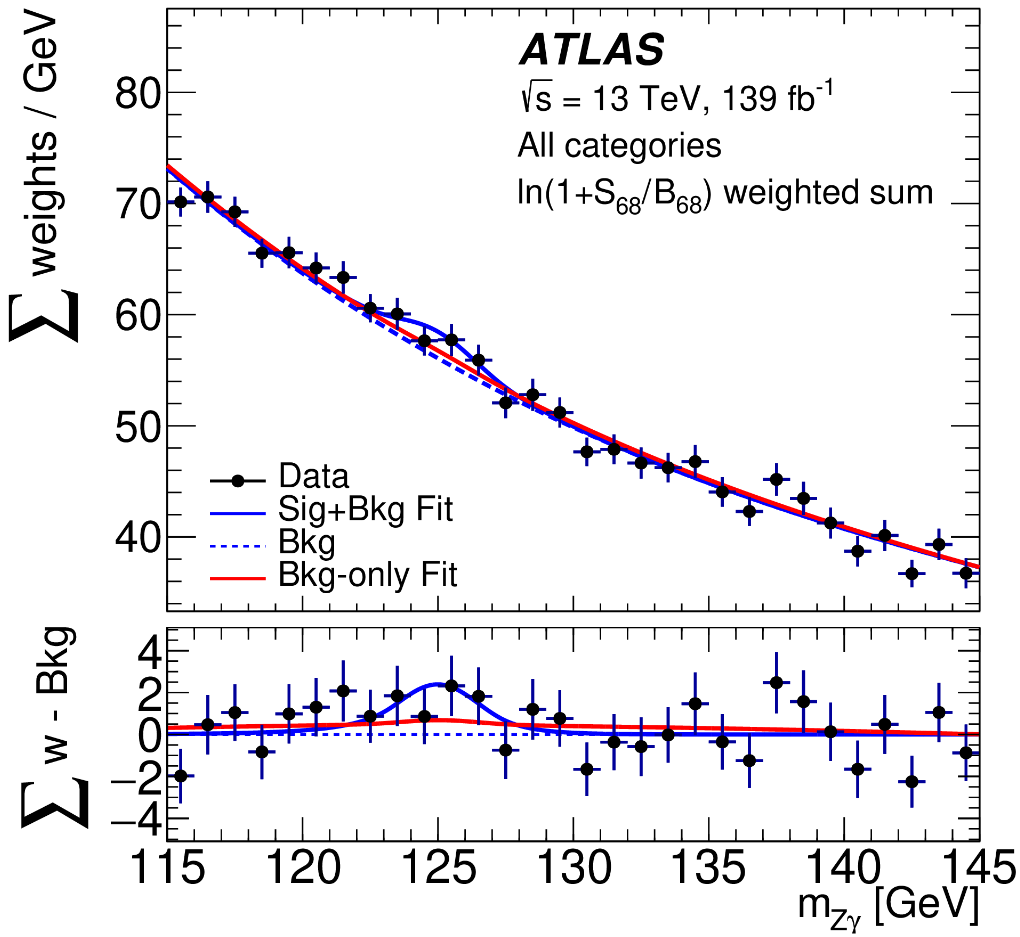
[Phys. Lett. B 809 (2020) 135754]

- Six mutually exclusive SR categories Simultaneous profile ML fit of the S+B model in the six regions.

- Kinematic fit of m_{ll}
- FSR correction in $\mu\mu$ channel

- Observed (expected) bkg. only fit *p*-value 1.3% (12.3%)

- Observed (expected) significance 2.2σ (1.2σ)

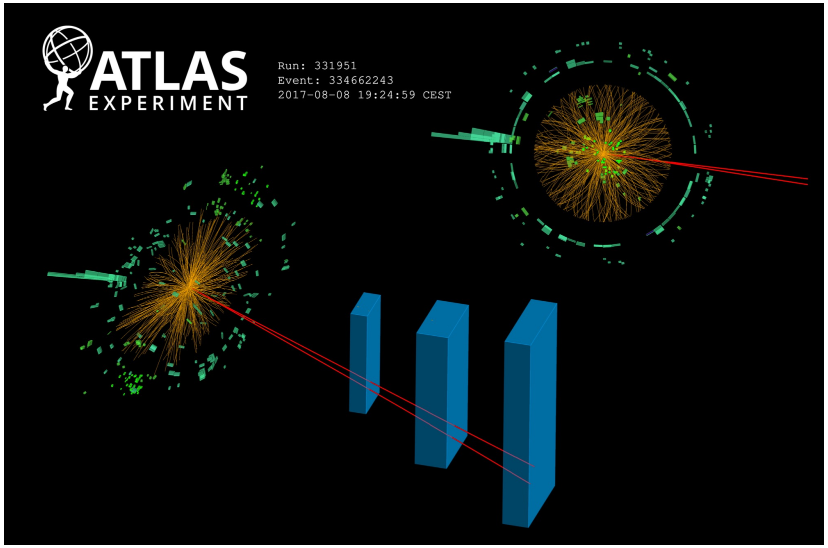


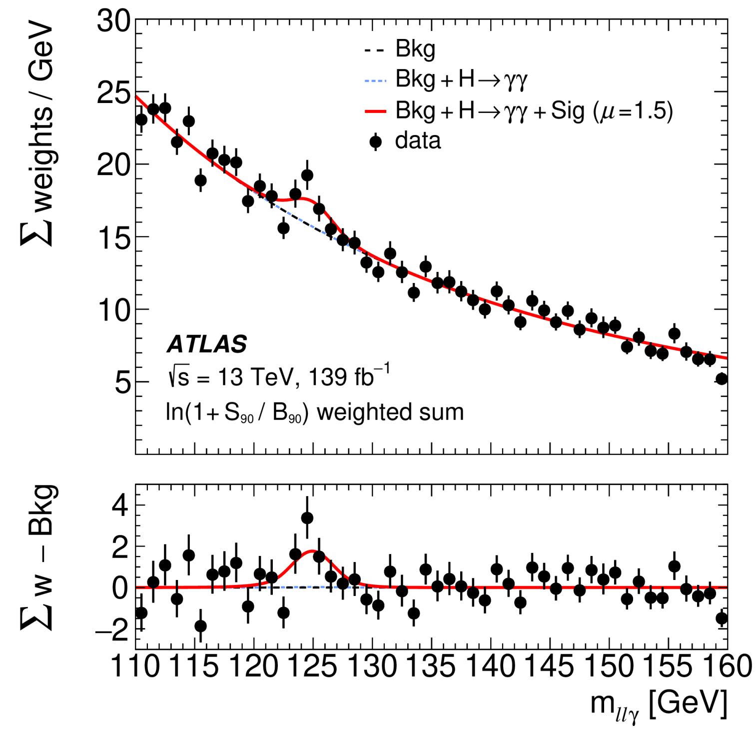
Fitted signal strength: $2.0 \pm 0.9(\text{stat.})\,^{+0.4}_{-0.3}(\text{syst.}) = 2.0\,^{+1.0}_{-0.9}(\text{tot.})$

95% CL upper limit on signal strength $3.6 \times$ SM (0.55% on $B(H\rightarrow Z\gamma)$)

$H\rightarrow \gamma^*(ll)_{lm}\gamma$ m_{ll}<30 GeV

[Phys. Lett. B 819 (2021) 136412]





- Three categories of ll pairs:
  1. $\mu\mu$ ($p_T > 3$ GeV)
  2. resolved ee ($p_T > 4.5$ GeV)
  3. merged ee ($p_T(ee) > 20$ GeV)
- Merged electrons distinguished from jets or single electrons using MVA methods
- 9 mutually orthogonal SR categories defined based on VBF/non-VBF, high/low p_{Tt}

Fitted signal strength: $1.5 \pm 0.5(\text{stat.})\,^{+0.2}_{-0.1}(\text{syst.}) = 1.5 \pm 0.5$ (tot.) ☆

⇒ observed (expected) significance: 3.2σ (2.1σ)

⇒ $\sigma\times B(H\rightarrow ll\gamma) = 8.7 \pm 2.7(\text{stat.})\,^{+0.7}_{-0.6}(\text{syst.})$ fb

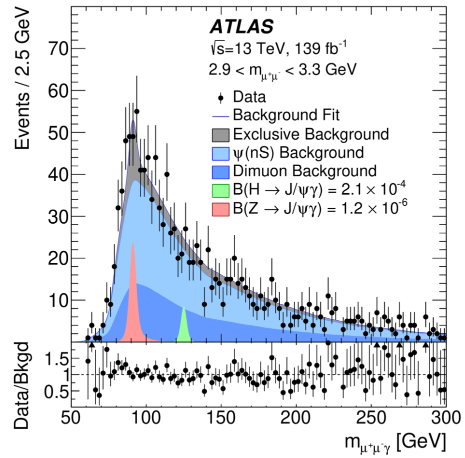
H→J/$\psi\gamma$, ψ(2S)γ, Υ(1S,2S,3S)γ
H→$\omega\gamma$, $K^*\gamma$ (flavour changing)

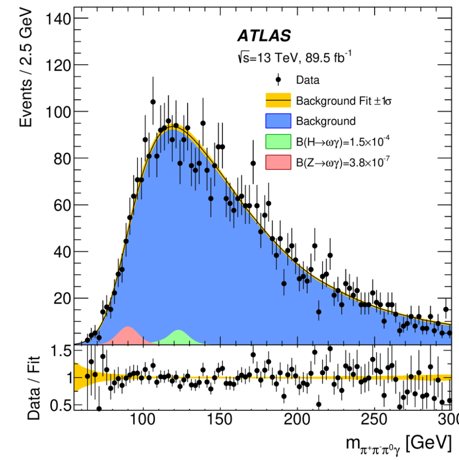
arXiv:2208.03122

arXiv:2301.09938

(JHEP 07 (2018) 127)

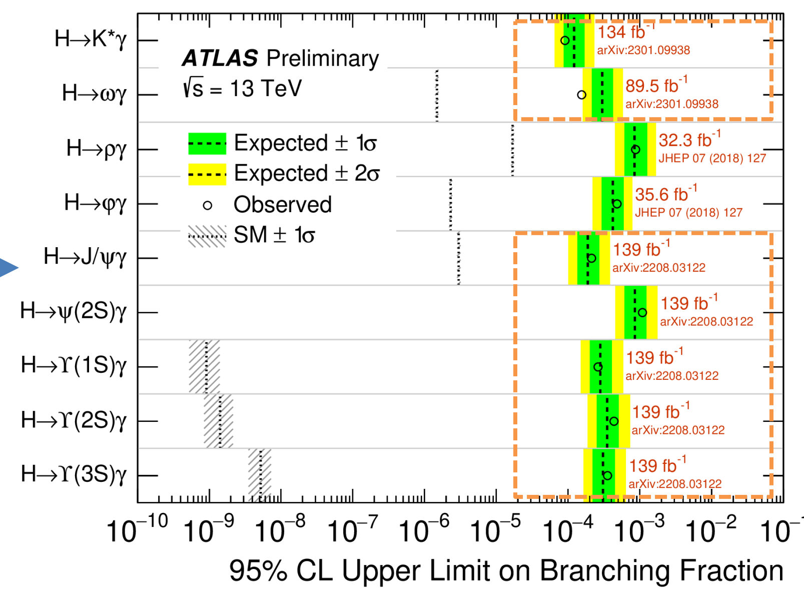
- Highly destructive interference of the indirect and direct diagrams!
- B(H→J/$\psi\gamma$) ~10^{-6}, B(H→$\Upsilon\gamma$) ~10^{-9}-10^{-8}
- B(H→ $\omega\gamma$) ~10^{-6}, B(H→ $K^*\gamma$) <<10^{-11}
- J/ψ, ψ(2S), Υ→ $\mu^+\mu^-$
- ω→ $\pi^+\pi^-\pi^0$, K^*→ $K^+\pi^-$ (exclusive!)



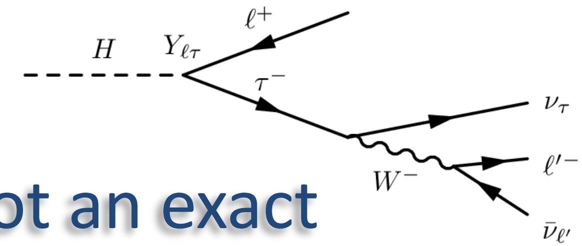


- Inclusive background (all except for DY+FSR γ) from ‘generation region’ (SR with relaxed isolation) in data. Correlated sampling, normalisation from the fit. (arXiv: 2112.00650 [hep-ex])

- The search is performed for both H and Z decays to $Q\gamma$ (except K^*)
- Data remain consistent with the background only hypothesis.
- 95% CL limits on B(H→Qγ) are set
- 95% CL limits on B(Z→Qγ)~$O(10^{-6})$



Search for Lepton Flavour Violation in the Higgs sector

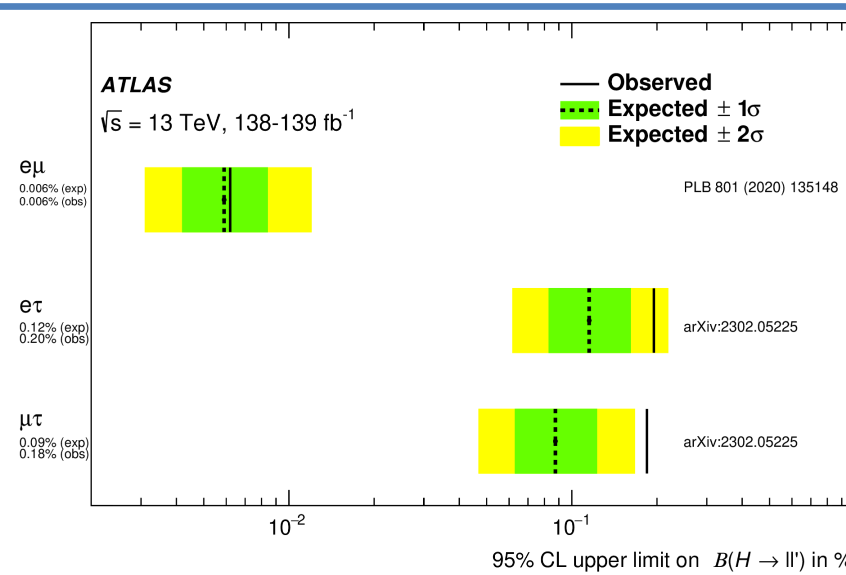


- Neutrinos oscillate: lepton flavour is not an exact symmetry
- Is the Higgs sector responsible?
- Naturally occurs in >1 HDM, composite Higgs, Randall-Sundrum warped ED, etc.

$H \rightarrow e\mu$

$H \rightarrow e\tau \quad (\tau_l, \tau_{\text{had}})$

$H \rightarrow \mu\tau \quad (\tau_l, \tau_{\text{had}})$

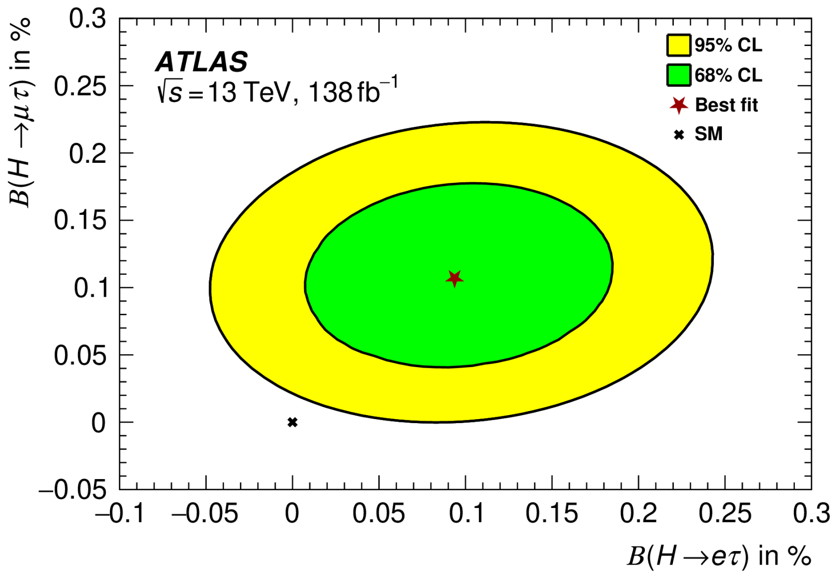


H→$e\tau$, H→$\mu\tau$ (τ_l, τ_{had})

arXiv:2302.05225

1 PoI: Combined fit to $l\tau_l$ & $l\tau_{\text{had}}$ non-VBF & VBF, using MC-template method for all but $l\tau_l$ VBF. Branching ratio for the opposite light lepton set to 0.
2 PoI: Combined fit in all regions using MC-template method in 8 SR's + 8 CR's ($Z\rightarrow\tau\tau$ and top-quark)

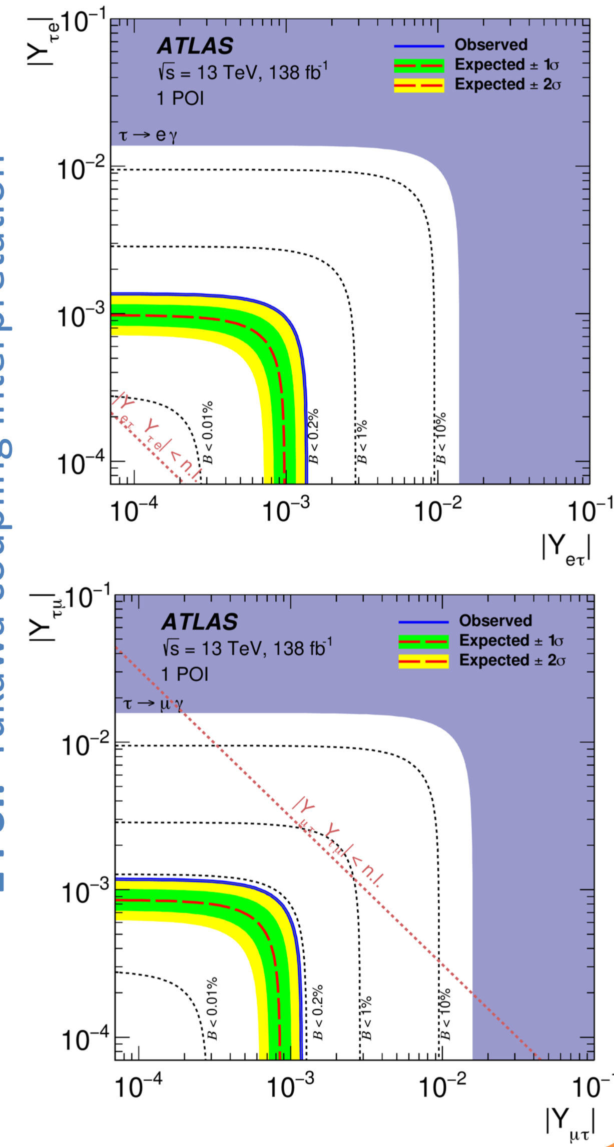
2 PoI combined fit



2.1σ ☆

2 PoI observed (expected) 95% CL upper limits on :
B(H→$e\tau$): 0.20% (0.12%), B(H→$\mu\tau$): 0.18% (0.09%)

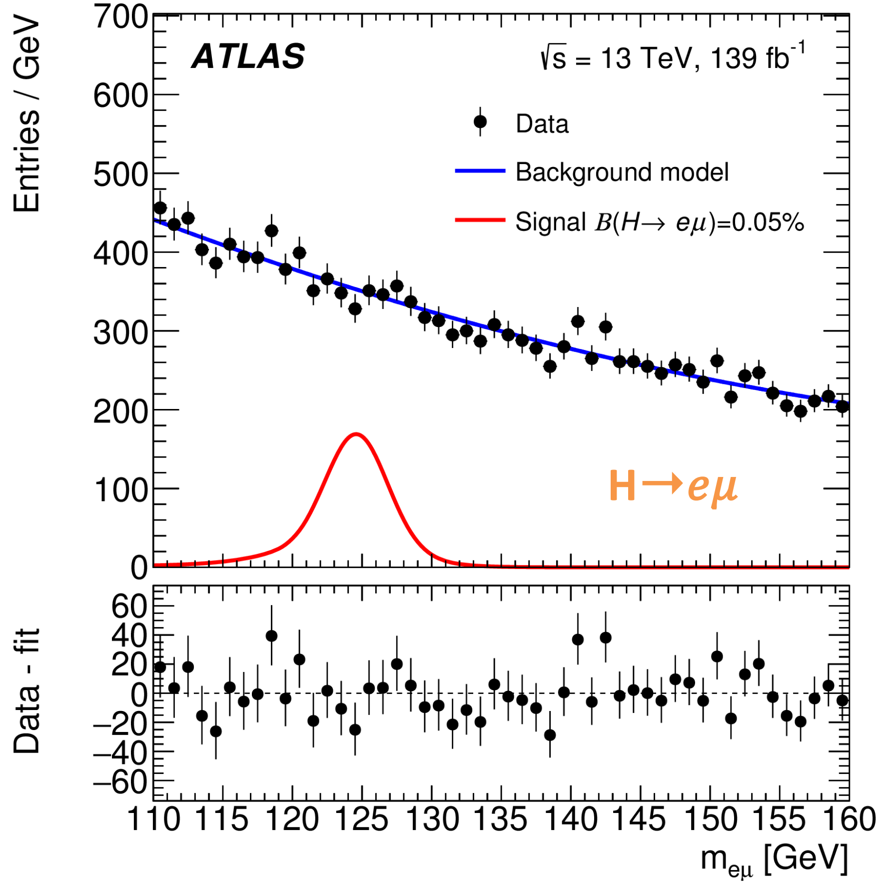
1 PoI: Yukawa coupling interpretation



H→$e\mu$

[Phys. Lett. B 801 (2020) 135148]

- OS lepton pairs $p_T > 27(15)$ GeV
- Veto on identified *b*-jets (suppress top background)
- $E_T^{miss}/\sqrt{H_T} < 1.75\ \text{GeV}^{1/2}$
- Categorisation:
  - VBF and non-VBF
  - Central ($|\eta^l| < 1$) and Non-central
  - Low, Medium and High p_T^{ll}
- Simultaneous binned ML fits to the observed m_{ll} distributions in the range $110 < m_{ll} < 160$ GeV



H→$e\mu$

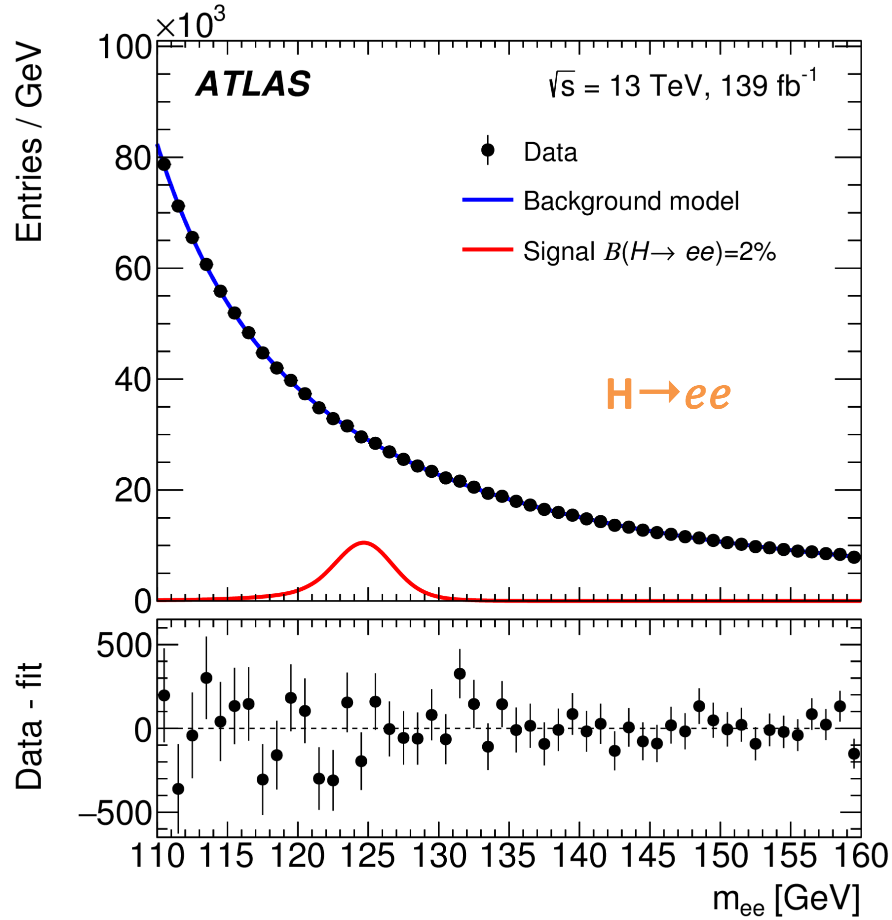
- Main bkg.: DY $Z/\gamma^* \to \tau\tau$, top, di-boson, misidentified leptons

Observed (expected) 95% CL upper limits on $B(\text{H}\to e\mu)$: 6.2×10^{-5} (5.9×10^{-5})

H→*ee*

[Phys. Lett. B 801 (2020) 135148]

- OS lepton pairs $p_T > 27(15)$ GeV
- Veto on identified *b*-jets (suppress top background)
- $E_T^{miss}/\sqrt{H_T} < 3.5\ \text{GeV}^{1/2}$
- Categorisation:
  - VBF and non-VBF
  - Central ($|\eta^l| < 1$) and Non-central
  - Low, Medium and High p_T^{ll}
- Simultaneous binned ML fits to the observed m_{ll} distributions in the range $110 < m_{ll} < 160$ GeV



H→*ee*

- Main bkg.: DY $Z/\gamma^* \to ee$

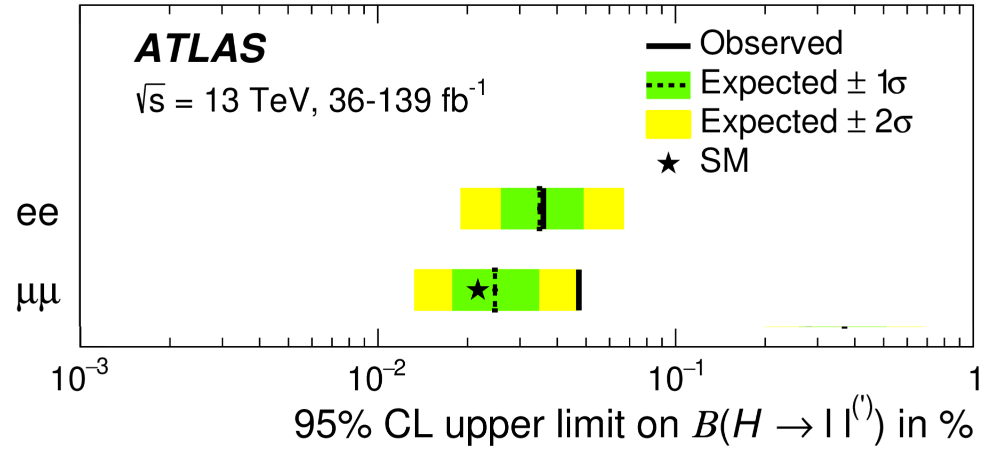
Observed (expected) 95% CL upper limits on $B(\text{H}\to ee)$: 3.6×10^{-4} (3.5×10^{-4})

Can we observe Higgs decays to 1st and 2nd generation leptons?

- $B(H \rightarrow ee)_{SM} \sim 5\times10^{-9}$
- $B(H \rightarrow \mu\mu)_{SM} \sim 2\times10^{-4}$
- Can we confirm SM couplings?
- Any indication of BSM-induced enhancement?

$H \rightarrow ee$

$H \rightarrow \mu\mu$

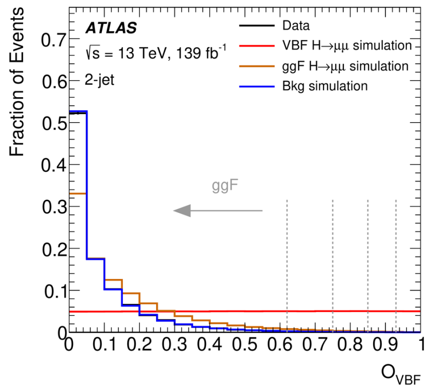


H→μμ

[Phys. Lett. B 812 (2021) 135980]

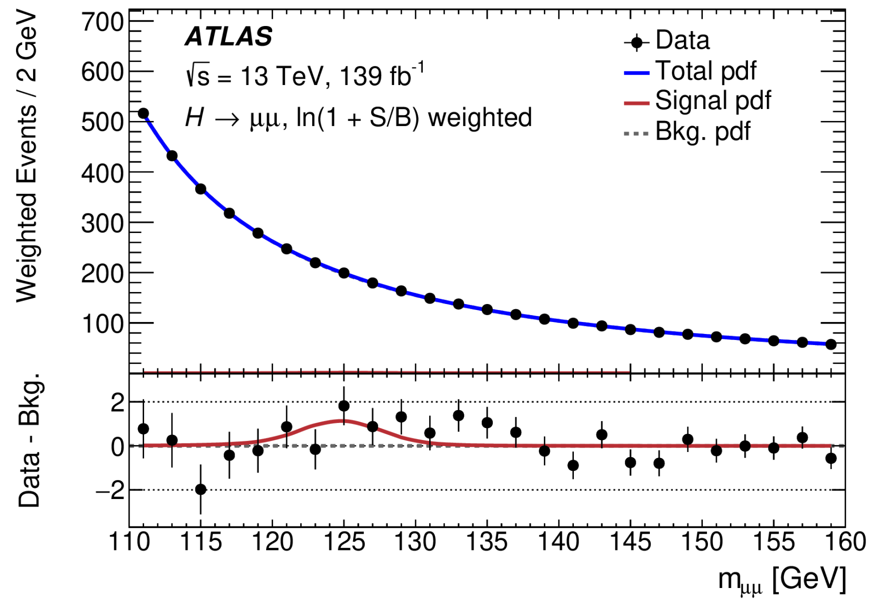
- OS muon pairs $p_T > 27(15)$ GeV
- Veto on identified b-jets (except ttH)

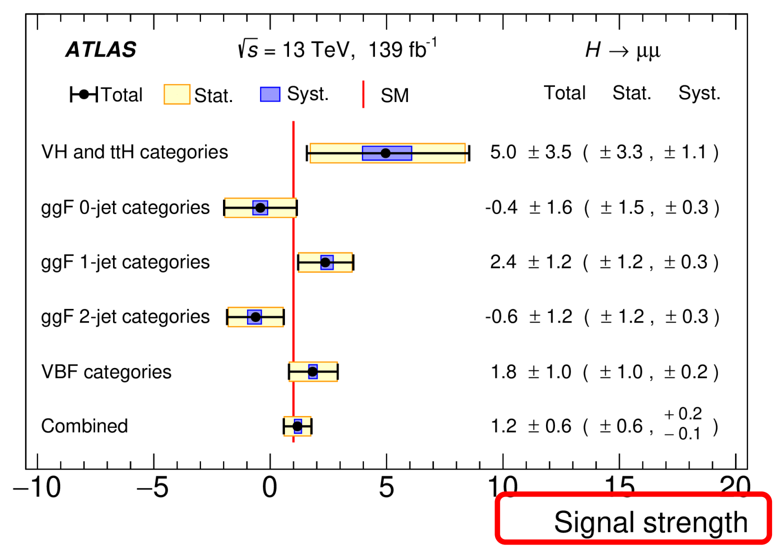
- 20 mutually exclusive categories:
  - S/B from dedicated BDT's
  - VBF
  - ggF
  - VH
  - ttH



- Simultaneous binned ML fits to the observed $m_{\mu\mu}$ distributions in the range $110 < m_{\mu\mu} < 160$ GeV
- Main bkg.: DY $Z/\gamma^* \rightarrow \mu\mu$

Obs. (exp.) significance: S=2.0σ (1.7σ)

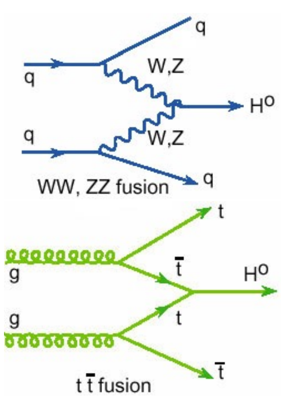


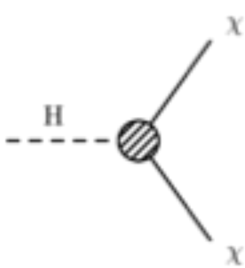


Higgs – portal to the DM sector?

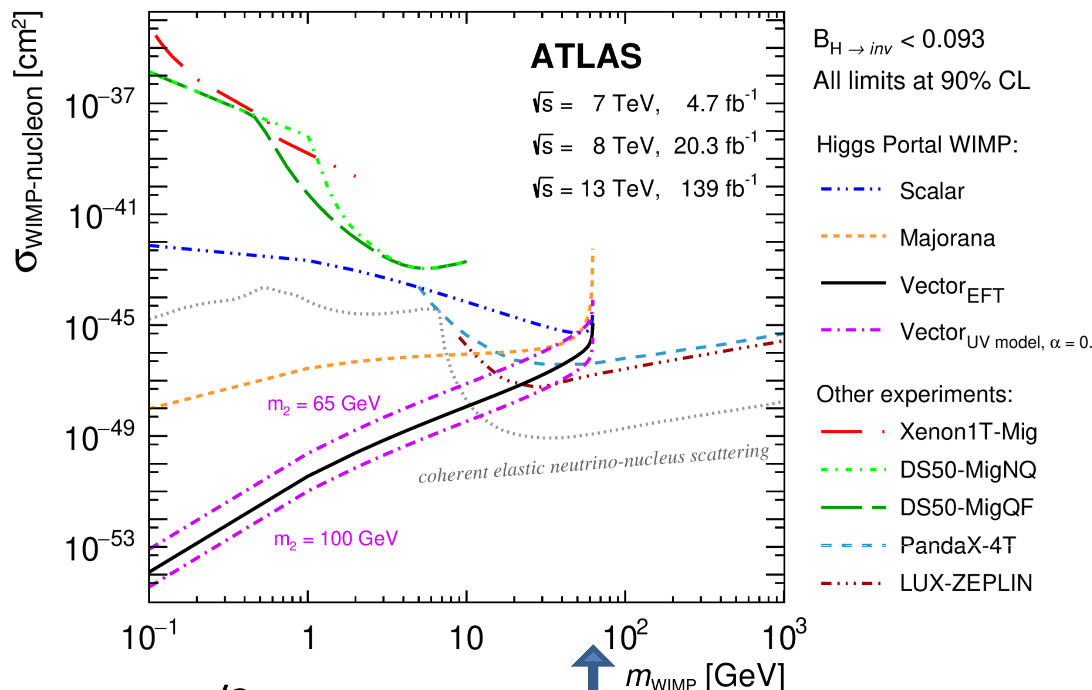
- Maybe the Higgs is the only known particle that „talks” to the dark matter particles (Higgs is a mixture of SM and DM scalar).
- Probability of Higgs decaying into a pair of WIMP's can be converted into probability for WIMP-nucleon scattering.

Higgs produced via the VBF or in association with a top pair. Missing Energy is the key signature.





Phys. Lett. B 842 (2023) 137963

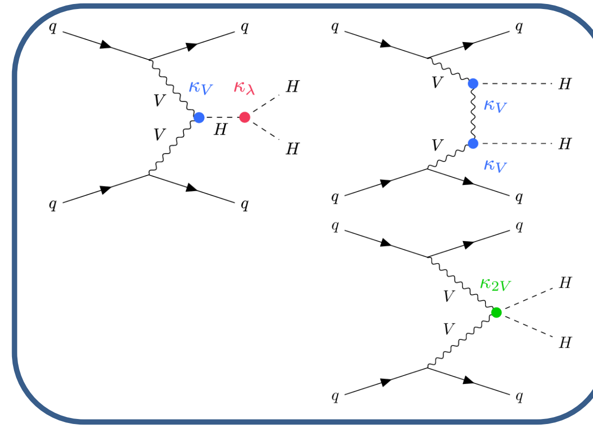


$m_H/2$

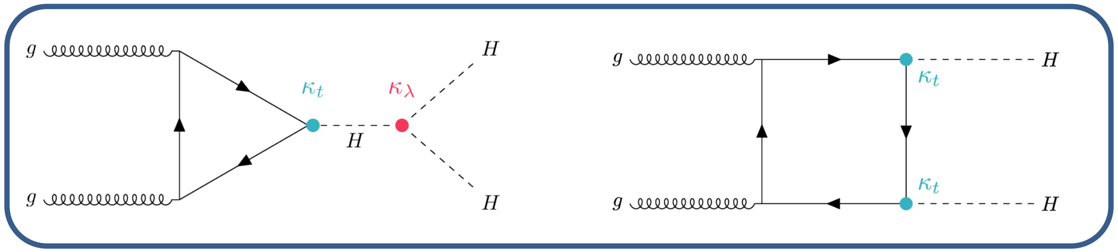
Understanding the Higgs potential…

$$V(\phi) \sim \ \lambda v^2 h(x)^2 + \lambda v\, h(x)^3 + \tfrac{1}{4}\lambda h(x)^4$$

VBF: will help in the future



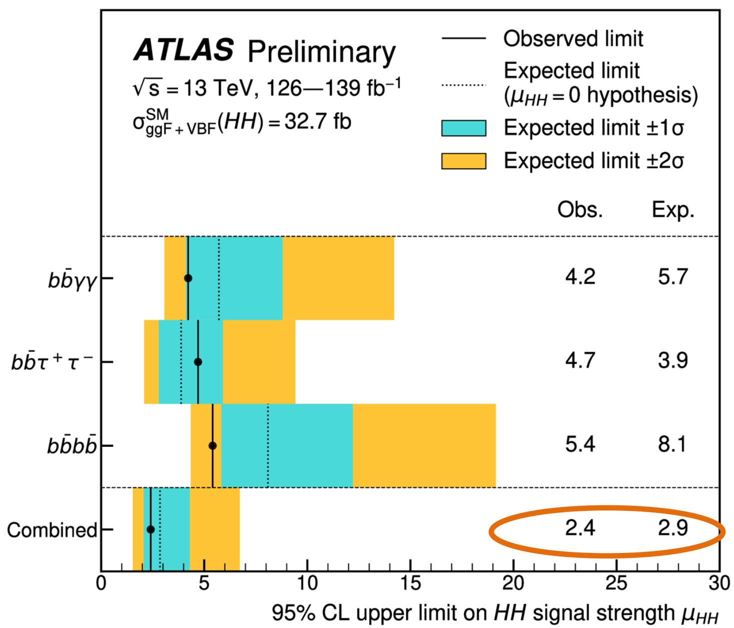
ggF: 90% of SM x-section (interfere destructively)

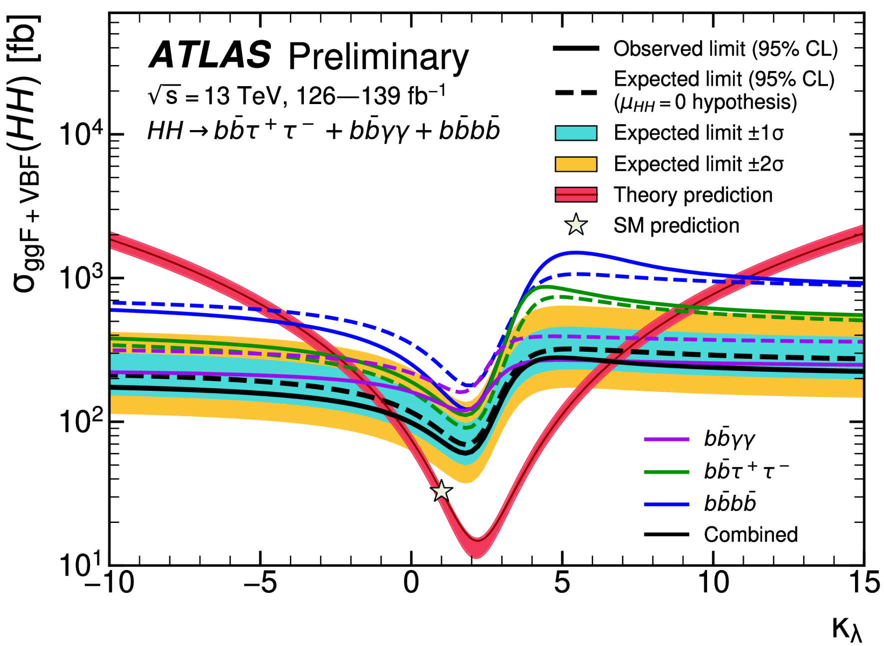


$b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}b\bar{b}$

Non-resonant HH search

Phys. Lett. B 843 (2023) 137745



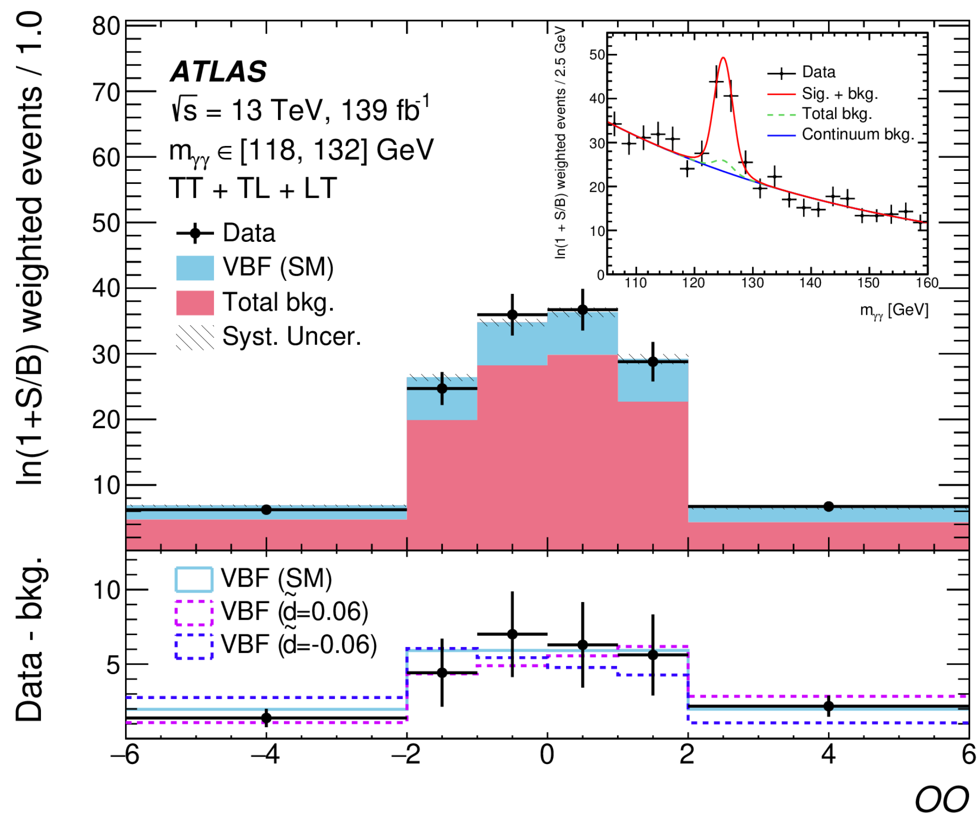


Does Higgs sector contribute to CP violation?

Phys. Rev. Lett. 131 (2023) 061802

VBF $H \to \gamma\gamma$

In lack of CP-odd contribution the distribution of OO is symmetric



$$OO = 2 \cdot \mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}} \cdot \mathcal{M}_{\mathrm{CP-odd}}) / |\mathcal{M}_{\mathrm{SM}}|^2$$

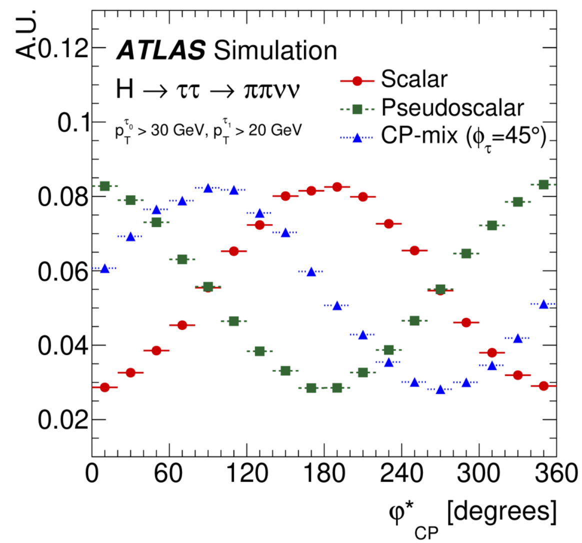
Obtained:
the most stringent constraint on the dimension-six CP-odd contribution to the H-V interaction EFT Lagrangian.

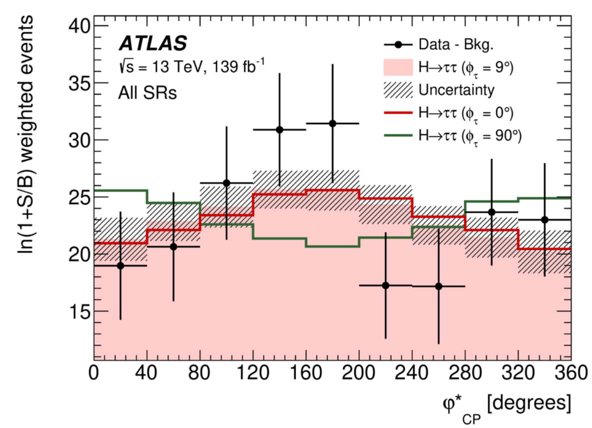
Does Higgs sector contribute to CP violation?

Eur. Phys. J. C 83 (2023) 563

$H \longrightarrow \tau\tau$

CP-odd interactions with fermions can occur at tree level. ϕ_{CP} denotes angle between τ decay products sensitive to τ-τ spin correlation. ϕ_τ denotes the mixing angle between CP-even and CP-odd amplitude (ϕ_τ^{SM}=0)





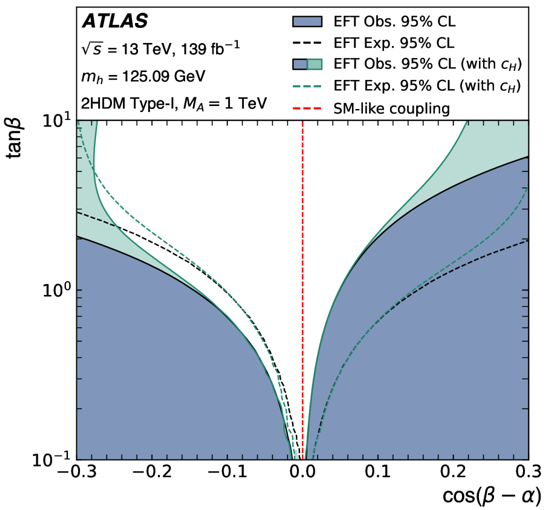
Obtained: $\phi_\tau = 9^\circ \pm 16^\circ$

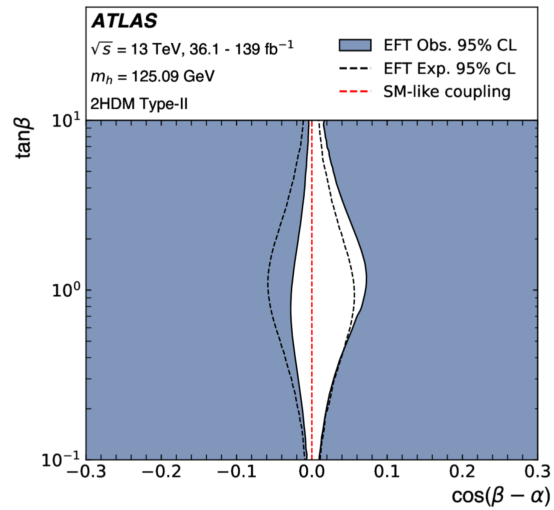
The pure CP-odd hypothesis is disfavoured at a level of 3.4σ

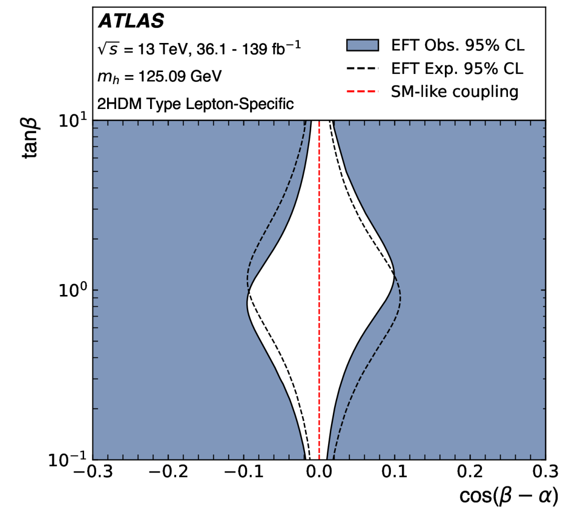
Extended scalar sector – 2HDM

arXiv:2402.05742

$\tan\beta \equiv v_2/v_1$	$g^{2HDM}_{hVV}/g^{SM}_{hVV} = \sin(\beta-\alpha)$	0.95
$v_1^2 + v_2^2 = v^2 \approx (246\ \mathrm{GeV})^2$	$g^{2HDM}_{HVV}/g^{SM}_{HVV} = \cos(\beta-\alpha)$	⬇ 0.30 !







~~FCNC~~ ⇒ (no fermions get mass from both dublets)

h_{125} couplings Coupling scale factor	fermiophobic Type I	MSSM-like Type II	lepton-specific Type III	flipped Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

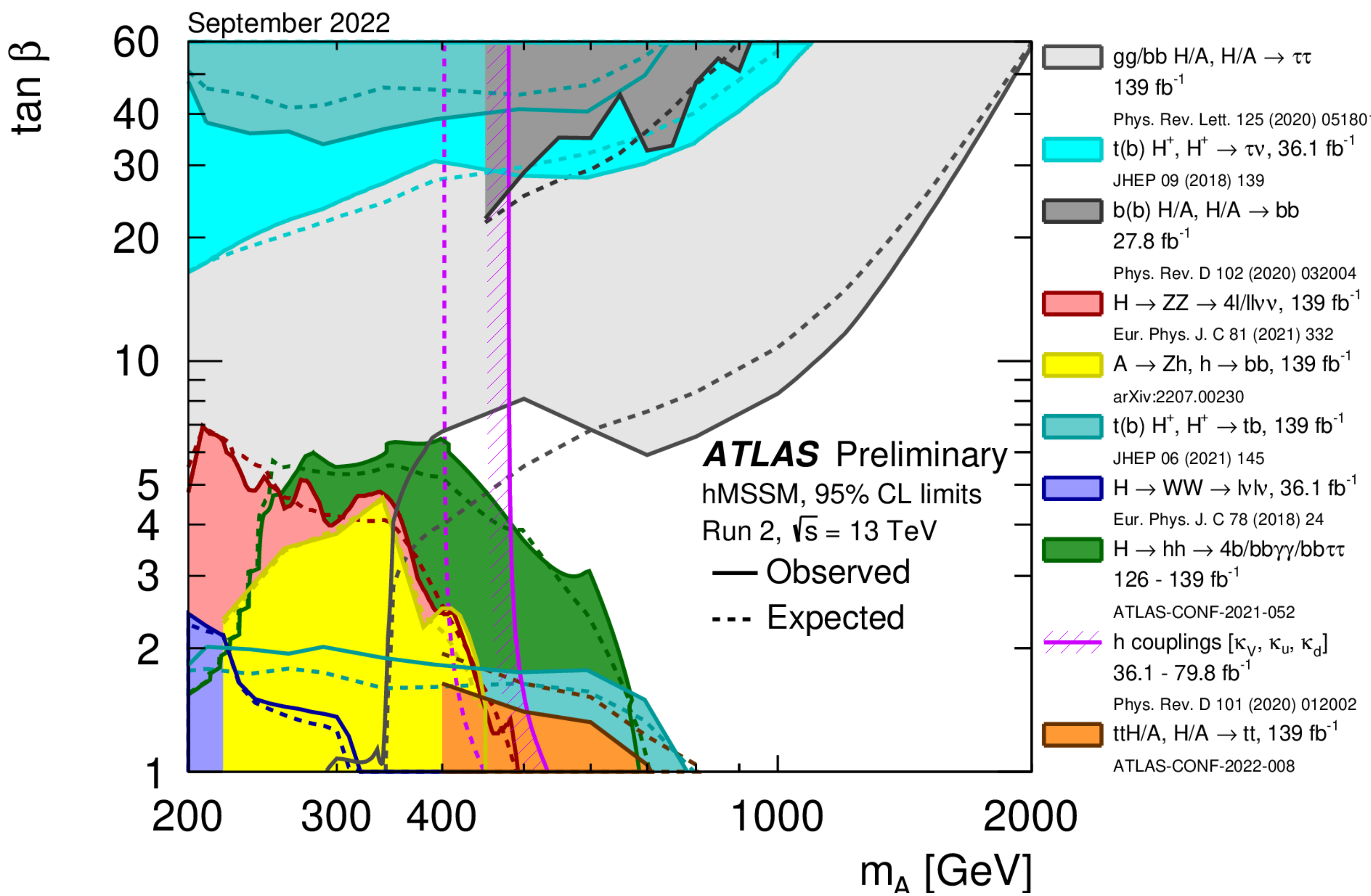
Extended scalar sector – 2HDM

Most commonly considered, motivated e.g. by MSSM:

h_{125}, H^0, A^0, H^+, H^-

$$\tan\beta \equiv v_2/v_1$$

$$v_1^2 + v_2^2 = v^2 \approx (246\ \text{GeV})^2$$

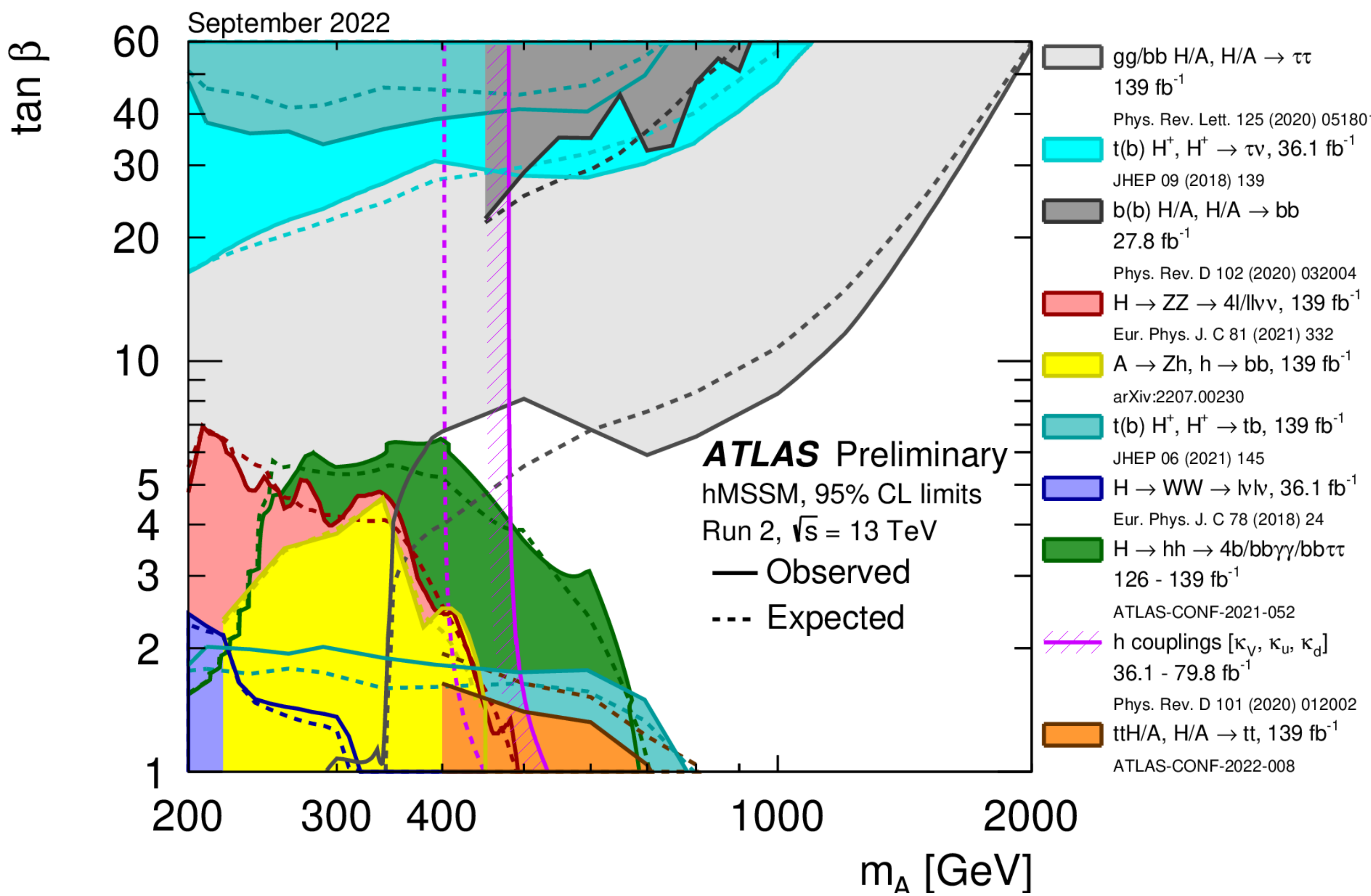


ATL-PHYS-PUB-2022-043

Extended scalar sector – 2HDM

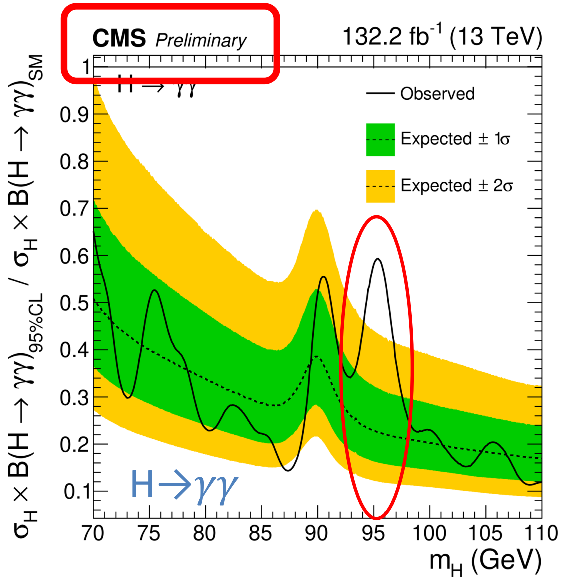
Let me sneak in a little publicity ;)

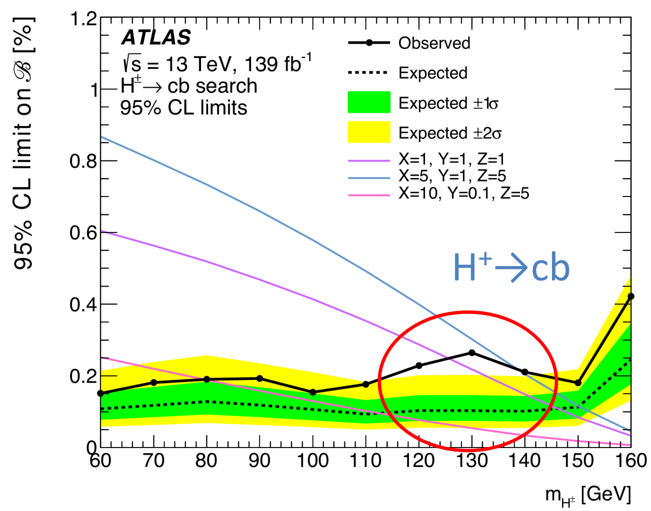
Krakow group contributions

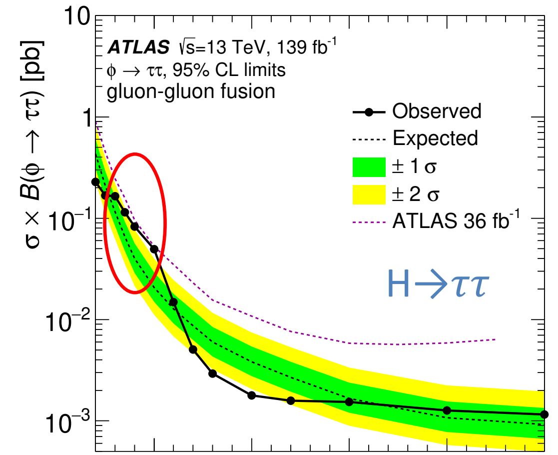


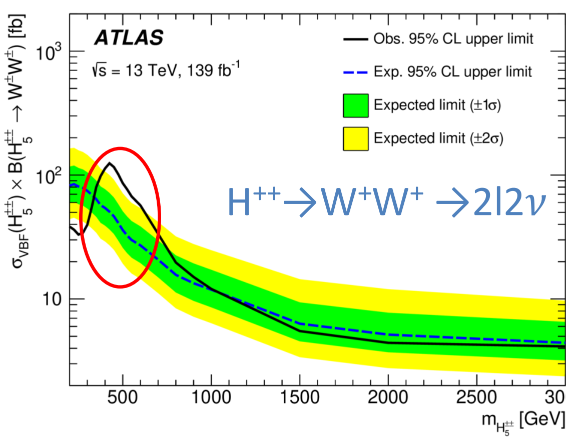
ATL-PHYS-PUB-2022-043

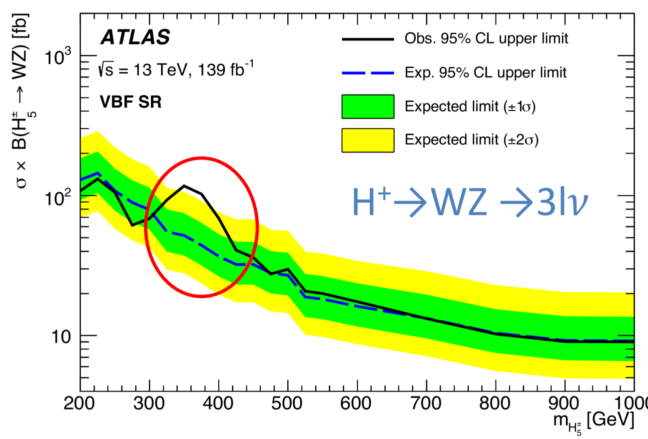
Direct searches – any hints yet?

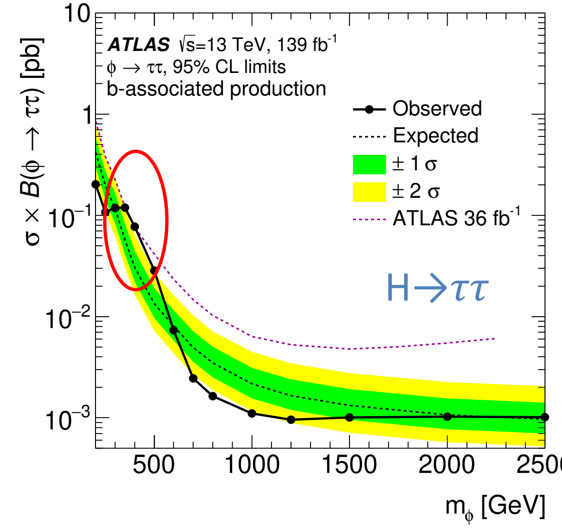












Just a few examples. There are more. All (global) significances remain under 3σ.
Yet, nothing to get overexcited about ;)

Projections for HL-LHC & FCC-ee

Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9*	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4*	1.0 / 0.88

Huge leap expected from FCC-ee !

Taken from the FCC feasibility study mid-term report (2023)

SUMMARY

- Rich program of 125 GeV Higgs property measurements.
- Complemented by direct searches for additional scalars.
- We leave no stone unturned in exploration of the Higgs sector. It might bear answers to some most fundamental questions.
- Stay tuned for what HL-LHC reveals...
- FCC-ee has a potential to pinpoint Higgs properties with an unprecedented precision.

THANK YOU