The 10 years of Higgs physics and other major milestones at the LHC

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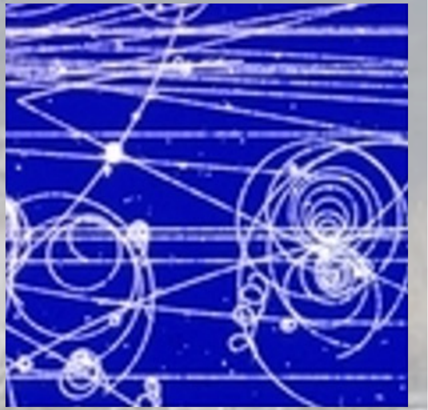
2nd part



Index

- The Large Hadron Collider, the ATLAS and CMS experiments
- The Standard Model Higgs boson
- Short history of Higgs boson discovery at the LHC
- Higgs boson couplings and properties
- Higgs selfcoupling
- BSM Higgs boson searches
- Higgs Prospects at the High-Luminosity LHC

- Connections to precision top and W mass measurements, searches for Vector Boson Scattering and Dark Matter

From the kappa framework to EFT studies

- The kappa framework is ”easy” to understand but it is not appropriate when looking for small deviations of Higgs coupling from SM predictions
- Ideally one would like to combine information from rates, differential distributions, and CP properties
- Also, this framework does not include correlations with other important physics quantities in the theory
- ➔ **move to an approach based to EFT**
    - Well-defined theoretical approach
    - Assumes New Physics states are heavy
    - Write Effective Lagrangian with only light (SM) particles
    - BSM effects can be incorporated as a momentum expansion

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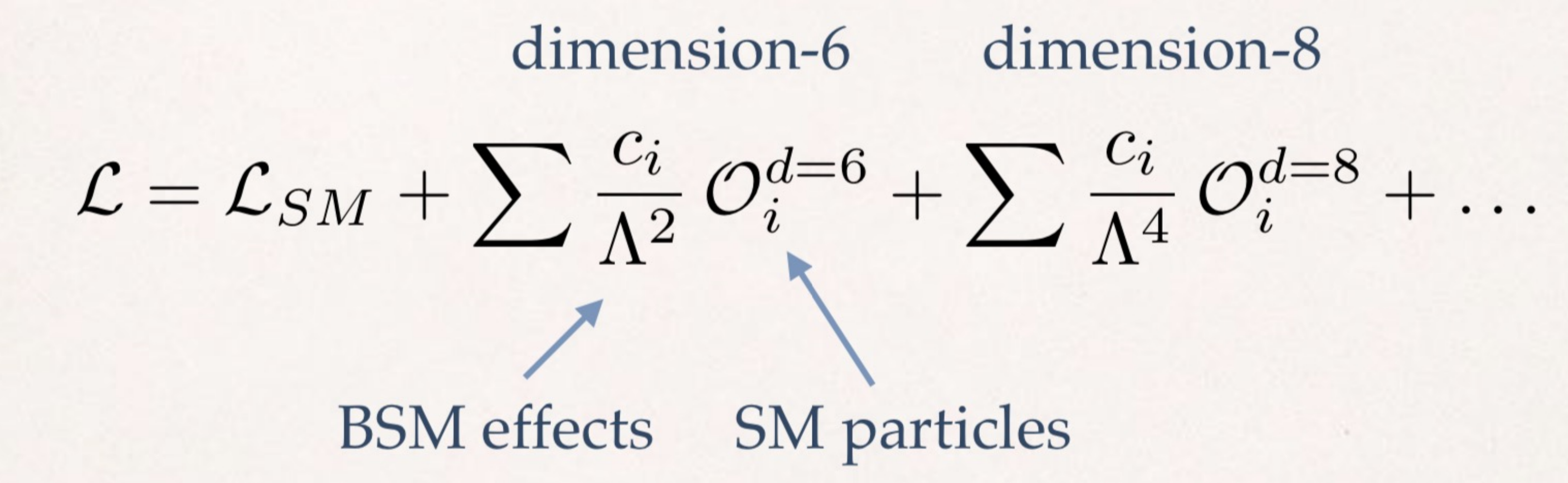
- ➔ **move to an approach based to EFT**



$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \ldots$$

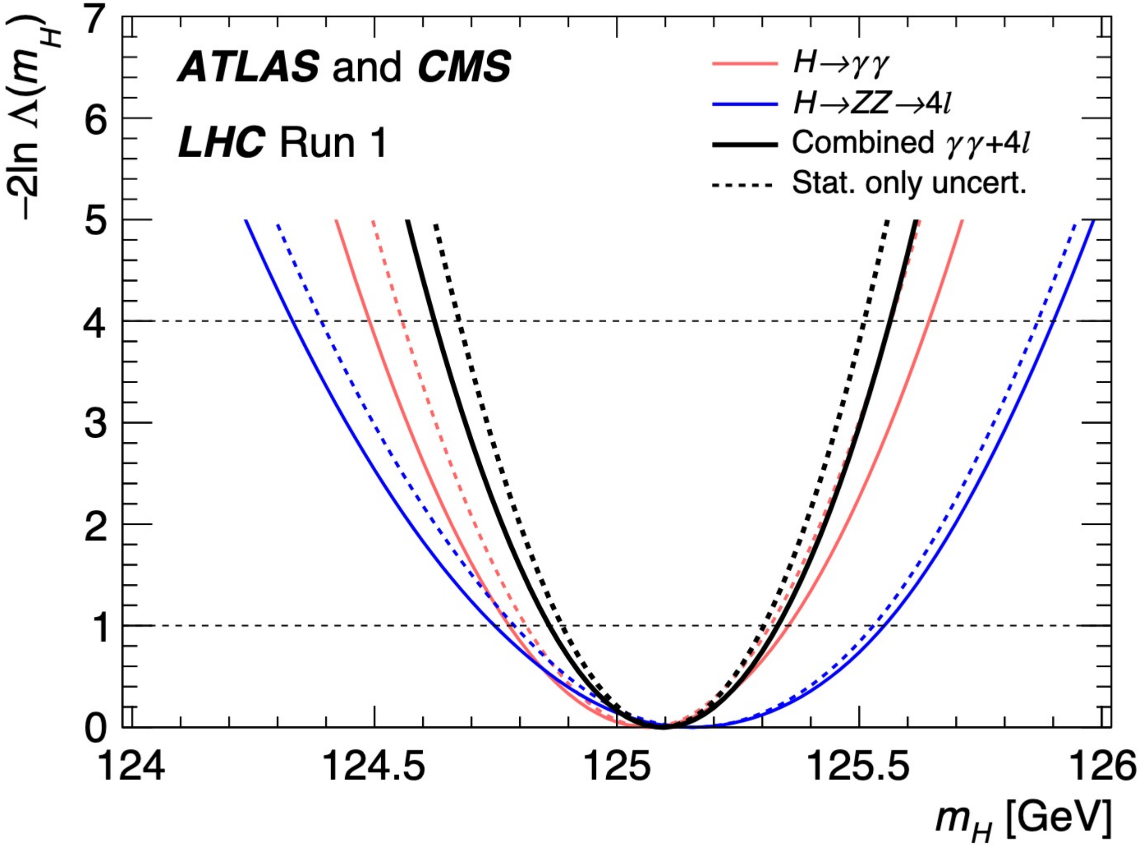
Characterization of this new particle: physics properties

The Higgs boson mass

- In the Standard Model, the electroweak symmetry breaking is achieved through the introduction of a complex doublet scalar field, leading to the prediction of the Higgs boson H whose **mass m_H** is, however, **not predicted by the theory**.
- the ATLAS and CMS Collaborations at the LHC announced the discovery of a particle with Higgs boson-like properties and a mass of **about 125 GeV**.
- These Collaborations have independently measured m_H using the samples of proton-proton collision data collected in 2011 and 2012 (Run 1), ~5 fb^{-1} of integrated luminosity at $\sqrt{s} = 7$ TeV, and ~20 fb^{-1} at $\sqrt{s} = 8$ TeV, for each experiment.
- A combination of Run 1 data from the two experiments lead to an improved precision for m_H
- In 2014, the combination is performed using only the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ decay channels, because these two channels offer the best mass resolution.
    - interference between the Higgs boson signal and the continuum background is expected to produce a downward shift of the signal peak relative to the true value of m_H. Very small effect wrt achievable precision.

The Higgs boson mass

Phys. Rev. Lett. 114, 191803 (2015)



twice the negative log-likelihood ratio as functions of the Higgs boson mass m_H for the ATLAS and CMS combination of the H→γγ and H → ZZ → 4l, and combined channels.

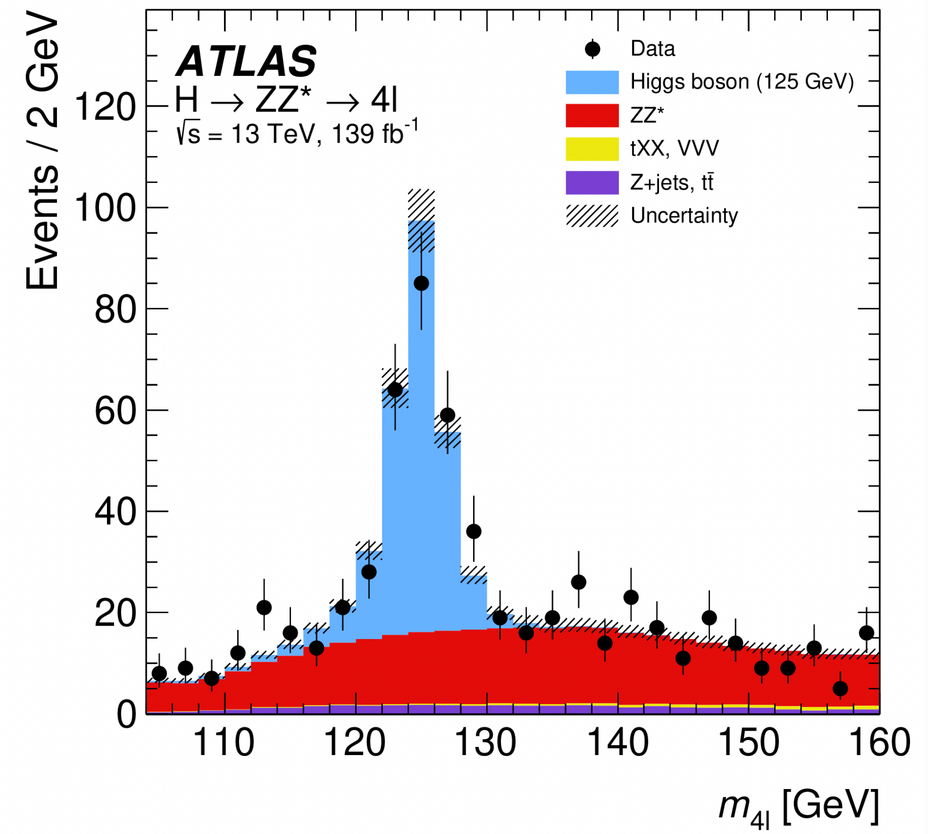
- **total uncertainty** is dominated by the **statistical term**
- **systematic uncertainty dominated** by effects related to the **photon, electron, and muon energy or momentum scales and resolutions**.

$$
\begin{aligned}
m_H &= 125.09 \pm 0.24\ \mathrm{GeV} \\
&= 125.09 \pm 0.21\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst})\ \mathrm{GeV},
\end{aligned}
$$

0.2% accuracy

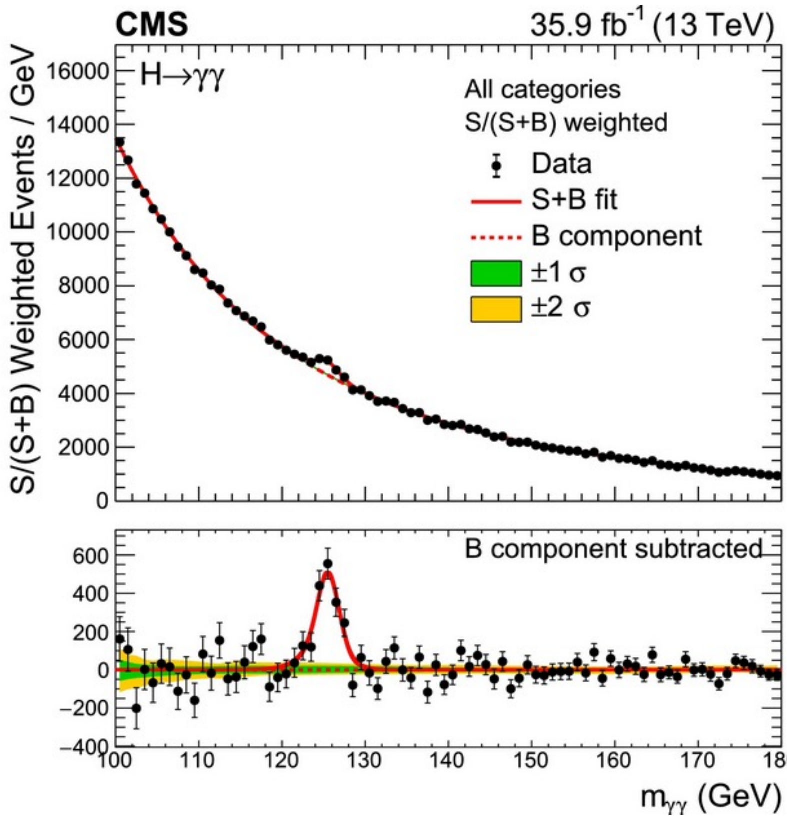
The Higgs boson mass: most recent resuts

Phys. Lett. B 784 , 2018 ATLAS-CONF-2020-005



Data and signal-plus-background model fit where the categories are summed weighted by their corresponding sensitivities, given by S/(S+B) (right). Lower panel: residuals after the background subtraction.

Phys. Lett. B 805 , 2020



Run2: H→ZZ→4l: m_H = 124.71±0.30 (stat)±0.05 (syst) GeV = 124.71±0.30 GeV.

H→$\gamma\gamma$: m_H = 125.32 ±0.19 (stat) ± 0.29 (syst) GeV = 125.32 ± 0.35 GeV

Combination: m_H = 124.86 ± 0.27 GeV

4l: m_H = 125.46 ± 0.16 GeV

$\gamma\gamma$: m_H = 125.78 ± 0.26 GeV

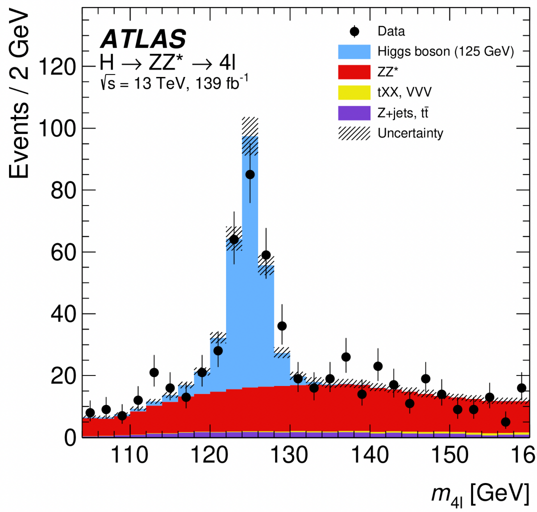
13 TeV ATLAS 4l: $m_H = 124.92^{+0.21}_{-0.20}$ GeV

~ 0.1% accuracy

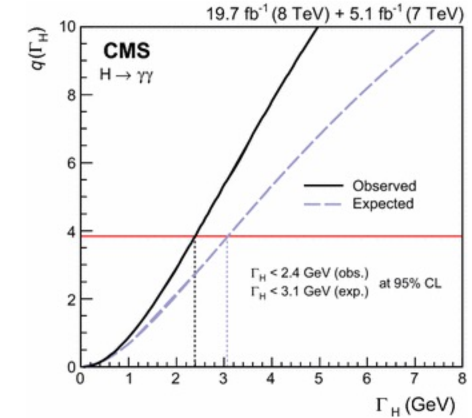
CMS: $m_H = 125.38 \pm 0.14$ GeV

The Higgs boson natural width

- **Predicted Standard Model Higgs boson natural width Γ_H^{SM}: 4.07 MeV**
- this width is too small to be measured directly from the line shape because of the limited mass resolution of order 1 GeV achievable with the present LHC detectors
- ➔ Probe the impact of Γ_H in the "off-shell" region, i.e. studying the line shape of final states such as, for example, – the four lepton final states.

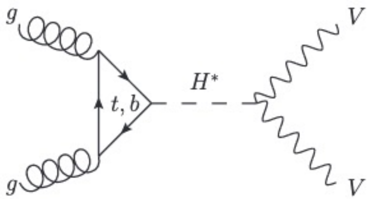


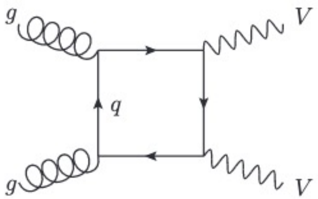
Direct measurement severely limited by detector resolution! One (old) example:

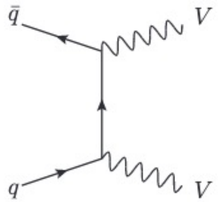


EPJC volume 74, 3076

$\Gamma < 2.4$ GeV @ 95% CL





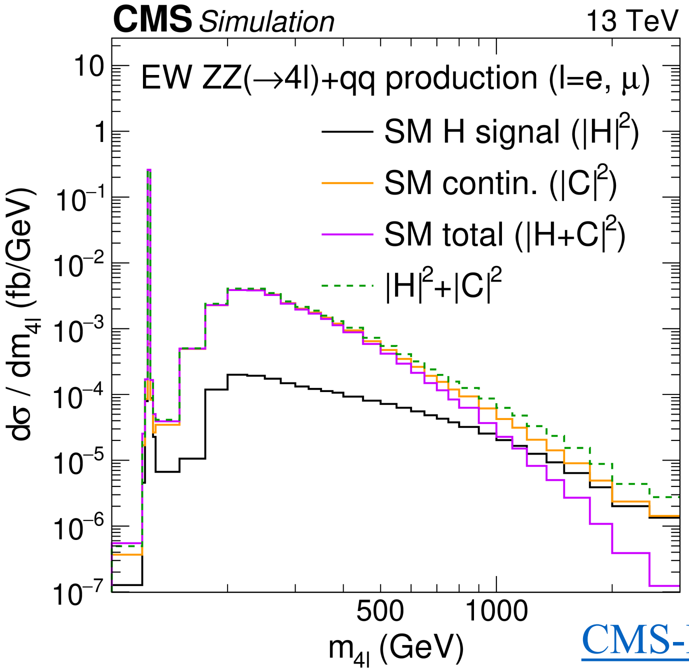


$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

Assuming on-shell and off shell couplings are equal:

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{SM}}$$

arXiv:1307.4935v3



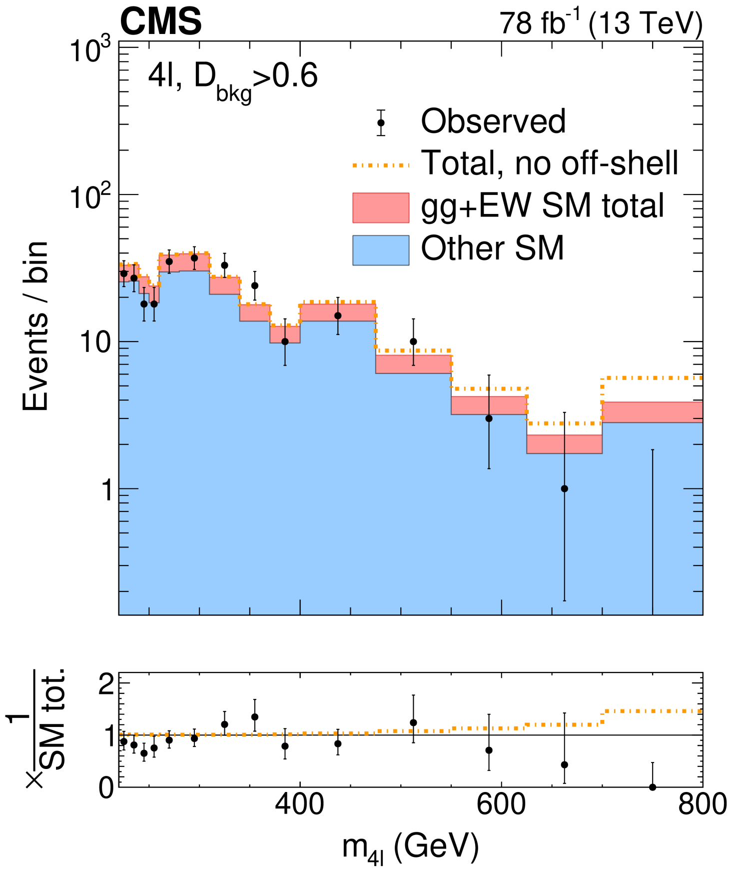
- **Standard Model calculations of $m_{4\ell}$.**
- **Dashed green curve: direct sum without the interference**
- **solid magenta curve: sum with interference included.**

Note that the interference is destructive, and its importance grows as the mass increases.

CMS-HIG-21-013

The Higgs boson natural width

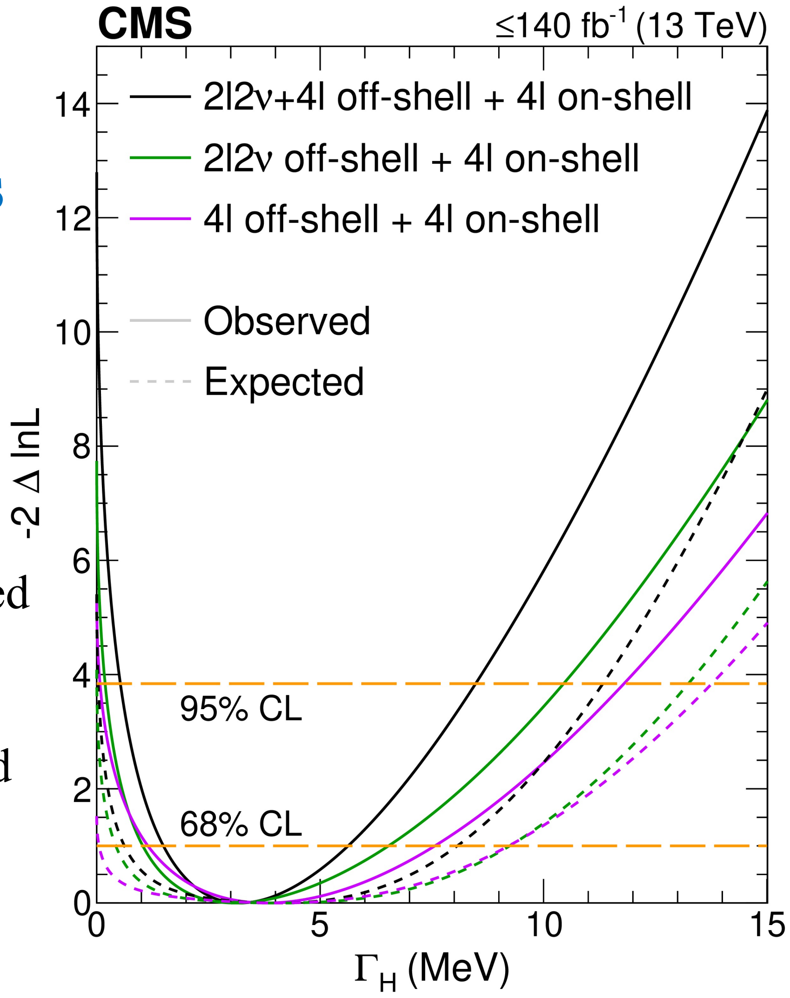
CMS-HIG-21-013



- Distribution of $m_{4\ell}$ in the 4ℓ off-shell signal regions.
- Stacked histograms display the different predicted contributions after a fit to the data with SM couplings.
  - gold dot-dashed line shows the distribution after a fit to the no off-shell (Γ_H= 0 MeV) hypothesis
  - black points show the observed data, which is consistent with the prediction with SM couplings within one standard deviation
  - last bins contain the overflow.
- Bottom pad: ratio of the data or dashed histograms to the stacked histogram.

Study the *2l2ν* off-shell and the *4l* on-shell + off-shell final states

- The observed (solid) and expected (dashed) one-parameter likelihood scans over Γ_H.
- The integrated luminosity reaches up to 140 fb^{-1} as on-shell 4ℓ events are included in performing these scans.
- The exclusion of the no off-shell hypothesis is consistent with 3.6 standard deviations on both panels.



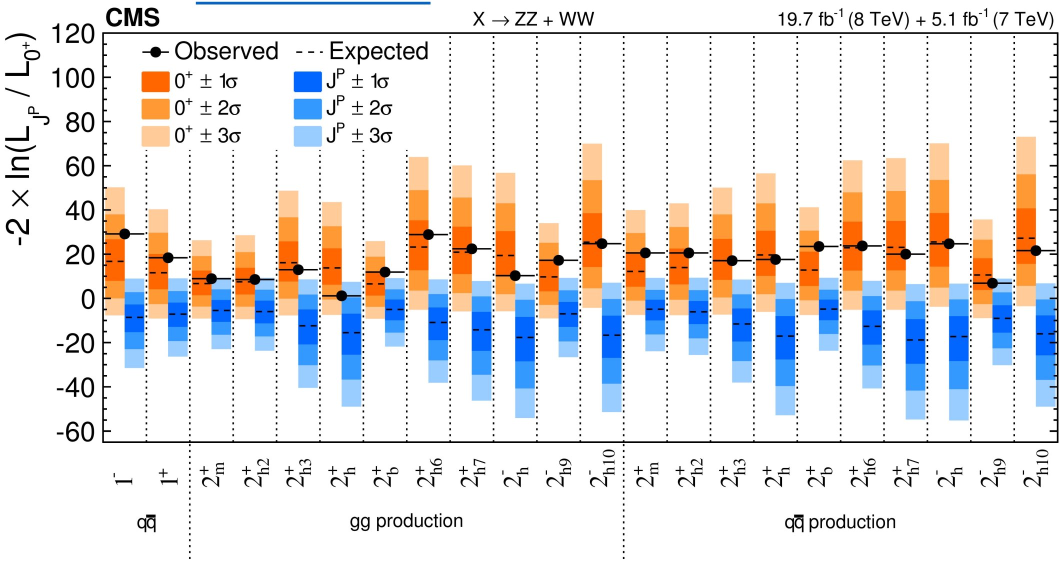
The no off-shell scenario with $\Gamma_H = 0$ is excluded at 99.97%

$$\Gamma = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

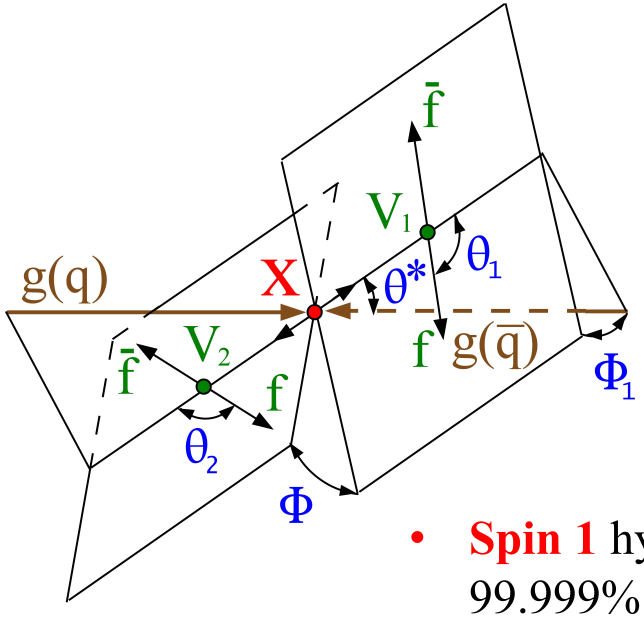
The Higgs boson spin

- In Standard Model the Higgs boson has spin 0 and parity +1, $J^P = 0^+$
- Studies have been made to test other J^P configurations

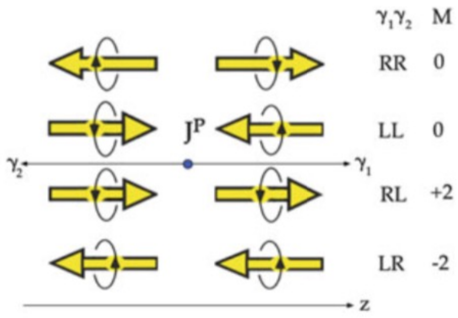
CMS HIG-14-018



Distributions of the test statistic $q = -2\ln(L_{JP}/L_{0+})$ for the spin-one and spin-two J^P models tested against the SM Higgs boson hypothesis in the combined $X \rightarrow ZZ$ and WW analyses. The observed q values are indicated by the black dots.



The Landau-Yang theorem

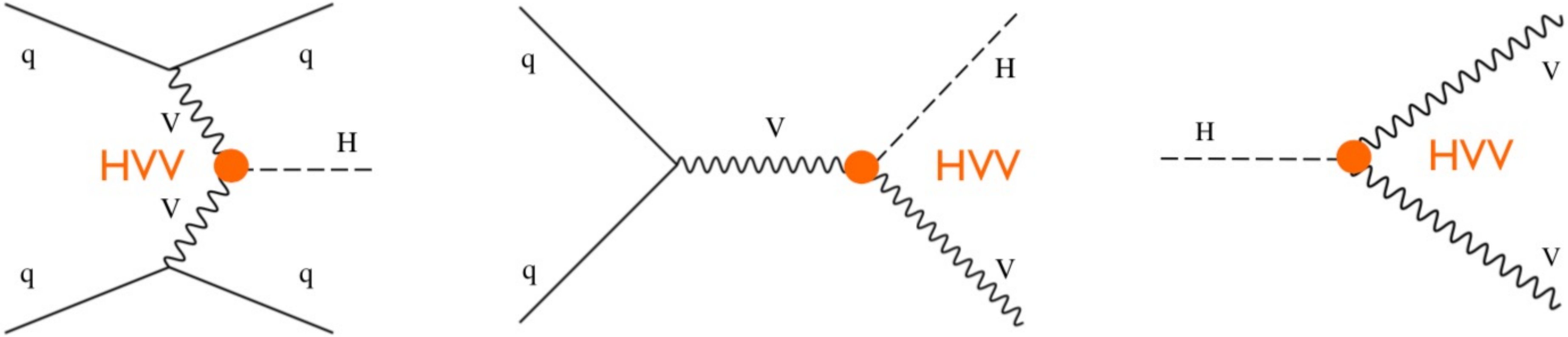


- **Spin 1** hypotheses are excluded at a greater than 99.999% CL in the ZZ and WW modes, while the γγ mode is excluded by the Landau-Yang theorem
- **Spin 2** models are excluded at > 99 % CL

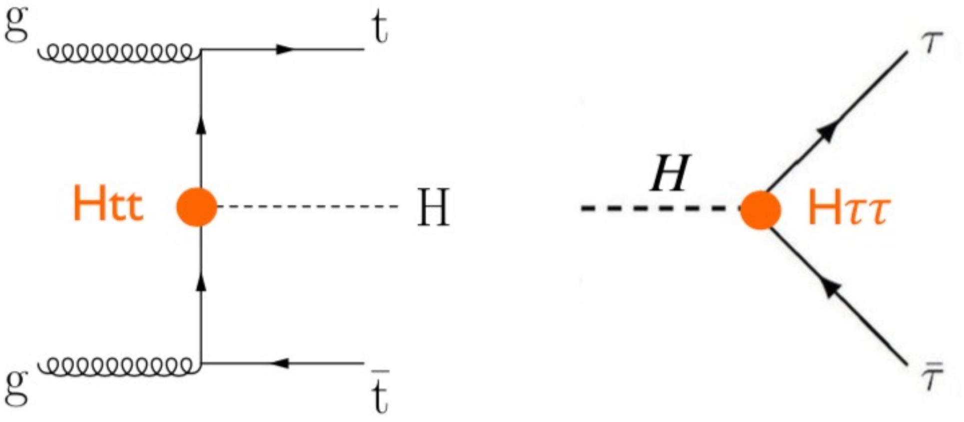
Higgs boson CP properties

Spin is property of the particle, CP of the coupling…

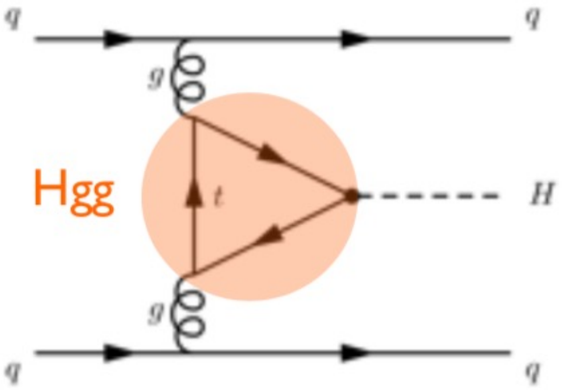
coupling to EW vector bosons



coupling to fermions



coupling to gluons



Higgs CP and CP violation

- The SM H is even under charge-parity (CP) inversion
- A sizeable deviation from a pure CP-even interaction of the Higgs boson with any of the SM particles would be a direct indication of physics beyond SM
- ➔ The CP structure of the couplings of the H is of paramount interest
- Furthermore, there are strong theoretical motivations to search for CP-violating effects in Higgs couplings
- CP-violation in the Higgs sector **remains a possible source of the baryon asymmetry of the universe**
- A renormalisable **CP-violating Higgs-to-fermion coupling may occur at tree level**
  - in the case of couplings to V bosons, CP-odd contributions are suppressed by powers of $1/\Lambda^2$ (Λ is the scale of the physics beyond the SM in an effective field theory)
- The τ lepton and top quark Yukawa couplings, $H\tau\tau$ and Htt, respectively, are therefore the optimal couplings for CP studies in pp collisions

CP properties with ttH

The top quark – Higgs boson interaction can be be extended beyond the SM [Eur. Phys. J. C 74 (2014)] with Effective Lagrangian for Yukawa coupling to top quarks parameterized by CP-even and CP-odd components:

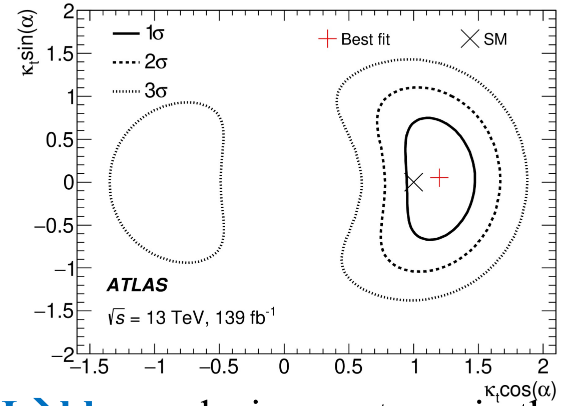
$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + i\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

CP even **CP odd**

m_t: top quark mass
v: Higgs vacuum expectation value
κ_t: top quark Yukawa coupling parameter
α: is the CP mixing angle
H: is the higgs field
ψ_t and ψ_t-bar are top quark spinor fields
γ_5: is a Dirac matrix

in SM: $\kappa_t = 1$ and $\alpha = 0$

Phys. Rev. Lett. 125 (2020) 061802

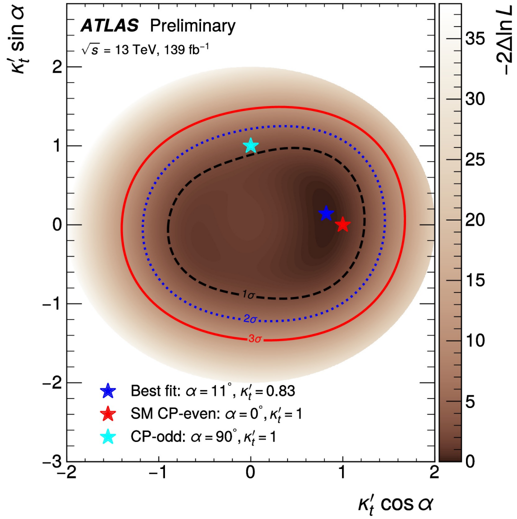


Two-dimensional likelihood contours for $\kappa_t\cos(\alpha)$ and $\kappa_t\sin(\alpha)$ with ggF and **H → γγ** constrained by the Higgs boson coupling combination

pure CP-odd coupling excluded at 3.9σ

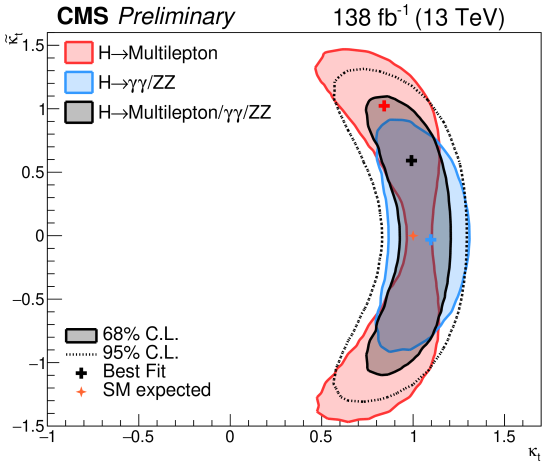
ttH, H→bb: exclusion contours in the $\kappa_t'\cos\alpha$ - $\kappa_t'\sin\alpha$ plane. Regions in the black, blue and red lines are compatible with the best-fit results at 1, 2 and 3 standard deviations. The stars represent CP-even (-odd) with $\kappa_t'=1$ in red and the best-fit result.

pure CP-odd coupling disfavoured at 1.2σ



ATLAS-CONF-2022-016

CMS PAS HIG-21-006



ttH, tH: Likelihood scan as a function of κ_t and $\tilde{\kappa}_t$. Two-dimensional confidence intervals at 68% CL are shown for **multilepton final states**, the combination of **H → γγ** and **H → ZZ**, and the combination of the three channels.

κ_t is proportional to cos(α), while
$\tilde{\kappa}_t$ is proportional to sin(α)

pure CP-odd coupling excluded at 3.7σ

CP properties with H→ττ

The τ lepton – Higgs boson interaction can be be extended beyond the SM [Eur. Phys. J. C74 (2014) , Phys. Rev. D 92 (2015) 096012] with Effective Lagrangian for Yukawa coupling to tau leptons parameterized by CP-even and CP-odd components :

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

CP even **CP odd**

m_τ : tau lepton mass

v: Higgs vacuum expectation value

κ_τ : tau lepton Yukawa coupling parameter

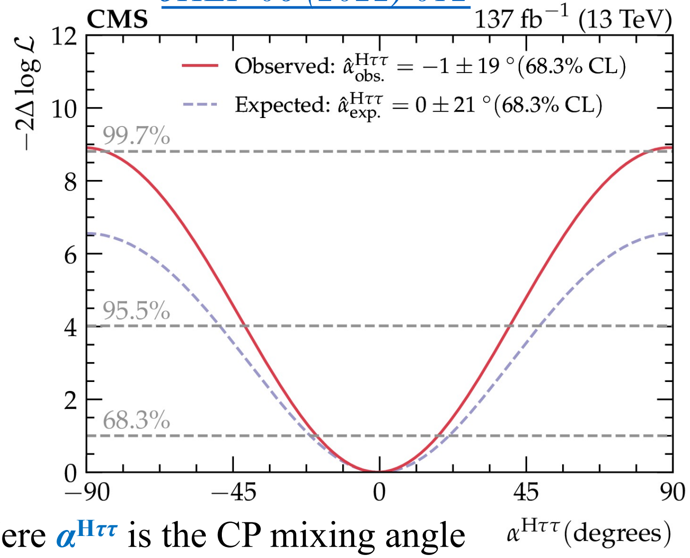
ϕ_τ : is the CP mixing angle

H: is the higgs field

γ_5: is a Dirac matrix

in SM: $\kappa_\tau = 1$ and $\alpha = 0$

JHEP 06 (2022) 012



Here $\alpha^{H\tau\tau}$ is the CP mixing angle

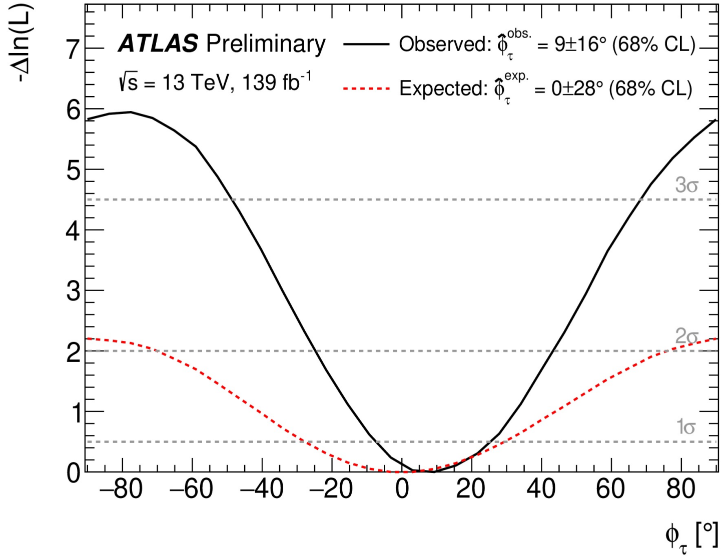
The observed (expected) sensitivity to distinguish between the scalar and pseudoscalar hypotheses, defined at $\alpha^{H\tau\tau} = 0$ and ±90°, respectively, is 3.0σ (2.6σ).

The observed (expected) value for $\alpha^{H\tau\tau}$ is −1±19° (0±21°) at the 68.3% CL. At 95.5% CL the range is ±41° (±49°), and at the 99.7% CL the observed range is ±84°.

ϕ_τ = -1 ± 19° (21° expected)

pure CP-odd coupling excluded at 3 s.d.

ATLAS-CONF-2022-032



Likelihood scan of φ_τ. The observed (expected) value of φ_τ is 9±16° (0±28°) at the 68% confidence level (CL), and ± 34° ($_{-70}^{+75°}$) at the 95.5% CL. **The CP-odd hypothesis is rejected at 3.4σ (expected at 2.1σ) level.**

ϕ_τ = 9 ± 16° (28° expected)

pure CP-odd coupling excluded at 3.4 s.d.

The Higgs boson spin and CP properties

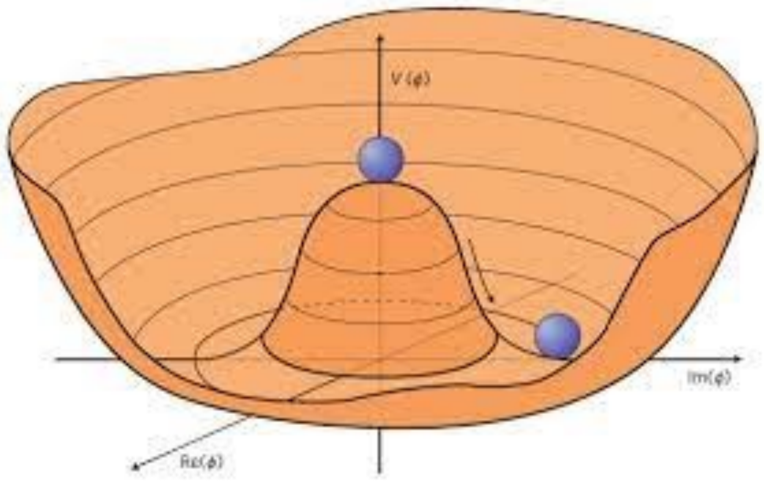
- Spin 1 and 2 hypotheses are excluded at more than 99.9% C.L.
- CP structure of various Higgs couplings variety of production and decay modes probed for Higgs boson interactions with vector bosons ($W^{\pm}$ and Z) as well as for interactions with fermions, with a variety of production and decays modes
- Measurement globally in accord with SM CP-even hypothesis
- Pure CP-odd H-t coupling excluded at ~3.9 s.d. (per experiment)
- Pure CP-odd H-τ coupling excluded at ~3.4 s.d. (per experiment)
- The leading uncertainty in the measurement is statistical,
  ➔ precision of the measurement will increase with the accumulation of more collision data.
- The measurement is consistent with the Standard Model expectation, but still room for BSM scenarios

The Higgs Potential and the Higgs self-coupling

The Higgs Potential

$$\mathcal{L} = T - V = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \left(\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4\right)$$

in SM, this potential is fully defined by two parameters, that can be inferred by the v.e.v. v and the Higgs boson mass m_h



Expanding around the minimum, $\phi = v + h$:

$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 = \frac{1}{2} m_h{}^2 h^2 + \lambda_3 h^3 + \lambda_4 h^4$$

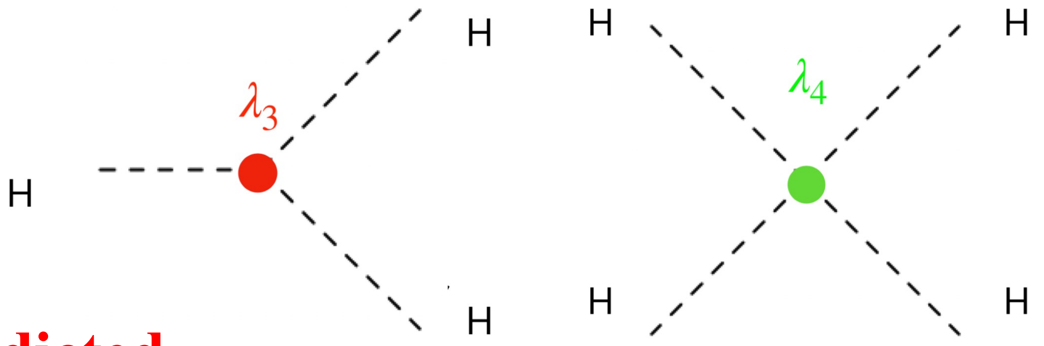
mass term

Higgs triple coupling

Higgs quartic coupling

$$m_h{}^2 = 2\lambda v^2 \qquad \lambda_3 = \lambda v = m_h{}^2/2v$$

$$\lambda_4 = \lambda/4 = mh^2/8v^2$$



Higgs boson pair (HH) production allows to probe *directly* the Higgs boson self-interaction and, ultimately, the shape of the Higgs potential.

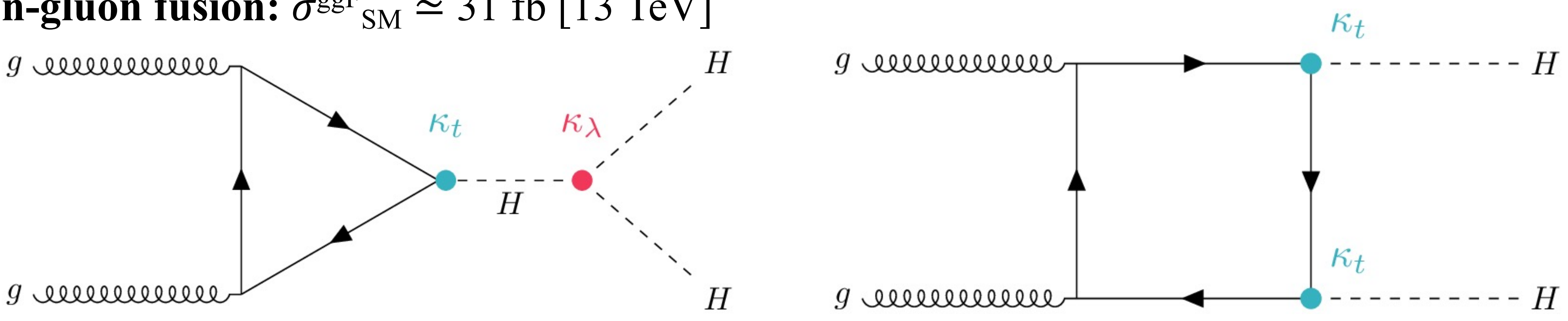
➔Any deviation from the self-interaction predicted by the SM would be a sign of new physics!

Higgs Pair production

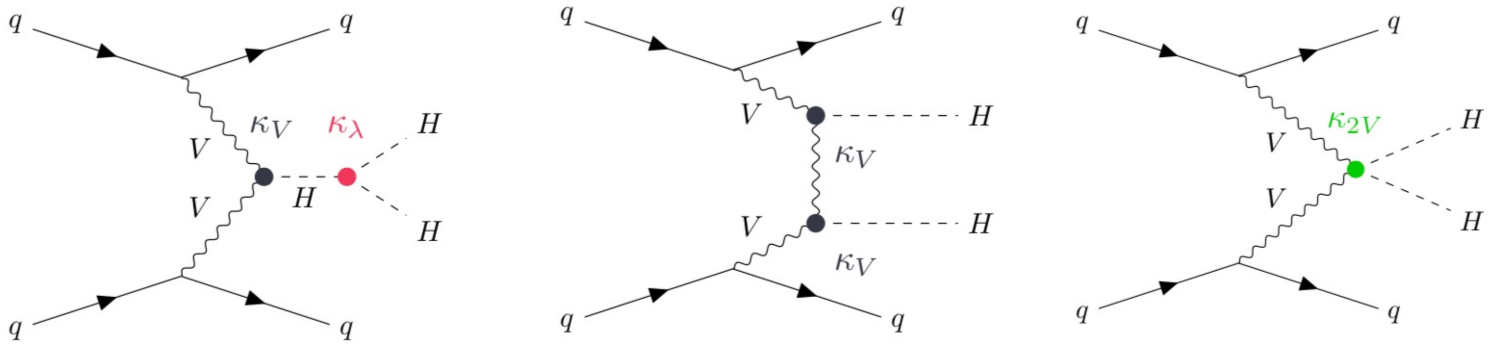
Several processes contribute to the Higgs boson pair production, “resonant” and “non resonant” (continuum)

Very small production cross sections: more than 1000 times smaller than single-Higgs production!

Gluon-gluon fusion: $\sigma^{ggF}_{SM} \simeq 31$ fb [13 TeV]



Vector Boson fusion: $\sigma^{VBF}_{SM} \simeq 1.7$ fb [13 TeV]



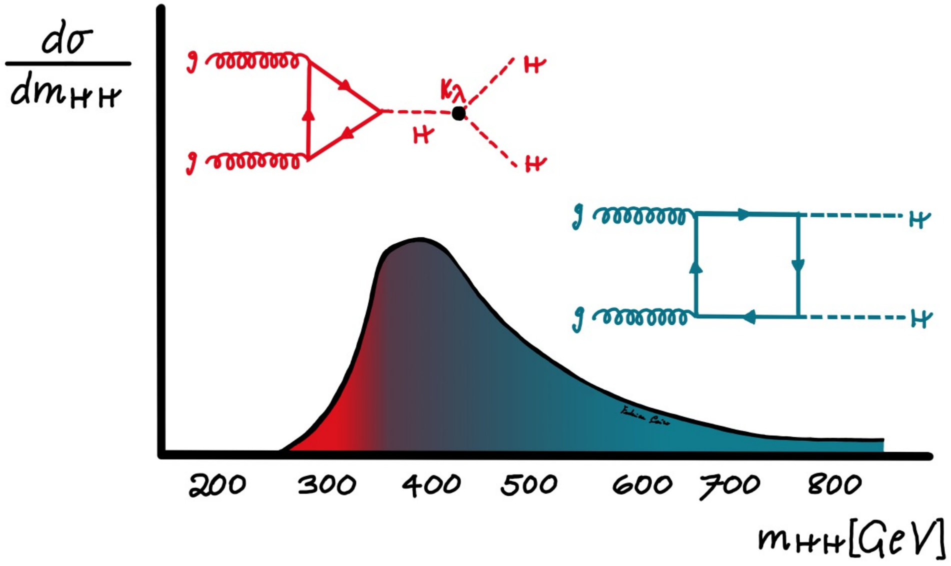
Interference between different processes (but with same initial and final states) is important!

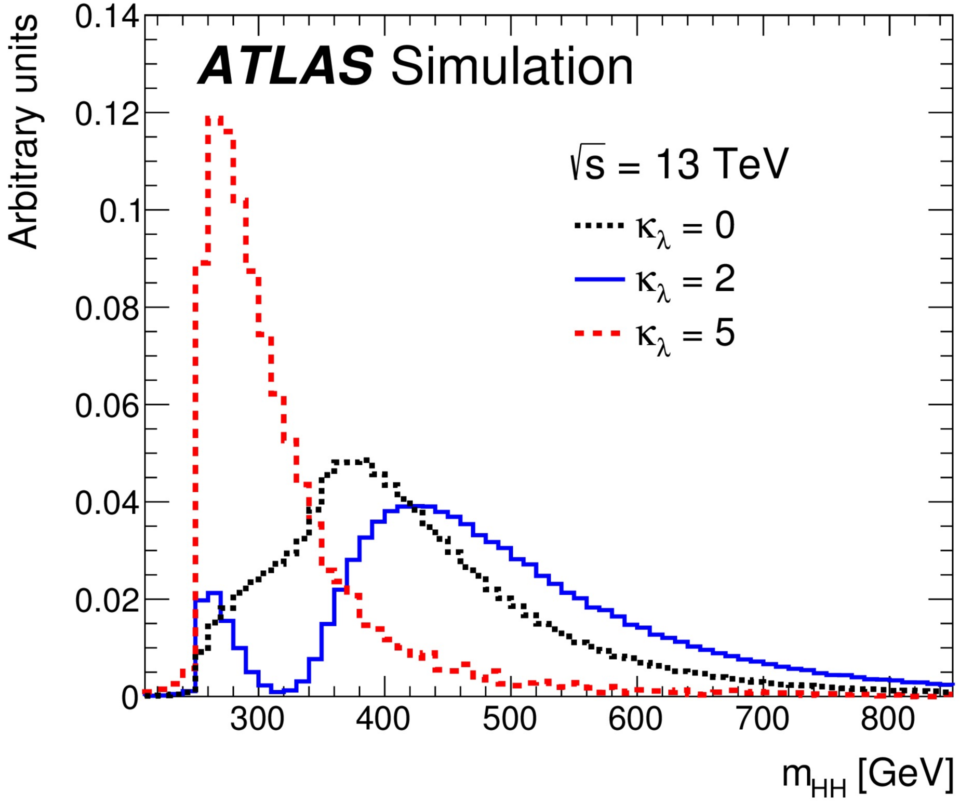
Other production modes (e.g. VHH, ttHH) have even smaller cross-sections

Higgs Pair production

HH events from the self-interaction diagrams are soft

⇒ Challenging for triggers and detector object reconstruction/identification!

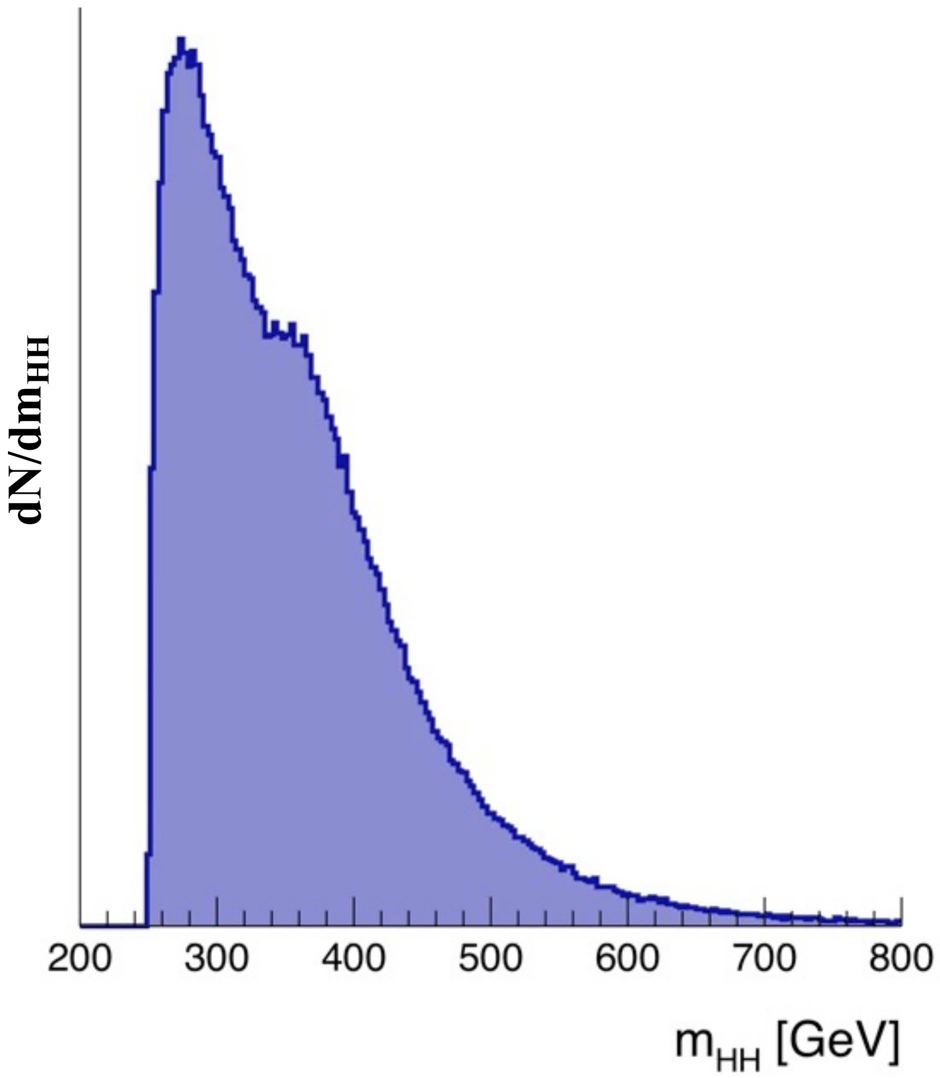


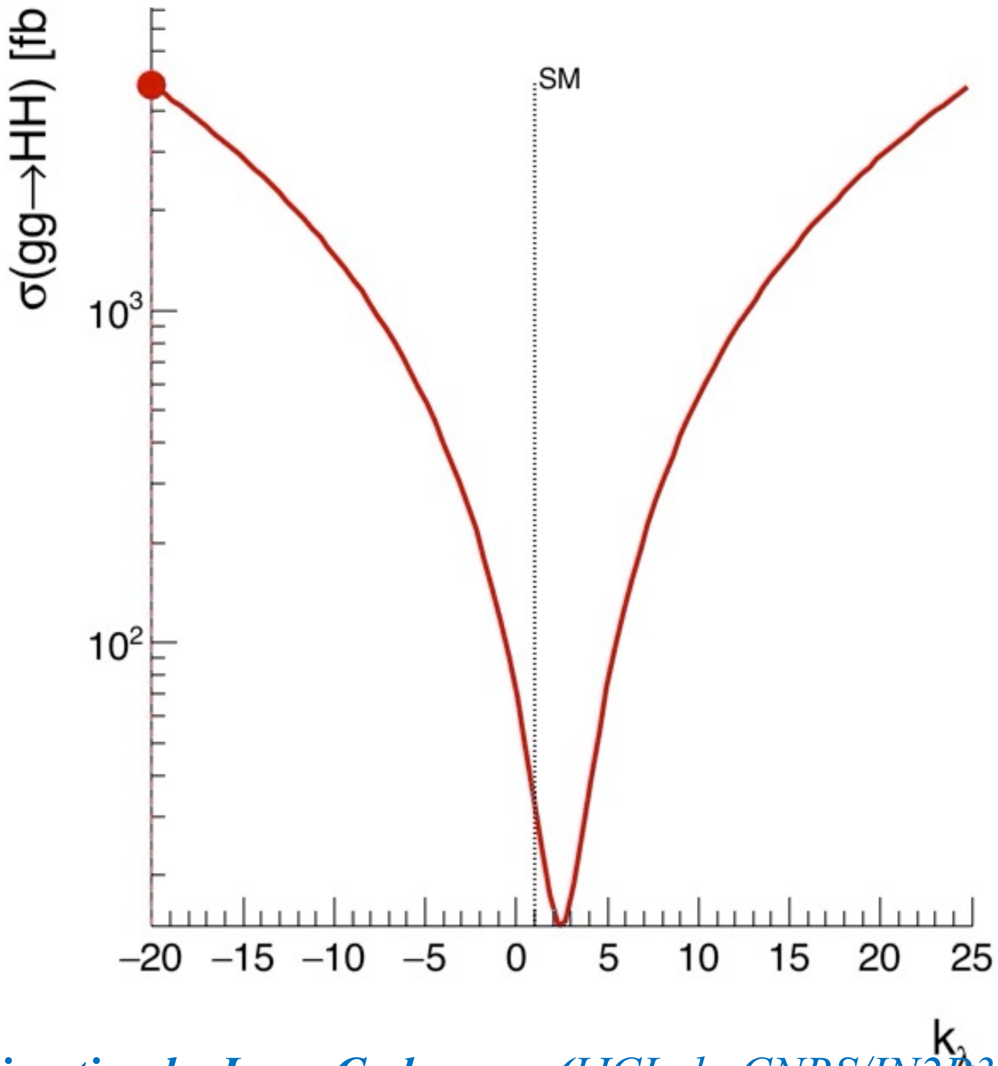


Values of λ different from λ_{SM} modify significantly the production cross section, and the kinematic properties of HH

ggF: *triangle-box* interference

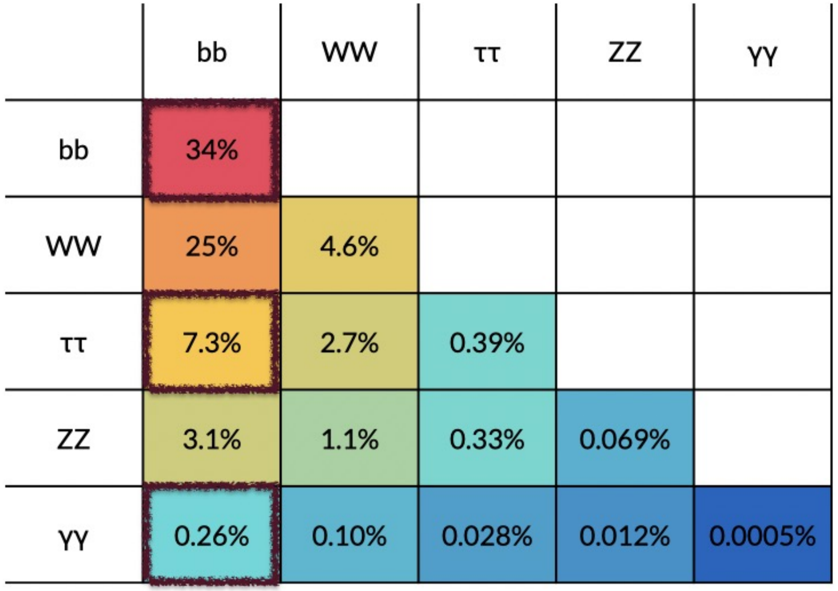
$$P(x) = |\Psi(x,t)|^2 = |\Psi_A(x,t)|^2 + |\Psi_B(x,t)|^2 + (\Psi_A^*(x,t)\Psi_B(x,t) + \Psi_A(x,t)\Psi_B^*(x,t))$$





***animation by Luca Cadamuro** (IJCLab, CNRS/IN2P3)*

HH final states



	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%

picture by Katharine Leney

There are three *main* channels:

HH→ bb$\gamma\gamma$
HH→ bb$\tau\tau$
HH→ bbbb

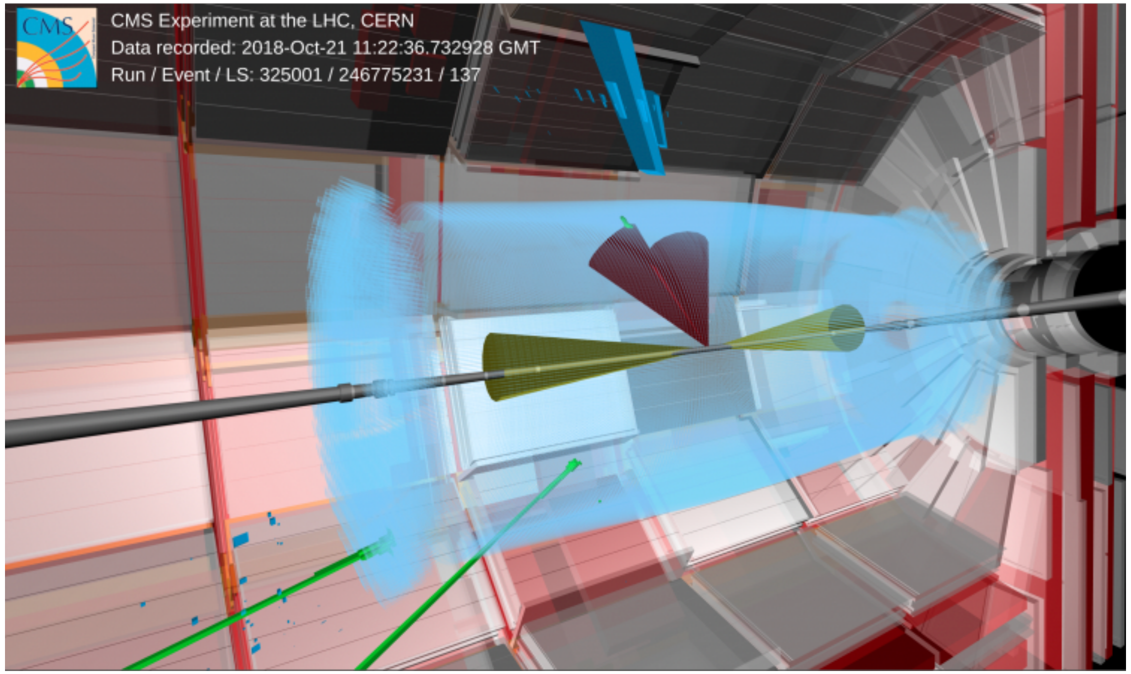
Putting together two Higgs bosons, the variety of final states is quite large, and taking into account the modest total production cross section (assuming a SM scenario), there is no a clear “gold channel” for its detection

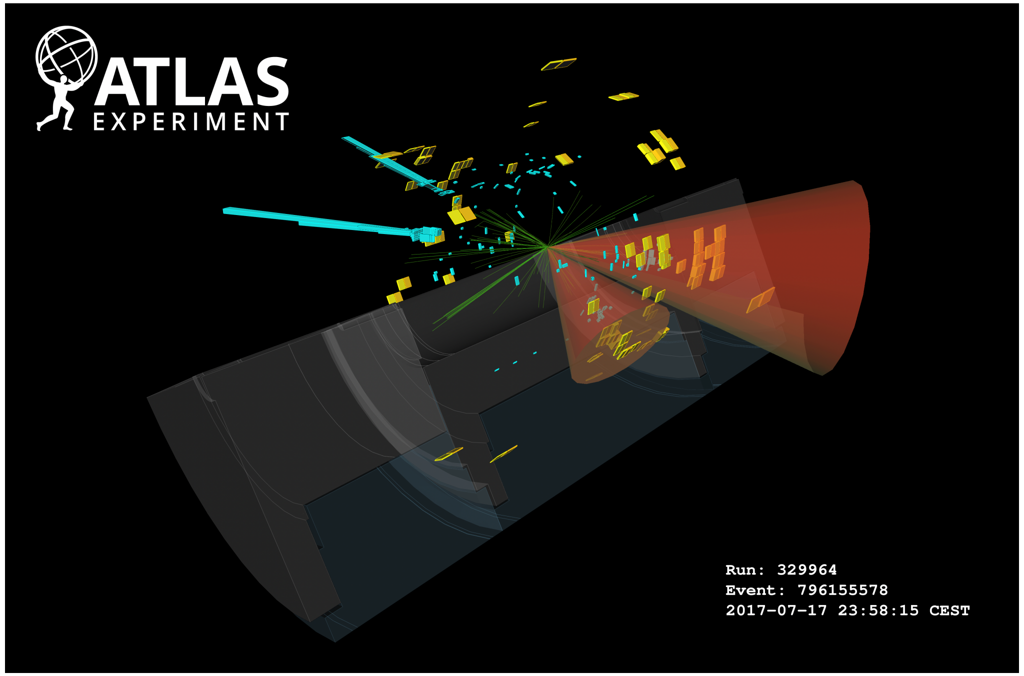
Higgs boson decay branching ratios are tipically small, in particular for “gold” channels such as $\gamma\gamma$ and 4-lepton

- ➔ Consider in particular final states with at least one H decaying in **bb** (largest BR): **HH→bbX**
- ➔ **Need of high trigger efficiencies and high efficiency of physics object reconstruction and identification**
- ➔ Need of studying as many decay final states as possible, allowing then for their combination

these channels require high performance of b-jet tagging to reject events from light jets mis-identified as b-jets and high b-jet identification efficiency, as well as good b-jet reconstruction

HH→bb$\gamma\gamma$



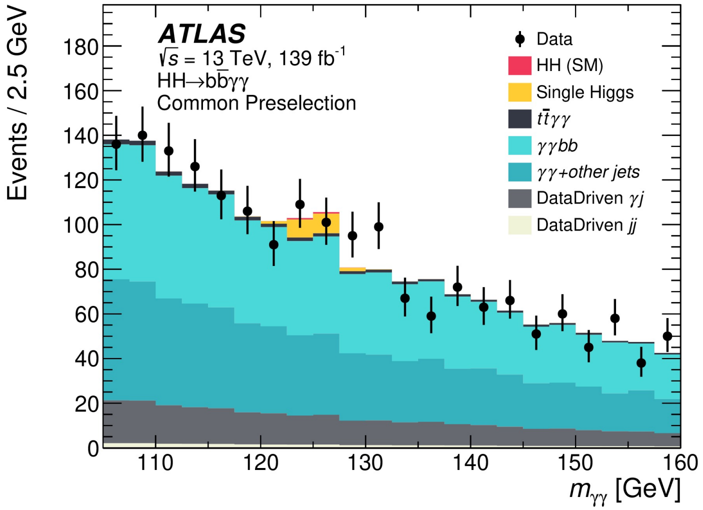


- Tiny branching ratio: 0.26% … but very clean signature: excellent $m_{\gamma\gamma}$ resolution and reasonably small background!
- Background:
  - irreducible: pp → bb$\gamma\gamma$
  - reducible: pp → tt$\gamma\gamma$, jj$\gamma\gamma$, jjjγ, jjjj, single H

HH→bb$\gamma\gamma$

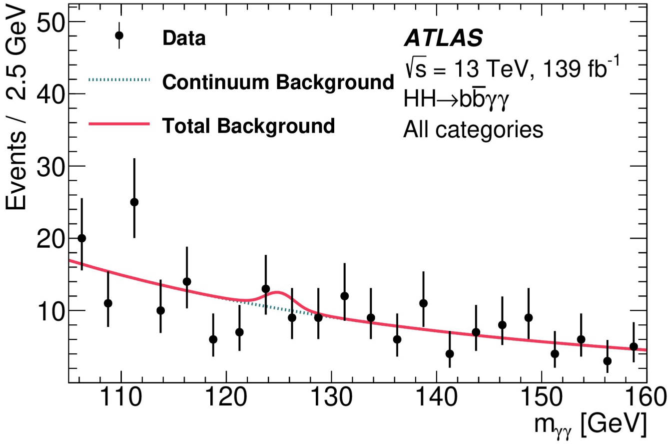
- Consider ggF and VBF production
- $\gamma\gamma$+jets background modelled with exponential function derived from data in *control regions* and single-Higgs modelled with double-sided Crystal-Ball function derived from Monte Carlo simulations
    - Signal shape also modelled with double-sided Crystal- ball function derived from Monte Carlo simulations
- Boosted Decision Trees used to discriminate signal and background
- Important input variable: reconstructed invariant mass of the Higgs boson candidate m_{bb}
- 4 signal region categories defined by selections on $m_{bb\gamma\gamma}$ and on BDT outputs

arXiv:2112.11



Distributions $m_{\gamma\gamma}$ for events satisfying the common preselection criteria

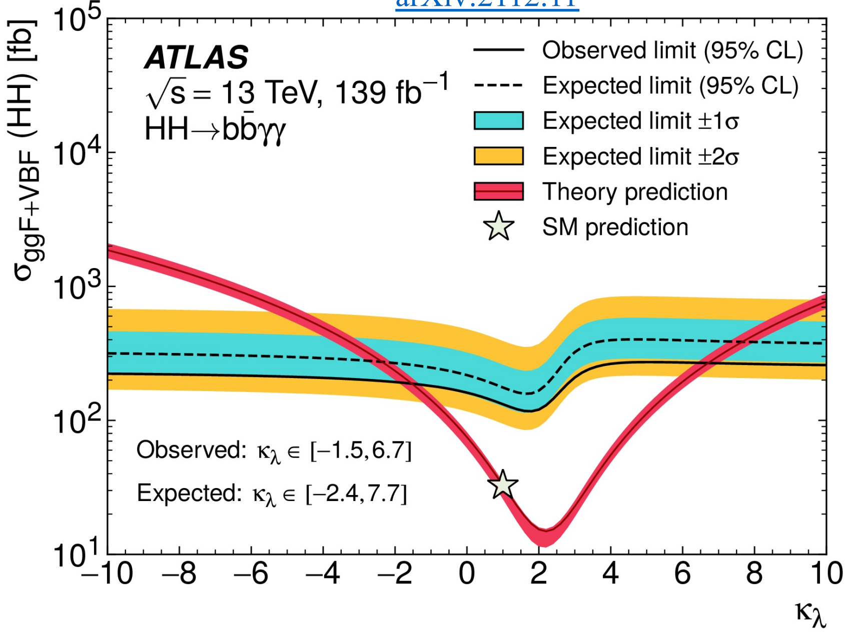
11 HH→bb$\gamma\gamma$ events (SM) are produced



Data are compared to the background-only fit for the sum of the events in the four BDT categories of the non resonant search.
Both the continuum background and the background from single Higgs boson production are considered.

HH→bb$\gamma\gamma$

arXiv:2112.11



Observed and expected limits at 95% CL on the cross section of non resonant Higgs boson pair production as a function of the Higgs boson self-coupling modifier $\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$.
Expected constraints on κ_λ are obtained with a background hypothesis excluding pp → HH production.
The theory prediction curve represents the scenario where all parameters and couplings are set to their SM values except for κ_λ.

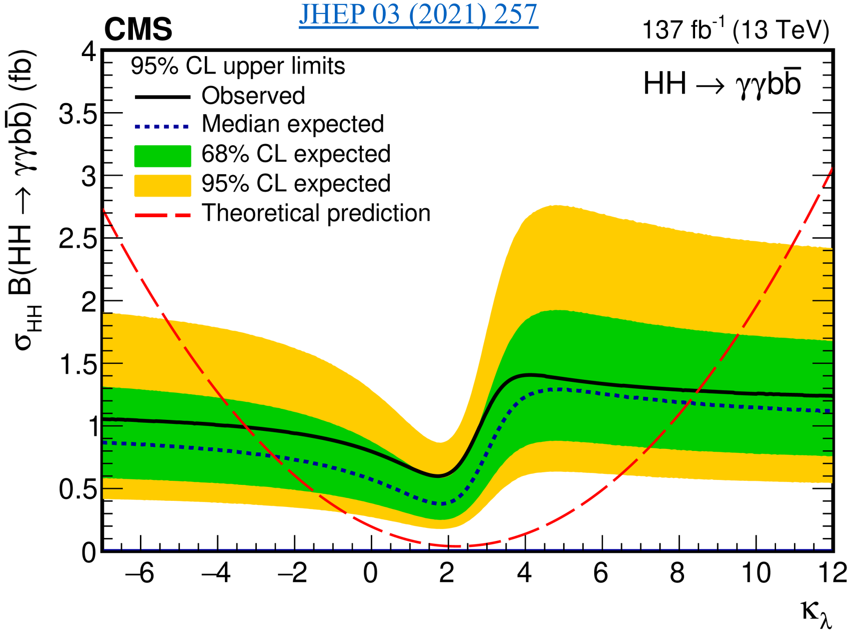
Observed: $\kappa_\lambda \in [-1.5, 6.7]$
Expected: $\kappa_\lambda \in [-2.4, 7.7]$

Observed and expected 95% CL upper limits on the product of the HH production cross section and $BR(HH \to \gamma\gamma bb)$ obtained for different values of κ_λ assuming $\kappa_t = 1$.

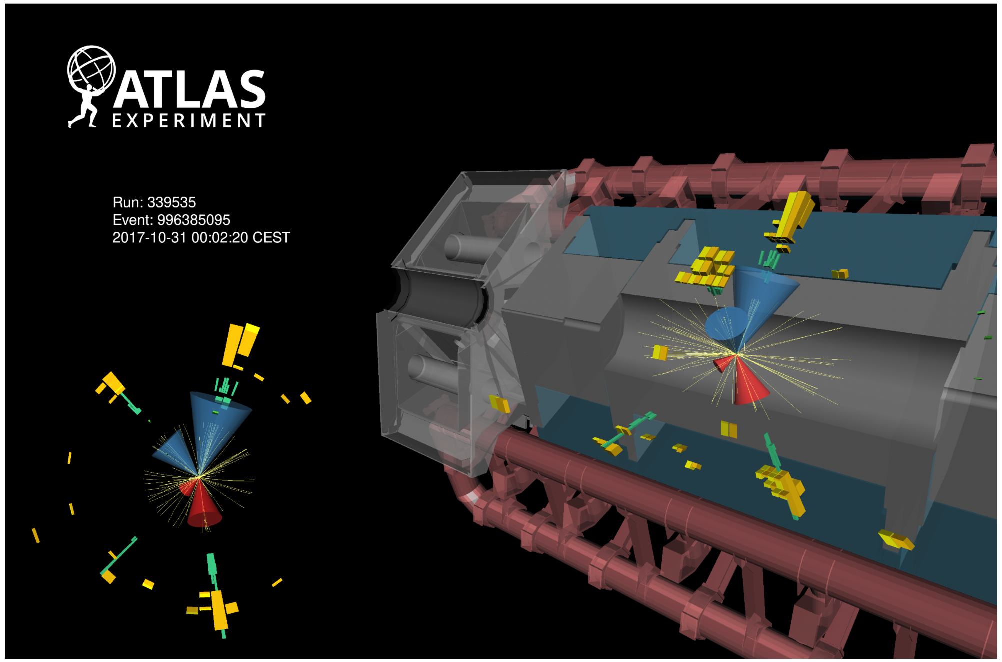
The observed (expected) 95% CL upper limit on σ_{HH} B(HH → γγbb) amounts to 0.67 (0.45) fb.

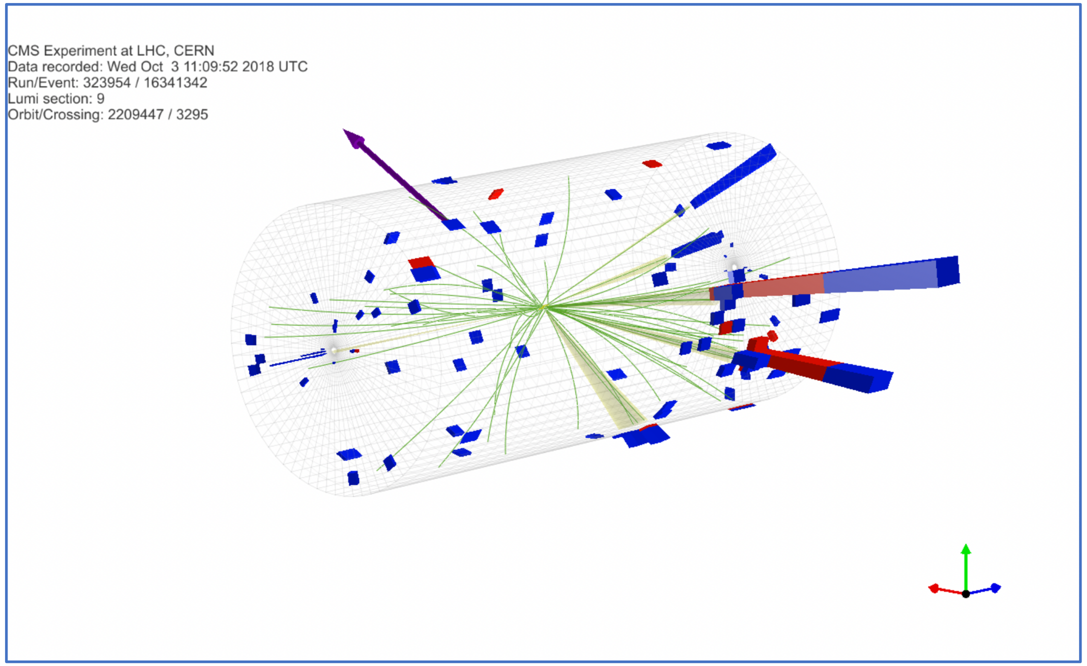
Observed: $\kappa_\lambda \in [-3.3, 8.5]$
Expected: $\kappa_\lambda \in [-2.5, 8.2]$

JHEP 03 (2021) 257



HH→bb$\tau\tau$

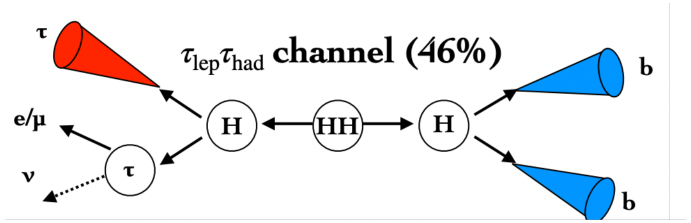


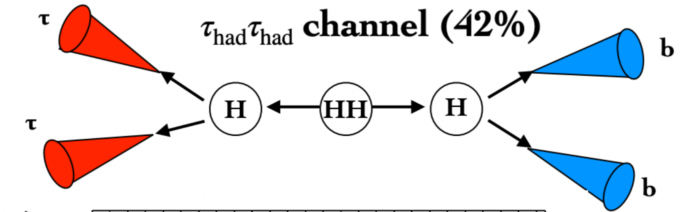


- good branching fraction (7.3%), reasonable background to contrast
- consider **$\tau\tau$ final states** with at least one τ decaying hadronically: $\tau_h\tau_\mu$, $\tau_h\tau_e$, $\tau_h\tau_h$ (no $\tau_{lep}\tau_{lep}$, 12.4%)
- H→bb topology: consider 2b resolved , 1b resolved and 1b boosted) (CMS)

$\tau \to e\nu_e\nu_\tau$ 17.8%
$\tau \to \mu\nu_\mu\nu_\tau$ 17.4%
$\tau \to h\nu_\tau$ 64.8%

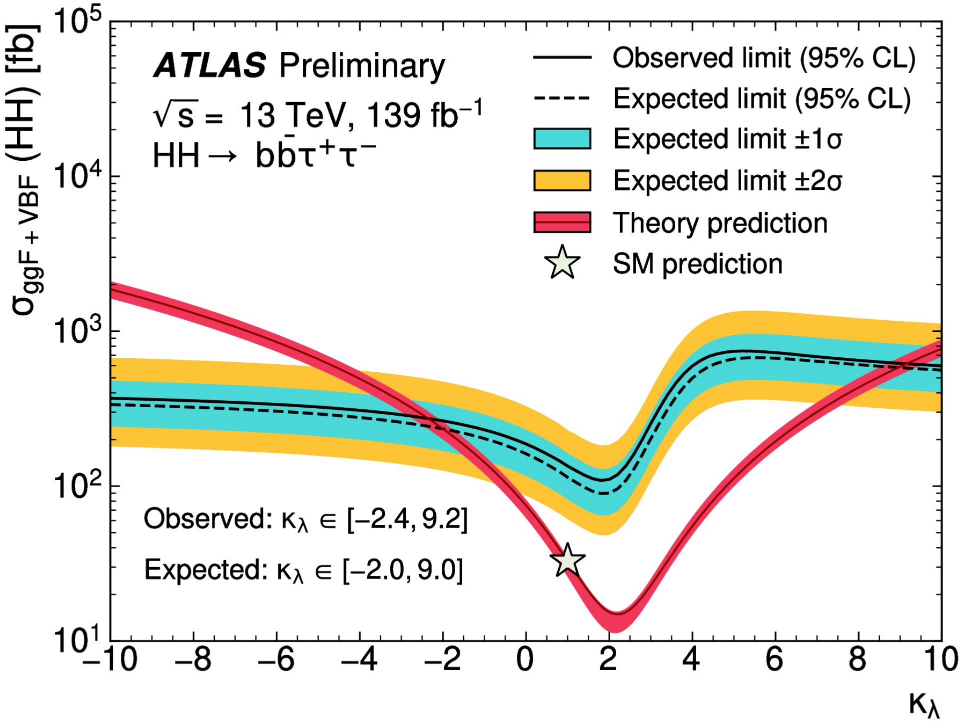
- Signal categorisation
- Background modelling:
  - $t\bar{t}$ and Z+jets: simulation with data-driven corrections;
  - data-driven method if a gluon- or quark-initiated jet mimics τ_h.
- Signal extraction: MVA classifiers for both ATLAS and CMS





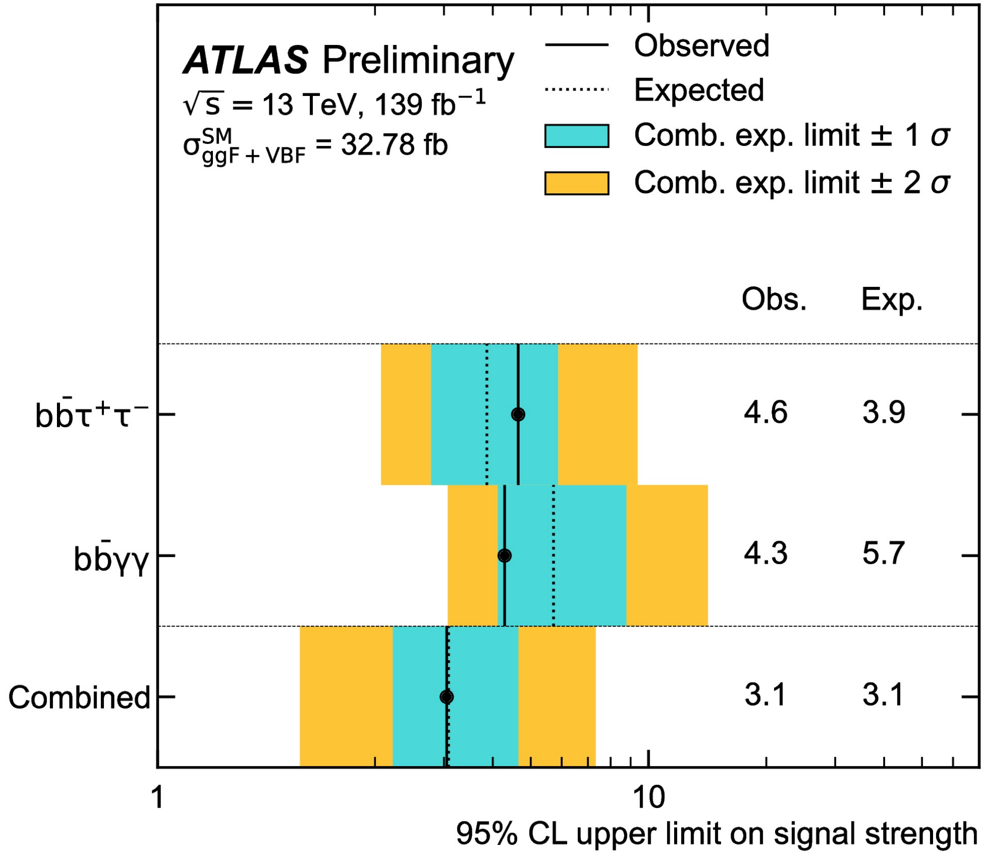
HH→bb$\tau\tau$ and combination with HH→bb$\gamma\gamma$

ATLAS-CONF-2021-052



Observed: $\kappa_\lambda \in [-2.4, 9.2]$
Expected: $\kappa_\lambda \in [-2.0, 9.0]$

Observed and expected 95% CL upper limits on non-resonant HH production cross-section as a function of κ_λ in the $b\bar{b}\tau^+\tau^-$ channel. The theory prediction curve represents the scenario where all parameters and couplings are set to their SM values except for κ_λ.



CMS: see
JHEP 11 (2021) 057

Observed and expected 95% confidence level upper limits on the signal strength for SM HH production in the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ searches, and their statistical combination. The expected limits assume no HH production.

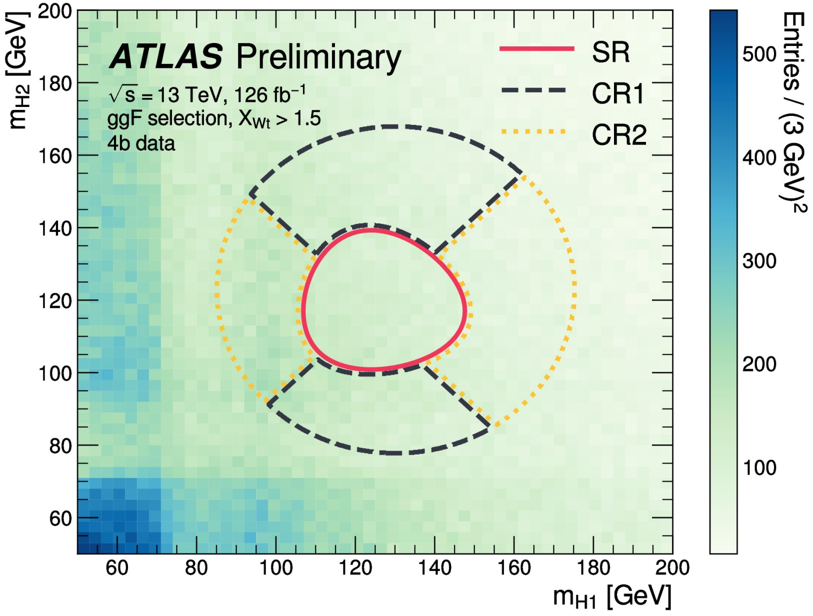
Observed (expected) 95% confidence level limit on κ_λ:

$-1.0 \leq \kappa_\lambda \leq 6.6$ $(-1.2 \leq \kappa\lambda \leq 7.2)$

HH→bbbb

- Highest branching ratio
- Mostly probes large m_{HH} ⇒ sensitivity to HH events with large p_T^H.
- large multijet background, difficult to simulate (large modelling uncertainties) ➔ estimate this background from data

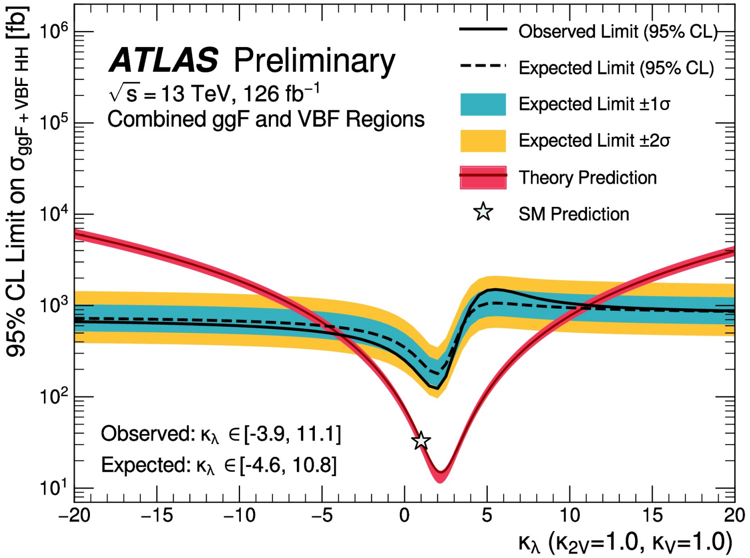
ATLAS-CONF-2022-035



ATLAS: Select exactly 2 b-jet events which pass the same b-jet triggers and the same selection criteria as the 4b events. The jets selected to form the two higgs boson candidates are the 2 b-tagged jets and the two untagged jets with the highest p_T.

CMS: uses 3 b-jet event control samples

Define a Signal Region (SR) and four Control Regions (2 in CR1 and 2 in CR2)



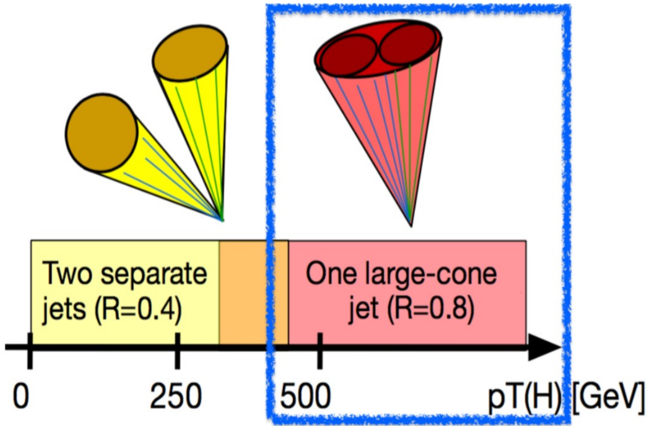
The observed 95% CL_s exclusion limits as a function of κ_λ

The observed and expected constraints on the HHH coupling modifiers κ_λ are found to be

κ_λ: -3.9; 11.1 (-4.6; 10.6) at 95% C.L.

κ_{2V}: -0.03; 2.11 (-0.05; 2.12) at 95% C.L.

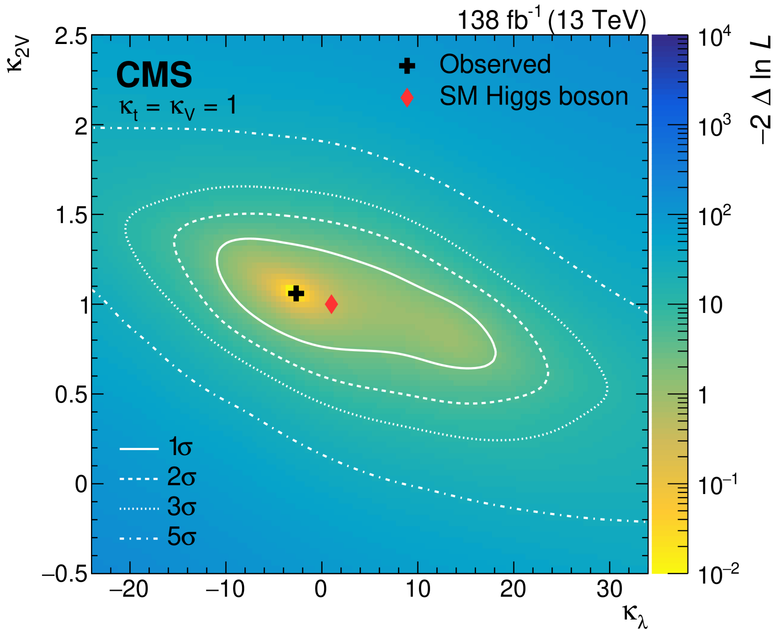
HH→bbbb



cartoon by Daniel Guerrero

- CMS studied also HH→bbbb production in highly energetic Higgs bosons decays
- ➔ boosted 2b-jet topologies
  - Two large-radius jets as H→bb candidates.
  - Sophisticated tagger to discriminate against QCD-induced jets.
  - Sophisticated boosted jets reconstruction algorithms

CMS arXiv:2205.06667



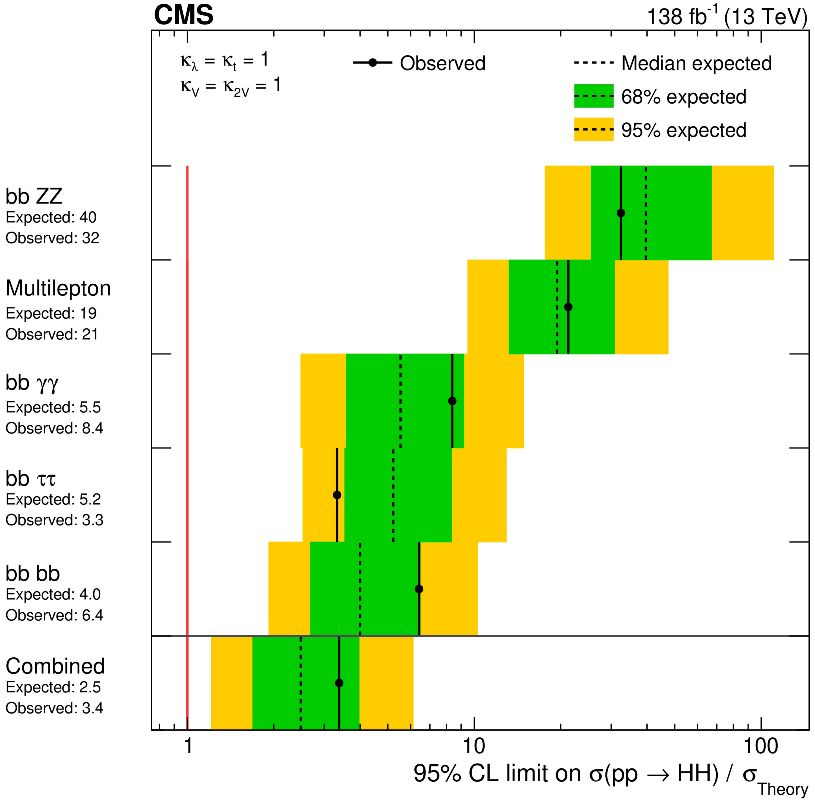
Two-parameter profile likelihood test statistic ($-2\Delta\ln L$) scan in data as a function of κ_λ and κ_{2V}. The black cross indicates the minimum, while the red diamond marks the SM expectation (κ_λ=κ_{2V}= 1).

κ_λ: [−9.9, 16.9] ([−5.1, 12.2]) at 95% C.L.
κ_{2V}: [0.62, 1.41] ([0.66, 1.37]) at 95% C.L.

⇒ $\kappa 2V$ = 0 hypothesis excluded with ≳ 6σ (other κ's at 1)!

HH Summary

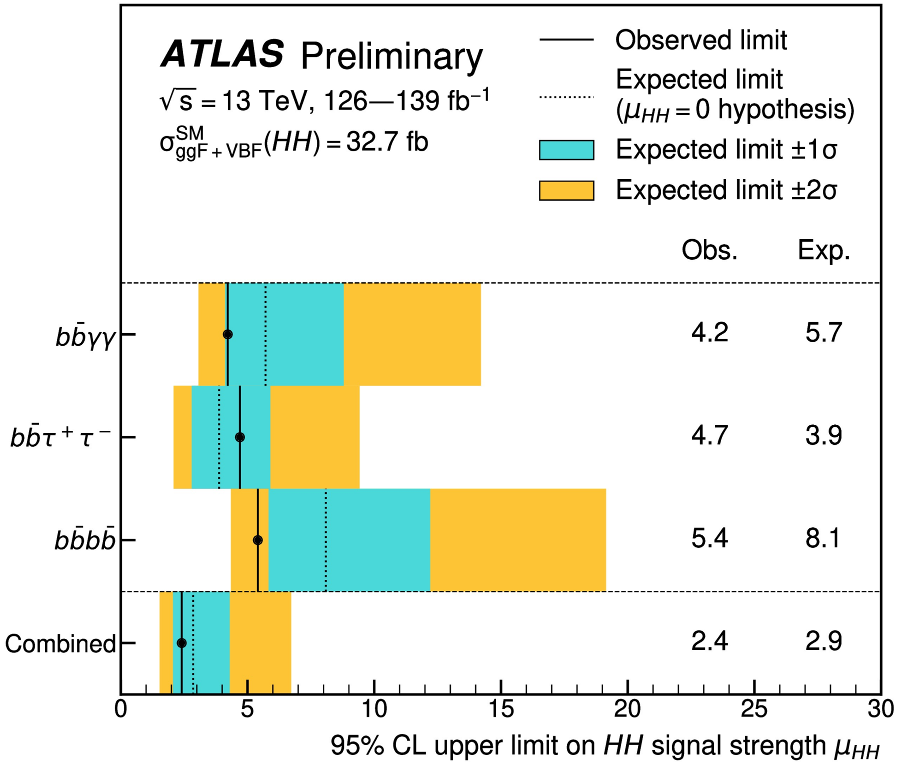
Nature 607, 60 (2022)



Expected and observed limits on the ratio of experimentally estimated production cross section and the expectation from the SM (σ_{theory}) in searches using different final states and their combination

The Higgs boson pair production cross section is found to be less than 3.4 times the SM expectation at 95% CL

ATLAS-CONF-2022-050



Observed and expected 95% CL upper limits on the signal strength for double-Higgs production from the $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ decay channels, and their statistical combination (assuming $m_H = 125.09$ GeV)

The Higgs boson pair production cross section is found to be less than 2.4 times the SM expectation at 95% CL

Why Higgs self-coupling is so important?

- The Higgs field is a particular scalar field that includes a $\lambda\varphi^4$ term
- This term generates self-interactions
- In SM, the Higgs field is fully established:

$$V = -\left(\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4\right)$$

- We have two parameters: μ and λ, trade by m_H and ν, the v.e.v.:
  - λ is adimensional
  - $\mu = m_H/\sqrt{2}$ and $\lambda = m_H^2/(2\nu^2) \cong 0.13$
- It is of paramount importance to study this potential, and in particular its shape, to understand
  - To probe the validity of the SM ➔ search for new phenomena
  - The fate of the Universe

Marcela Carena

10th CERN LATIN-AMERICAN SCHOOL OF HEP
Villa General Belgrano, Cordoba, Argentina, March 17-18, 2019
https://indico.cern.ch/event/763013/contributions/3358697/

Stability Bounds and the Running Quartic Coupling

The Higgs mass is governed by the value of the quartic coupling at the weak scale. This coupling evolves with energy, affected mostly by top quark loops, self interactions and weak gauge couplings

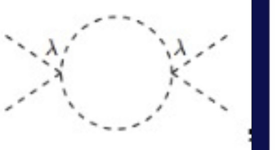
$$16\pi^2 \frac{d\lambda}{dt} = 12(\lambda^2 + h_t^2\,\lambda - h_t^4) + \mathcal{O}(g^4, g^2\lambda) \qquad t = \log(Q^2)$$

- There is the usual situation of non-asymptotic freedom for sufficiently large Q^2

↓

λ becomes too large
(strongly interacting, close to Landau pole)

From requiring perturbative validity of the model up to scale Λ or M_{pl}



$$\lambda^{max}(\Lambda)/4\pi = 1 \Rightarrow m_h^{max} = 2\sqrt{\lambda^{max}}\,v$$

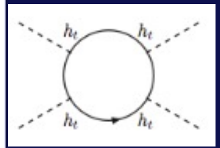
- The part of the β_λ independent of λ can drive $\lambda(Q)$ to negative values ==> destabilizing the electroweak minimum

↓

Lower bound on $\lambda(m_h)$ from stability requirement

m_h^{min} strongly dependent on m_t

h_t is the top quark Yukawa coupling



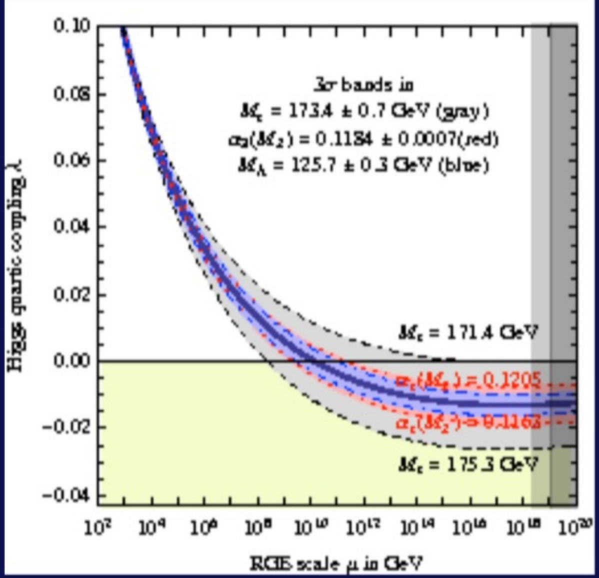
- If the Higgs mass were larger than the weak scale, the quartic coupling would be large and the theory could develop a Landau Pole. However, the observed Higgs mass leads to a value of $\lambda = 0.125$ and therefore the main effects are associated with the top loops.

The Higgs and the fate of our universe in the SM

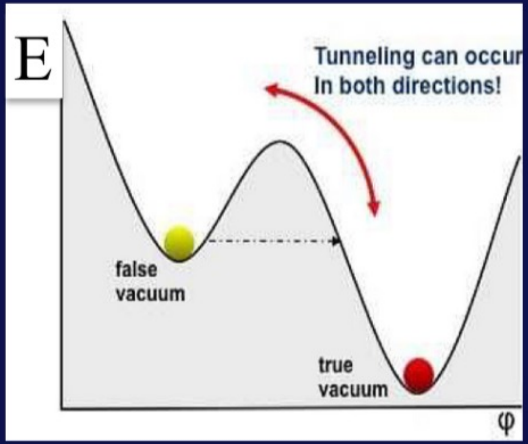
- The top quark loops tend to push the quartic coupling to negative values, inducing a possible instability of the electroweak symmetry breaking vacuum.

λ evolves with energy

Buttazzo et al., *JHEP* 989 (2012)



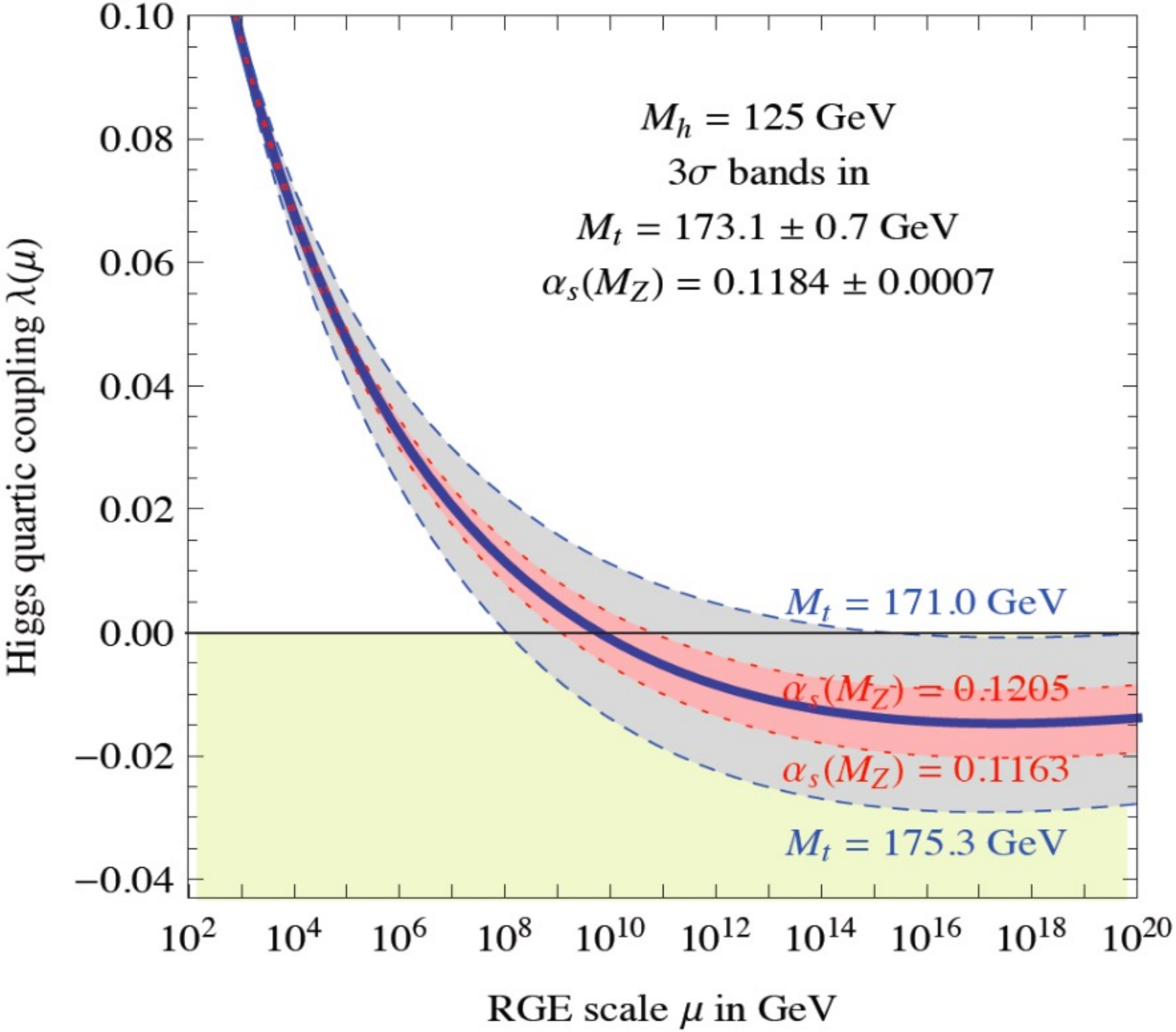
The EW vacuum is metastable



See also the talk by Juan G. Bellido (IFT)

A careful analysis, solving the coupled RG equations of the quartic and Yukawa couplings up to three loop order shows that the turning point would be at scales of order $10^{10\text{-}12}$ GeV. Therefore the electroweak symmetry breaking minimum is not stable.

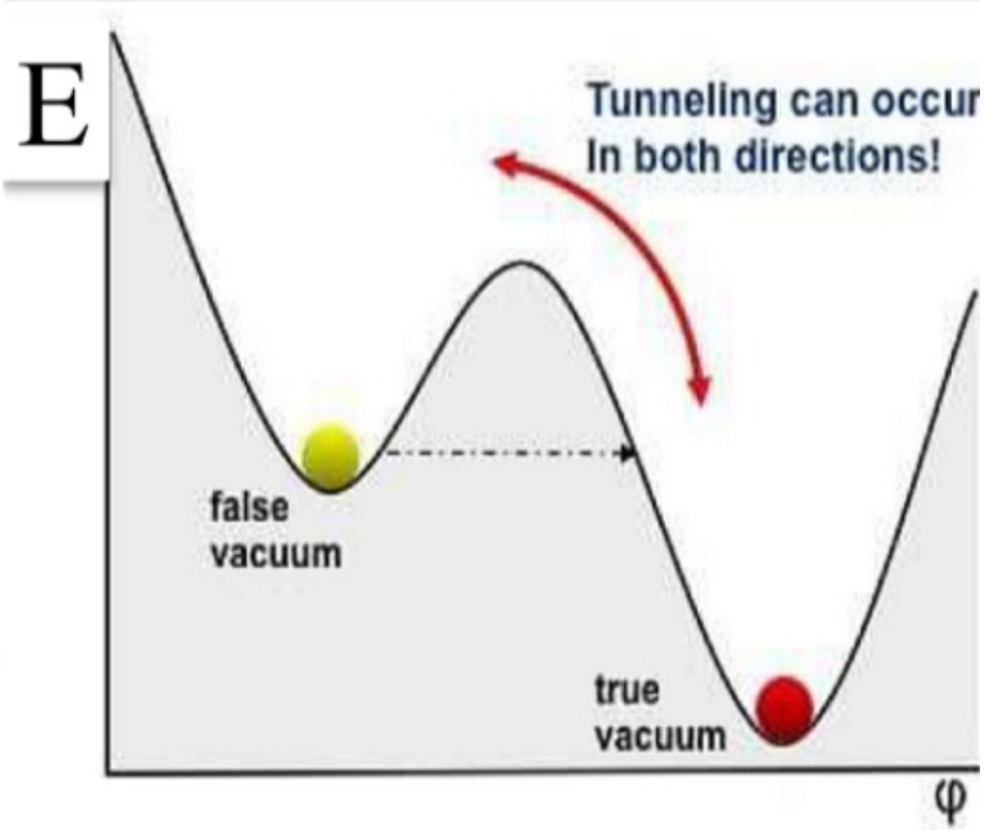
Degrassi et al. 2012



For large field values ($h \gg v$), the potential is very well approximated by its RG-improved tree-level expression

$$V_{\mathrm{eff}}(h) = \frac{\lambda_{\mathrm{eff}}(h)}{4} h^4$$

with $\mu = O(h)$



The Higgs and the fate of our universe in the SM

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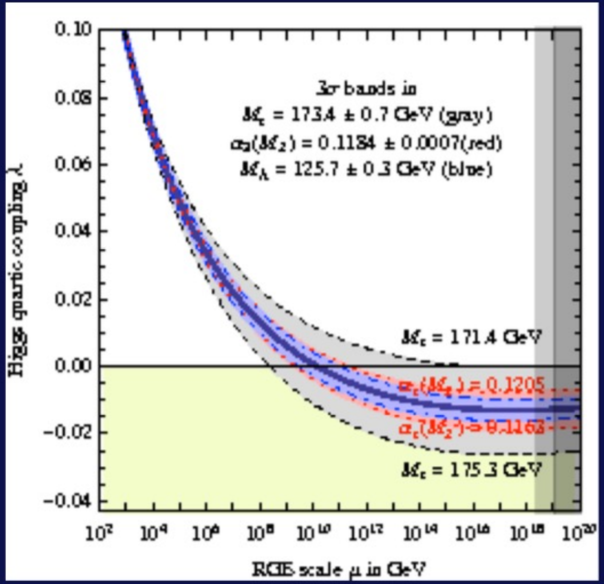
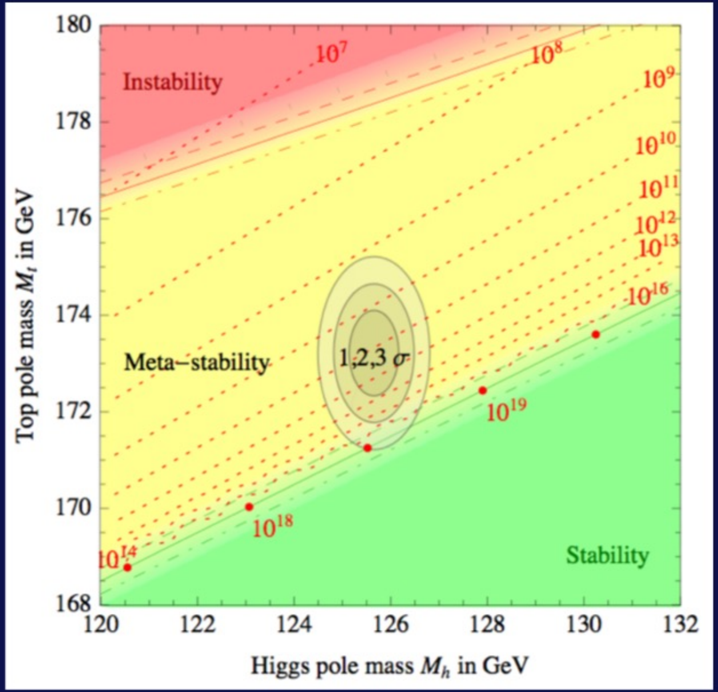
λ evolves with energy



The EW vacuum is metastable



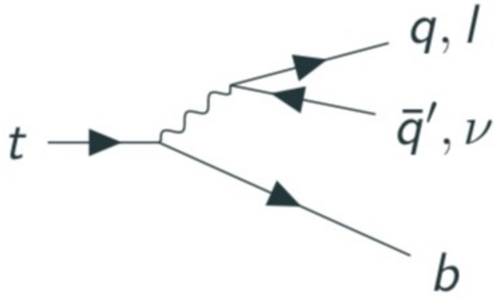
A careful analysis, solving the coupled RG equations of the quartic and Yukawa couplings up to three loop order shows that the turning point would be at scales of order $10^{10\text{-}12}$ GeV. Therefore the electroweak symmetry breaking minimum is not stable.

The top quark mass

- **The top-quark mass (m_t) is a fundamental Standard Model (SM) parameter**
- **Accurate & precise measurement of m_t *very* important (i.e. SM-consistency fits)**
- **top-quark is the heaviest SM particle →m_t affects many new physics models**
- **Warning: when experimental uncertainties on m_t becomes of sub-GeV size, arguments on the theoretical interpretation of the m_t parameter becomes relevant.**

Measurement of the top quark mass:

- **Direct**: from kinematic reconstruction of variables related to the top-quark momentum
- **Indirect**: infer from production cross section measurement

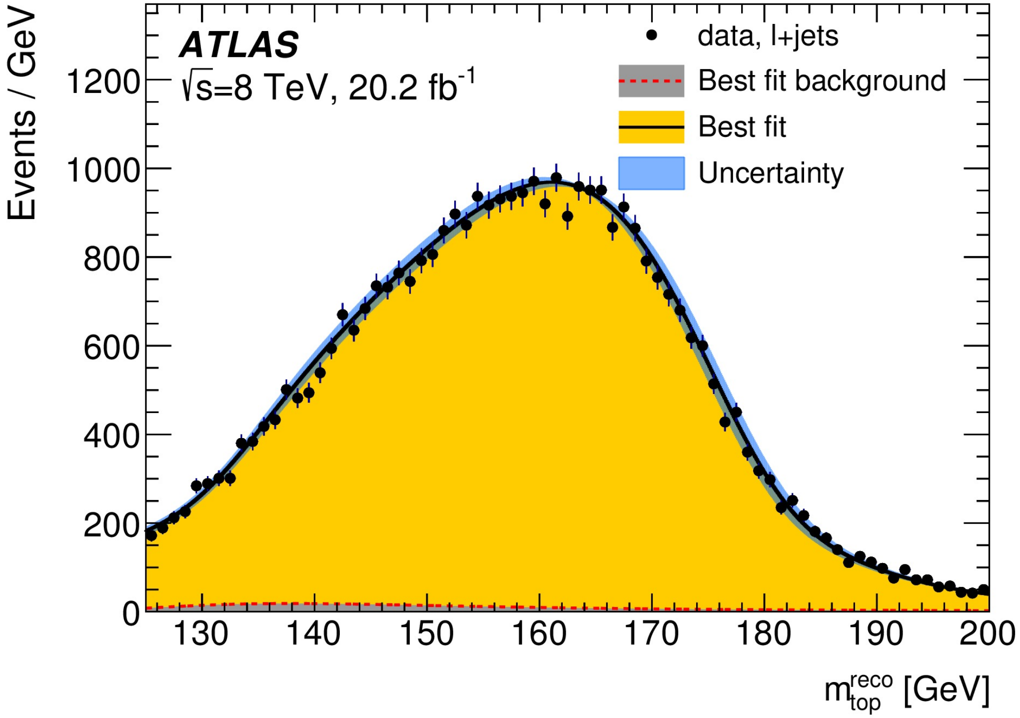


The top quark mass

Tevatron: $m_t = 174.30 \pm 0.35$ (stat) ± 0.54 (syst) GeV = 174.30 ± 0.65 GeV

LHC: it is a top factory, unique opportunity for top quark precision physics

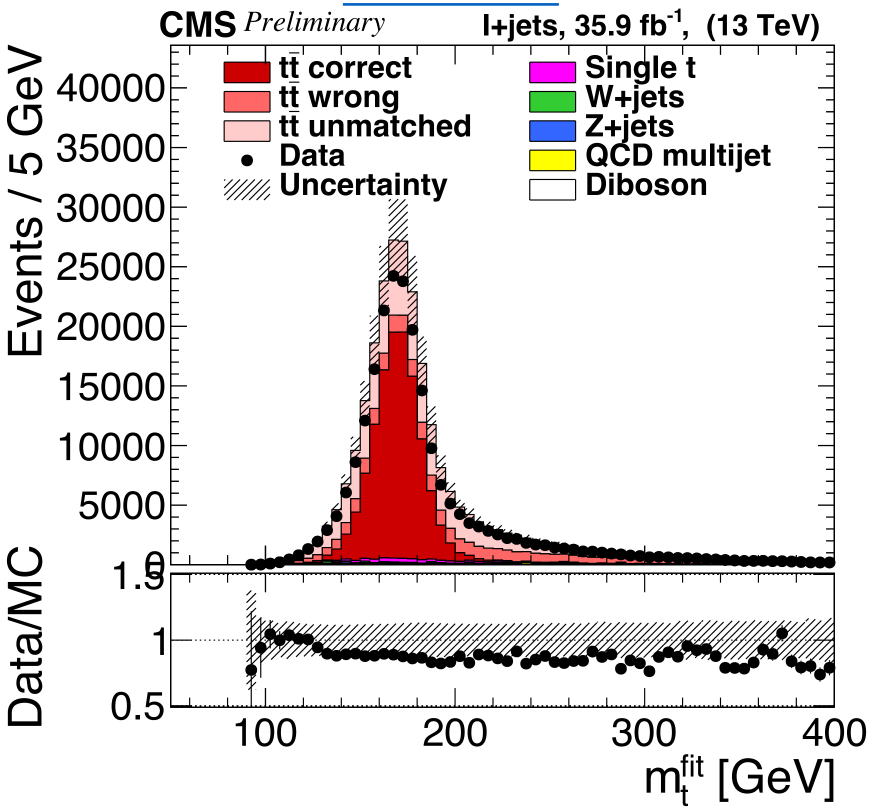
Eur. Phys. J. C



ATLAS combination √s = 7 and 8 TeV:
172.69 ± 0.25 (stat) ± 0.41 (syst) GeV

new ATLAS direct measurement at √s = 13 TeV: see next slide

TOP-20-008



CMS latest lepton+jet analysis √s = 13 TeV:
171.77 ± 0.38 GeV (0.04 GeV stat. included)

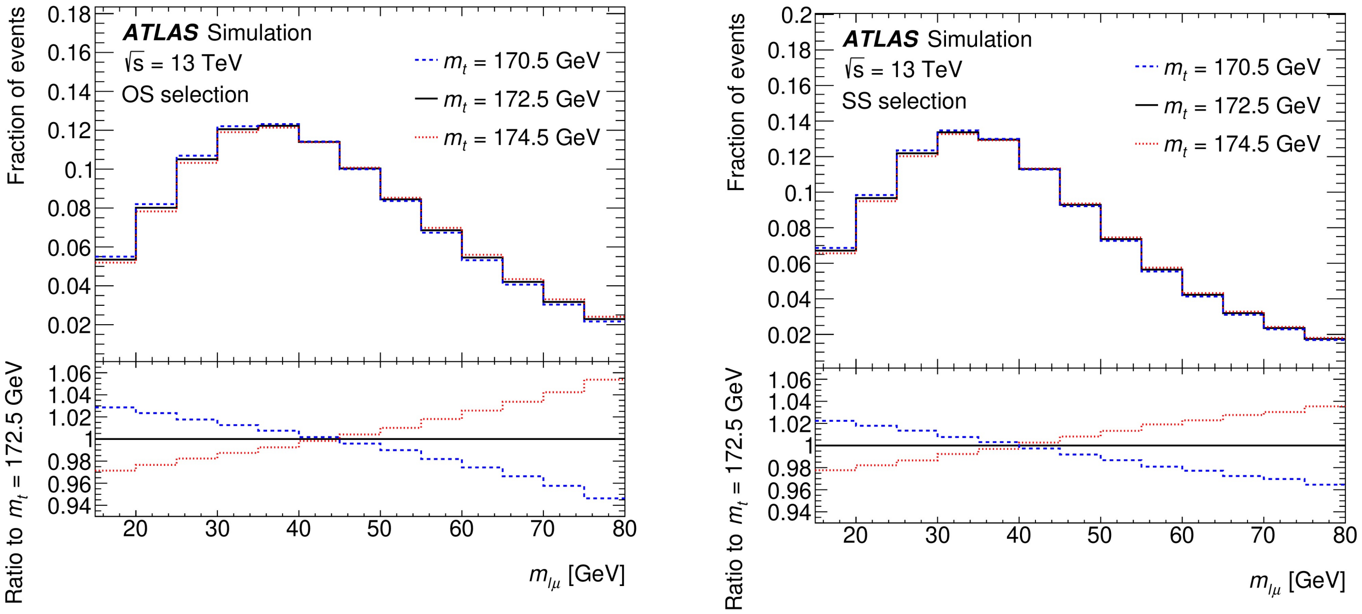
The top quark mass

Tevatron: $m_t = 174.30 \pm 0.35$ (stat) ± 0.54 (syst) GeV $= 174.30 \pm 0.65$ GeV

LHC: it is a top factory, unique opportunity for top quark precision physics

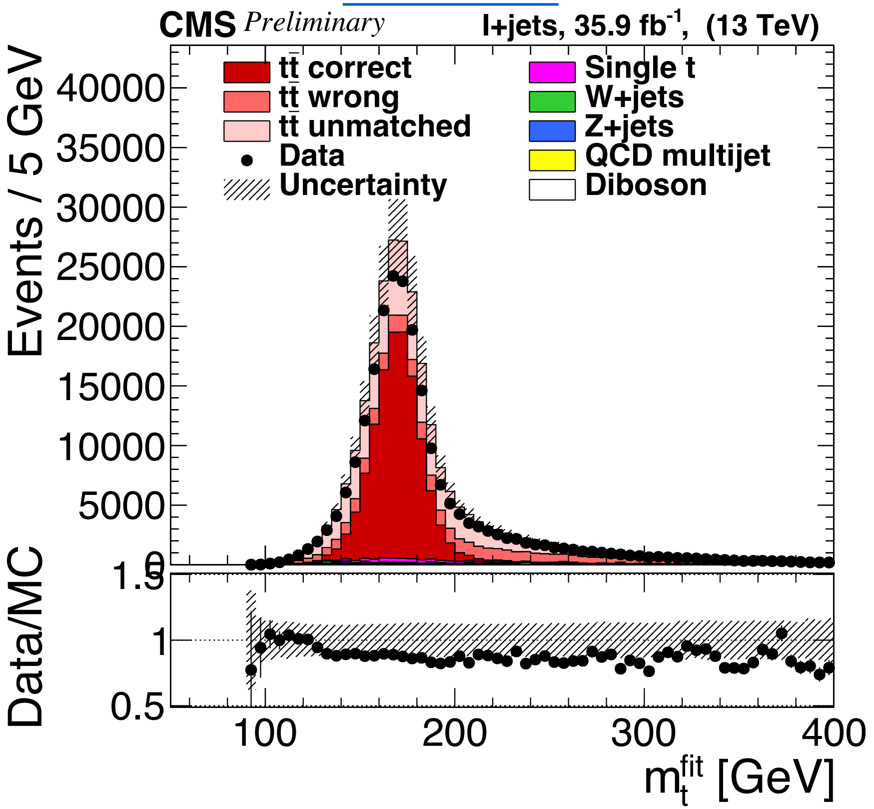
new ATLAS direct measurement at √s = 13 TeV:

$t \rightarrow Wb \rightarrow l + \mu + \dots$ **$L = 36.1\ \mathrm{fb}^{-1}$** Submitted to JHEP



$m_t = 174.41 \pm 0.39$ (stat) ± 0.66 (syst) ± 0.25 (recoil) GeV

TOP-20-008



CMS latest lepton+jet analysis √s = 13 TeV:
171.77 ± 0.38 GeV (0.04 GeV stat. included)

The W mass

The electroweak gauge sector of the Standard Model is constrained by three precisely measured parameters

$$
\begin{aligned}
\alpha &= 1/137.035999139(31) \\
G_F &= 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2} \\
m_Z &= 91.1876(21)\ \mathrm{GeV}
\end{aligned}
$$

At tree level, other EW parameters can be expressed as

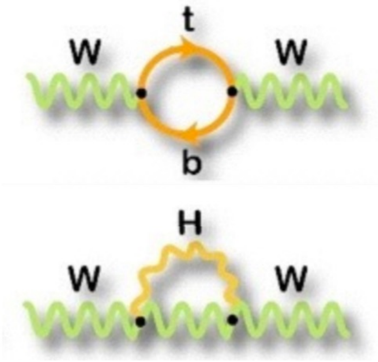
$$
\left\{
\begin{aligned}
m_W^2 &= \frac{\pi\alpha}{\sqrt{2}G_F\left(1 - m_W^2/m_Z^2\right)(1-\Delta r)} \\
\sin^2_{\mathrm{eff}}\theta_W &= \left(1 - \frac{m_W^2}{m_Z^2}\right)\kappa \\
\Gamma_W &= \frac{3G_F m_W^3}{2\sqrt{2}\pi}\rho
\end{aligned}
\right.
$$

Higher order corrections modify these relations, and determine sensitivity to other particle masses and couplings

by Stefano Camarda

the W mass

Radiative corrections Δr to m_W are dominated by top quark and Higgs boson loops



$$m_W = 80.3799 - 0.05429 \ln (m_H/100\ \mathrm{GeV}) + 0.5256[(m_t/174.3\mathrm{GeV})^2-1] + \ldots\ (\mathrm{GeV})$$

https://arxiv.org/abs/0811.0009

The relation between m_t, m_H and m_W provides a stringent test of the SM

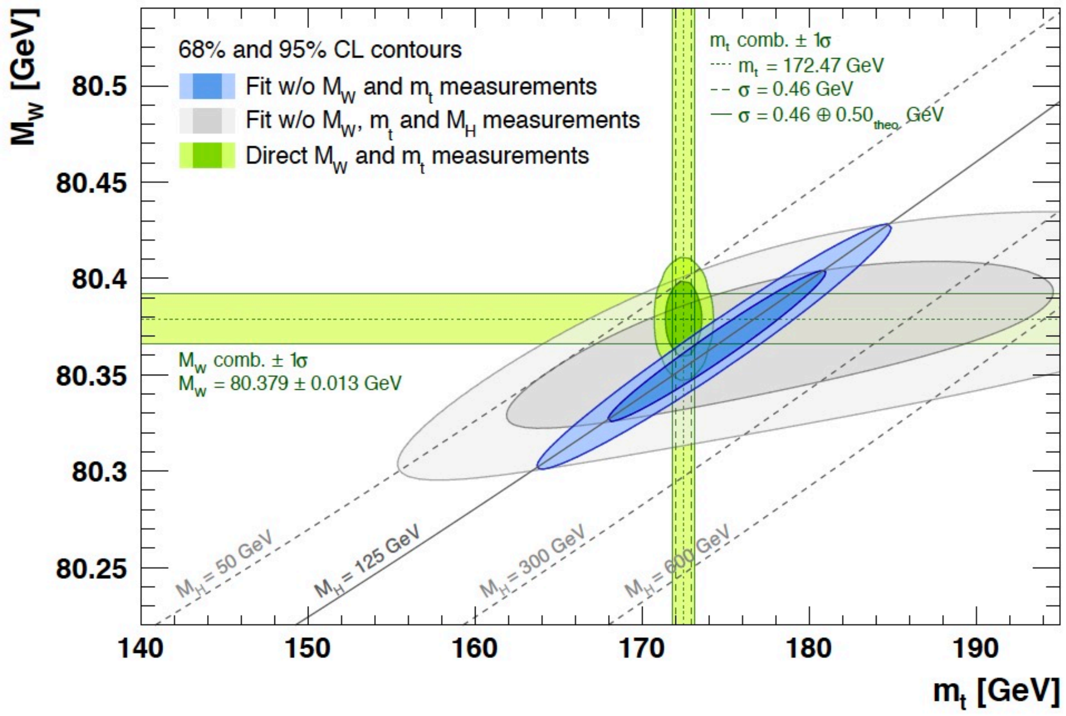
SM fit without the W mass: m_W = 80354 ±7 MeV

Pre-LHC combined m_W measurements :

LEP m_W = 80376 ± 33 MeV

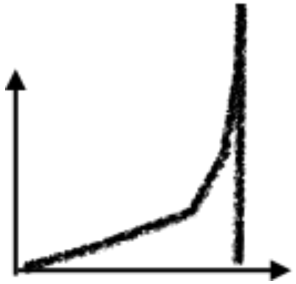
Tevatron m_W = 80387 ± 16 MeV

arXiv 1803.01853



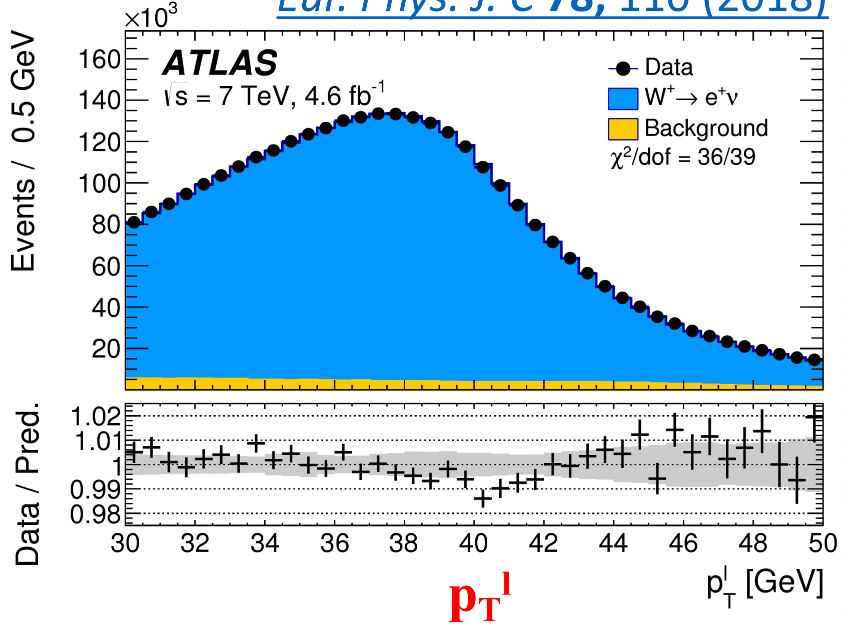
m_W measurement strategy at hadron colliders

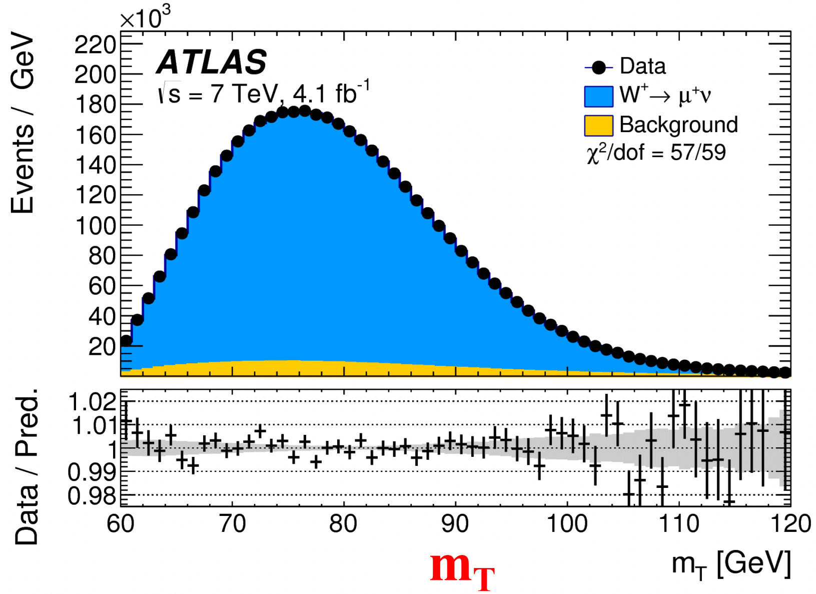
- At Leading Order, the lepton transverse momentum p_T^l has a Jacobian peak at $m_W/2$, the transverse mass m_T has an endpoint at m_W
- Different effects modify the reconstructed p_T^l and m_T distributions:
  - initial and final state radiation (QED);
  - the W boson p_T^W distribution (QCD);
  - the detector response.
- Method:
  Fit the distribution of p_T^l and m_T using MC templates generated with different m_W
  - m_T less sensitive to W boson p_T , but more sensitive to hadronic recoil
  - p_T^l not directly dependent on recoil, but more sensitive to p_T^W



LO : $d\sigma/d\cos\vartheta^* \propto (1+\cos^2\vartheta^*)$

Eur. Phys. J. C **78,** 110 (2018)



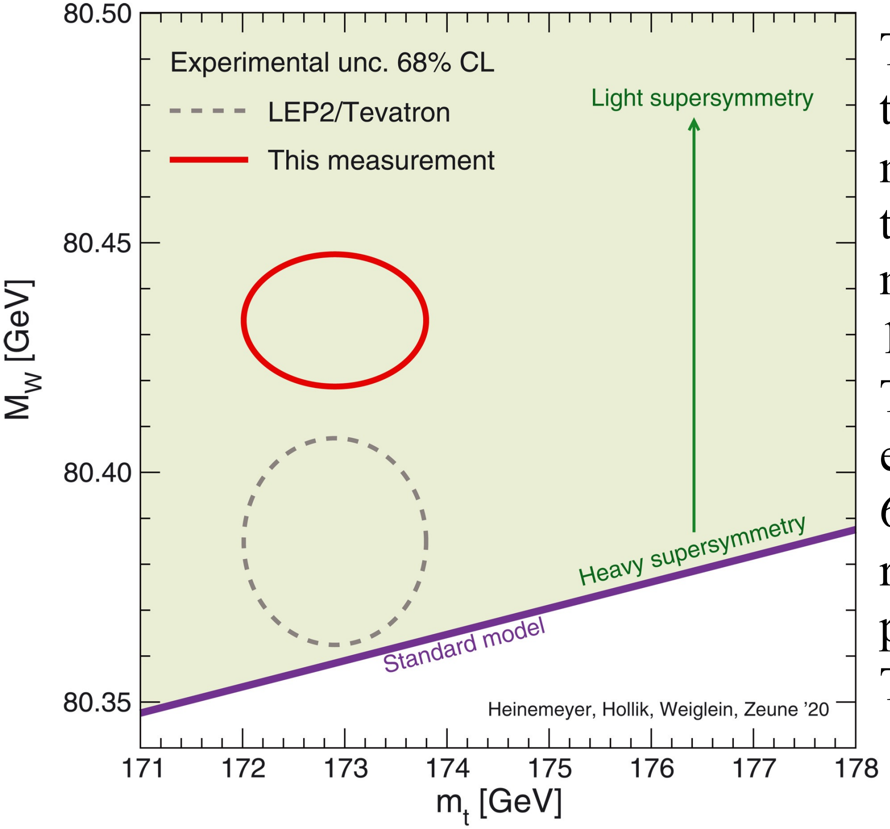


(ATLAS) m_W = 80370 ± 7 (stat.) ± 11(exp. syst.) ± 14 (mod. syst.) MeV

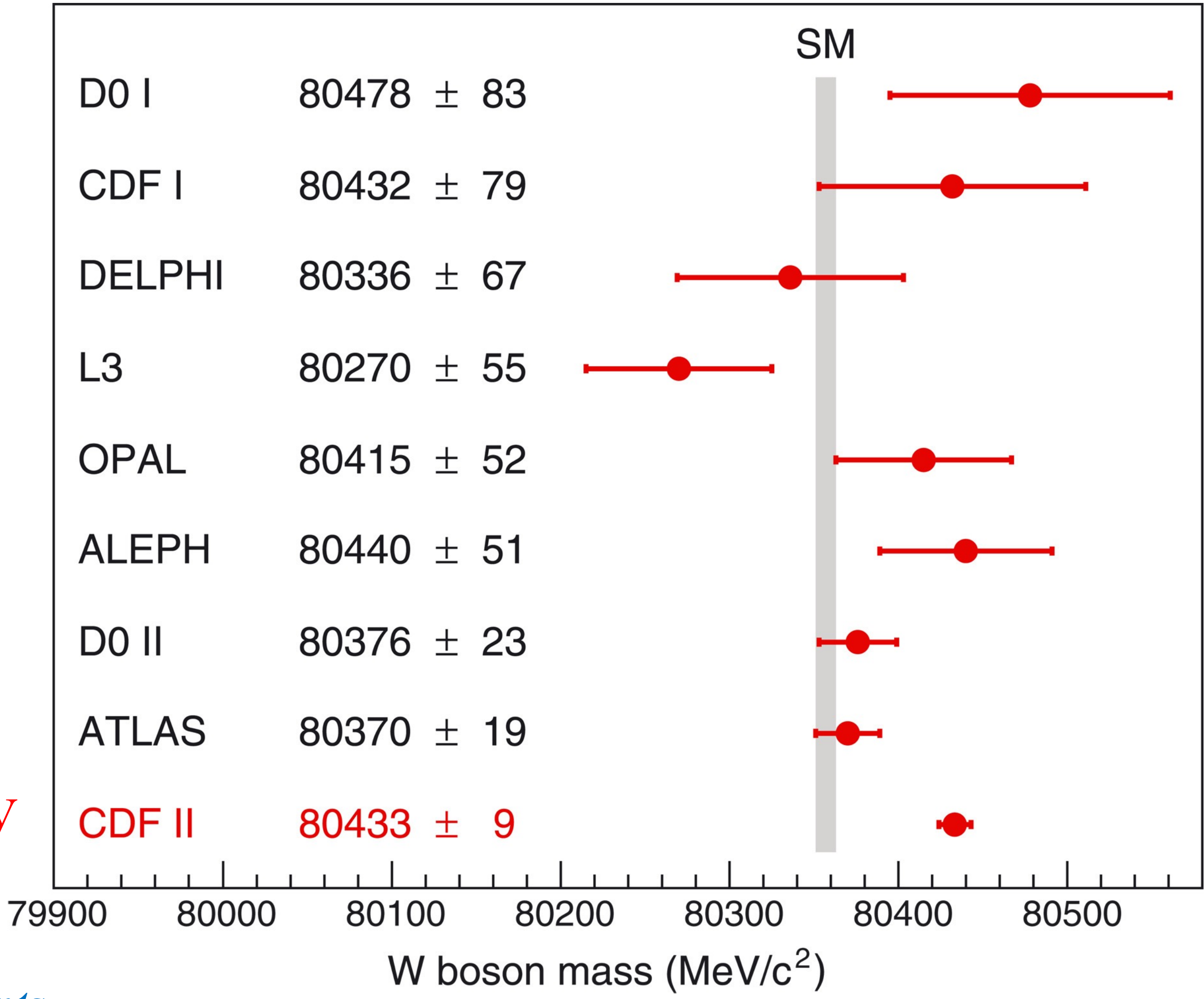
= **80370 ± 19 MeV**

the W mass: status

Science 7 Apr 2022 Vol 376, Issue 6589



The red ellipse shows the CDF II M_W measurement and the top quark mass measurement m_t= 172.89±0.59 GeV. The gray dashed ellipse shows the 68% confidence level region allowed by the previous LEP-Tevatron combination



Comparison of this CDF II measurement and past M_W measurements with the SM expectation.

m_W=80,433.5 ± 6.4(stat) ± 6.9(syst) = 80,433.5 ± 9.4 MeV

CDF II: ***This measurement is in significant tension with the standard model expectation.***

Significance of 7.0 σ and suggests the possibility of improvements to the SM calculation or of extensions to the SM.

future m_W investigations

- The W-boson mass measurement is dominating the global fit of the electroweak observables
- Impressive precision by CDF II on the W boson mass measurement, still with a large statistical component!
- The new CDF II m_W measurement shows an impressive tension with SM
- This challenges future, more precise, measurements at the LHC and at future colliders
  - CMS m_W mass measurement expected “soon”

Extended Higgs sector models - an example: the 2HDM model

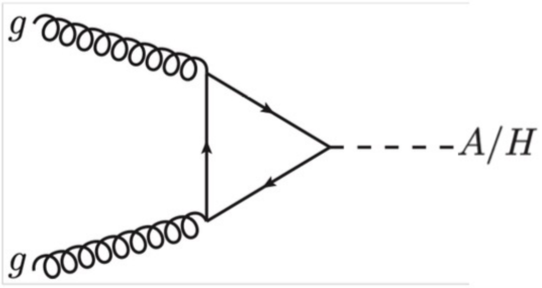
Extended Higgs sector models: the 2HDM model

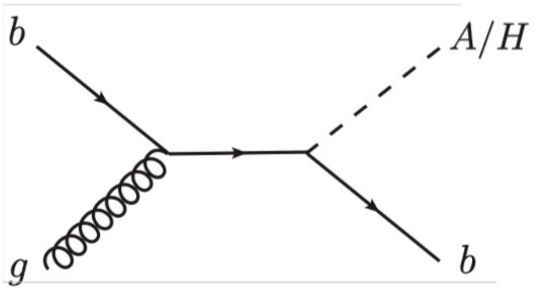
- The **two-Higgs-doublet model** (2HDM) is an extension of the Standard Model of particle physics.
- The 2HDM model is one of the natural choices for beyond-SM models containing two Higgs doublets instead of just one, as in SM.
  - There are also models with more than two Higgs doublets, for example three Higgs doublet models etc.
- In this model, we have two vacuum-expectation-values (*v.e.v.*s), vev_1 and vev_2, that give origin to five Higgs bosons:
  - **Two neutral** Higgs bosons, **CP-even**, ***H*** and ***h***, the angle α diagonalizes the mass matrix
  - **One neutral** Higgs boson, **CP-odd**, **A**
  - Two charged Higgs bosons, $H^{\pm}$
  - $vev_2/vev_1 = \tan\beta$
- In total we have six parameters (the four masses and the two angles), only two in SM

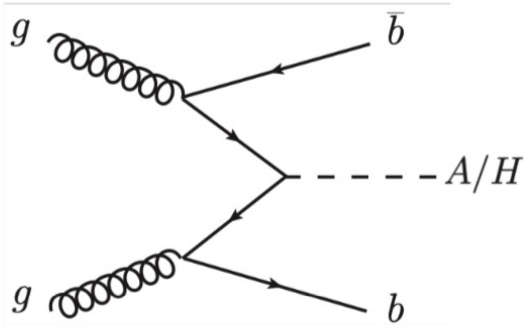
skip

Higgs production in 2HDM

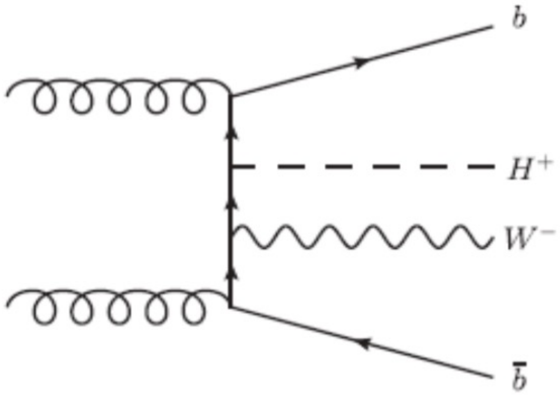
Neutral Higgs Production A/H

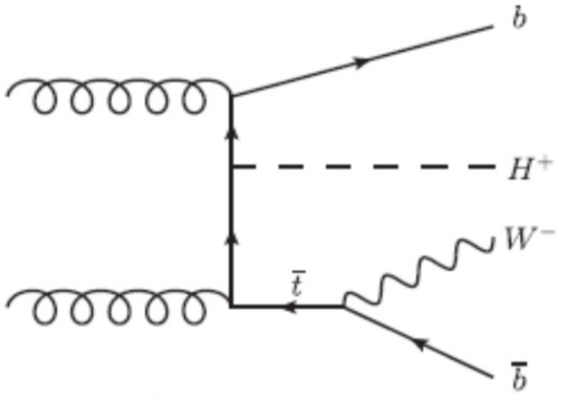


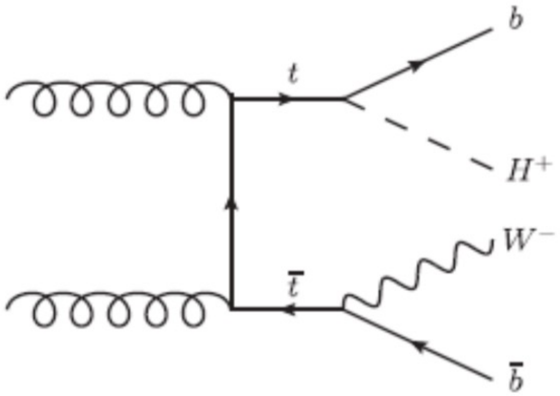




Charged Higgs Production $H^{\pm}$

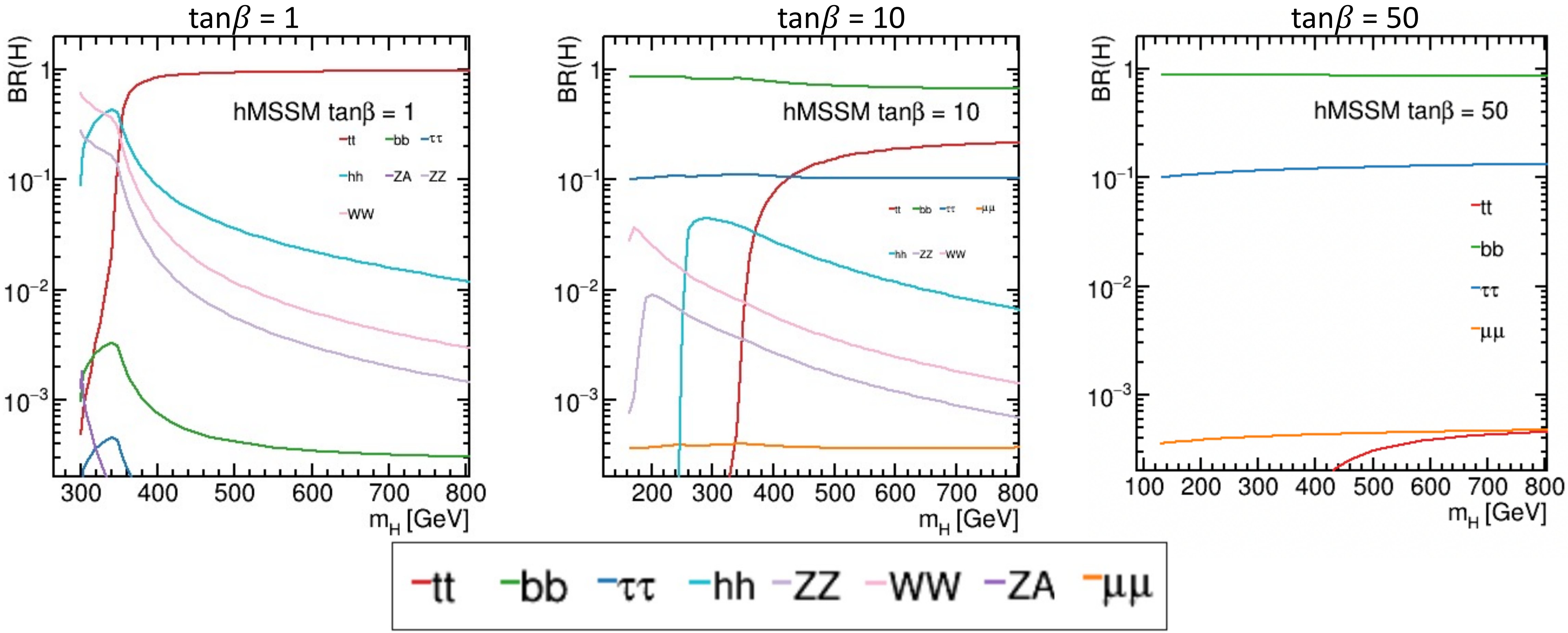






Scalar Higgs Decay

Rich phenomenology with several final states
Example benchmark hMSSM



tanβ = 1

tanβ = 10

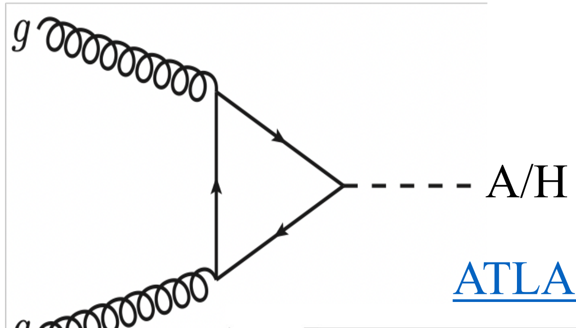
tanβ = 50

[Handbook of LHC Cross Sections: 4. Deciphering the Nature of the Higgs Sector](#)

[Talk by Verena Martinez Outschoorn](#)

[Handbook of LHC Cross Sections: 3. Higgs Properties](#)

A/H → $\gamma\gamma$

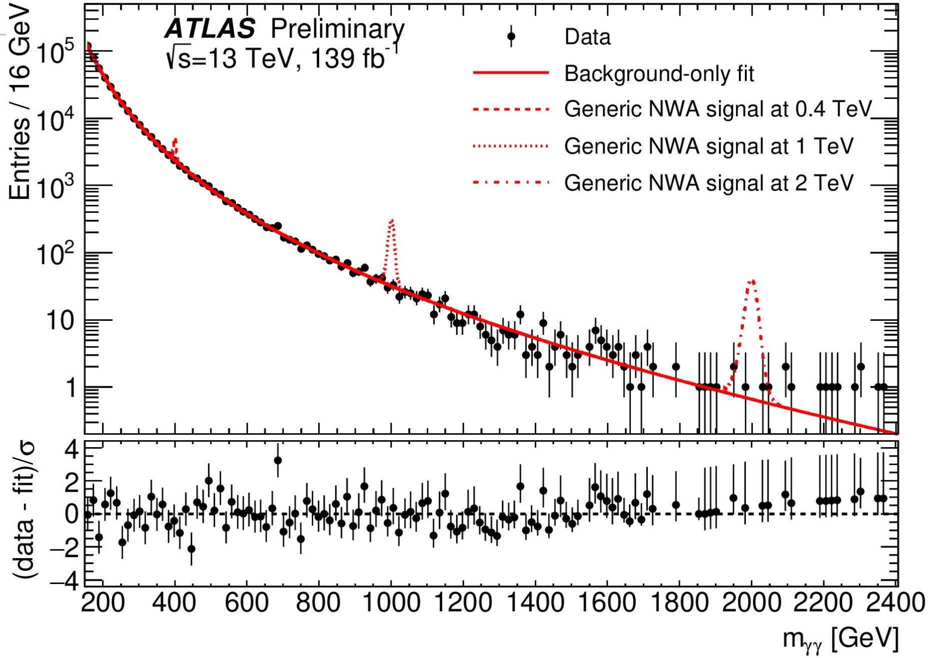


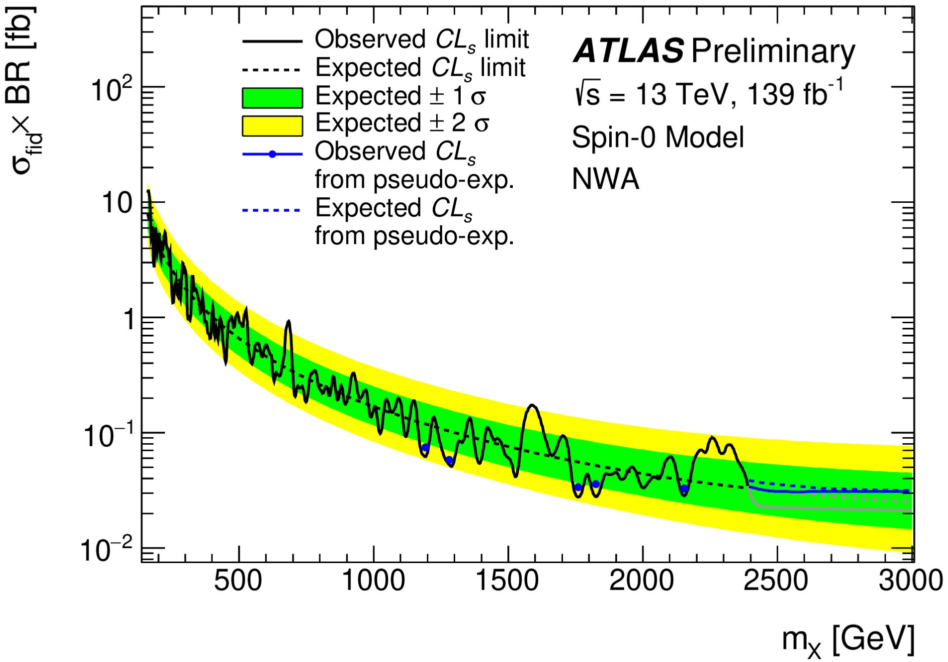
Search for high mass resonance – excellent resolution of diphoton pair

Study the $m_{\gamma\gamma}$ distribution

ATLAS-CONF-2020-037

Full Run 2
Dataset 139 fb^{-1}





Signal: double-sided crystal ball

Background: **power-law functional form - choice of function & systematics from MC templates**

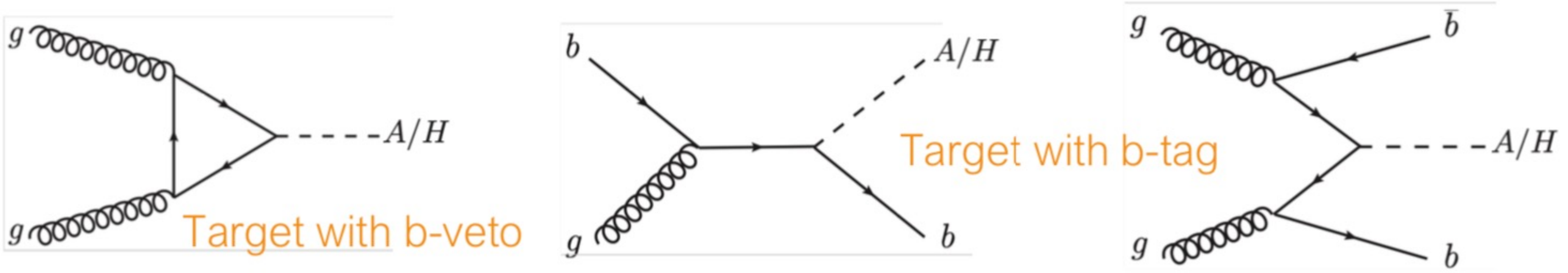
Narrow & large widths also considered (up to $\Gamma_X / m_X = 10\%$)

spin-0 resonance search: observed 95% CL upper limits on the fiducial cross section times branching ratio for a narrow-width signal range from 12.5 fb at 160 GeV to about 0.03 fb at 2800 GeV

spin-2 resonance search: spin-2 resonance search, observed limits on the total cross section times branching ratio for k/MPl = 0.1 range from 3.2 fb to about 0.04 fb for a graviton mass between 500 and 5000 GeV

A/H→ττ

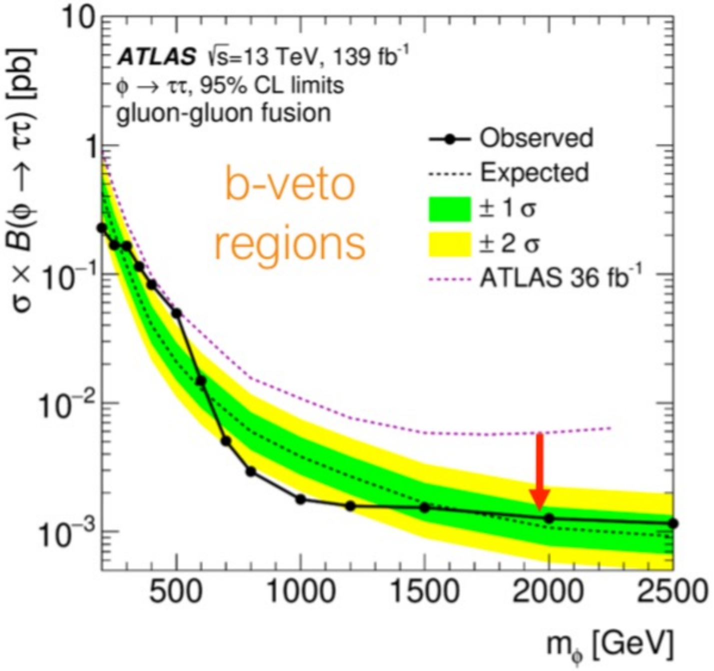
Full Run 2
Dataset 139 fb^{-1}



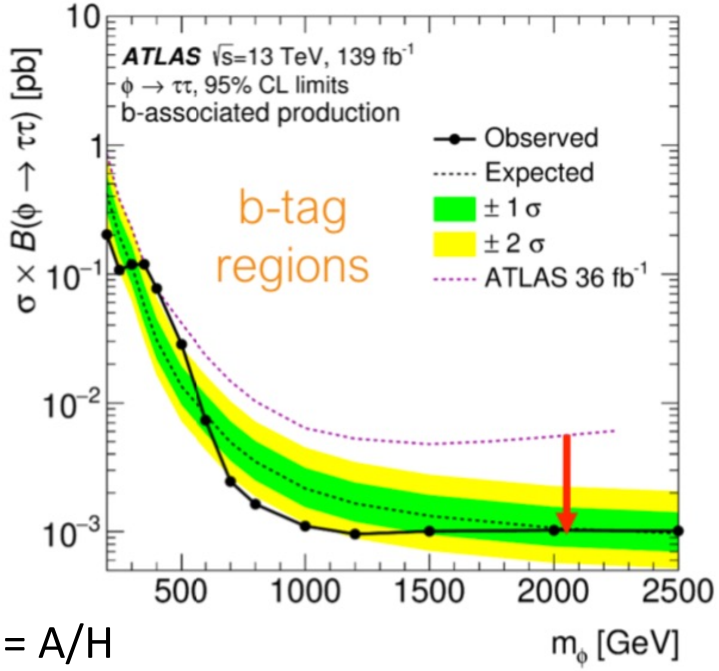
Target with b-veto

Target with b-tag

Key channel in several new physics scenarios such as 2HDM (MSSM) with large tanβ



b-veto regions



b-tag regions

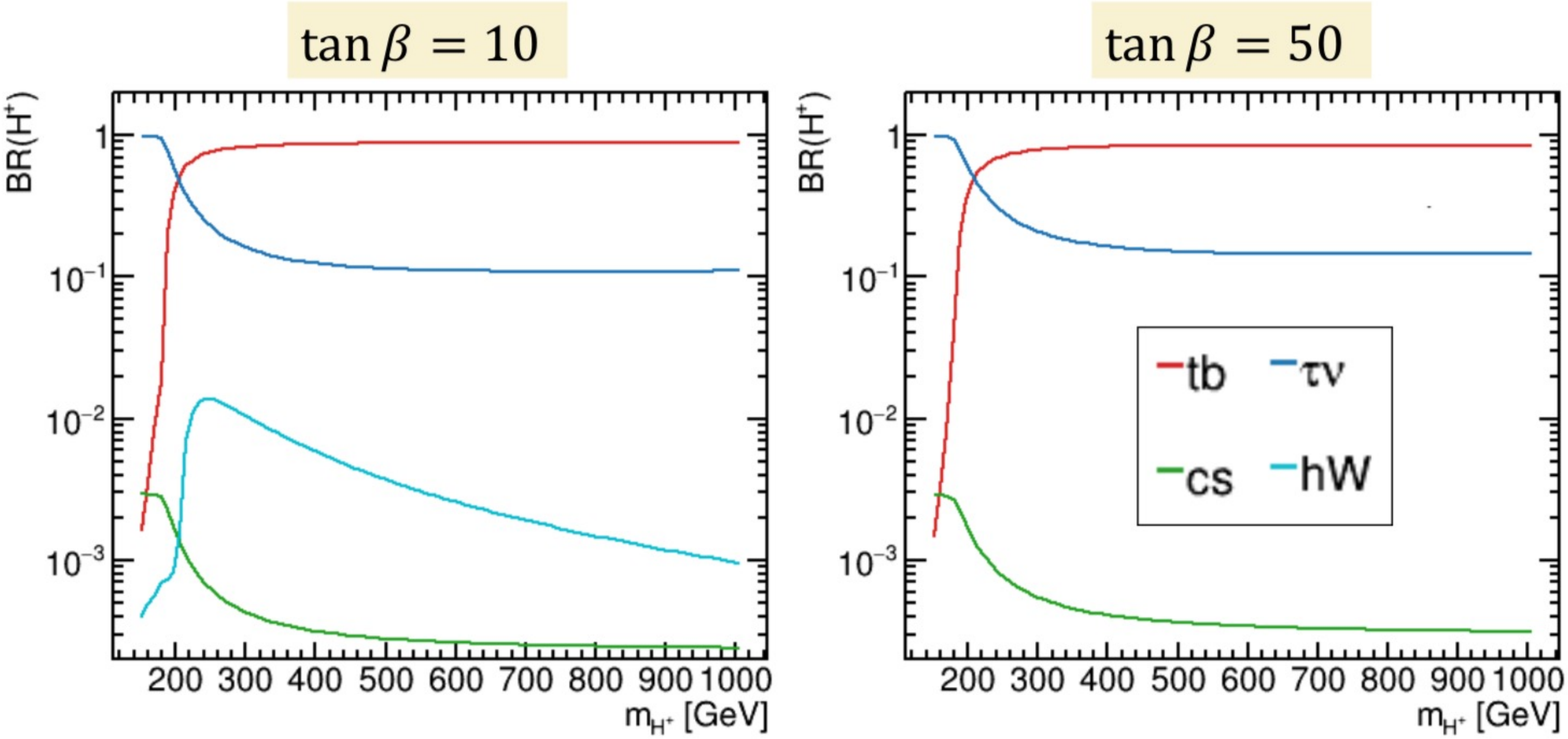
ϕ = A/H

Higher sensitivity due to increased luminosity, improved tau ID and optimization

PRL 125 (2020) 051801

Charged Higgs Decay

- *BR H*$^{\pm}$ - depends strongly on tanβ and m$^{H\pm}$



$\tan\beta = 10$

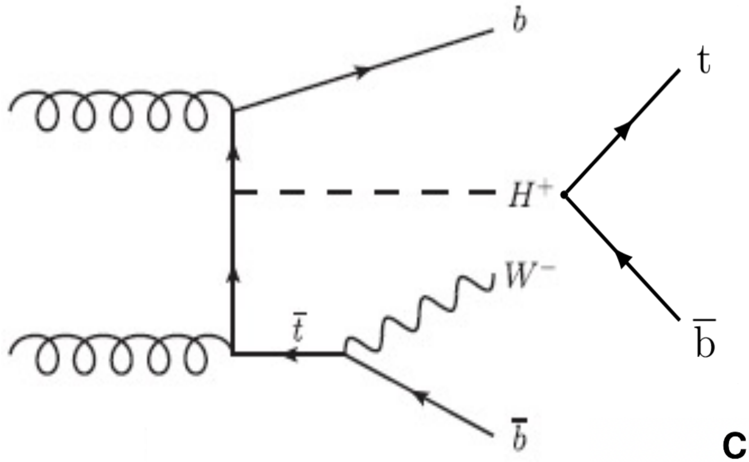
$\tan\beta = 50$

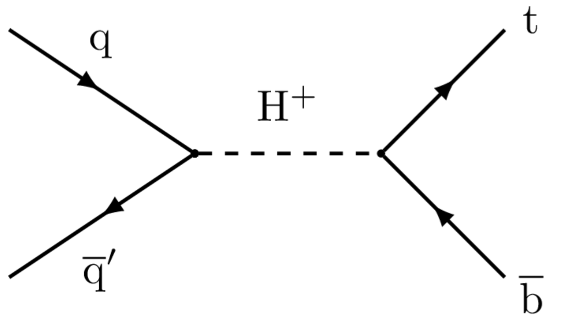
[Handbook of LHC Cross Sections: 4. Deciphering the Nature of the Higgs Sector](#)

[Talk by Verena Martinez Outschoorn](#) [Handbook of LHC Cross Sections: 3. Higgs Properties](#)

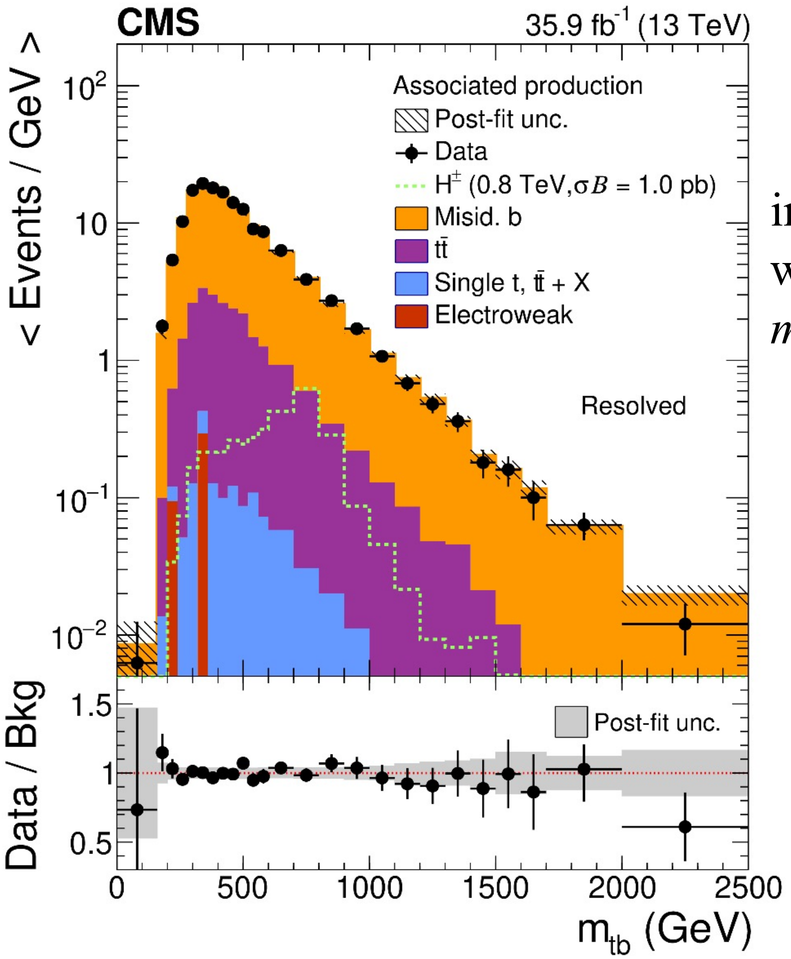
$H^+ \rightarrow tb$ in the all-Hadronic Channel

Key channel in several new physics scenarios such as 2HDM (MSSM) at high H^+ mass

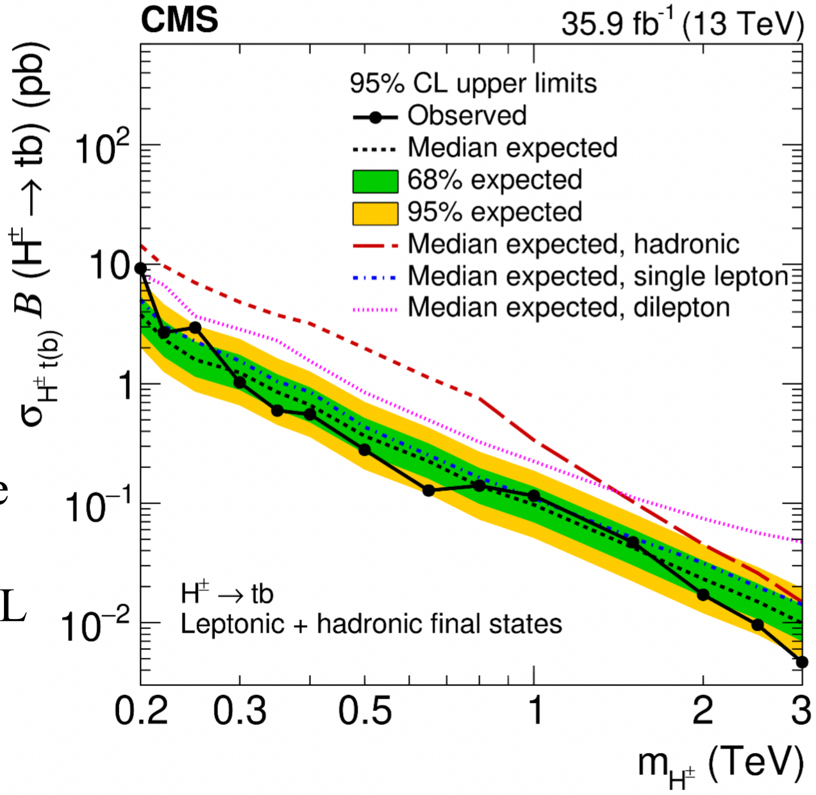




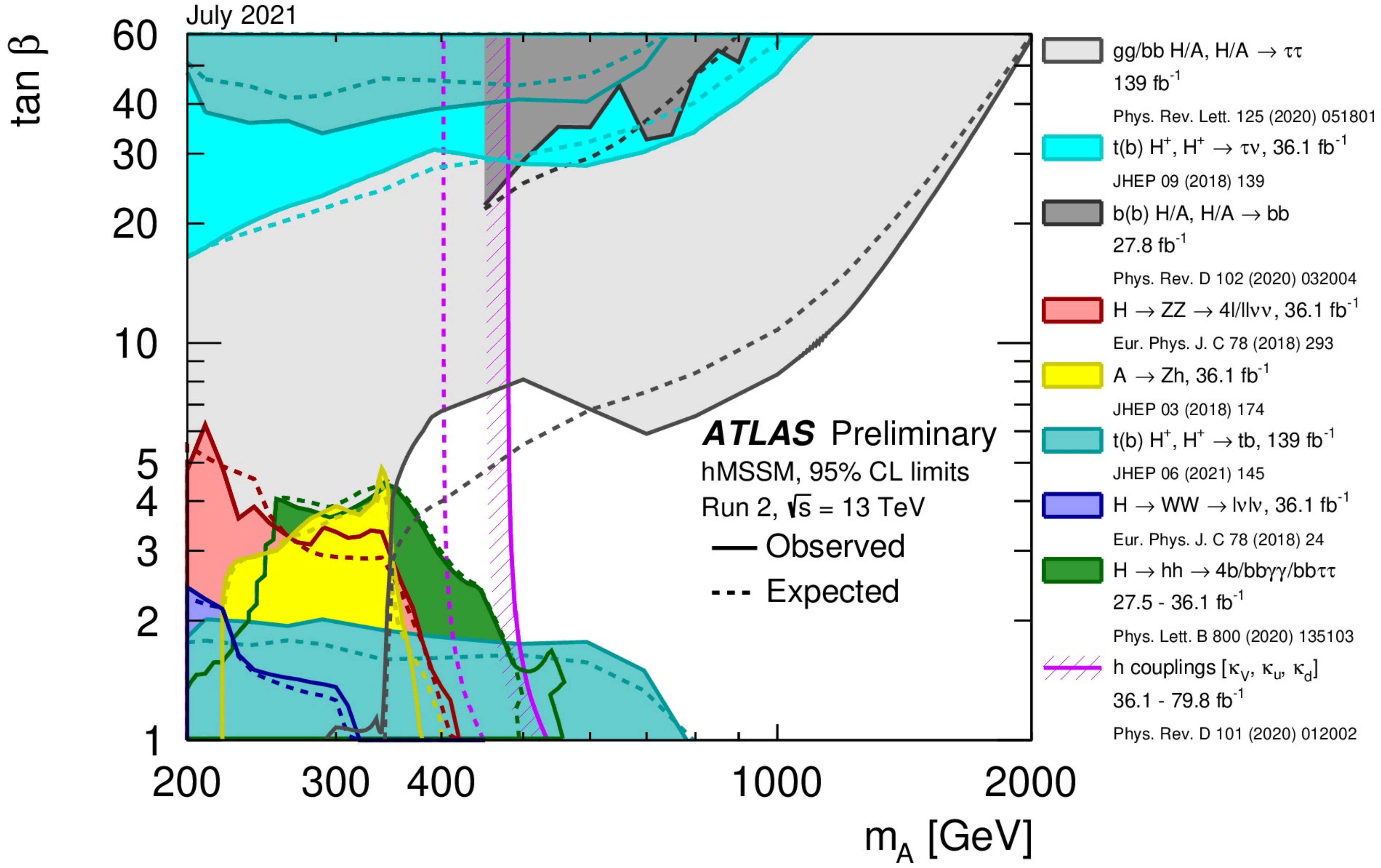
JHEP 07 (2020) 126



invariant mass of the $H^\pm$ candidates, with the expected signal shown for $m_{H\pm}$= 0.8 TeV.



No significant deviation is observed above the expected standard model background. Model-independent upper limits at 95% CL on the cross section times branching fraction $\sigma_{H\pm tb}$ as function of $m_{H\pm}$



Regions of the $[m_A , \tan\beta]$ plane excluded in the hMSSM via direct searches for heavy Higgs bosons

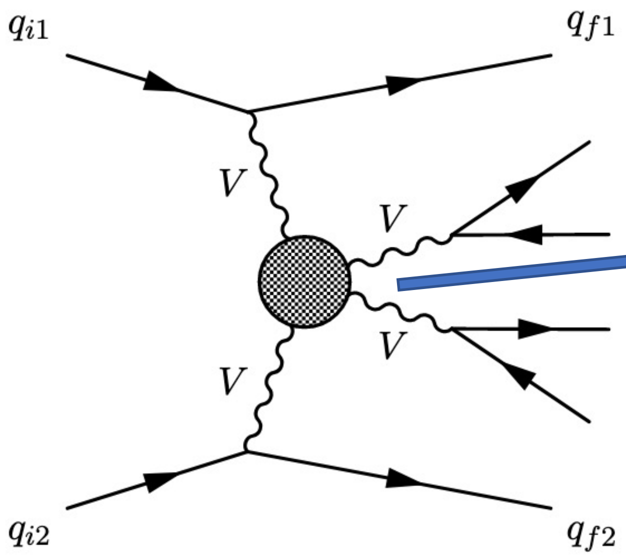
Vector Boson Scattering

Vector Boson Scattering

- Observation of the Higgs boson
  - Consistent with SM, within current uncertainties
  - W and Z acquire longitudinal polarization via the Brout-Englert-Higgs mechanism

- In Standard Model, the Higgs boson regularizes the Vector Boson Scattering (VBS) process at high energies, in particular the longitudinally polarised vector W^+_L-W^+_L scattering

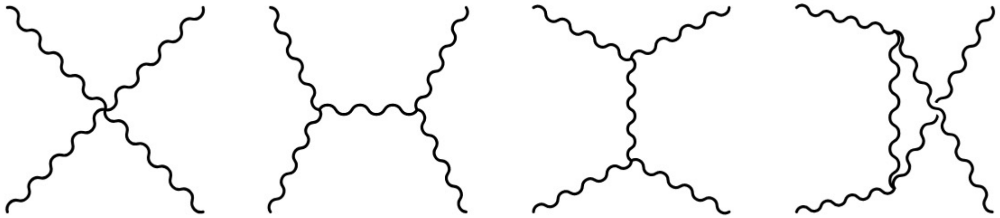
With no Higgs boson, the VBS process diverges with increasing energy



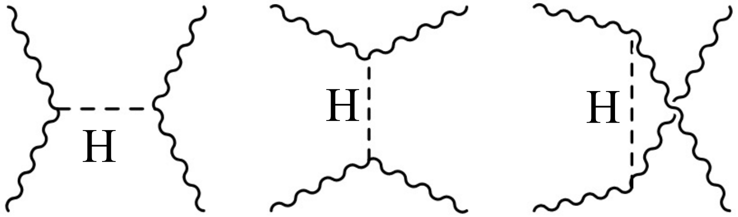
Vector Boson Scattering

diagram with quartic gauge coupling

diagrams with triple-gauge couplings



(a) Contributions from electroweak gauge boson interactions.



Higgs exchange contribution

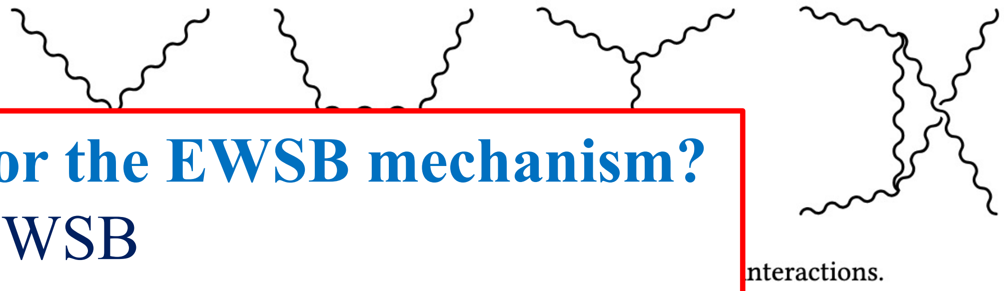
Vector Boson Scattering

- Observation of the Higgs boson
  - Consistent with SM, within current uncertainties
  - W and Z acquire longitudinal polarization via the Brout-Englert-Higgs mechanism
- In Standard Model, the Higgs boson regularizes the Vector Boson Scattering (VBS) process at high energies, in particular the longitudinally polarised vector W^+_L-W^+_L scattering

With no Higgs boson, the VBS process diverges with increasing energy

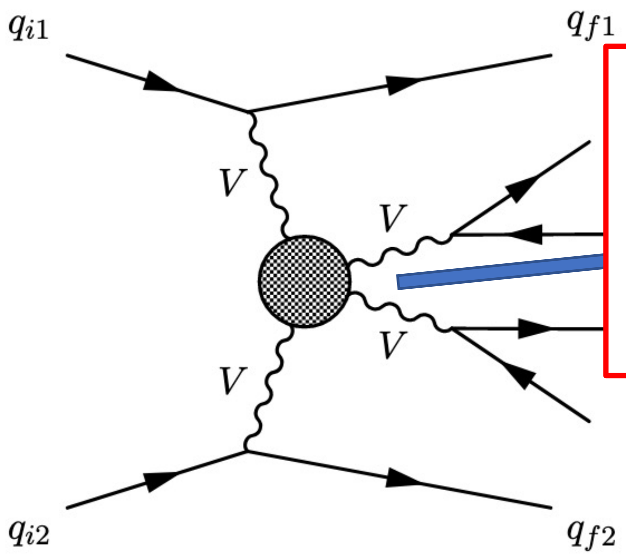
diagram with quartic gauge coupling

diagrams with triple-gauge couplings

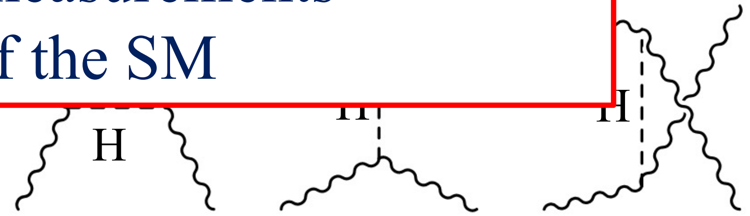


Is the Higgs the only player for the EWSB mechanism?

- VBS is key process to test EWSB
- Complementary to direct Higgs measurements
- Precision needed to careful test of the SM



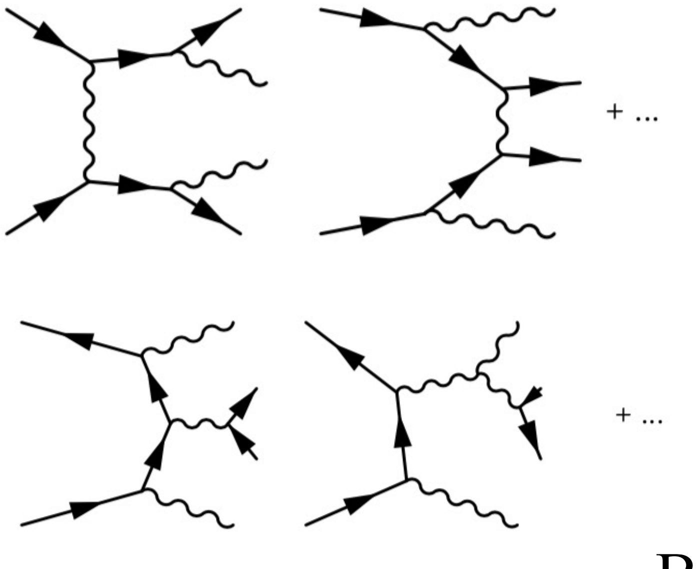
Vector Boson Scattering



Higgs exchange contribution

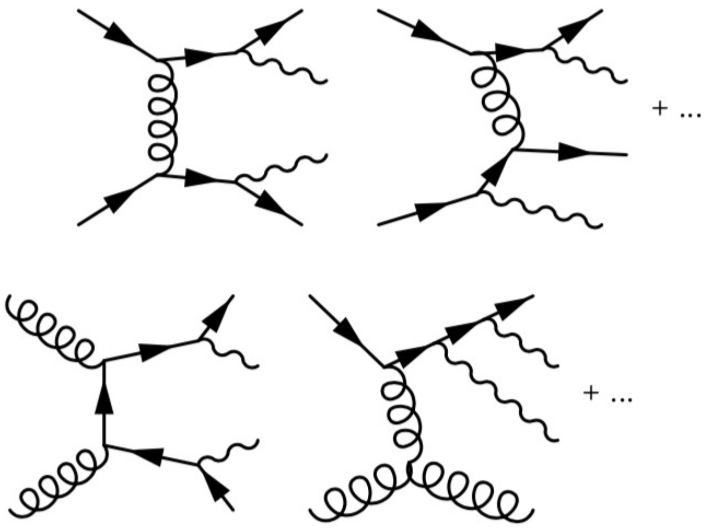
Other diboson production processes

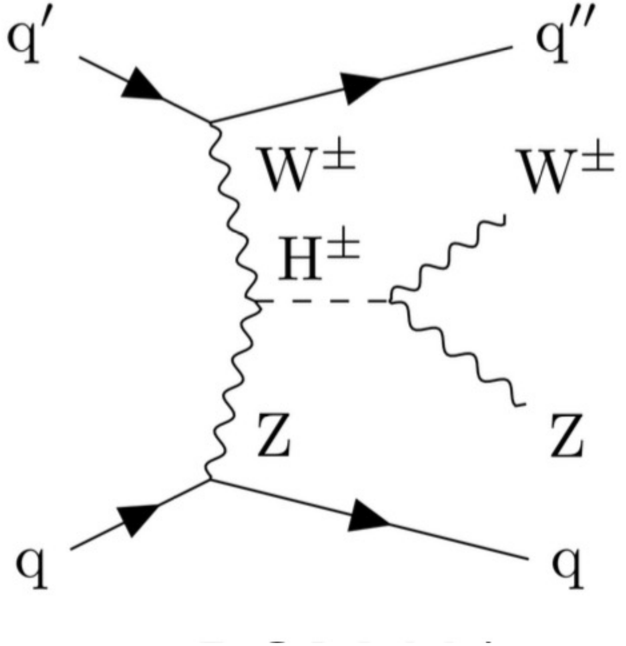
VVjj Electroweak processes



Background processes

VVjj QCD processes





Example of BSM process mediated by H±

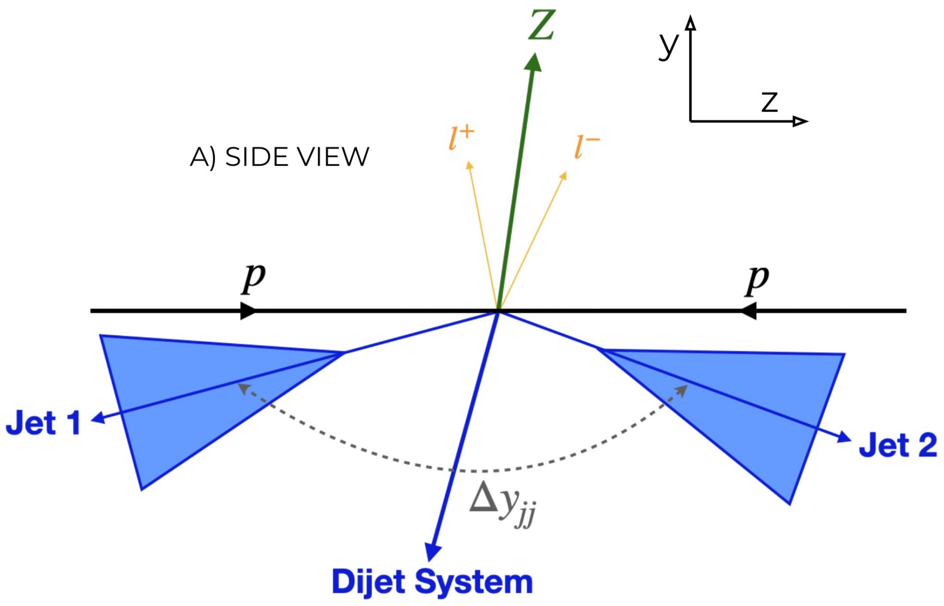
Experimental signature

- Event topology
  - – 2 vector bosons produced centrally
  - – 2 energetic forward jets in opposite hemispheres
  - – Large m_{jj} and $\Delta|\eta|_{jj}$
- Signature defined on diboson final state
- – Fully leptonic: up to 4 e/μ + 2 jets

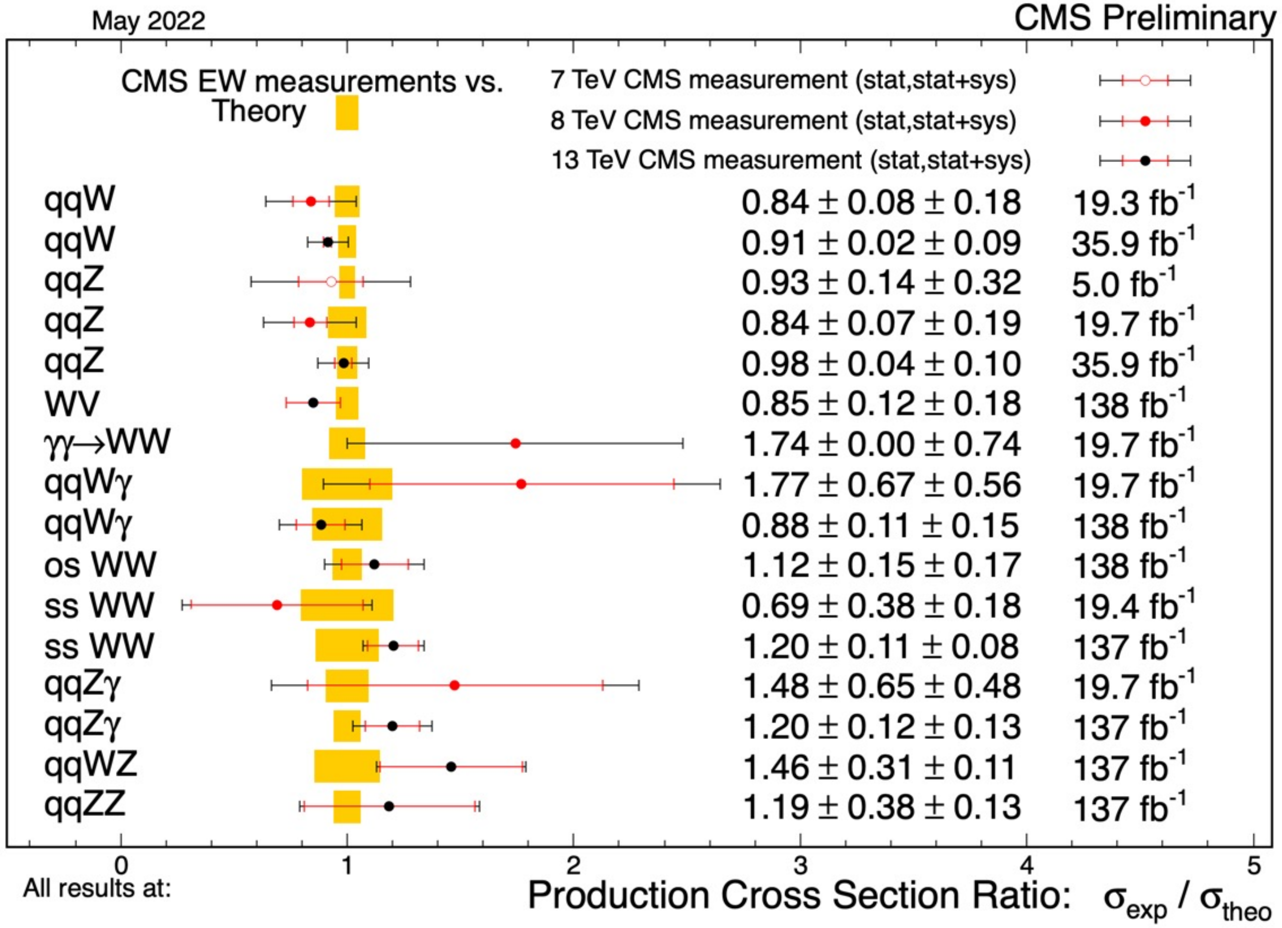
– Semi-leptonic/hadronic: 1(2) e/μ + jets

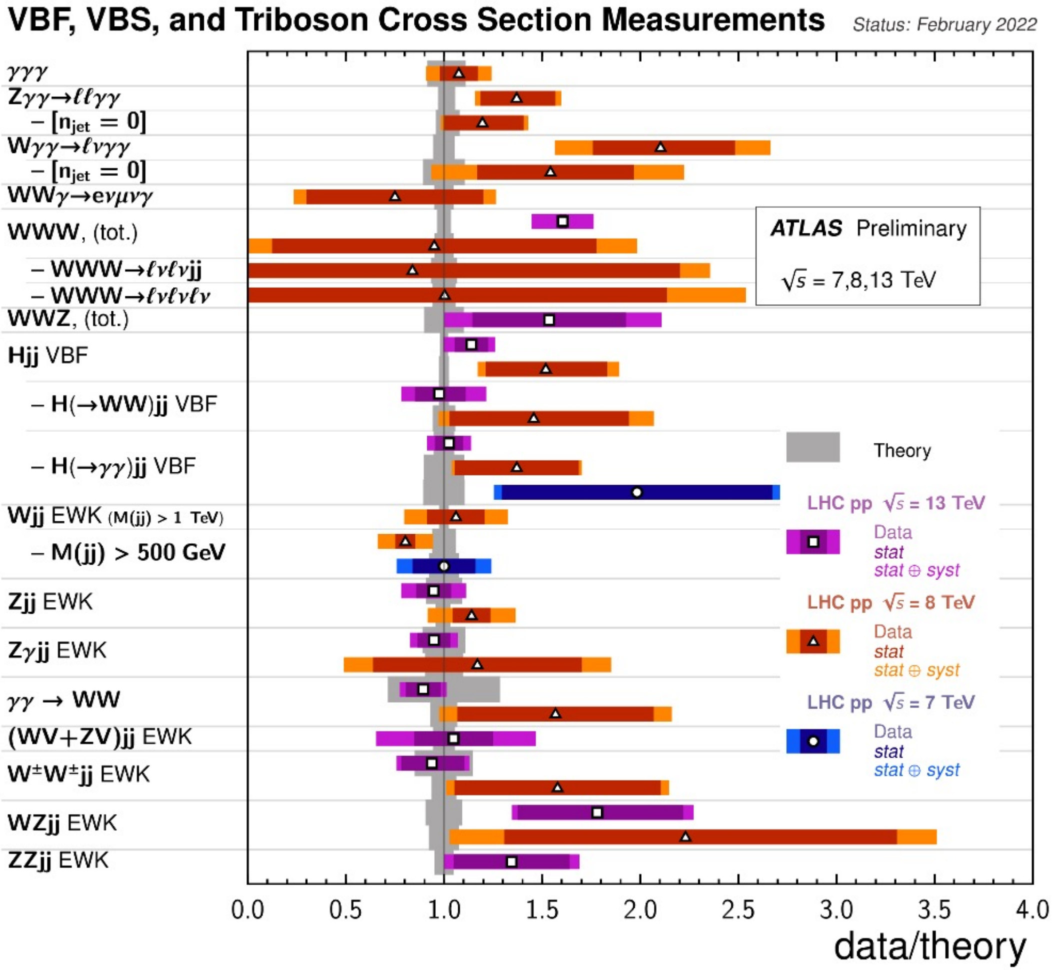
– Fully hadronic: 4 or 6 jets

- Tree-level contributions to final state
  - – EWK: signal component $O(\alpha_{\mathrm{EW}}^4)$
  - – QCD: background, $O(\alpha_{\mathrm{EW}}^2\,\alpha_s^2)$, suppressed at high m_{jj}, high $\Delta|\eta|_{jj}$ region
  - – Interference: O(%) of signal



Cross section summary





- Good agreement with SM
- Important to model QCD contribution

The LHC Luminosity Upgrade
-
Higgs prospects

The LHC luminosity upgrade: HL-LHC

by Frédérick Bordry

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation **beyond 2025 and up to 2035**

Devise beam parameters and operation scenarios for:

enabling a total integrated luminosity of **3000 fb^{-1}**

implying an integrated luminosity of **250-300 fb^{-1} per year**,

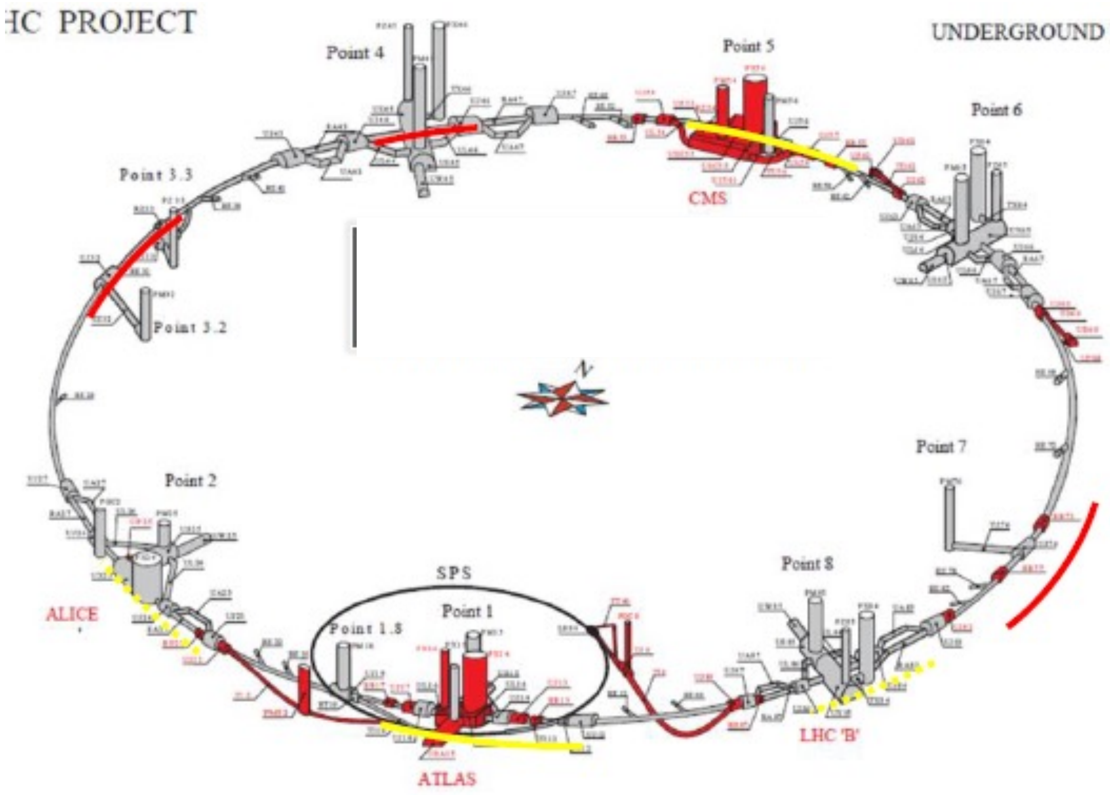
design for **$\mu \sim 140$ (~ 200)** (➔ peak luminosity of **5 (7) 10^{34} cm^{-2} s^{-1}**)

design equipment for 'ultimate' performance of **7.5 10^{34} cm^{-2} s^{-1}** and **4000 fb^{-1}**

=> Ten times the luminosity reach of first 10 years of LHC operation

Furthemore…$\sqrt{s}$: 14 TeV

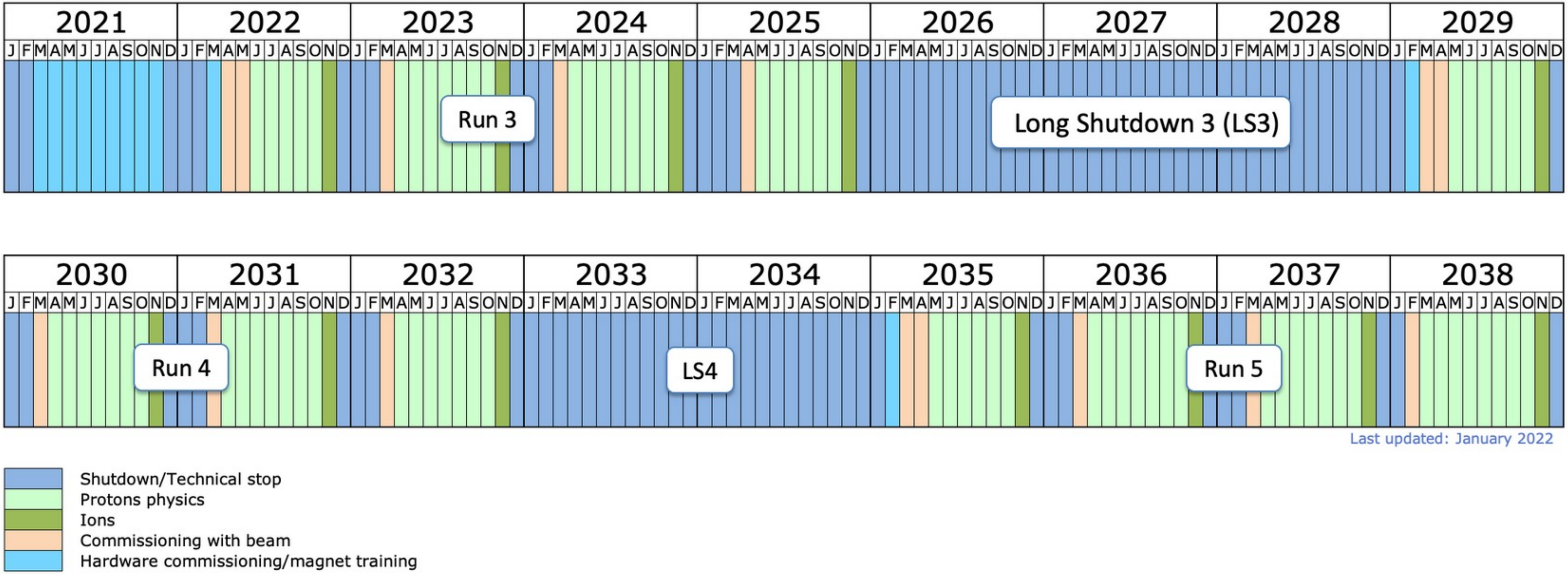
The HL-LHC Project



- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

The LHC / HL-LHC timeline

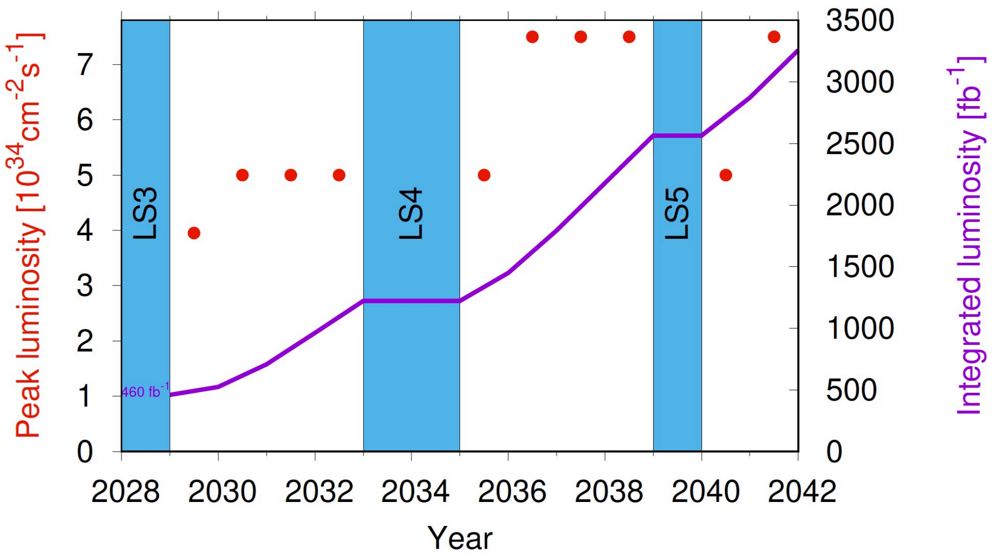


Last updated: January 2022

by Mike Lamont
10 Years Higgs Boson Discovery

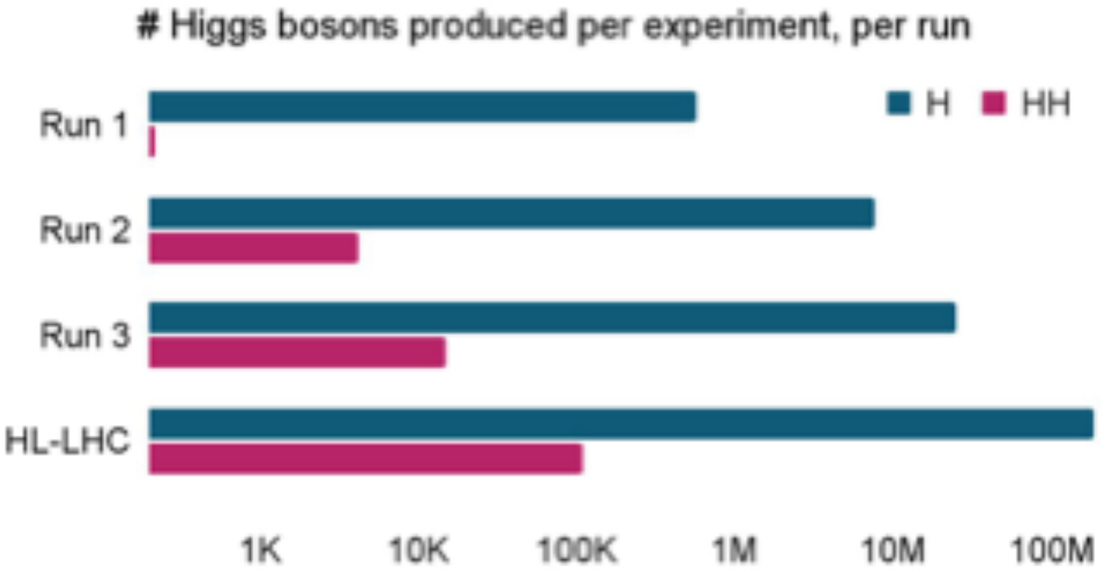
Then another miracle happens…

Year	ppb $[10^{11}]$	Virtual lumi. $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	Days in physics	θ $[\mu\text{rad}]$	β^*_{start} [cm]	β^*_{end} [cm]	CC	Max. PU
2029	1.8	4.4	90	380	70	30	exp	116
2030	2.2	9.7	120	500	100	30	on	132
2031	2.2	11.3	160	500	100	25	on	132
2032	2.2	13.5	160	500	100	20	on	132
2033-34			Long shutdown 4					
2035	2.2	13.5	140	500	100	20	on	132
2036	2.2	16.9	170	500	100	15	on	132
2036	2.2	16.9	200	500	100	15	on	200



Higgs Physics

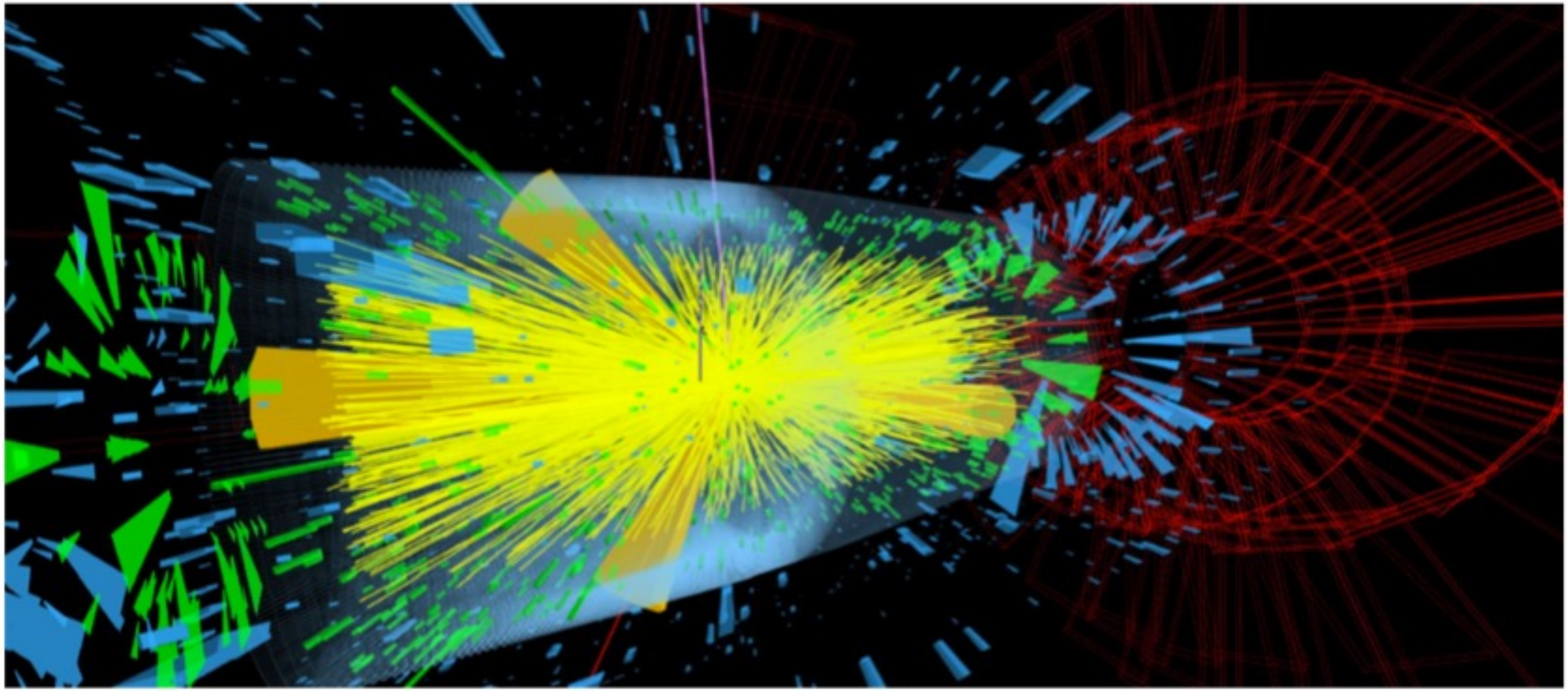
- The detailed and precision study of the mechanism of the electroweak symmetry breaking is one of the outstanding items of the high-energy physics physics program now and of the near an d far future
- The Higgs sector is key to this investigation though the analysis of the Higgs boson that includes
    - Couplings to SM particles, mass and width
    - Search for rare decays
    - HH production cross section and trilinear self-coupling
    - Possible connection to new physics
- The HL-LHC offers an unique opportunity for the next decade to perform this investigation



Cross sections from the [LHC Higgs Working Group](#)

by Elizabeth Brost - Higgs@10 Symposium - July 4th, 2022

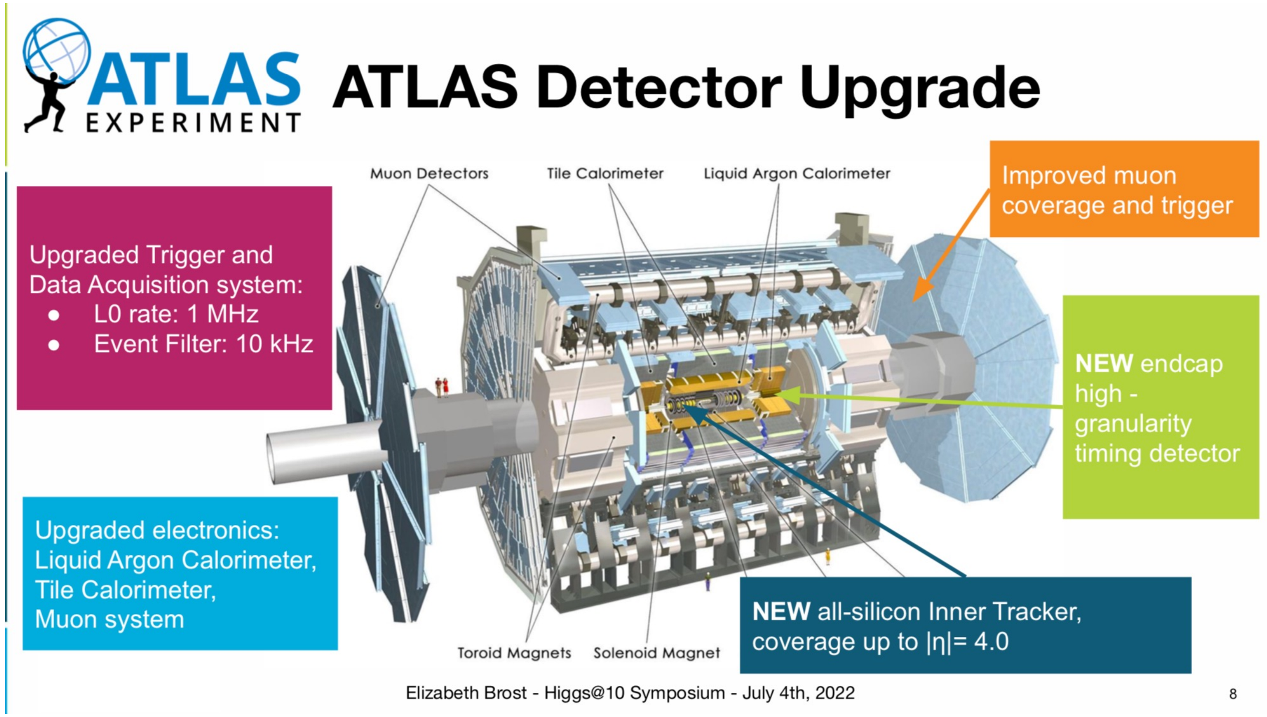
Challenge: Pileup



Simulated VBF $H \rightarrow \tau\tau$ event in CMS
(with pileup 200)

High pileup environment at the HL-LHC brings new challenges: detector irradiation, higher detector occupancy, higher trigger rates

HL-LHC Detector Upgrade



ATLAS Detector Upgrade

ATLAS EXPERIMENT

Upgraded Trigger and Data Acquisition system:

- L0 rate: 1 MHz
- Event Filter: 10 kHz

Upgraded electronics: Liquid Argon Calorimeter, Tile Calorimeter, Muon system

Improved muon coverage and trigger

NEW endcap high - granularity timing detector

NEW all-silicon Inner Tracker, coverage up to |η|= 4.0

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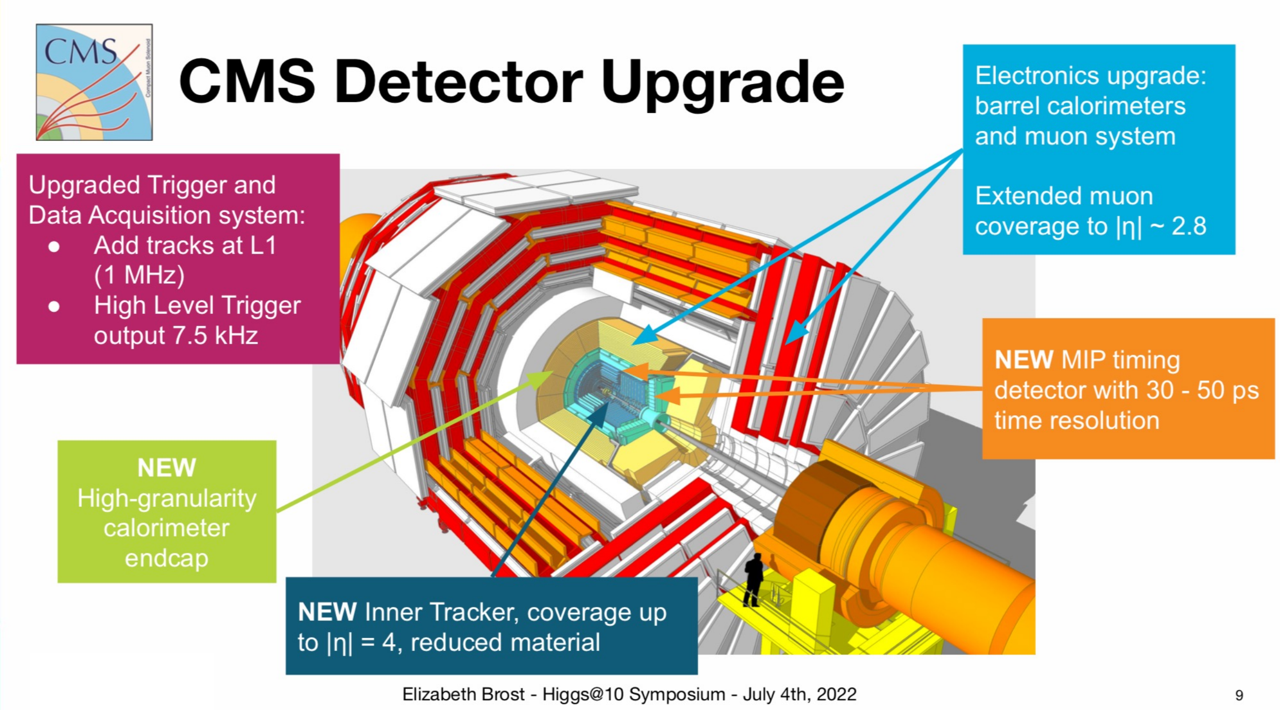

CMS Detector Upgrade

Upgraded Trigger and Data Acquisition system:

- Add tracks at L1 (1 MHz)
- High Level Trigger output 7.5 kHz

Electronics upgrade: barrel calorimeters and muon system

Extended muon coverage to |η| ~ 2.8

NEW MIP timing detector with 30 - 50 ps time resolution

NEW High-granularity calorimeter endcap

NEW Inner Tracker, coverage up to |η| = 4, reduced material

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HL-LHC projections

- HL-LHC complete full simulation studies very challenging and very expensive (resources) at this point in time
- Procedure adopted:
  - Start from published LHC Run 2 studies and/or
  - Simplified simulation (using for example, DELPHES)
  - Adapt to HL-LHC conditions
    - center-of-mass energy: center-of-mass energy: $\sqrt{s} = 14$ TeV
    - pileup: 30 → 140 or 200
    - Final statistics: 3000 fb^{-1} per experiment
    - simulated detector and reconstruction performance
- Systematic uncertainties, Baseline Scenario: the increase of the systematic experimental uncertainties is compensated by the superior HL-LHC detector performance:
  - detector and trigger performance comparable to Run 2:
    - **Studied improvements to object reconstruction and the impact of detector upgrades, using full simulation with pile-up**
  - most experimental uncertainties scaled down with $\sqrt{L}$
  - theoretical uncertainties scaled by 1/2 with respect to current values
  - 1% luminosity uncertainty

HL-LHC Physics prospects studies

- **European Strategy Update (2018-2020)**

“The European Strategy for Particle Physics provides a clear prioritisation of European ambitions in advancing the science of particle physics. It takes into account the worldwide particle physics landscape and developments in related fields”

Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC

- **Snowmass Community Planning Exercise (2020-2022)**

“The Particle Physics Community Planning Exercise (a.k.a. “Snowmass”) ... provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners.”

2022 Snowmass Summer Study

Higgs couplings

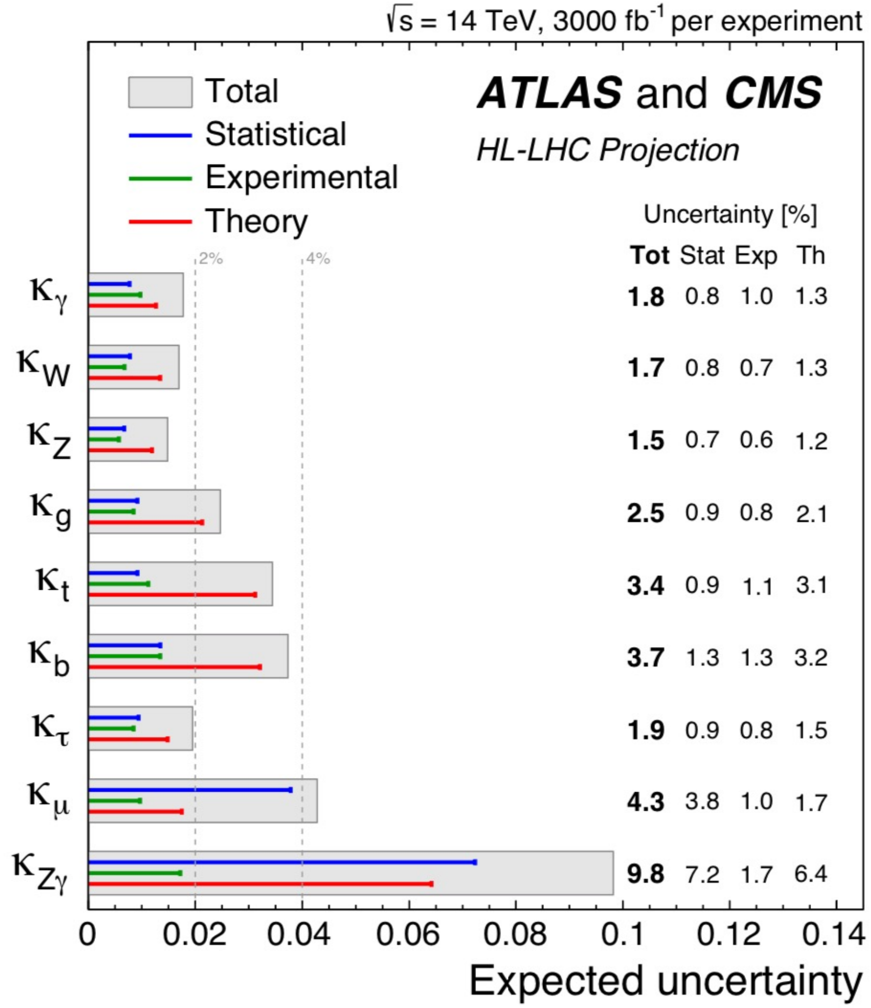
Precision Higgs coupling measurement at HL-LHC

Precision on couplings to γ, W, Z and τ < 2 %

Precision on couplings to g, t, b and μ < 5 %

Precision on couplings to $Z\gamma$ < 10 %

Many projections show limitation from theory Uncertainties (despite the assumptions made)



Dominated by: theory uncertainties, statistics

total expected ±1s.d. uncertainties on the coupling modifier parameters for the combination of ATLAS and CMS extrapolations

Rare Higgs boson decays: H→$\mu\mu$

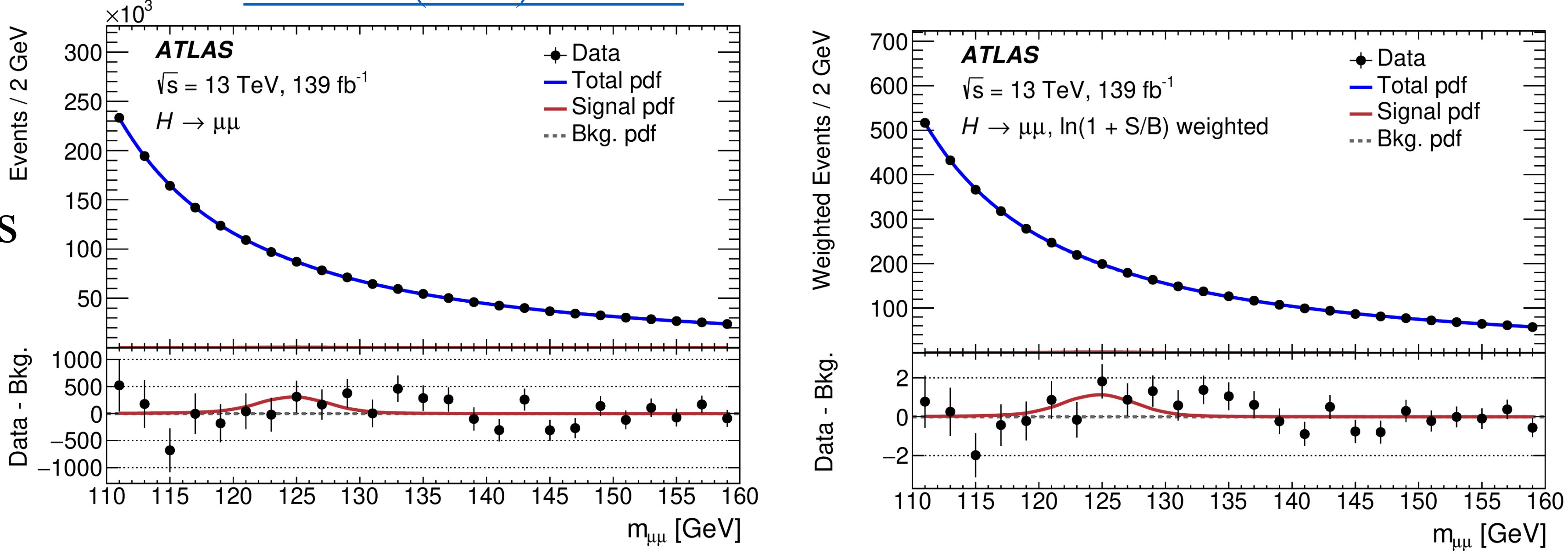
SM BR(H→ μμ) ~ 2.2 × 10^{-4}

- Large irreducivble SM Drell-Yan →$\mu\mu$ background
- S/B ~ 10^{-3} for inclusive events
- Improved analysis:
- Define categories targetting different production modes
- Use MVA analysis
- Signal extraction from mμμ fit Background parametrisation

ATLAS Observed (expected) significance:
2.0 (1.7) s.d. $\mu = 1.2 \pm 0.6$

CMS Observed (expected) significance:
3.0 (2.5) s.d. $\mu = 1.19^{+0.44}_{-0.42}$

PLB 812 (2021) 135980



Dimuon invariant mass spectrum in all the analysis categories observed in data:

Left: Unweighted sum of all events and signal plus background probability density functions

Right: events and pdfs are weighted by ln(1 + S/B), where S are the observed signal yields and B are the background yields derived from the fit to data in the $m_{\mu\mu}$ = 120–130 GeV window

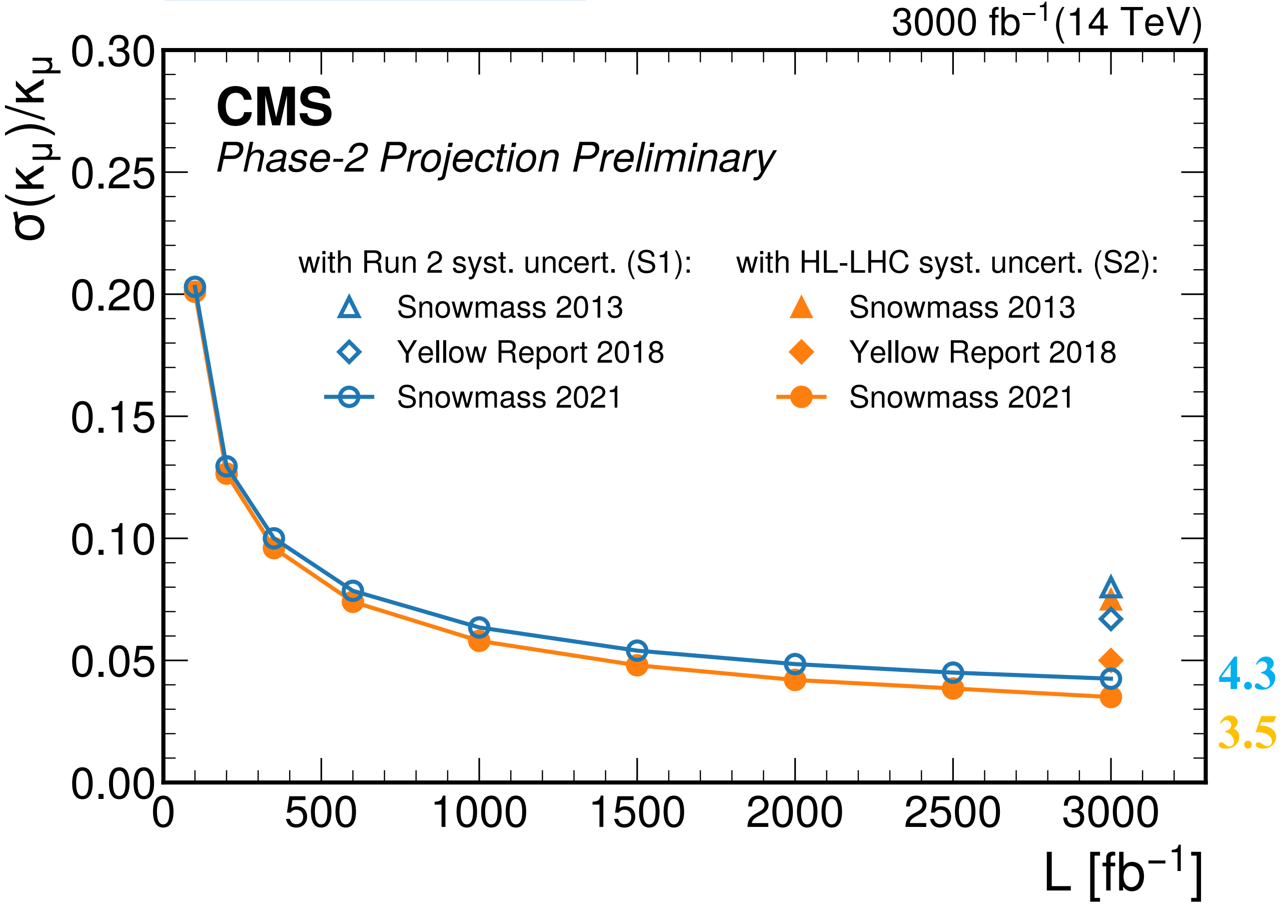
Rare Higgs boson decays: H→$\mu\mu$

H → μμ projection based on the CMS Run 2 analysis, see previous slide

Estimate increases in signal and background yields due to new detectors

- uncertainty on the H → μμ signal strength was estimated to be 8.5% (7.0%)
- uncertainty on coupling modifier κ_μ was estimated to be 4.3% (3.5%) for uncertainty scenario S1 (S2).

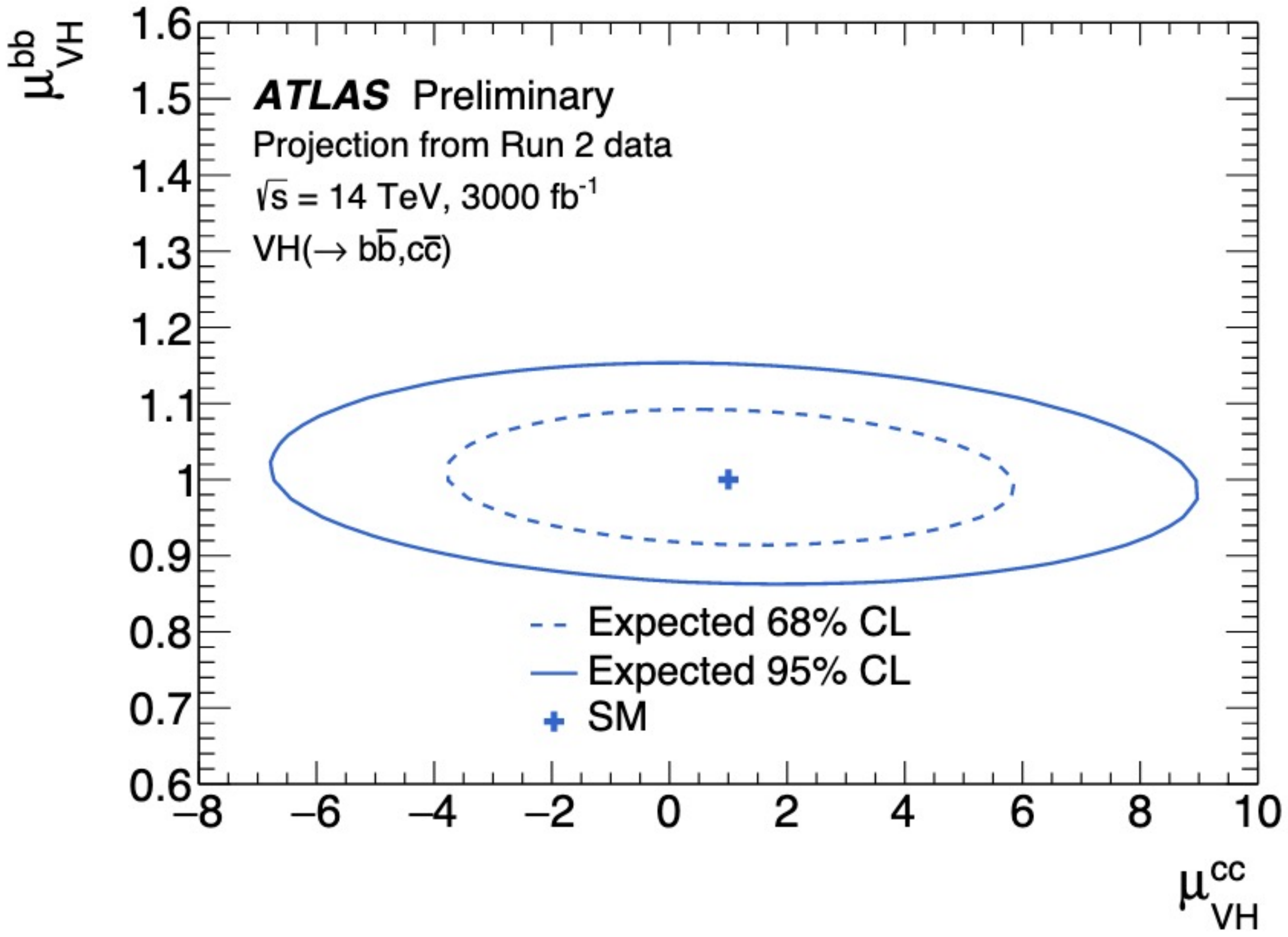
CMS-PAS-FTR-21-006



Improvement over previous projection: ~ 30%

Similar results from ATLAS

H→cc



Expected profile likelihood scans for the VH, H → bb/cc combination extrapolated to a dataset of 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV.

Higgs to invisible

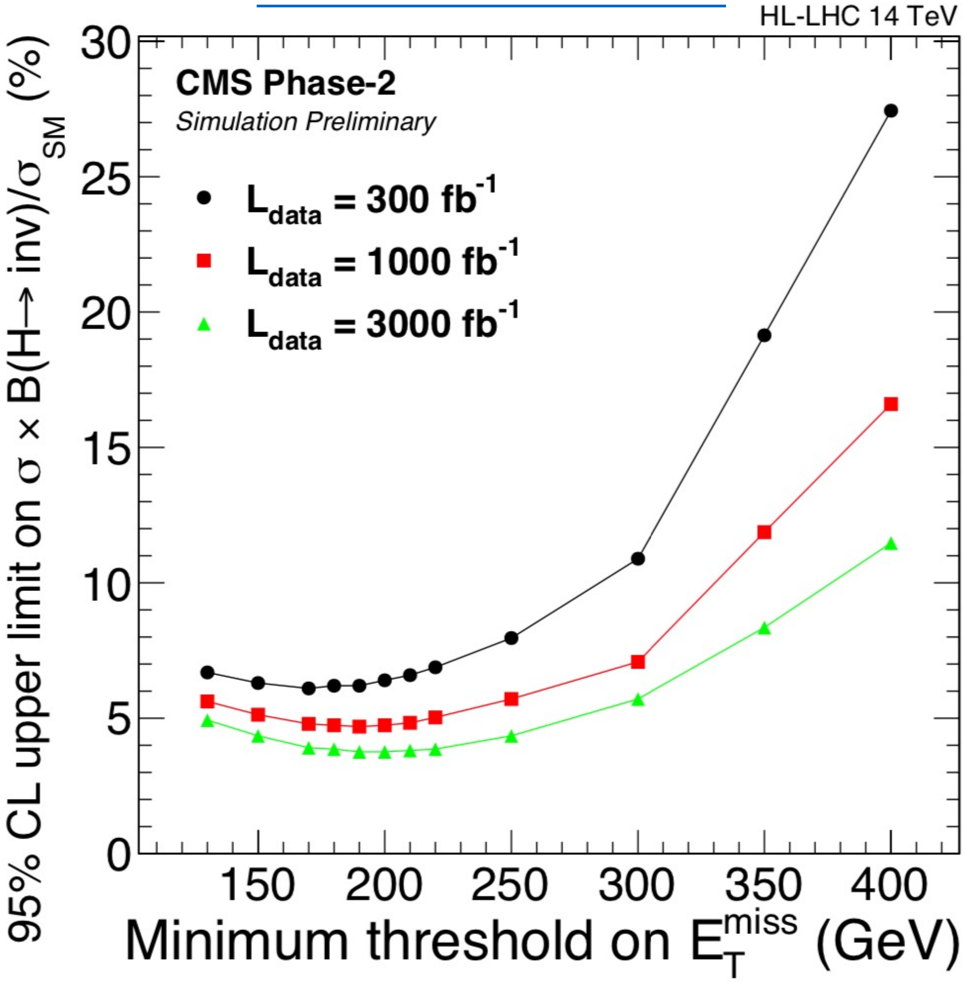
The SM Higgs branching ratio to invisible is below current O(10%) experimental limits: BR(H→ZZ→4**ν**) ~ 0.1%

Higgs → invisible searches rely on the E_T^{miss} trigger - significantly more challenging with more pileup

CMS search for H → dark matter in VBF events: BR(H → invisible) < 3.8%, for MET > 190 GeV

ATLAS+CMS VBF+VH combination gives BR(H → invisible) < 2.5%

CMS-PAS-FTR-18-016



95% CL limits for scenarios with different integrated luminosities.

HH production

European Strategy 2019

Combination of 5 HH channels, many based on partial Run 2 analysis strategy
- **bbbb, bb$\gamma\gamma$, bb$\tau\tau$, bbZZ(4l), bbVV(lνlν)**

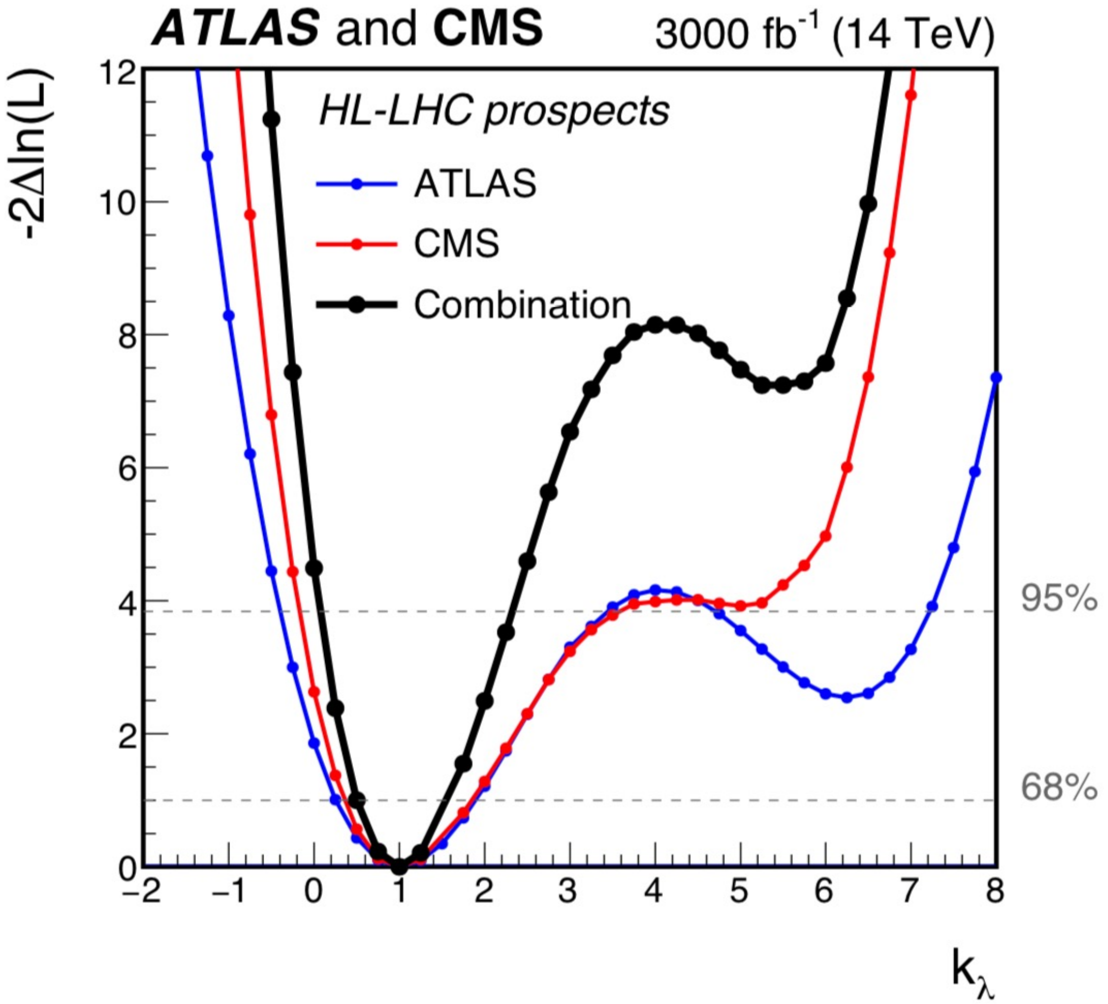
4σ SM HH significance (ATLAS+CMS)

50% precision on self-coupling

68% Confidence Interval:

$0.52 \leq \kappa_\lambda \leq 1.5$ and $0.57 \leq \kappa_\lambda \leq 1.5$

with and without systematic uncertainties respectively



negative-log-likelihood as a function of κλ, calculated by performing a condi- tional signal+background fit to the background and SM signal

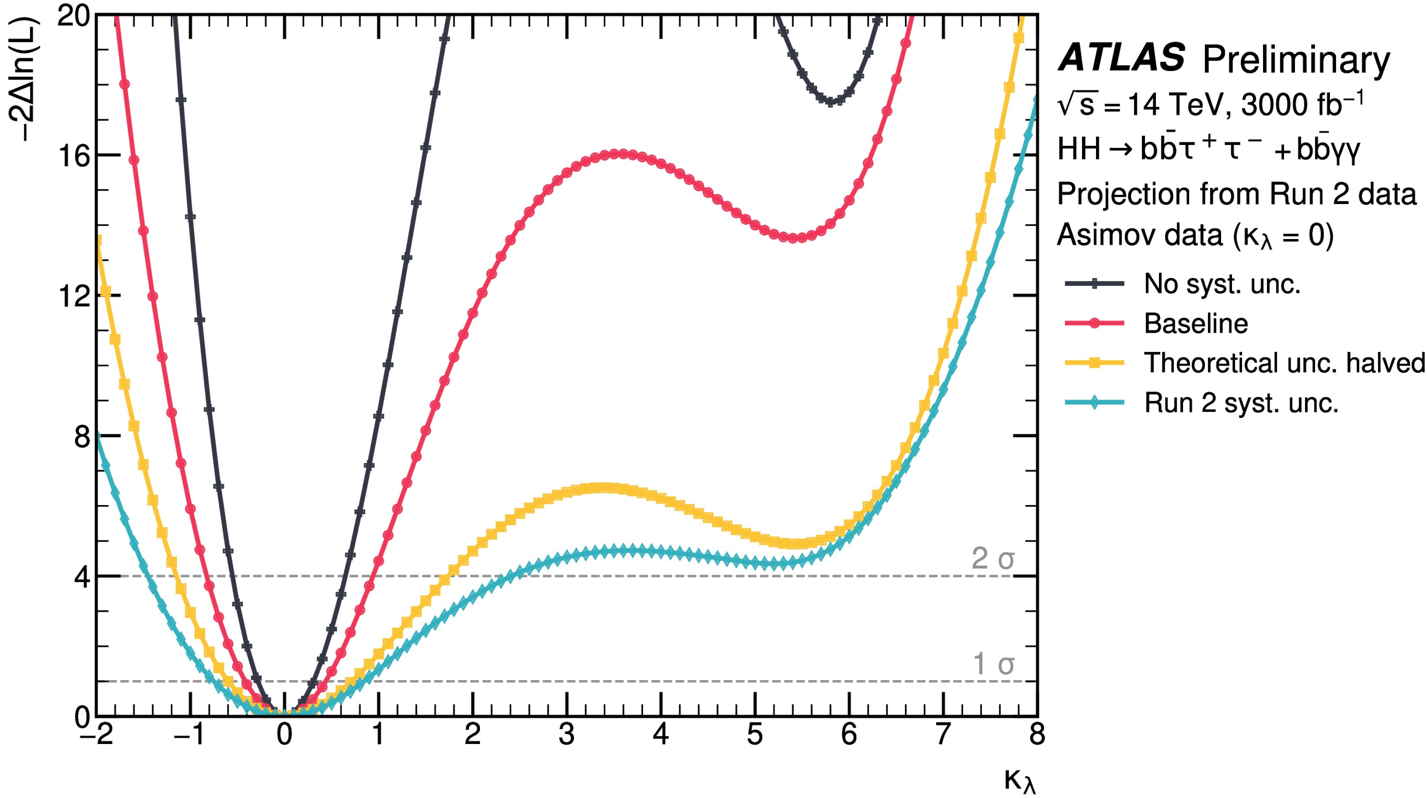
HH production

Snowmass update 2021-2022)

ATLAS γγbb+bbττ combination: **3.2σ**

CMS updated γγbb results, added γγWW, γγττ, ttHH(bbbb)

→ **~5σ SM HH significance** (?) with a back-of-the-envelope calculation



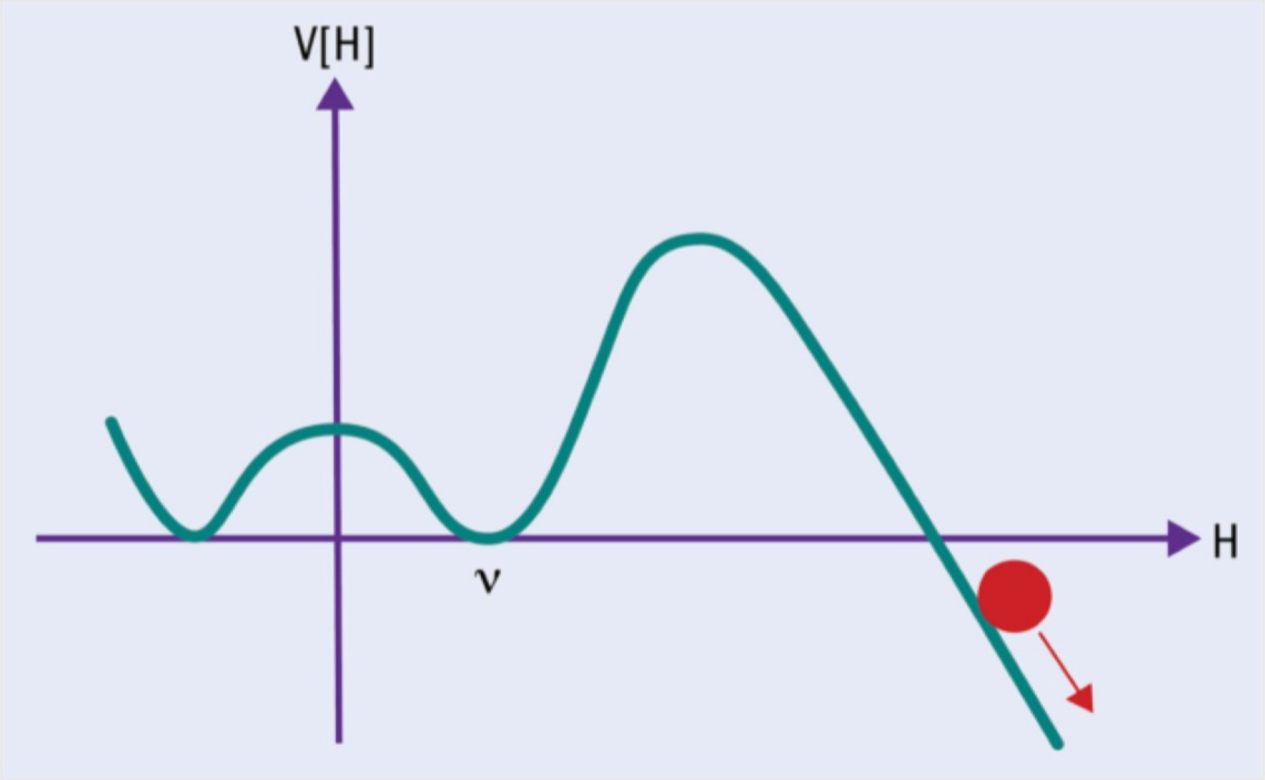
Negative logarithm of the combined likelihood ratio comparing different $\kappa\lambda$ hypotheses to an Asimov dataset constructed under the hypothesis of $\kappa\lambda = 0$ assuming the four different uncertainty scenarios.

Conclusions

- The discovery of the 125 GeV Higgs boson set a new milestone in the understanding of our world
- LHC has gone from discovery to precision Higgs physics
- Measurements performed in 10 years of studies indicate that this new particle is consistent with the Higgs boson predicted Standard Model
  - We have never observed a fundamental scalar so far – the really new particle we've seen
  - The Standard Model (SM) is a theory
  - Still room for New Physics beyond SM at (HL-)LHC
- This discovery opened a new sector of studies in high-energy physics
- Run 3 and the upgrade of LHC, HL-LHC, will produce 20 times more data that those produced and analysed to date
  - ATLAS and CMS detector upgrades will maintain or improve upon current performance
  - Continuation of hard work and creativity in reconstruction and analysis techniques will be crucial at HL-LHC
  - Interplay of theory and experiment crucial in the future, continuing program of theory calculations is essential in order to match experimental precision on Higgs measurements
- The Higgs boson plays a fundamental role in searches for new particles and new fields: **combination** of **precision physics** and **direct searches** is crucial in the search for **new physics beyond Standard Model**

backup

The fate of the Universe

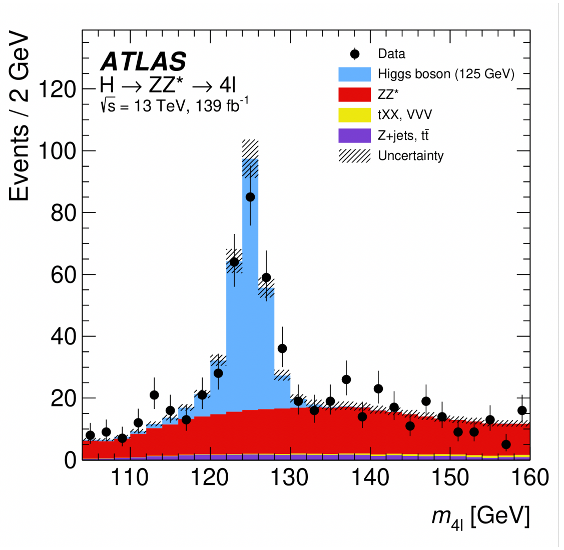


New depths The transition of the universe to a different vacuum state after electroweak symmetry breaking can be pictured as a ball rolling along a potential. If the SM is correct and there is no new physics beyond it, then the current value of the BEH field (v ~246 GeV) does not have the lowest energy and hence is not the true vacuum of the universe. Rather, the potential "turns over" at around 10^{12} GeV and becomes negative, suggesting that the universe might one day tunnel out of its current state (diagram not to scale). Credit: J Ellis

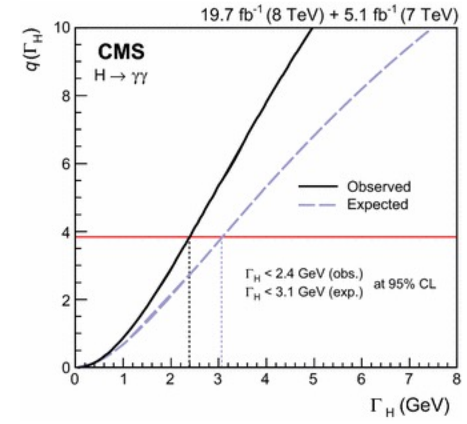
J. Ellis, CERN Courier, **HIGGS AND ELECTROWEAK**, **1 July 2022**

The Higgs boson natural width

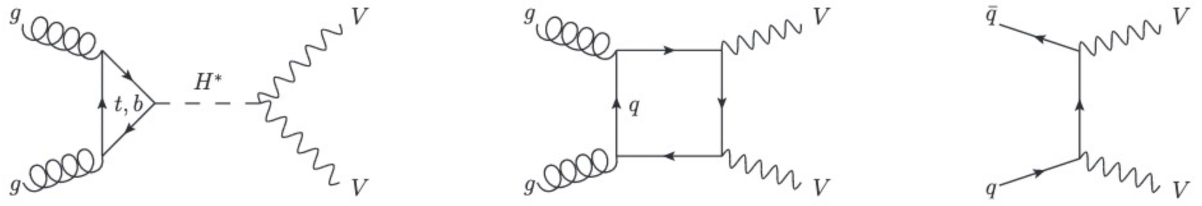
- **Predicted Standard Model Higgs boson natural width Γ_H^{SM}: 4.07 MeV**
- this width is too small to be measured directly from the line shape because of the limited mass resolution of order 1 GeV achievable with the present LHC detectors
- ➔ Probe the impact of Γ_H in the "off-shell" region, i.e. studying the line shape of final states such as, for example, – the four lepton final states.



Direct measurement severely limited by detector resolution! One (old) example:



EPJC volume 74, 3076

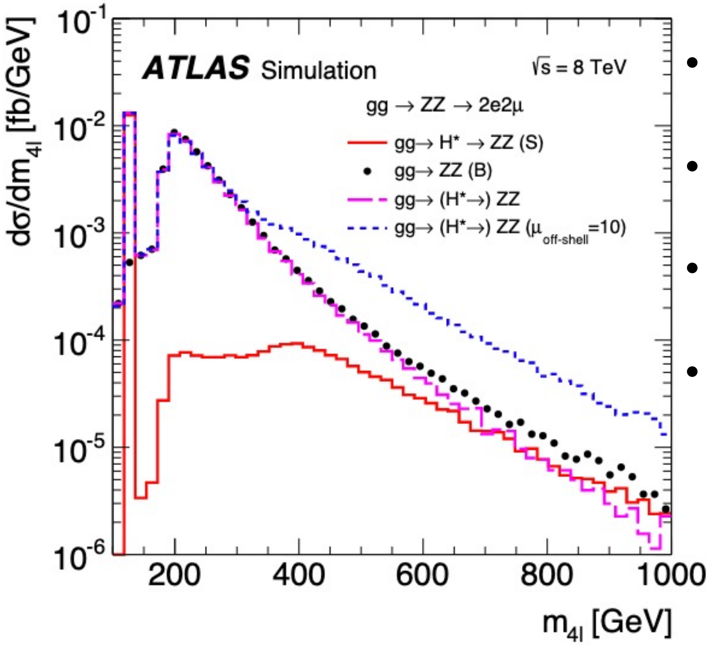


$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2\, g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

Assuming on-shell and off shell couplings are equal:

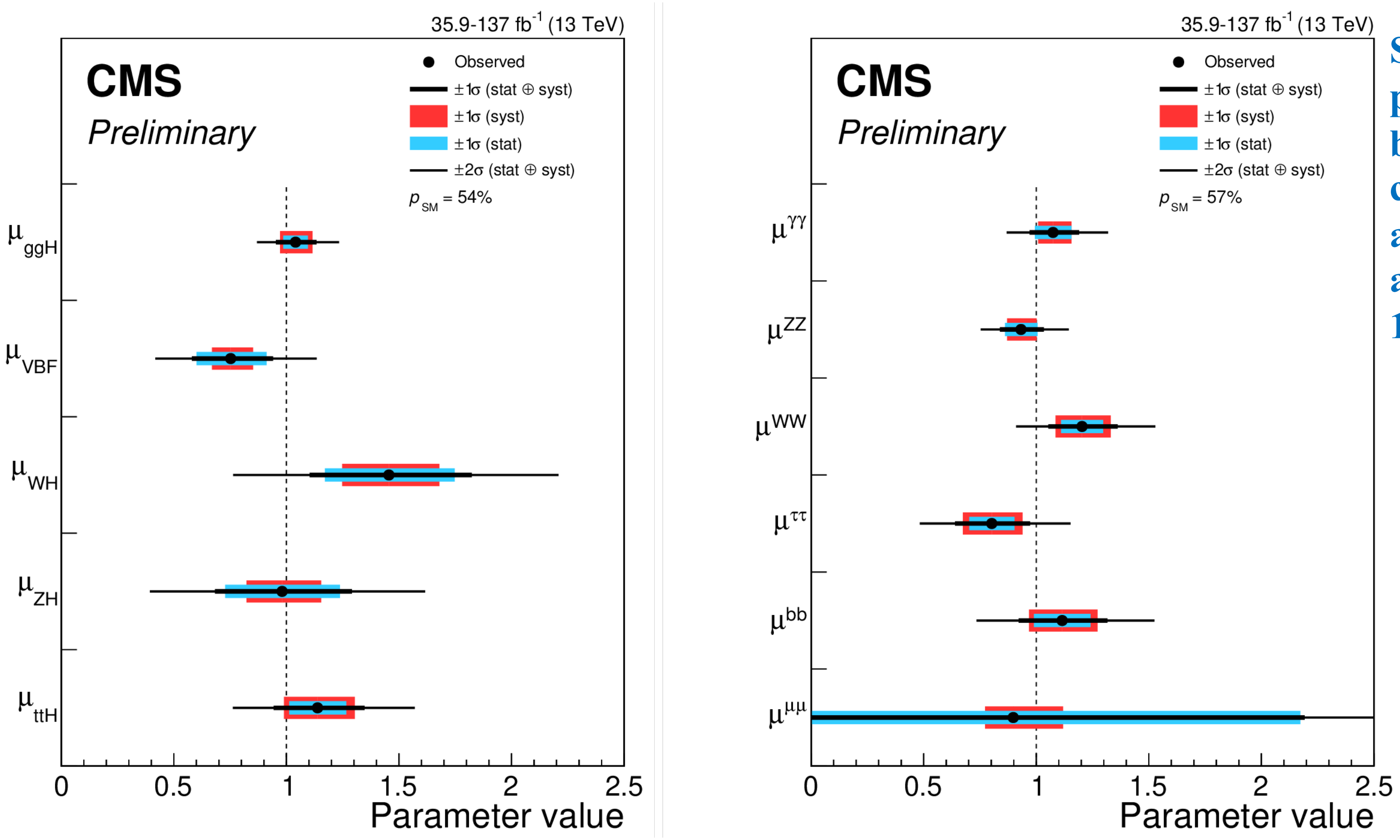
$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{\text{SM}}}$$

arXiv:1307.4935v3



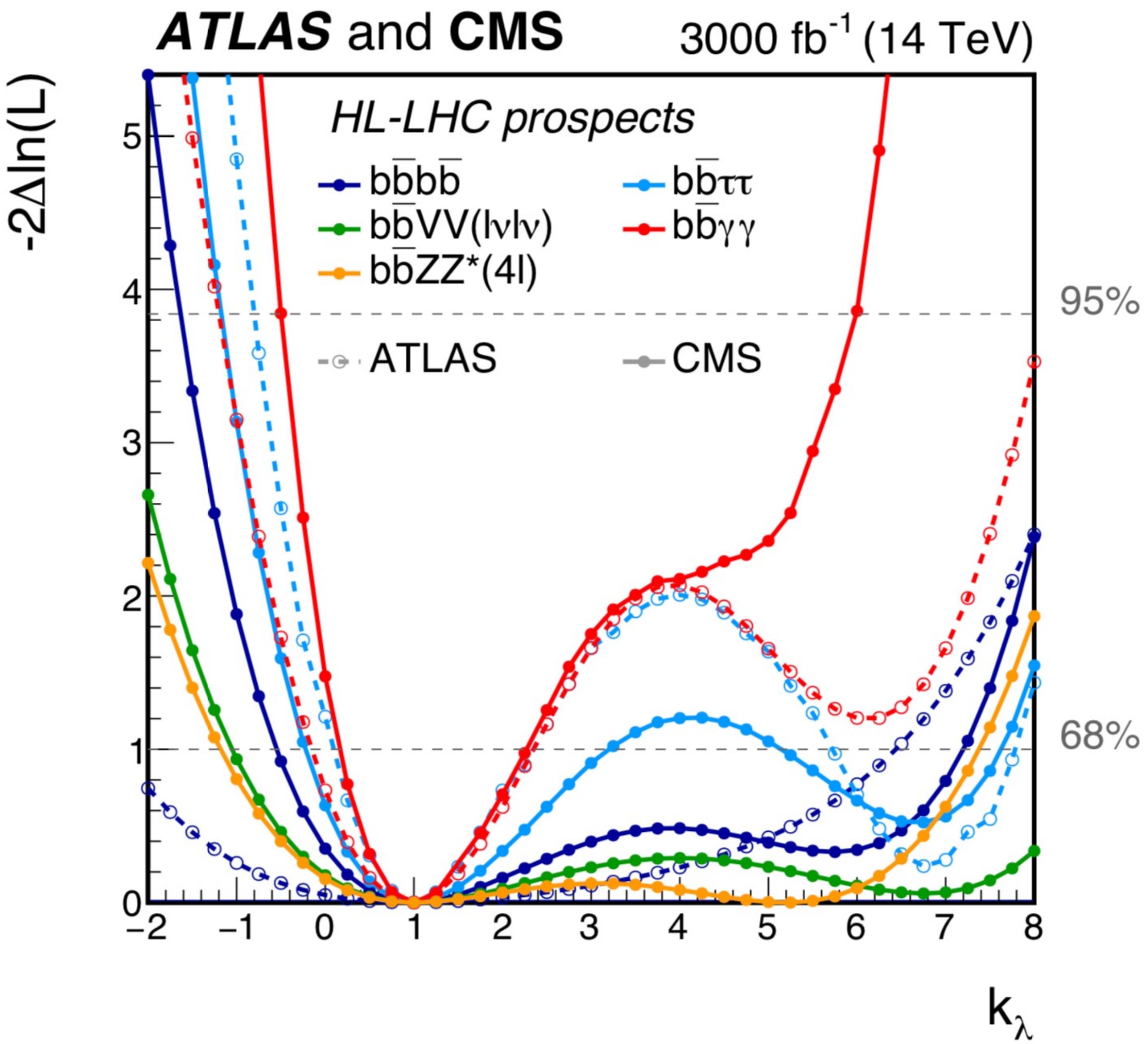
- **Solid line: SM gg → $H^{(*)}$ → ZZ signal**
- **dots: gg → ZZ continuum background**
- **long dashed: including interference**
- **dashed: including interference and assuming 10 times the SM Γ_H^{SM}**

CMS-PAS-HIG-19-005



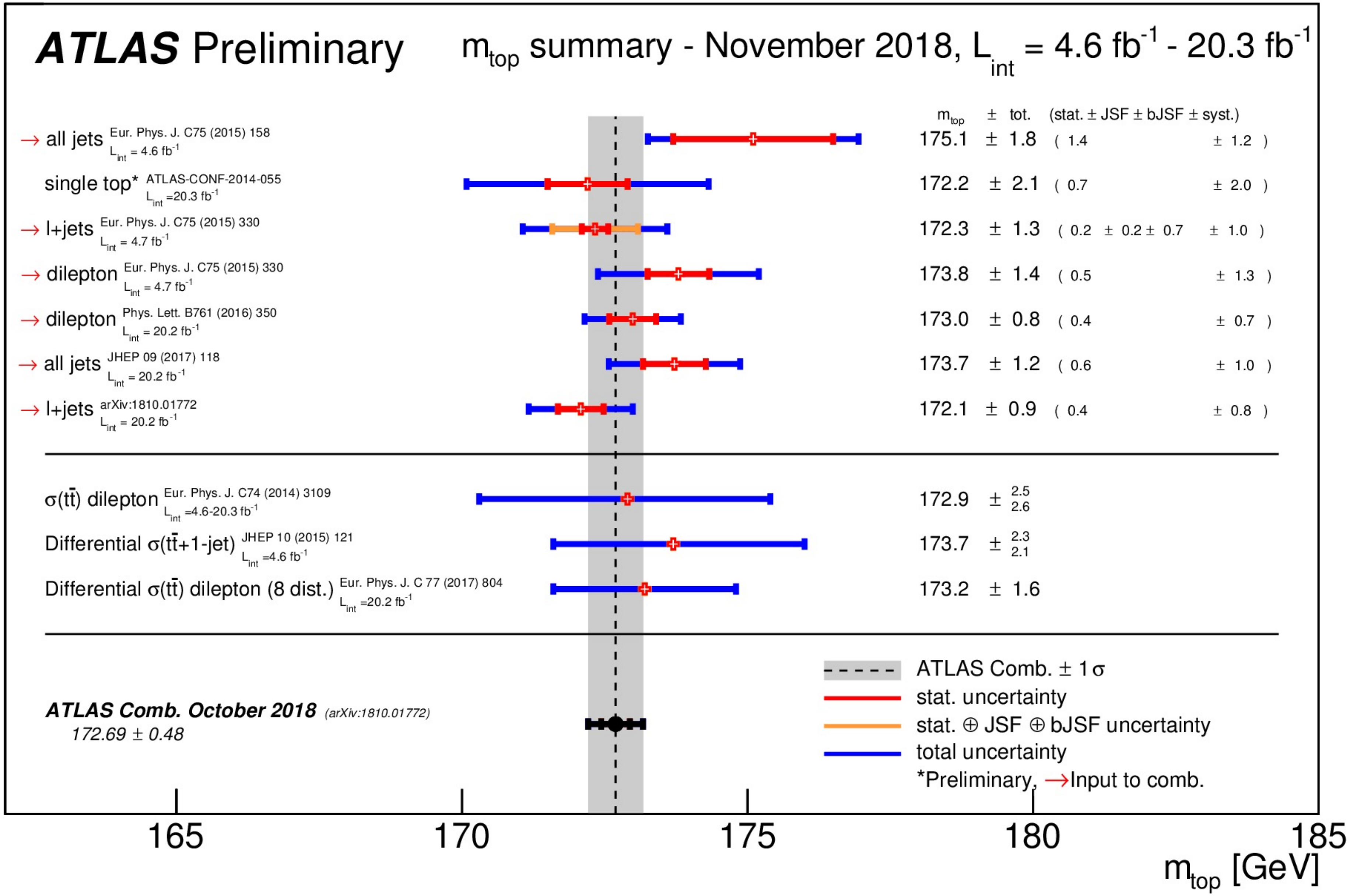
Signal strength modifiers for the production, μ_i. The thick (thin) black lines report the 1σ (2σ) confidence intervals. The thick blue and red lines report the statistical and systematic components of the 1σ confidence intervals.

HH – European Strategy



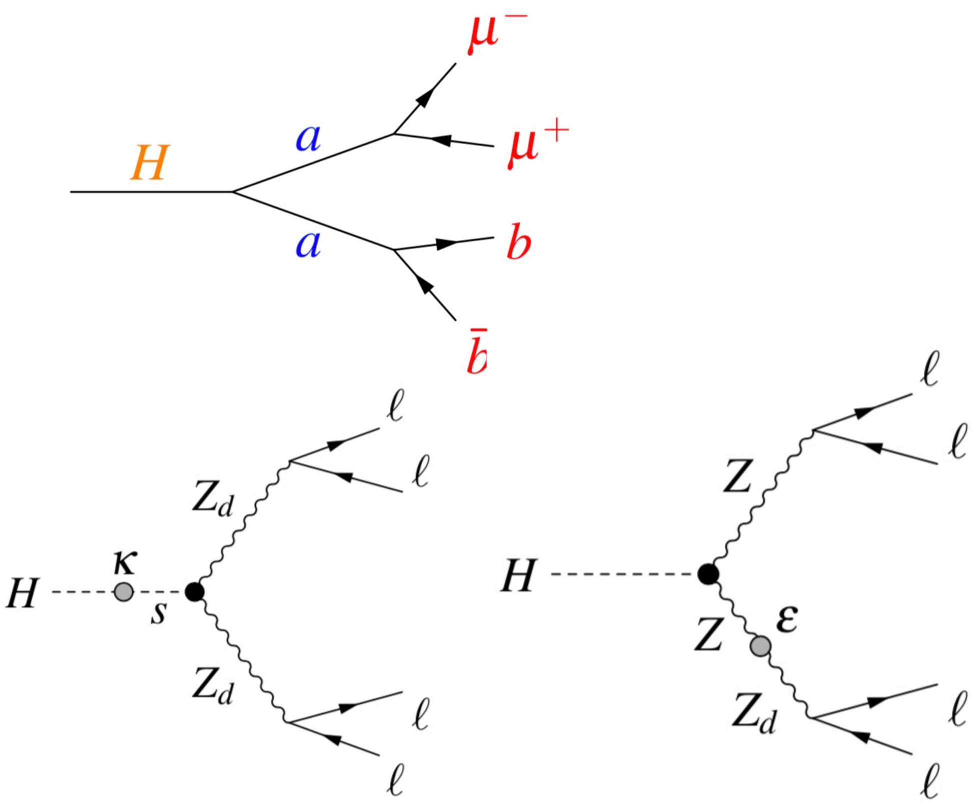
The different colours correspond to the different channels, the plain lines correspond to the CMS results while the dashed lines correspond to the ATLAS results.

Summary of the latest ATLAS direct and indirect mtop measurements.



Examples of Exotic Higgs boson decays

- Higgs → scalars
  - Some extensions to the SM include Higgs decays via a pair of on-shell (pseudo)scalars, eg 2HDM+S
  - a → bb generally dominates, but other decays may also be significant depending on the model, such as a→μμ, a→ ττ, a→γγ, a→gg
- Higgs decays to dark photons
  - Many SM extensions include a U(1) dark gauge symmetry with gauge boson Zd mixing with SM Higgs via κ and with hypercharge gauge boson via ε
- Lepton Flavour violation
  - H → ll′ forbidden in SM but allowed in some extensions: SUSY, composite Higgs, Randall-Sundrum, etc.
  - B(H → eμ) < 6.2×10^{-5} (5.9×10^{-5}) @ 95% C.L.
  - B(H → μτ) < 0.15 (0.15)% @ 95% C.L.



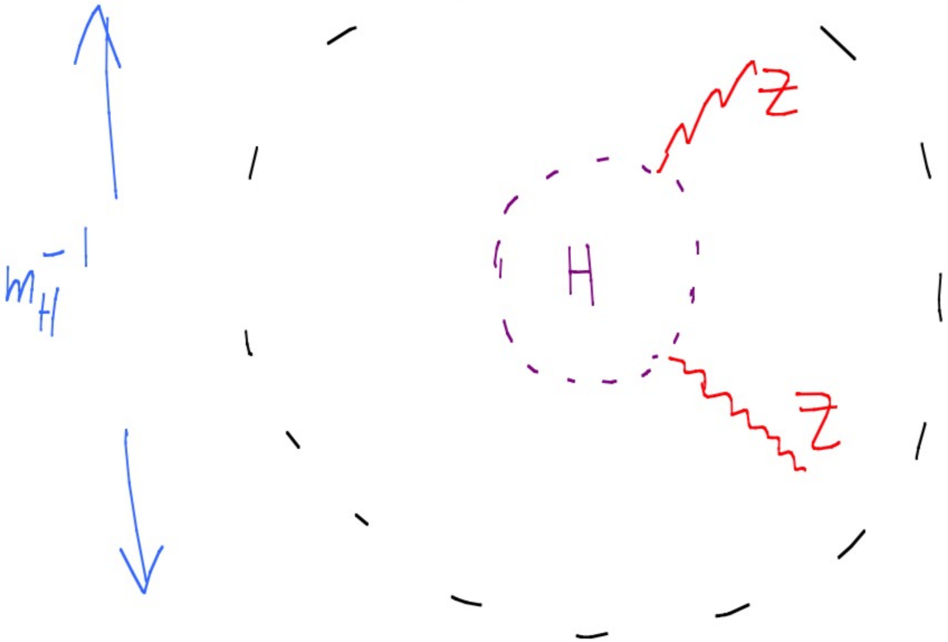
Higgs is Really New Physics!

- * We've never seen anything like it
- * Harbinger of Profound New Principles at work in quantum vacuum

PUT IT UNDER MICROSCOPE

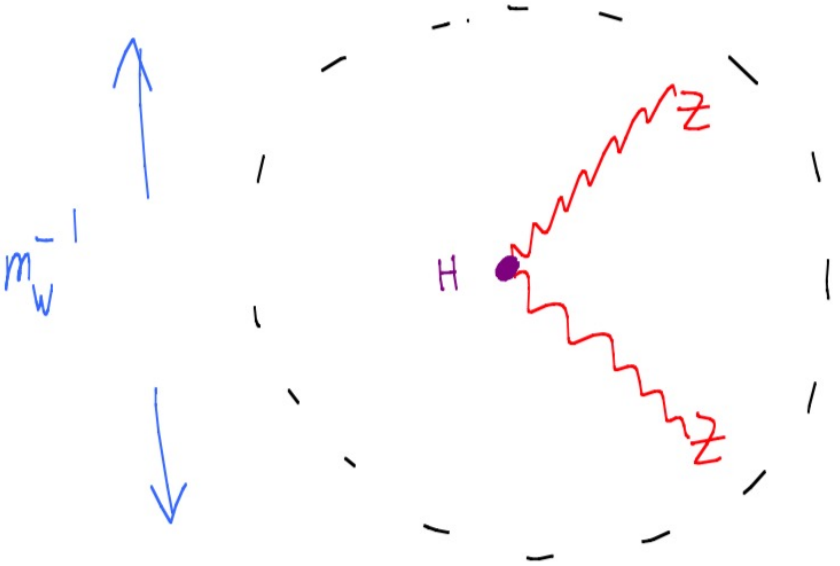
STUDY IT TO DEATH

Never Seen Point-Like Scalar



So, how pointlike is it?

Never Seen Point-Like Scalar



Higgs Factory

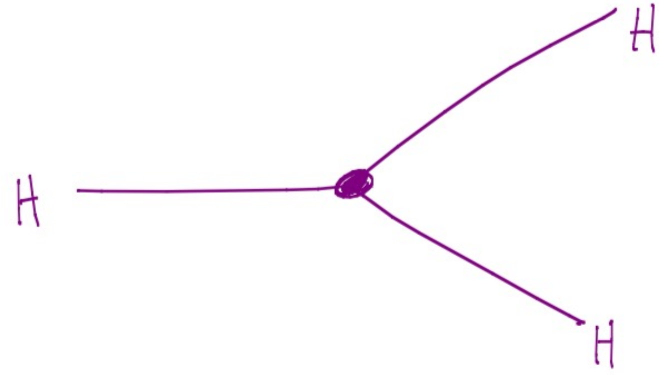
+

We will know

FOR SURE

if it's "like a Pion"

Never Seen Self-Interacting Fundamental Particles



100 TeV Collider

Measured to ~ few %