Recent CMS results in top and Higgs physics

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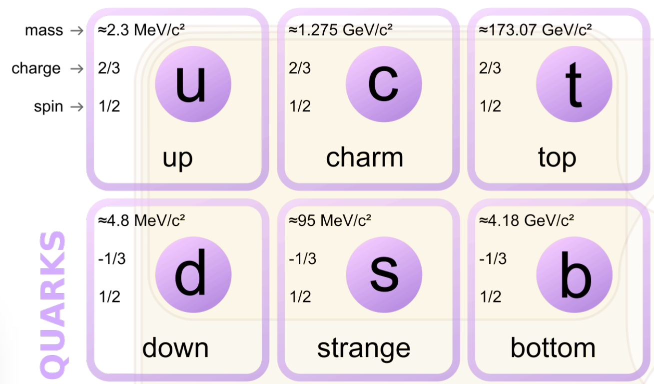
February 24, 1995

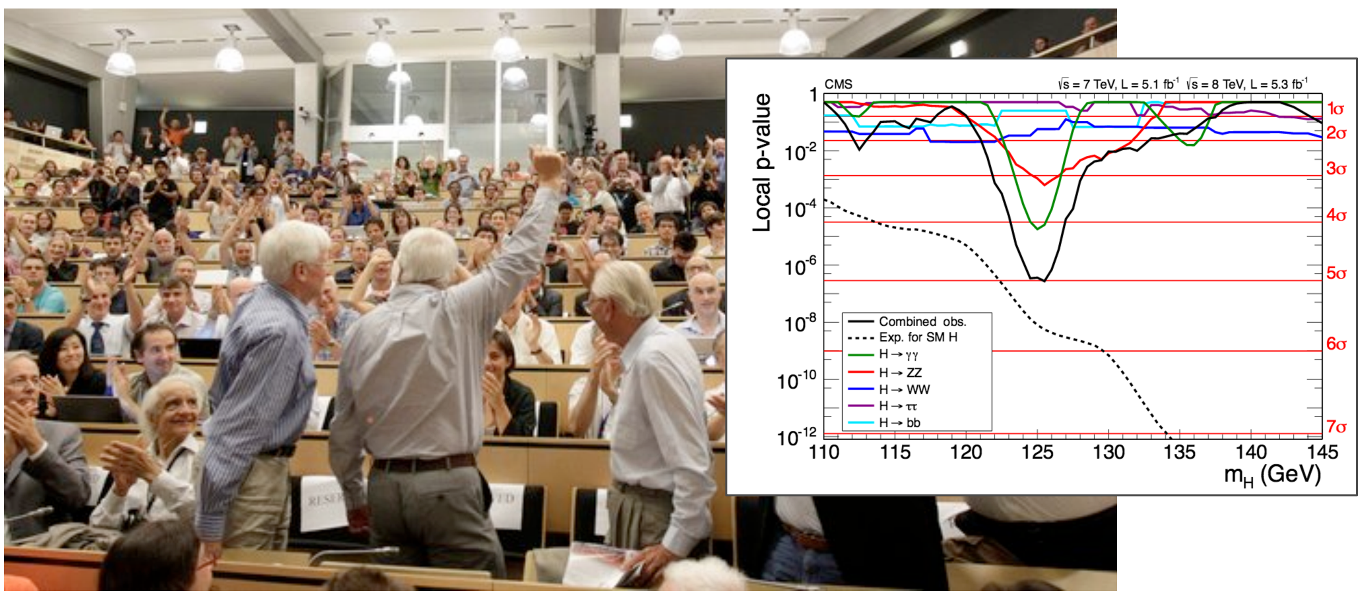
- CDF and DZero, submitted the Top Discovery papers to PRL:
  - [PRL 74, 2626–2631, PRL 74, 2632–2637]
- **The quark family picture was completed**, and it happened here, 20 years ago
  - https://indico.fnal.gov/conferenceDisplay.py?confId=8961



I was 13 years old…

July 4, 2012

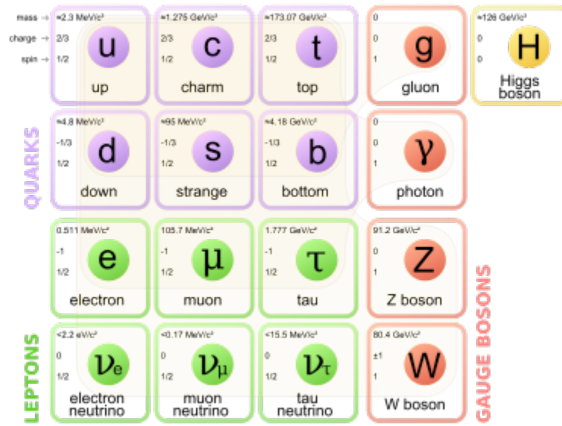
- CERN reported the discovery of the Higgs boson at the LHC:
  - http://press.web.cern.ch/press-releases/2012/07/cern-experiments-observe-particle-consistent-long-sought-higgs-boson → papers by ATLAS and CMS [arXiv:1207.7235] followed
- **The Higgs boson was finally found** after 60 years of searches



And I was 30…

The (in)complete SM picture

- The first scalar particle was observed, candidate to confirm the Higgs mechanism of mass generation via spontaneous EW symmetry breaking

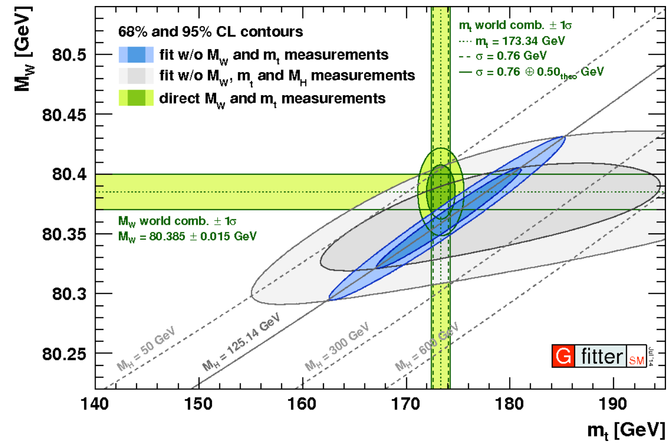


- **But the first run of the LHC found no other hint of new phenomena**, and there are <u>experimental facts that the SM cannot explain</u> (yet)
  - i.e.: Neutrino masses, the CP problem, dark matter and energy, baryon asymmetry in the Universe…

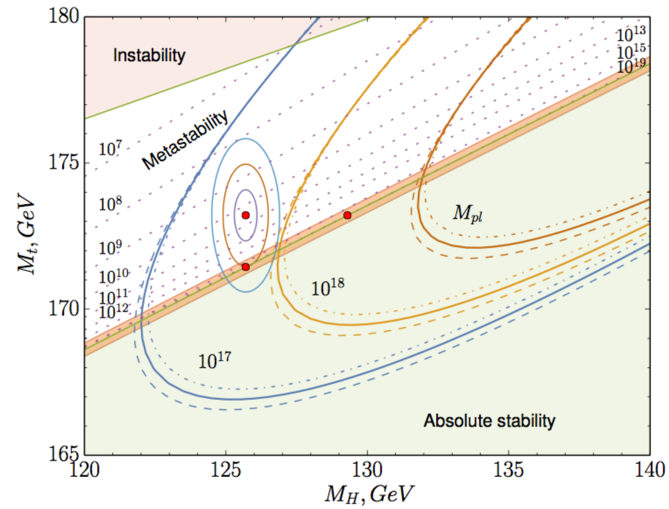
Both the top quark and the Higgs boson, independently, could be the gateway to new physics at the LHC → maybe also **together**

Top and Higgs

- Top and Higgs are <u>deeply related</u>
  - The measurement of **the top quark mass,** together with the W boson mass places **constraints on the mass of the Standard Model Higgs boson**
  - A precise measurement of the mass of the Higgs and the mass of the top allows conclusions regarding the fate of the Universe via the **analysis of the vacuum stability**
  - **The coupling of the Higgs to top quarks is very strong** in the SM and suggest a special role in the electroweak breaking mechanism and in its possible extensions



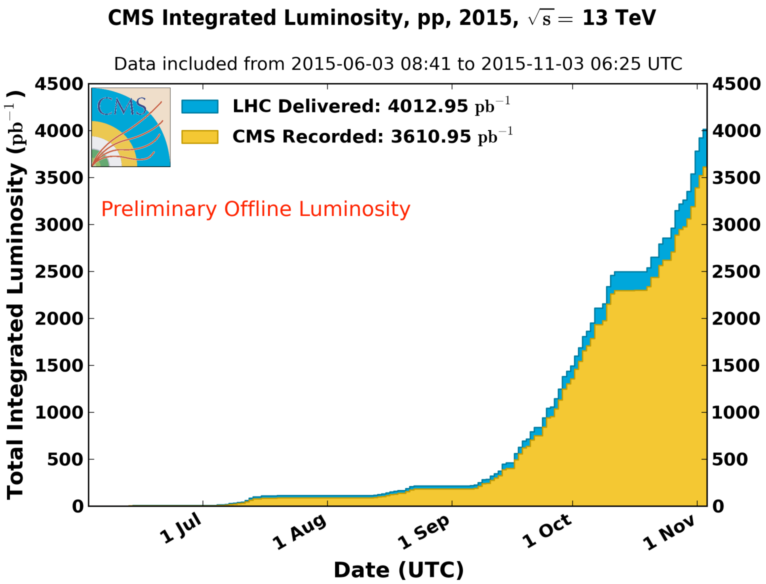
gfitter



Phys. Rev. Lett. 115 (2015) 201802

arXiv:1507.08833

Current status of the LHC



- We have entered a **new energy regime**
- The LHC started running again this year

  → **the 2015 pp run at 13TeV ended Nov. 4th**
- Though the full potential of Run-2 is still ahead of us
  - the LHC already delivered **4fb^{-1} of integrated luminosity**

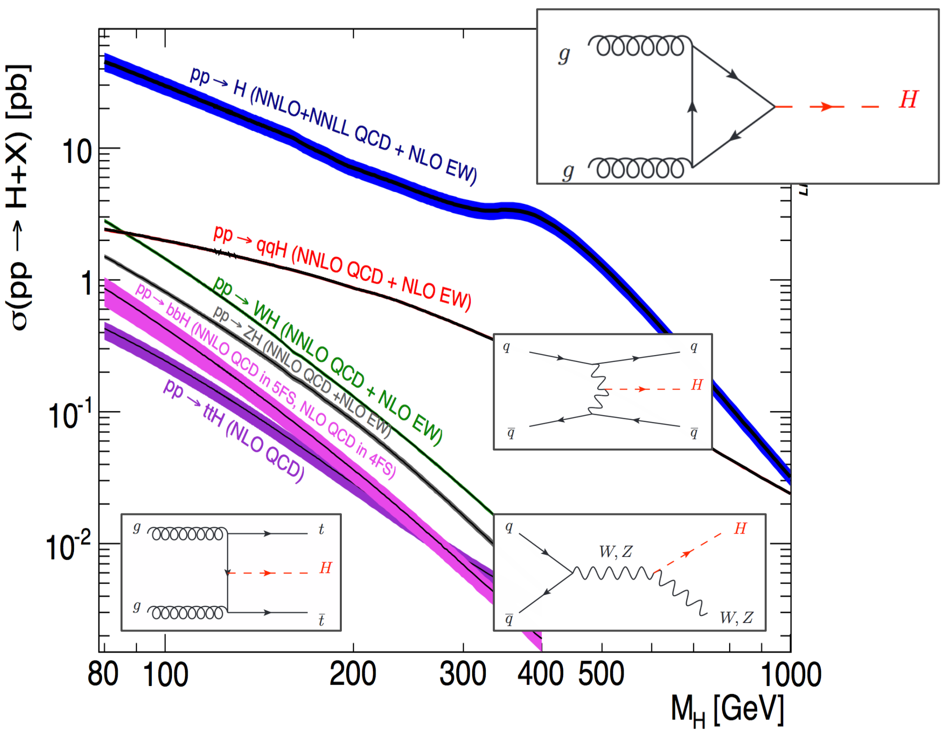
- **The Run-1 dataset is still being analyzed**
  - 5.1 fb^{-1} at 7 TeV and up to 19.7 fb^{-1} at 8 TeV
  - Higgs: Not only observation, also the first characterization of its properties
- **The first Run-2 results are arriving**
  - Top results already did! → stay tuned for Moriond 2016

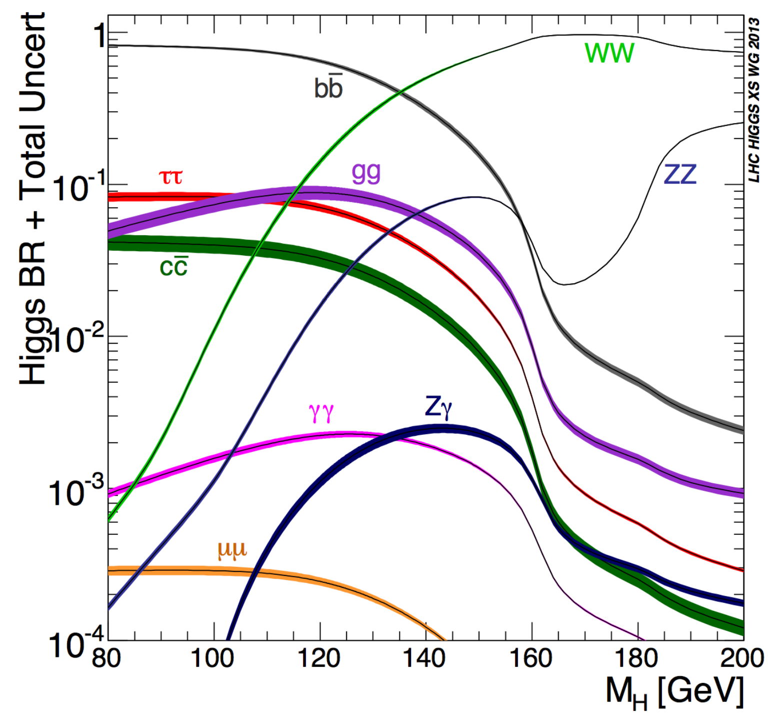
Higgs physics at the LHC today

The Run-1 legacy

The Higgs searches

- The start of the Run-1 found us looking for the Higgs everywhere → we performed a **full mass scan from the LEP limit of 114.4 until above 600GeV**
- And we found it → We observed it with different levels of confidence, in a variety of decay channels, exploiting all possible production modes





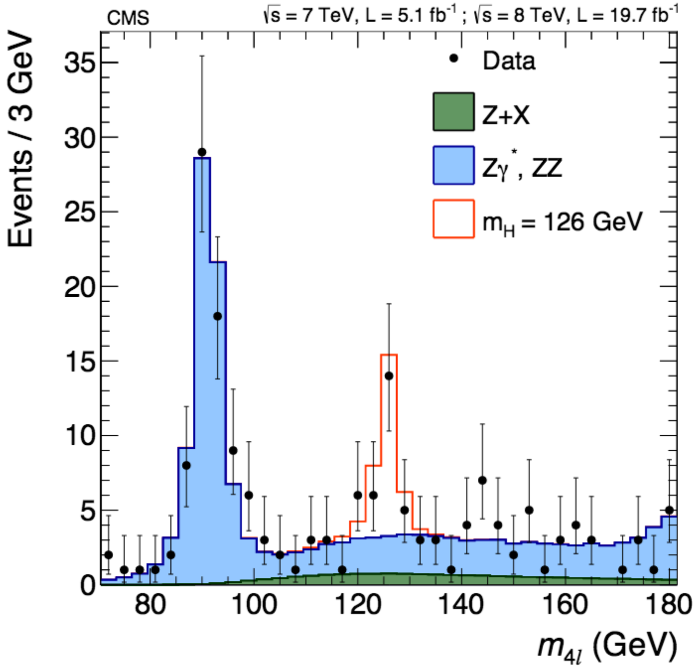
Main Channels

Eur. Phys. J. C 75 (2015) 212
arXiv:1412.8662

Channel grouping	Significance (σ) Observed	Expected
$H \to ZZ$ tagged	6.5	6.3
$H \to \gamma\gamma$ tagged	5.6	5.3
$H \to WW$ tagged	4.7	5.4
Grouped as in Ref. [22]	4.3	5.4
$H \to \tau\tau$ tagged	3.8	3.9
Grouped as in Ref. [23]	3.9	3.9
$H \to bb$ tagged	2.0	2.6
Grouped as in Ref. [21]	2.1	2.5
$H \to \mu\mu$ tagged	< 0.1	0.4

Observed and median expected significances of the excesses for each decay mode

Phys. Rev. D 89 (2014) 092007
arXiv:1312.5353



$H \to ZZ \to 4l$
Clear four-lepton mass peak over a small continuum background

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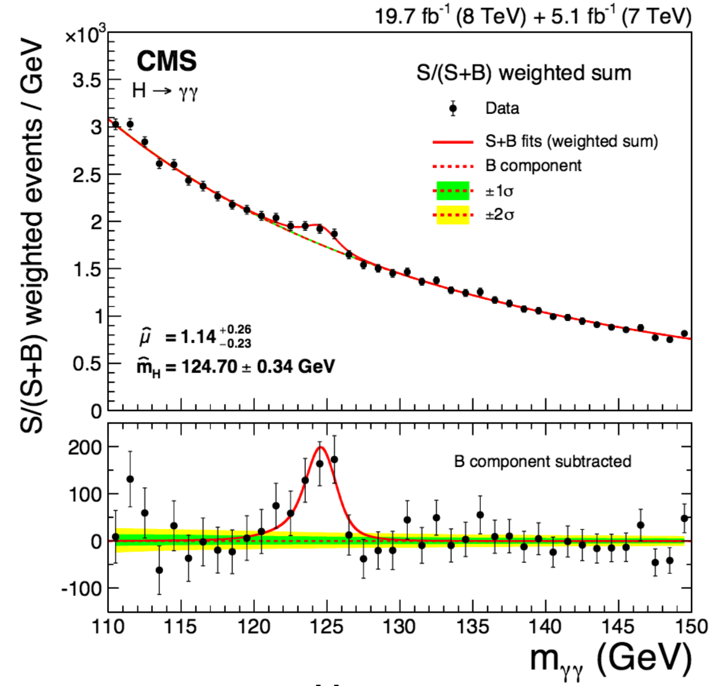
Observed and median expected significances of the excesses for each decay mode

Eur. Phys. J. C 74 (2014) 3076
arXiv:1407.0558



$H \to \gamma\gamma$
mass peak on a smooth background

Main Channels

Eur. Phys. J. C 75 (2015) 212
arXiv:1412.8662

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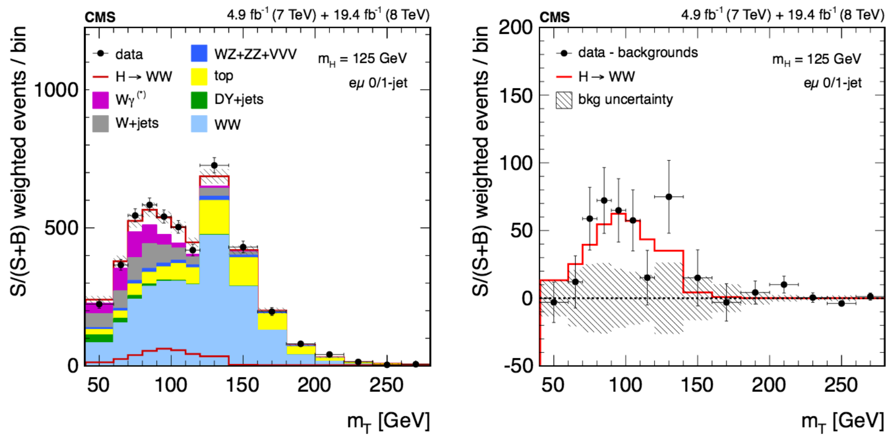
Observed and median expected significances of the excesses for each decay mode

JHEP 01 (2014) 096
arXiv:1312.1129



H→WW
No mass peak but clear signature (opposite sign leptons, *Etmiss*) second branching ratio at 125GeV

Main Channels

Eur. Phys. J. C 75 (2015) 212
arXiv:1412.8662

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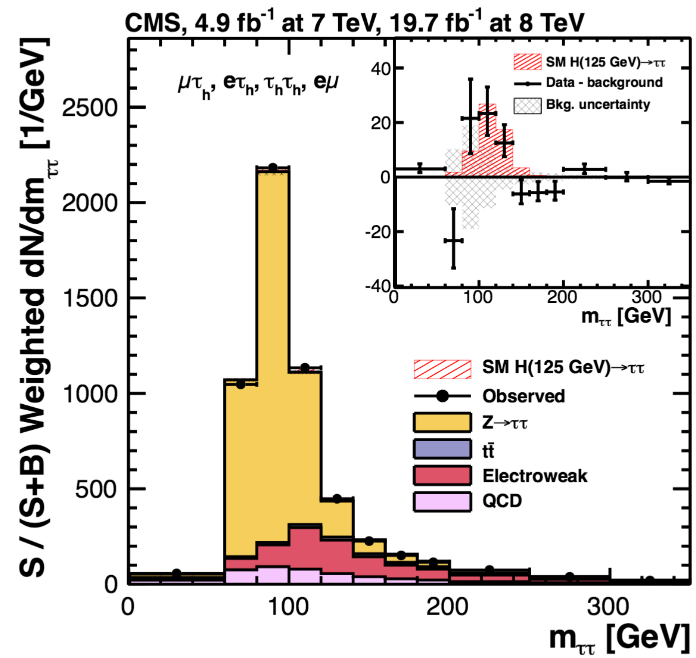
Observed and median expected significances of the excesses for each decay mode

JHEP 05 (2014) 104
arXiv:1401.5041



$\mathrm{H} \to \tau\tau$

excess of events over SM background using multiple final-state signatures

Main Channels

Eur. Phys. J. C 75 (2015) 212
arXiv:1412.8662

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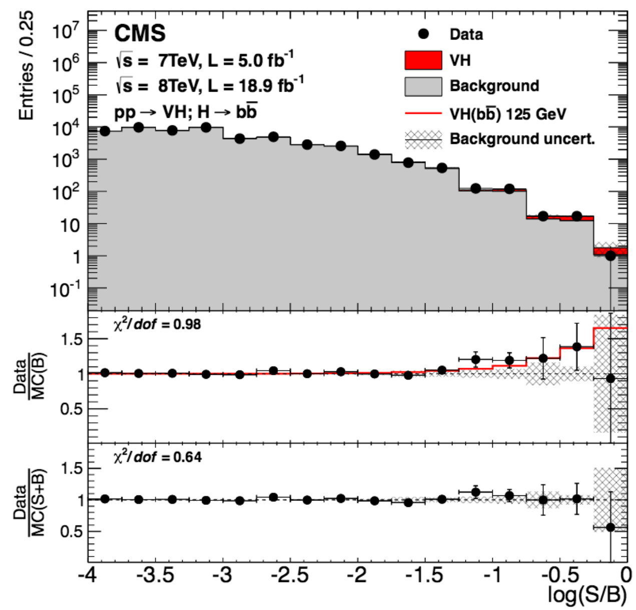
Observed and median expected significances of the excesses for each decay mode

Phys. Rev. D 89, 012003 (2014)
arXiv:1310.3687



$H \to bb$
Highest branching fraction, VH production

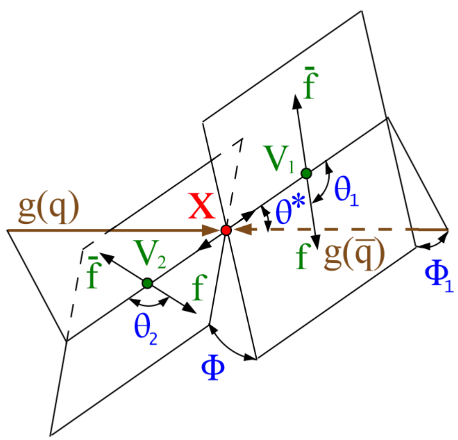
Higgs properties

- There is clearly a new particle, that is produced and decays much like a SM Higgs would
- Next step after the searches → Precisely measure its properties
  - **Charge, Couplings, Spin, Parity, Mass, Width…**
- Properties are handles to find deviations with respect to the SM expectations, corners where new physics may be hiding:

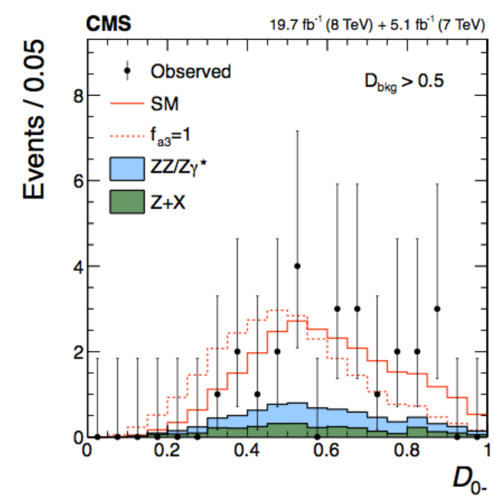
How much can be done already with Run-1 data?

Spin and tensor structure

- **H→VV** decays (V=Z,W,γ)
- The analysis is done via the study of the **kinematic distributions of the decay products** that are determined by the tensor structure of the HVV interactions
- The number of kinematic variables available determines the strategy followed in each channel, and depends on the Higgs decay
  - H→WW limited sensitivity due to undetected neutrinos in the dilepton final state
  - **H→ZZ→4l, complete final state can be reconstructed** → **Full kinematic information accessible**



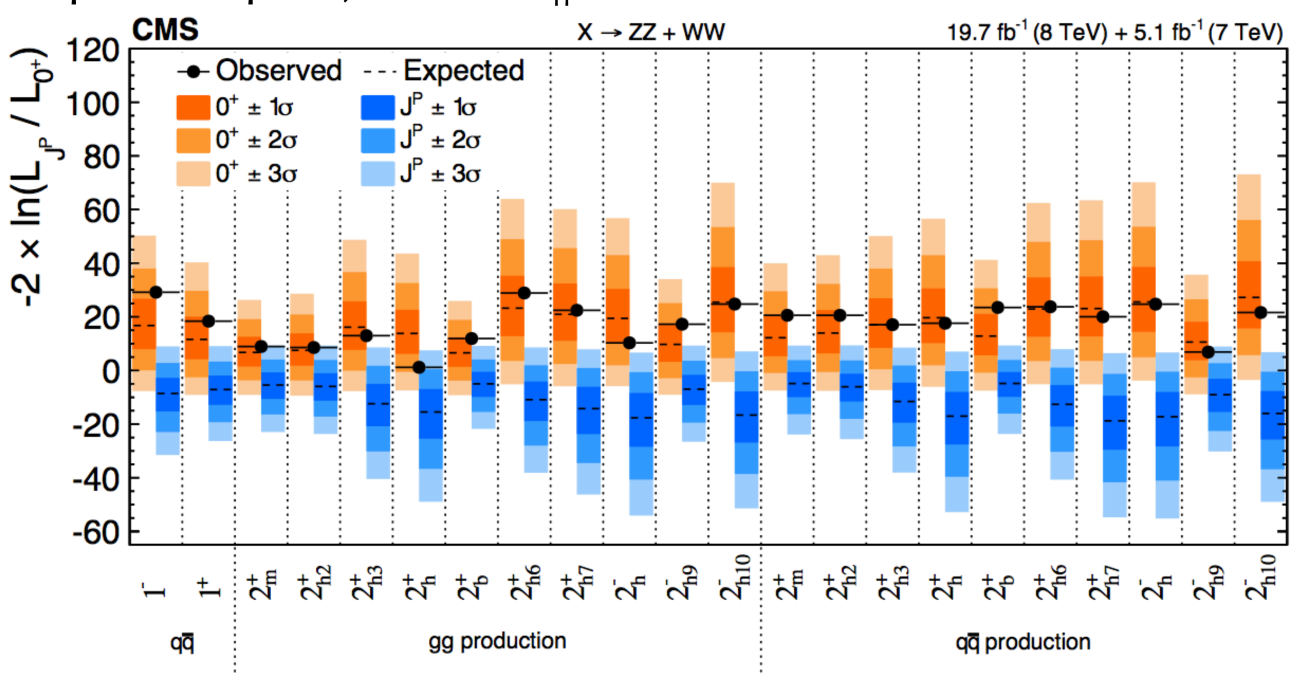
The information is condensed in a set of discriminants



Phys. Rev. D 92, 012004 (2015)
arXiv:1411.3441

Exotic spin

- We tested **different BSM spin and CP hypotheses** in HWW and HZZ
  - → Exotic spin-1 or spin-2, BSM 0^- 0^+_h



All spin-1 hypotheses excluded at > 99.999% CL , Spin-2 boson 2^+_m, excluded at a 99.87% CL, other spin-2 hypotheses excluded at a ≥99% CL

→ Spin 0 particle favored

Spin-0: CMS

- **Once the exotic spin hypothesis is ruled out** → study of the tensor structure of the HVV interactions setting **limits on anomalous couplings** under spin-0 assumption

- The decay amplitude for a spin-0 boson to a pair of V bosons can be described as:

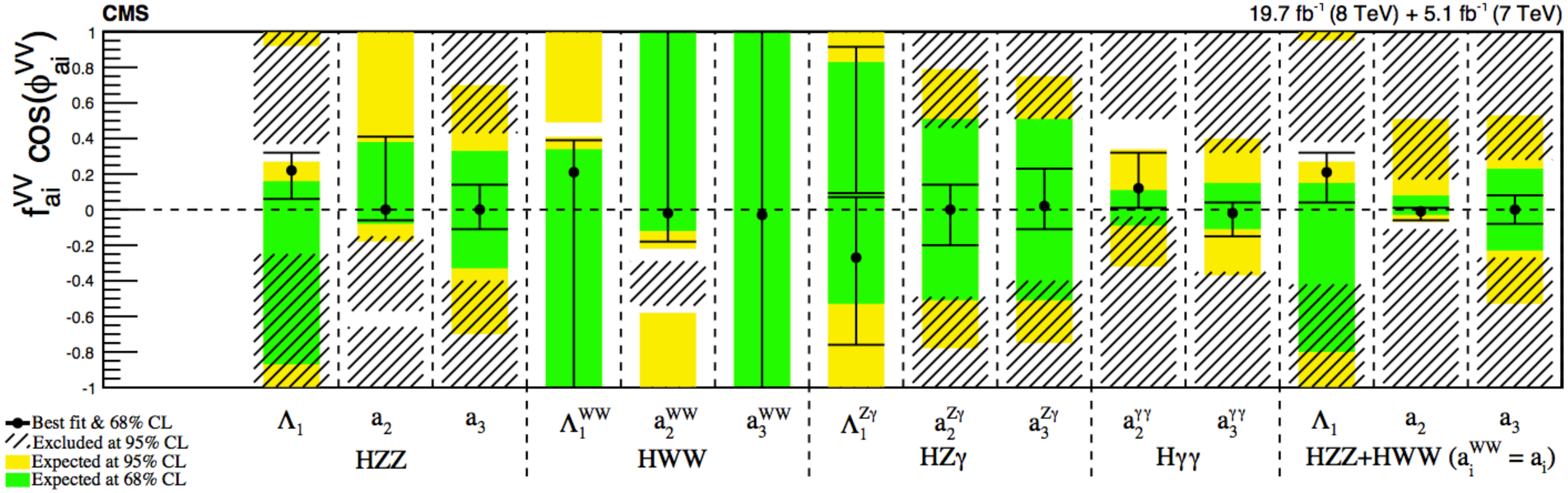
$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \underbrace{\frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2}}_{\Lambda_1 \text{ term, leading momentum expansion}} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \underbrace{a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu}}_{a_2 \text{ term, CP even state}} + \underbrace{a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}}_{a_3 \text{ term, CP odd state}}$$

- We choose a parameterization that relates the anomalous couplings coefficients: a_2, a_3, and Λ_1 to cross sections fractions (f_{a2}, f_{a3}, $f_{\Lambda 1}$)

- **The analysis is based on likelihood scans for the three effective fractions**
  - Full set of scans available in ZZ and WW decays → all consistent with the SM

Summary of anomalous couplings

- **Allowed confidence level intervals** for anomalous coupling parameters assuming real coupling ratios (π or 0)



Parameter	Observed	Expected
$(\Lambda_1\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda_1})$	$[-\infty, -100\,\mathrm{GeV}] \cup [103\,\mathrm{GeV}, \infty]$	$[-\infty, 43\,\mathrm{GeV}] \cup [116\,\mathrm{GeV}, \infty]$
a_2/a_1	$[-0.58, 0.76]$	$[-0.45, 1.67]$
a_3/a_1	$[-1.54, 1.57]$	$[-2.65, 2.65]$

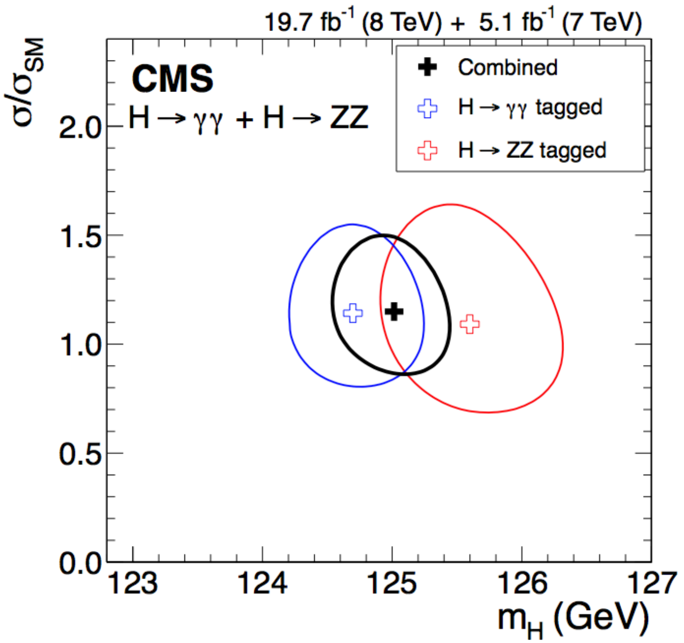
- Assuming custodial symmetry: **pure 0_h^+ (related to f_{a2}) excluded at 99.93% CL and pure 0^- (pseudoscalar, related to f_{a3}) excluded at 99.99% CL**

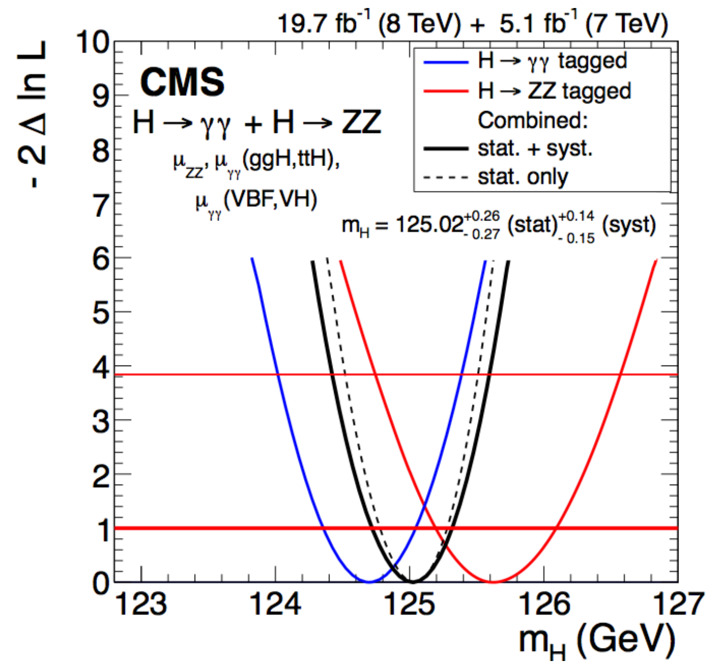
Mass measurement

- CMS performed a **combined Higgs measurement** using information from all the channels studied during Run-1
- In the high-resolution $\gamma\gamma$ and ZZ channels, the mass of the Higgs boson is determined to be:

m_H = 125.02 +0.26 (stat) +0.14 (syst) GeV

Eur. Phys. J. C 75 (2015) 212
arXiv:1412.8662

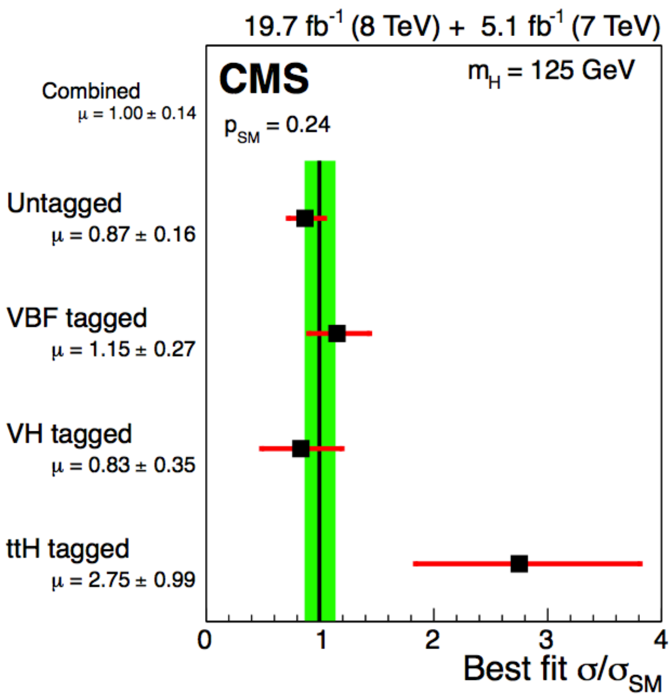


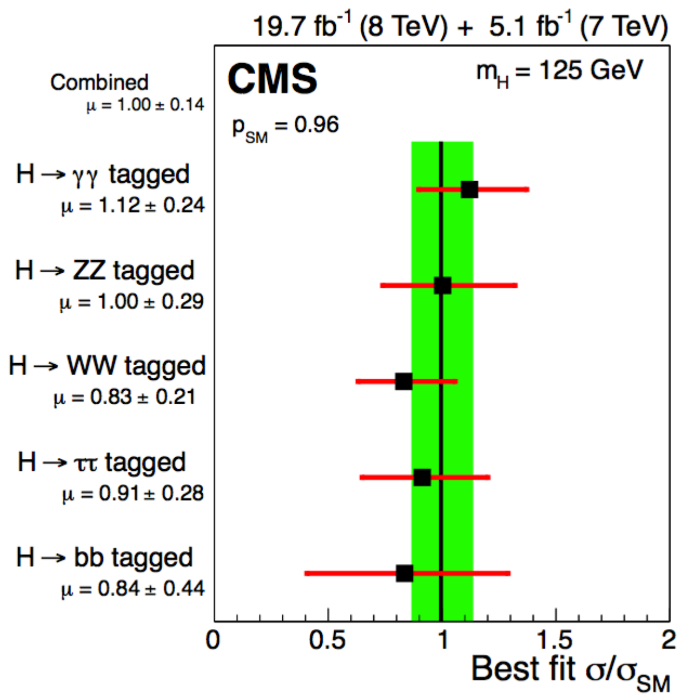


Compatibility with SM σ

- The combined best-fit signal relative to the standard model expectation at the measured mass is:

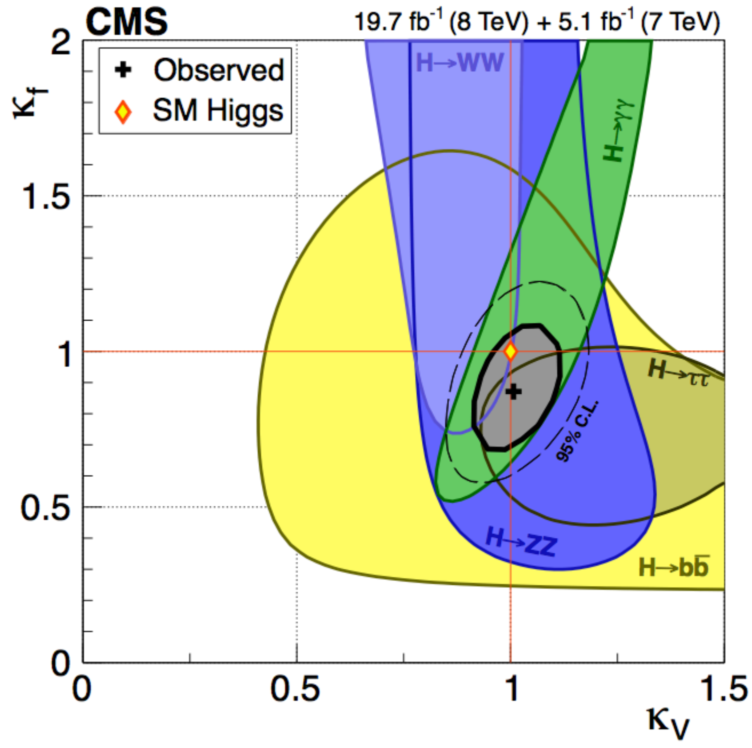
$$1.00 \pm 0.09\,(\text{stat}) + 0.08\,(\text{theo}) \pm 0.07\,(\text{syst})$$

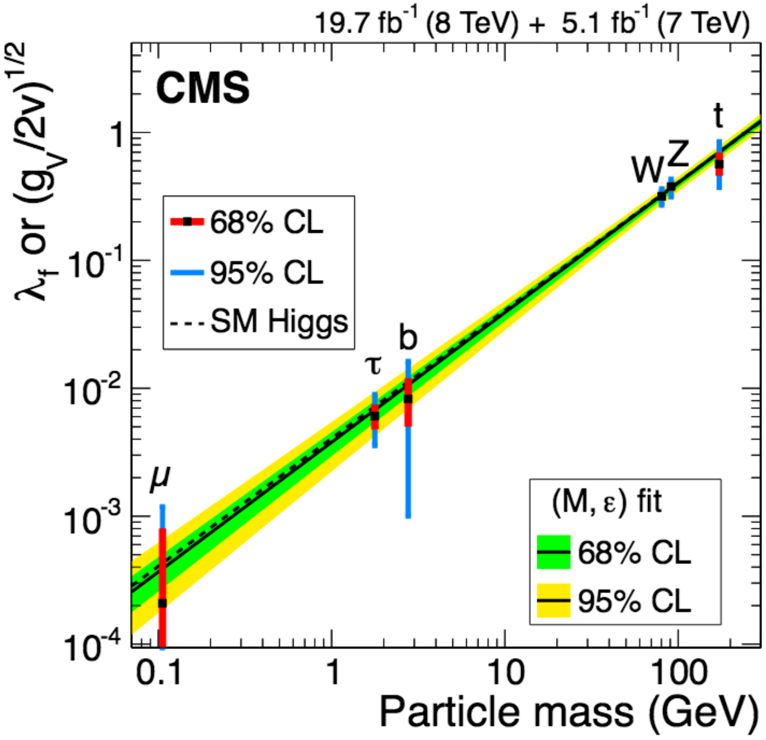




Couplings deviations

- The couplings to massive vector bosons and fermions are also explored



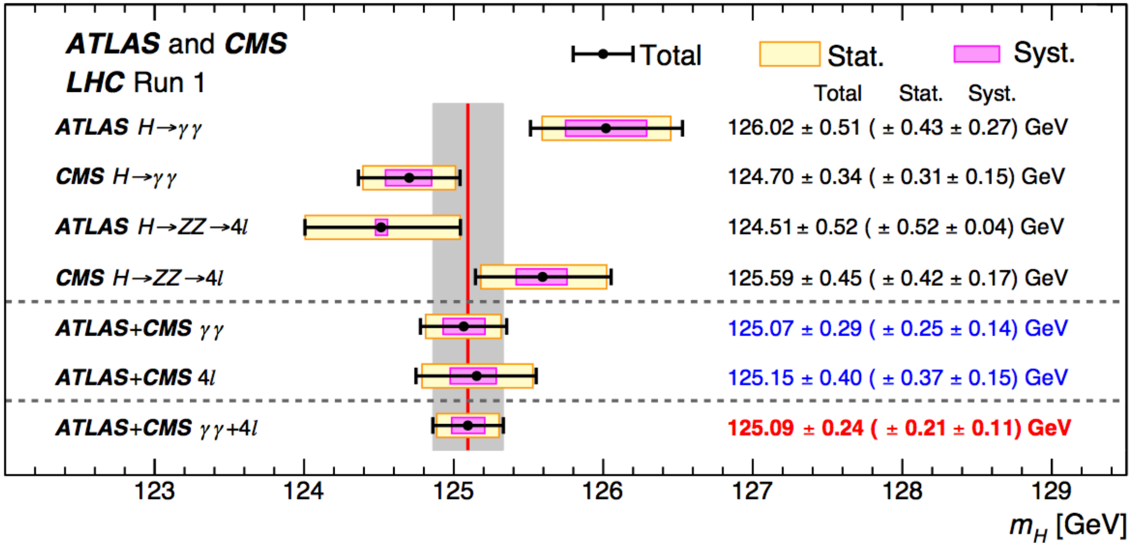


Within uncertainties, everything is consistent with a SM Higgs

LHC mass combination

- Combination of the Run 1 data from the two experiments, leading to improved precision for m_H *(0.2%)*

Phys. Rev. Lett. 114, 191803 (2015)
arXiv:1503.07589

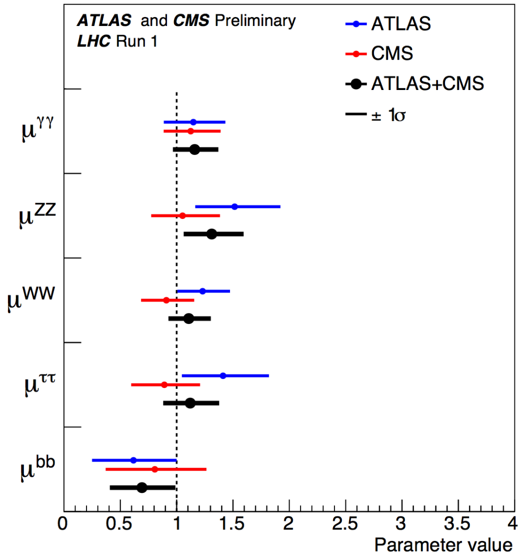


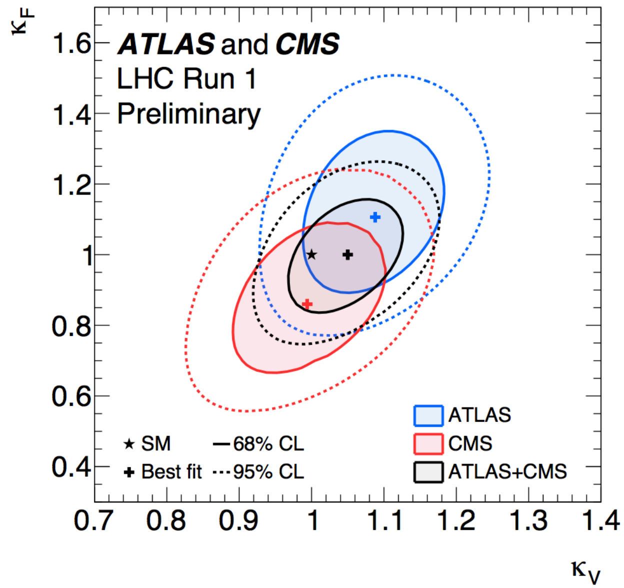
m_H=125.09±0.24 GeV=125.09±0.21(stat.) ±0.11(syst.)GeV

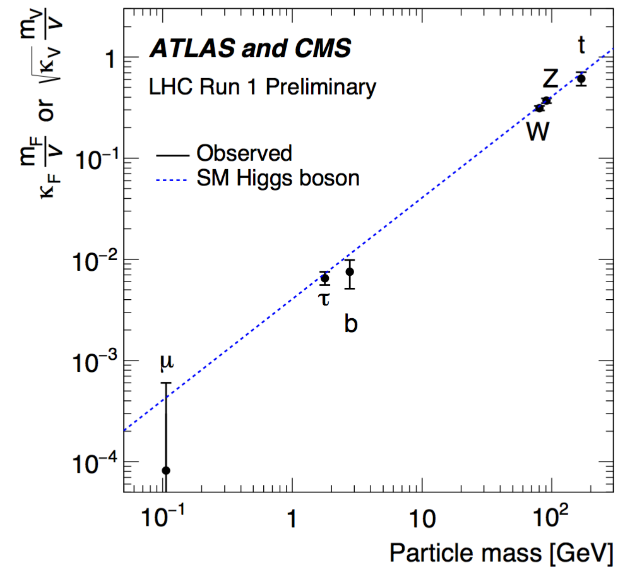
- The uncertainty is dominated by the statistical term, systematic uncertainty dominated by the energy/momentum scales/resolution of γ, e, and μ

LHC combination

CMS-PAS-HIG-15-002





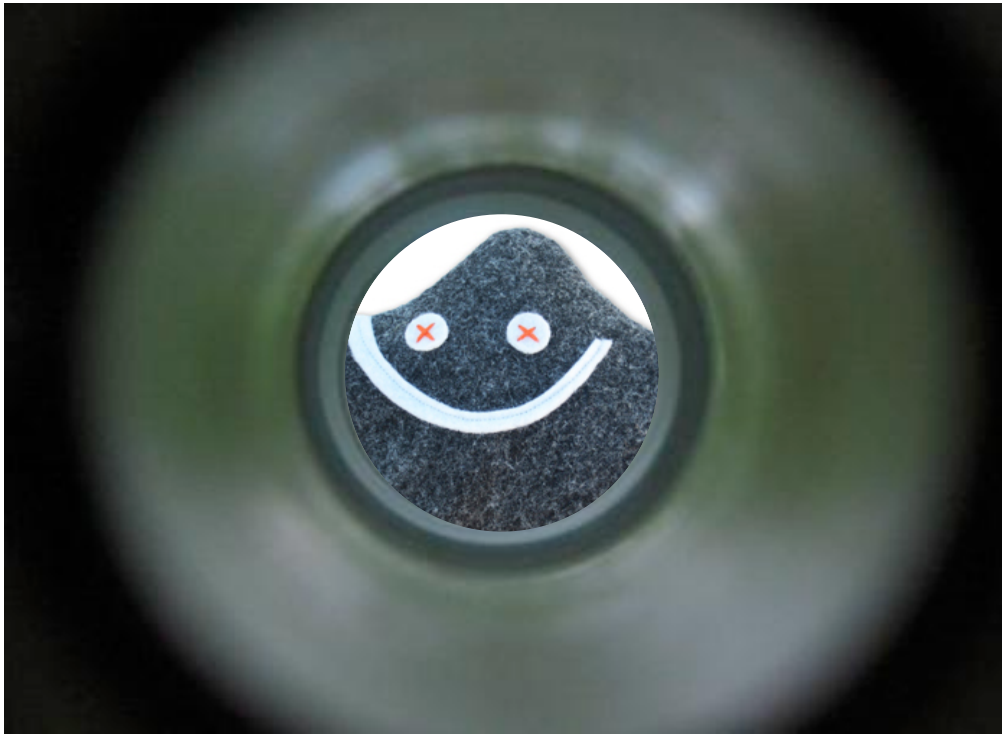


The combined signal yield relative to the SM expectation is measured to be **1.09±0.11**

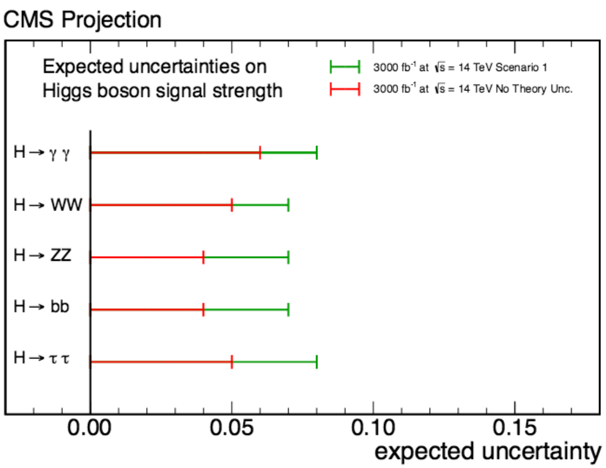
It achieved observation of $H \rightarrow \tau\tau$ and VBF production, not possible by the experiments on their own

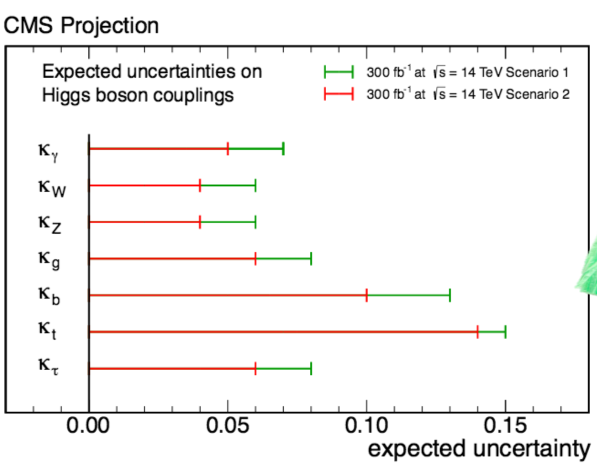
Weak neutral resonance, with quantum numbers $J^{CP} = 0^{++}$, coupling strengths compatible with the SM Higgs boson, and a mass of 125.09, well within the allowed SM Higgs mass in the EWK fits

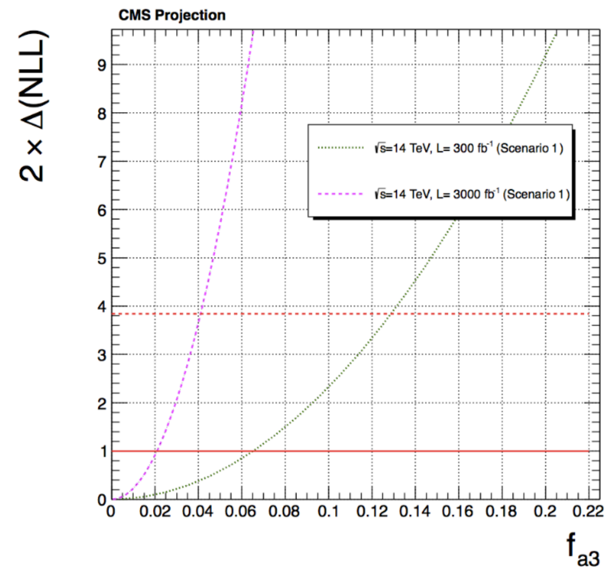
Looks like the SM Higgs from here



But only more data will tell







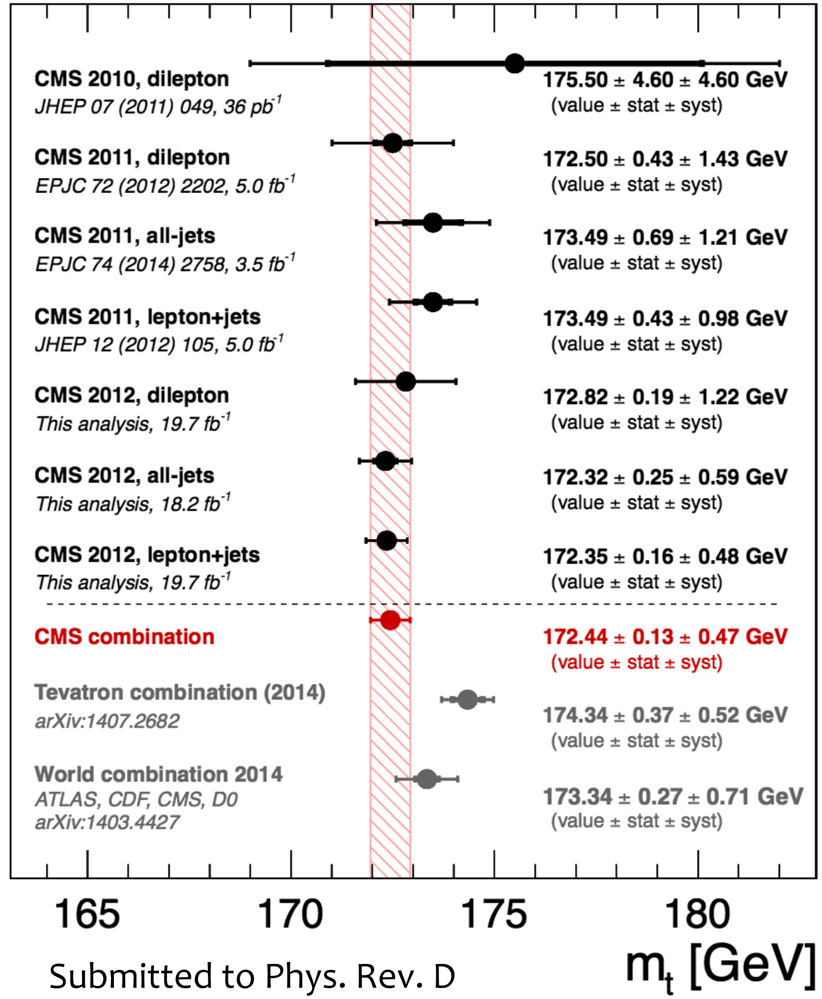
Projections at 14TeV-300/3000 fb^{-1}
From Snowmass
arXiv:1307.7135

Top physics at the LHC today

Early analyses at 13TeV

The top quark

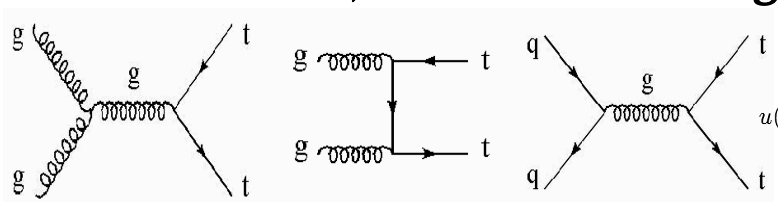
- **The Tevatron legacy**, together with a certified top factory → we are getting to know the top quark really well
- Already in the high precision regime:
  - **m_{top} =172.44±0.13 (stat)±0.47 (syst) GeV**
  - prompts for a better understanding on how to link our simulation to fixed order calculation of m_{top}
- The **heaviest elementary particle known**
- Short lived → only quark that decays before hadronizing
  - direct access to properties
- Good candidate to play a role in many scenarios of physics beyond the SM

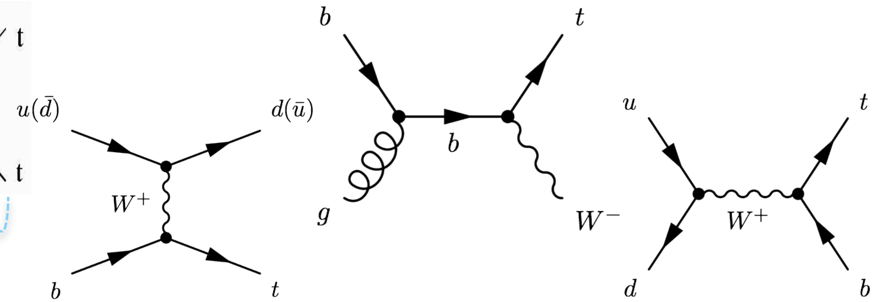


Submitted to Phys. Rev. D
arXiv:1509.04044

Production and decay

- At the LHC, top quarks are produced mainly in **ttbar pairs** → **strong interaction**
- Alternative mode, at a lower rate: **Single top quark production**→ **EWK interaction**

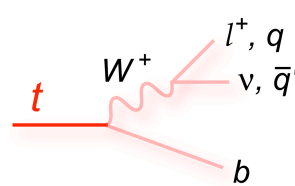




σ [pb]	ttbar	t-channel	tW	s-channel
Tevatron (1.96TeV)	7.08	2.08	0.22	1.046
LHC @ 7TeV	177.31	63.89	15.74	4.29
LHC @ 8TeV	252.89	84.69	22.2	5.24
LHC @ 13TeV	831.76	216.99	71.2	10.32

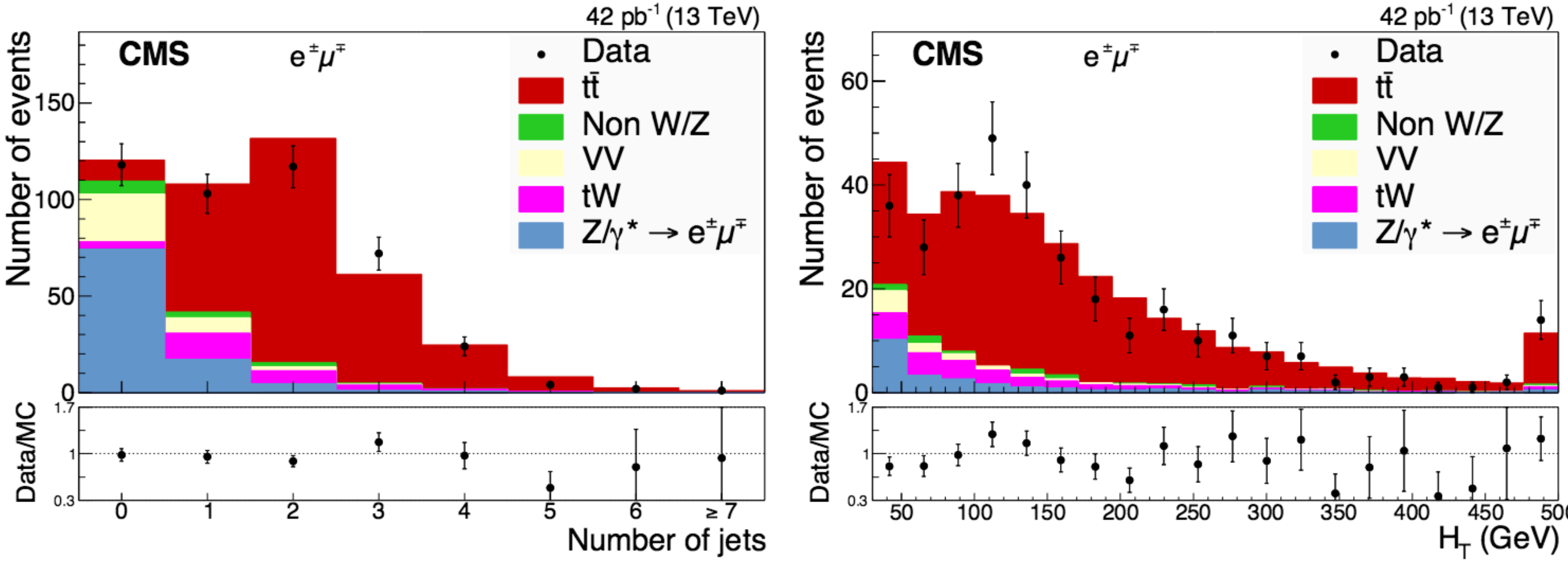
Top quarks decay almost exclusively as t→Wb

- **W → lnu (~32%), qq (~67%)**



Dilepton cross section at 13TeV

- Already with the very early data of Run-2 we measured the top pair production cross section
- eμ final state, 42pb^{-1}, no b-tagging
- Main systematics: trigger, lepton identification and isolation efficiencies (<5%)

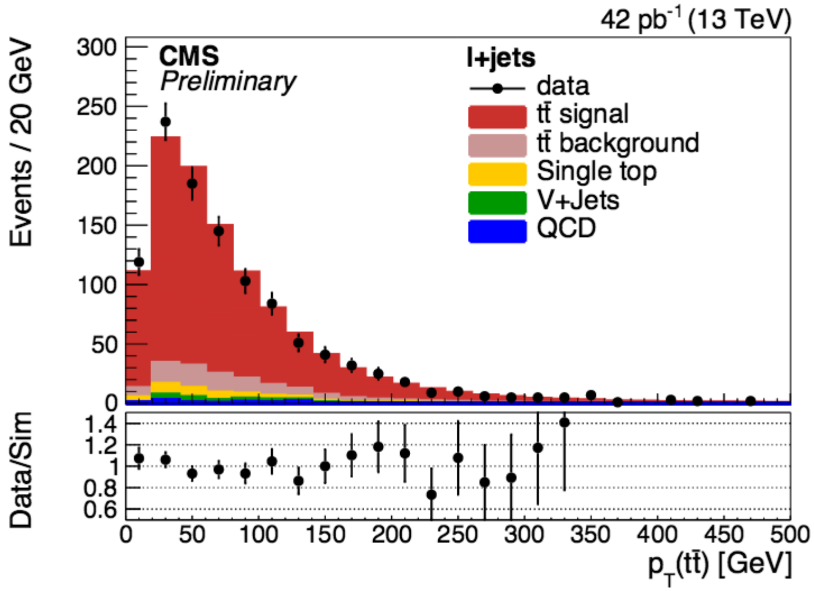


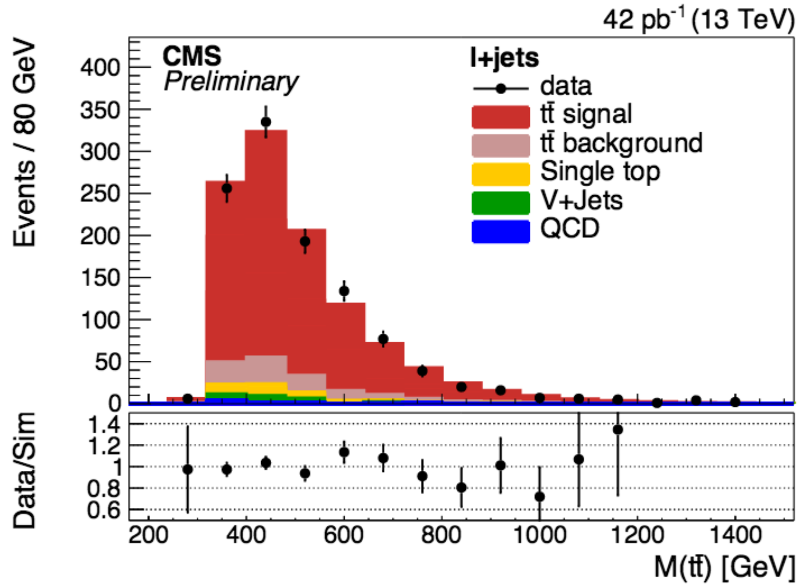
σ_{tt}= 769±60 (stat)±55 (syst)±92 (lumi) pb

Submitted to Phys. Rev. Lett
arXiv:1510.05302

l+jets cross section at 13TeV

- With the same luminosity, also the l+jets channel is explored
- Events with at least four jets (one b-tagged) and exactly one e or μ
- Full system reconstructed
- Main systematic uncertainties: b-tagging, PDF (~5%)





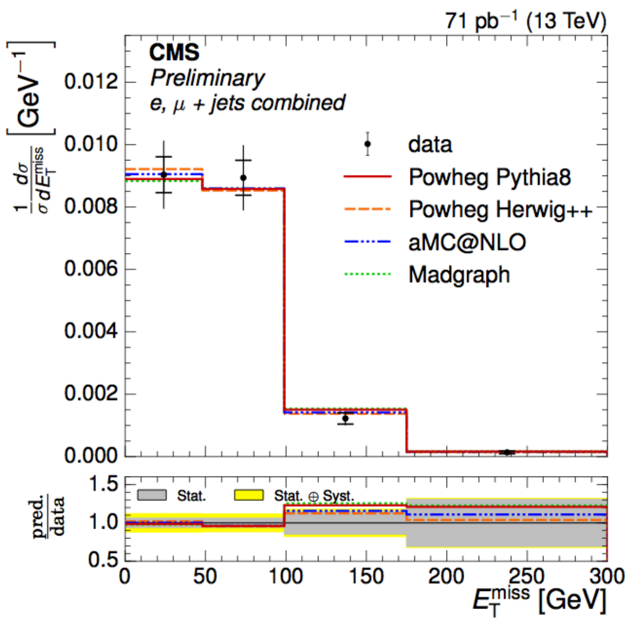
σ_{tt}= 836±27(stat)±84(sys)±100(lumi) pb

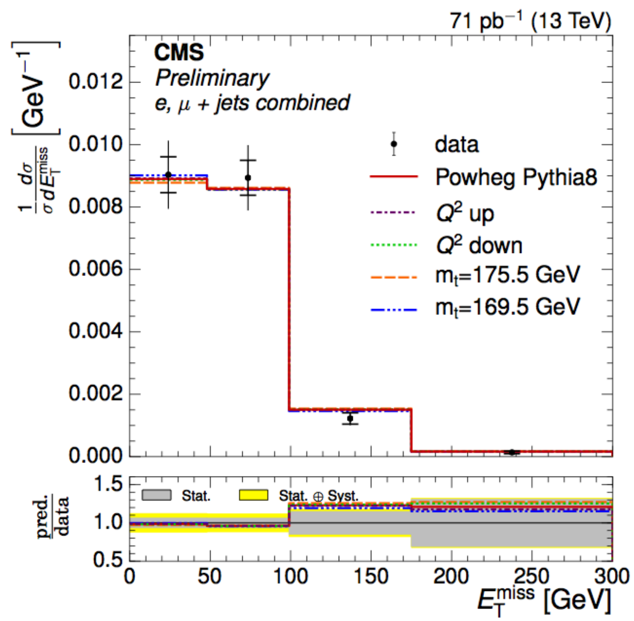
CMS-PAS-TOP-15-005

Differential distributions

- With 71pb^{-1} at 13TeV, in the l+jets channel
- The distributions of $\mathbf{E_T^{miss}}$, $\mathbf{H_T}$, $\mathbf{S_T}$, $\mathbf{p^W_T}$, **jet multiplicity, lepton** $\mathbf{p_T}$**, and lepton** $|\eta|$ are **unfolded to particle level** and compared to predictions from different event generators and MC tunes
- Main systematic uncertainties: modeling of the hadronization, choice of NLO generator, QCD background estimation

CMS-PAS-TOP-15-013

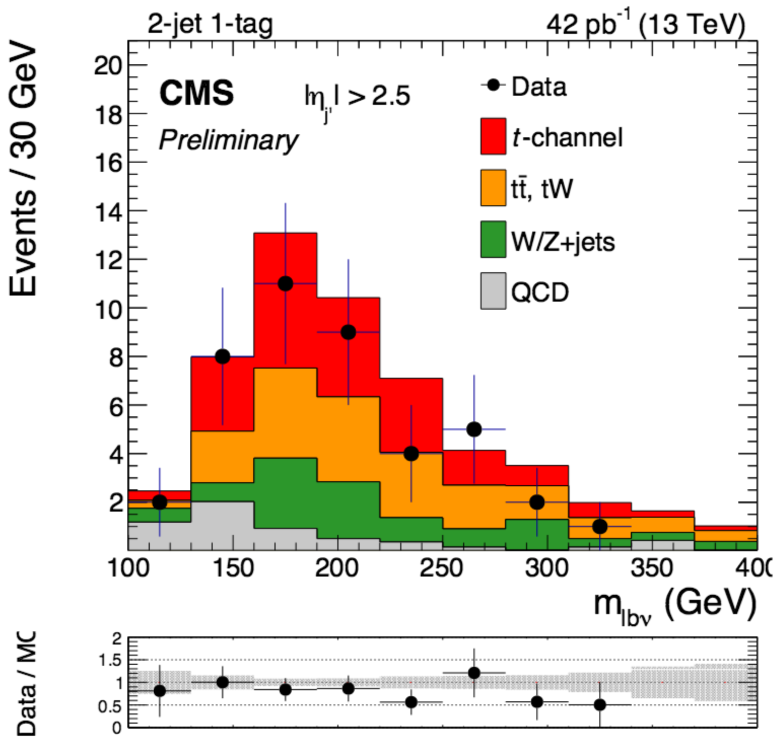




MET distribution: bridge from top to ttH, H→invisible, and to tt+SUSY
See for example: arXiv:1408.0011

Single top at 13TeV

- Already with $42pb^{-1}$ → single top cross section is measured in the t-channel



μ only
Follows Run-1 strategies
cross section from a fit on the pseudorapidity of the light-quark jet that comes from the hard scattering process -often forward-, $|\eta_{j'}|$

Statistically limited
Main systematic: JES
Observed significance: **3.5σ**

$\sigma_{t\text{-channel}}$ =274±98(stat.)±52(syst.)±33(lumi.) pb

Once a rare top production mode that was also observed for the first time here (2009), the single top production is already a SM candle

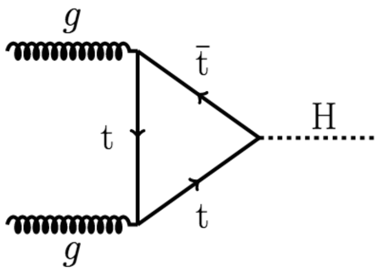
Top AND Higgs physics at the LHC today

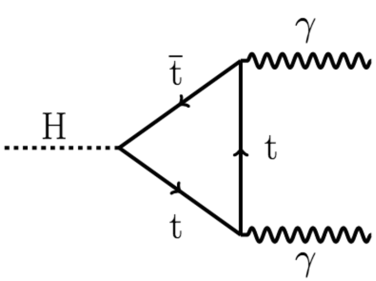
Looking at the future

Top - Higgs coupling

- **The top-Higgs coupling is very strong in the SM**, and because the top is heavier than the Higgs → it cannot be assessed by measuring Higgs decays to top quark pairs

Can be experimentally constrained in **gluon fusion production** → happens via a fermion loop, top provides the dominant contribution -assuming no new physics are contributing to the loop





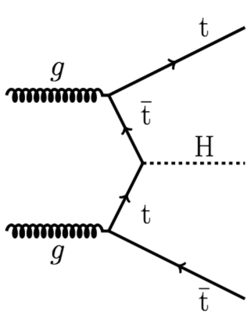
H→γγ has a fermion loop diagram dominated by the top-quark contribution

Within uncertainties, current measurements are so far consistent with the SM expectations

> Probing the top-Higgs Yukawa coupling directly requires a process that results in both a Higgs boson and top quarks explicitly reconstructed via their final-state decay products

Production: ttH

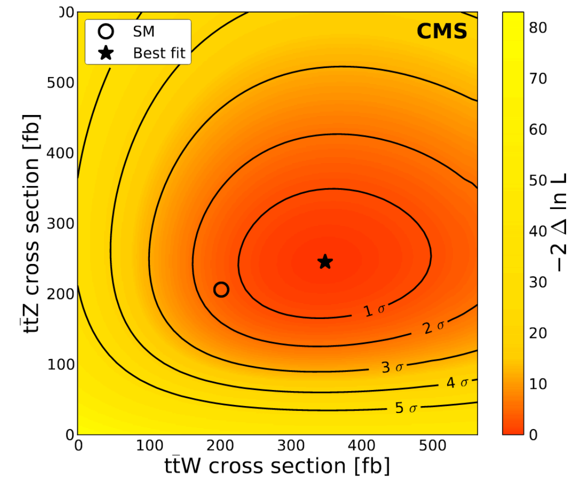
- **Higgs produced in association with a top pair**
- It does not happen often:
  - It is the **sixth process** in terms of production cross section at the LHC (with a slightly lower rate than bbH) → 0.5pb at 13TeV
    [though grows fast with √s → 0.13pb at 8TeV]
- But when it does, it is flashy:
  - Final states with a Higgs decay and two tops → **HWWbb**
- With Run-1 data, we have studied this production in all possible channels
  - H→bb
  - H → γγ
  - H→WW
  - H→ZZ
  - H → ττ



JHEP 09 (2014) 087
arXiv:1408.1682

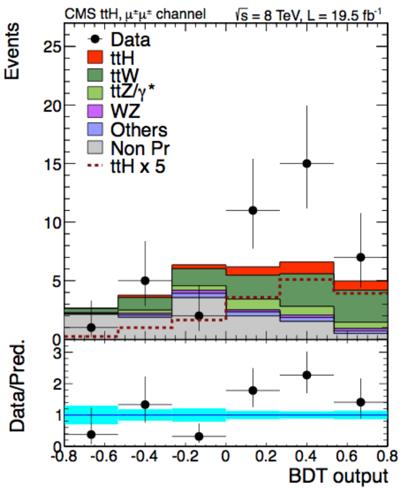
Direct bridge from top physics: tt+V processes

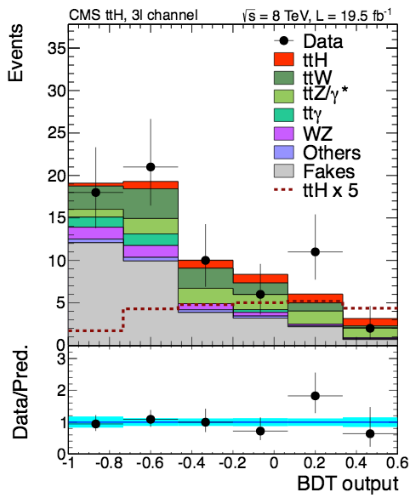
Submitted to JHEP
arXiv:1510.01131

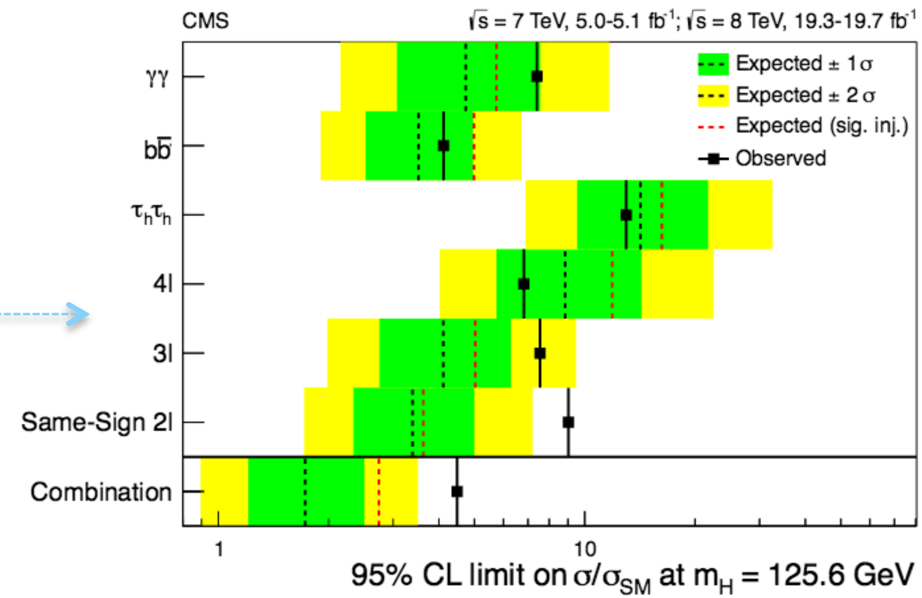


Production: ttH

- **All channels are statistically limited**, no statement can be said regarding ttH production with Run-1 data, but limits are set
- All the channels studied are combined and the best-fit value for the signal strength is 2.8 → excess above background-only of 3.4 standard deviations (2σ upward deviation with respect to the SM prediction)

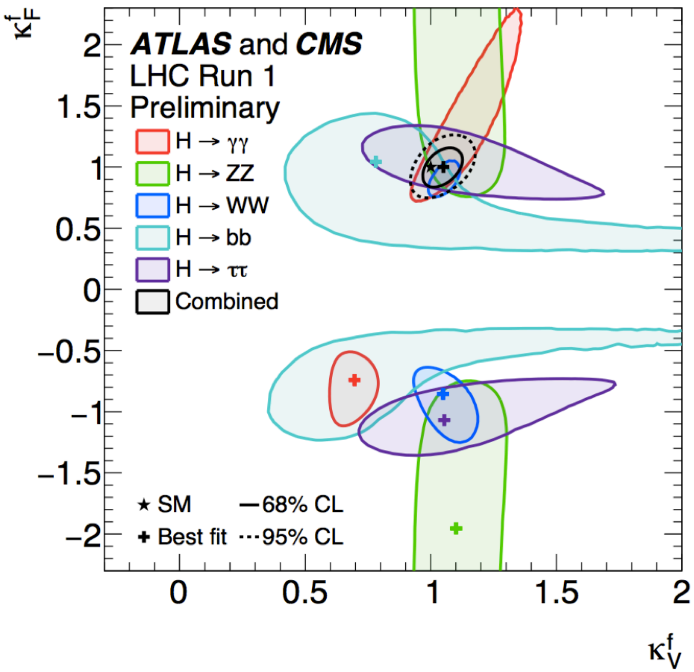


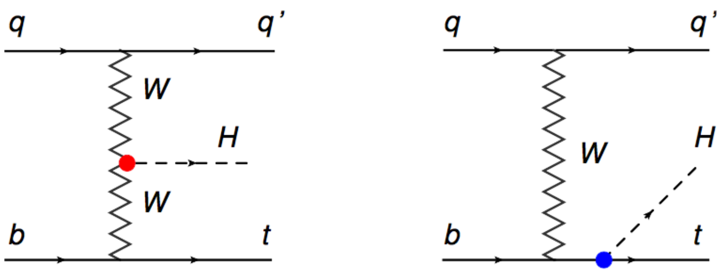




Production: tHq

- However, the only process in which top and Higgs are produced together that is sensitive to **the sign** of the top Higgs coupling is
  - **tHq production**

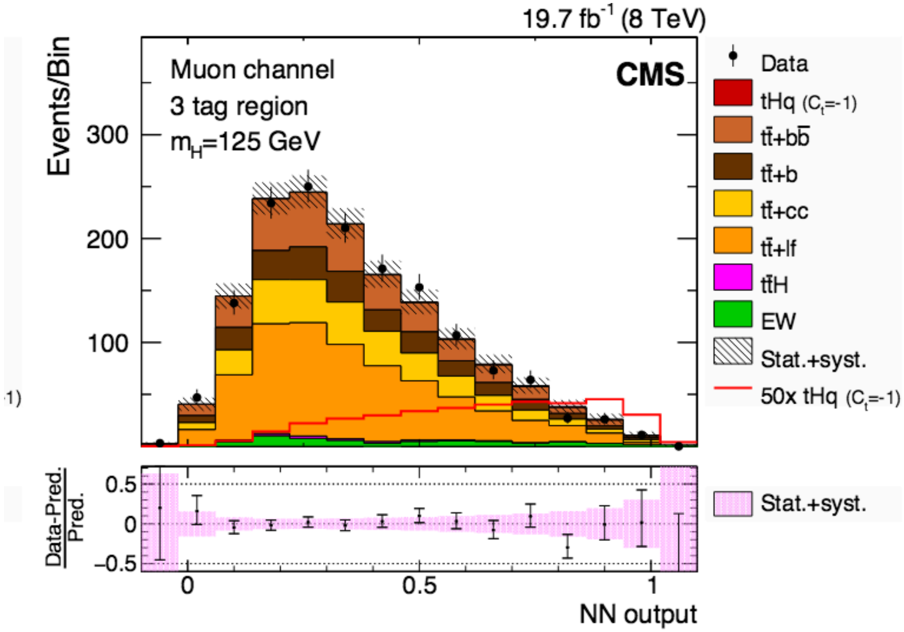




tHq is highly suppressed in the SM (0.018 pb @8TeV)
However, its production rate could be affected by anomalous top-Higgs couplings
In particular, a negative value of the coupling would increase the tHq cross section x15

Production: tHq

- tHq production has very characteristic signatures:
  - A Higgs decay, a top decay (b-tagging), and a forward light jet (single top t-channel handle)
- In CMS we have also studied it using Run-1 data, in almost as many channels as ttH:
  - $H \to bb$*
  - $H \to \gamma\gamma$ *
  - $H \to WW$*
  - $H \to \tau\tau$

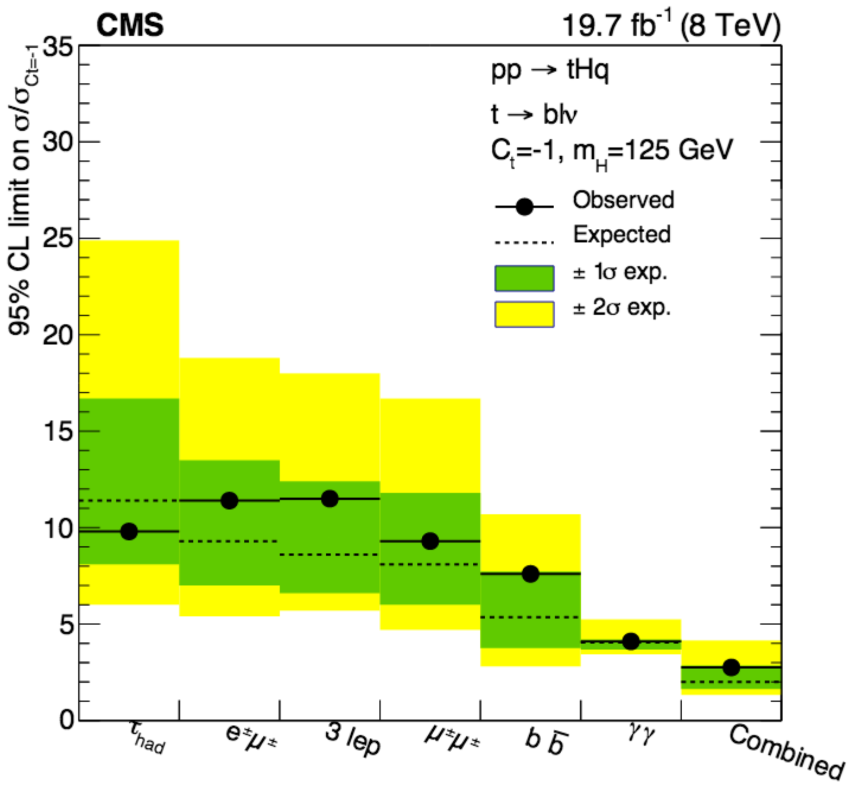


* Each of these had its own independent PAS

Submitted to JHEP
arXiv:1509.08159

Production: tHq

- The sensitivity to a SM tHq will not be reached until well into Run-2 (or 3)
- But sensitivity to a negative coupling will arrive much earlier



Production: tHq

- A **large rate of single top quark plus Higgs** boson events could mean:
  - New physics showing up as **Higgs boson mediated flavor changing neutral currents**
  - Direct production of **heavy new particles** as predicted in composite and little Higgs models
    - **8TeV:** Vector-like T quarks decaying to top quarks and Higgs bosons ($T \rightarrow tH$) [arXiv:1503.01952]

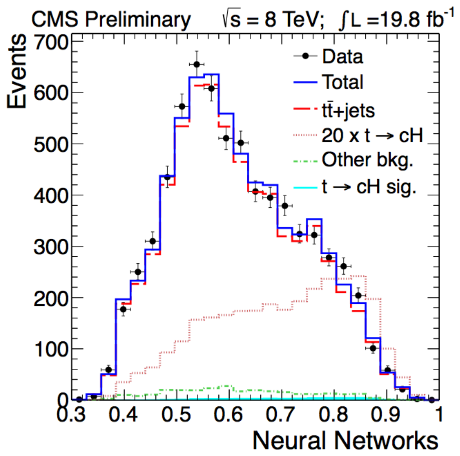
- Moreover:
  - The exclusion of $\kappa_F<0$ is made under the assumption that no new particles contribute to the ggH and $H\rightarrow\gamma\gamma$ loops, and that there are no BSM decays

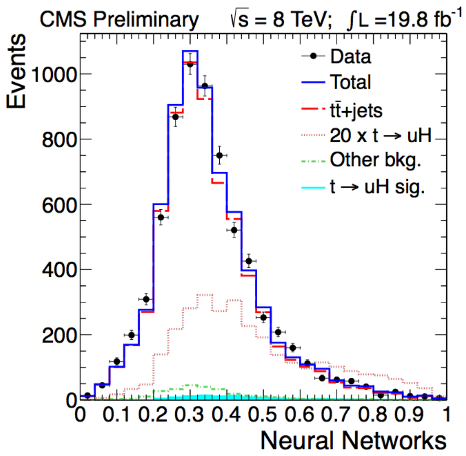
tHq: Sensitive to the size and sign of the top-Higgs coupling, and relative sign between the couplings of vector bosons and fermions to the Higgs + **BSM smoking gun**

Decay: $t \to Hq$

- $t \to Hq$
- Flavor-changing neutral current Higgs (**FCNH**) → SM BR < $O(10^{-13})$
- Extensions of the SM predict a larger branching fraction:
  - two-Higgs-doublet model, R-parity violating MSSM models, warped extra dimensions

- 8TeV analysis exploring **tt→WbHq→lnubbbq**
- Full reconstruction of the top quark mass $\mathbf{m_{Hj}}$ **or** $\mathbf{m_{bW}}$ using MV techniques





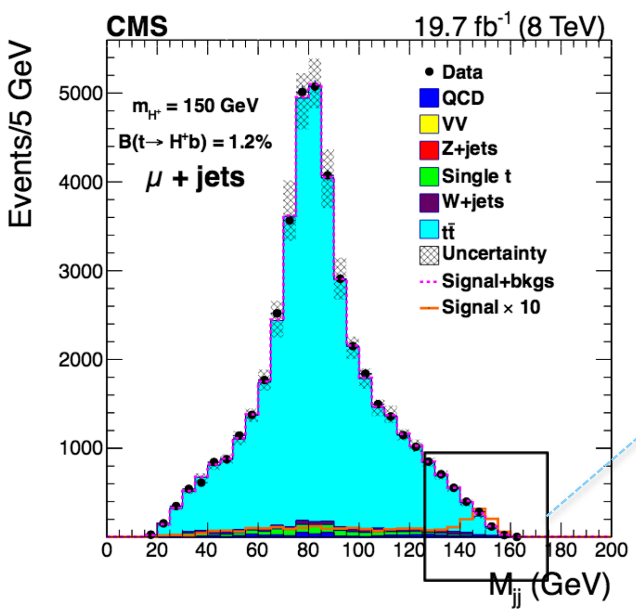
NN are used to extract the signal (separated in $t \to cH$ and $t \to uH$)

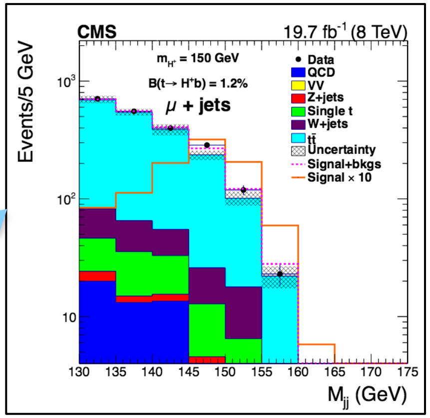
No excess of events over the SM background observed
$B(t \to cH) > 1.16\%$ and $B(t \to uH) > 1.92\%$ excluded at 95% CL

CMS-PAS-TOP-14-020

Charged Higgs searches

- The Higgs sector of the minimal supersymmetric standard model (MSSM) consists of two Higgs doublets→ five physical states:
  - Light/heavy CP-even h/H, CP-odd A, and two **charged Higgs bosons $H^{\pm}$**
- For a low mass charged Higgs, $t\rightarrow H^{+}b$, for $\tan\beta < 1$ in some scenarios, $H^{+}\rightarrow cs$
- **$tt\rightarrow bH^{+}bW$**, $W\rightarrow l\nu$, using Run-1 data





Upper limits on $B(t\rightarrow H^{+}b)$ assuming $B(H^{+}\rightarrow cs)$ =100%
95% CL upper limits in the range 1.2–6.5% for a charged Higgs boson mass between 90 and 160 GeV

Submitted to J. High Energy Phys
arXiv:1510.04252

Ramping up

- The number of top+Higgs results in CMS is increasing with time -and center of mass energy:
- **ttH:**
  - 8TeV: H→bb using ME [arXiv:1502.02485]
  - 7TeV + 5fb-1 of 8TeV: H→bb [arXiv:1303.0763]
- **FCNC decays:**
  - 8TeV: t→Hq, H → $\gamma\gamma$ [PAS-TOP-14-019]
  - 8TeV: t→Hq, H → $WW/ZZ/\tau\tau$ [PAS-TOP-13-017]
- **Charged Higgs:**
  - 8TeV: Light and heavy charged Higgs in tt decay and produced together with a top, decaying either via $H^+\to\tau\nu$ or $H^+\to tb$ [arXiv:1508.07774]
  - 7TeV: Light charged Higgs in tt decays: $t\to H^+b$, $H^+\to\tau\nu$ -tanβ >5 [arXiv:1205.5736]

What's next?

- **Run-2 → we have 3 years ahead, and > 100fb^{-1} to look forward to**
- With the new data:
  - We will scrutinize the top sector in search for new phenomena
    - Rare top decays
    - Heavy resonances decaying to top
    - New particles produced with top
    - Top partners…
  - The Higgs will be fully characterized
    - Precision measurements of properties
    - And many exotic Higgs scenarios studied
  - SM and BSM channels with top and Higgs produced together will be explored
    - Sensitivity to observe ttH production will be achieved
    - top-Higgs Yukawa coupling measured
    - Exotic searches with top and Higgs will become more relevant

Summary

- The Higgs boson and the Top quark could have a role in the search for new physics during Run-2 and beyond → also Top and Higgs together
- We are entering in a precision era for Higgs
  - New physics could be hiding in deviations with respect to the SM
  - So far, **everything consistent with the predictions**
- The LHC continues being very powerful for top physics
  - Unprecedented precision in Run-1
  - **With the first Run-2 data tt and single top t-channel were already studied**
- **Signatures with top and Higgs could be key to future discoveries**
  - First analyses in place during Run-1, will only be sensitive with Run-2 data