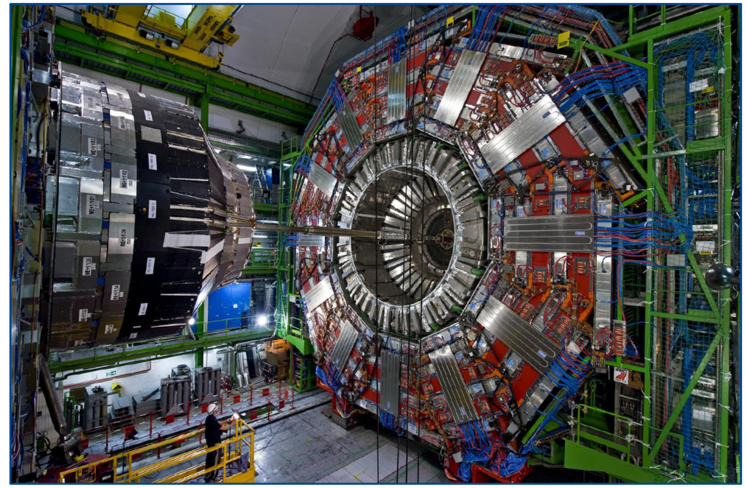


SM Higgs Results @CMS

Mingshui Chen

中国科学院高能物理研究所

牡丹江论坛

2018.09.15-16 济南

Large Hadron Collider (LHC) at CERN

周长27km，跨越瑞士法国国境，位于地下100米

世界上最大、能量最高(质心系能量13TeV)、最贵(～44亿美元)的加速器

Large Hadron Collider (LHC) at CERN

The Higgs boson, found in 2012, “completes” the Standard Model of particle physics.

But ...

- The SM model still does not explain many of the phenomena of our physical universe
  - neutrino masses, baryon asymmetry of the universe, dark matter .....
- Need “Beyond the Standard Model (BSM)”: many ideas, theories and models
  - A broad investigation on many fronts is necessary
- **The discovery of the Higgs boson opens a new window for us to understand the universe**
  - Studying the properties of the Higgs, looking for deviations from the SM predictions ......

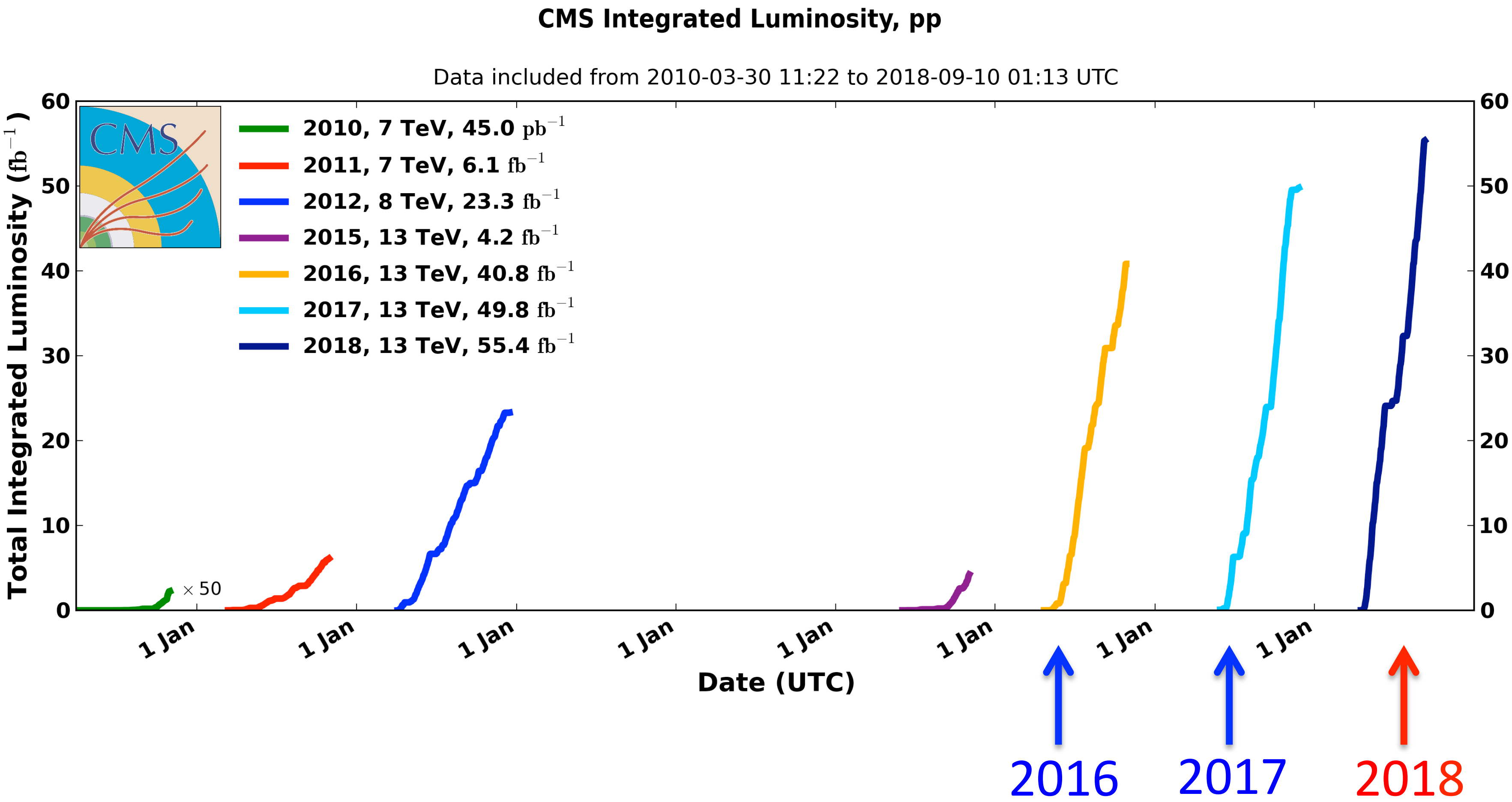
→**Require more statistics**

Outline

- LHC and CMS status
- Recent SM Higgs Results
  - Bosonic Channels
  - Higgs Yukawa interactions
  - Combination
- Outlook and Summary

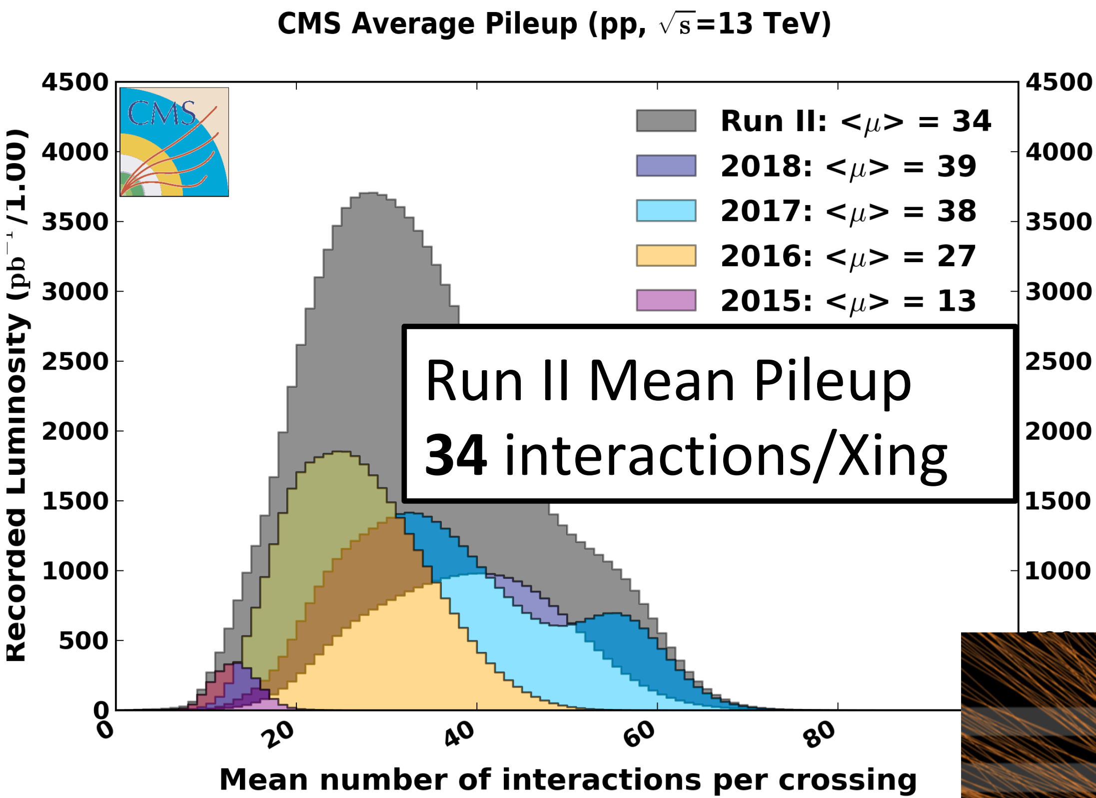
CMS 所有物理结果请参考
http://cms-results.web.cern.ch/cms-results/public-results/publications/

Run Status



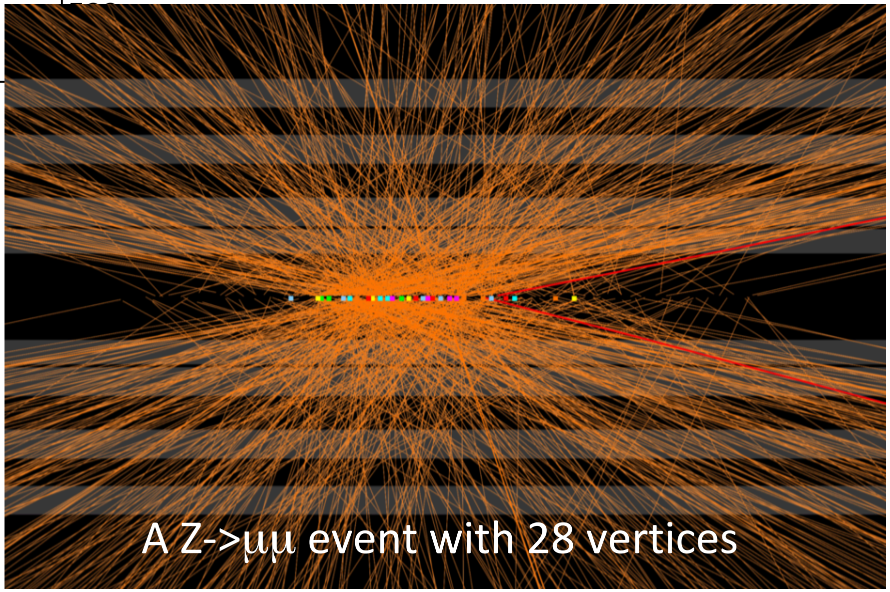
Results shown here mostly based on 2016 w/wo 2017 data

Challenge to the experiments



Run II Mean Pileup
34 interactions/Xing

Peak Lumi.
$\sim 2\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$

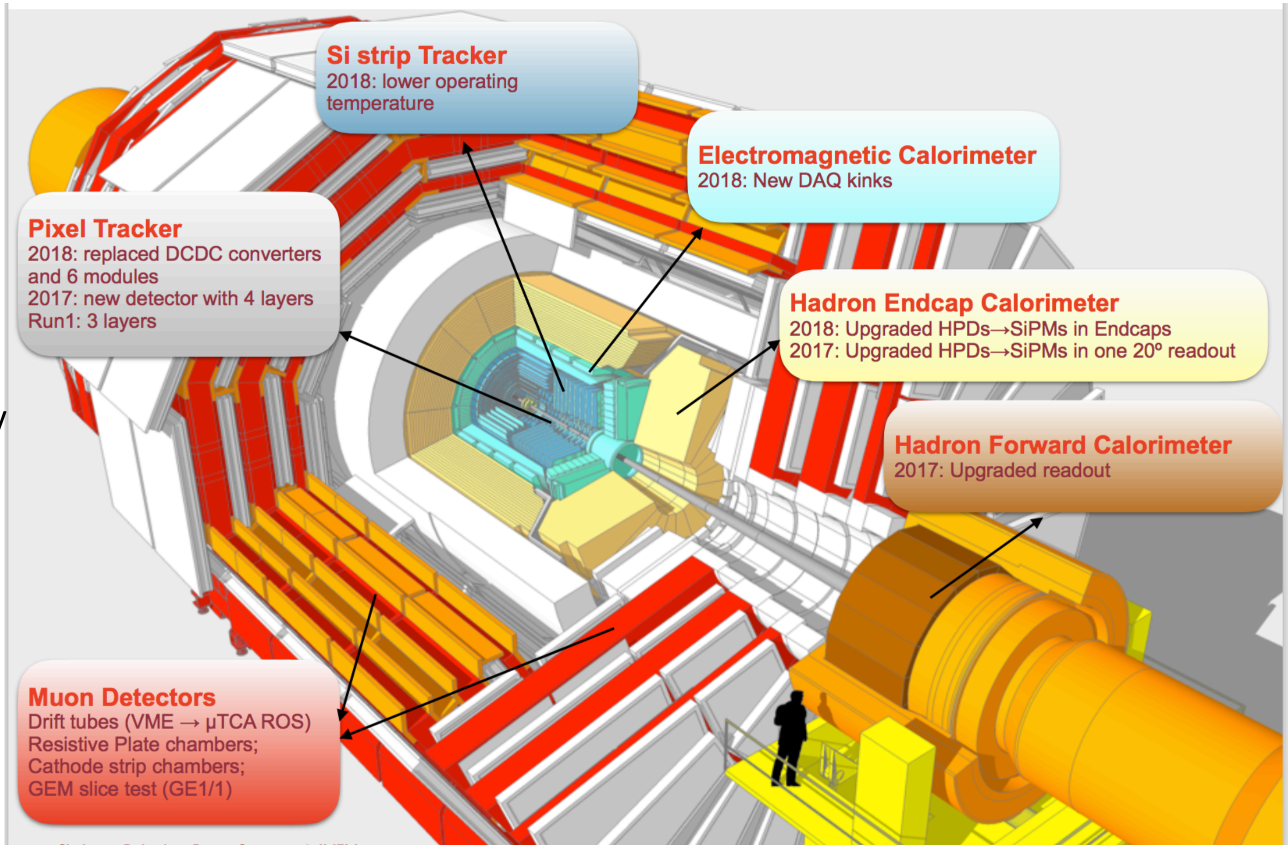


A Z->μμ event with 28 vertices

CMS Evolution in 2017/18

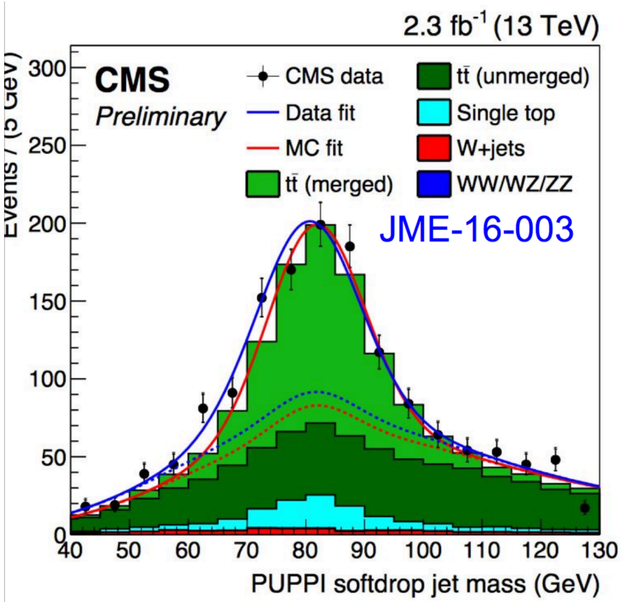
CMS Design

- Very large solenoid - 6m diameter x 13 m long
  - Tracking and calorimetry fit inside
- Very strong field – 3.8T
  - Excellent momentum resolution
- Chambers in the return iron track and identify muons, leading to a very compact system
- A lead tungstate crystal calorimeter (~76K crystals) for photon and electron reconstruction
- Hadron calorimeters for jet and missing E_t reconstruction to η~5
- Charged Particle Tracking with all-silicon components
  - A silicon pixel detector out to radius ~ 20 cm
  - A silicon microstrip detector from there out to 1.1 m
- Weight, dominated by steel, is 14,000 Tons

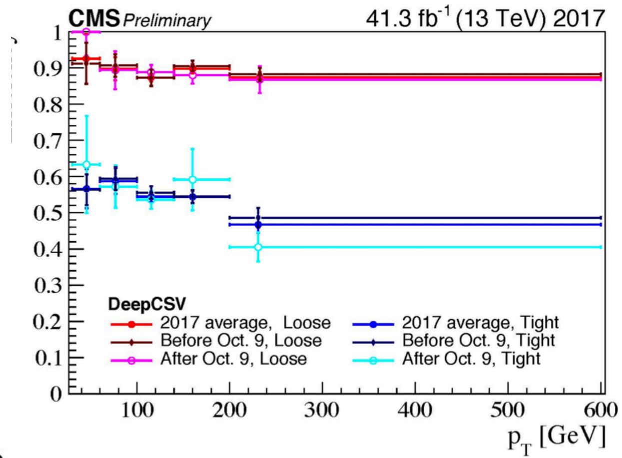


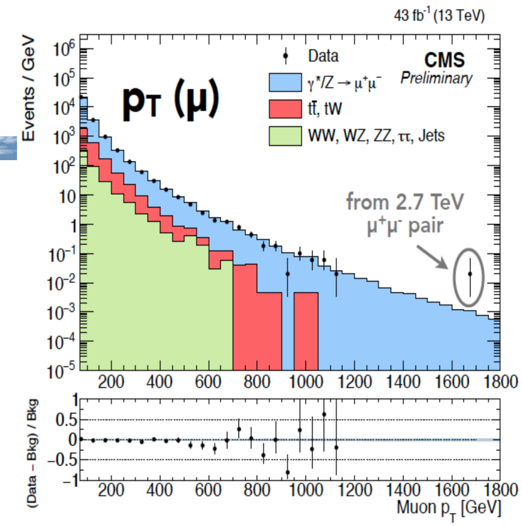
CMS is continuously upgraded to handle higher luminosity and do better physics

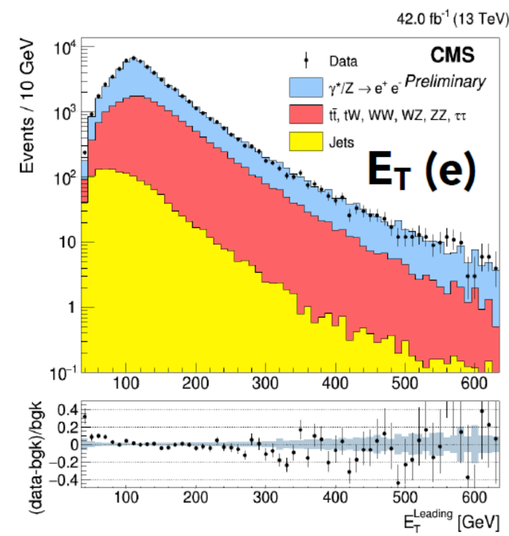
Detector performance

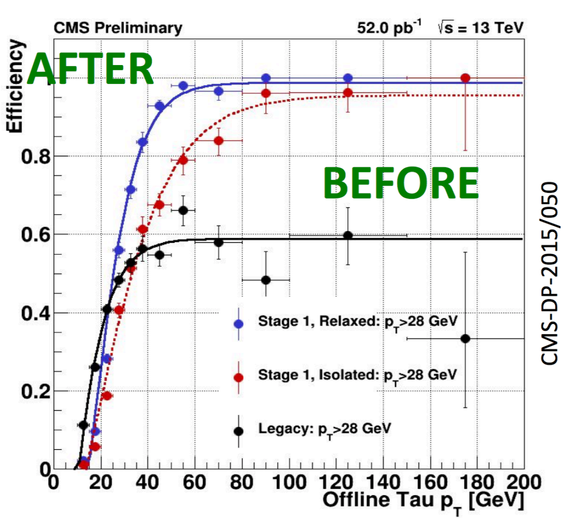


b tagging efficiency

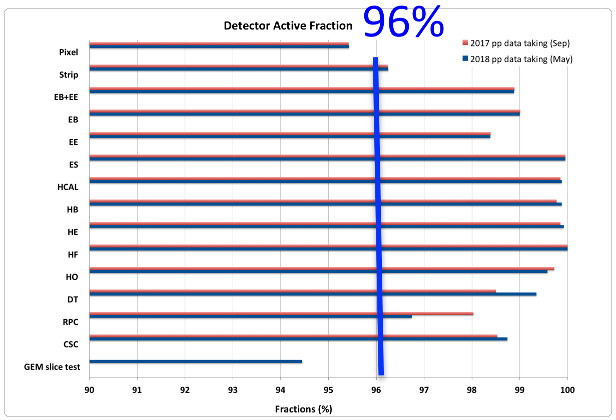




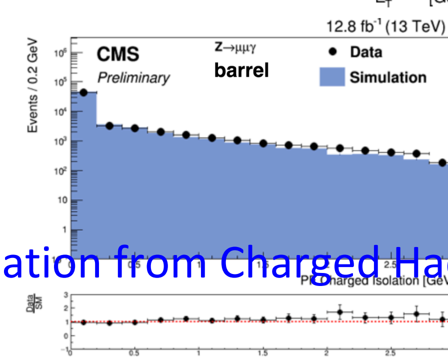




Tau trigger efficiency



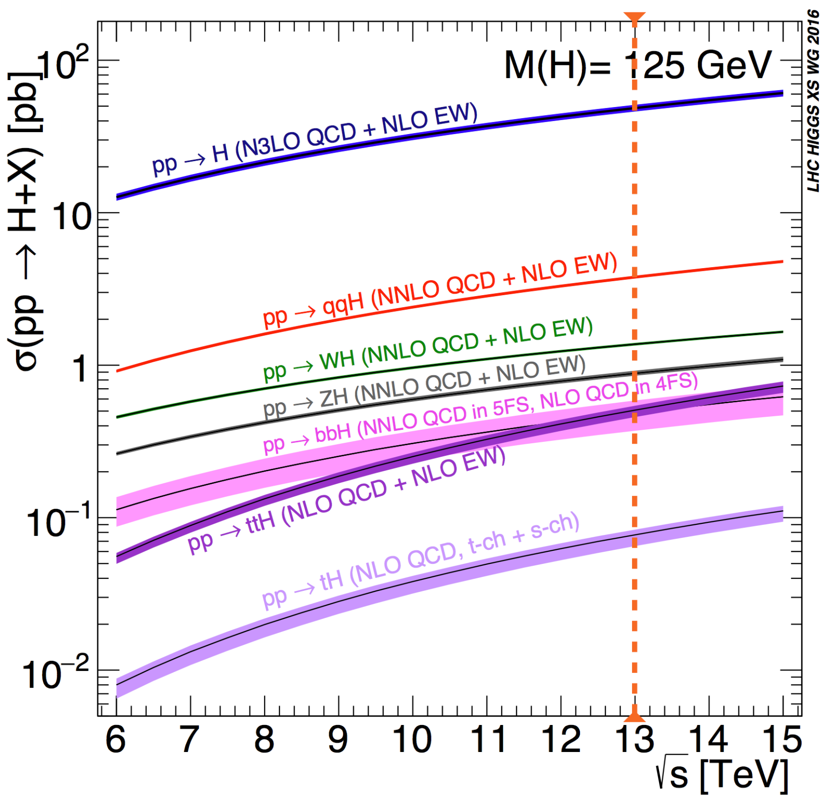
fraction of active channels

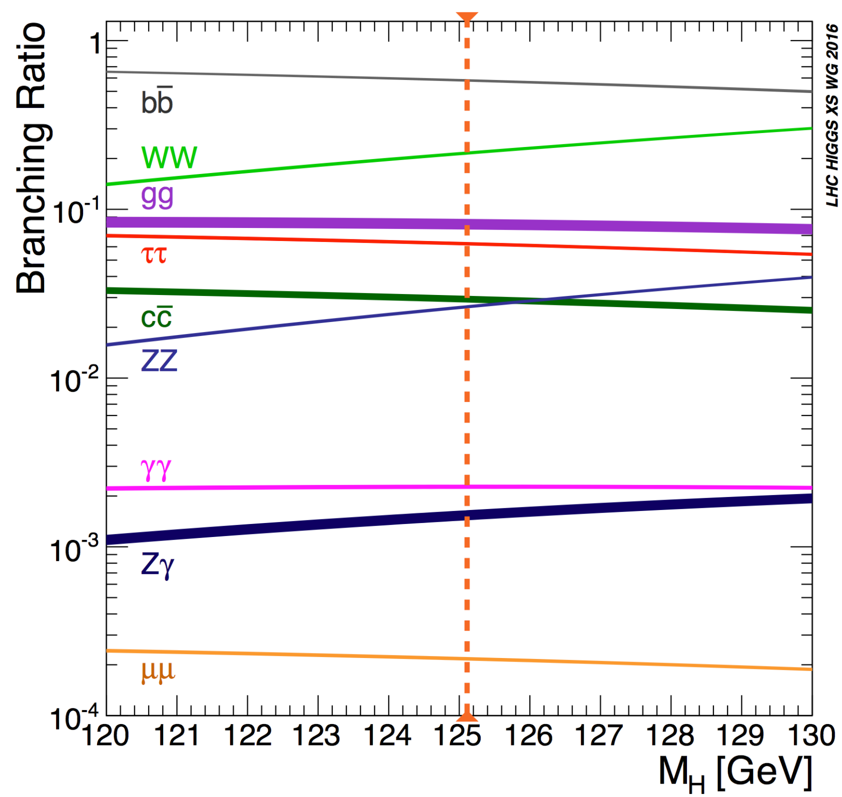


Photon Isolation from Charged Hadron

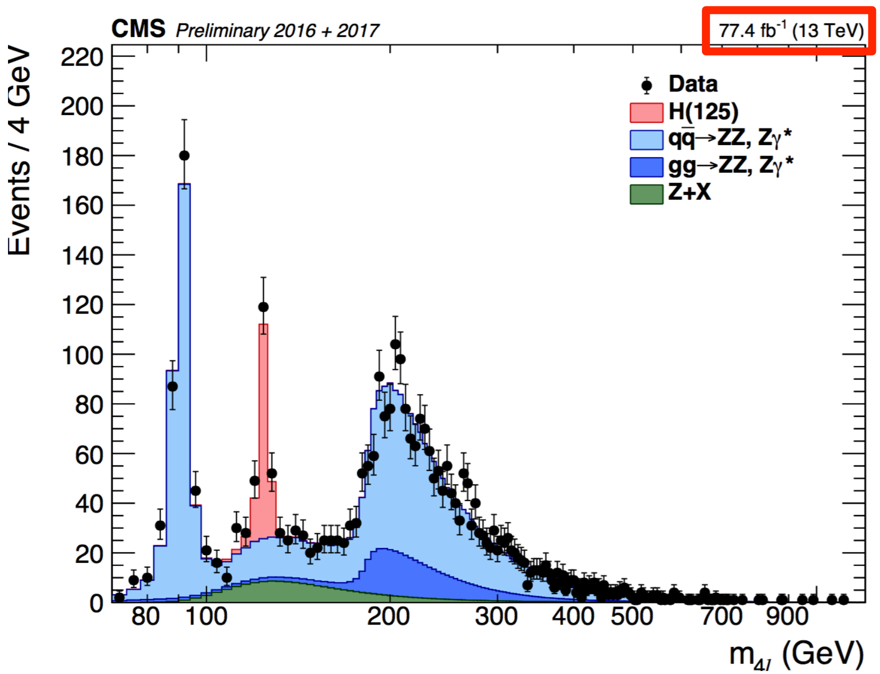
Higgs @ LHC

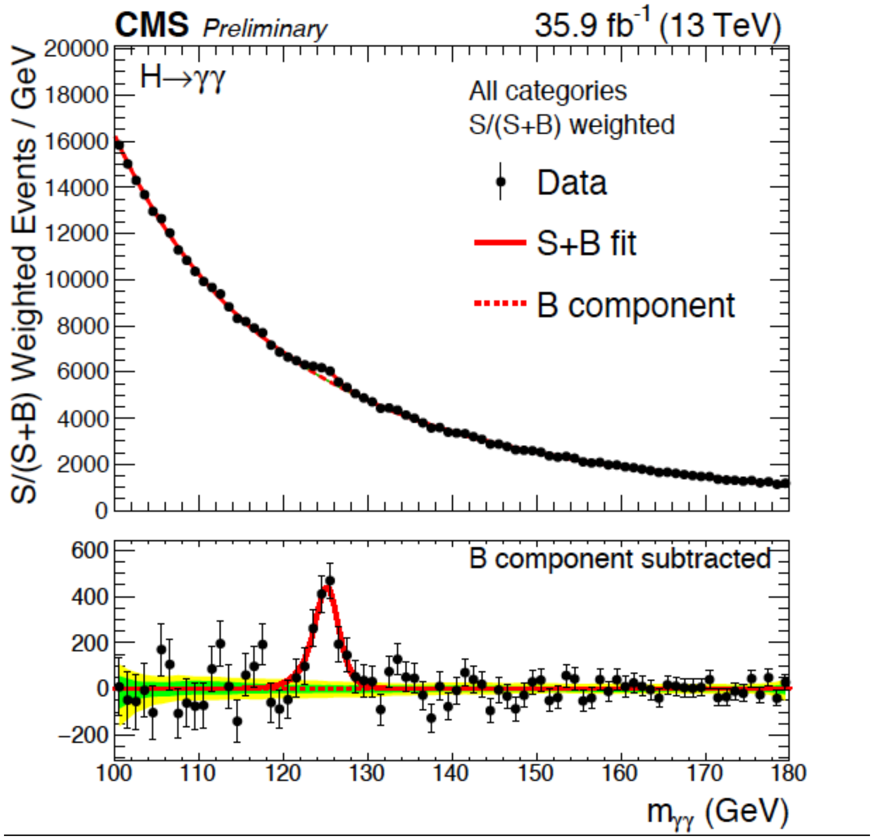
- Thanks to the Higgs mass ~ 125 GeV, very rich program on Higgs @ LHC
- All the main production and decay modes are under scrutiny by ATLAS and CMS





Higgs to bosons – entering precision era

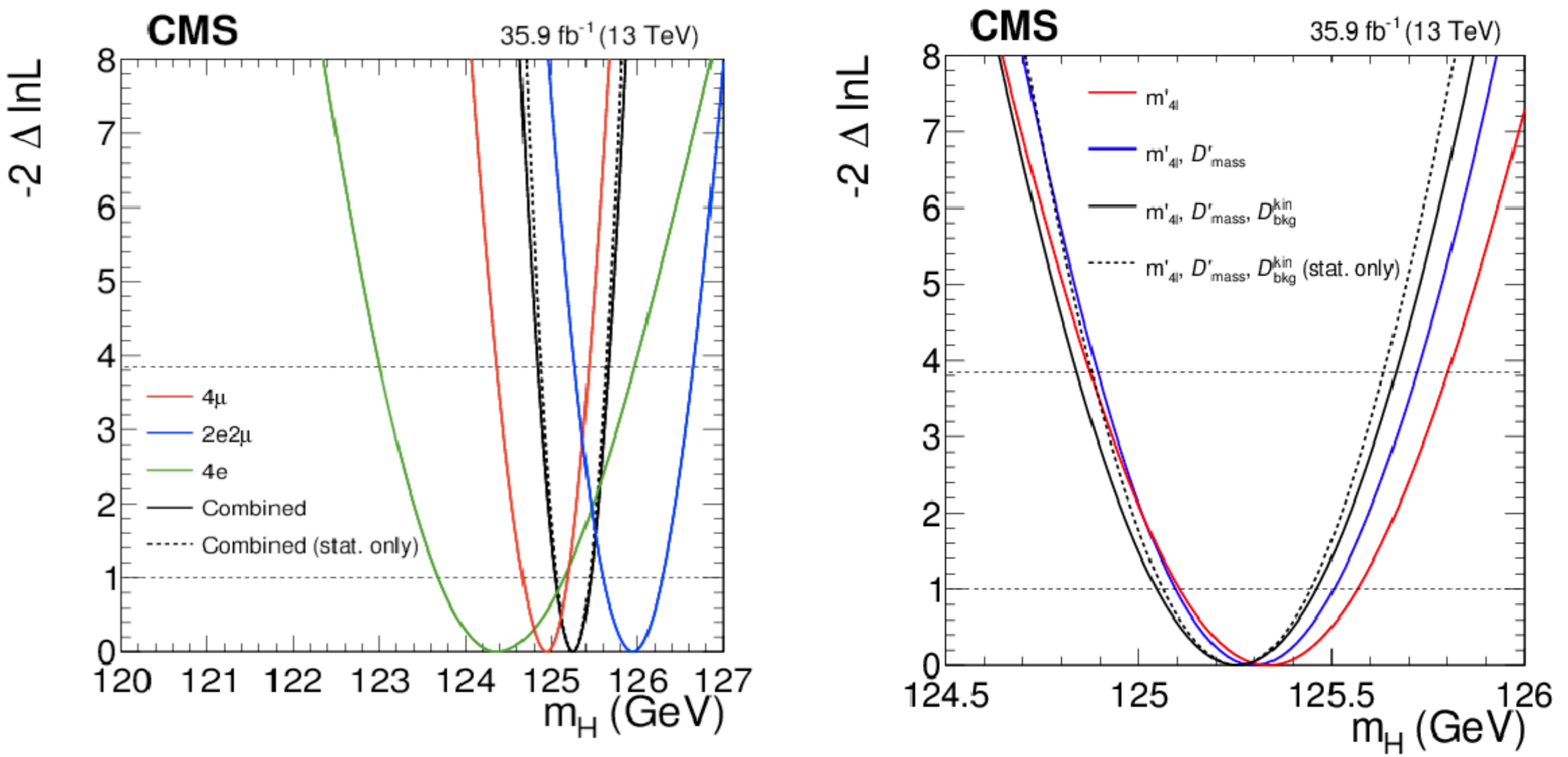




ZZ and γγ: Low branching ratios but clean signatures and full system reconstruction

Higgs mass

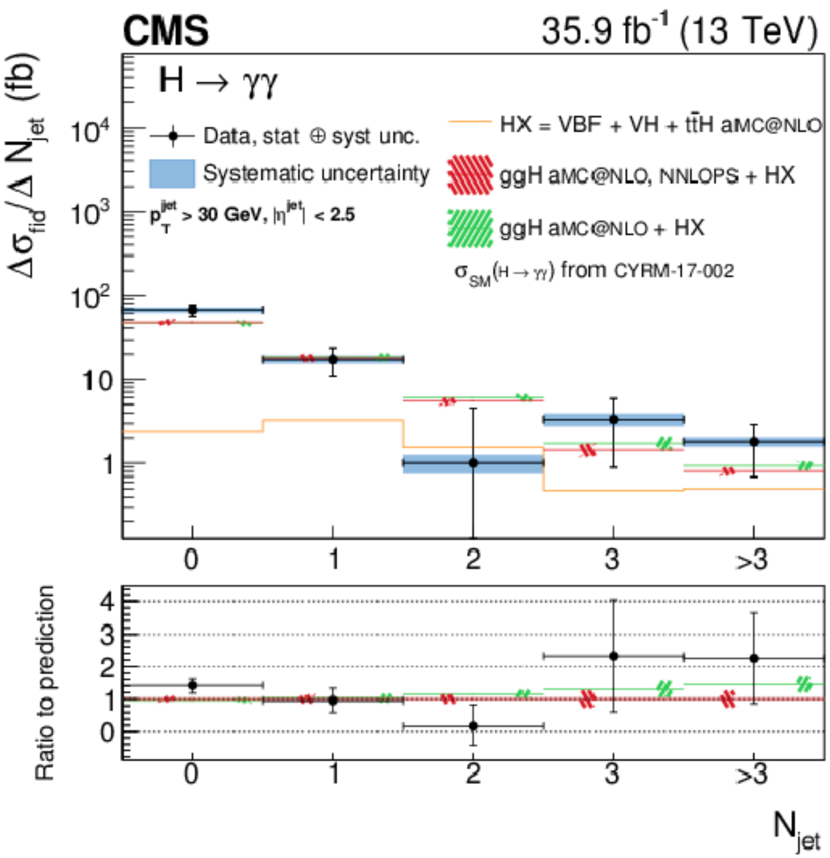
JHEP 11 (2017) 04

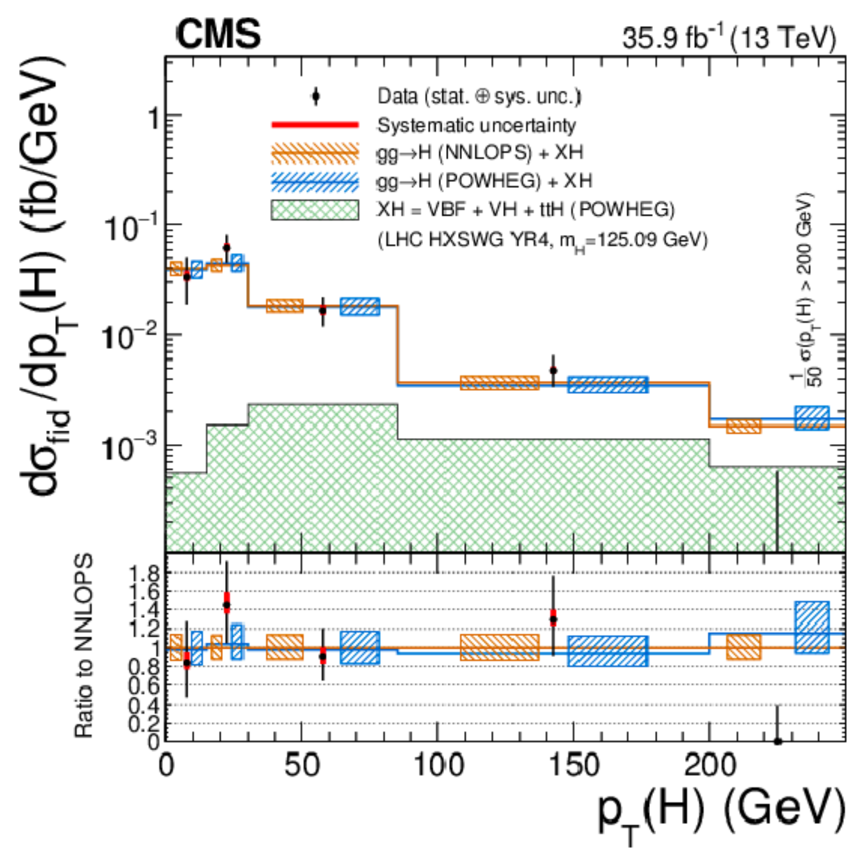


- Most precise measurement at the moment comes from CMS H→ZZ→4l mass measurement with 2016 data
  m_H = 125.26±0.21 GeV
- Still limited by statistical uncertainties → impact on coupling ~0.5%

Higgs differential cross sections

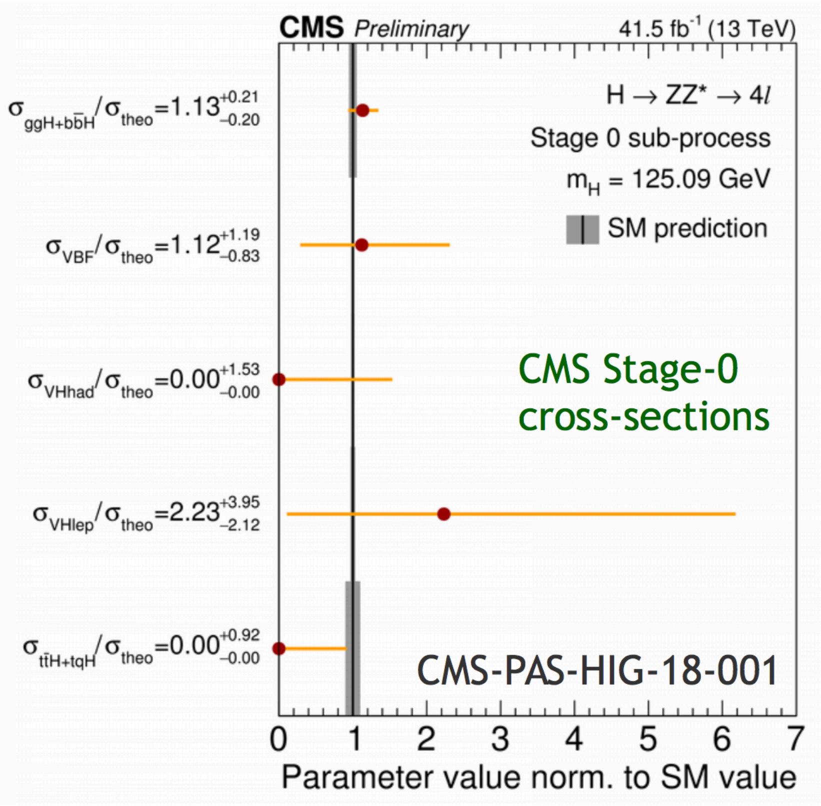
- Measurements of fiducial and differential cross-section distributions made already at Run-1 with low statistics
- Now with more bins and better precision

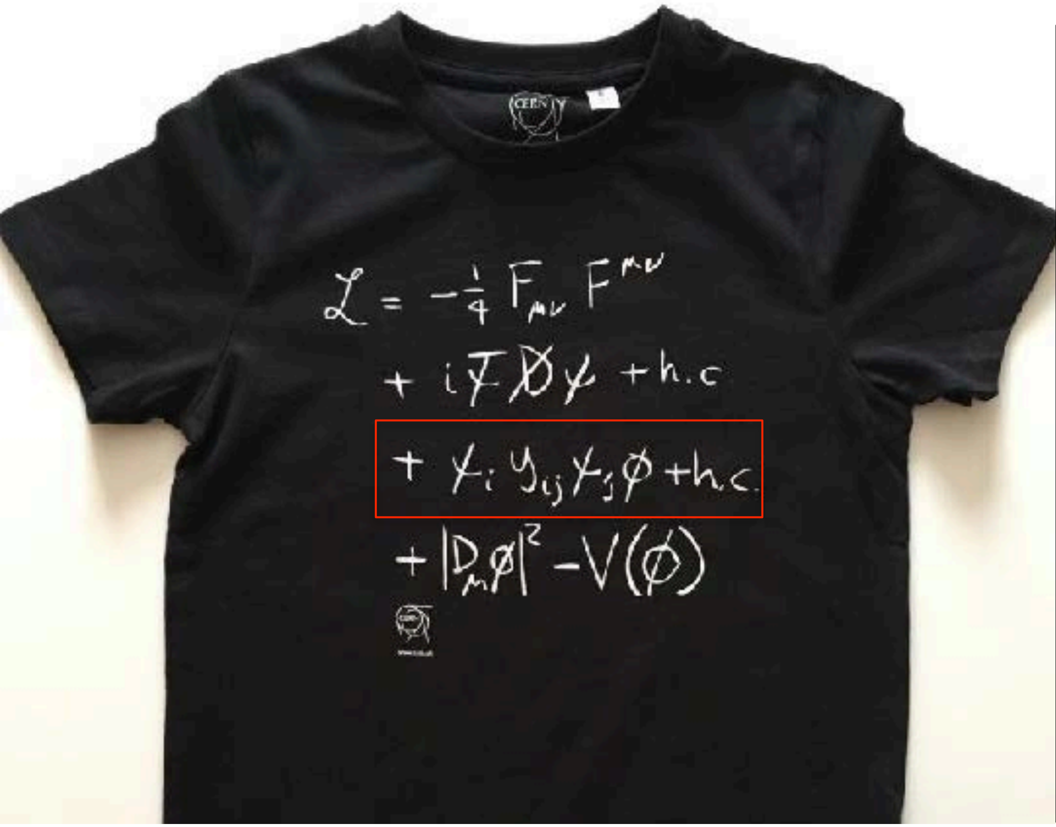


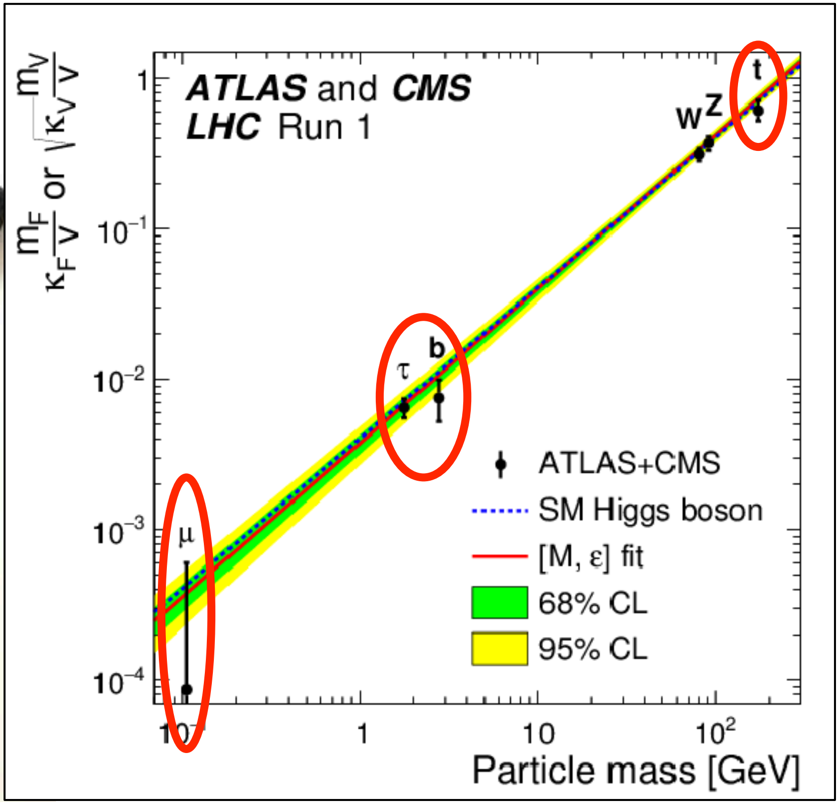


Simplified template cross sections

- Simplified template cross-sections (STXS) defined by common effort in the LHC Higgs cross-section group: LHC-wide agreement phase-space and object definition
- Cross Sections split by **production mode and region of phase space**
- Using these, and/or individual experimental measurements, EFT fits will allow more detailed SM tests – and perhaps provide hints of BSM structure







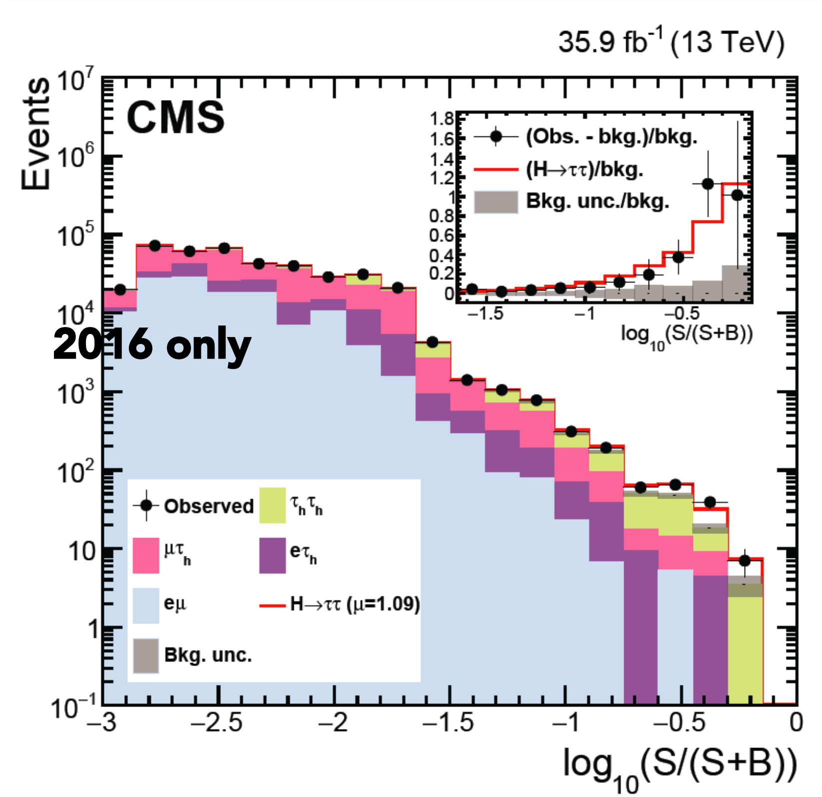
Over the last few years, CMS has worked hard to establish the Yukawa couplings to the heaviest fermions, τ, b, top

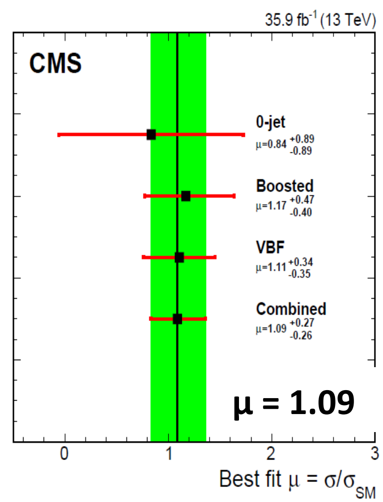
➙ The Higgs Yukawa interaction is a highly motivated conjecture to give mass to the fermions

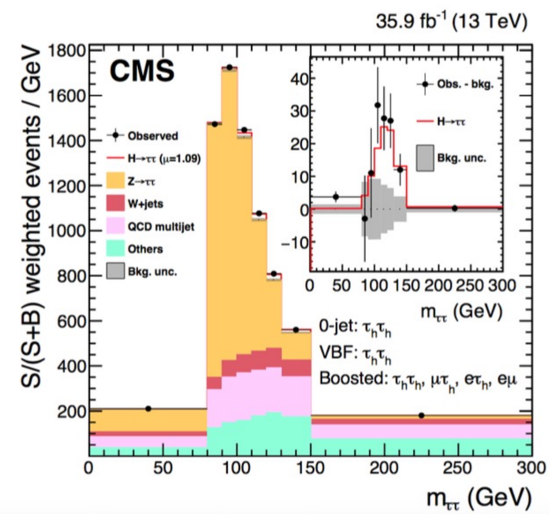
Observation of H→$\tau^+\tau^-$

PLB 779 (2018) 283

- BR~ 6.3%, best channel to establish coupling of Higgs boson to fermions
- Final states: $\tau_h\tau_h$; $e\tau_h$; $\mu\tau_h$; eμ → Significance of 4.9σ observed (4.7σ expected) with 2016 13 TeV data
- Combination with 7, 8 TeV data: 5.9σ obs. (5.9σ exp.) and μ = 0.98 ± 0.18







First direct observation by a single experiment of Higgs coupling to fermions!

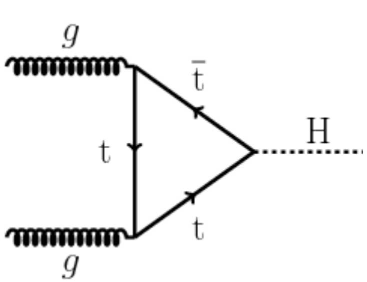
-Observed before in CMS+ATLAS combination

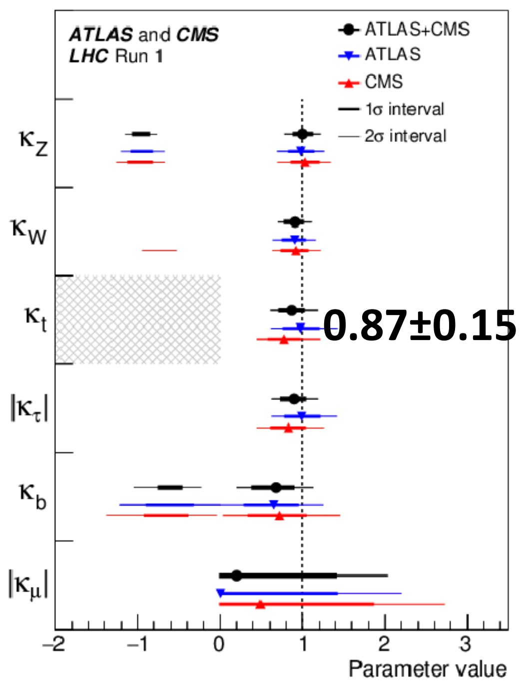
First direct observation of H coupling to leptons and to fermions of the 3rd generation!

$t\bar{t}H$ coupling (two years ago)

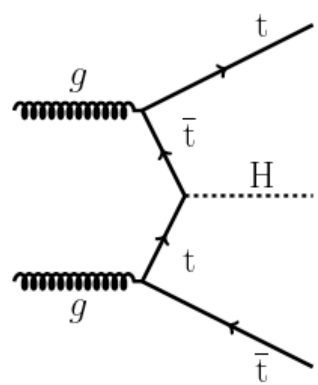
JHEP 08 (2016) 045

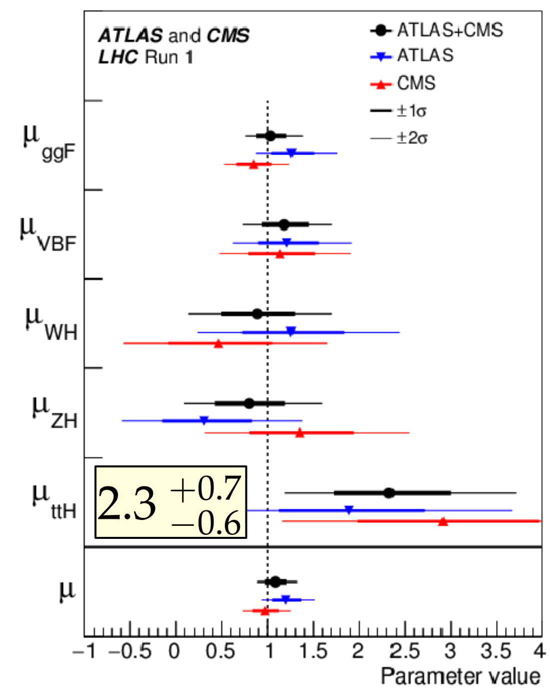
- Indirectly established at Run 1 through the ggH loop process, but model dependent
- The direct ttH coupling was evident, but somewhat higher than expectation





SM structures and no BSM assumed

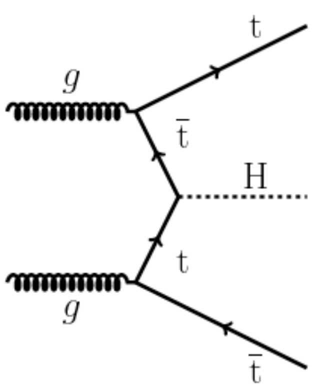


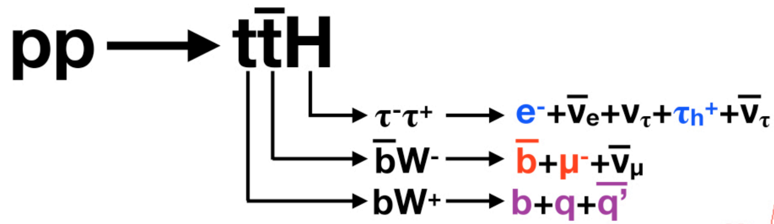


Obs. (exp.) 4.4σ (2.0σ)

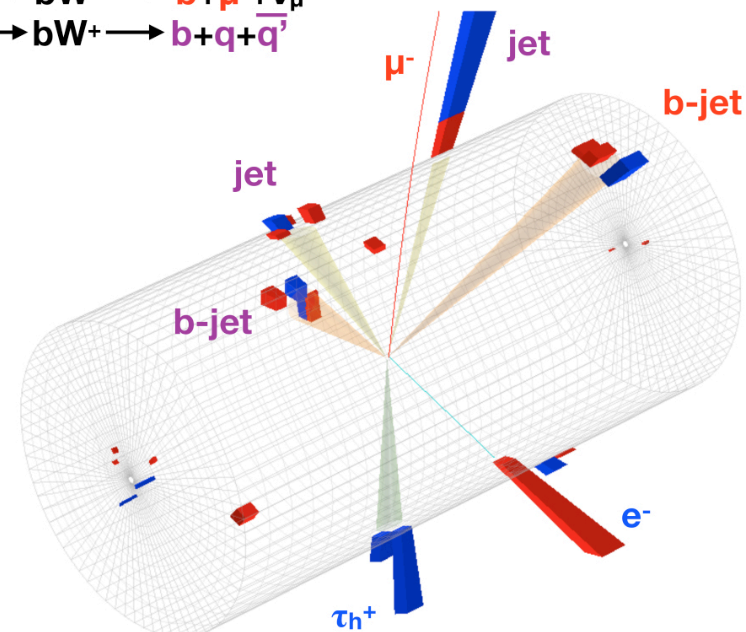
Direct $t\bar{t}H$ searches

- Very sophisticated analyses, pushing detector performance very far, many channels, MVAs...





CMS ttH candidate event

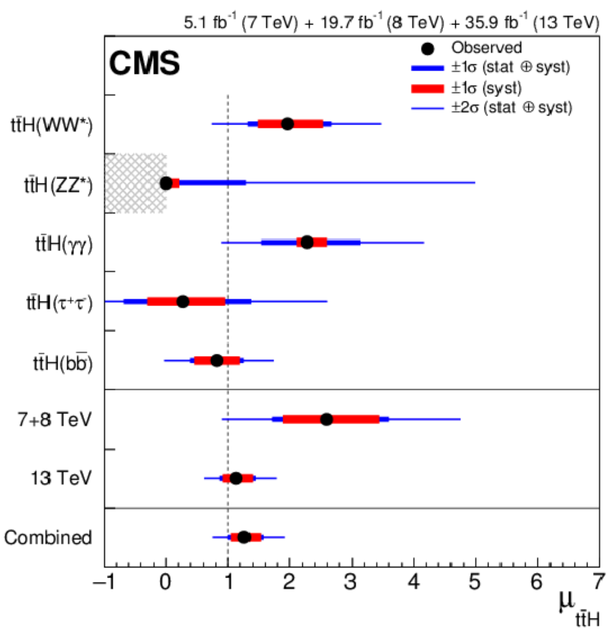


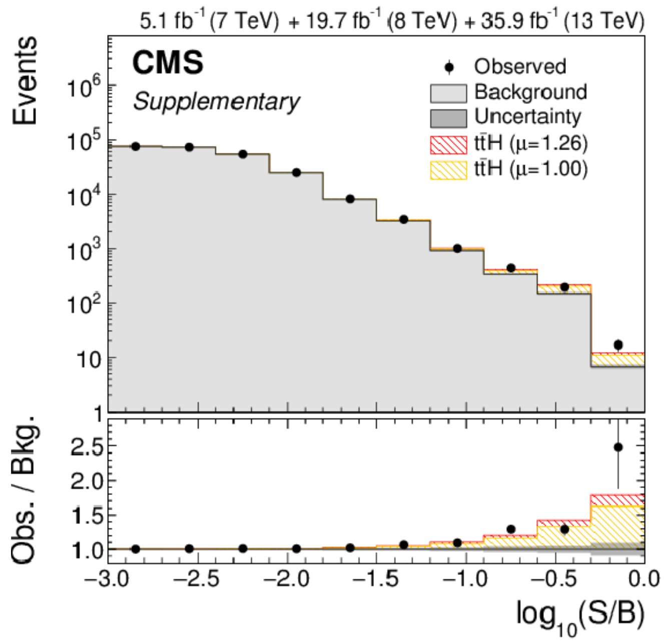
Rare production, only 1% of ggH cross section

Direct $t\bar{t}H$ searches

Phys. Rev. Lett. 120, 231801 (2018)

- Very sophisticated analyses, pushing detector performance very far, many channels, MVAs...



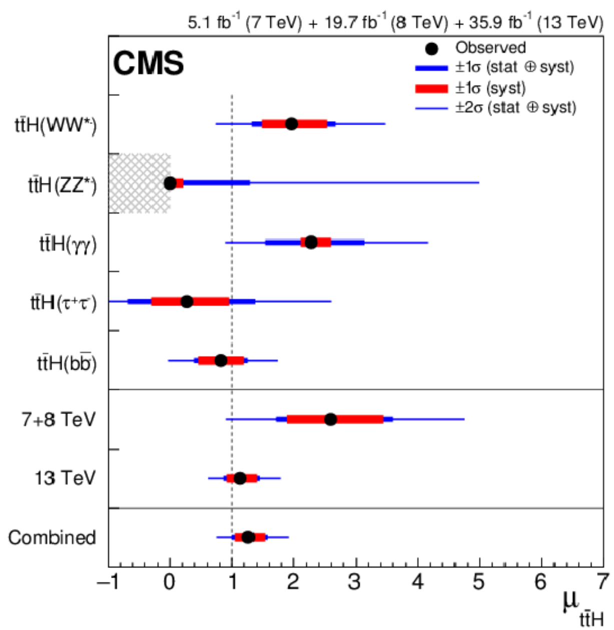


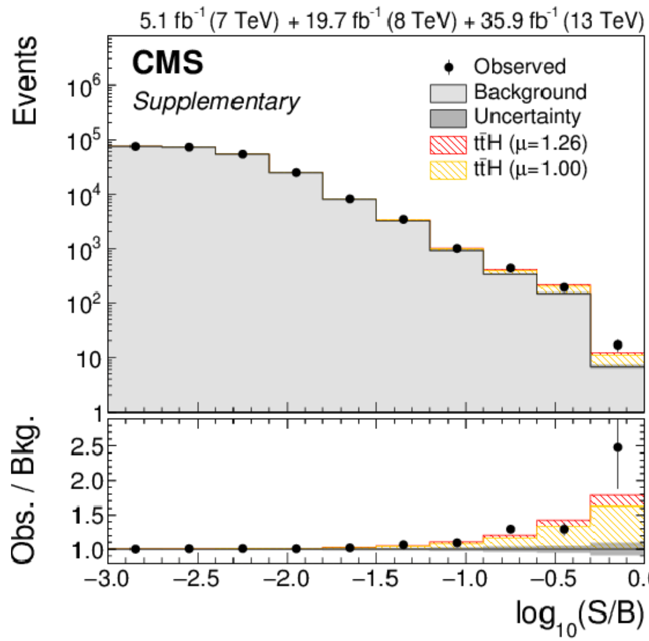
$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat.})\,^{+0.17}_{-0.15}(\text{exp.})\,^{+0.14}_{-0.13}(\text{bkg. th.})\,^{+0.15}_{-0.07}(\text{sig. th.})$$

First $t\bar{t}H$ observation

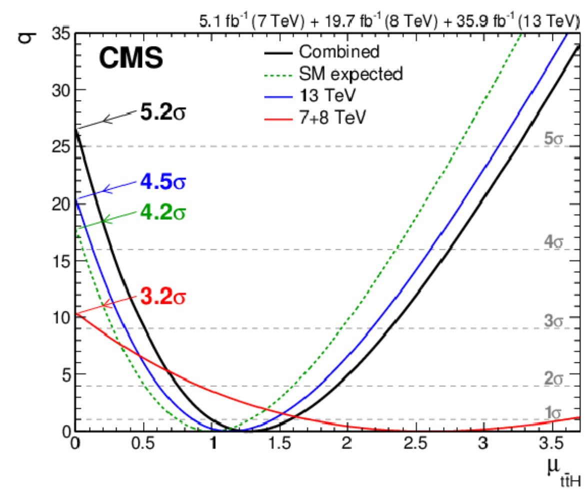
Phys. Rev. Lett. 120, 231801 (2018)

- Very sophisticated analyses, pushing detector performance very far, many channels, MVAs...
- First 5σ observation of $t\bar{t}H$





Obs. (exp.) 5.2σ (4.2σ)



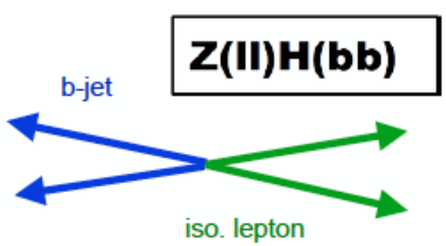
$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat.})\,^{+0.17}_{-0.15}(\text{exp.})\,^{+0.14}_{-0.13}(\text{bkg. th.})\,^{+0.15}_{-0.07}(\text{sig. th.})$$

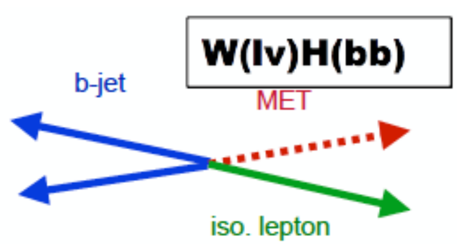
Establishes directly the tree-level coupling to an up-type quark

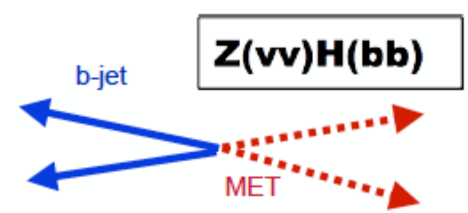
Higgs → bb

arxiv:1808.08242

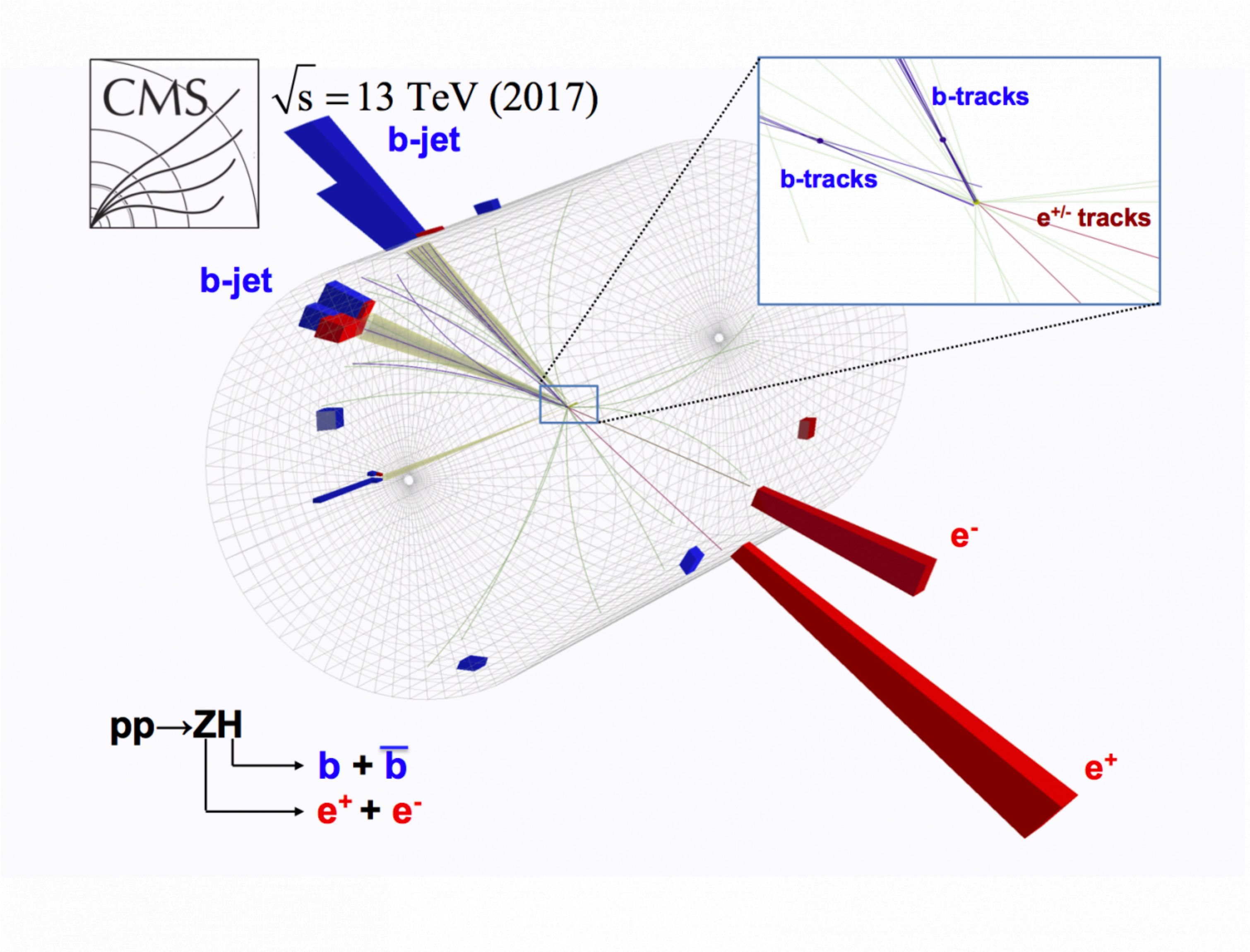
- **Biggest branching fraction, but massive bb background from QCD** processes
  - Choose a weak interaction production mode to reduce hadronic backgrounds (QCD multijet, top, mainly **Associated Production with a W or Z, VH(bb)**
- Signal is a di-jet mass enhancement which has many challenges
- Three channels in VH(bb): V(W→*l* n,Z→*ll*,Z→*nn*) H(bb)
  - Require Vector Boson to be back-to-back w.r.t. the bb system
- Several improvements for 2017 analysis, including heavy reliance on DNNs, DEEPCSV
- Analysis validated using VZ(bb)







ZH(bb) Candidate Event



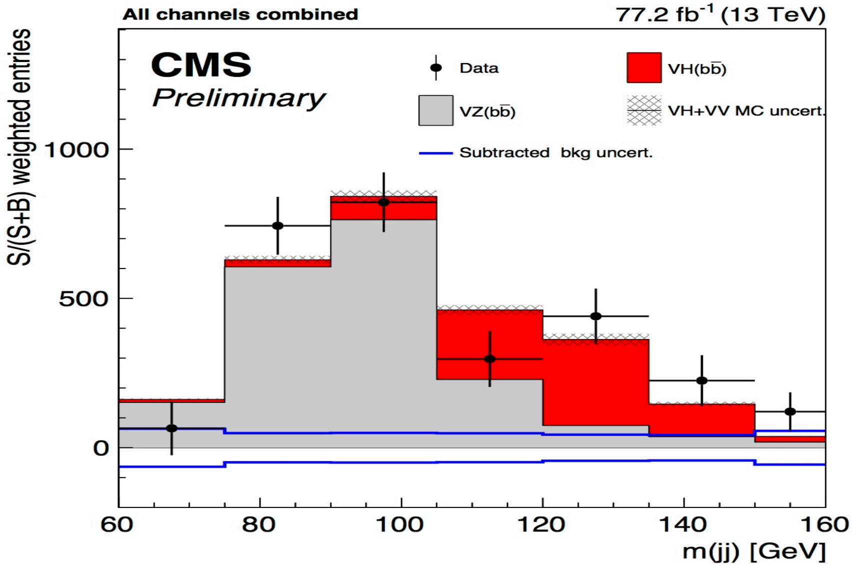
Combination of all H->bb results from Run 1 and 2

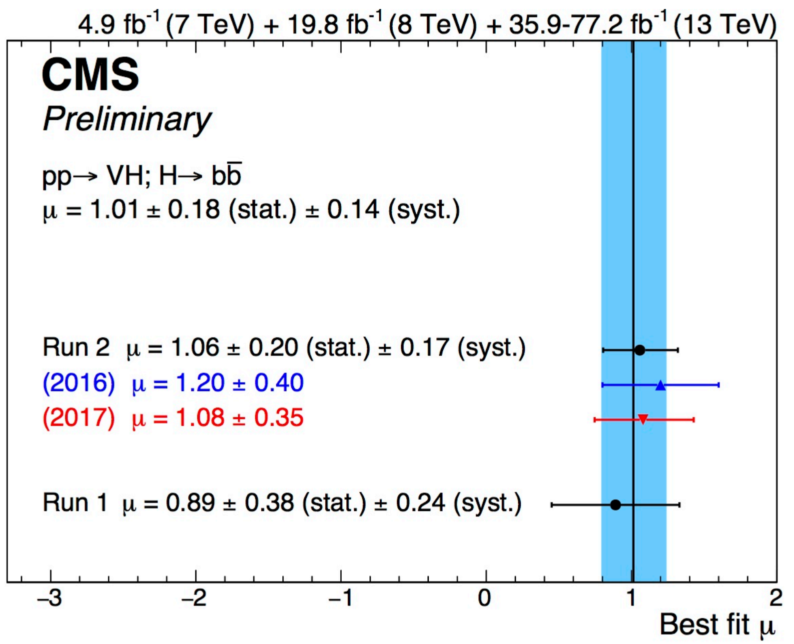
arxiv:1808.08242

- **VH(bb) from 2016/17 at 13 TeV, 77.2 fb^{-1}**
  - **Significance: 4.4 σ obs (4.2 exp)**
- With VH(bb) including also 7 and 8 TeV
  - Significance: 4.8 σ obs (4.9 exp)
- Including new results and all published data from Run 1 and Run 2
  - Run 1:
    - ttH(bb), VBF H→bb, VH(bb)
  - Run 2:
    - ttH(bb), Boosted ggH(bb) (2016)
    - VH, H→bb (2016 + 2017)

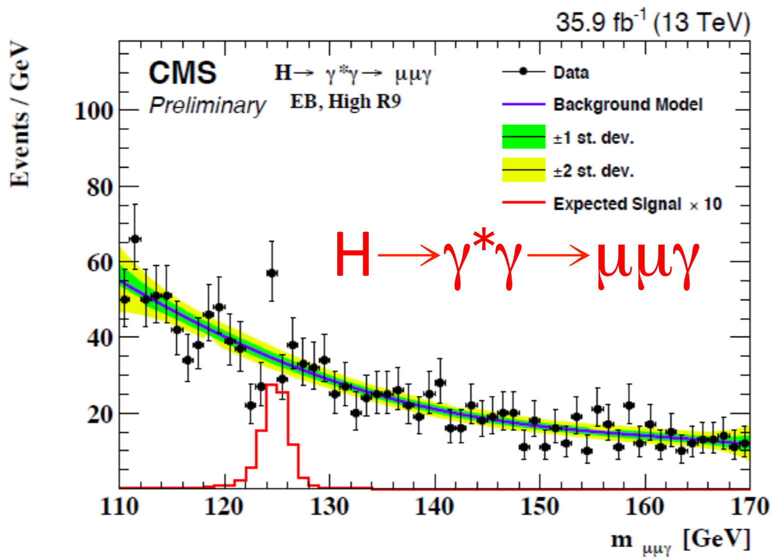
5.6 (5.5) σ observed (exp.) for H→bb!

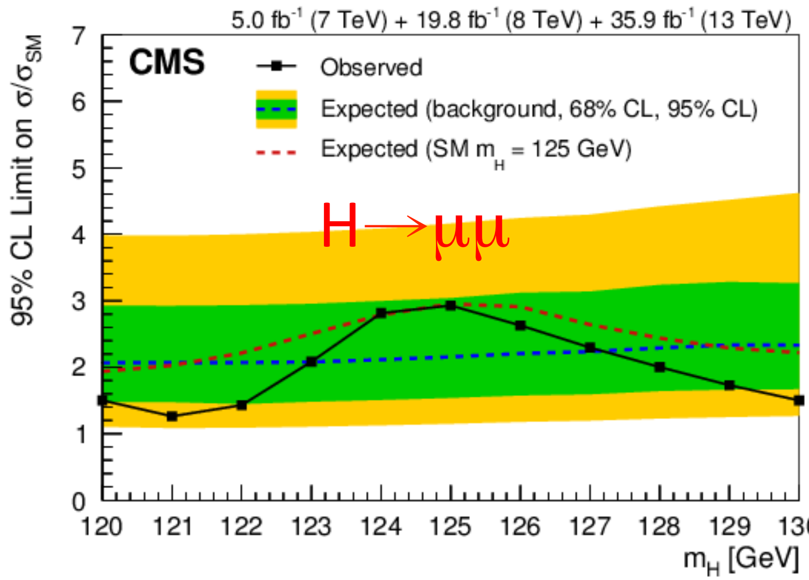
$$\mu = 1.04^{+0.20}_{-0.19}$$

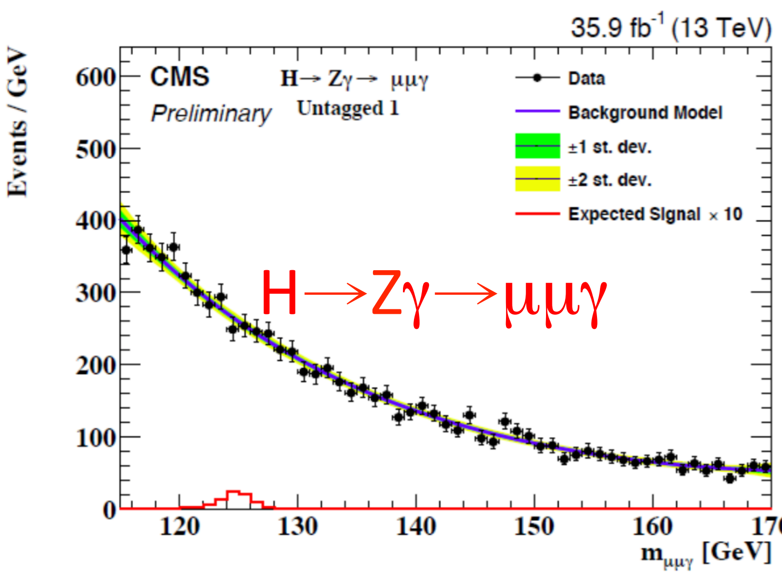


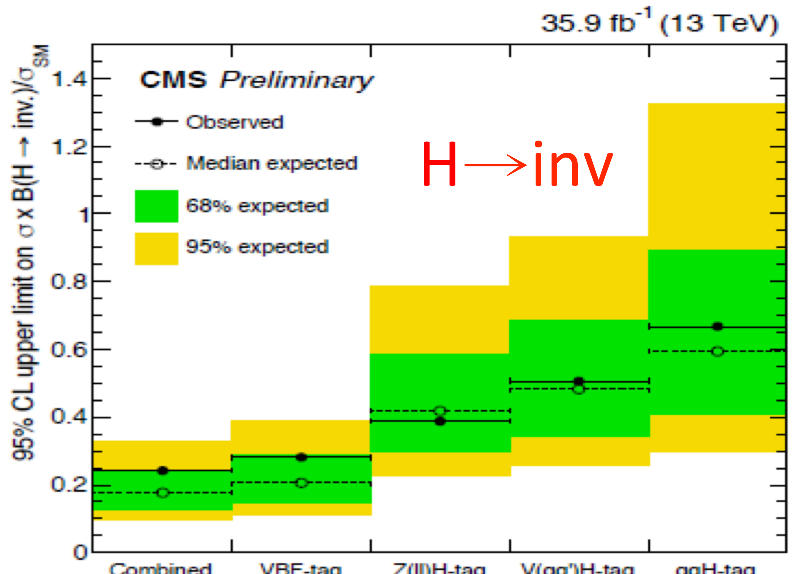


Higgs rare decays









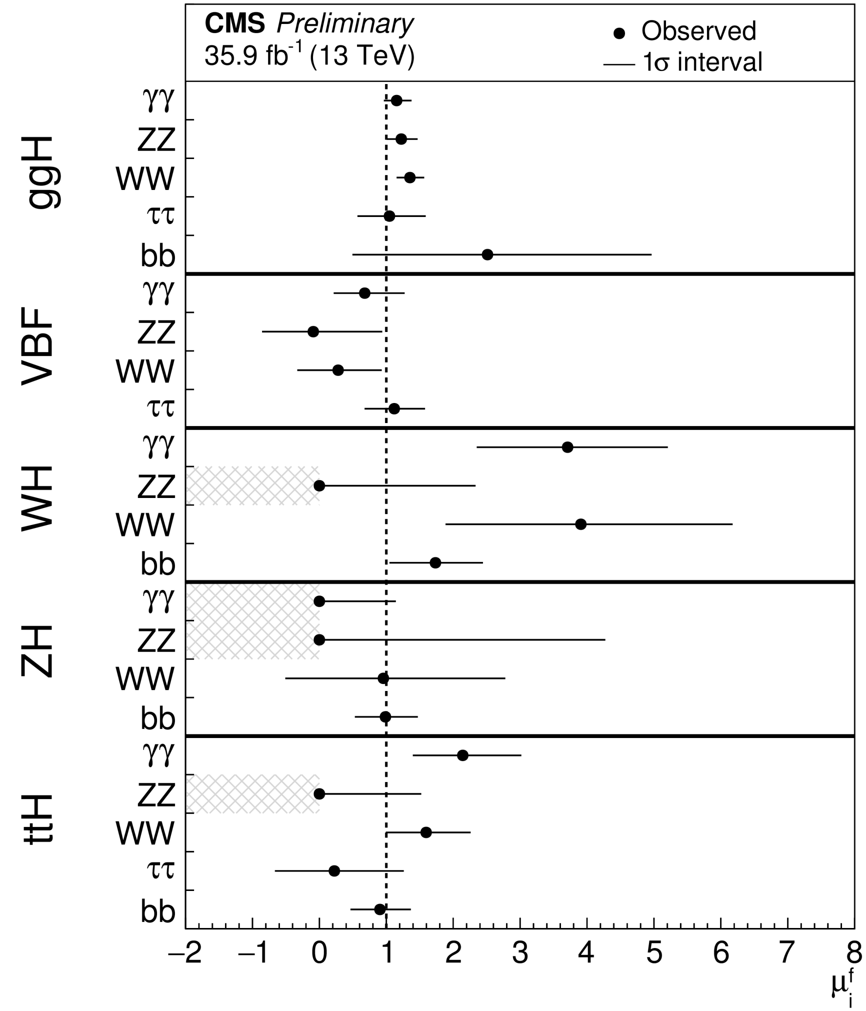
Many studies, all compatible with SM predictions

Higgs Combination

CMS-PAS-HIG-17-031

- Analyses used for combination cover all main production and decay modes on 2016 13 TeV dataset (35.9 fb^{-1})
  - VH(→ττ) missing
- Total of 250 individual categories (counting signal and control regions) and ~ 5400 nuisance parameters in the combined fit

	ggF	VBF	VH	ttH
H→ZZ→4l	●	●	●	●
H→γγ	●	●	●	●
H→WW	●	●	●	●
H→bb	●		●	●
H→ττ	●	●		●
H→μμ	●	●		
H→inv	●	●	●	

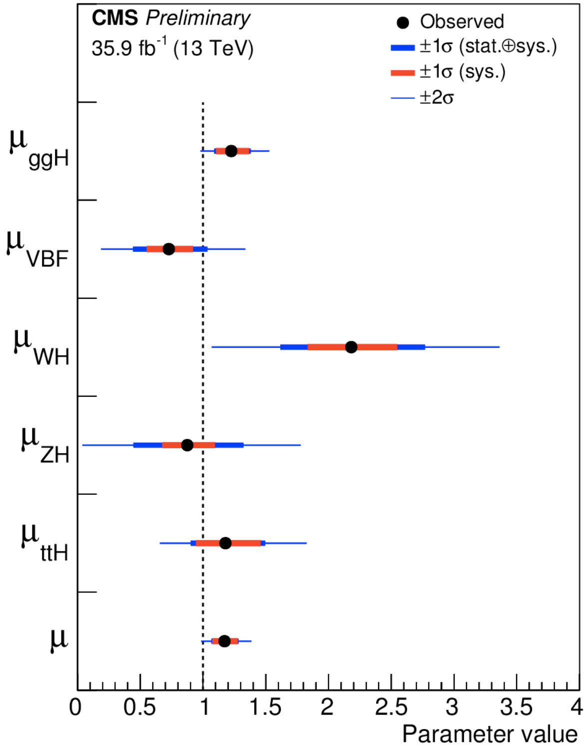


$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{SM}}$$

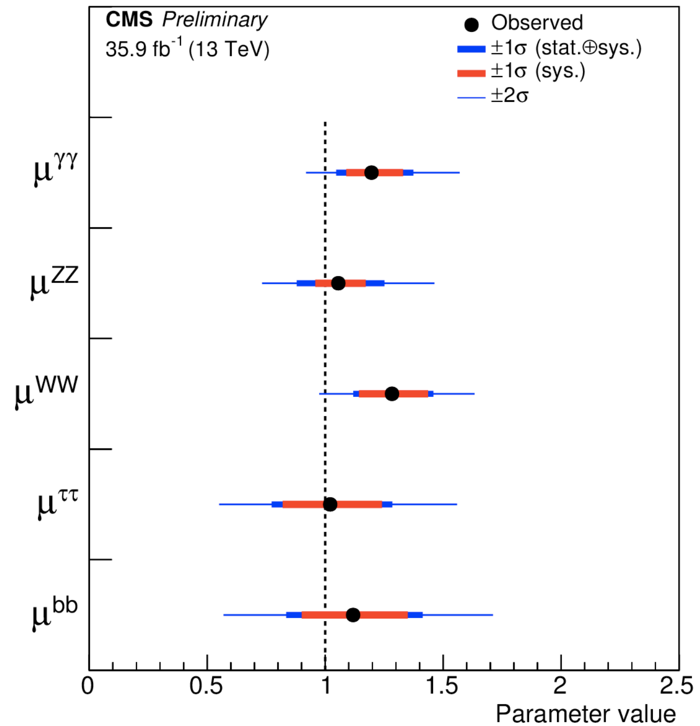
Signal strengths

- Overall signal strength compatible with the SM
- Not anymore dominated by statistics, already moving to less inclusive measurements

Production Mode



Decay Mode



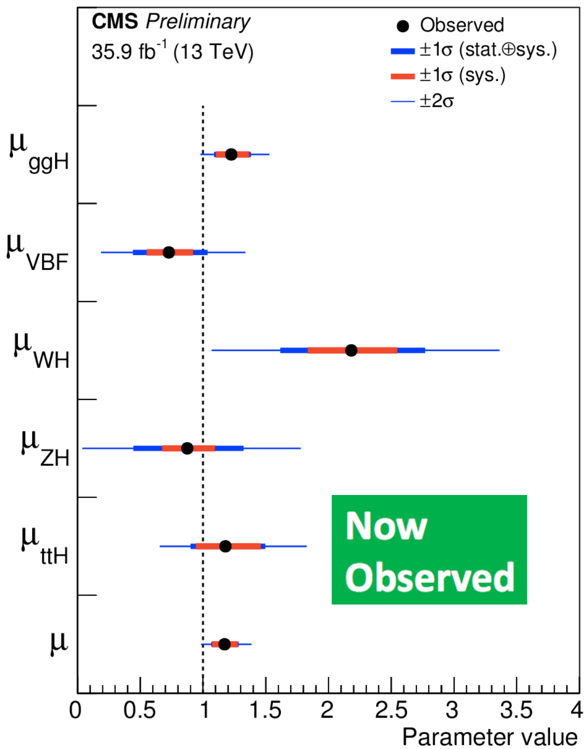
$$\mu = 1.17^{+0.10}_{-0.10} \quad = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$$

Signal strengths

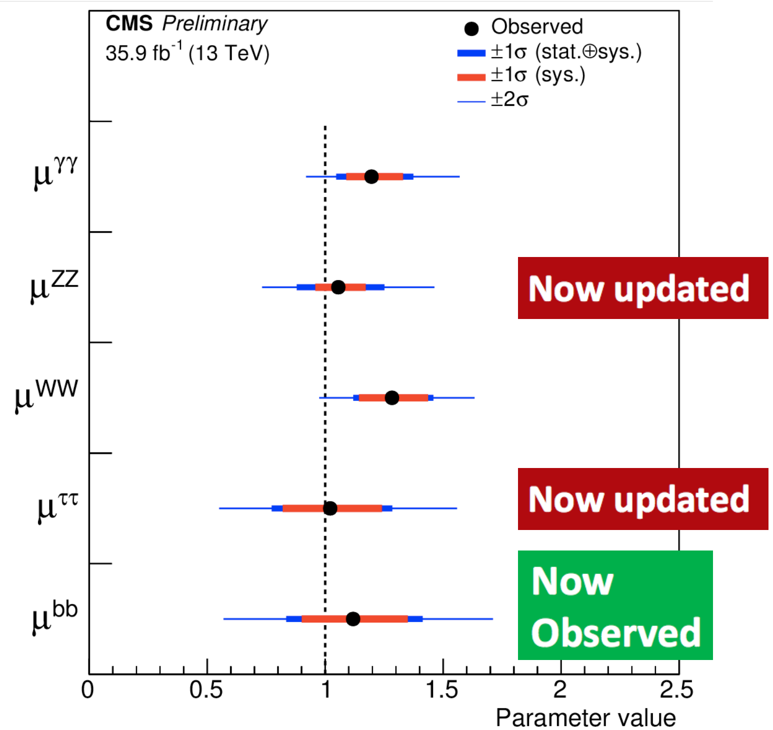
CMS-PAS-HIG-17-031

- Overall signal strength compatible with the SM
- Not anymore dominated by statistics, already moving to less inclusive measurements

Production Mode



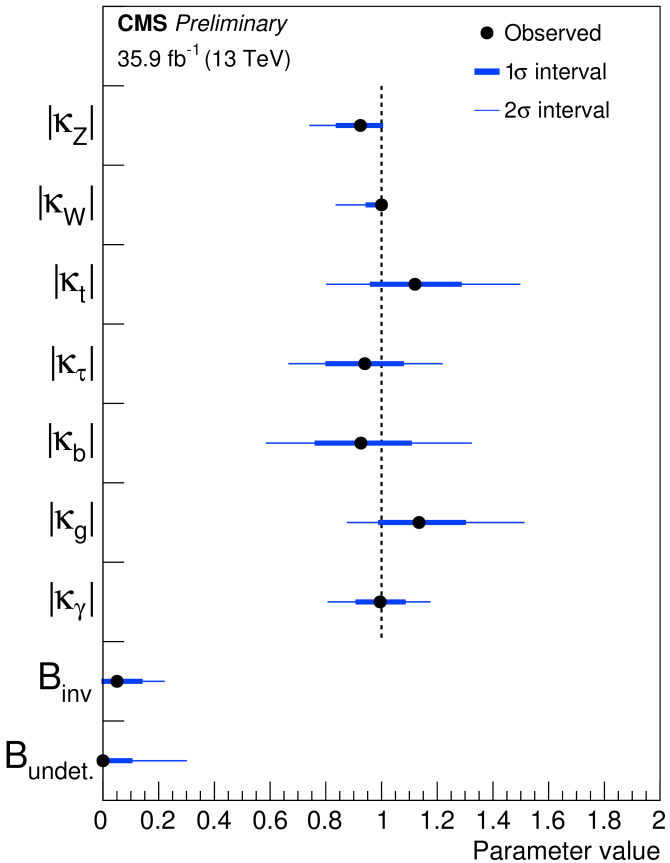
Decay Mode



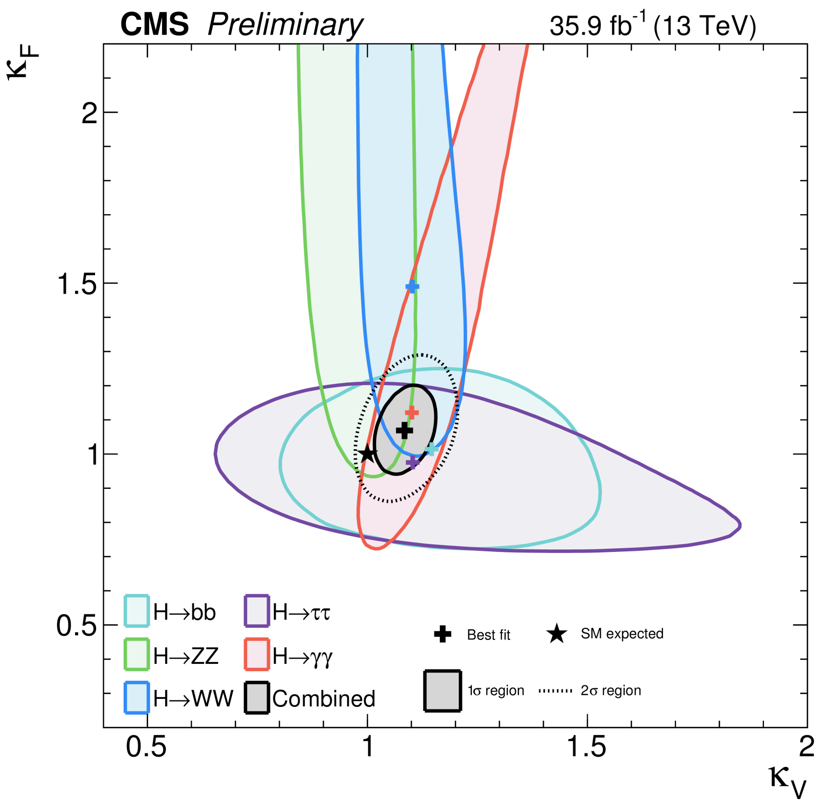
$$\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$$

Kappa models

- Benchmark model fits: kappa framework and further test for deviations from SM expectations



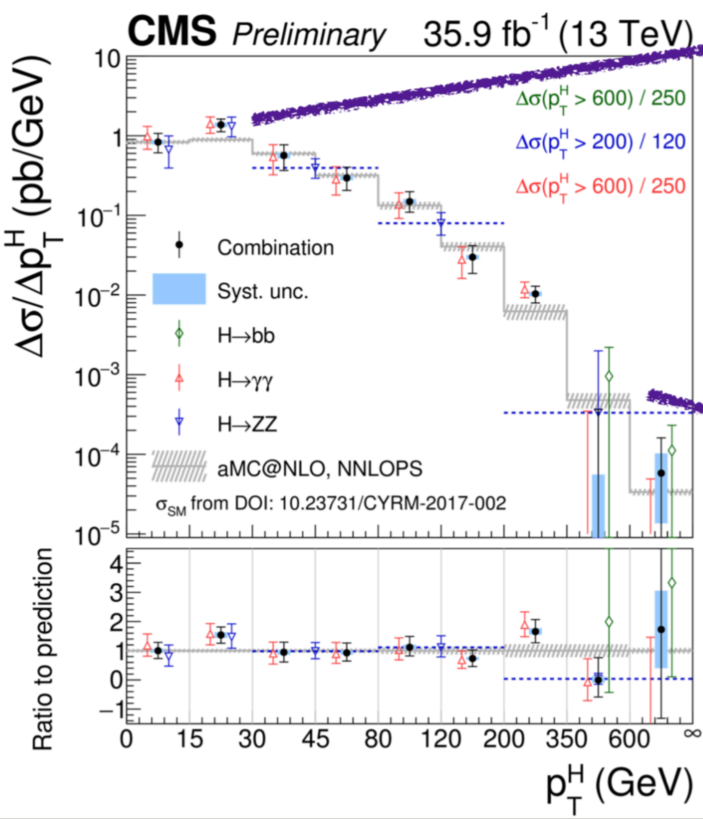
$$\kappa_j^2 = \sigma_j/\sigma_j^{\rm SM} \quad \kappa_j^2 = \Gamma_j/\Gamma_j^{\rm SM}$$

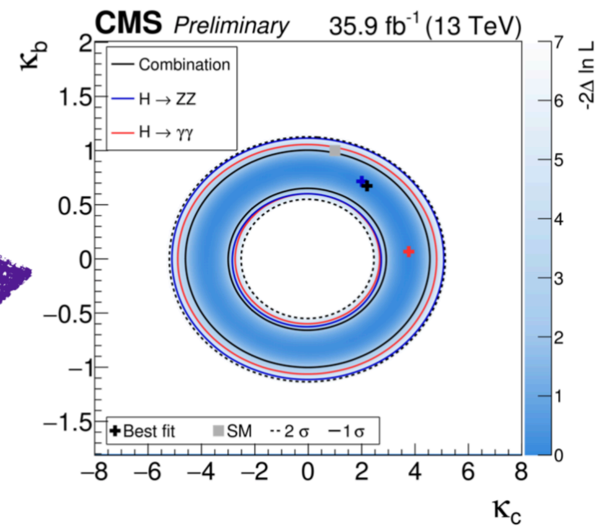


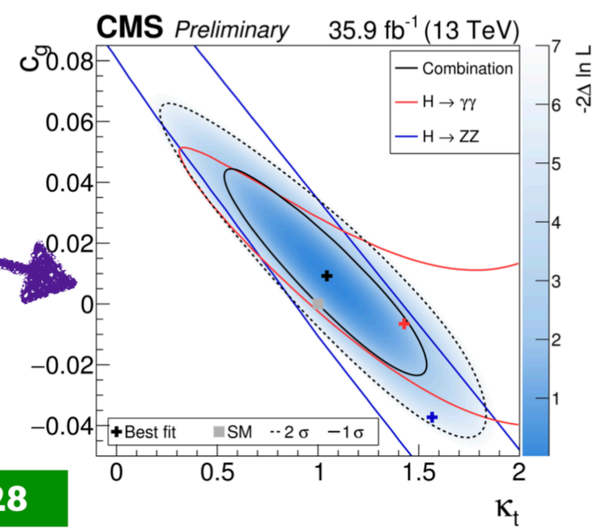
- Coupling modifiers known to the 10-20% level

Combination of differential cross sections

- Differential cross sections
  - Dominated by statistical uncertainty
  - All for an EFT interpretation of Higgs differential distributions -> coupling constraints
  - Sensitive to k_b/k_c (low p_T), k_t/BSM (high p_T)

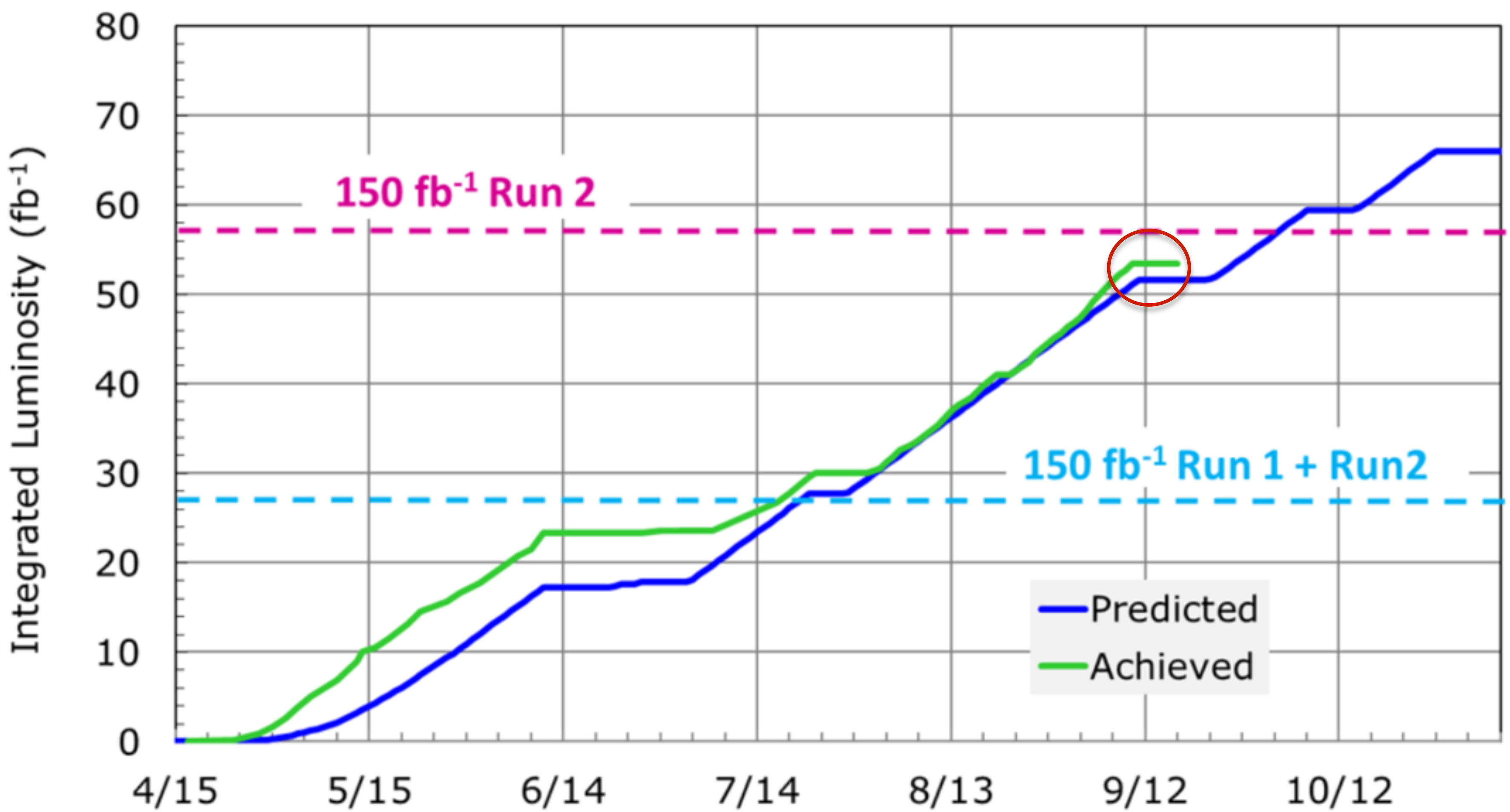






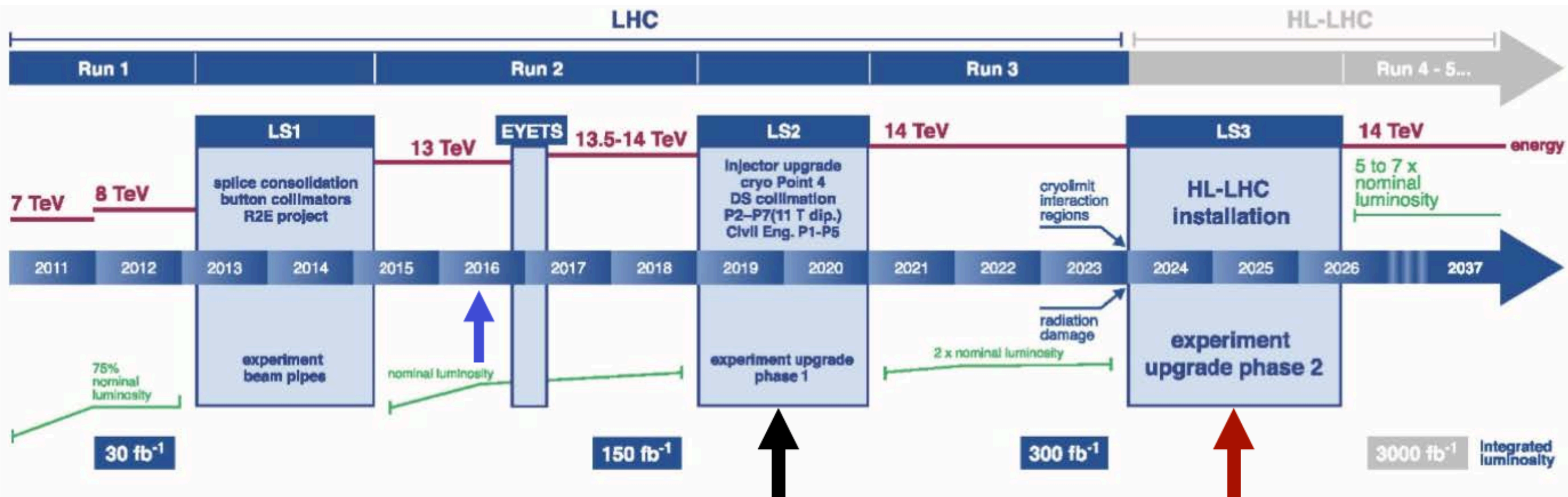
CMS PAS HIG-17-028

Looking forwards



- Good hope to reach 150 fb^{-1} in Run 2 alone

Much more work now devoted to upgrades



LS2 (2019-2020):

- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

LS3 (2024-2026):

- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

Schedule driven by radiation damage to inner triplet (eol: 2023)

Summary

- Approaching a decade after the start, the LHC is now a mature machine, and the detectors are stable, and very well understood
- Direct observation on ttH: it's there at tree-level, and $y_t \approx 1$
- Established the Yukawa couplings to the heaviest fermions, τ, b, top
- Still no significant deviation/excess from CMS, but only two percents of the full LHC data sample analyzed!
- Completion of Run-2, upgrades and then much more data beyond
- **Let's hope something is still hiding out there**

The future is bright!

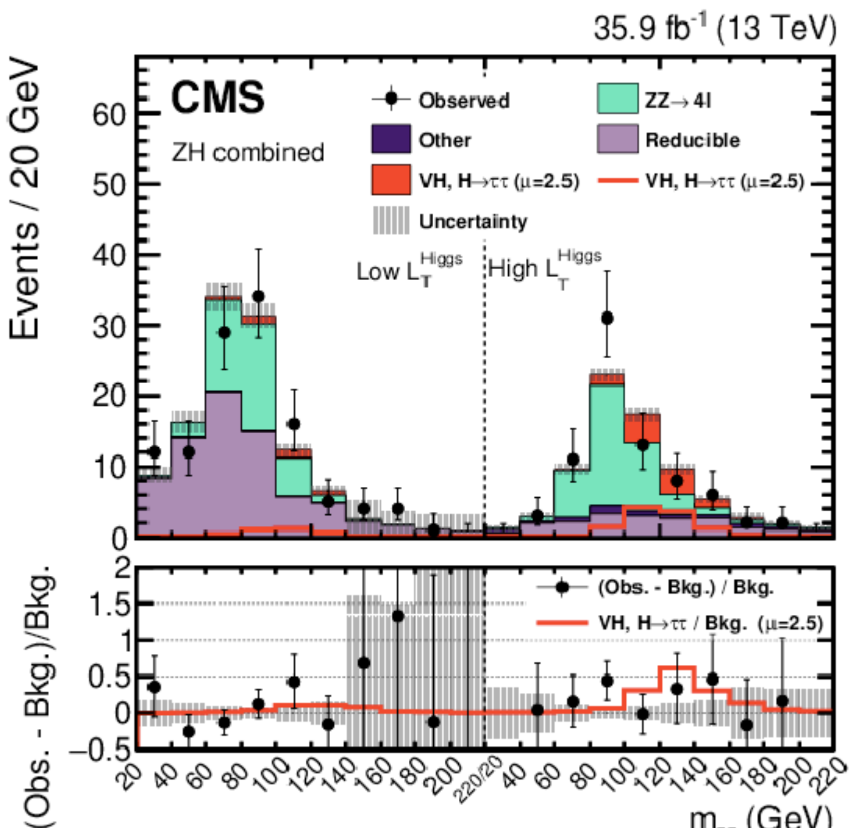
"钱"景光明!

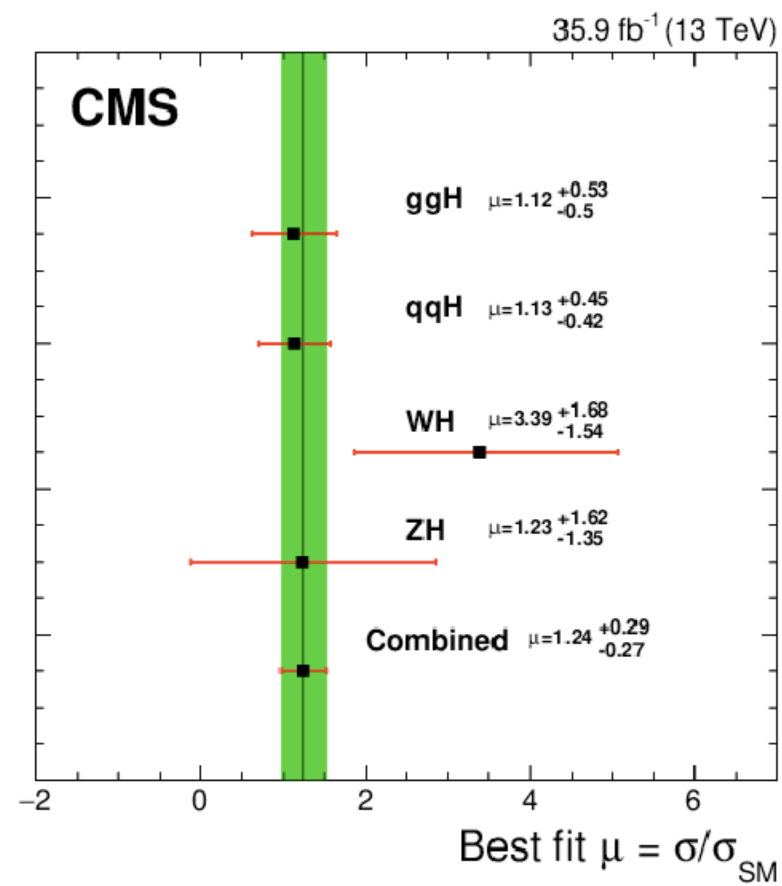
back up

Observation of H→$\tau^+\tau^-$ with Run 2 data

arXiv:1809.03590

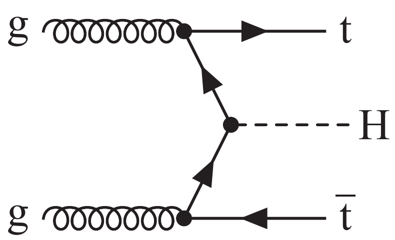
- ggH+VBF (Run2): 4.9 σ (3.7 σ exp.)
- VH (Run2): 2.3 σ (1.0 σ exp.)
- ggH+VBF+VH combination (Run2): 5.5 σ (4.8 σ exp.)



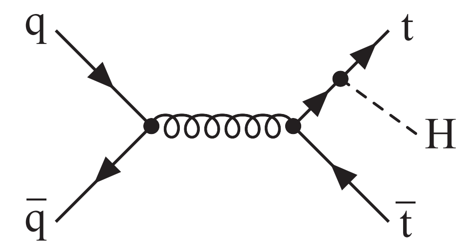


ttH

Phys. Rev. Lett. 120, 231801 – Published 4 June 2018



Higgs is too light to decay into two tops

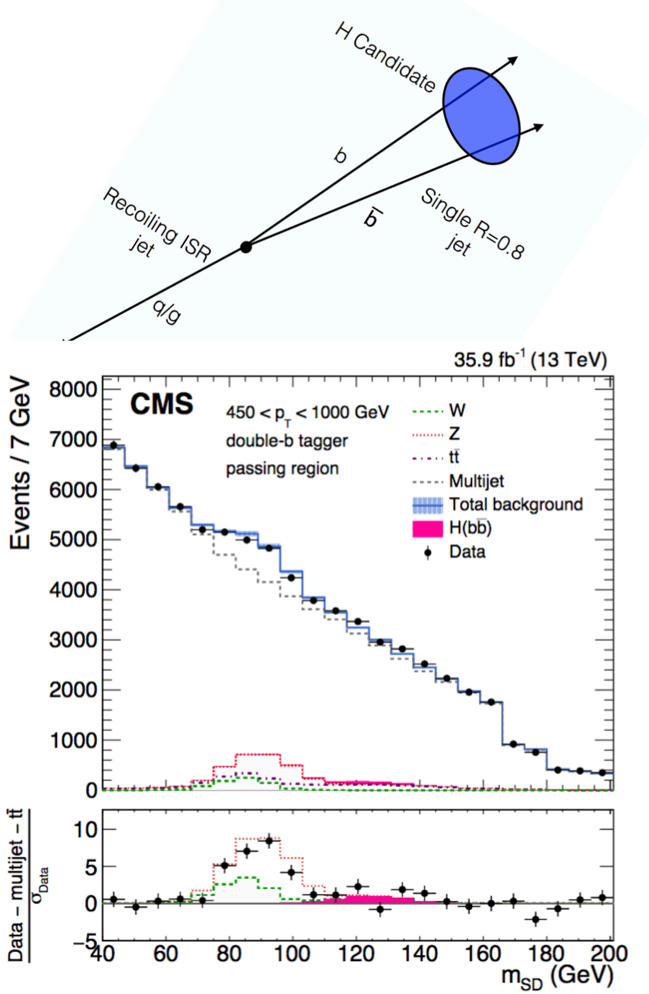


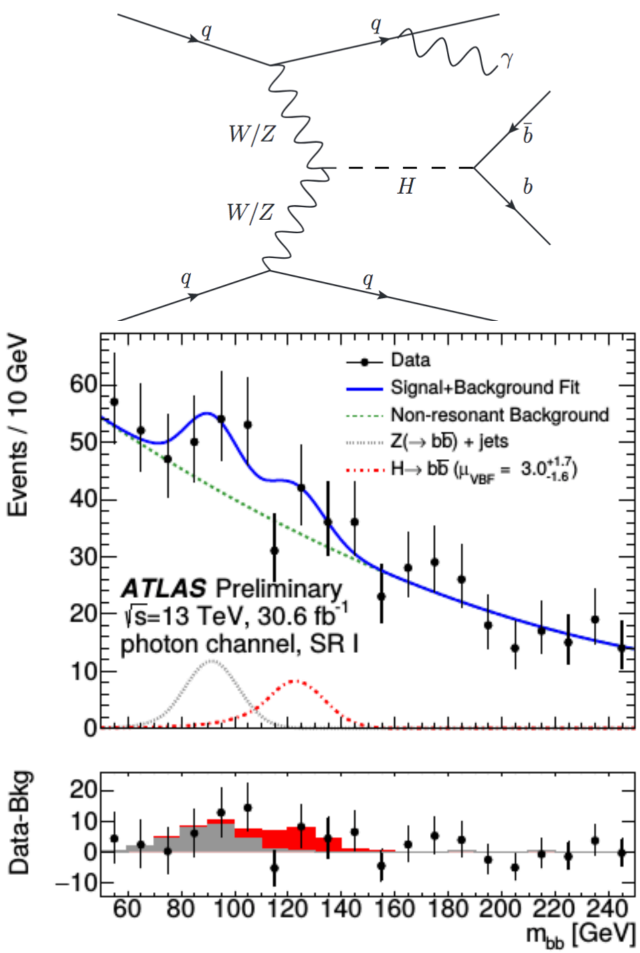
- Signature is production of two top quarks and a Higgs
  - The top is observed its its decay to Wb with the W decaying leptonically or hadronically
  - The analysis uses Higgs decays to bottom-quark-anti quark pairs, $\tau^+\tau^-$, $\gamma\gamma$, WW* and ZZ* (various quark and multi-lepton channels)
    - Hadronic τ decays, τ_h, are used
  - A total of 88 different event topologies, consisting of leptons, photons and jets, are combined to get the result
  - Use of Deep Neural Nets is pervasive
- Main systematic uncertainties are
  - Experimental: lepton and b jet identification efficiencies; τ_h and jet energy scales
  - Theory on background calculations: modelling uncertainties in tt production in association with a W or Z or a pair of b or c jets
  - Theory on signal calculations: effect of higher order corrections on ttH cross sections and uncertainty in proton PDFs
- The $\gamma\gamma$ and ZZ* states are limited by statistics; H→ bb and H→leptons by systematics

H→b$\bar{b}$: explore new regimes/ideas

Phys.Rev.Lett. 120 (2018) 071802, CERN-EP-2018-140

- Direct search for gg→H→bb with boosted H→bb events
- Search for VBF, with an additional high p_T photon

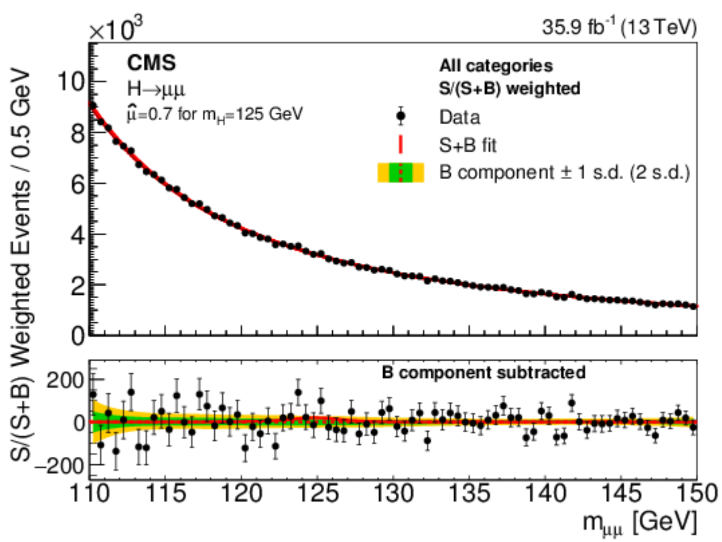


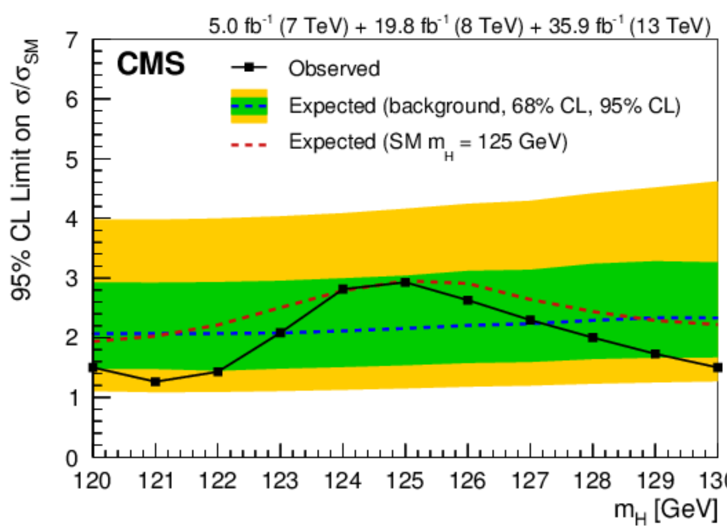


Higgs → $\mu^+\mu^-$

CMS-HIG-17-019

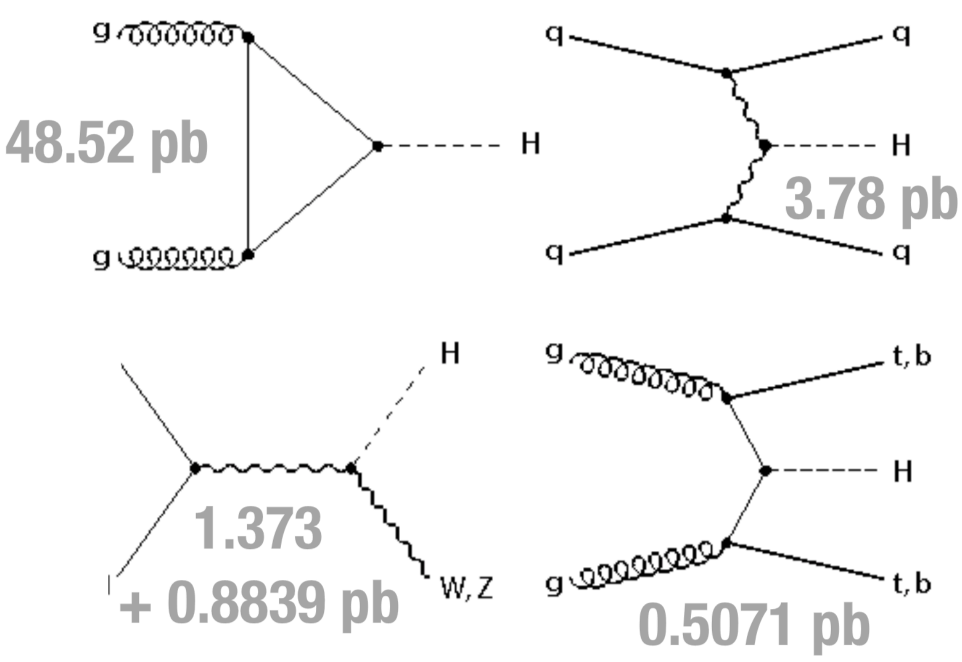
- Best chance at measuring a coupling to a second generation fermion, even though branching fraction (BR) ~ 2.2×10^{-4}, about 1/10 of $\gamma\gamma$.
- CMS has looked for this in 7,8, and 13 TeV (2016 only) data
- Current 95% CL upper limit on BR is 6.4×10^{-4}, 2.92 (observed) vs 2.16 (expected) of the SM prediction.

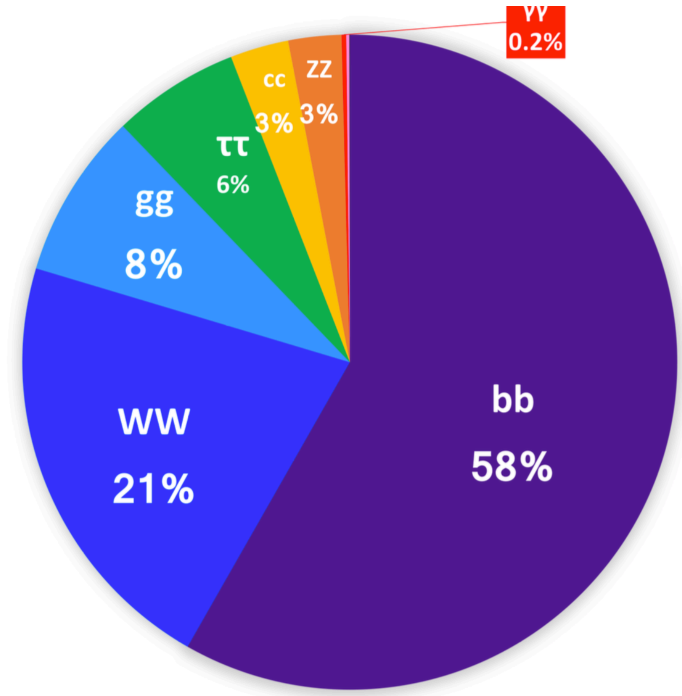




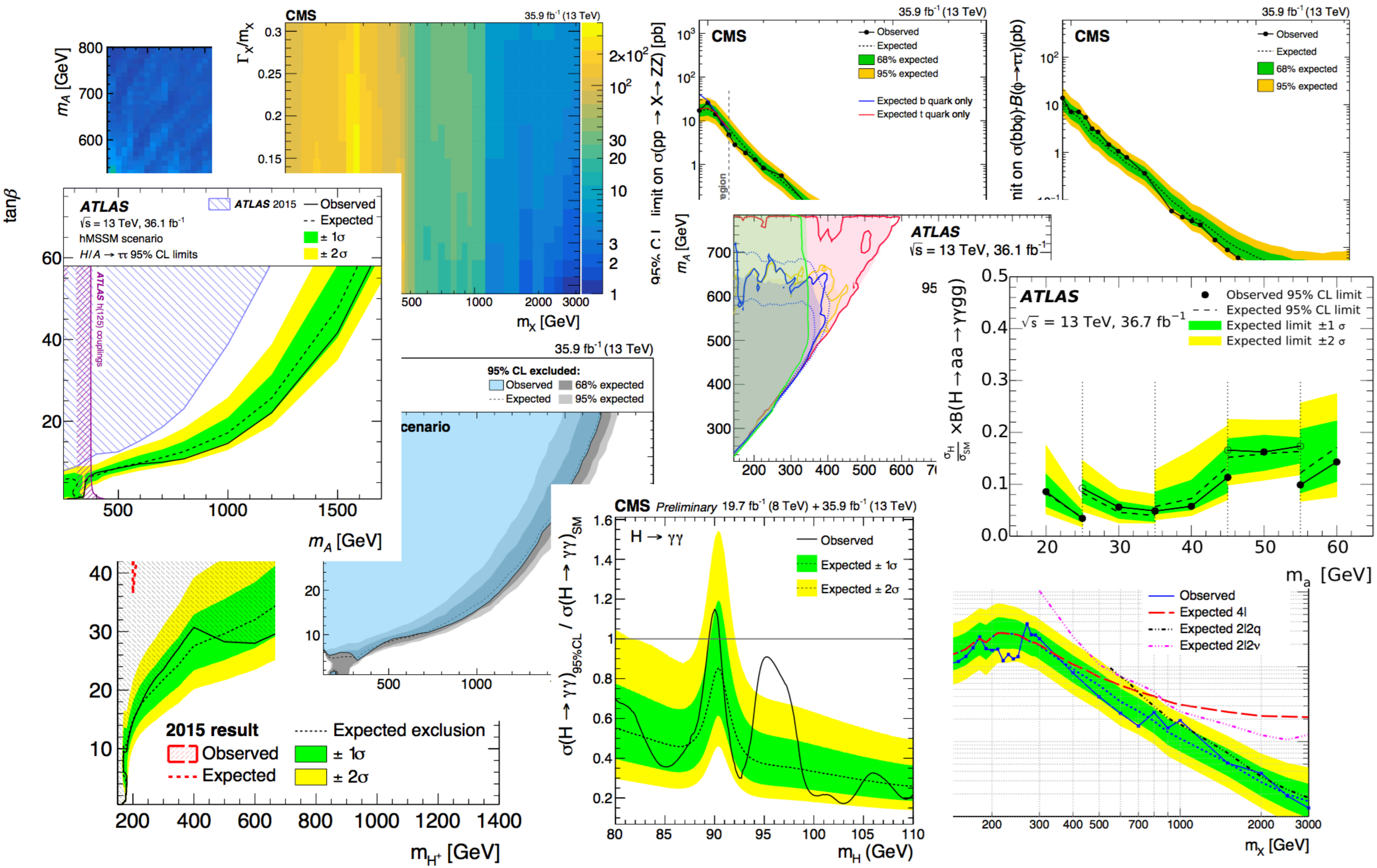
Higgs @ LHC

All the main production and decay modes are under scrutiny.





Additional Higgs ?



Many searches, no significant excess yet

Kappa models

- Use the LO coupling modifier or "kappa" framework to probe for deviations from the SM
- Parameters scale cross sections and partial widths relative to SM
- Option to consider decay to BSM particles via BR_{BSM} term which also scale total width

$$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}} \quad \kappa_j^2 = \Gamma_j/\Gamma_j^{\mathrm{SM}}$$

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

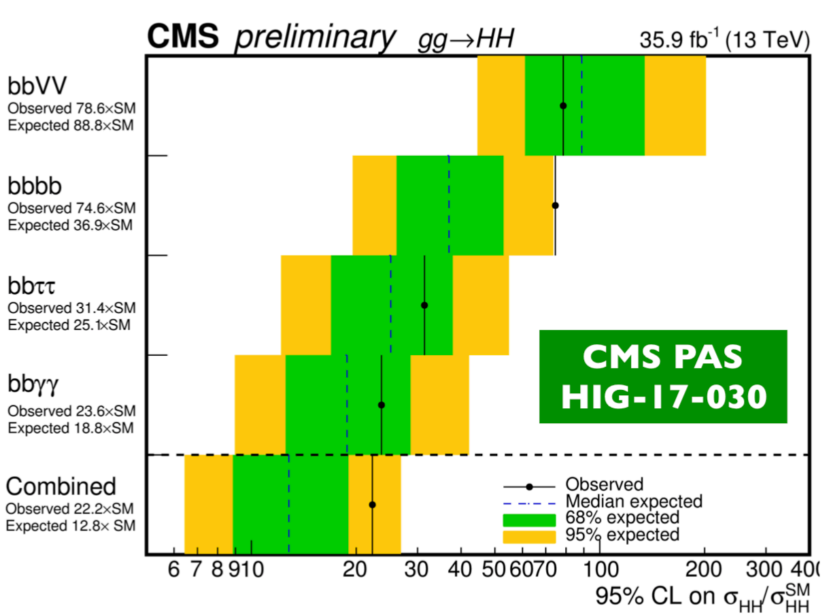
$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

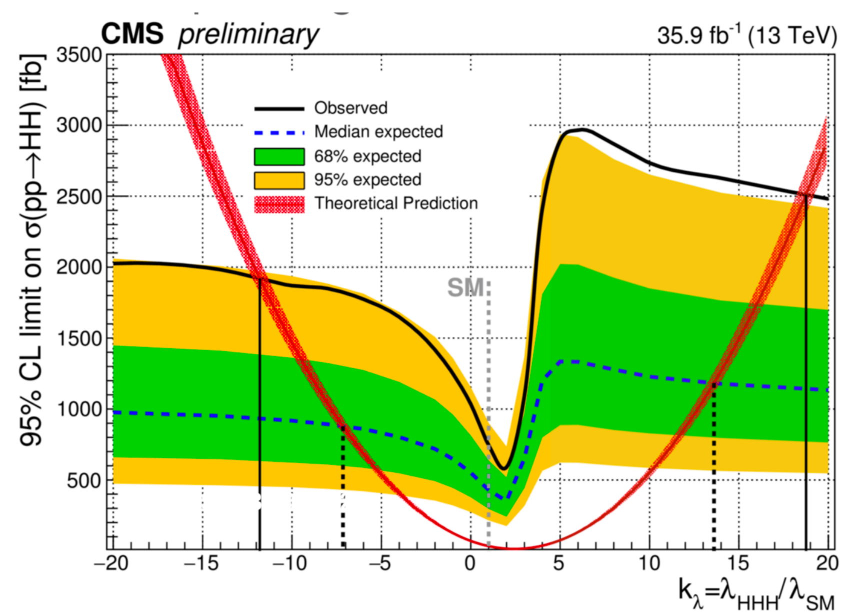
$$\kappa_H^2 = \sum_j \mathrm{BR}_{\mathrm{SM}}^j \kappa_j^2$$

$$\mathrm{BR}_{\mathrm{BSM}} = \mathrm{BR}_{inv.} + \mathrm{BR}_{undet.}$$

SM HH production

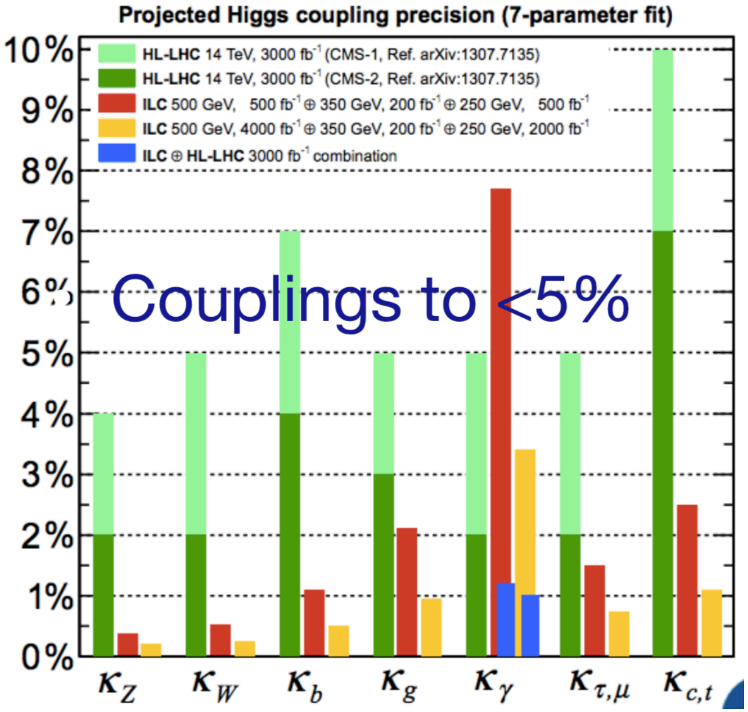
- Low cross section (31 fb @ 13 TeV): destructive interference
- SM cross section not accessible with Run 2 data
  - HL-LHC benchmark
- Expanding list of final states for studies





combined constraint on the self coupling

Prospect @ HL-LHC



arXiv:1506.05992