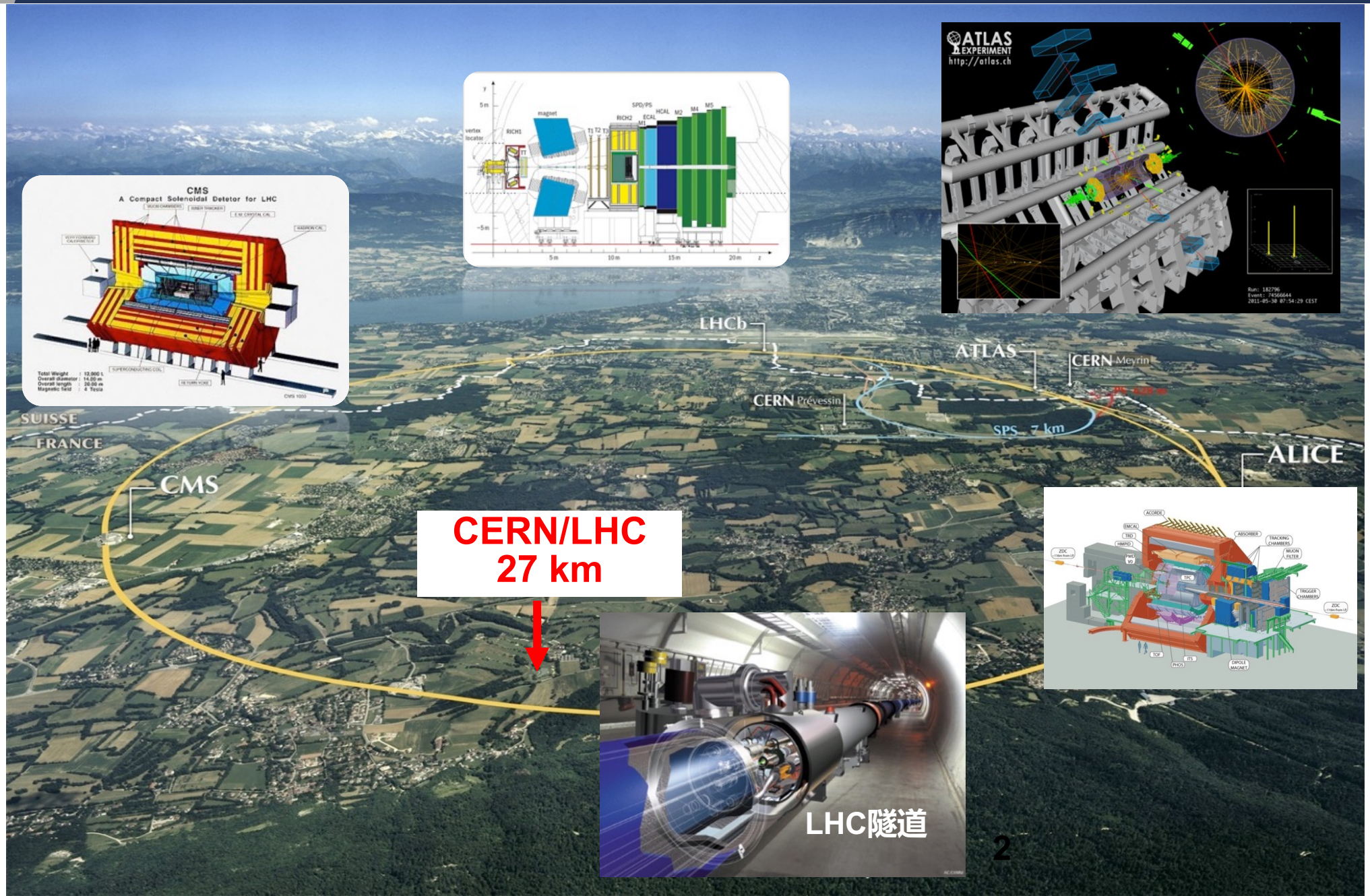
Status of Higgs at CMS

Mingshui Chen (IHEP)

2021.07.15

1st Tibet HEP Forum @ Lhasa

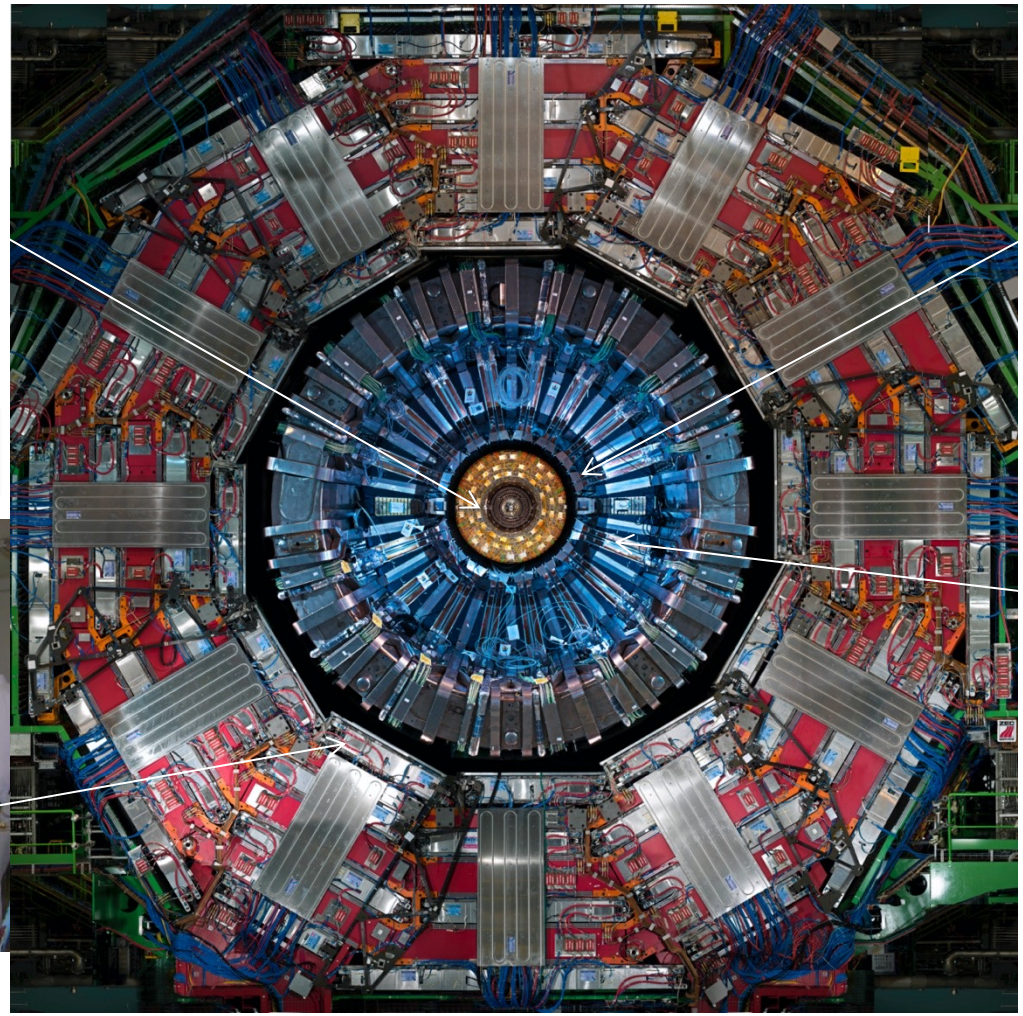
LHC及其实验


CMS
A Compact Solenoidal Detetor for LHC
ATLAS EXPERIMENT
http://atlas.ch
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
ALICE
SUISSE
FRANCE
CMS
CERN/LHC
27 km
LHC隧道

CMS探测器：从概念设计到运行采集数据 – 18年

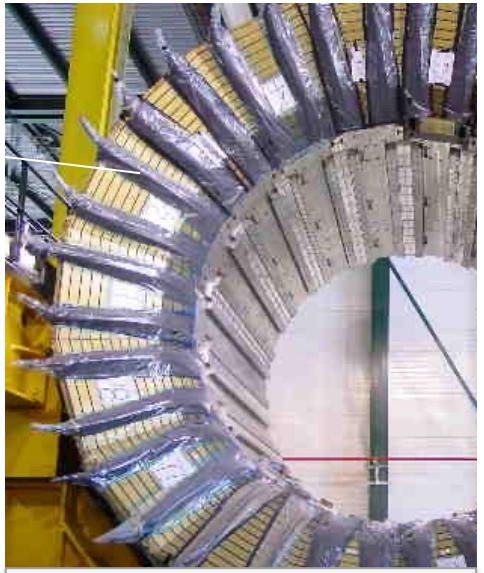
Silicon Tracker

Gas ionization chambers



CMS cut in mid-plane

Scintillating Crystals



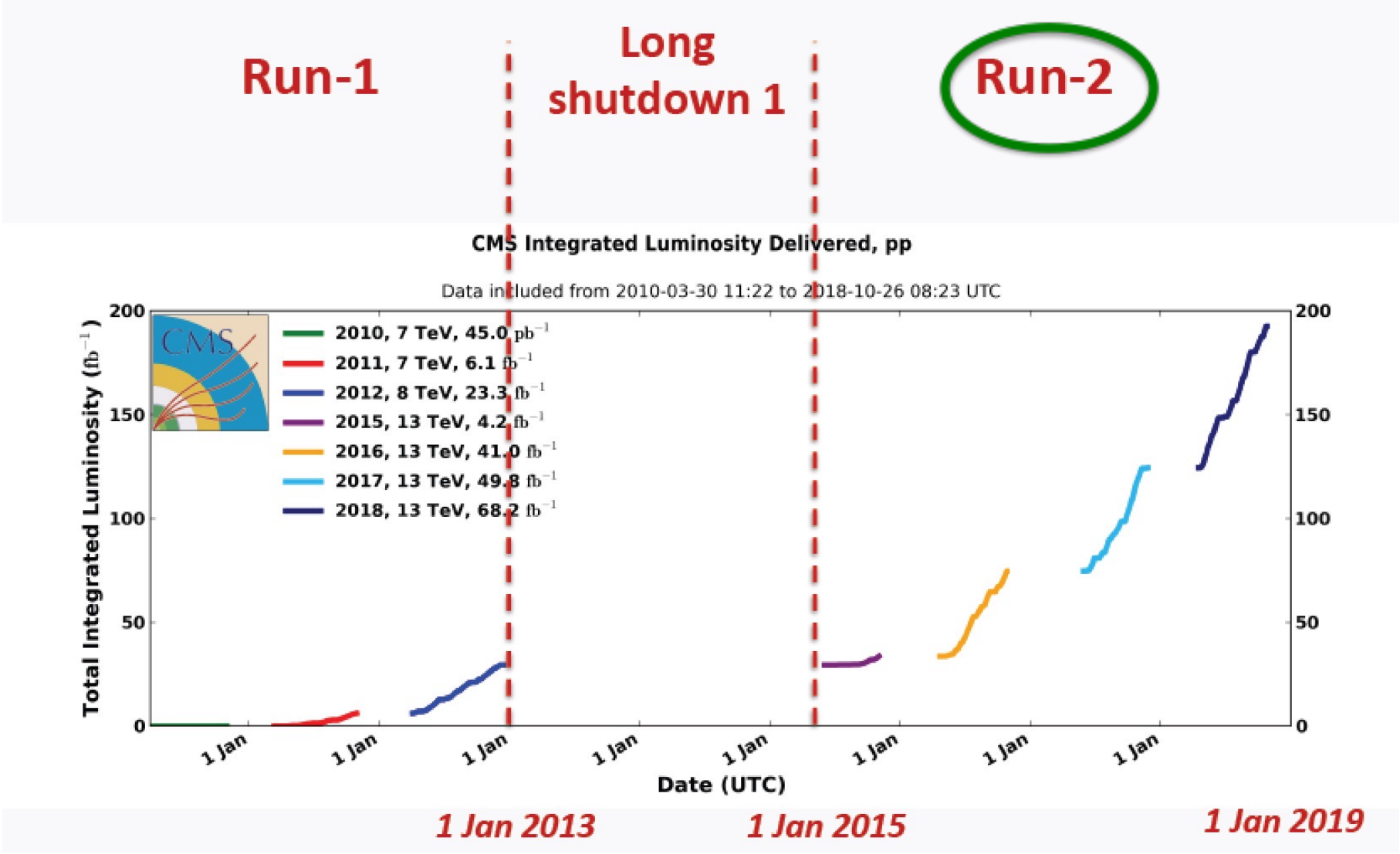
Brass plastic scintillator

CMS合作组：50多个国家或地区的220余单位的近5000人

CMS中国组

中国组自90年代即加入了CMS合作组，由最开始的两个单位发展成目前为7个单位（高能所、北大、北航、清华、中山、浙大、复旦）约130余名成员，另外南师为附属单位

LHC performance thus far



146 Higgs papers from CMS, and counting (73 on Run-2 Data)

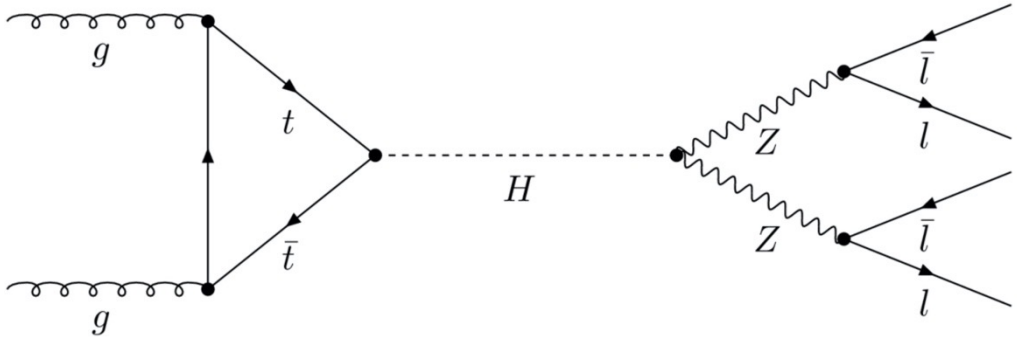
CMS Higgs Publications Online:
http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html

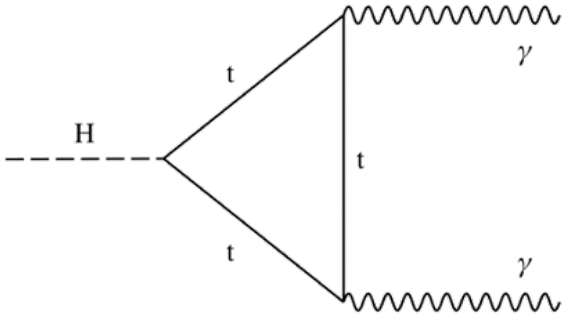
What is there to follow up in Run-3?

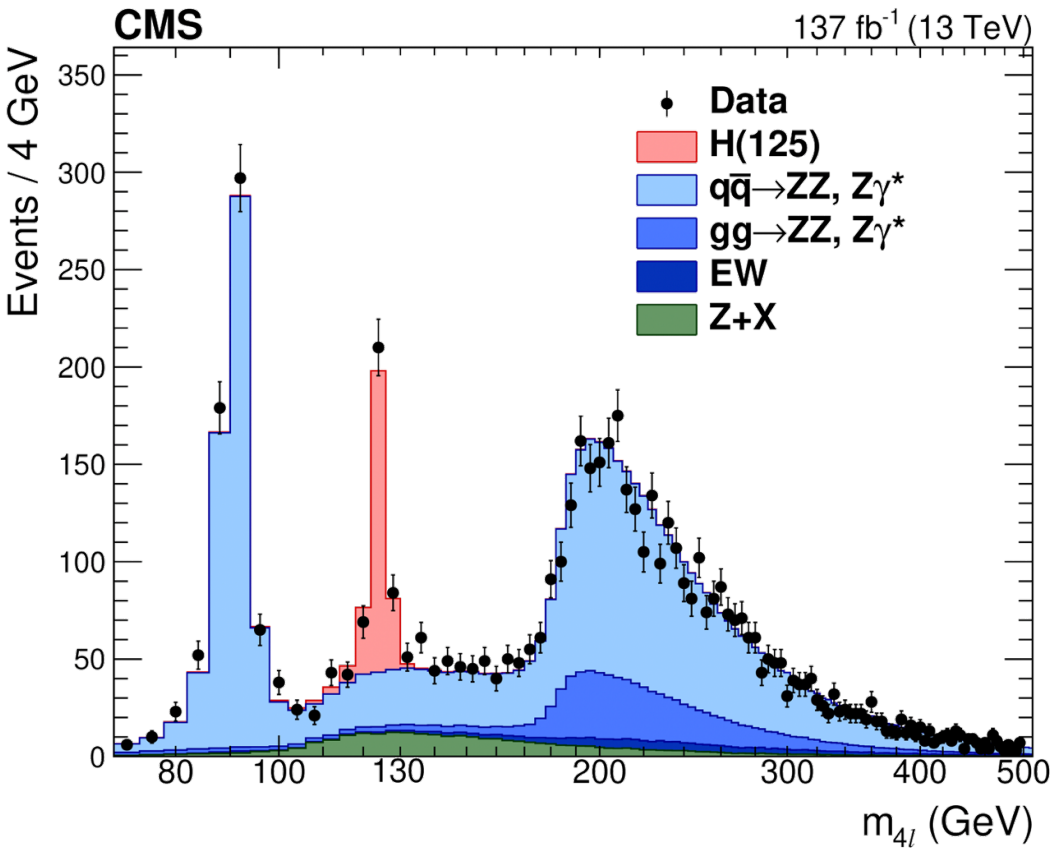
- Run-3 will > double the existing data
- What is statistically limited?
- What improvements are feasible systematically?

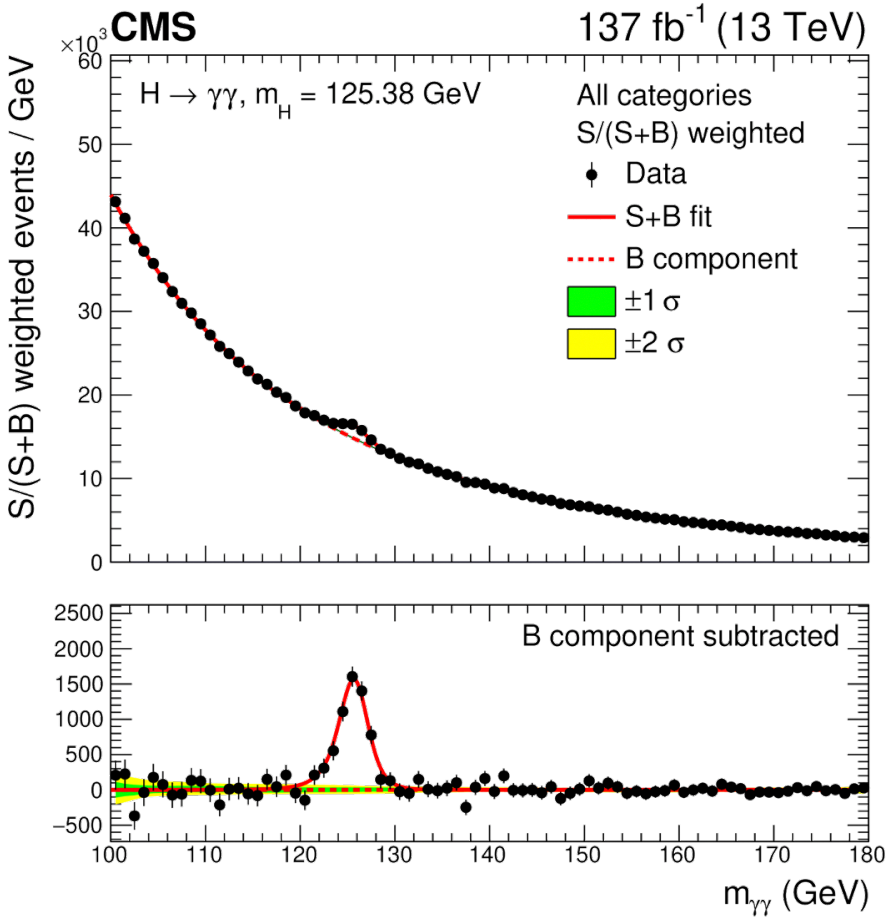
146	HIG-20-014	Search for a heavy Higgs boson decaying into two lighter Higgs bosons in the $\tau\tau$bb final state at 13 TeV	Submitted to JHEP	18 June 2021
145	HIG-20-009	Search for lepton-flavor violating decays of the Higgs boson in the $\mu\tau$ and eτ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV	Accepted by PRD	7 May 2021
144	HIG-19-009	Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state	Accepted by PRD	25 April 2021
143	HIG-20-017	Search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector boson pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to EPJC	10 April 2021
142	HIG-19-015	Measurements of Higgs boson production cross sections and couplings in the diphoton decay channel at $\sqrt{s} = 13$ TeV	JHEP 07 (2021) 027	12 March 2021
141	HIG-19-001	Measurements of production cross sections of the Higgs boson in the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV	EPJC 81 (2021) 488	8 March 2021
140	HIG-19-018	Search for nonresonant Higgs boson pair production in final states with two bottom quarks and two photons in proton-proton collisions at $\sqrt{s} = 13$ TeV	JHEP 03 (2021) 257	24 November 2020
139	HIG-19-008	Measurement of the Higgs boson production rate in association with top quarks in final states with electrons, muons, and hadronically decaying tau leptons at $\sqrt{s} = 13$ TeV	EPJC 81 (2021) 378	7 November 2020
138	HIG-19-006	Evidence for Higgs boson decay to a pair of muons	JHEP 01 (2021) 148	9 September 2020
137	HIG-19-012	Search for decays of the 125 GeV Higgs boson into a Z boson and a ρ or ϕ meson	JHEP 11 (2020) 039	9 July 2020
136	HIG-19-002	Measurement of the inclusive and differential Higgs boson production cross sections in the leptonic WW decay mode at $\sqrt{s} = 13$ TeV	JHEP 03 (2021) 003	4 July 2020
135	HIG-19-003	Inclusive search for highly boosted Higgs bosons decaying to bottom quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV	JHEP 12 (2020) 085	24 June 2020
134	HIG-18-013	Search for resonant pair production of Higgs bosons in the bbZZ channel in proton-proton collisions at $\sqrt{s} = 13$ TeV	PRD 102 (2020) 032003	11 June 2020
133	HIG-18-021	Search for a light charged Higgs boson in the $H^{\pm} \to cs$ channel in proton-proton collisions at $\sqrt{s} = 13$ TeV	PRD 102 (2020) 072001	18 May 2020
132	HIG-18-024	Search for a light pseudoscalar Higgs boson in the boosted $\mu\mu\tau\tau$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV	JHEP 08 (2020) 139	18 May 2020
131	HIG-19-013	Measurements of $t\bar{t}H$ production and the CP structure of the Yukawa interaction between the Higgs boson and top quark in the diphoton decay channel	PRL 125 (2020) 061801	25 March 2020
130	HIG-19-004	A measurement of the Higgs boson mass in the diphoton decay channel	PLB 805 (2020) 135425	15 February 2020
129	HIG-18-015	Search for charged Higgs bosons decaying into a top and a bottom quark in the all-jet final state of pp collisions at $\sqrt{s} = 13$ TeV	JHEP 07 (2020) 126	21 January 2020
128	HIG-18-027	A deep neural network for simultaneous estimation of b jet energy and resolution	CSBS 4 (2020) 10	12 December 2019
127	HIG-18-031	A search for the standard model Higgs boson decaying to charm quarks	JHEP 03 (2020) 131	3 December 2019
126	HIG-17-033	Search for a heavy Higgs boson decaying to a pair of W bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV	JHEP 03 (2020) 034	3 December 2019
125	HIG-18-017	Search for lepton flavour violating decays of a neutral heavy Higgs boson to $\mu\tau$ and eτ in proton-proton collisions at $\sqrt{s} = 13$ TeV	JHEP 03 (2020) 103	23 November 2019
124	HIG-18-012	Search for new neutral Higgs bosons through the $H \to ZA \to \ell^+\ell^-b\bar{b}$ process in pp collisions at $\sqrt{s} = 13$ TeV	JHEP 03 (2020) 055	9 November 2019
123	HIG-18-023	Search for a heavy pseudoscalar Higgs boson decaying into a 125 GeV Higgs boson and a Z boson in final states with two tau and two light leptons at $\sqrt{s} = 13$ TeV	JHEP 03 (2020) 065	25 October 2019
122	HIG-18-004	Search for a charged Higgs boson decaying into top and bottom quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV in events with electrons or muons	JHEP 01 (2020) 096	25 August 2019
121	HIG-17-027	Search for heavy Higgs bosons decaying to a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV	JHEP 04 (2020) 171	3 August 2019
120	HIG-18-006	Search for light pseudoscalar boson pairs produced from decays of the 125 GeV Higgs boson in final states with two muons and two nearby tracks in pp collisions at $\sqrt{s} = 13$ TeV	PLB 800 (2019) 135087	16 July 2019
119	HIG-18-010	Search for MSSM Higgs bosons decaying to $\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 13$ TeV	PLB 798 (2019) 134992	6 July 2019
118	HIG-18-025	Search for Higgs and Z boson decays to J/ψ or Υ pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV	PLB 797 (2019) 134811	24 May 2019

Precision measurements in diboson channels

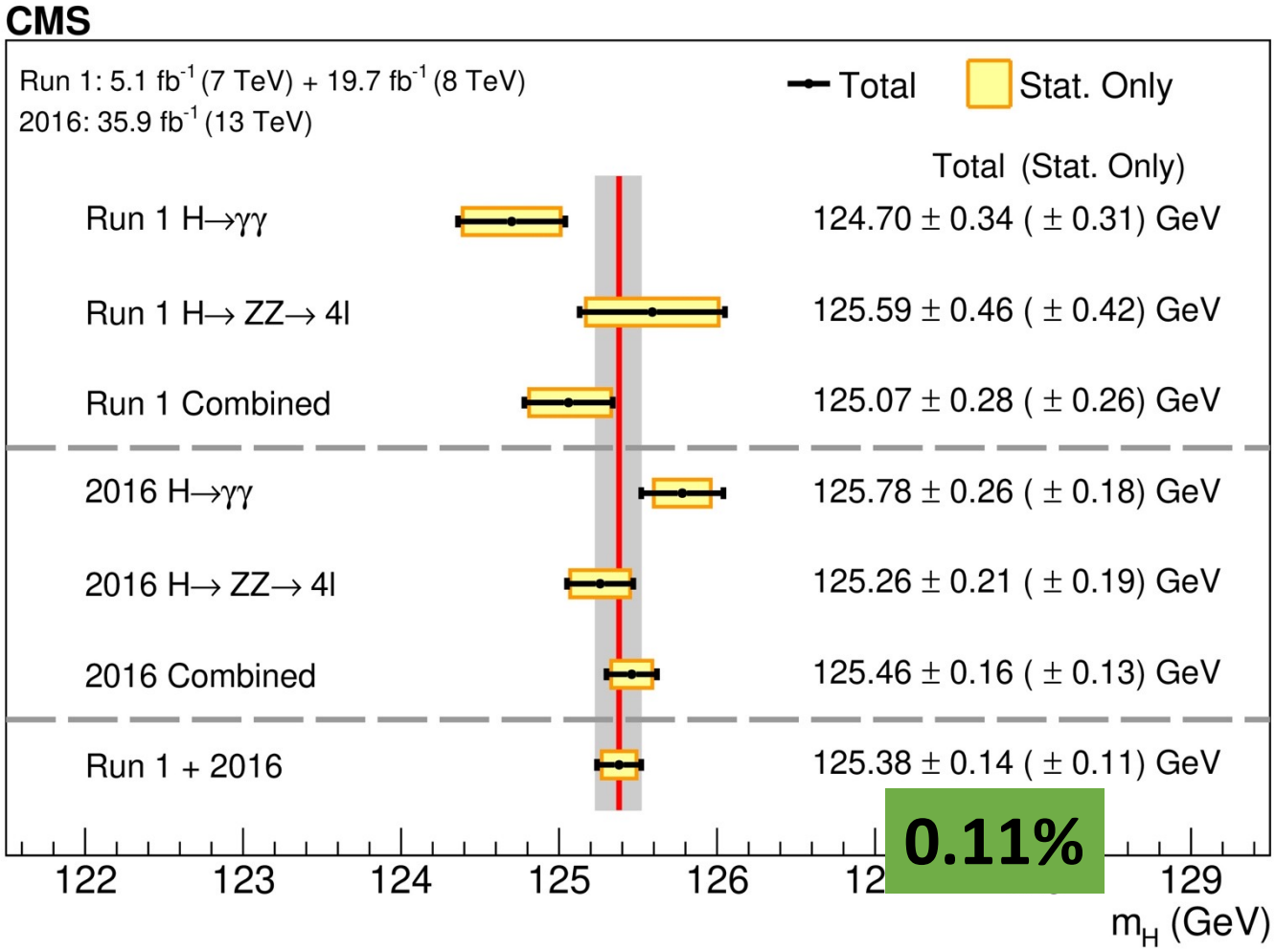


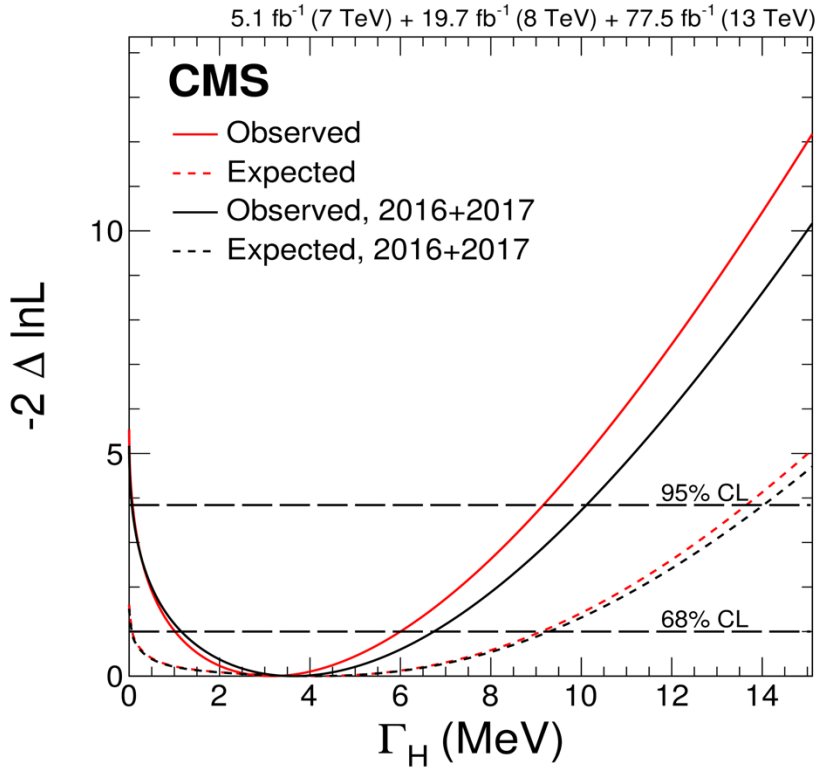






Higgs Mass and Width





$$\Gamma_H = 3.2^{+2.8}_{-2.2}\ \text{MeV}$$

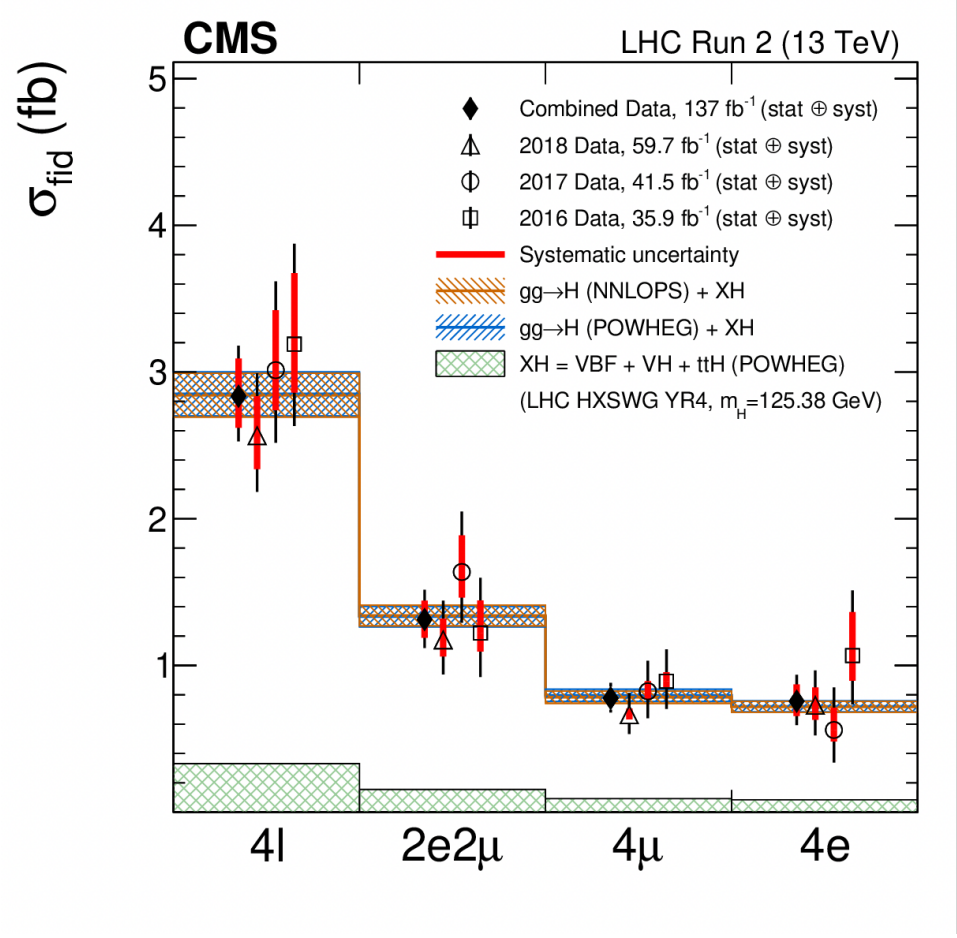
- Can we improve on mass measurement in Run-3?
  - Challenge of calibrations at the current level for EM calorimeter needs work

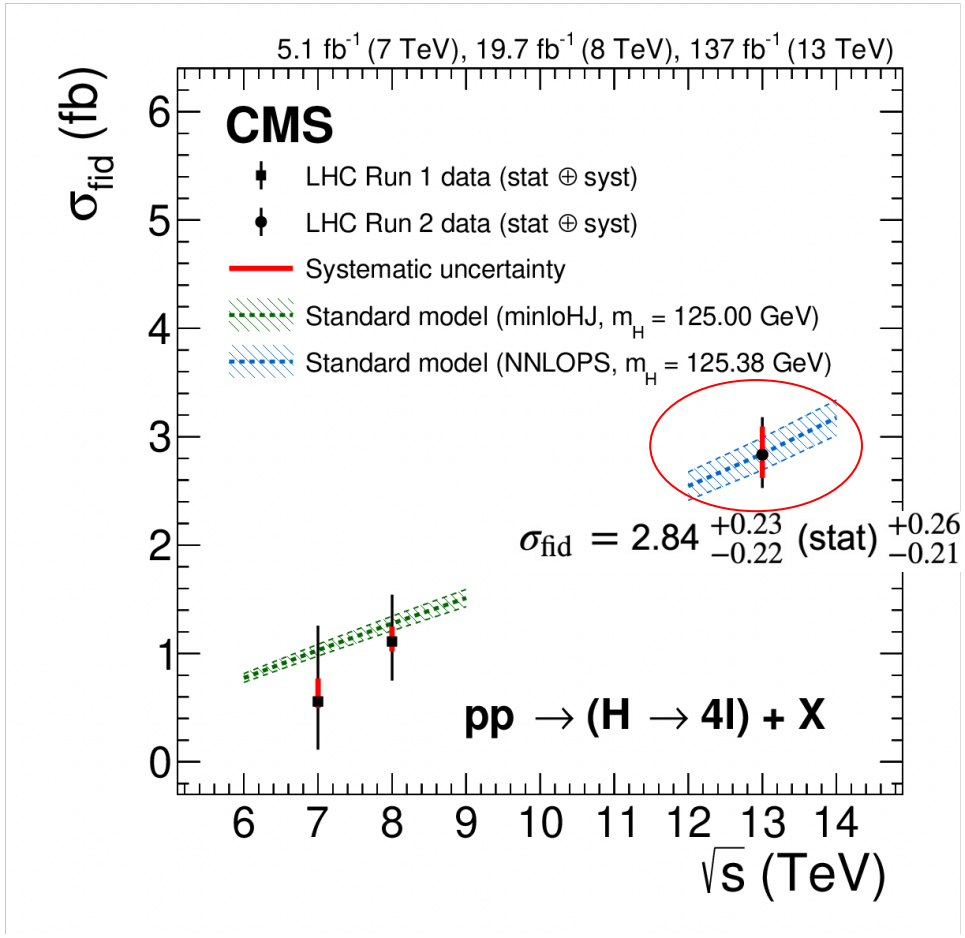
From the ratio of off-shell to on-shell rates using $H \to ZZ \to 4l$

And assuming:

- SM-like amplitude structure for $H \to ZZ$
- No significant BSM physics in $gg \to H$ up to mH*~1 TeV

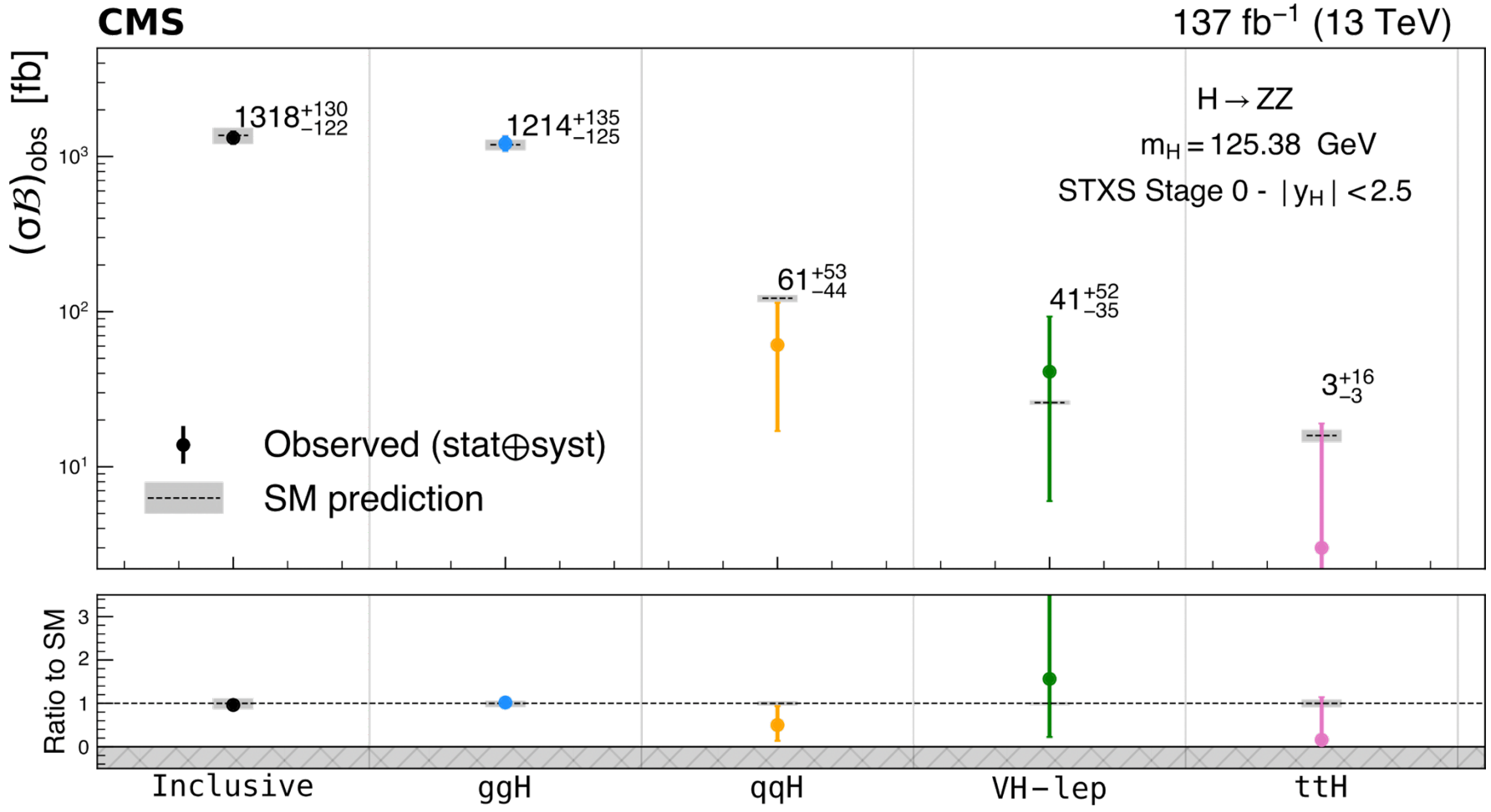
H→4l: Cross sections by final states and √s dependence





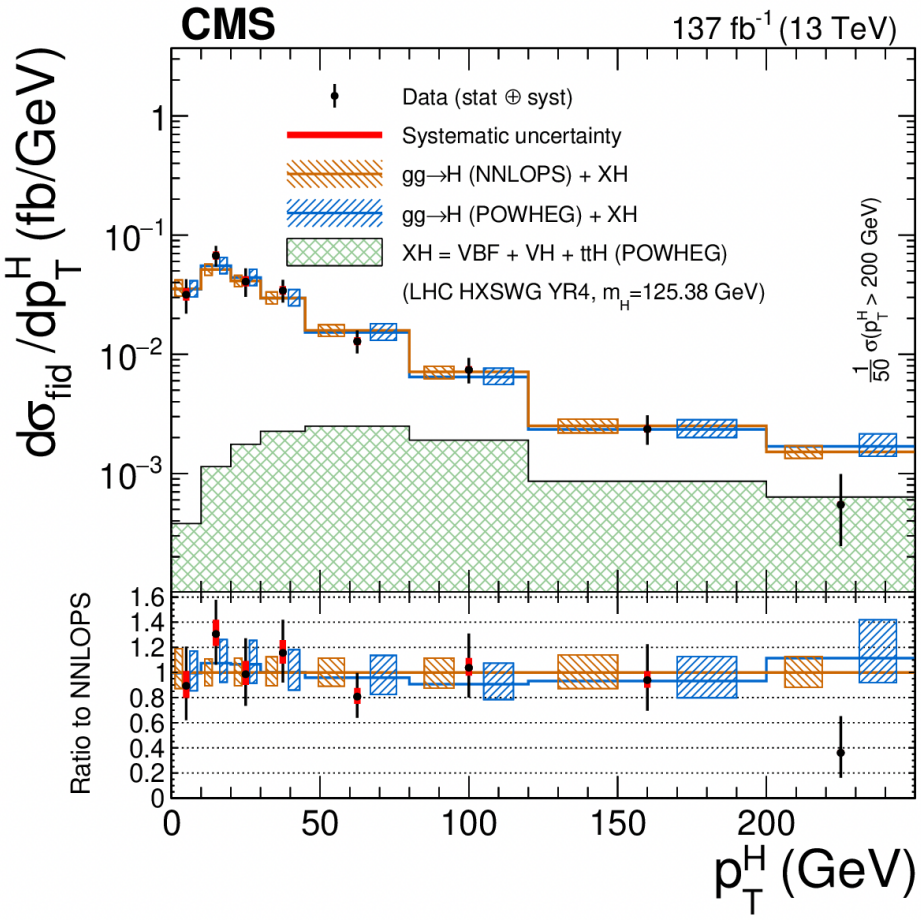
- Systematics driven by uncertainties on e/mu efficiencies

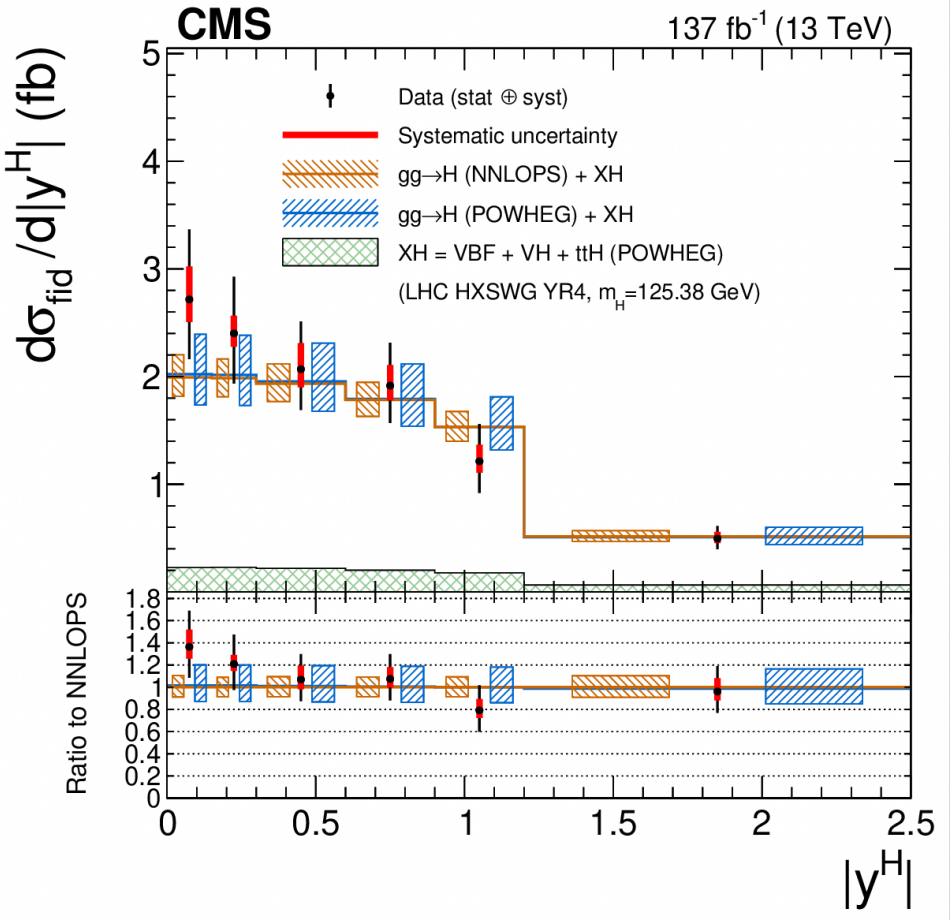
H⟶4l: Cross Sections By Production Mode



- Statistically limited measurements in low background channel – Run-3 will likely improve better than luminosity scaling as the fits get better

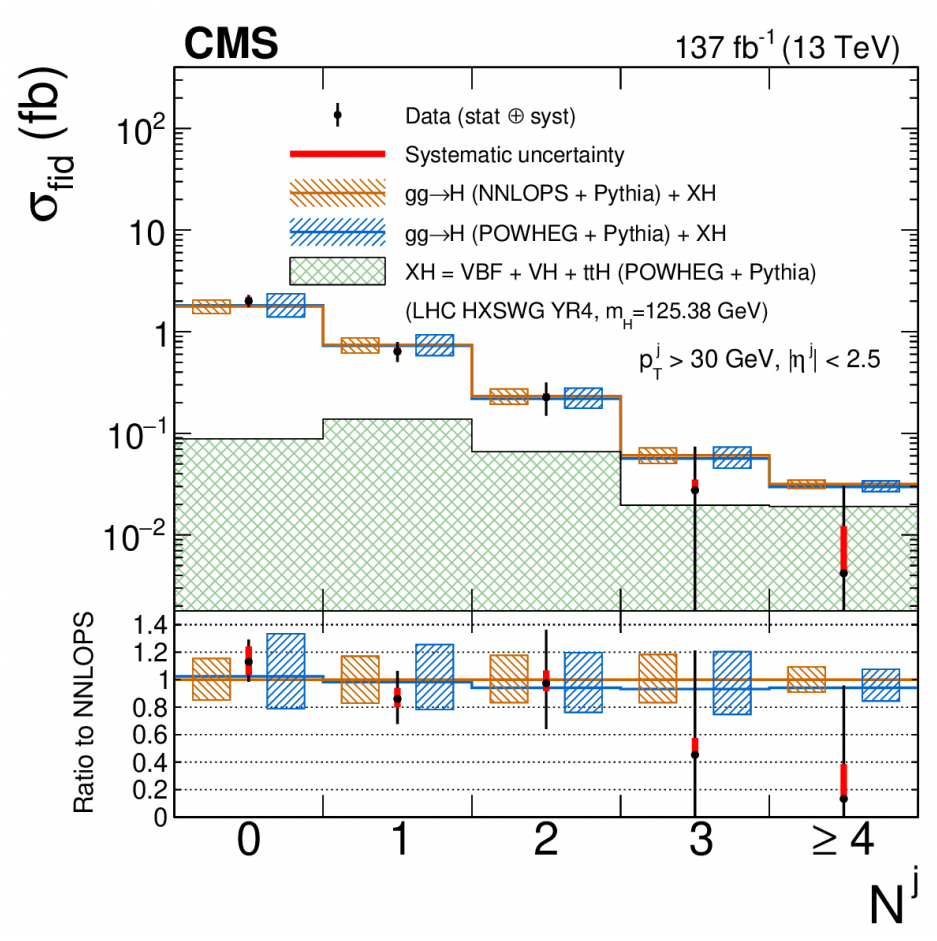
H⟶4l: Higgs PT & Rapidity Spectra

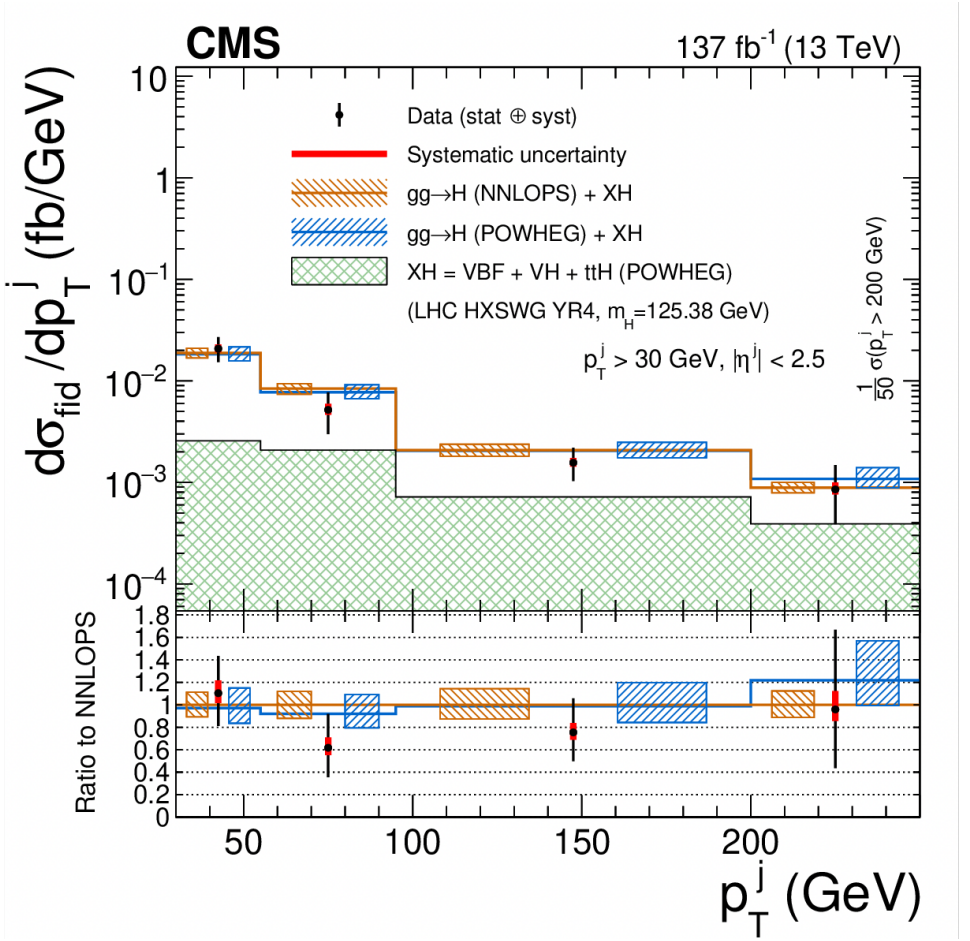




- Statistically limited measurements in low background channel –
  Run-3 will likely improve better than luminosity scaling as the fits get better

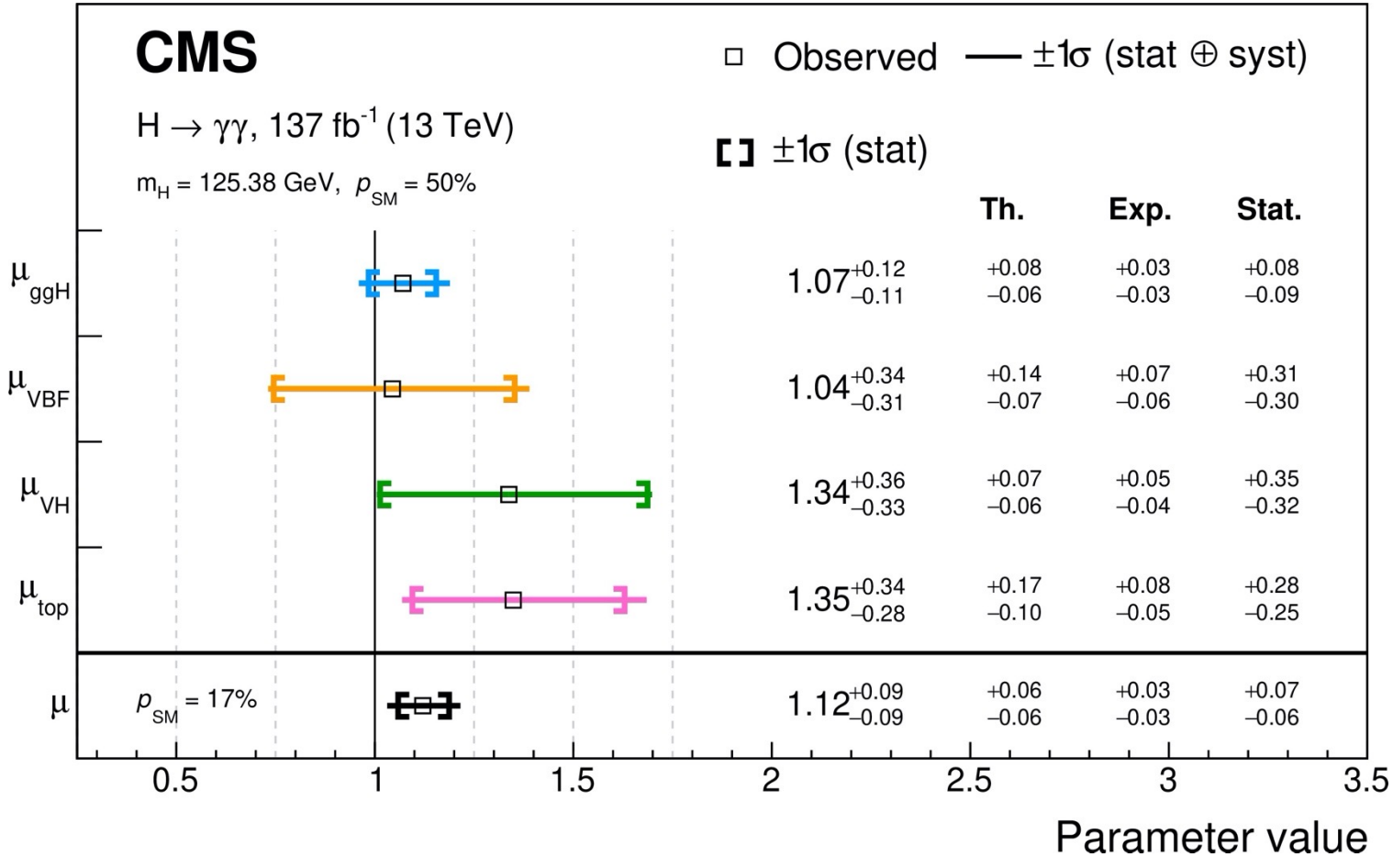
H⟶4l: Number of Jets & Jet PT Distributions





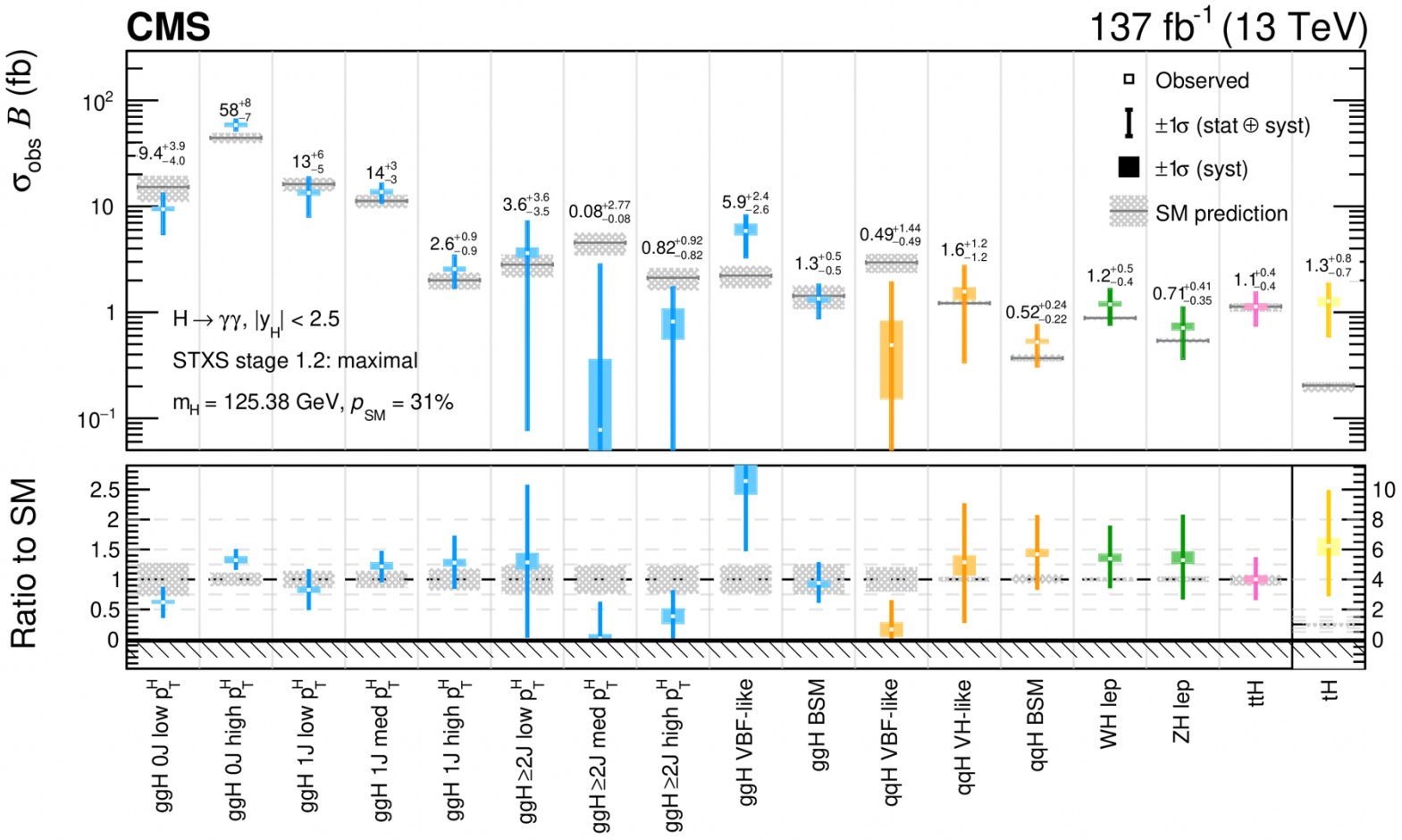
- Statistically limited measurements in low background channel – Run-3 will likely improve better than luminosity scaling as the fits get better

H→γγ: Partial Cross Sections



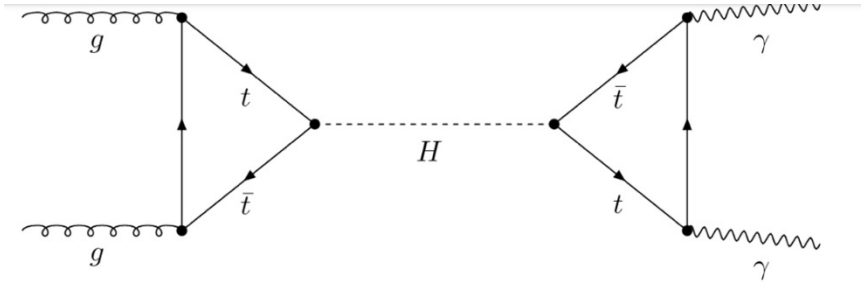
- Statistically limited measurements –
  Run-3 will likely improve – Will theory uncertainties get better?

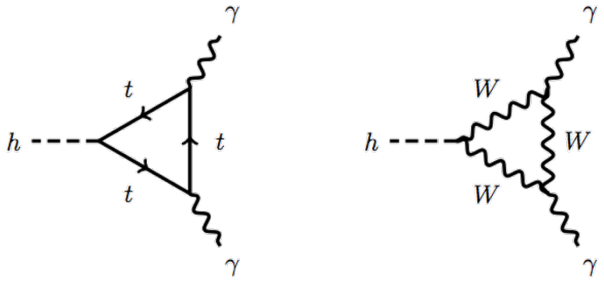
H→γγ: Simplified Template Cross Sections

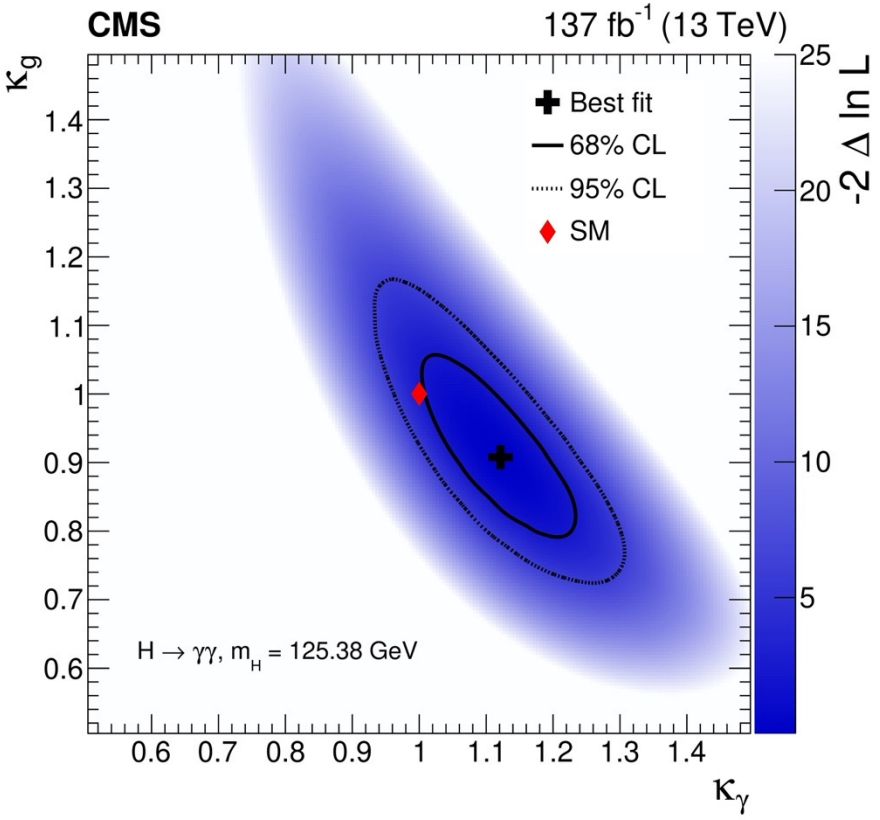


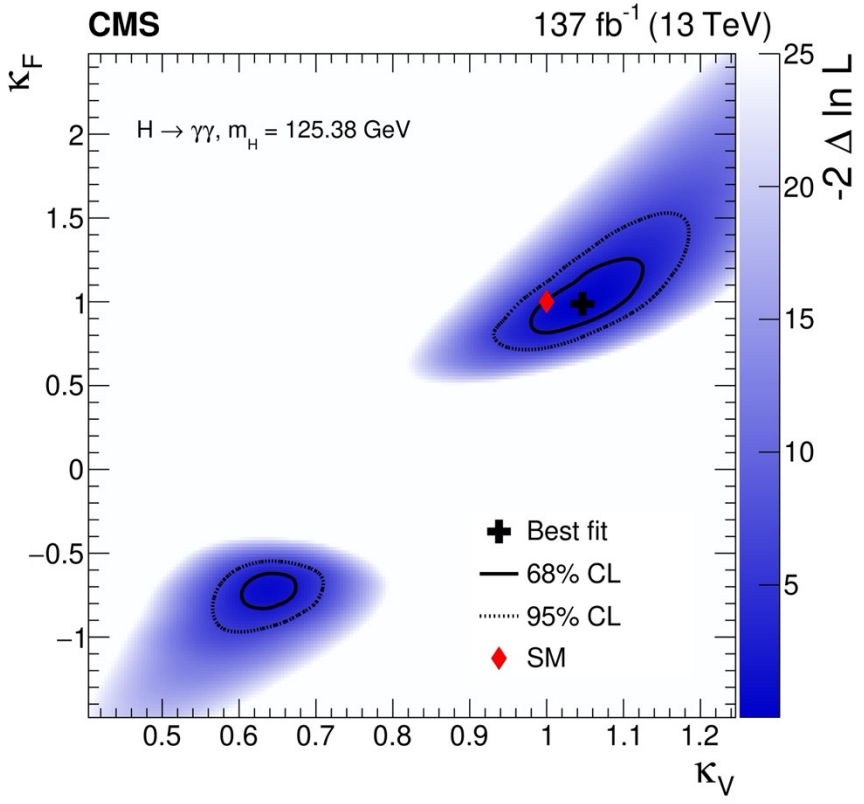
- Statistically limited measurements –
  Run-3 will likely improve better than luminosity scaling as the fits get better – Sensitivity to BSM

H→γγ: Coupling Scan in κ-framework







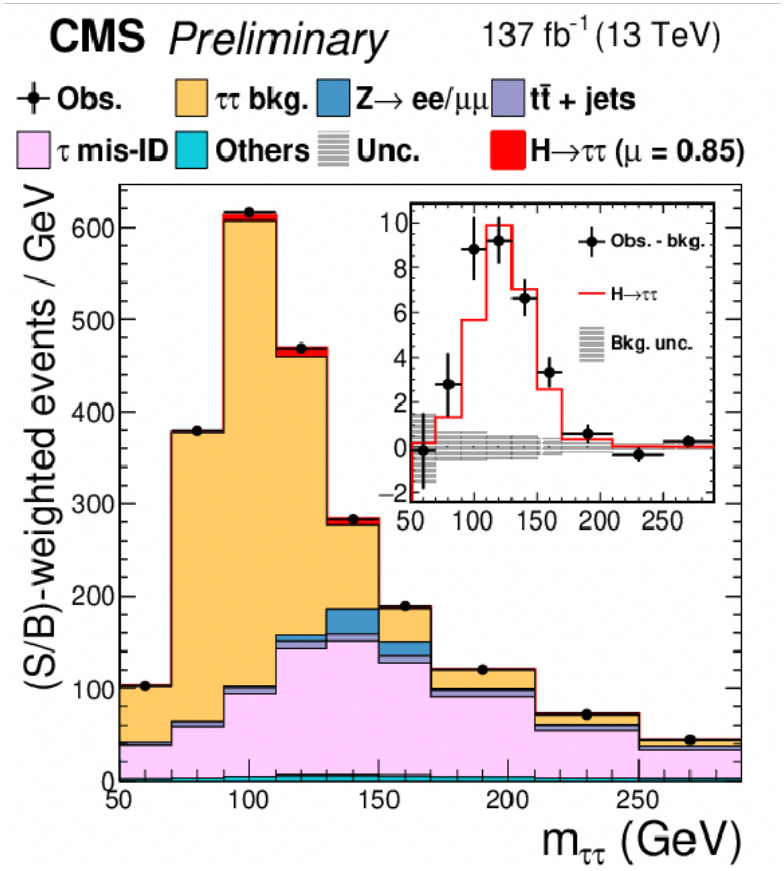


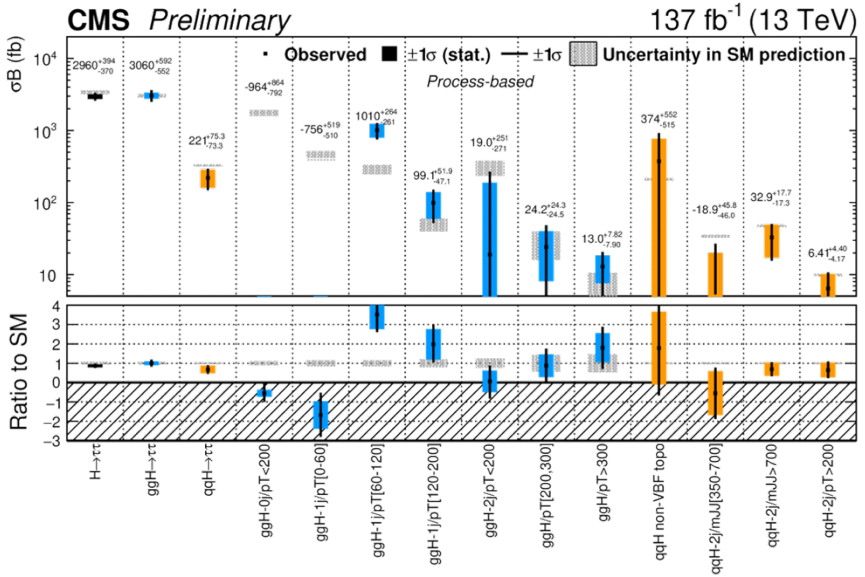
Higgs Yukawa Sector

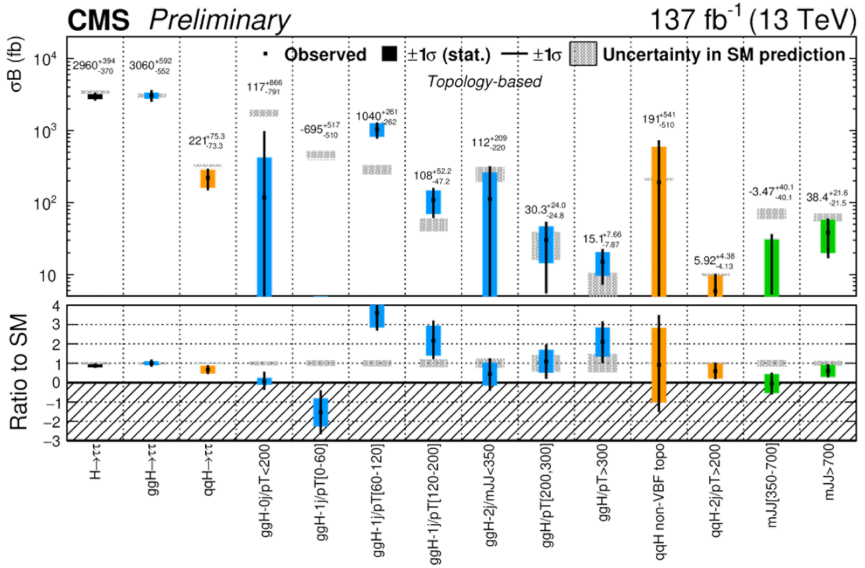
Higgs to τ Leptons

Observation of Higgs decays to τ leptons

- 2018 : First direct observation of Yukawa coupling
- 2020 : Updated to full Run-2 data (preliminary)
- Run-3 update useful again



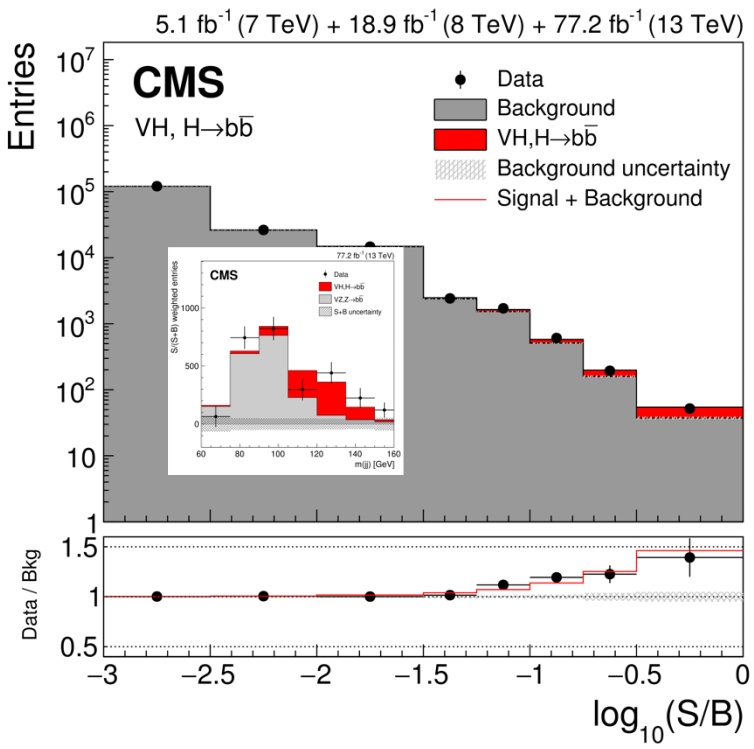


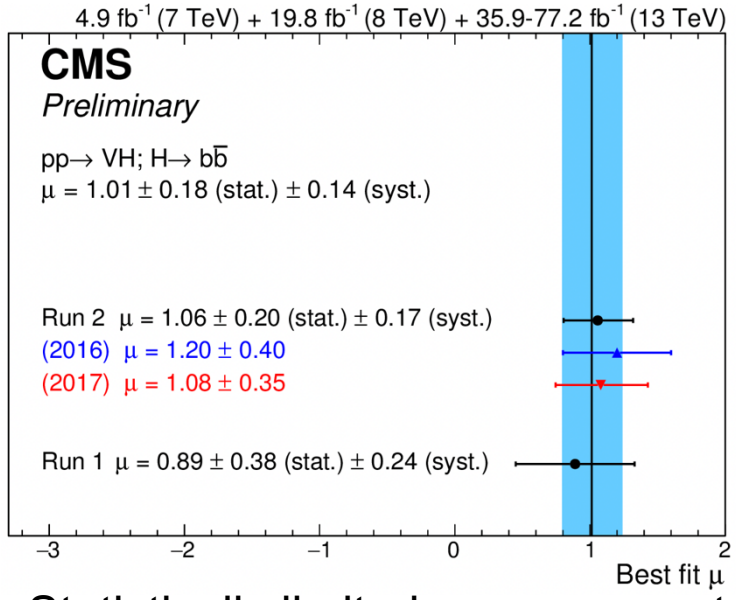


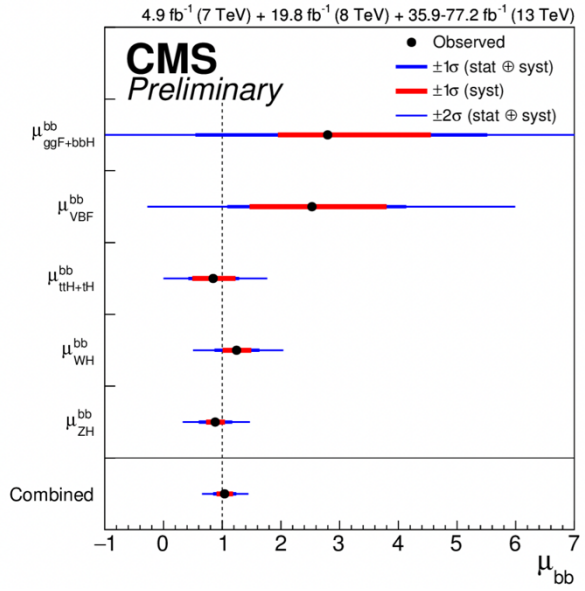
Higgs to Bottom Quark Pairs

Observation of H(125) decay to bottom-pairs at 5.6σ

- Largest branching fraction, but large backgrounds
- Focus on VH production mode with leptonic V decays providing trigger
- Relies on b-tagging and boosted topologies for background reduction
- Emphasis on jet energy corrections and calibrations for mass resolution
- **With full Run-2 data both statistical and systematic uncertainties should improve**





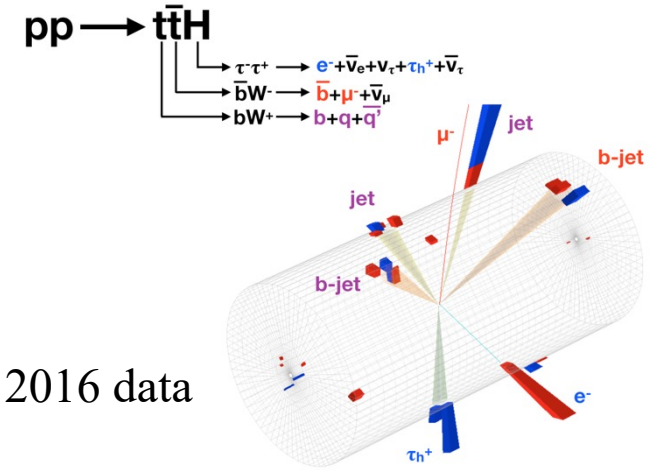


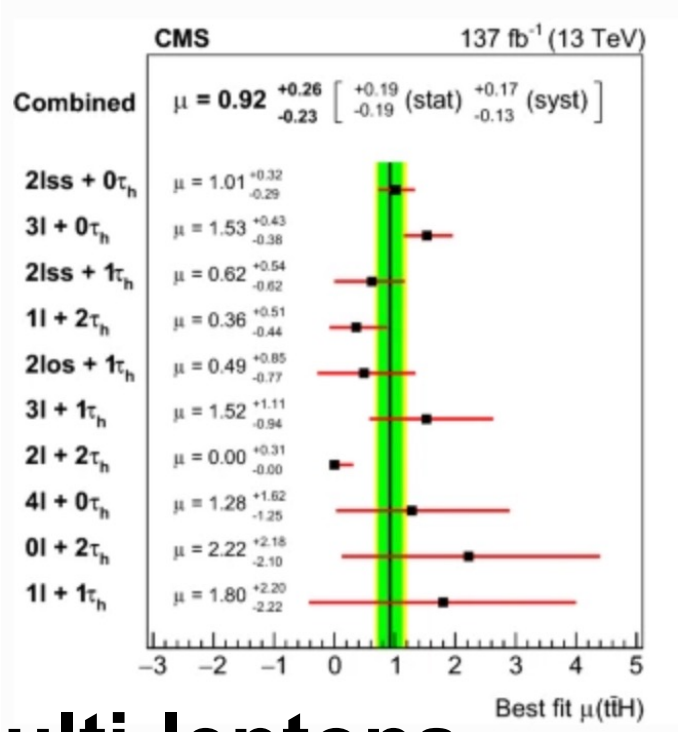
Statistically limited measurements:
Backgrounds can be better understood with Run-3 data.
Improved triggering may help with WHbb and VBF-Hbb.

Observation of ttH Production

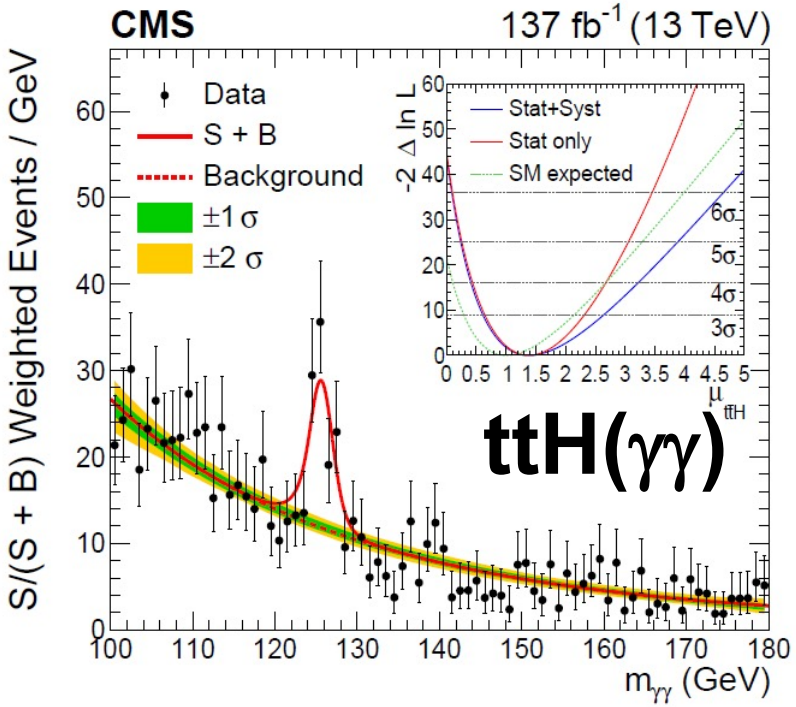
Higgs-Top Yukawa coupling is large

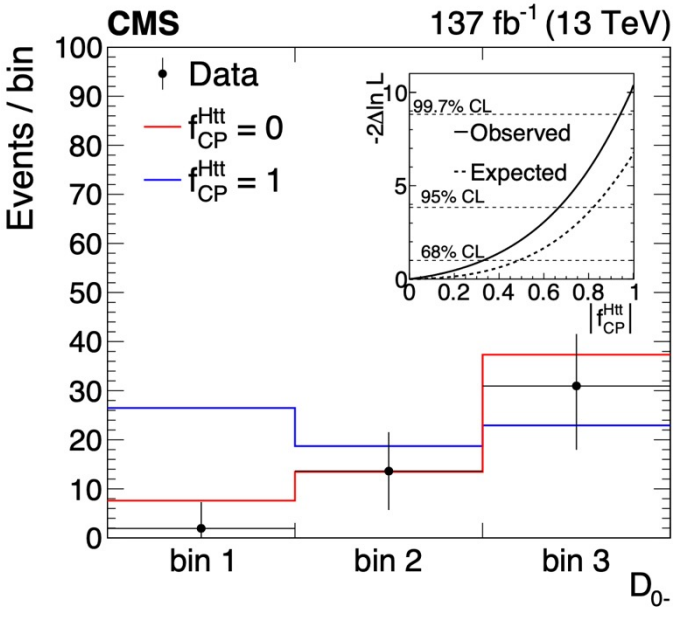
- Associated production with ttbar results in rather busy events
- A plethora of decay modes available
- A multivariate analysis to extract the signal strength was performed
- Observation at 5.2**σ** significance was made on including Run-1 and 2016 data
- With full Run-2 data, ttH established in single channels





multi-leptons



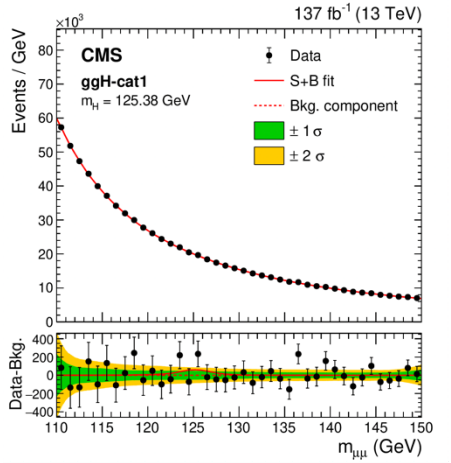


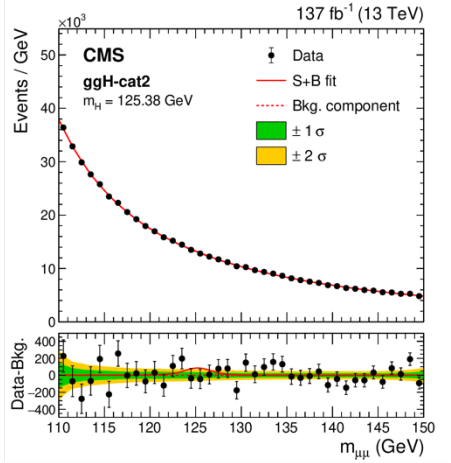
First measurement of CP structure of Htt coupling

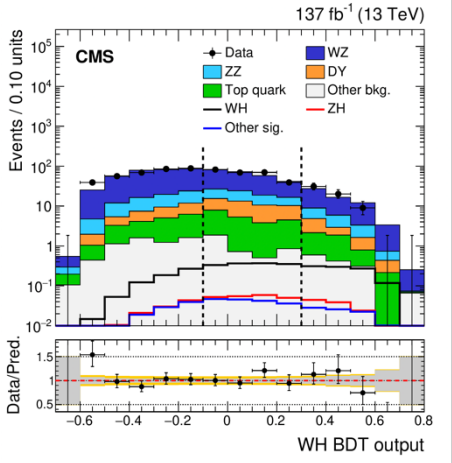
Evidence for H⟶μμ

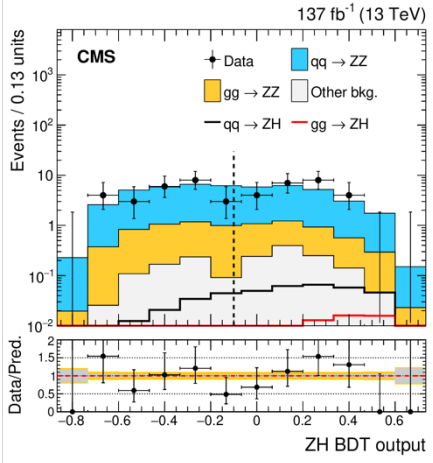
Observation of Higgs decays to muon pairs requires Run-3

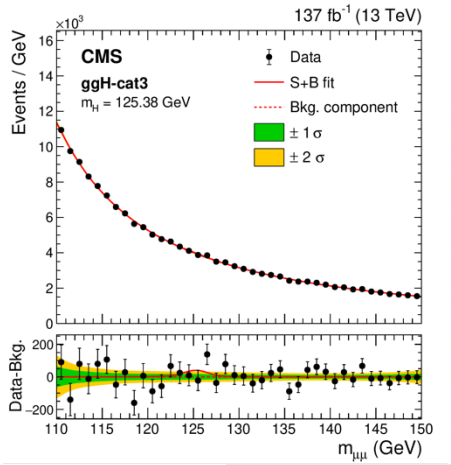
- Small Yukawa coupling but clean final state with good mass resolution
- However, the narrow peak is sitting on large-smooth DY continuum background

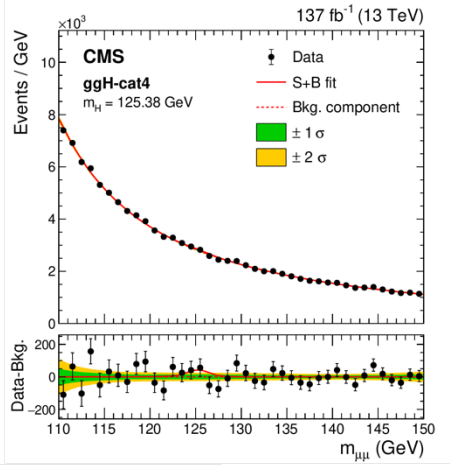


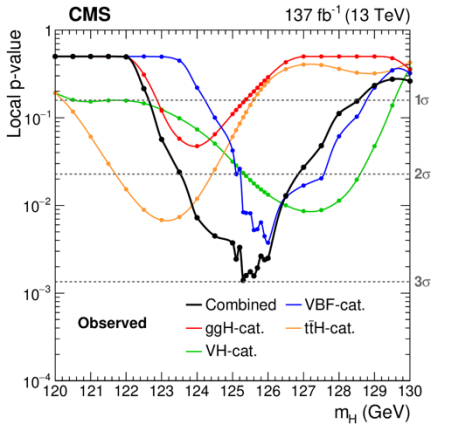


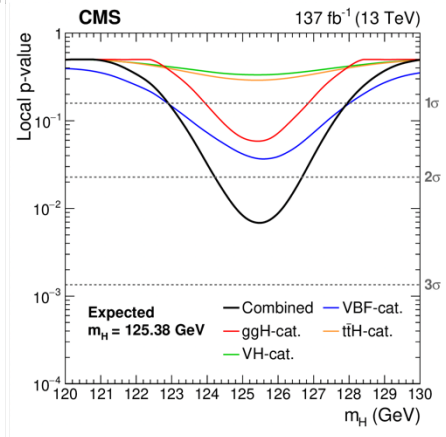








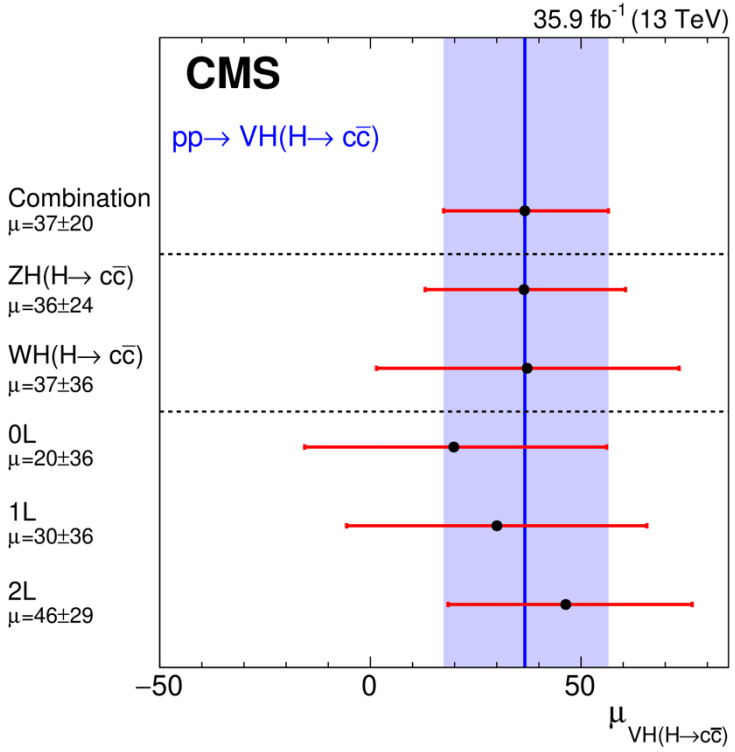


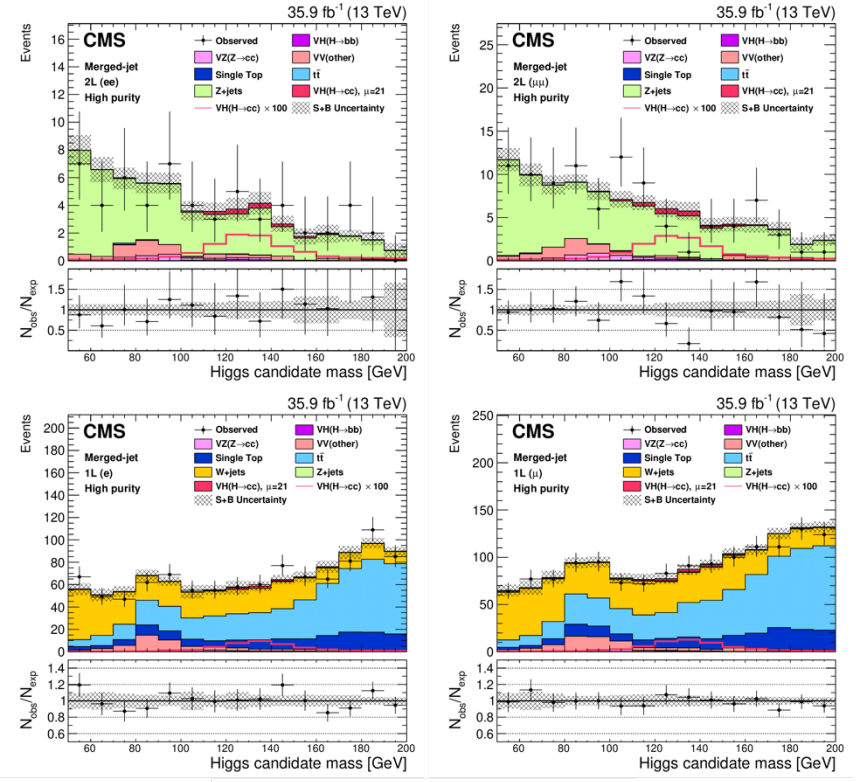


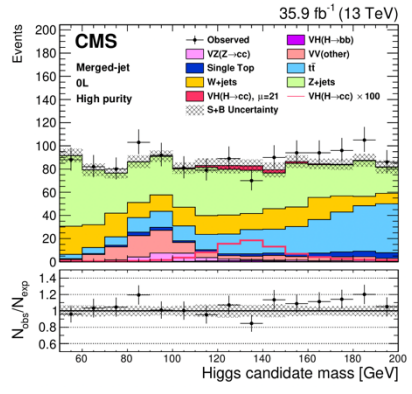
Can we possibly find H→cc?

Small branching fraction coupled by poor charm identification

- VH production
- Charm jet id with multi-classifier: DeepCSV
- Resolved and boosted jet topologies separated
- Perhaps, this awaits HL-LHC or possibly beyond



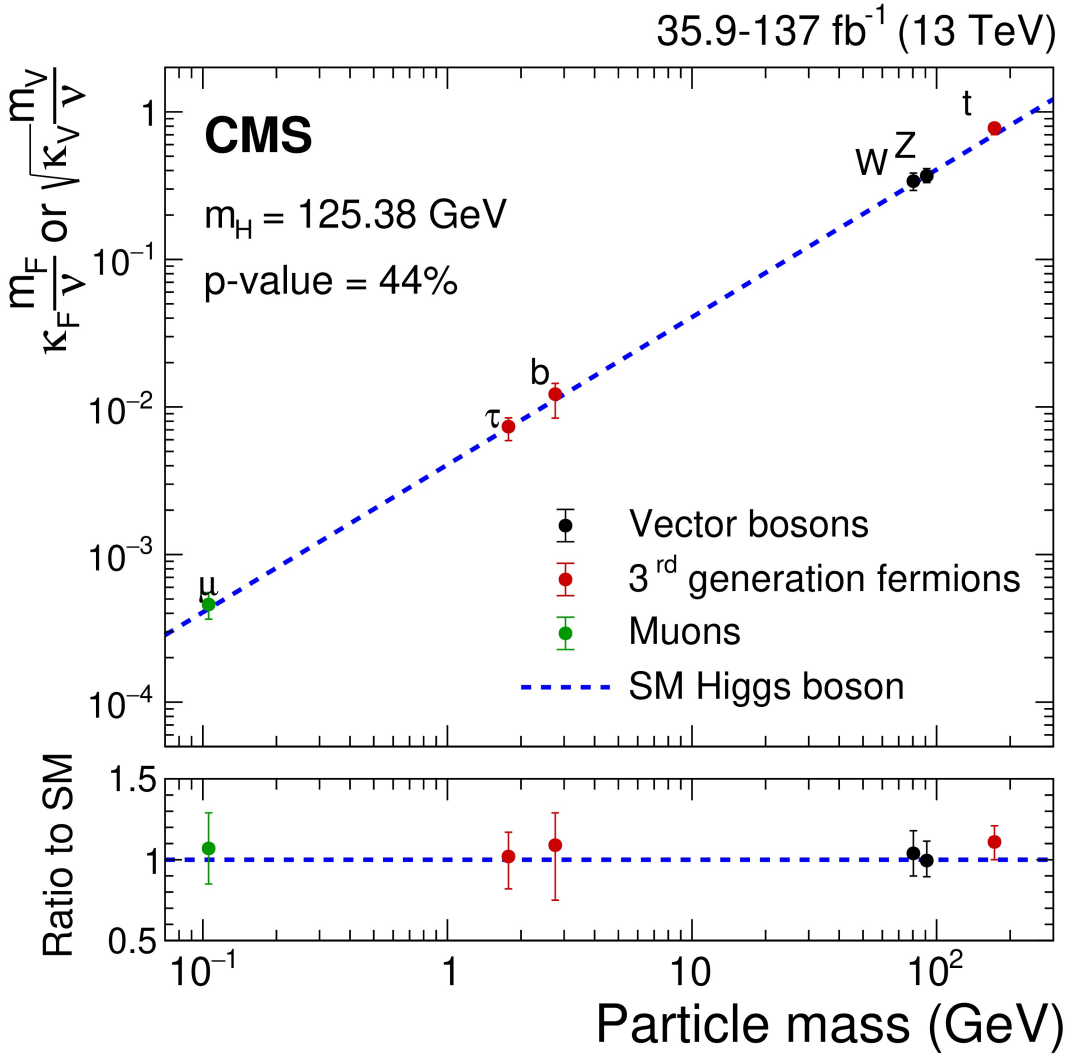




Higgs couplings

Our discovery of a Higgs boson completes the Standard Model

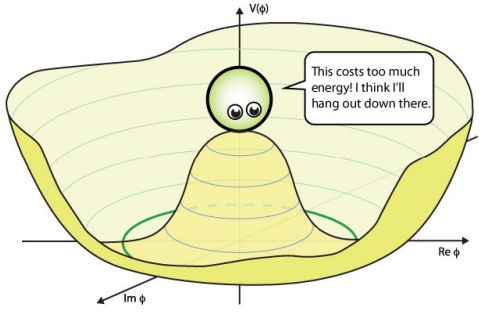
- 2018 : h(125) continues to look like The SM Higgs Boson
  - Deviations from fermionic & vector coupling SM expectations quantified
- 2021: Many channels updated to full Run-2 data of 137 fb^{-1}
  - Further constraints with Run-2 before Run-3 data-doubling begins



Higgs Self-coupling

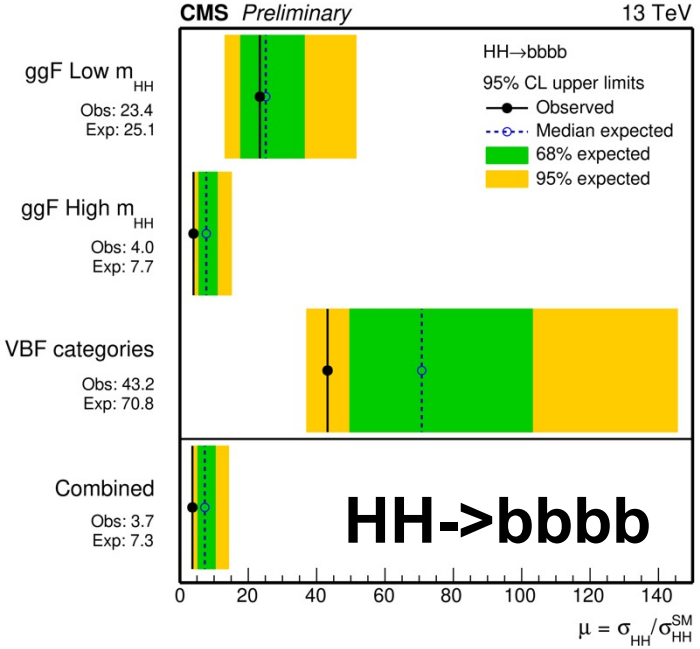
More in Jin Wang's talk

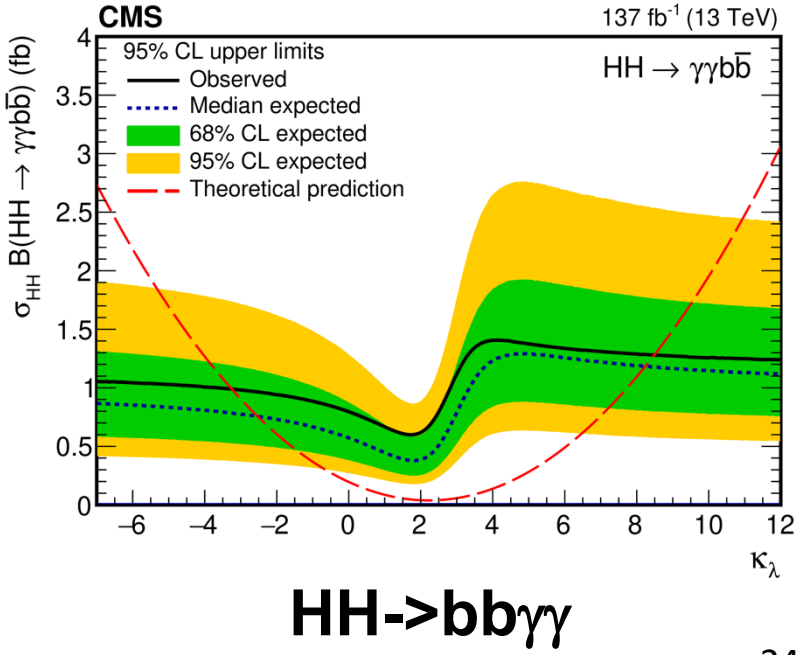
- SM HH production cross section is rather small
- Searches for enhancements due to new physics are of interest already
  - Are there deviations from the expected λ ?
- With more channels and optimizations, SM-level sensitivity with Run-3 ?



$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2 \Phi^2 - \lambda \Phi^4$$

For $\mu^2 < 0$, minimum $v = \sqrt{-\frac{\mu^2}{2\lambda}}$





Does it decay in unexpected ways ?

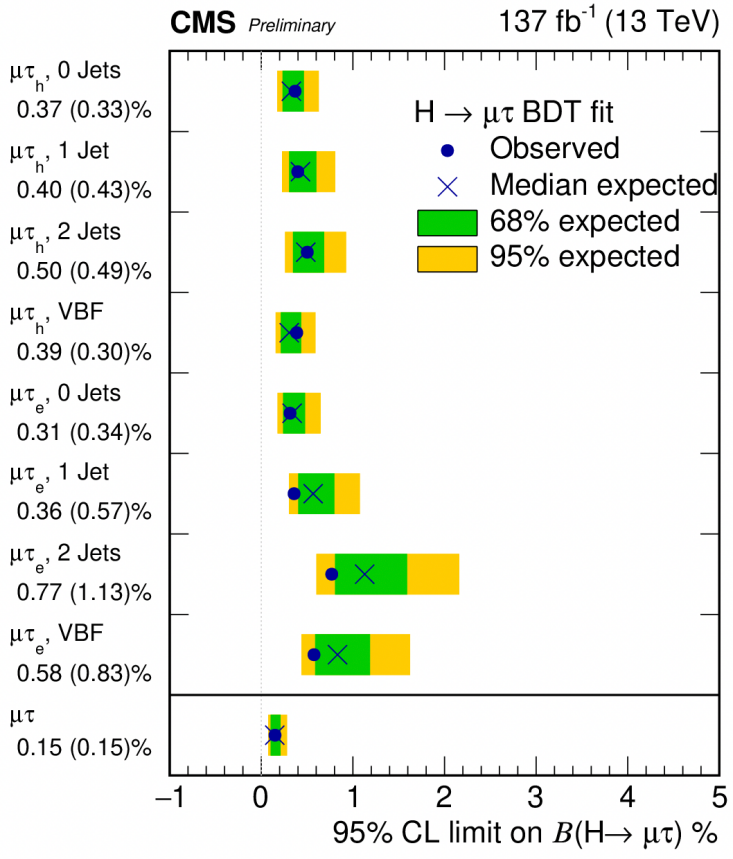
- LFV: Does it have non-diagonal Yukawa couplings leading to lepton flavor violations ?
- Connections to dark matter: Invisible decays
- Exotic decays: can it decay to a pair of light pseudo scalars ?

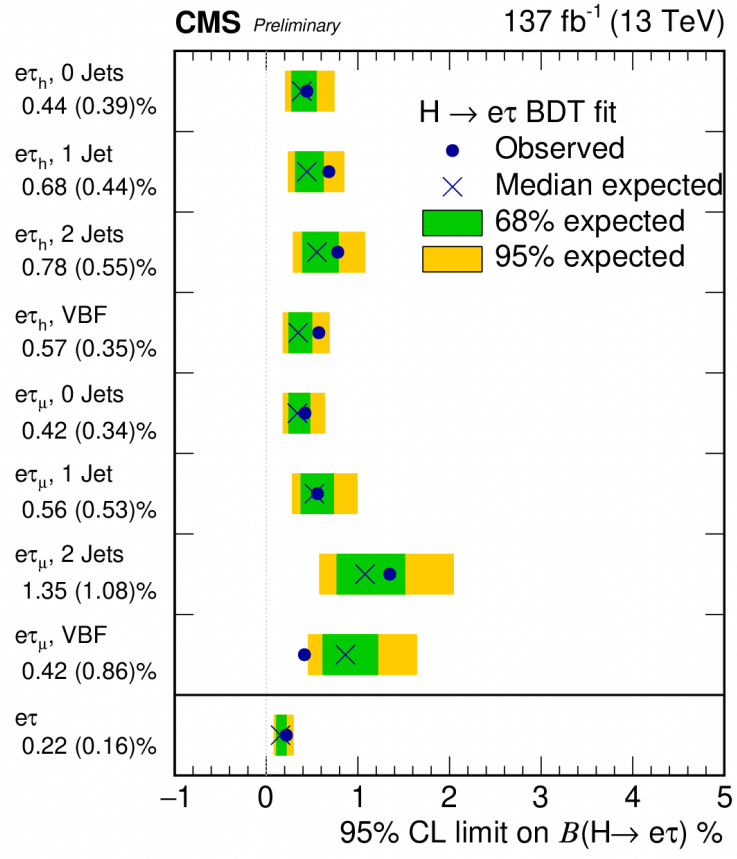
Lepton Flavor Violating Higgs decays

Searches for H→eτ and H→μτ

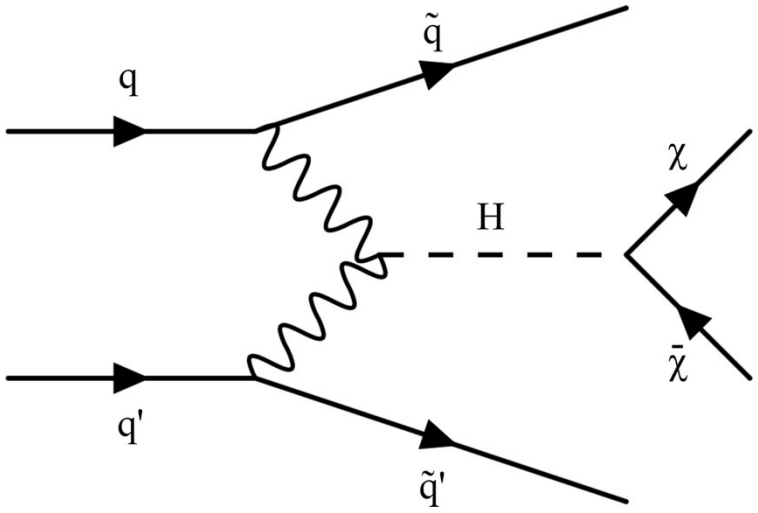
$$Y = \begin{pmatrix} \boxed{Y_{ee}} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & \boxed{Y_{\mu\mu}} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & \boxed{Y_{\tau\tau}} \end{pmatrix}$$

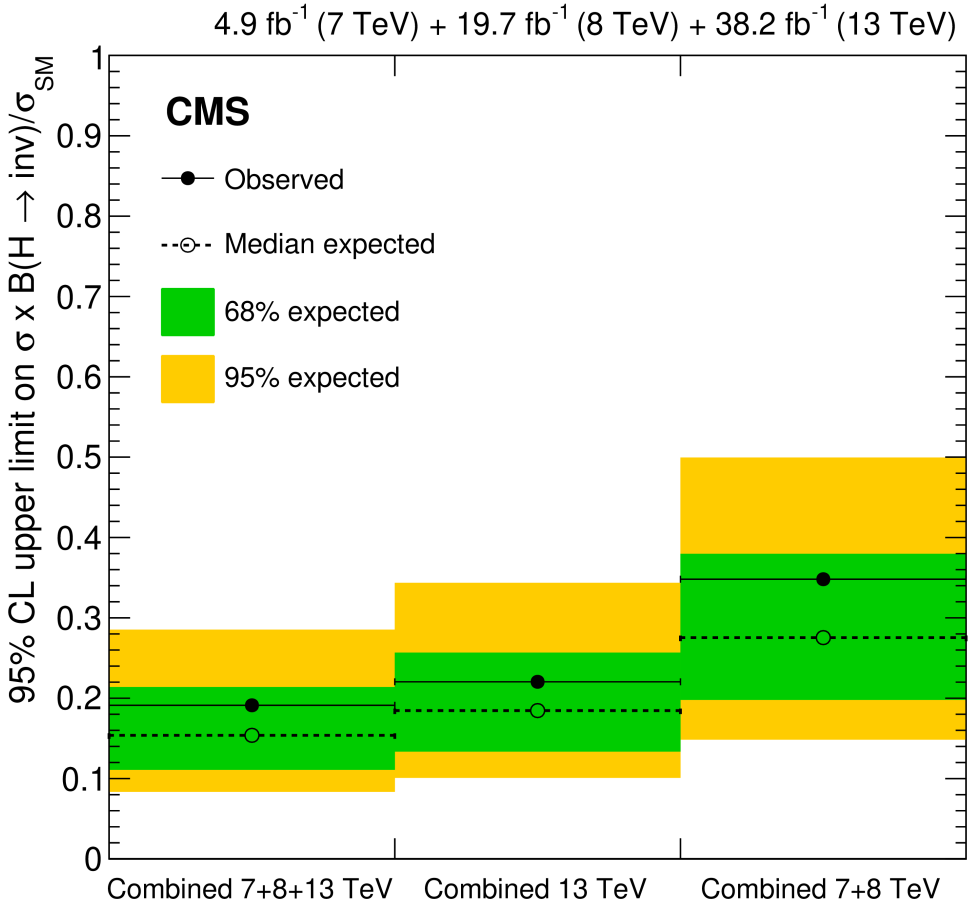
SM values





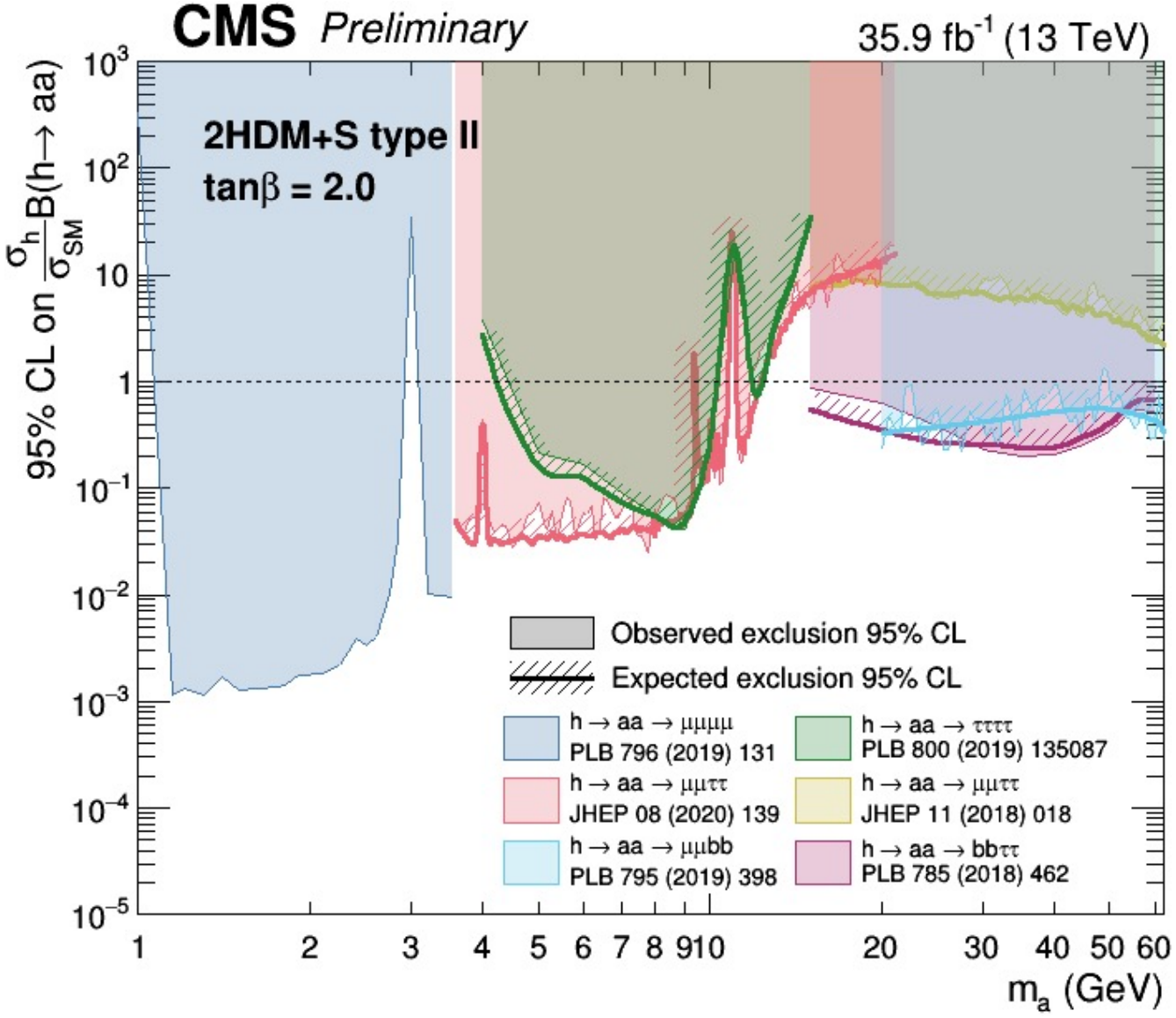
Invisible Higgs





- Main driver: VBF Process
  - Forward going jets have high η-separationa → large invariant mass
- Adding more production modes: ttH, ZH

Exotic Higgs decays



https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2

2021 Status : So, What's Next?

Our discovery of a Higgs boson completes the Standard Model

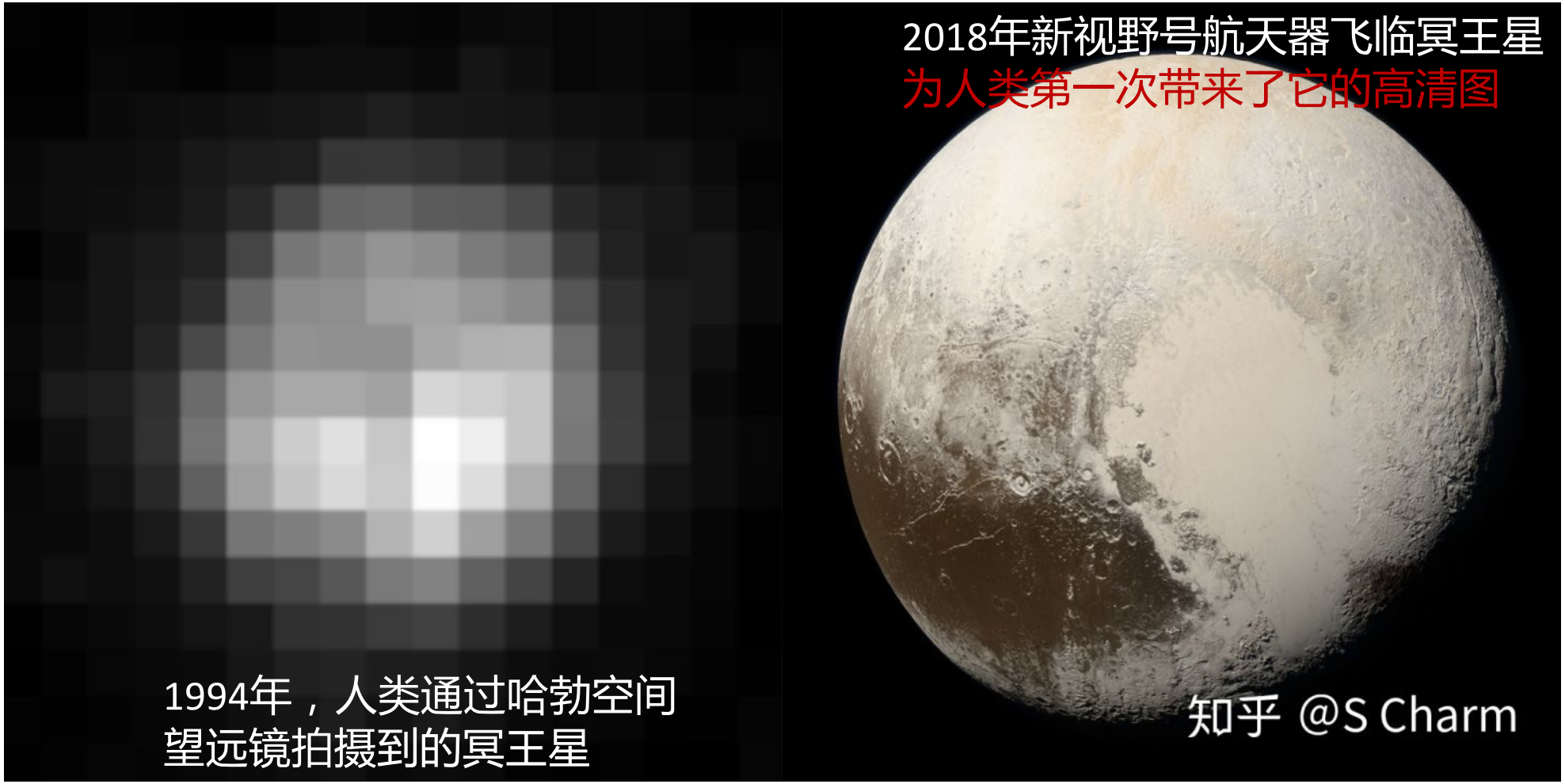
- 2012 : Higgs Boson Discovered
- 2013 : Physics Nobel Prize award!
- 2015 : Detailed Higgs Physics Exploration Began
- 2021 : h(125) continues to look like The SM Higgs Boson

However, the Standard Model can be convicted of incompleteness

- We do not fully understand the Higgs Boson yet (at 10-20% level)
  - Perhaps, in Higgs sector there is still tree level new physics to discover
  - Why is the Higgs mass so light? New ~> TeV particles?
- Exotic particle direct & indirect searches continue to confound us
- Only experiment can shed light, i.e., precise SM measurements needed

Eagerly awaiting discoveries this decade!

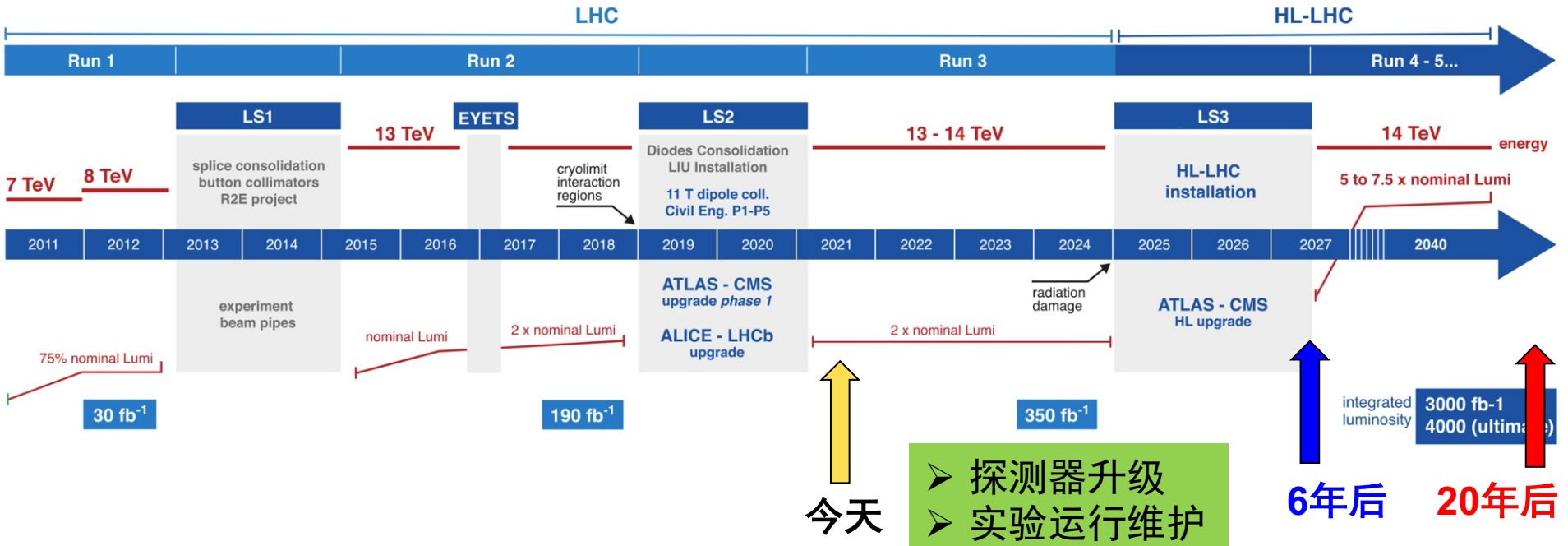
希格斯粒子的发展方向



现在人类所认知的希格斯粒子，就像是1994年人类所认知的冥王星，只有上百个像素。而这上百个像素，已经足以指明一个未来研究进展的方向。

Backup

高亮度LHC及其实验升级



- 探测器升级
- 实验运行维护
- 物理研究

未来十余年大型强子对撞机及其后续升级

仍将是世界上唯一的高能量前沿研究平台，唯一的希格斯玻色子研究场所

Explore wide phase space in SUSY, Dark matter, exotic, CP violation etc.