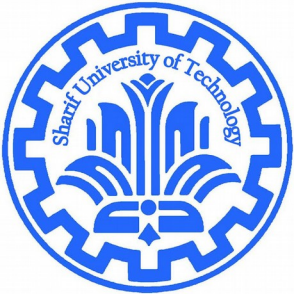


CMS probes for beyond the standard model physics via Higgs boson

Maryam Zeinali

Two Days with Particle Physics Workshop

Shahid Behehshti University (online)

Nov. 18, 2021

Outline

- SM prediction

- Higgs discovery

- Particle properties
  - Mass
  - X-section
  - Spin
  - CP

- Why only 1 Higgs?

- BSM searches
- Current limits

Prediction

- **SM prediction**

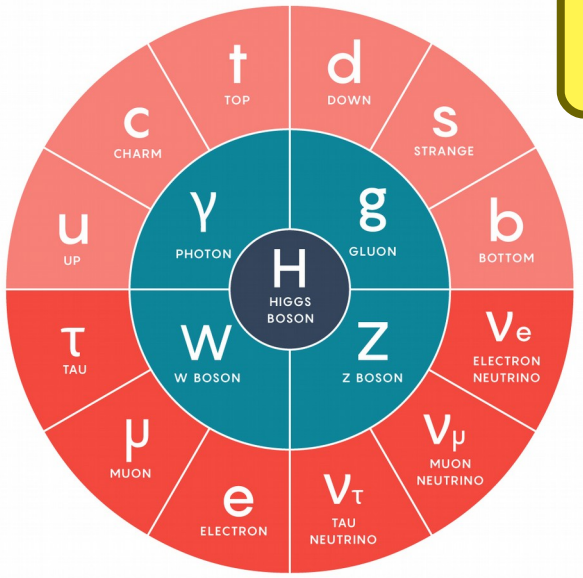
- Why only 1 Higgs?

- Higgs discovery

- Particle properties
  - Mass
  - X-section
  - Spin
  - CP

- BSM searches
- Current limits

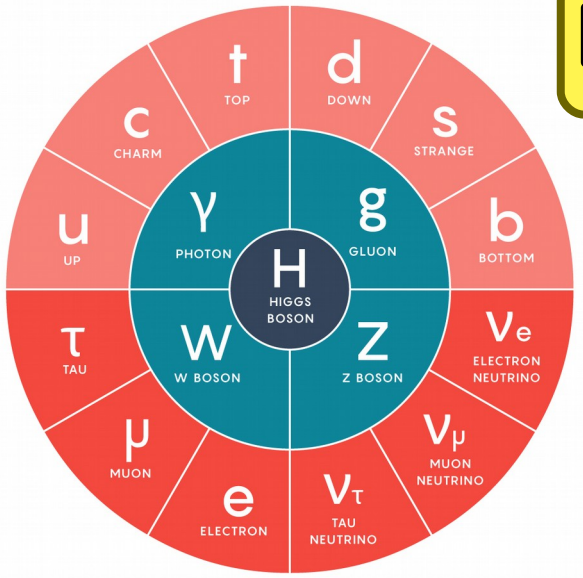
SM particle content



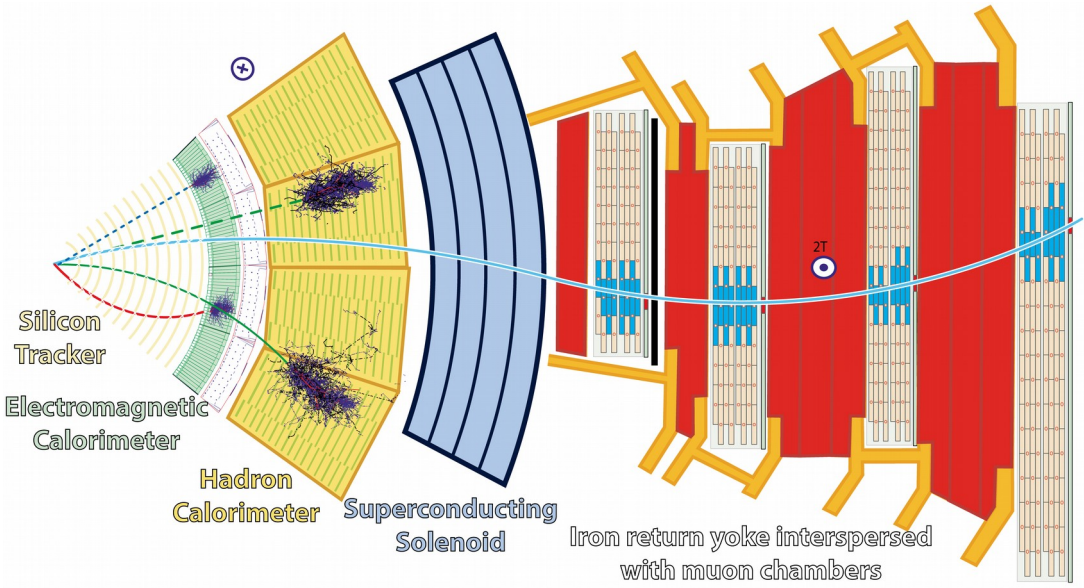
FERMIONS (matter) | BOSONS (force carriers)

Quarks Leptons | Gauge bosons Higgs boson

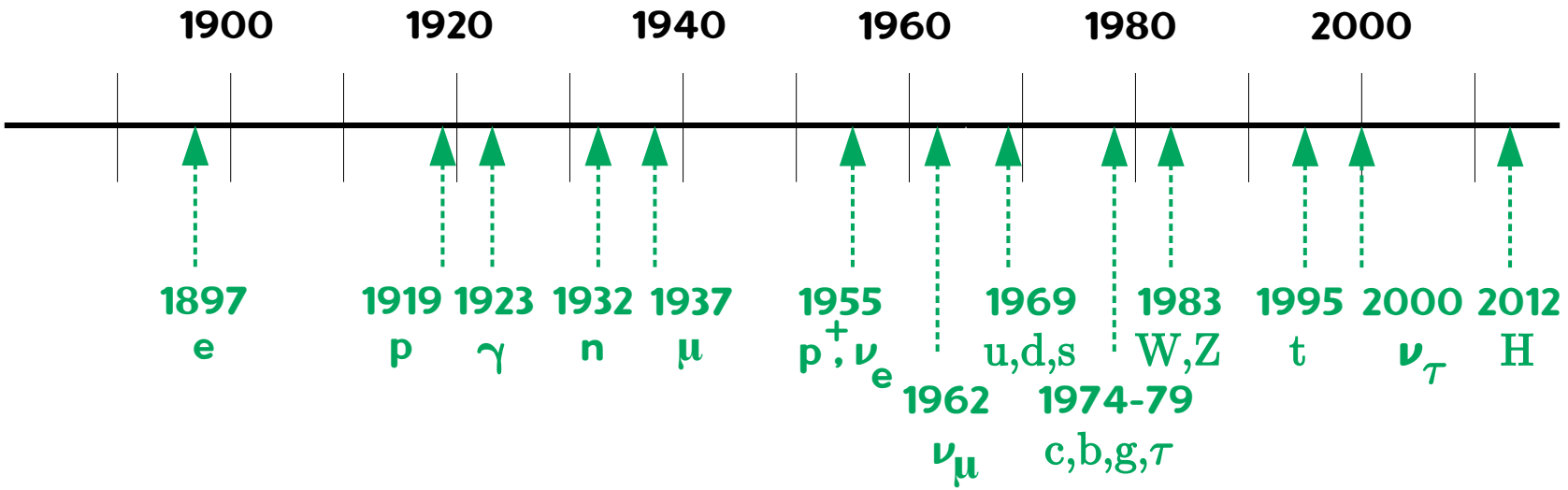
Detector observables



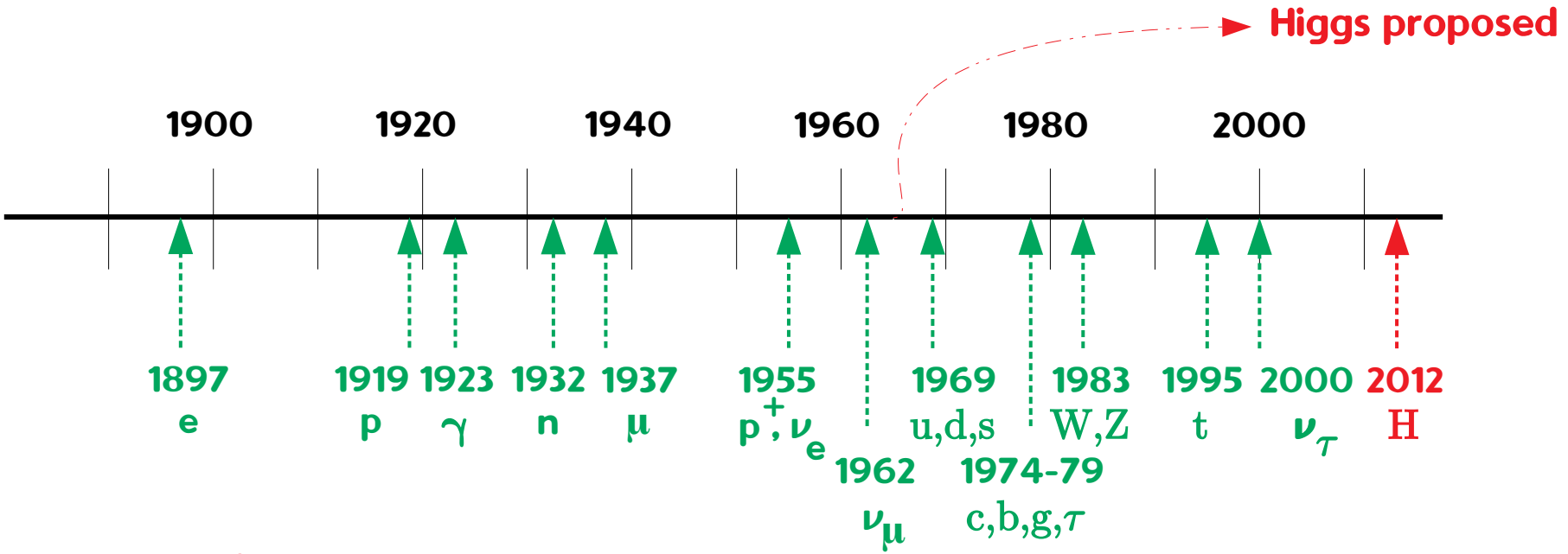
- **Detector observables?**
  - ONLY e , μ , γ and jets
  - Others are identified via their decay products
    - $Z \rightarrow ee/\mu\mu$
    - $t \rightarrow Wb \rightarrow e/\mu$ + jets + missing energy



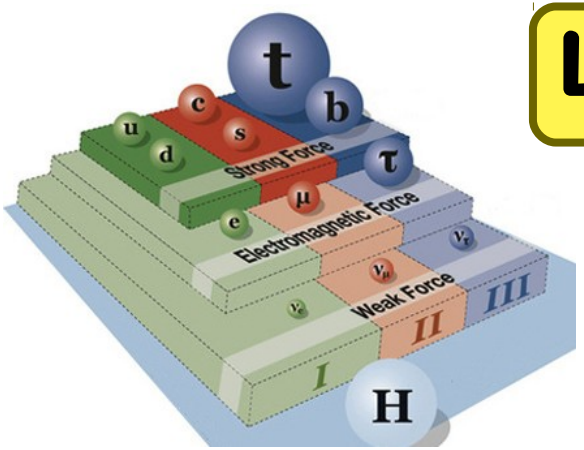
Particle discovery timeline



Particle discovery timeline

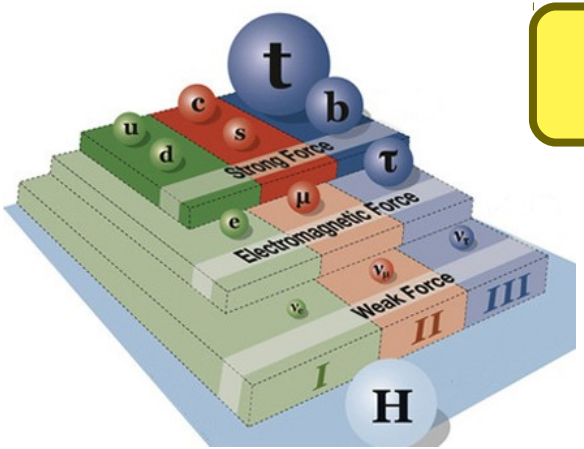


- Proposed in 70s , found 50 years later !
- All quarks and gluons are discovered before Higgs discovery !



Last piece of SM found

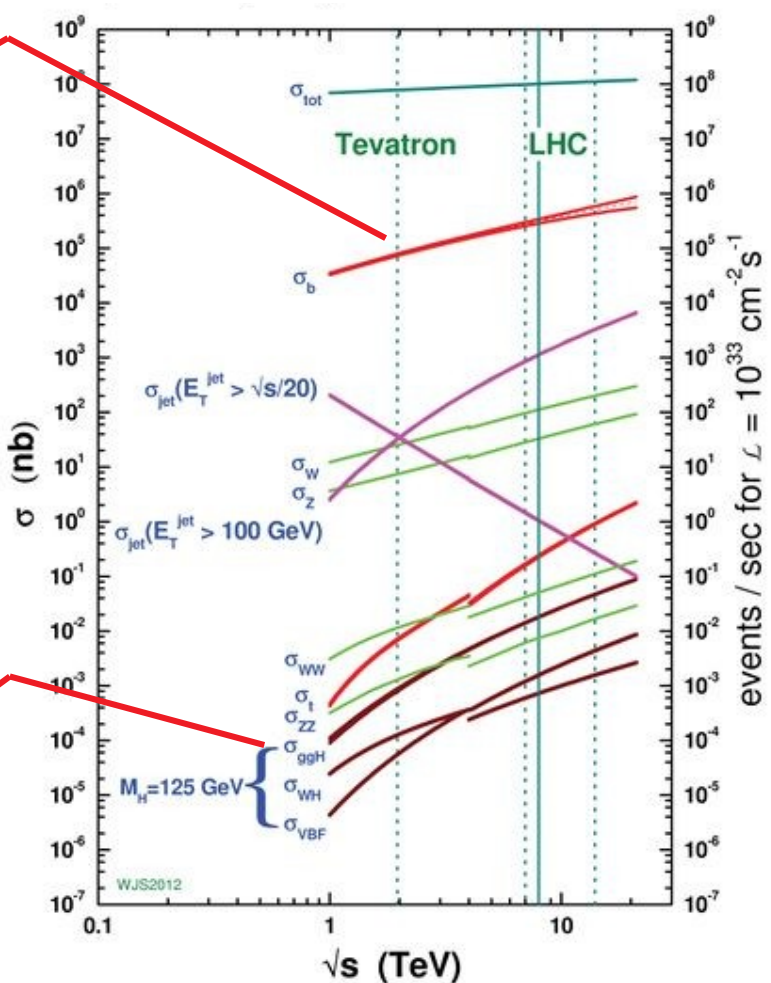
- **Being less massive than top quark, 17 years later discovered?**
  - Easier to produce and observe top quarks in experiments
  - Higgs boson does not carry color charge
    - Produced indirectly at a hadron collider



Higgs production rate

$\sigma \propto 10^{+5}\, nb$

$\sigma \propto 10^{-2}\, nb$



- **Being less massive than top quark, 17 years later discovered?**
  - Easier to produce and observe top quarks in experiments
  - Higgs boson does not carry color charge
    - Produced indirectly at a hadron collider

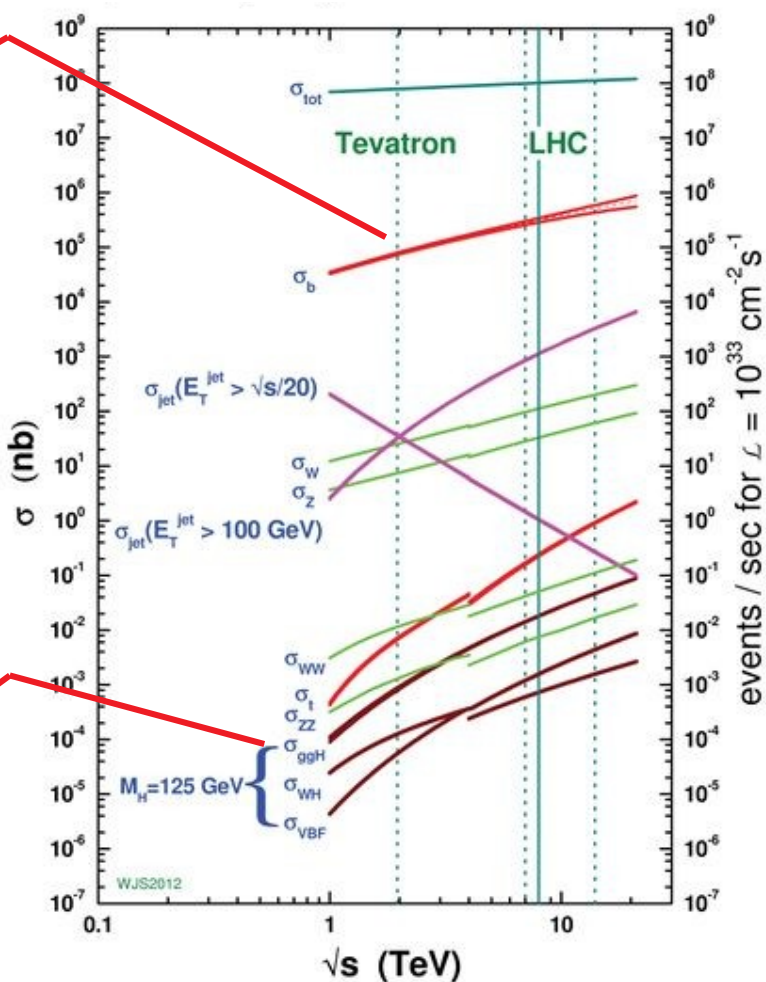
Expected Higgs multiplicity

- **Till the time of discovery:**
  - 200,000 Higgs events
    - $\sim$ 10/fb × 0.01 nb
  - 1,000,000,000,000,000 pp collisions
    - $\sim$ 10/fb × 100 mb

$\sigma \propto 10^{+5}\, nb$

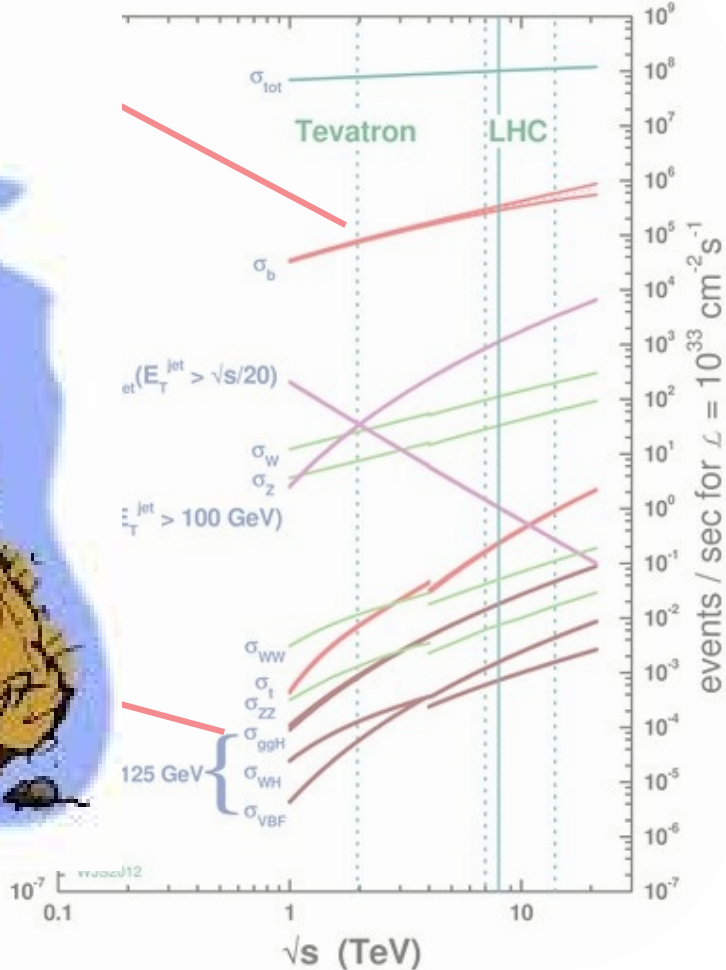
7 order smaller

$\sigma \propto 10^{-2}\, nb$



Indeed a fantastic job was done!

- Till the time of discovery
  - 200,000 Higgs events
    - ~ 10/fb × 0.01 nb
  - 1,000,000,000,000,000 p
    - ~ 10/fb × 100 mb



Discovery

- SM prediction

- Why only 1 Higgs?

- **Higgs discovery**

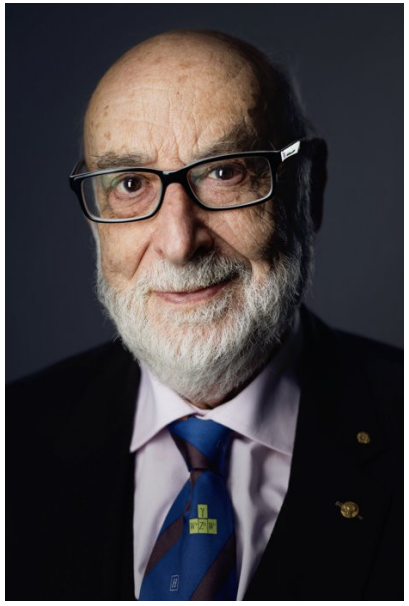
- Particle properties
  - Mass
  - X-section
  - Spin
  - CP

- BSM searches
- Current limits

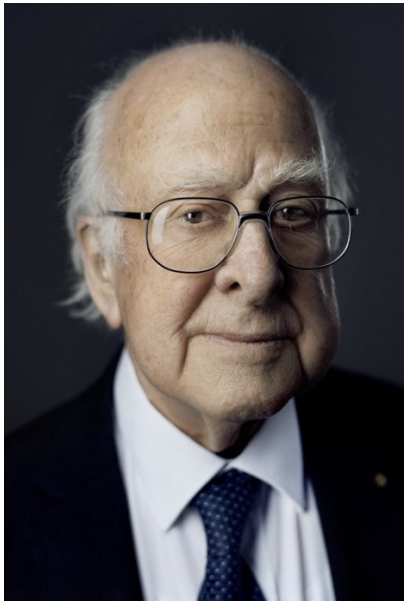
Eventually found in 2012

2013 Nobel prize

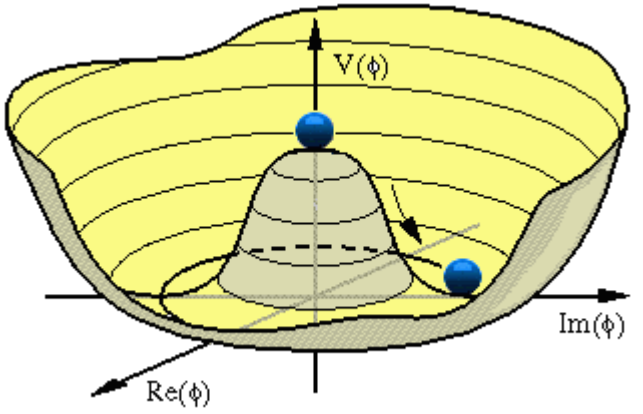
Francoise Englert



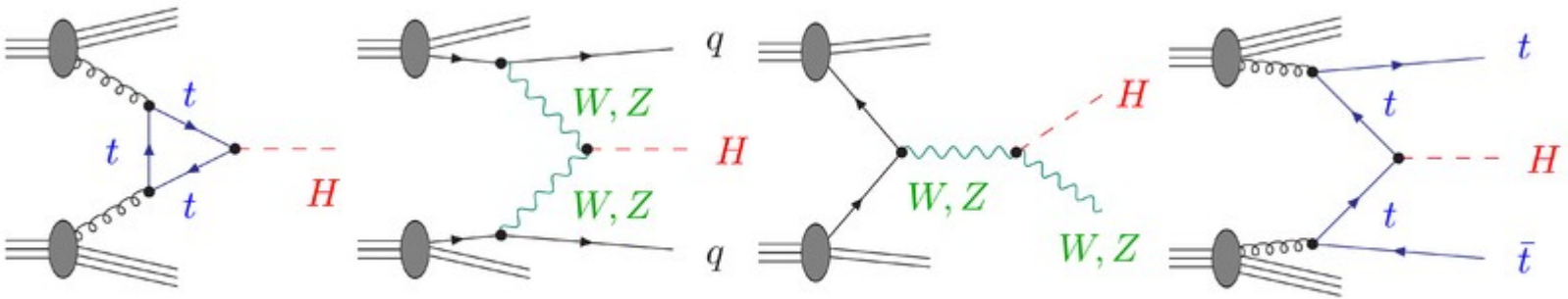
Peter Higgs



symmetry breaking mechanism



Higgs production channels



gg fusion

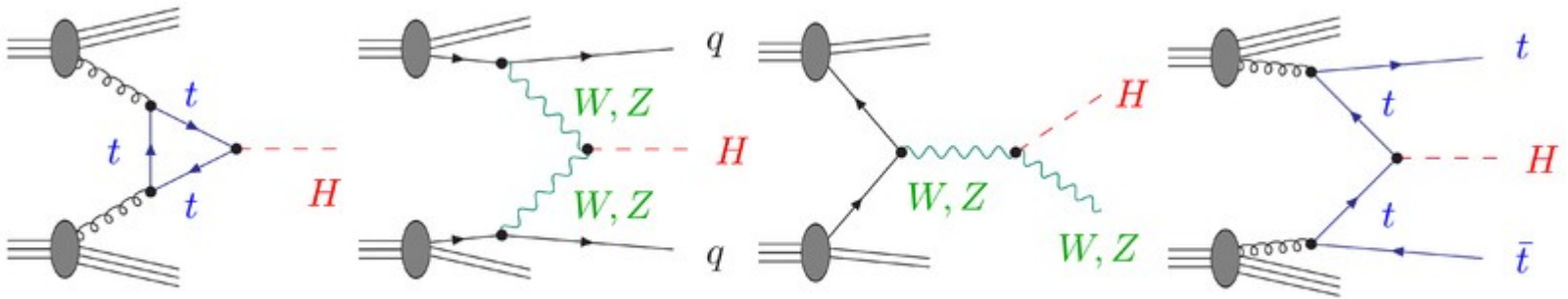
Vector boson fusion

associated VH

associated ttH

	ggF	VBF	VH	ttH
σ_{Th} (pb)	? depends on mass			

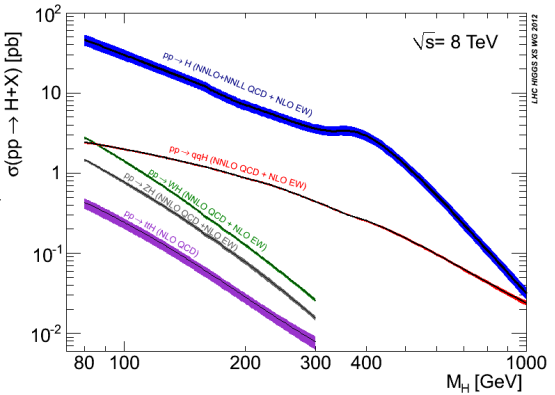
Higgs production channels



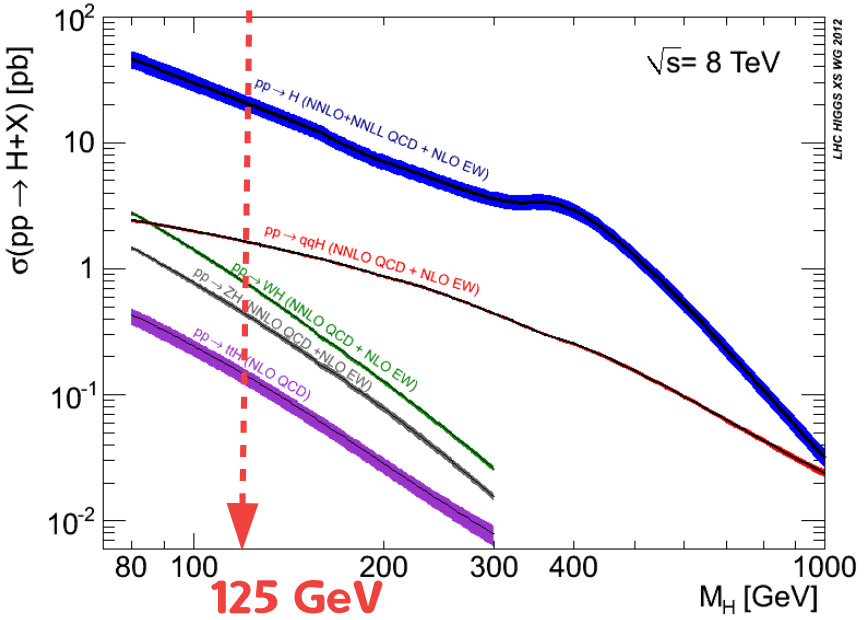
gg fusion | Vector boson fusion | associated VH | associated ttH

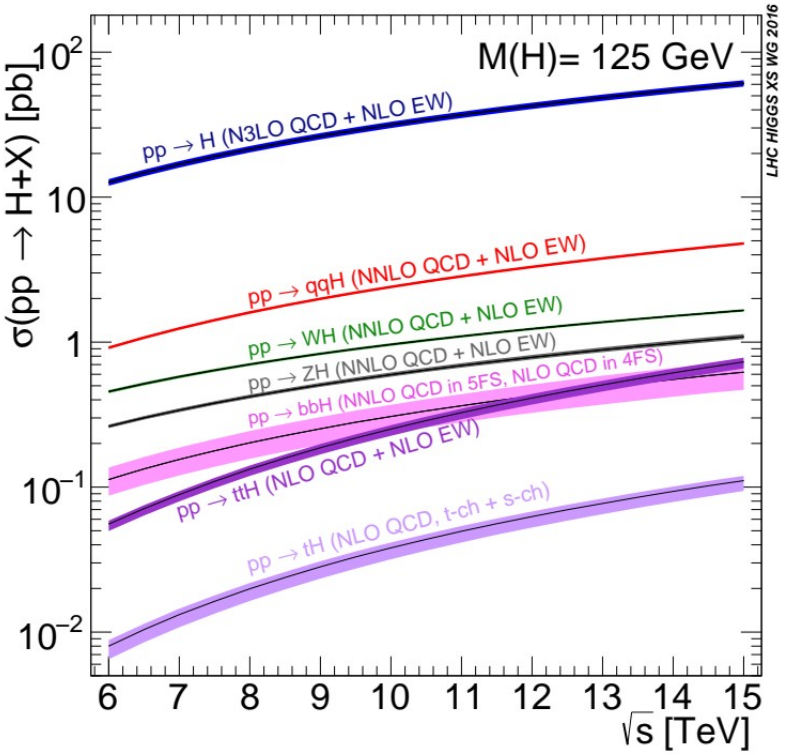
	ggF	VBF	VH	ttH
σ_{Th} (pb)	? depends on mass			

- ggF is dominant over the entire mass range



Higgs production x-section from theory





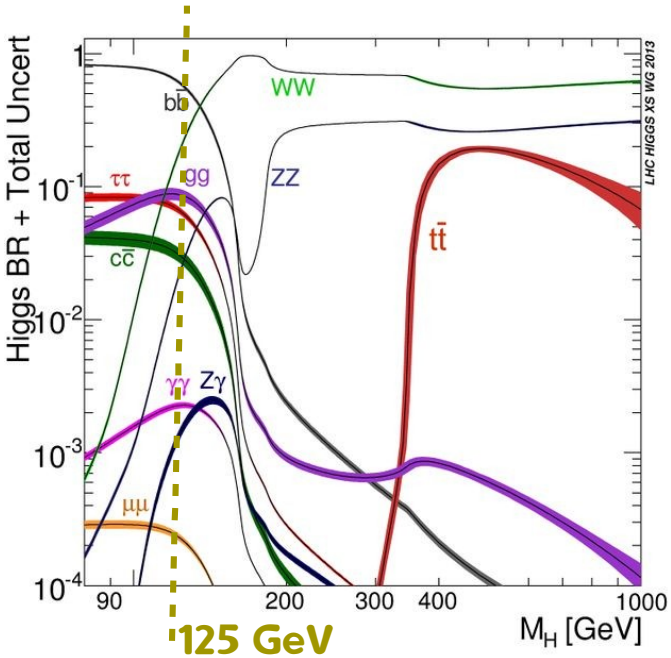
8 TeV	ggF	VBF	VH	ttH
σ_{exp}(pb)	21.4	1.6	0.7	0.1

13 TeV	ggF	VBF	VH	ttH
σ_{exp}(pb)	48.6	3.8	1.4	0.5

Higgs decay modes

Decreasing BR

- **Main decay channels:**
  - H → bb (60%)
  - H → WW (22%)
  - H → gg
  - H → ττ
  - H → cc
  - H → ZZ (3%)
  - H → γγ (0.2%)



Early modes of discovery

Decreasing BR

- **Main decay channels:**
  - H → bb
  - H → WW
  - H → gg
  - H → ττ
  - H → cc

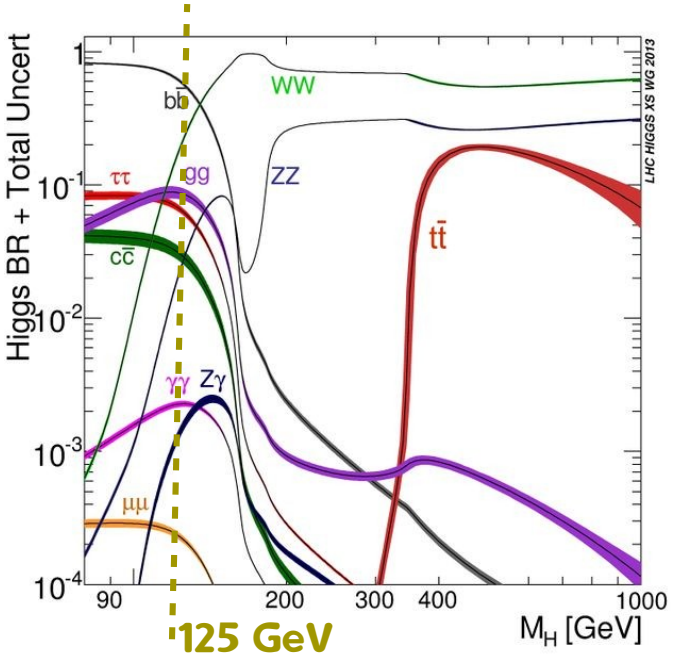
to control harsh background

- Distinctive final states used
- A few decay modes are used at the time of discovery

- H → ZZ
- H → γγ

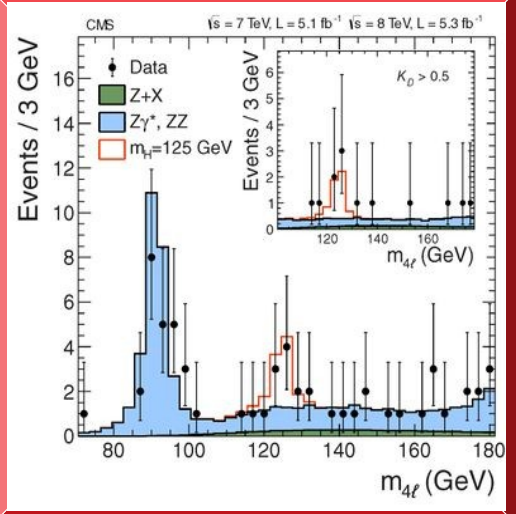
Golden channel !

- **Moderate production rate**
- **Leptons in the final state**

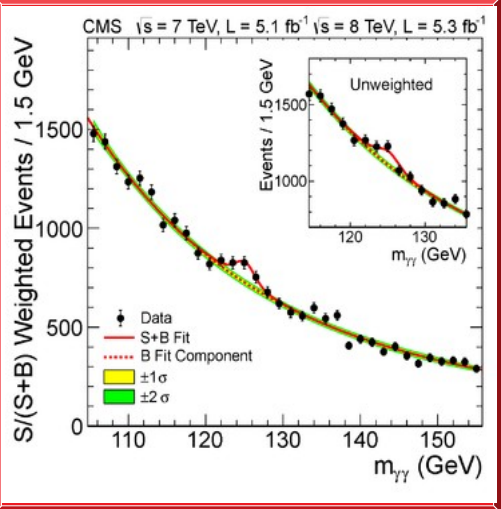


Higgs discovery plots

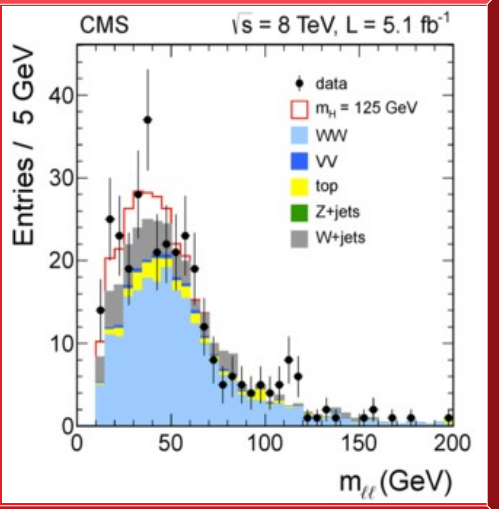
H → ZZ

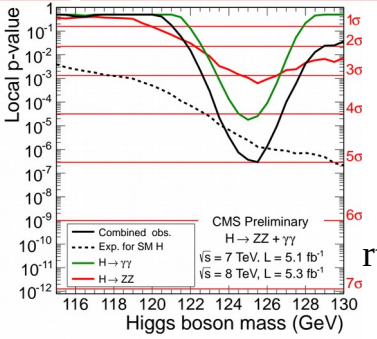


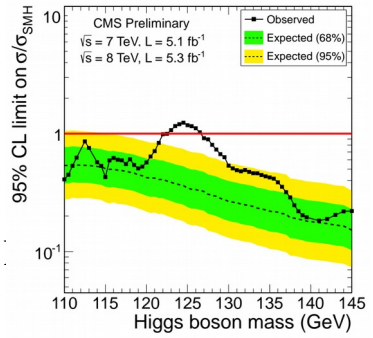
H → γγ



H → WW







Properties

- SM prediction

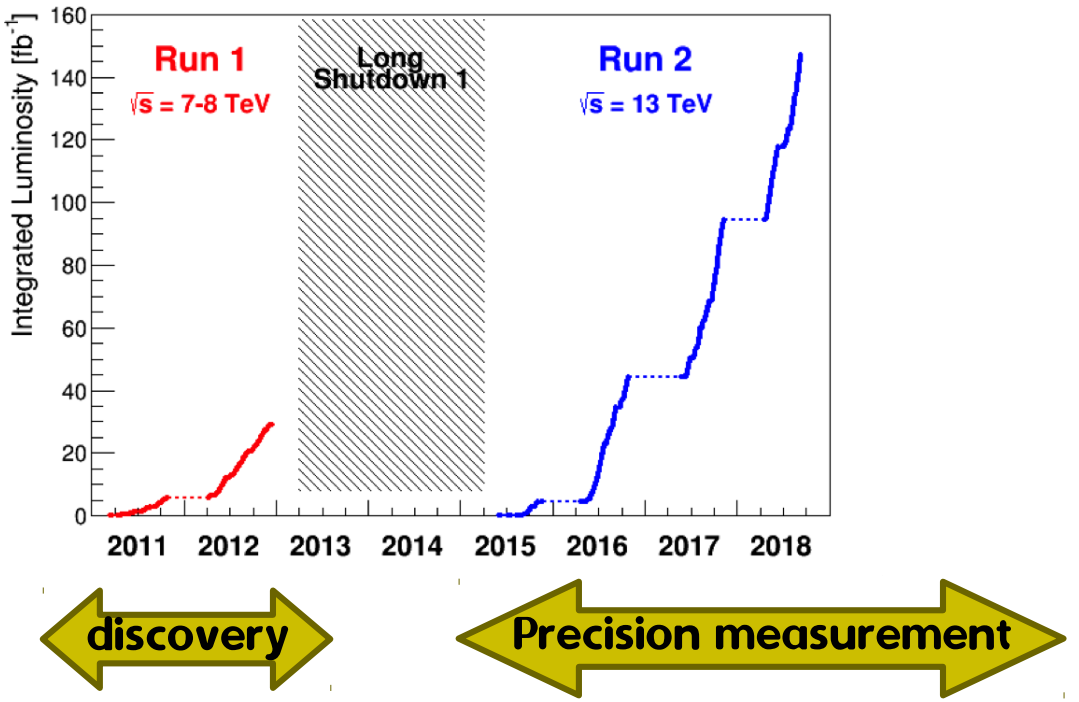
- Why only 1 Higgs?

- Higgs discovery

- **Particle properties**
  - **Mass**
  - **X-section**
  - **Spin**
  - **CP**

- BSM searches
- Current limits

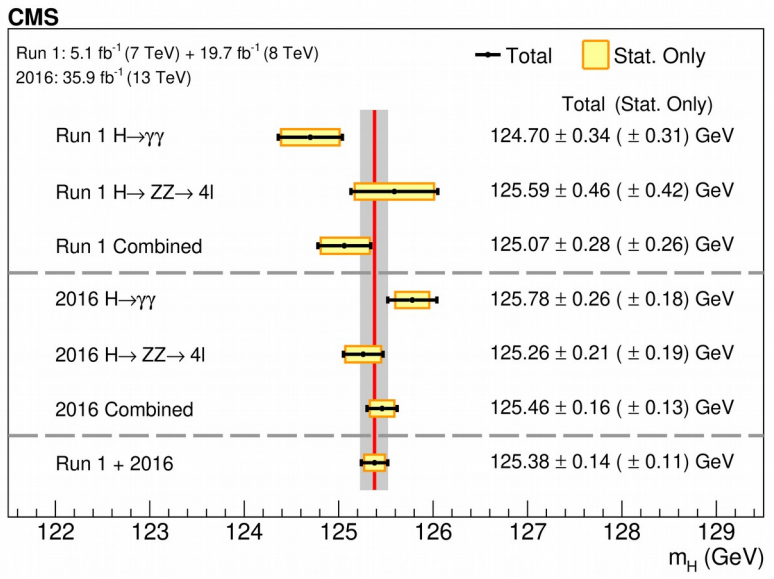
Now is time for precision measurement



Most precise Higgs mass measurement

Phys. Lett. B 805 (2020) 135425

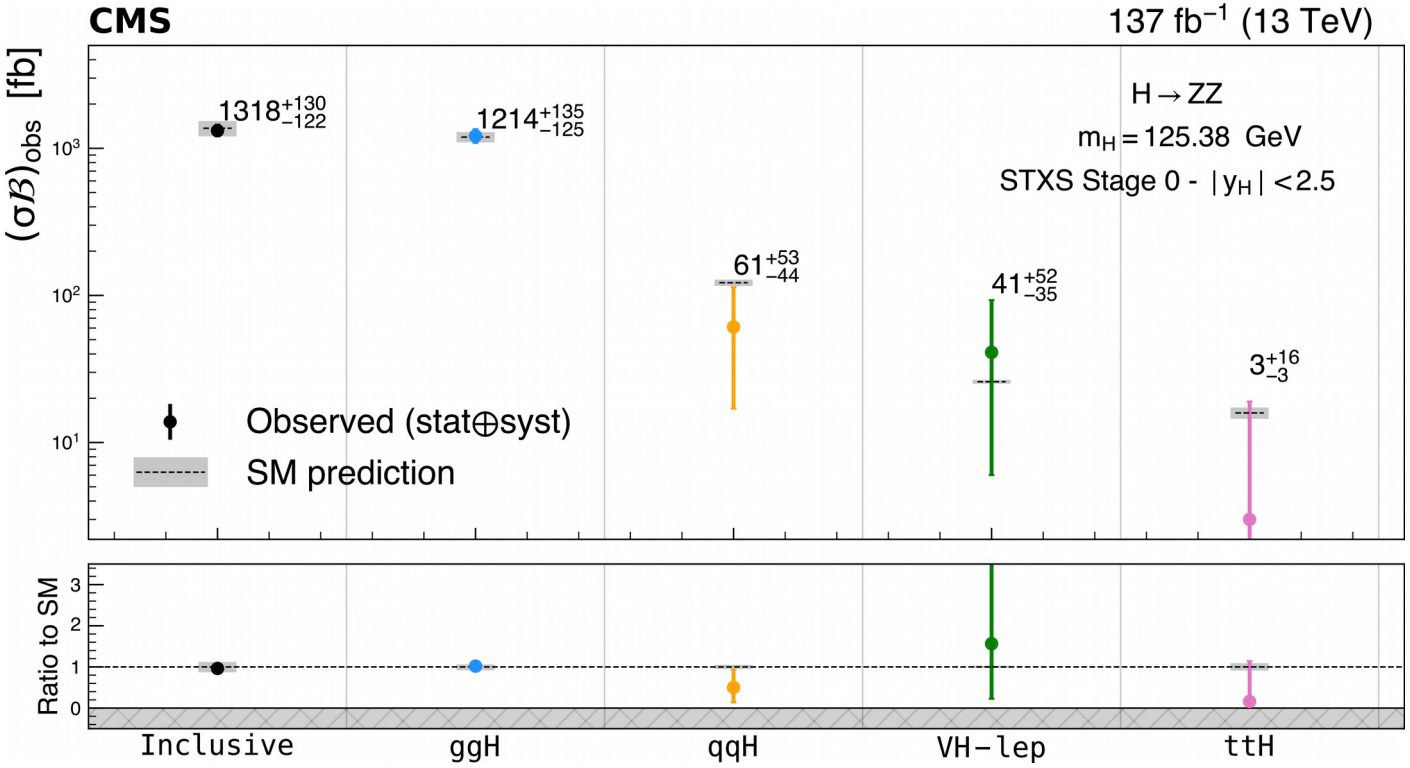
- Run 1: 7 & 8 TeV , 2016: 13 TeV
- Higgs mass measured by CMS (in $\gamma\gamma + 4l$) : 125.38 +- 0.14
- Highlights from the plot:
  - Higgs mass is known to 0.1% uncertainty
  - Still statistical unc. is dominant



Higgs production in various production modes

- The plot: product of cross-section times branching ratio for H→ZZ decay
  - Points with error bars: measured values
  - Black dashed lines with gray uncertainty bands: the SM predictions

- Highlights from the plot:
  - Higgs production cross-section decaying to ZZ is known up to 10% uncertainty
  - Better estimation in data rather than theory !

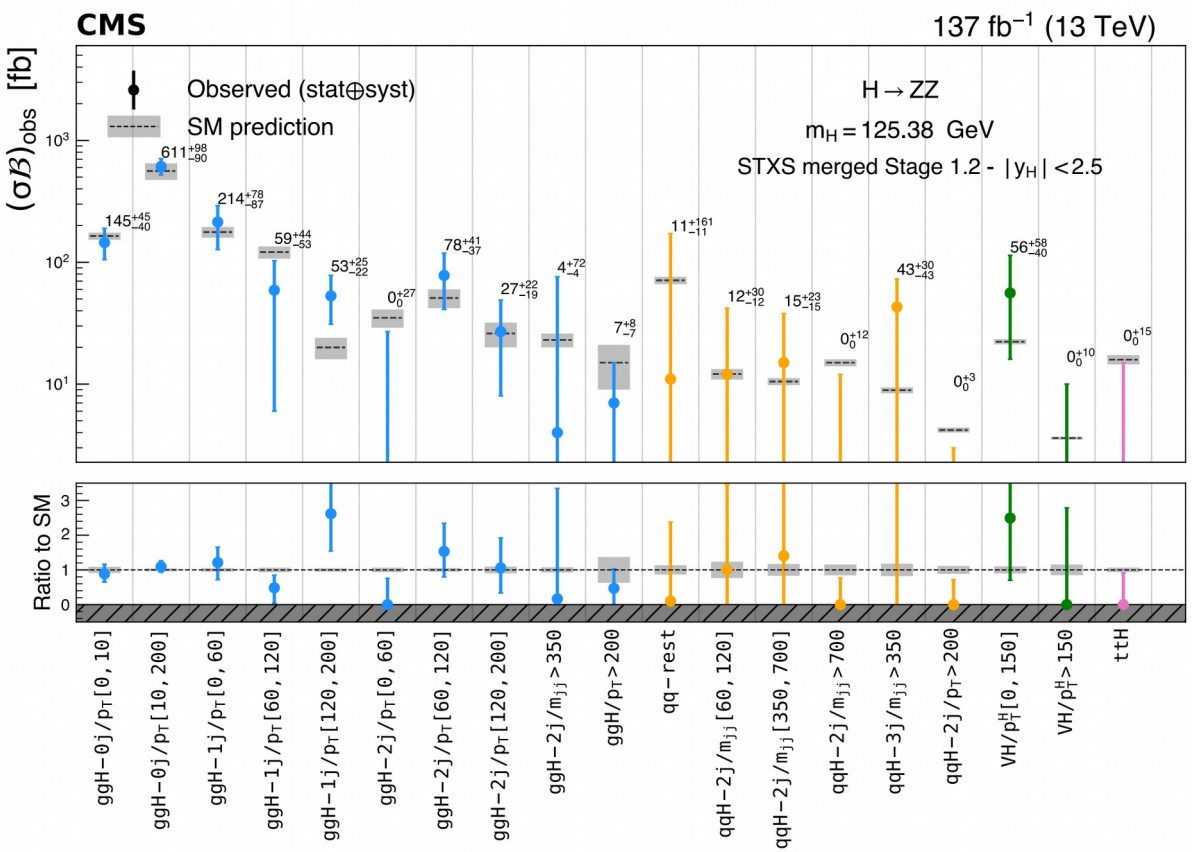


Eur. Phys. J. C 81 (2021) 488

Higgs production in various kinematic regions

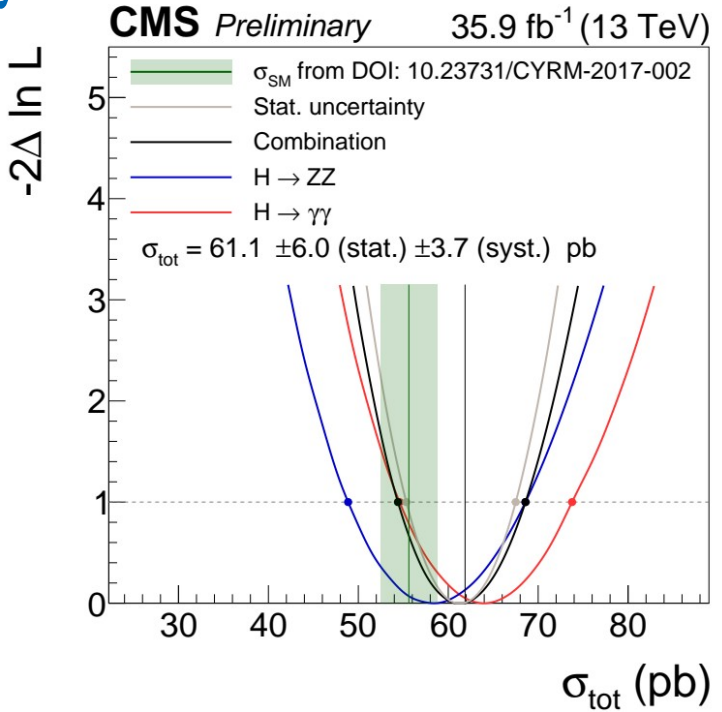
- To search for new phenomena, the cross sections in particular kinematic regions are measured
  - BSM theories predict different production rate for the Higgs with hight pT
- Four main production modes are split into even more categories
- Conclusion: measurement in agreement with theory within uncertainties

Eur. Phys. J. C 81 (2021) 488



Higgs production in various decay modes

- The plot: likelihood scan for the individual decay channels and their combination
  - Markers indicate one standard deviation confidence interval
- Highlights from the plot:
  - Measured cross-sections are compatible with theory
    - Theory: 55.6 +- 2.5 pb
    - Measurement: 61.1 +- 7.0 pb



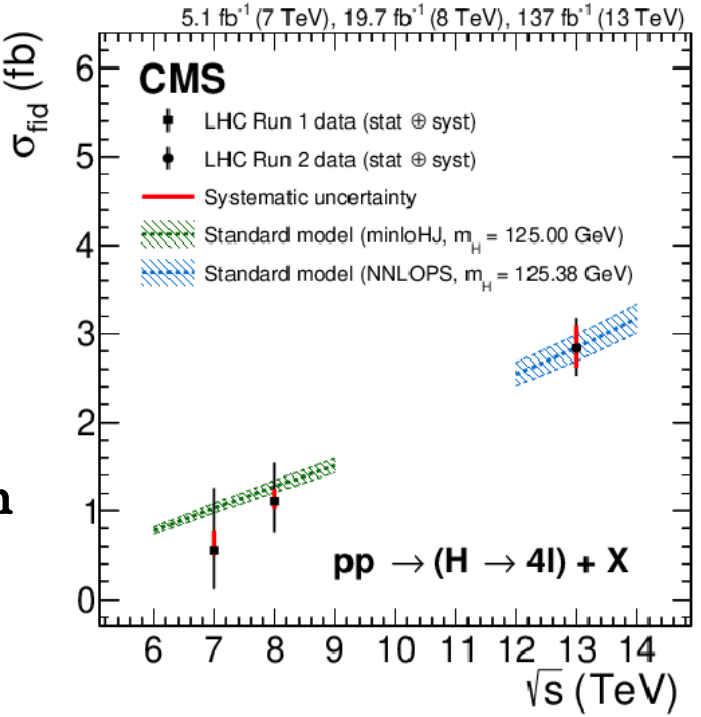
Phys. Lett. B 792 (2019) 369

Fiducial cross section measurement

- **Definition from Wikipedia:**
  - *Fiducial cross section, in particle physics experiments, a cross section for the subset of a process in which the distinctive process signatures are visible within the sensitive regions of the detector volume.*
- **Fiducial cross section:**
  - Extrapolation to the full phase space is avoided
  - Has the benefit of reducing systematic uncertainties
  - Attempt to be as model independent as possible

- **Measured inclusive fiducial cross section consistent with theory**

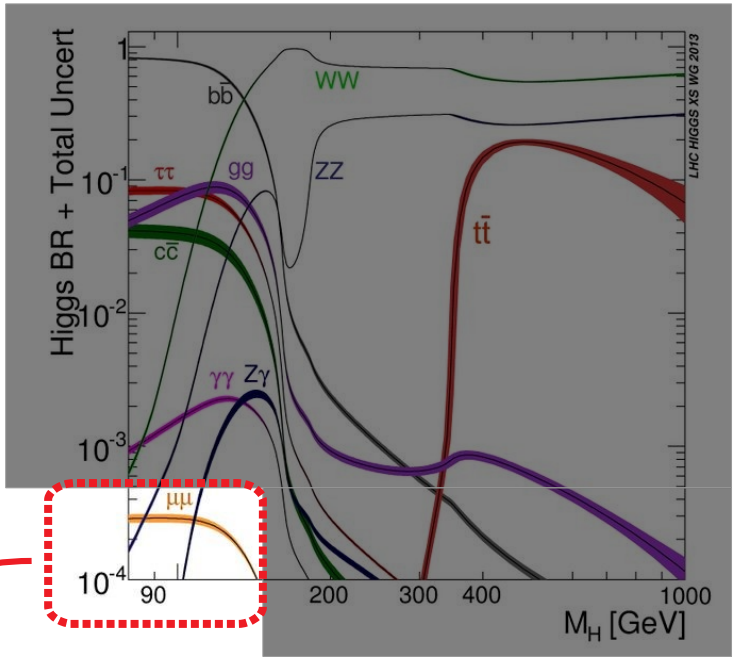
Eur. Phys. J. C 81 (2021) 488



Measurement of the Higgs rare decays

- Rare decay: small branching ratio
  - Higgs to muons: one in 10000
- SM prediction: coupling strength of the Higgs boson to fermion ~ fermion Mass
  - Branching fractions to light fermions expected to be small
  - Challenging measurement

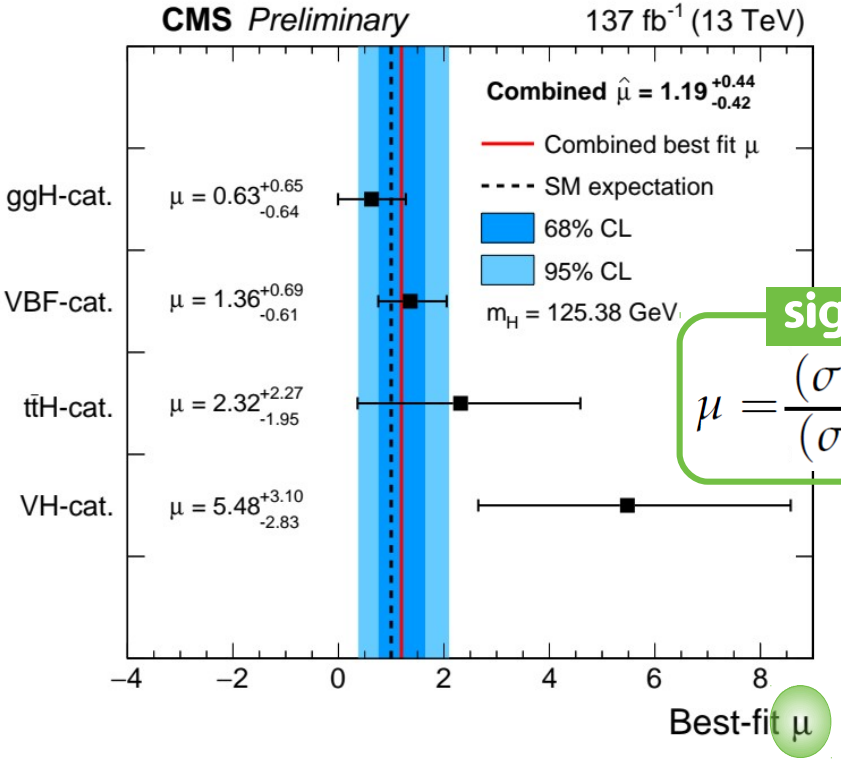
Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001



Evidence for Higgs→μμ

JHEP 01 (2021) 148

- Left plot: signal strength in each production category
  - Solid red line: combined fit
  - Dashed gray line: SM expectation

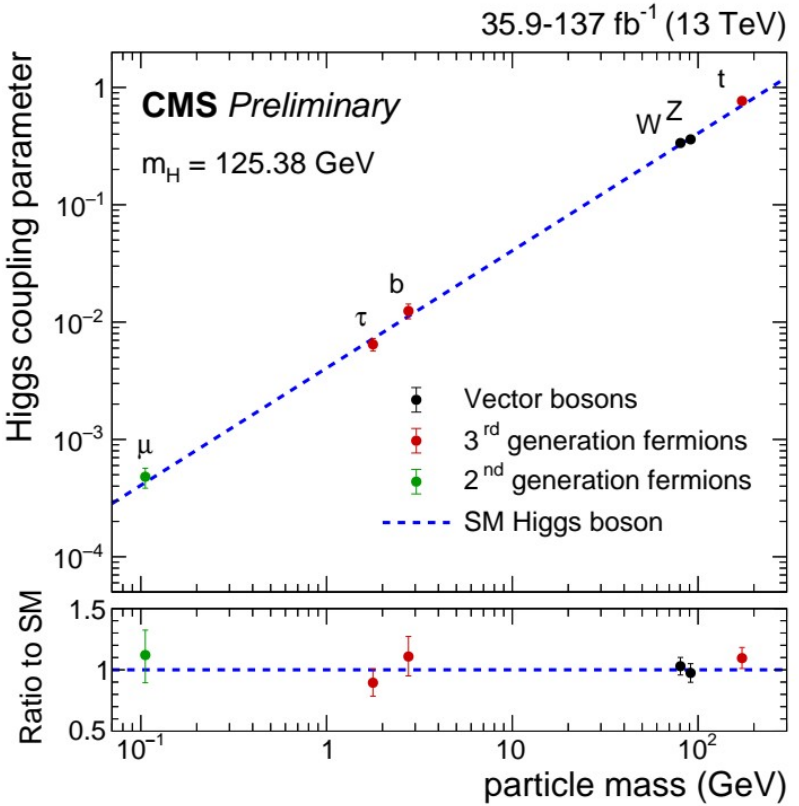


signal strength

$$\mu = \frac{(\sigma\mathcal{B}(H \to \mu\mu))_{obs}}{(\sigma\mathcal{B}(H \to \mu\mu))_{SM}}$$

's with Particle Physics V

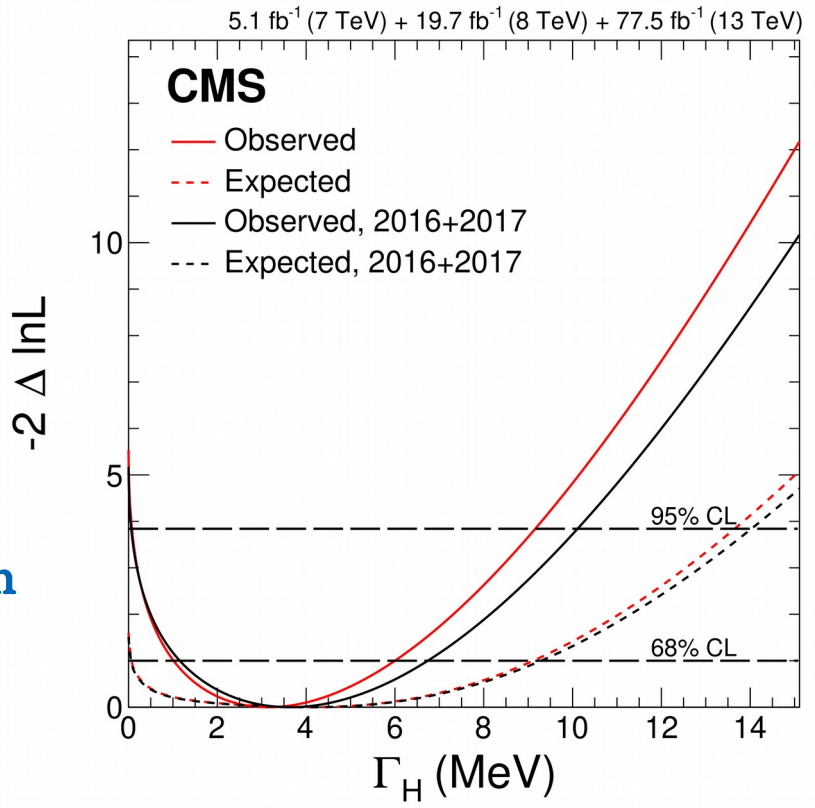
- Right plot: Higgs coupling to SM particles
  - First measurement of Higgs to 2nd generation fermions



Measurement of Higgs boson width

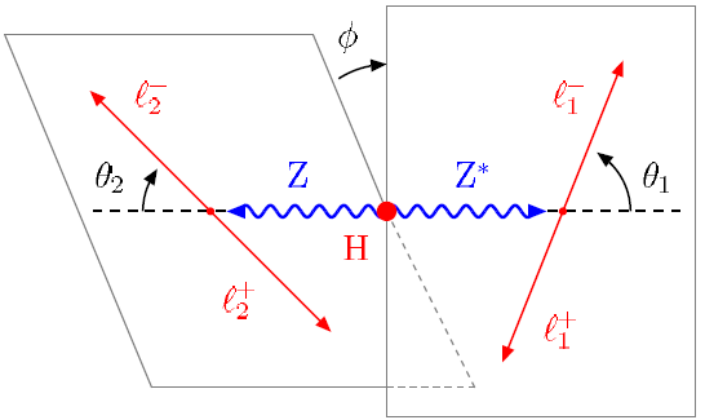
Phys. Rev. D 99, 112003 (2019)

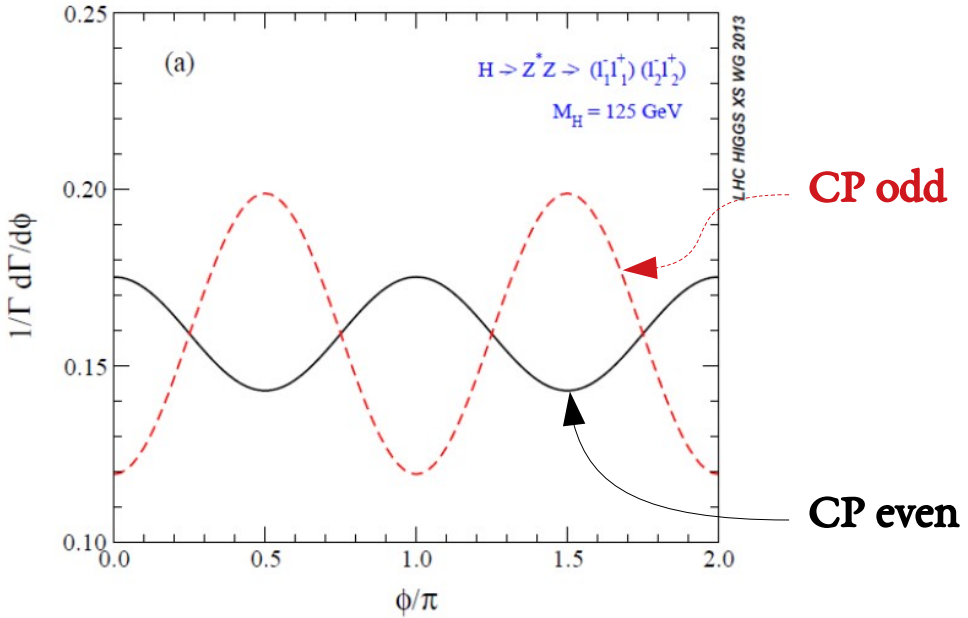
- Width measurement can be used to probe the existence of new physics that couple to the Higgs sector
- Direct precise measurement of Higgs boson width at hadron collider is not feasible
  - Width of the resonance peak is known up to about 100 MeV
- Methods are developed which relies on relative measurement of on-shell and off-shell production
  - Measured Γ: 3.2 + 2.8 - 2.2 GeV
  - SM expectation: 4 GeV
- Measured width is consistent with SM prediction
  - Presence of new particles to which the Higgs boson can decay is ruled out



Spin-parity properties from angular study

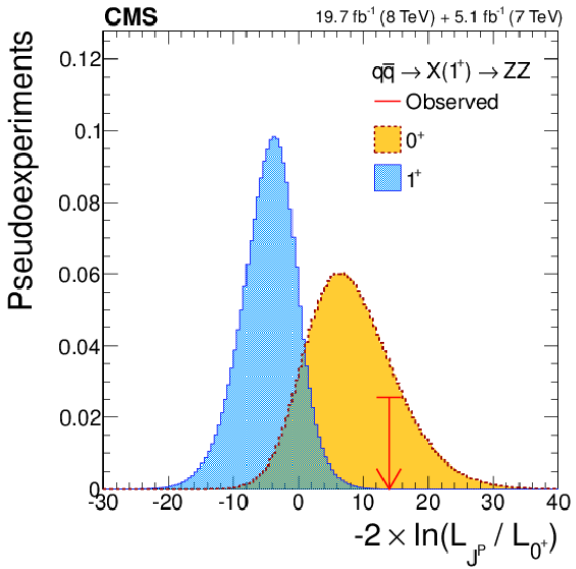
- Different behavior in φ distribution
  - Φ : angle between the two Z-Boson decay planes spanned by the flight directions of the two leptons in the Z-Boson rest frame





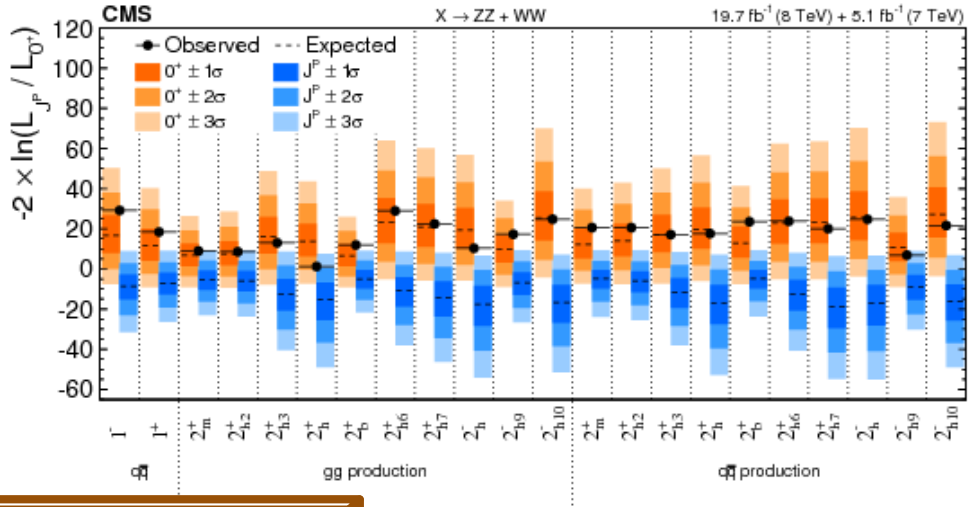
Spin and CP measurement

- Yellow : SM expectation
- Blue : alternative J^P hypothesis
- Red arrow: observed data



- H→VV couplings are investigated
- Several spin 1 and 2 hypotheses are tested
  - Alternative models are excluded

$J^{PC} = 0^{++}$



Phys. Rev. D 92, 012004 (2015)

Search for anomalous Higgs couplings

arXiv:2110.04836 , Submitted to JHEP

- SM Higgs boson is even under CP inversion
- Deviation from a purely scalar interaction would be a direct indication of new physics
- H→ττ coupling:

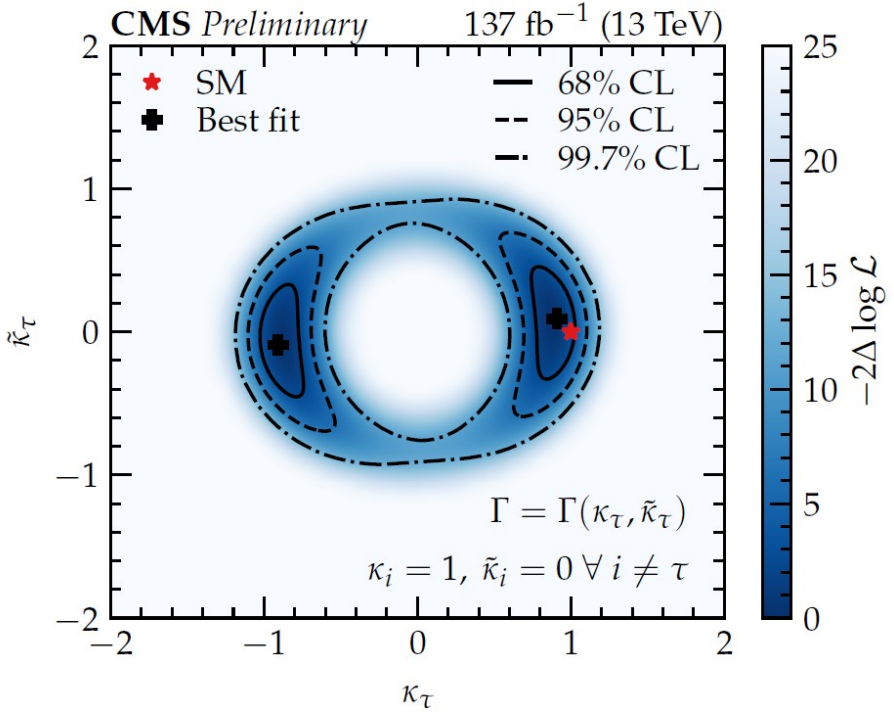
CP-even coupling

CP-odd coupling

$$\mathcal{L}_Y = -\frac{m_\tau \mathrm{H}}{\mathrm{v}}\left(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau\right)$$

$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

- Mixing angle φ determines the CP structure of the coupling
  - $\Phi = 0$: pure scalar
  - $\Phi = 90$: pure pseudo-scalar
  - $\Phi = 45$: maximally mixing states



Any more Higgs?

- SM prediction

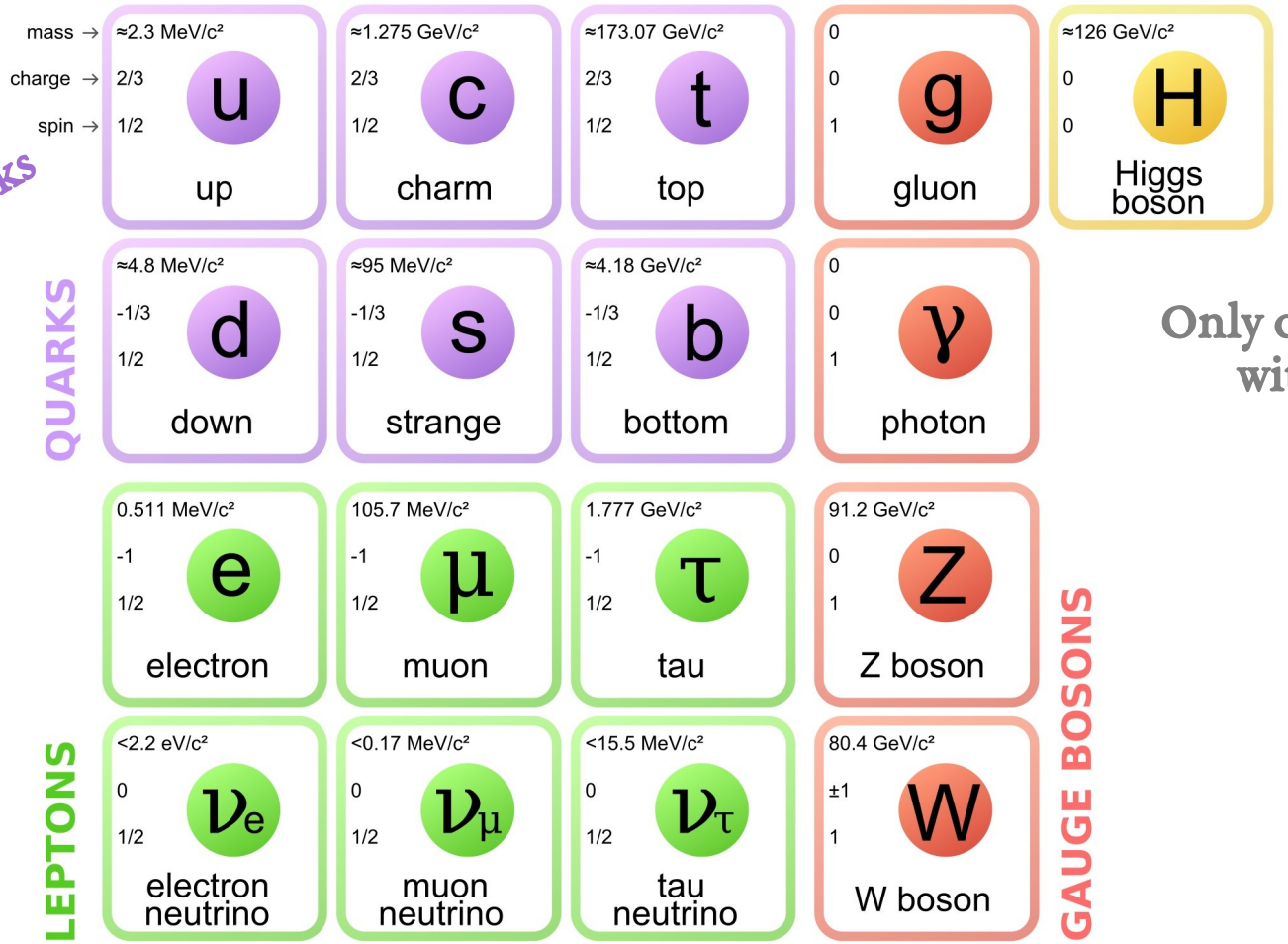
- Higgs discovery

- Particle properties
  - Mass
  - X-section
  - Spin
  - CP

- **Why only 1 Higgs?**

- BSM searches
- Current limits

Asymmetric pattern of SM particles



Many leptons & quarks with spin half

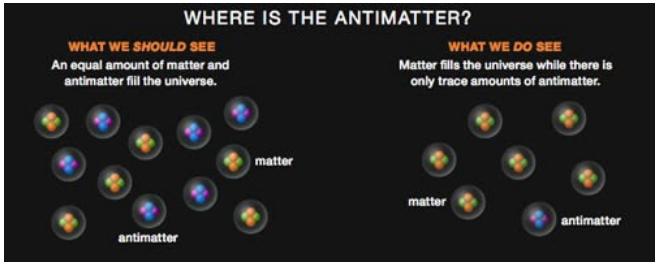
12 vector bosons with spin one

Only one scalar particle with spin zero ?!

Need to have BSM physics

Hierarchy Problem

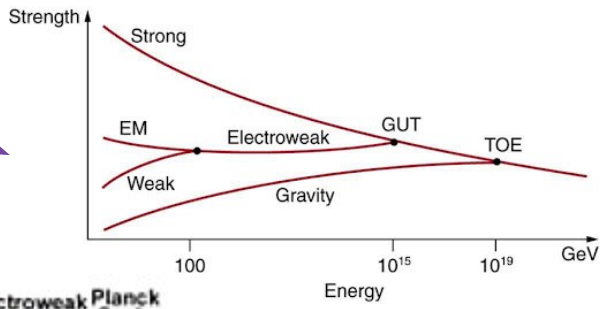
Baryon Asymmetry



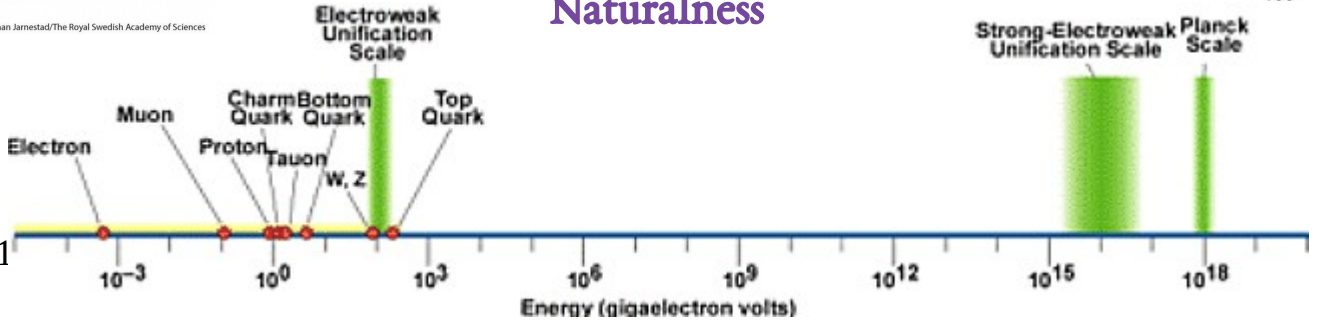
unanswered questions within SM

Neutrino Oscillation

Grand Unification

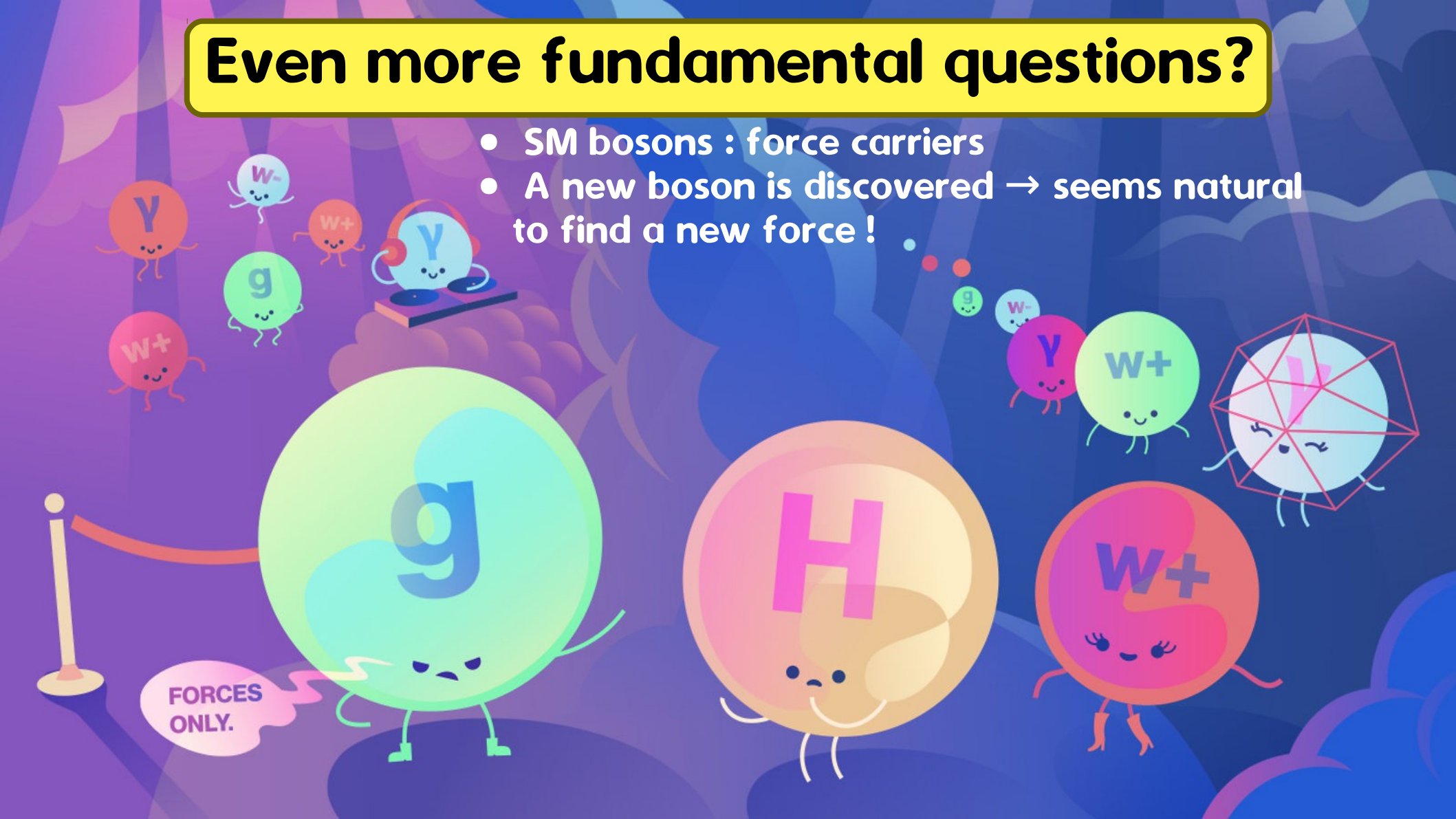


Naturalness



Even more fundamental questions?

- SM bosons : force carriers
- A new boson is discovered → seems natural to find a new force !



Higgs BSM searches

- SM prediction
- Why only 1 Higgs?
- Higgs discovery
- Particle properties
  - Mass
  - X-section
  - Spin
  - CP
- **BSM searches**
- **Current limits**

Room for Higgs BSM decay

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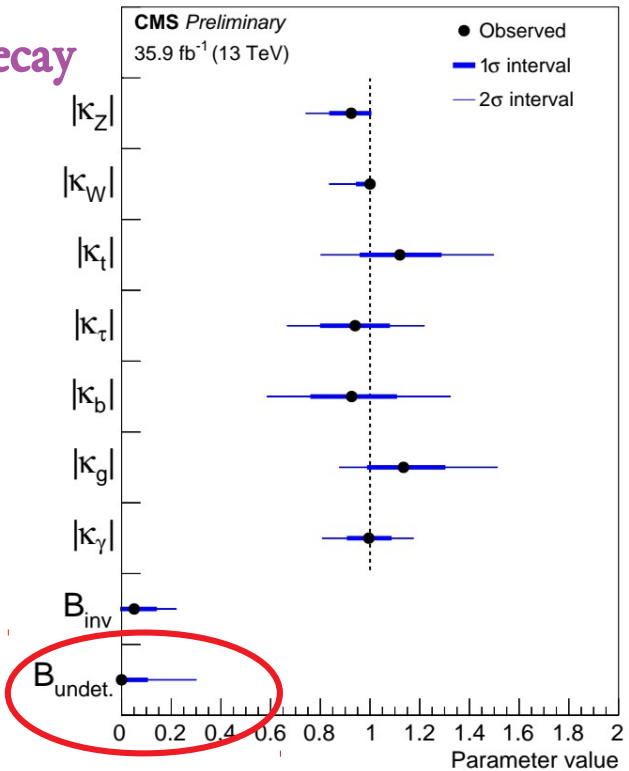
- Coupling modifiers: to test for deviations in Higgs coupling
  - Free parameters: κ_Z , κ_W, κ_t , κ_τ, κ_b, κ_g, κ_μ, κ_γ

Production cross-section for process *i*

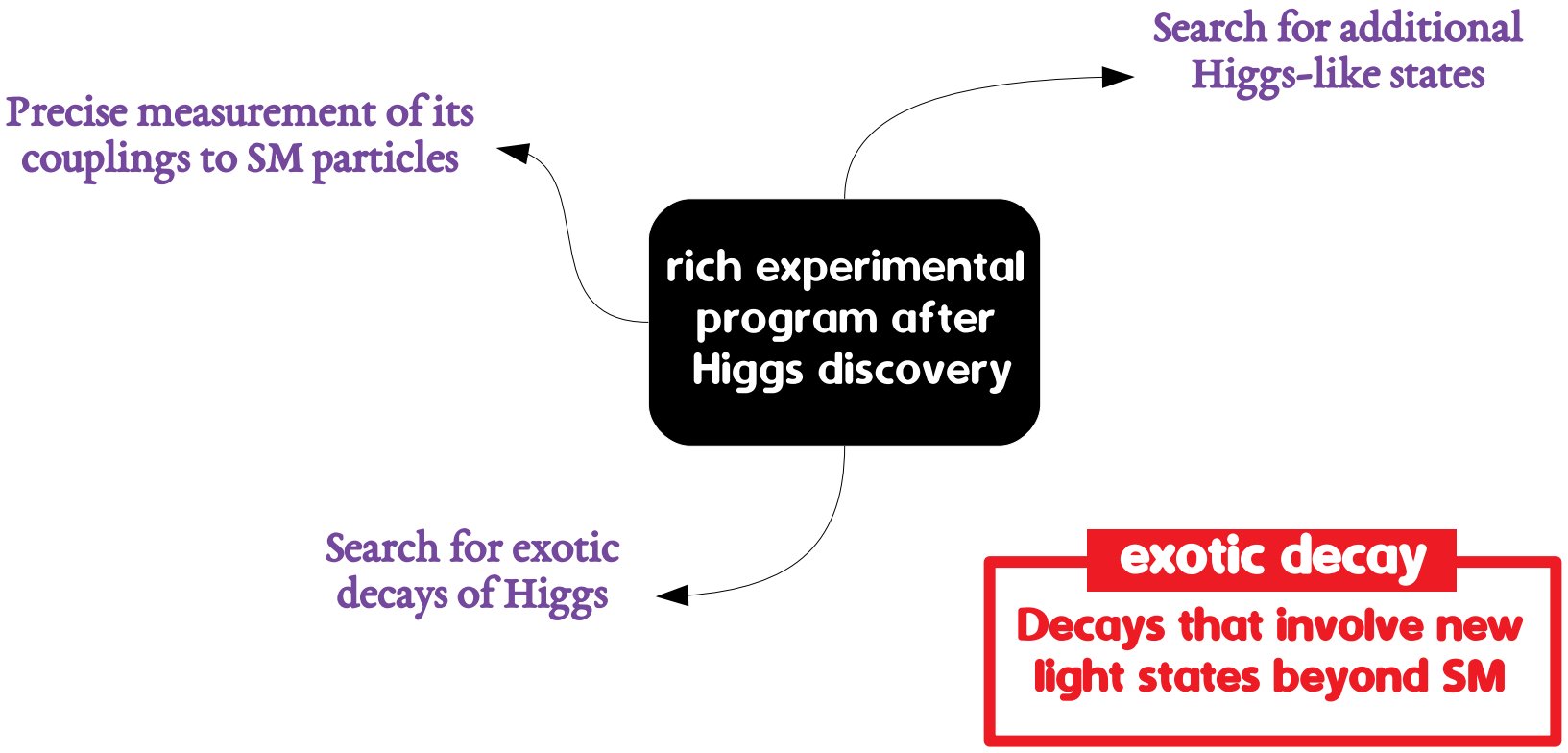
Partial width of Higgs decay to final state *f*

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

- $\mathrm{BR}_{\mathrm{undet.}}$: total branching ratio to any final state not detected by the channels included in this combined analysis
  - BR(Higgs→BSM) ~ 30%



Things we can do after Higgs discovery



Expected h→BSM in current data

- Assuming BR(h→BSM) ~ 10% → 1000000 BSM events already collected

8 TeV	ggF	VBF	VH	ttH
σ_{exp}(pb)	21.4	1.6	0.7	0.1
N , 20/fb	>42k	3200	1400	200

13 TeV	ggF	VBF	VH	ttH
σ_{exp}(pb)	48.6	3.8	1.4	0.5
N , 150/fb	~730k	57k	21k	7500

new physics may couple to Higgs boson

- Higgs decay width very small : ~ 4 MeV
  - Decays to SM fermions are suppressed by the small Yukawa couplings
  - Decays to $\gamma\gamma$ or gg are suppressed by loop factors
  - Decays to VV are suppressed by multibody phasespace

even a small coupling to another light state can easily open up additional sizable decay modes

Higgs as a portal to interact with hidden sector

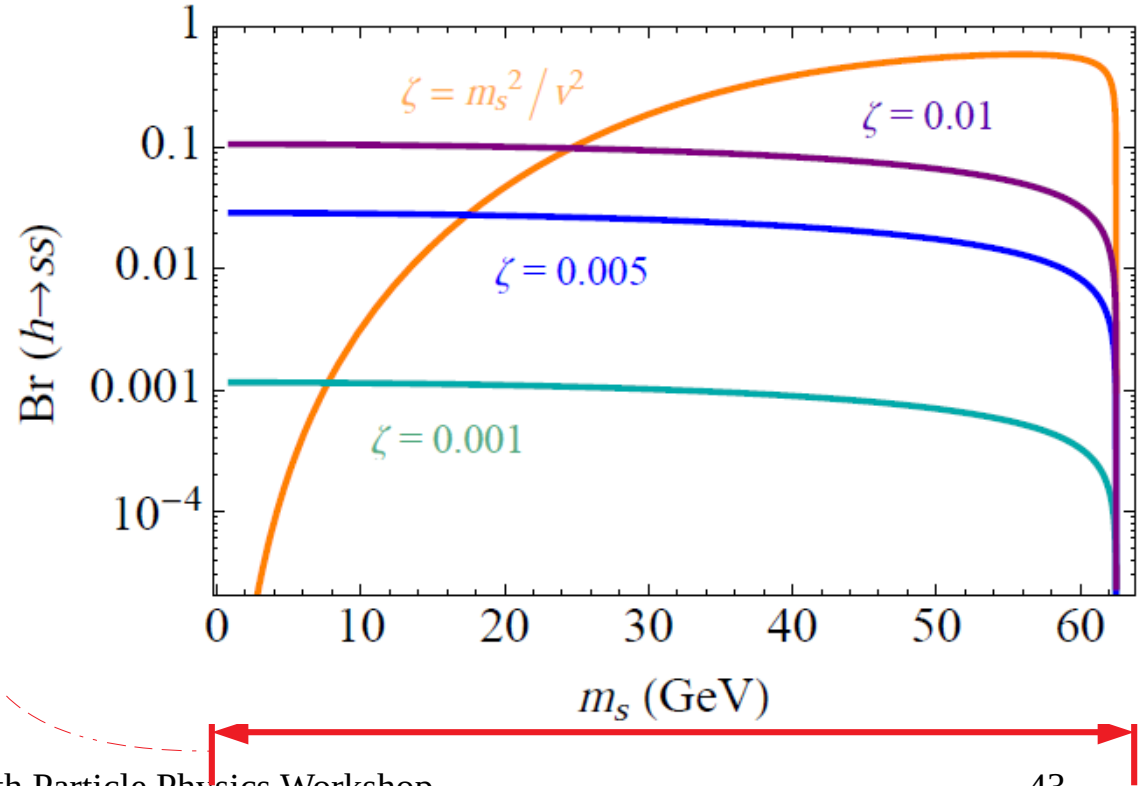
- Consider Higgs couples to a singlet scalar field s :

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

- Right: Br(h→ss) as a function of s mass
  - Even a small coupling yields BR ~ 10%

$$m_s < m_h/2$$

$$h \rightarrow ss \quad \textbf{is allowed}$$



Exotic Higgs decays in 2HDM+S

- In BSM models with more Higgs bosons, some can resemble the SM Higgs
- Adding another Higgs doublet to the SM plus a scalar
  - Motivated in many BSM models like NMSSM
- Yields:
  - h ➡ SM Higgs
  - a ➡ pseudoscalar
  - H° ➡ Heavy Higgs
  - $H^{\pm}$ ➡ charged Higgs

$$\tan\beta = v_2/v_1$$

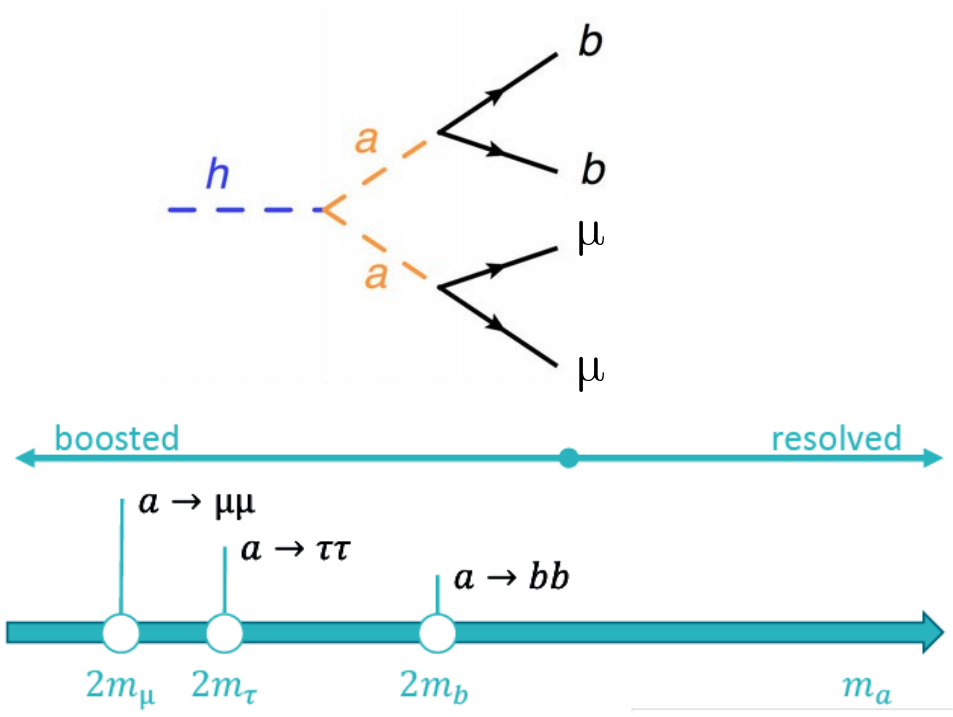
$v_{1,2}$: vacuum expectation values of the two doublets

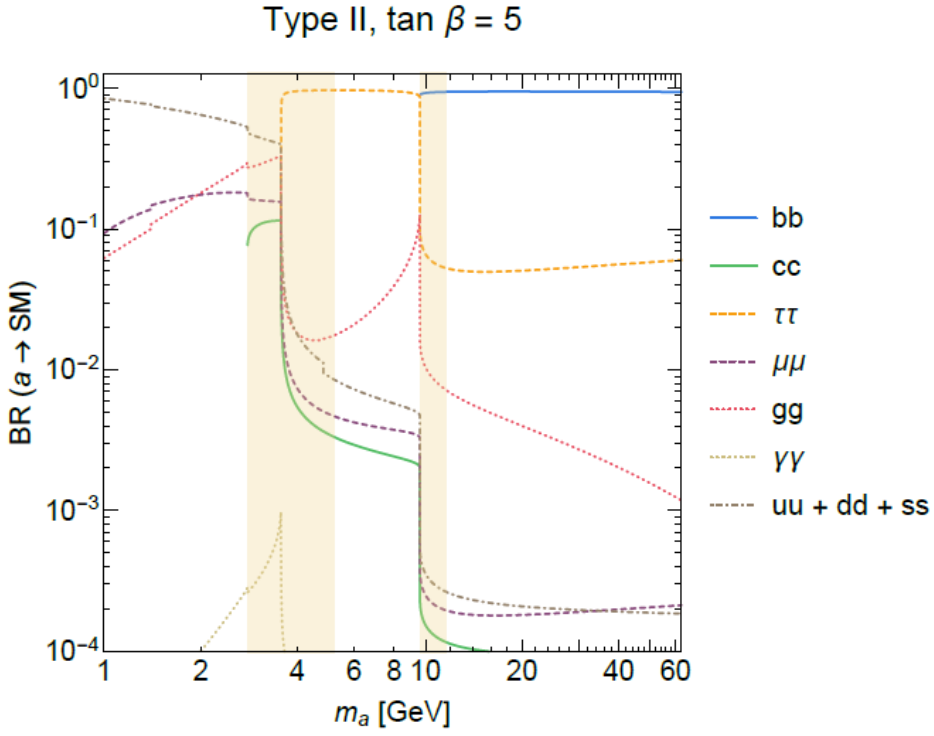
to avoid FCNC

- Fermions with same quantum numbers should couple to same Higgs field
  - 4 standard types of couplings
    - Type I: all couple to H2
    - Type II: dR, eR to H1 . uR to H2
    - Type III: leptons to H1, quarks to H2
    - Type IV: uR, eR to H2. dR to H1

Exotic Higgs decays in 2HDM+S

- Decays like h→aa→XXYY can happen in 2HDM+S





CMS searches for 2HDM+S in run2

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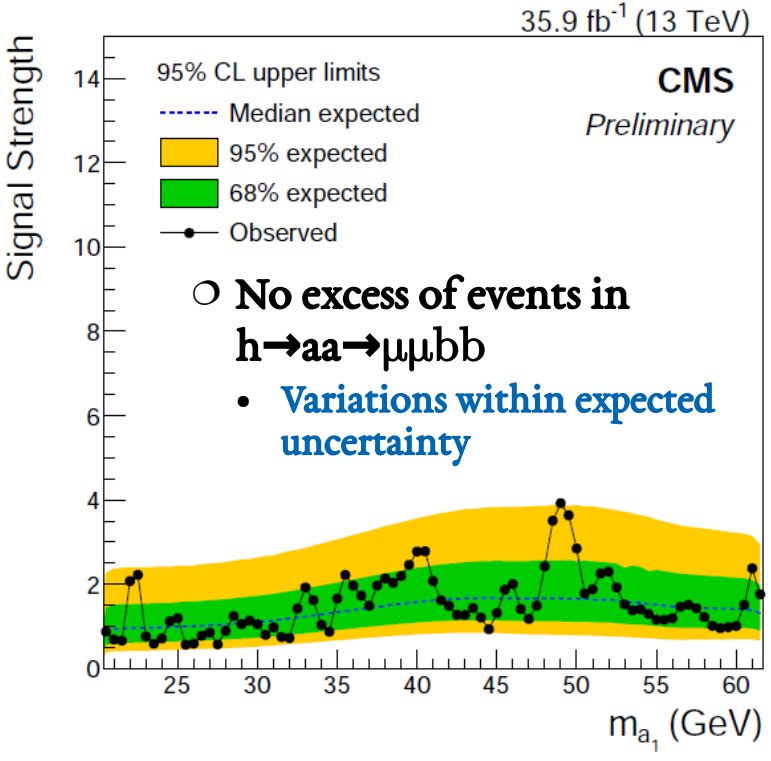
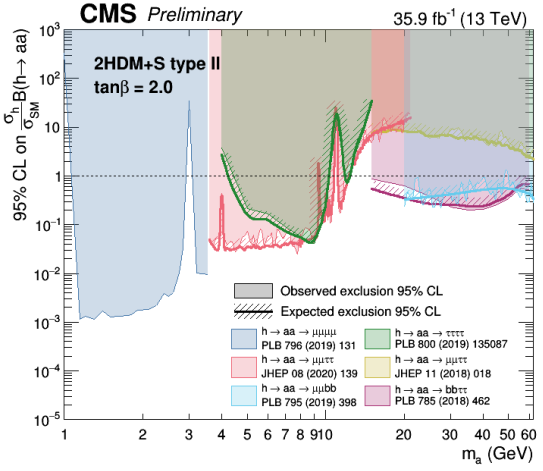
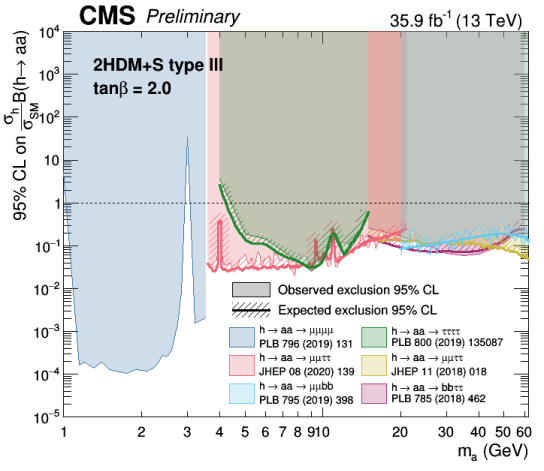


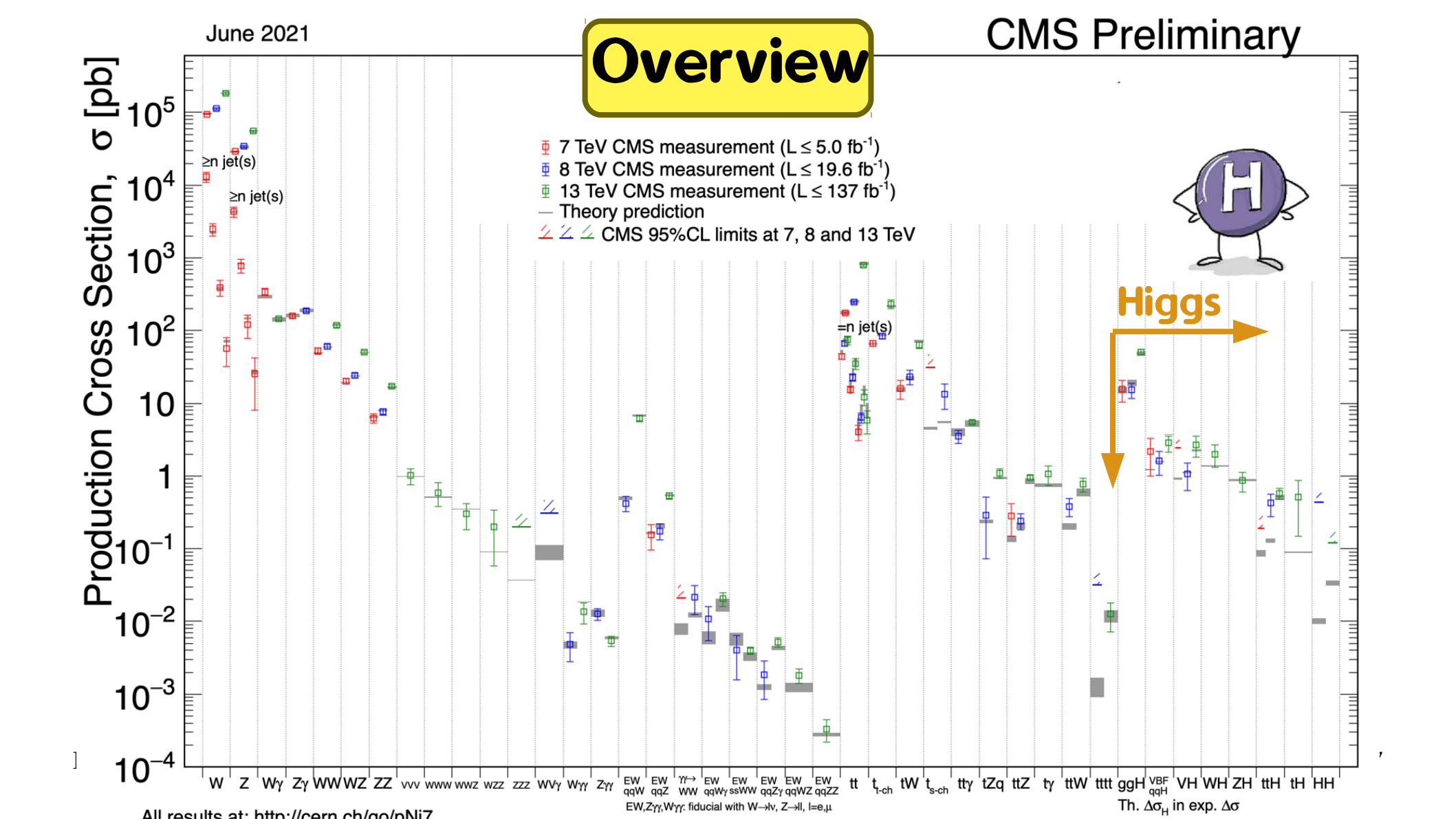
- No excess of events in h→aa→μμbb
  - Variations within expected uncertainty

set upperlimit

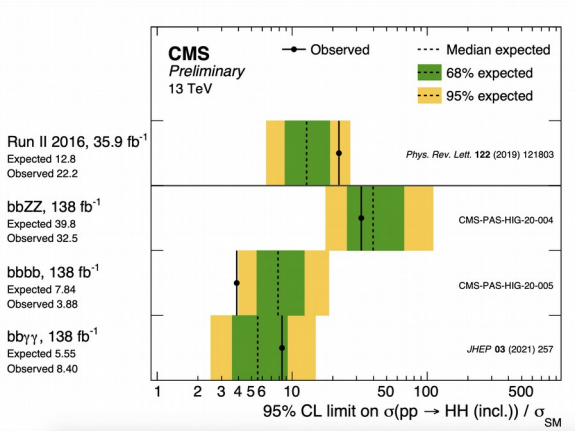
- 95% CL for exotic h decay searches in various scenarios of 2HDM+S

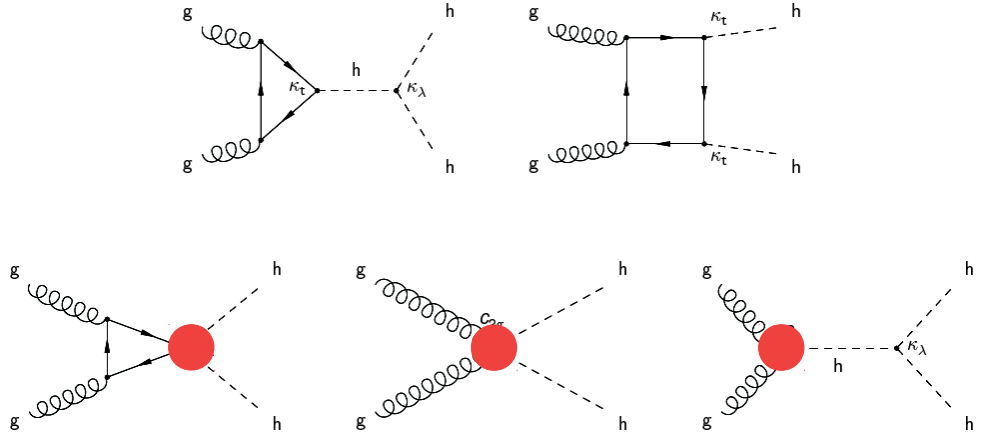


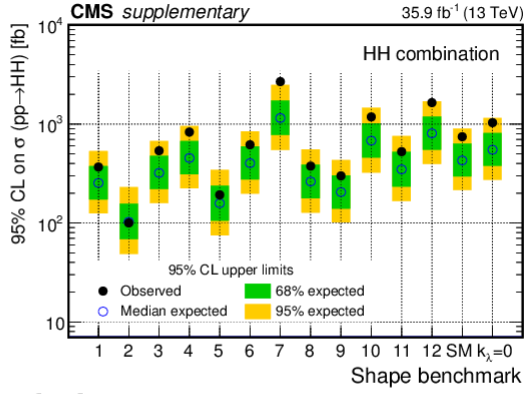


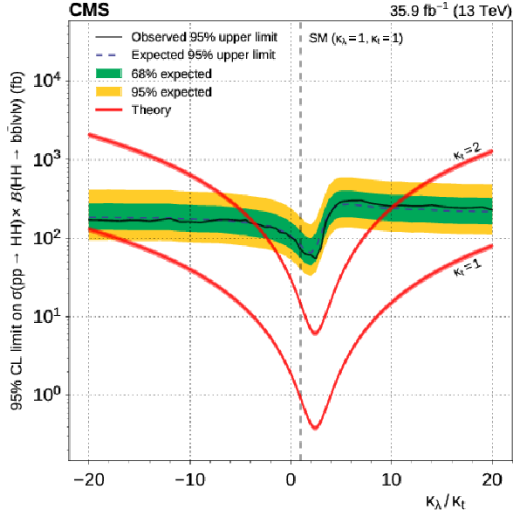

June 2021
Overview
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 137 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
Higgs
H
W Z Wγ Zγ WW WZ ZZ VVV WWW WWZ WZZ ZZZ WVγ Wγγ Zγγ EW qqW EW qqZ γγ→ WW EW qqWγ ssWW EW qqZγ EW qqWZ EW qqZZ tt t t-ch tW t s-ch ttγ tZq ttZ tγ ttW tttt ggH VBF qqH VH WH ZH ttH tH HH
EW,Zγγ,Wγγ: fiducial with W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ
All results at: http://cern.ch/go/pNj7

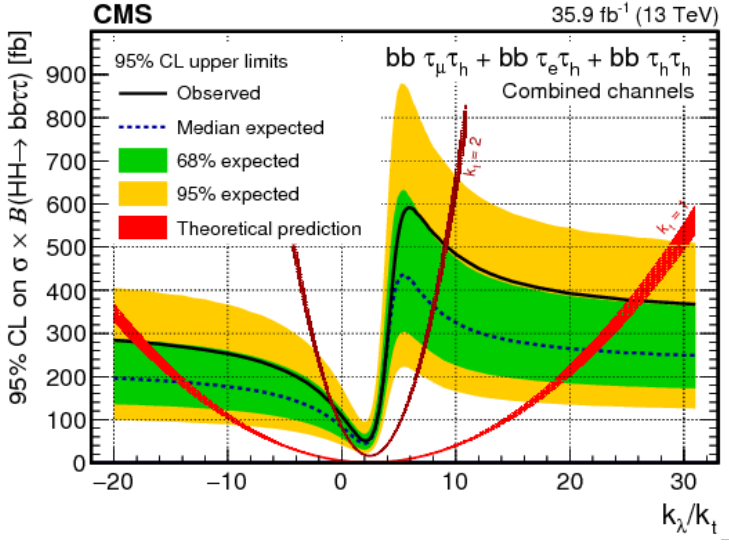
And many more which not discussed here...

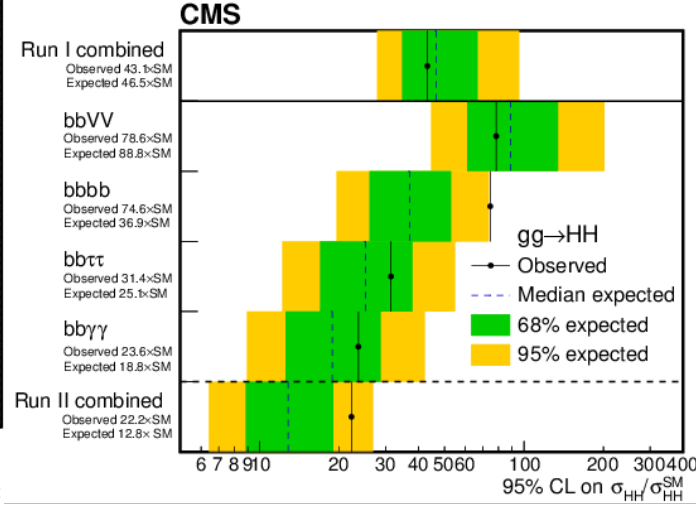












Higgs searches at Run3

- **First CMS analysis for VH; H→cc**
  - Sensitivity to charm Yukawa coupling
  - BR(H→cc) < 20 × BR(H→bb)
  - Run3 needed for first evidence of this challenging decay

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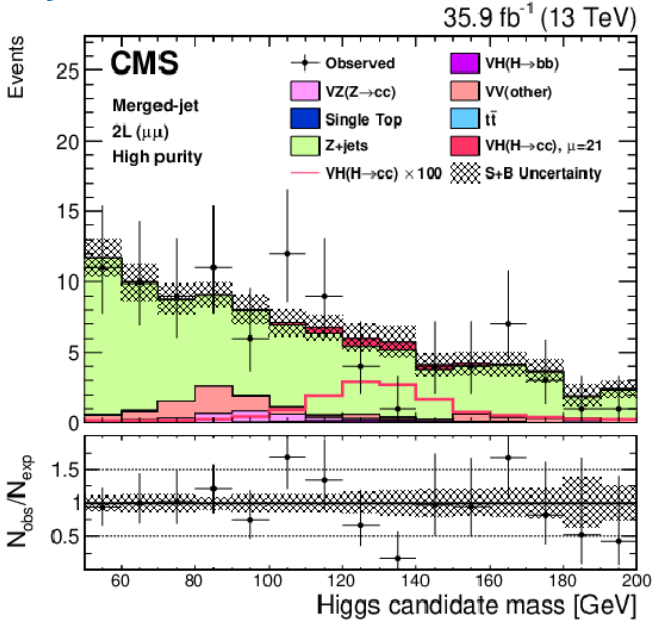

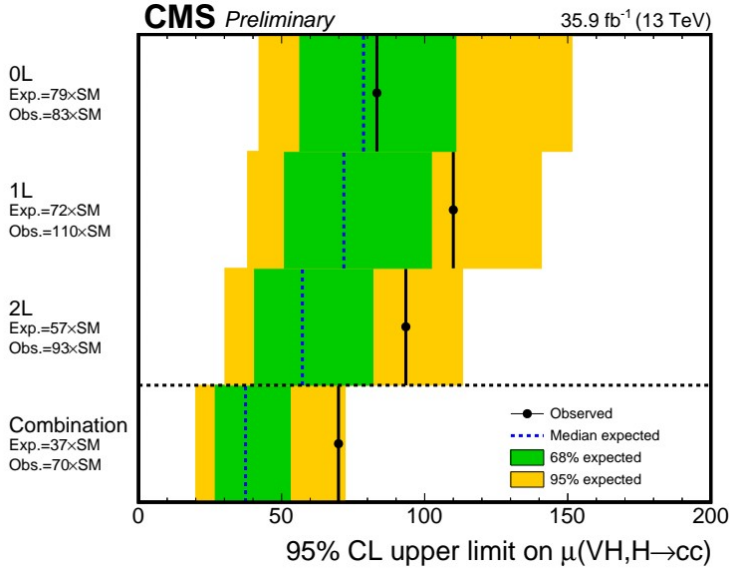

Towards high luminosity