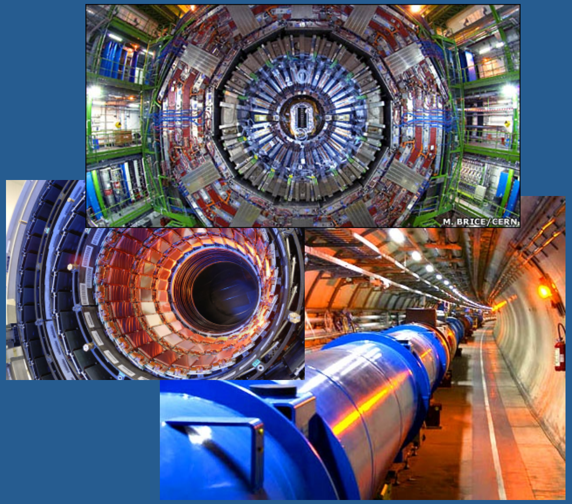
Higgs Physics at CMS:
Recent Highlights of the Post-Discovery Campaign

Prof. Chris Neu
Department of Physics
University of Virginia

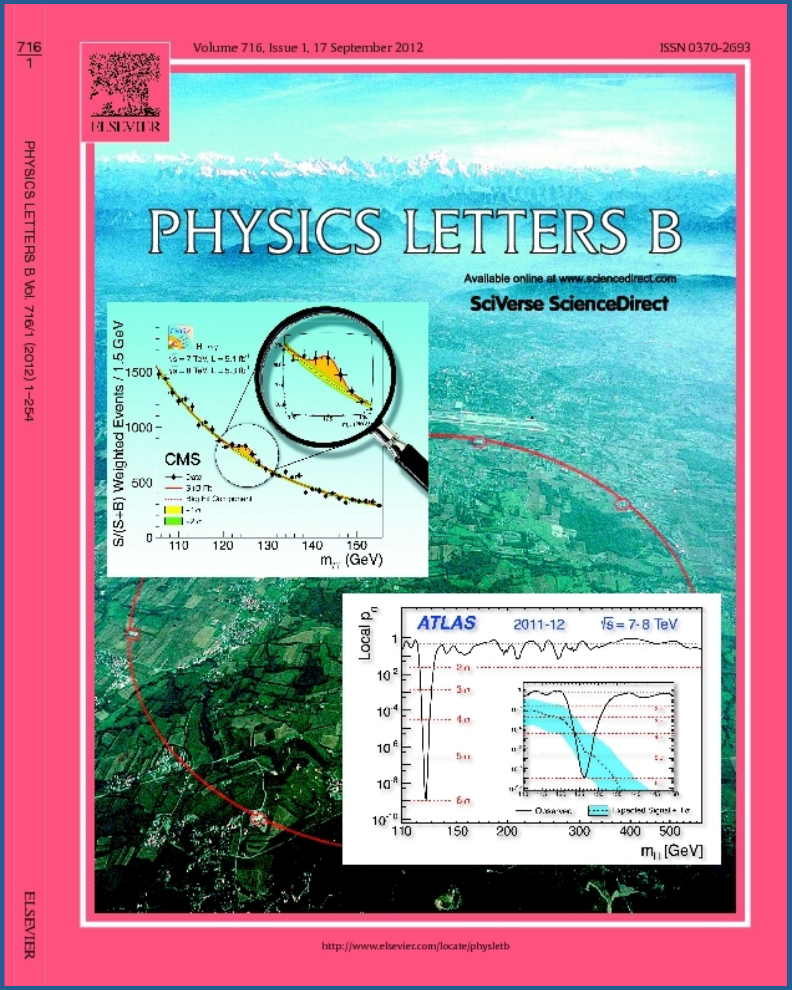


On behalf of
the CMS Collaboration

Introduction and Outline

- Long-sought Higgs boson finally discovered
  - Culmination of decades-long pursuit
    - LEP experiments through 2000
    - Tevatron through Runs 1 and 2
  - Finally, at the LHC:
    - 2012: "A new particle…"
    - 2013: "A Higgs boson..."

- In 2013, the focus shifted from searches to measurements:
  - Is this *the* Higgs boson of the SM?
  - Are there *any other Higgs bosons* to observe?
  - Is this Higgs *boson a window to new physics?*

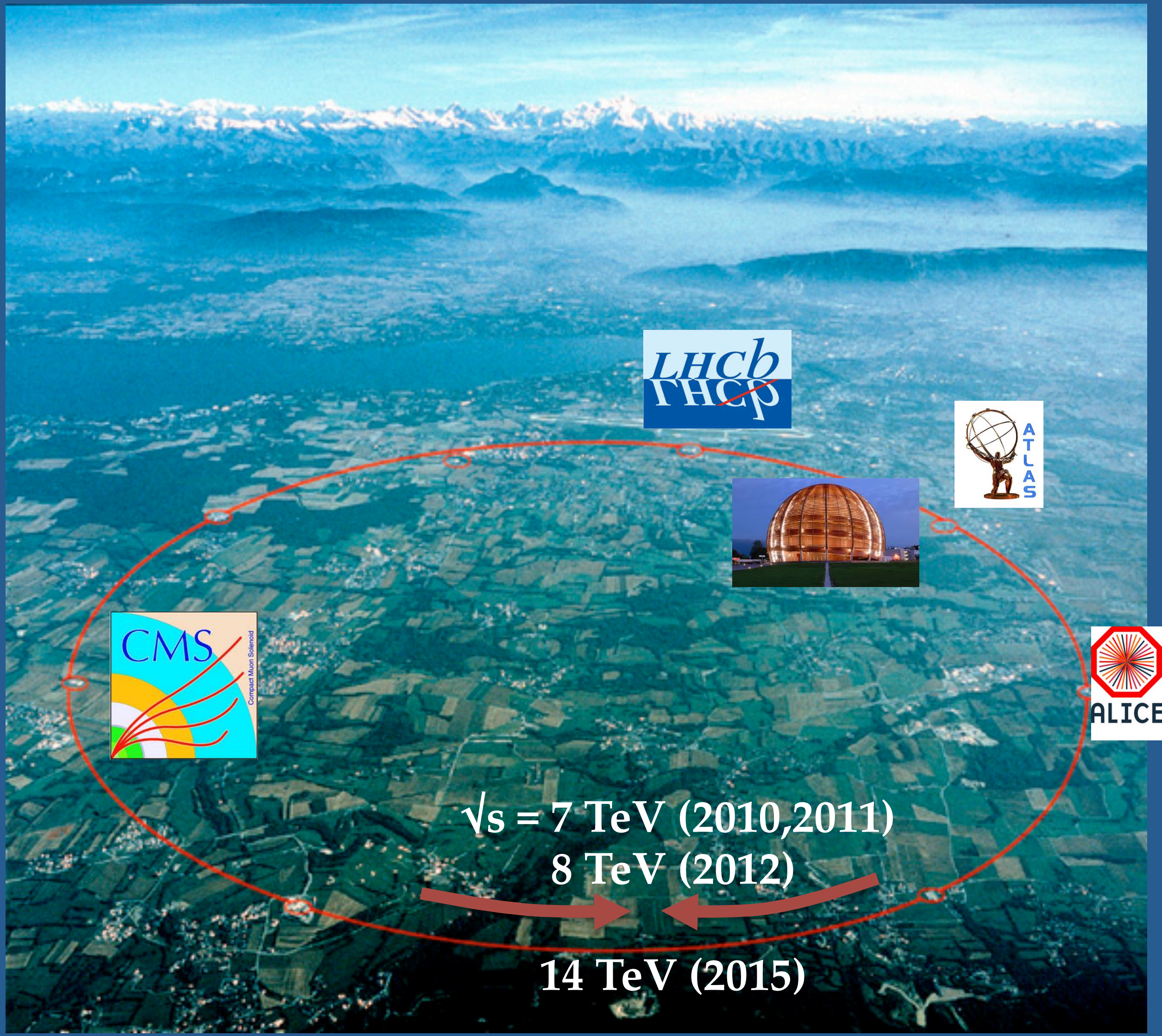


Phys.Lett. B71(2012) 1-29
Phys.Lett. B71(2012) 30-61

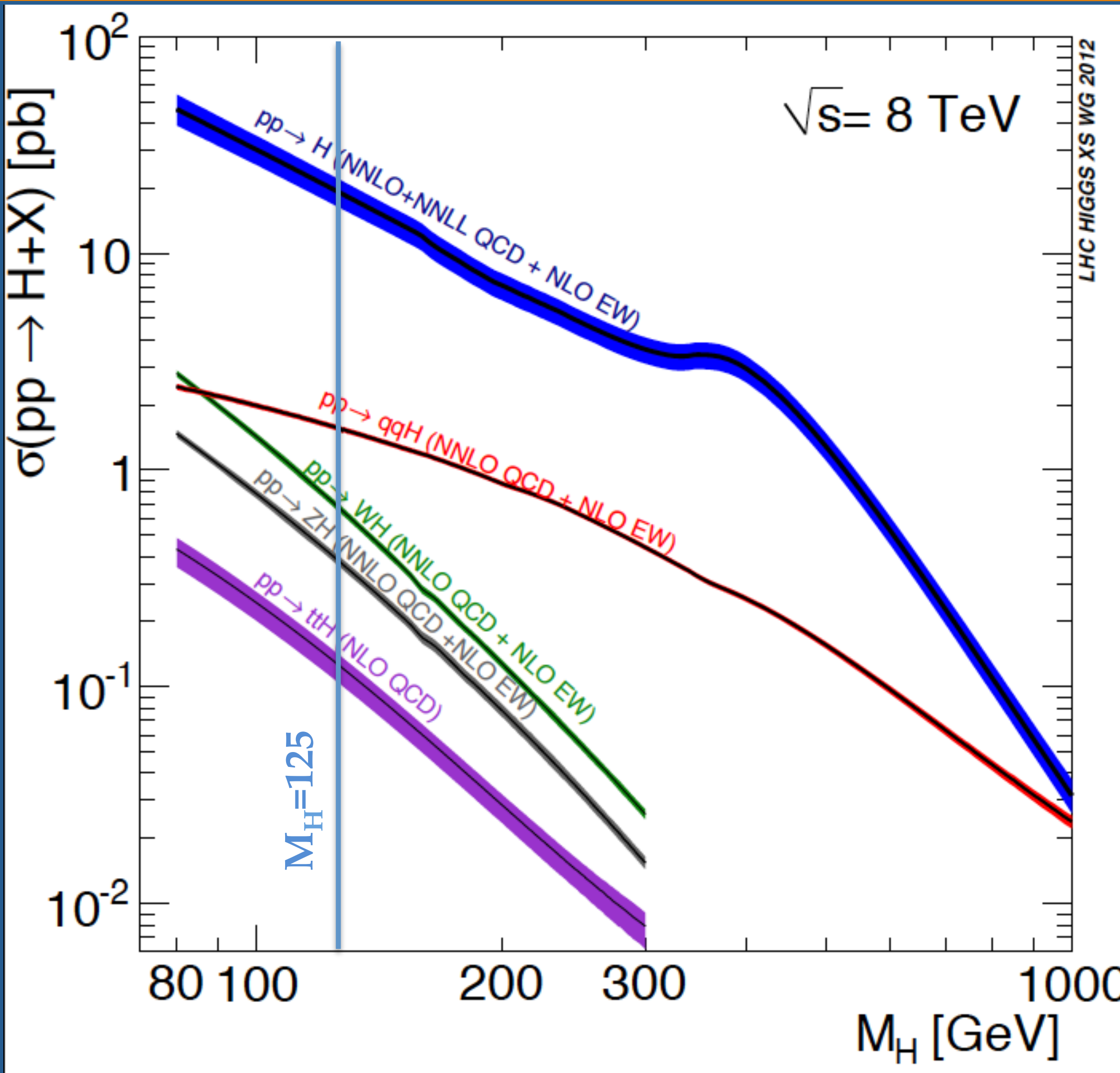
The Large Hadron Collider

- A proton-proton collider
  - 27 km in circumference
  - Beamlines ~100m underground
  - Four active interaction regions
  - Proton-proton collisions with up to 7+7 = 14 TeV

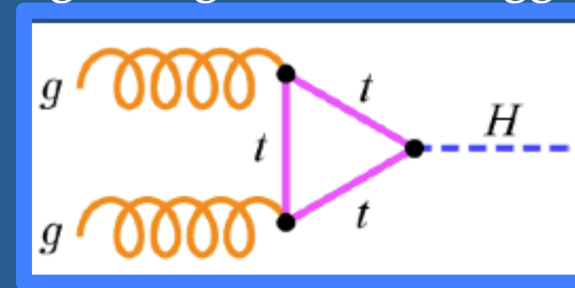
- Significant opportunity for discovery:
  - Highest energies ever achieved…
  - …at unprecedented collision rate
  - *A perfect place for searching for new physics*



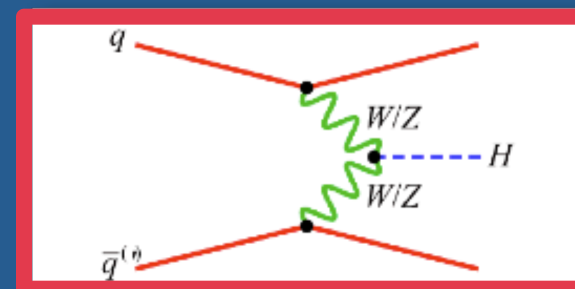
SM Higgs Boson Production at the LHC



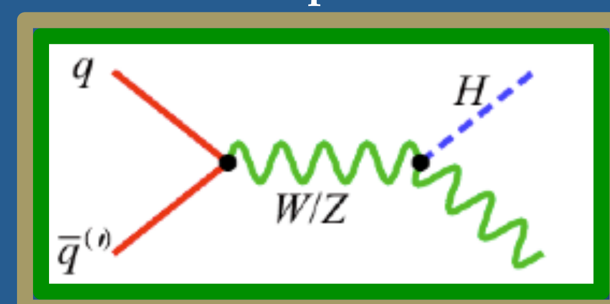
gluon-gluon fusion (ggF)



vector-boson fusion (VBF)

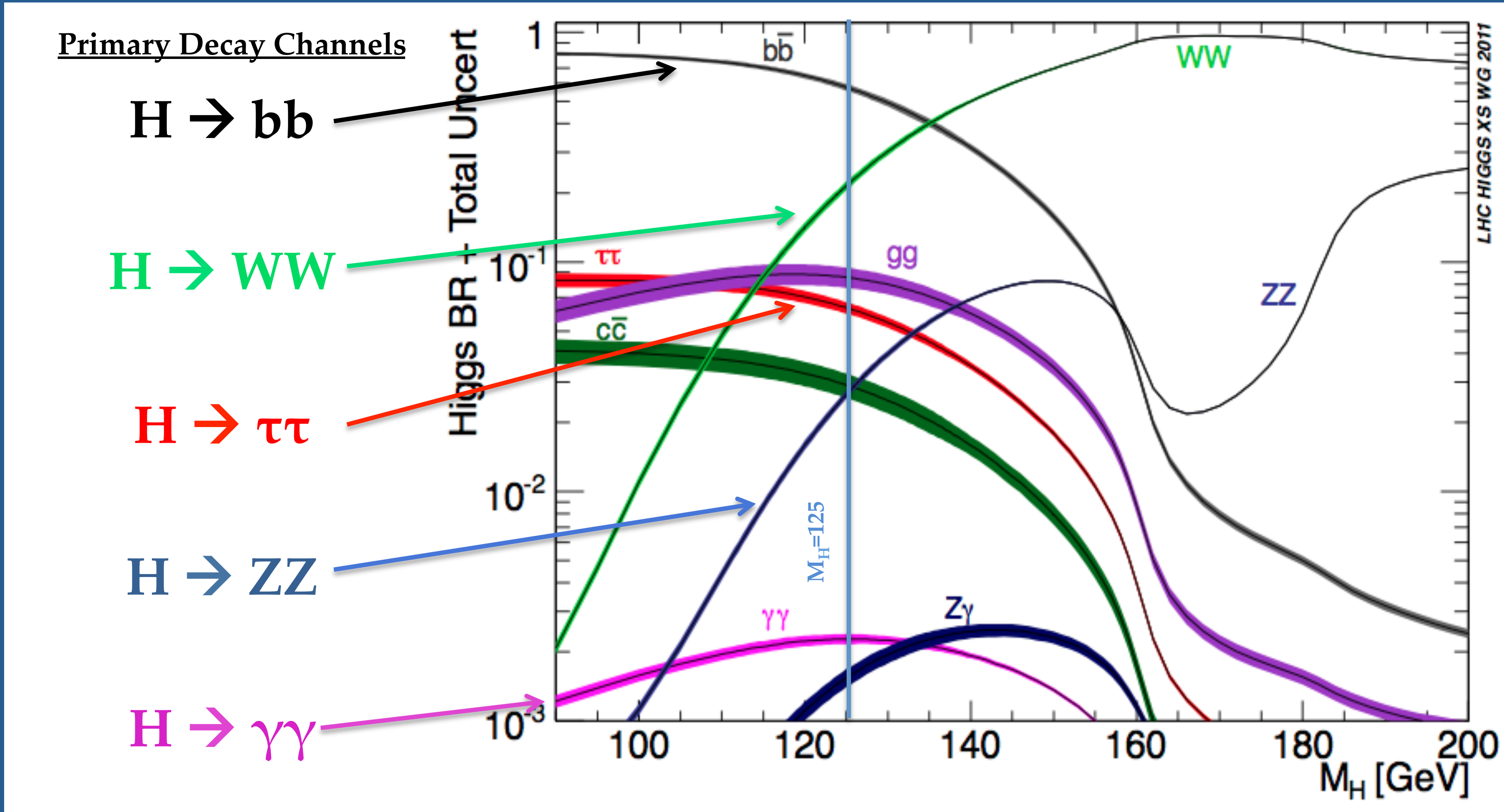


W/Z associated production (VH)



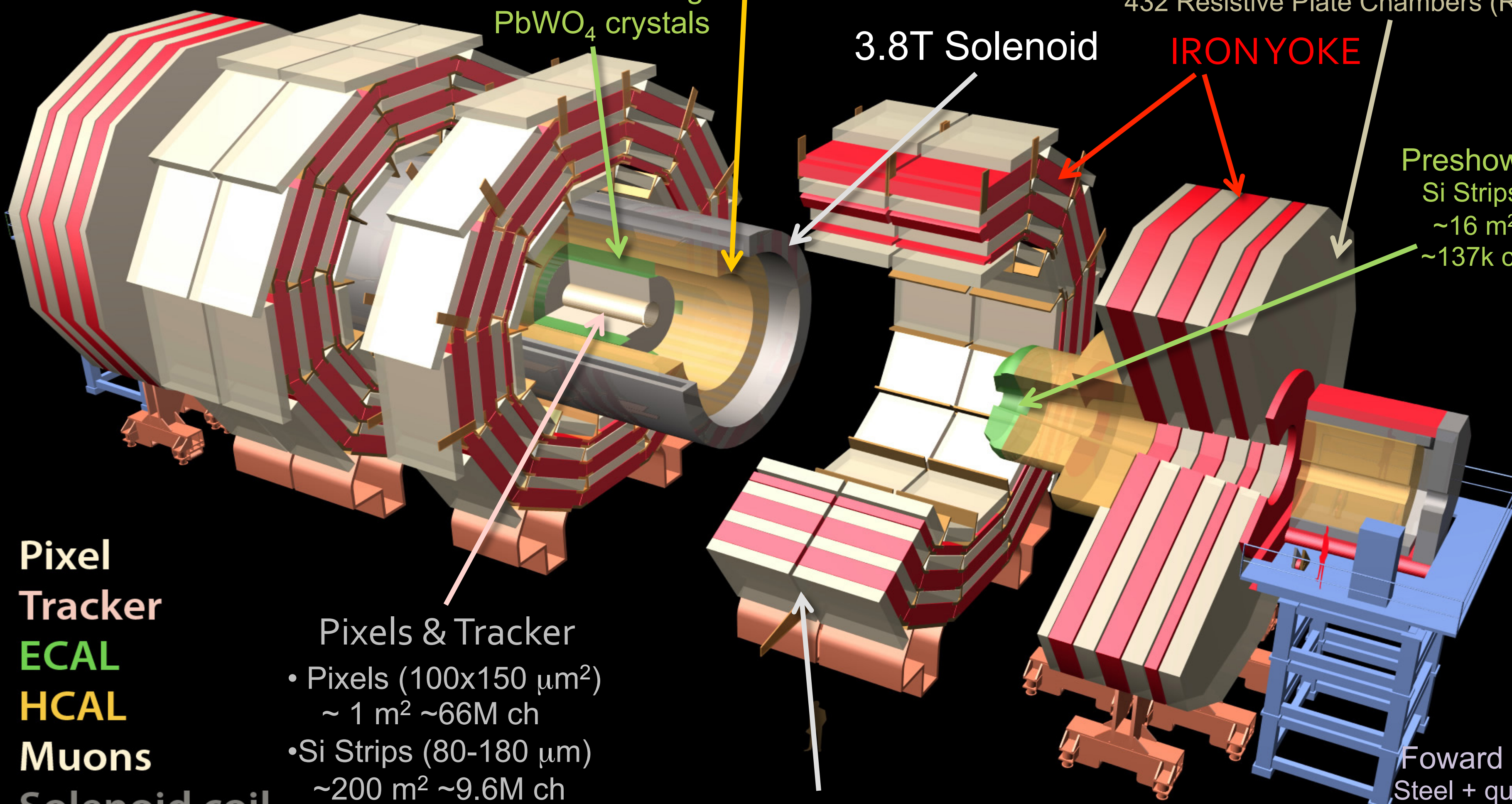
More on ttH production later…

SM Higgs Boson Decay Channels



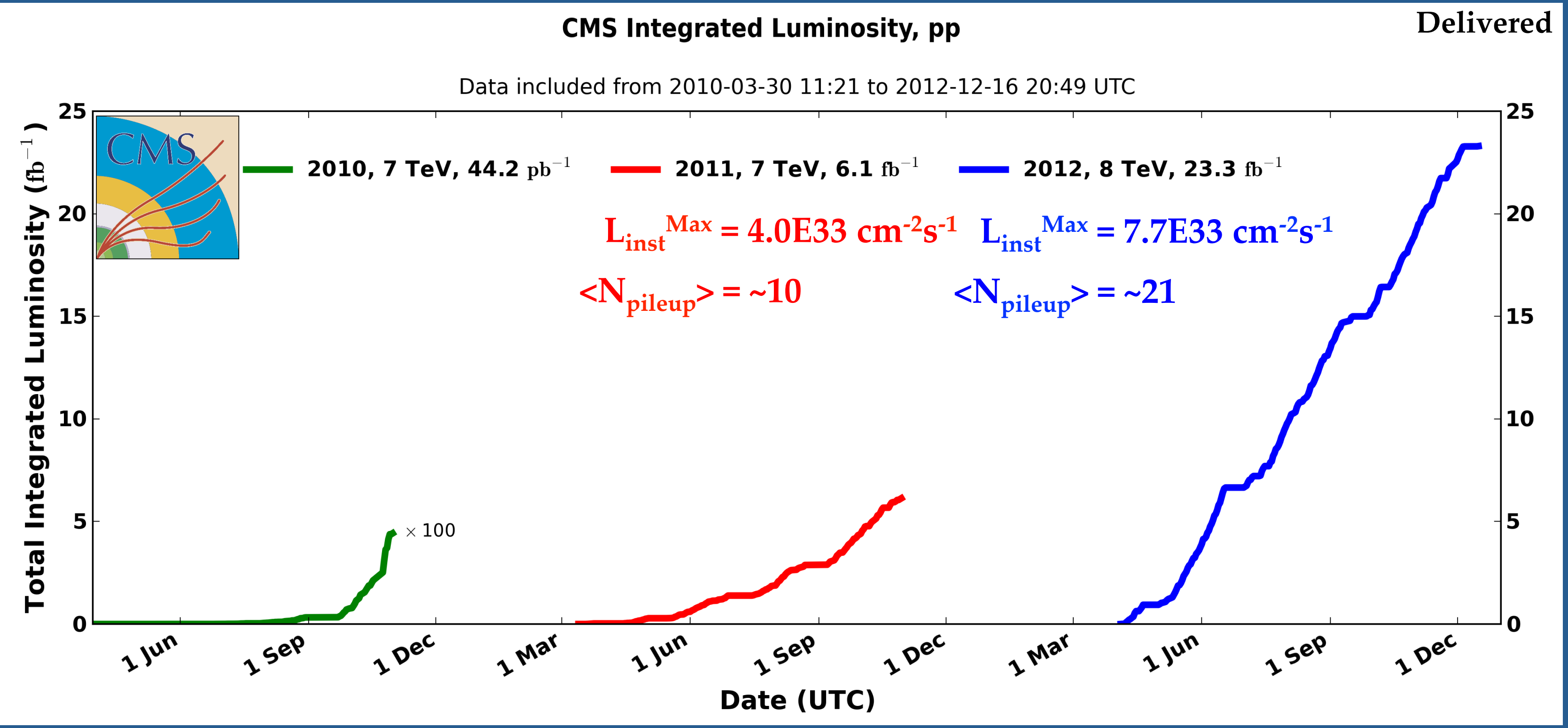
Rarer decay modes suffer from statistics but generally have lower levels of mundane processes ("background") obscuring the signal AND have a higher resolution on the mass of the Higgs before decay.

The CMS Detector



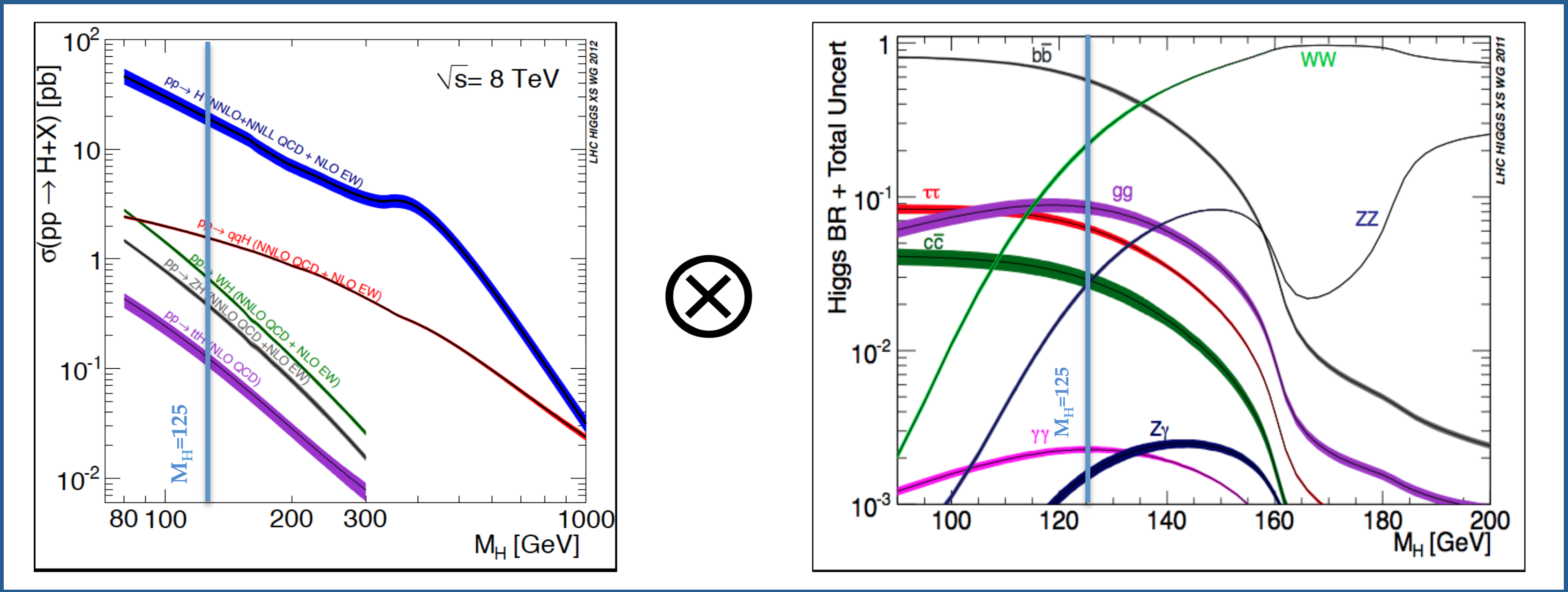
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m

The Run 1 CMS Data Sample



- Excellent performance of the LHC and CMS in 2011-12
  - Regularly recording 1/fb / week
  - CMS in 2012: 93% data-taking efficiency
  - Total integrated luminosity: ~25/fb
    - ~5/fb at 7 TeV in 2011
    - ~20/fb at 8 TeV in 2012

The Higgs Program at CMS



- Comprehensive Higgs pursuit campaign at CMS
  - Survey of each accessible production mechanism for each primary decay mode

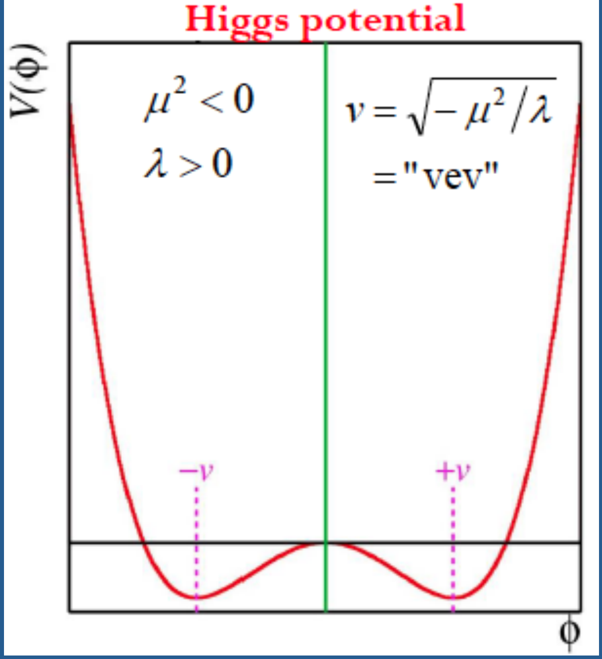
- All channels contribute to cumulative picture

Is this the Higgs Boson of the Standard Model?

Transition from Searches to Measurements

- In the post-discovery era, focus moves from search to precision measurements
  - First task:
    - Need precise measurements of all of its properties
    - Is this the Higgs Boson of the Standard Model?

$$L = \left(D_\mu \phi\right)^* \left(D^\mu \phi\right) - \left(\mu^2 \phi^2 + \lambda \phi^4\right) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$



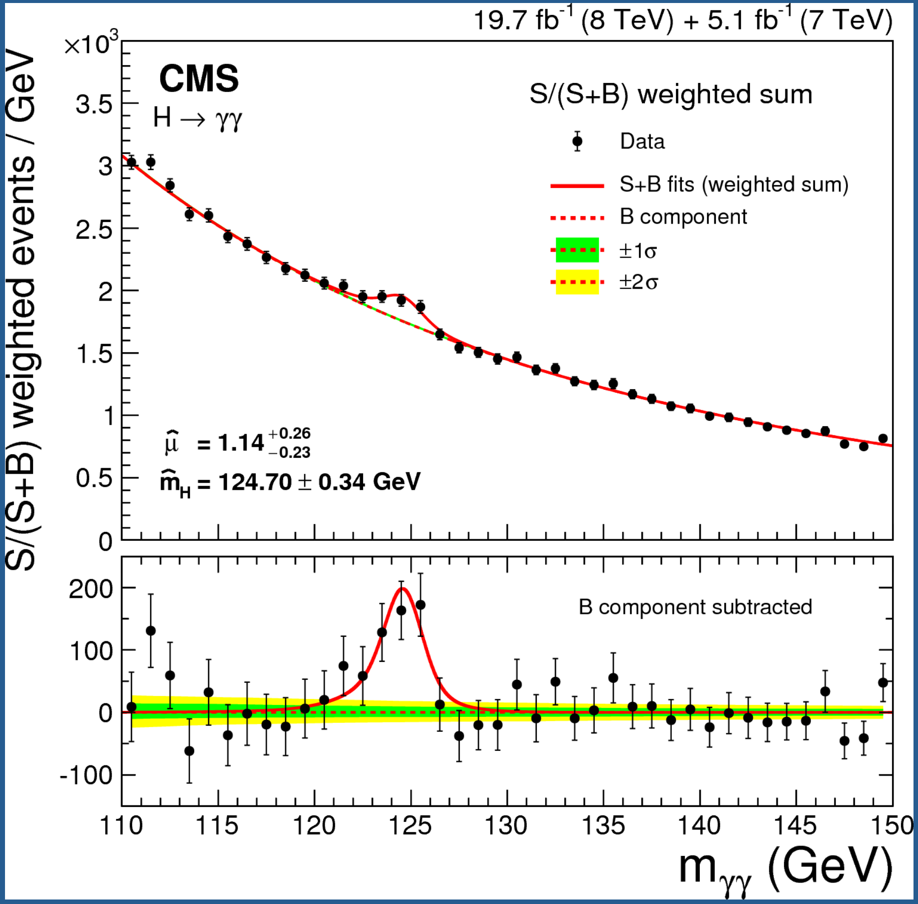
- Characteristics of the SM Higgs:
  - Decay modes
  - Couplings to other SM particles
  - Mass
  - Spin and parity
  - Width
  - Self-coupling

$$m_H = \sqrt{2\lambda} v$$

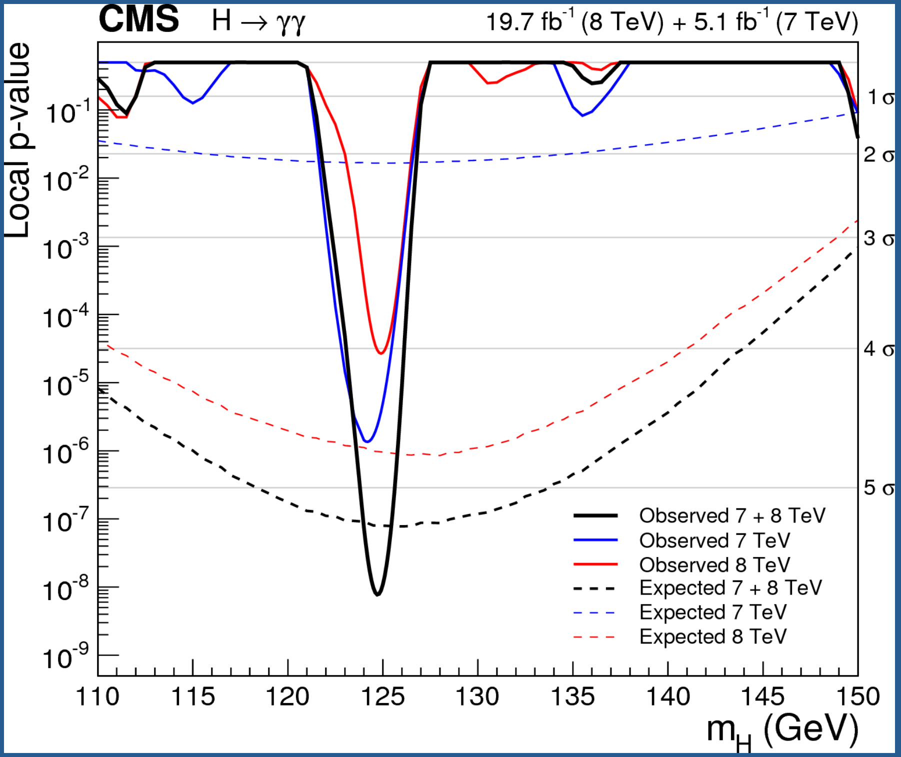
λ, μ unknown → m_H is a free parameter of the SM

$$g_{HVV} = 2\frac{m_V^2}{v} \qquad g_{Hff} = \frac{m_f}{v}$$

Higgs Decay Modes: H→γγ

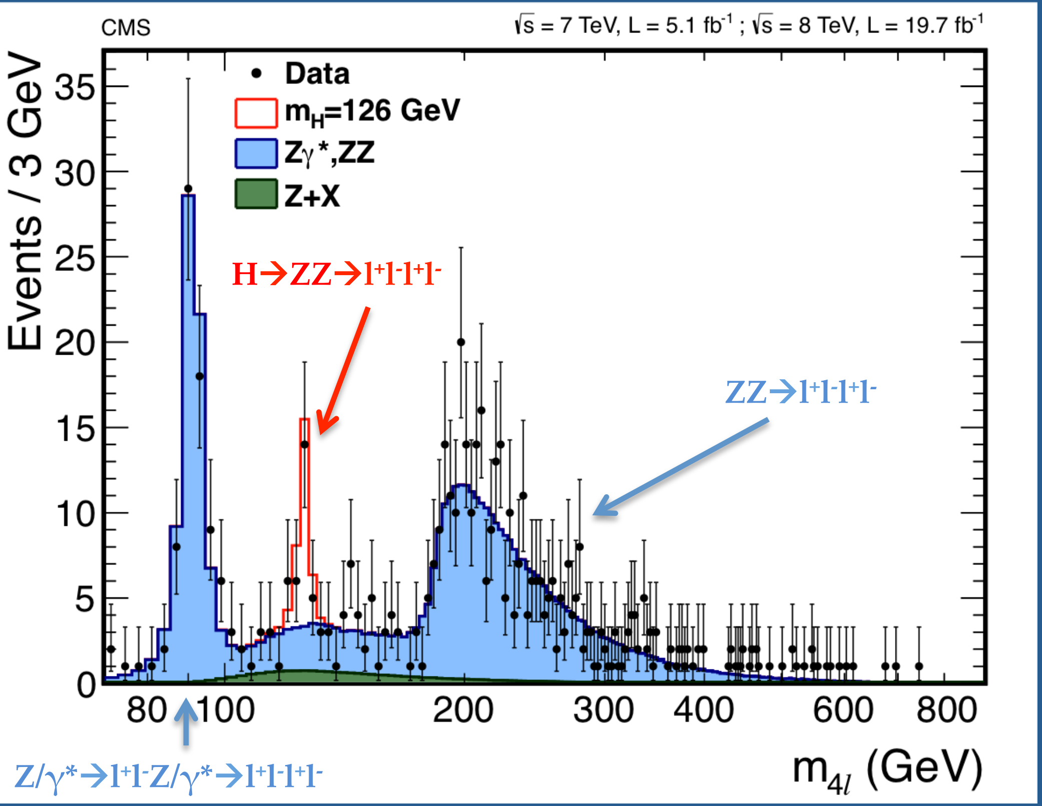


arXiv:1407.0558, submitted to EPJC

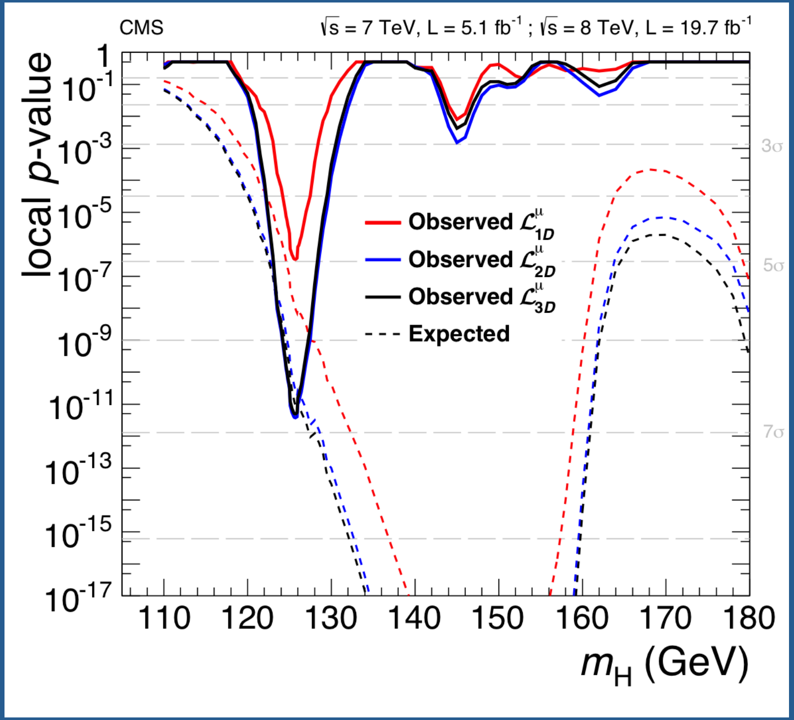


- Search for small mass peak over exponentially falling background
- Small BR but narrow mass peak → good mass resolution (1-2%)
- Significance of observation for ~125 GeV = 5.2σ (5.7σ) expected (observed)
  - Single decay-mode observation

Higgs Decay Modes: H→ZZ



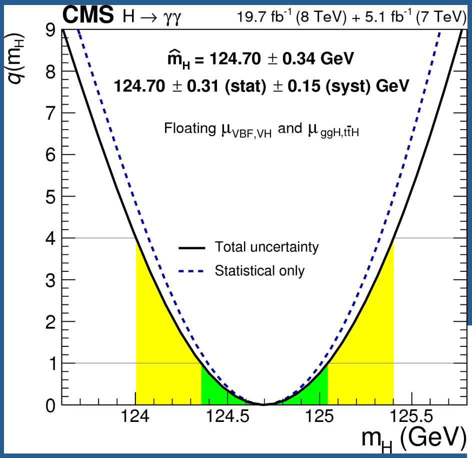
PhysRevD.89.092007



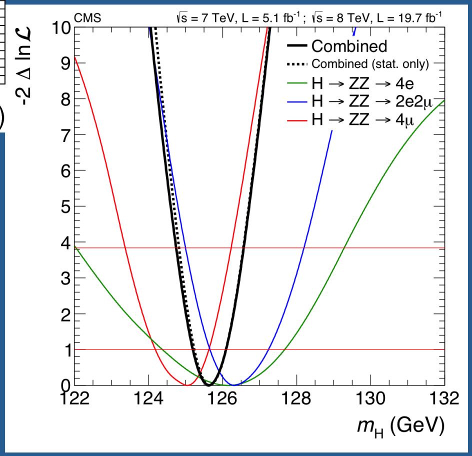
- Look for 2 high-mass pairs of oppositely charged leptons
  - Low BR but very clean signature for M_H = ~125 GeV
  - Good mass resolution (1-2%)
- Significance of observation for ~125 GeV = 6.7σ (6.8σ) expected (observed)
  - Single decay-mode observation

Characterizing the Higgs Boson: Mass

arXiv:1407.0558



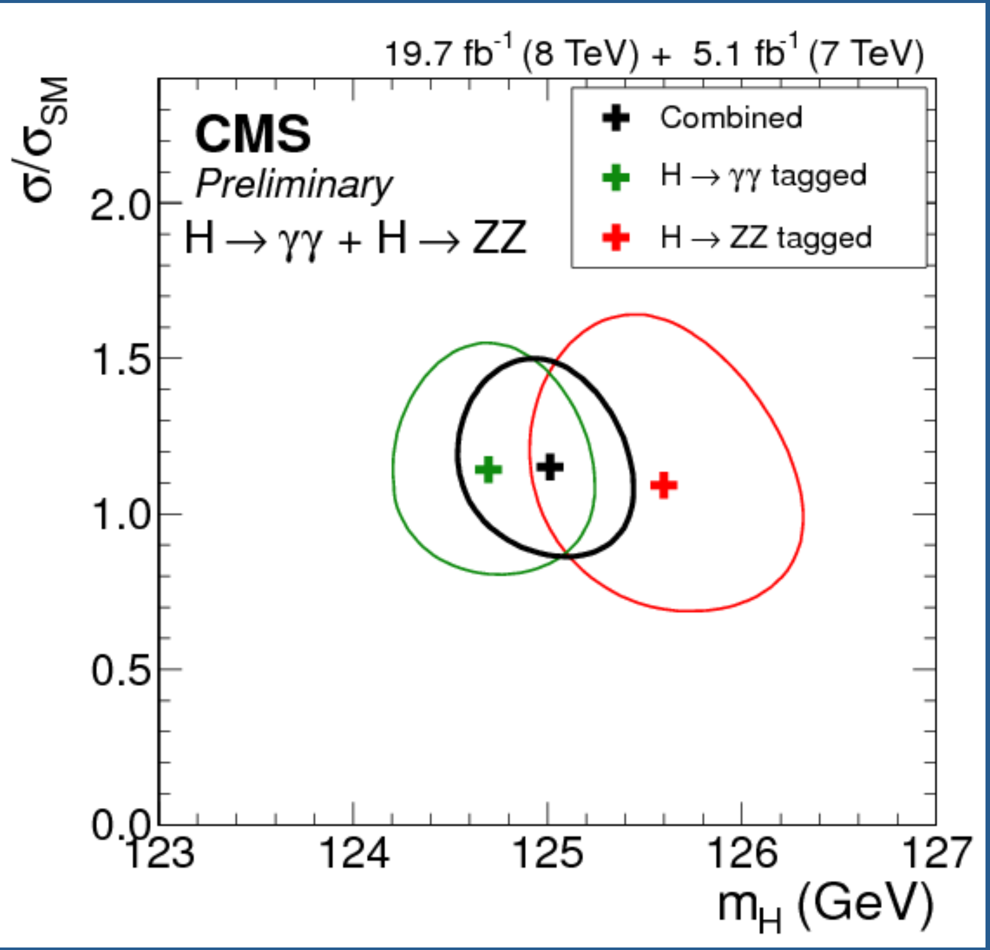
PhysRevD.89.092007



- Exploit highest mass resolution channels in combination for precise determination of m_H

Characterizing the Higgs Boson: Mass

CMS-PAS-HIG-14-009



- Exploit highest mass resolution channels in combination for precise determination of m_H
- Profile three independent signal strengths $\mu = \sigma/\sigma_{SM}$, treated as nuisance parameters:
  - (ggF,ttH) → $\gamma\gamma$
  - (VH,VBF) → $\gamma\gamma$
  - pp → H → ZZ

Characterizing the Higgs Boson: Mass

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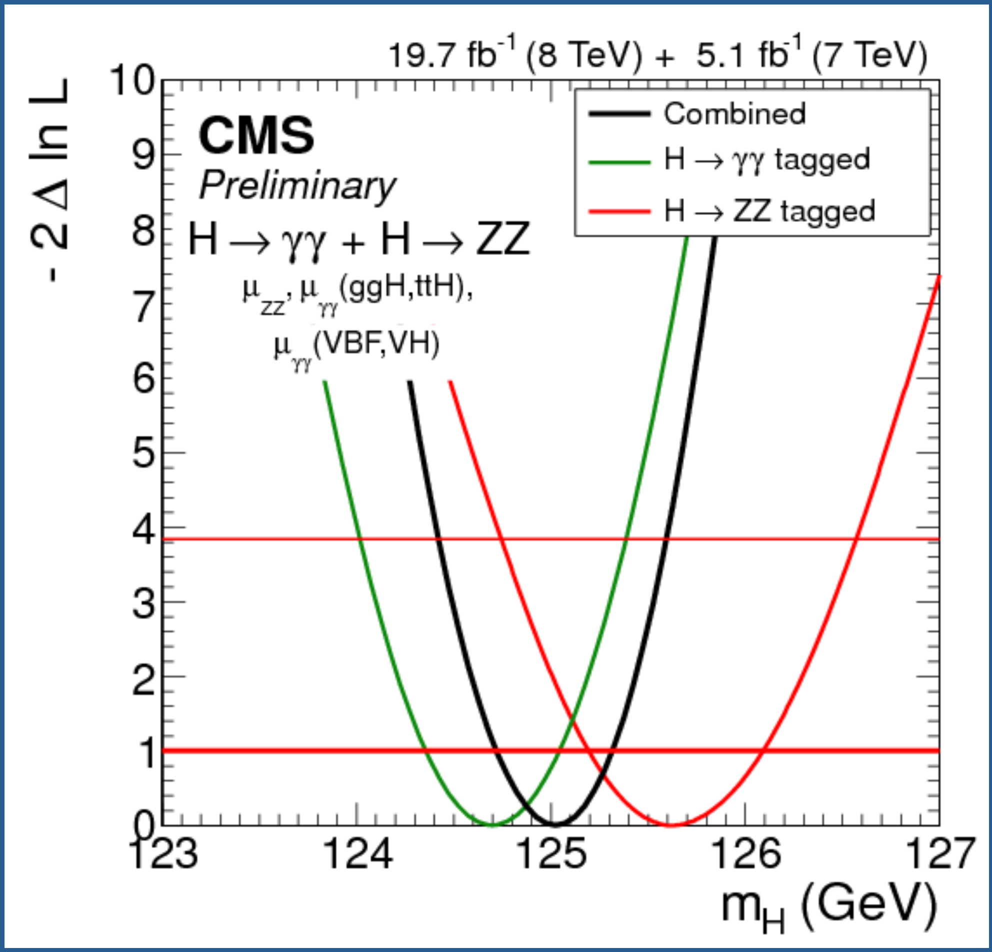


Individual channel results are consistent within 1.6 σ.

- Exploit highest mass resolution channels in combination for precise determination of m_H
- Profile three independent signal strengths $\mu = \sigma/\sigma_{SM}$, treated as nuisance parameters:
  - (ggF,ttH) → γγ
  - (VH,VBF) → γγ
  - pp → H → ZZ

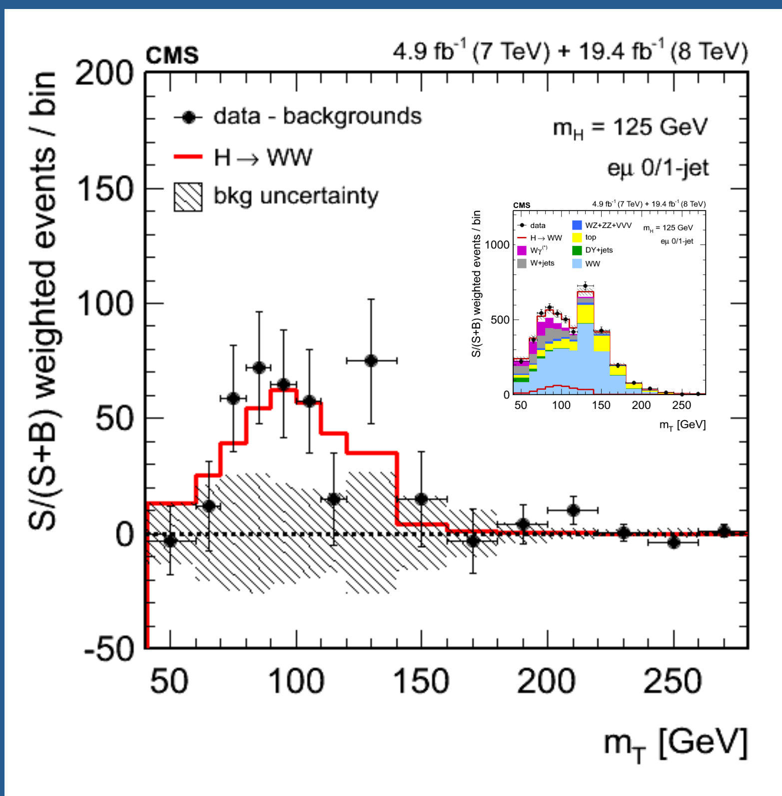
Channel	m_H [GeV]	$\pm\delta_{Stat}$ [GeV]	$\pm\delta_{Syst}$ [GeV]
H→γγ	124.7	0.31	0.15
H→ZZ	125.6	0.4	0.2
Comb	**125.03**	**$^{+0.26}_{-0.27}$**	**$^{+0.13}_{-0.15}$**

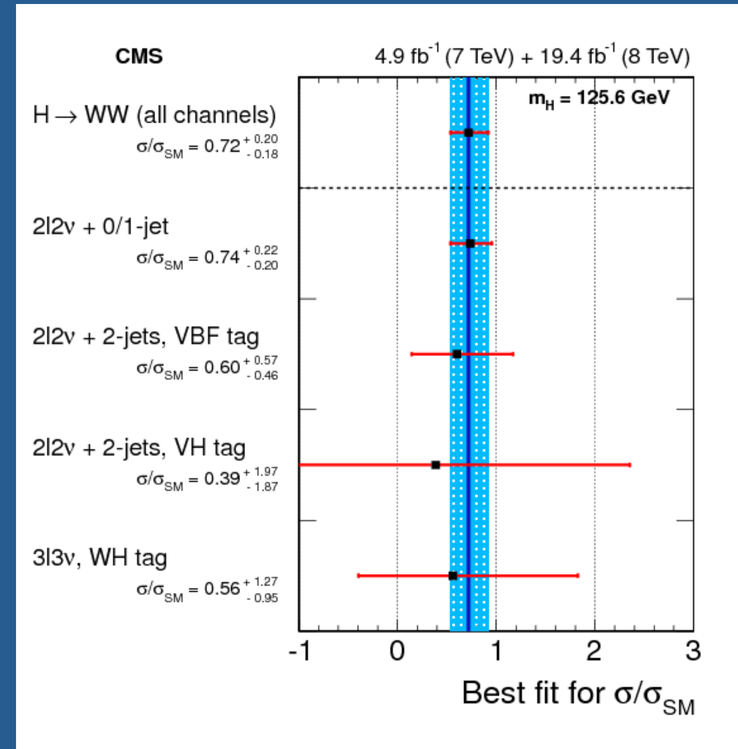
$m_H = 125.03\ ^{+0.29}_{-0.31}$ GeV
(δ_m/m_H = 2.4E-3)

Higgs Decay Modes: H→WW

JHEP 01 (2014) 096

- Focus so far: H→WW→lνlν
  - Two high p_T isolated leptons and large MET
  - No narrow mass peak (resolution ~20%) due to escaping ν's
  - Analysis executed in several channels
    - Sensitivity dominated by channels targeting ggF production with 0 or 1 jets

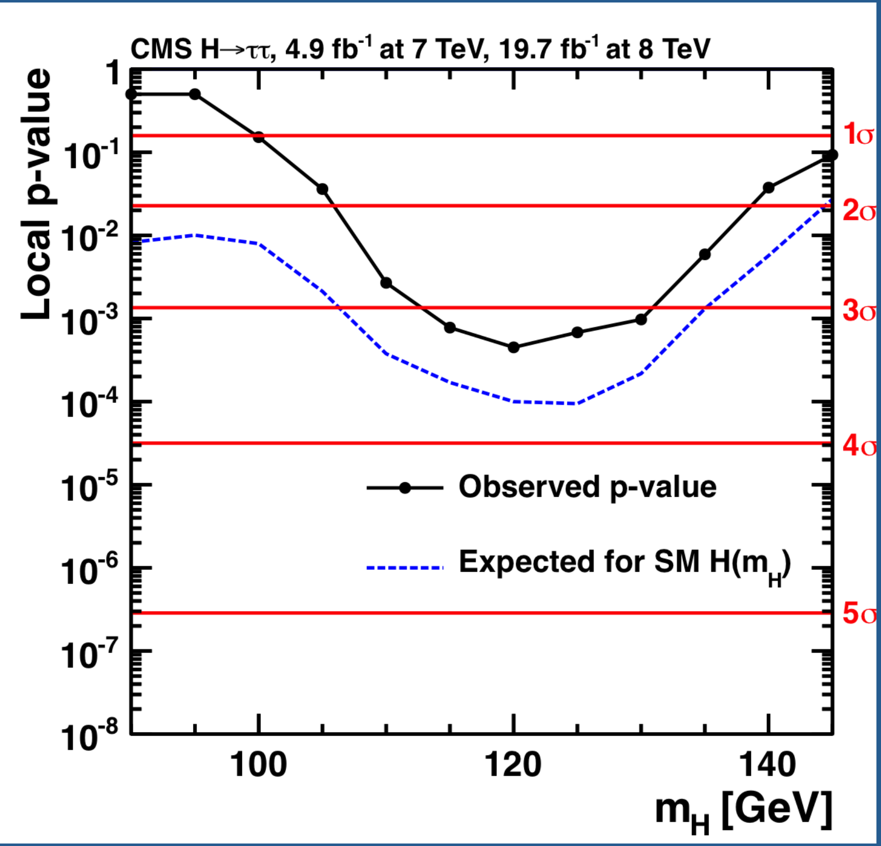




- Significance of observation for ~125 GeV = 5.8σ (4.3σ) expected (observed)
  - Small deficit in observation compared to expectation
- H→WW→lνjj:
  - Low-mass optimized search underway
  - Channel plays big role in high-mass Higgs searches (more on this later)

Higgs Decay Modes: H→ττ

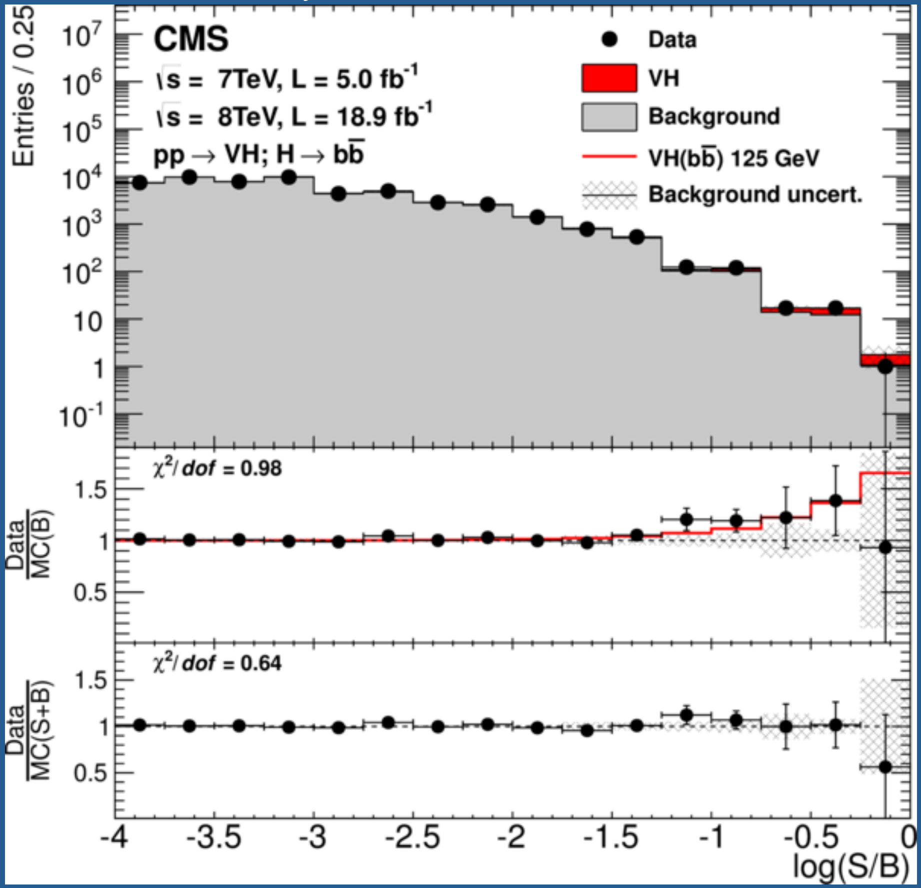
- Suite of analyses targeting many subchannels:
  - H→ττ decay modes:
    - ll +4ν (12%)
    - $l\tau_h$ +3ν (46%)
    - $\tau_h\tau_h$ +2ν (42%)
  - Analysis signatures:
    - 0-jet
    - 1-jet boosted
    - 2-jet VBF
    - VH



- Significance of observation for ~125 GeV = 3.7σ (3.2σ) expected (observed)
  - Evidence for Higgs coupling to τ leptons

Higgs Decay Modes: H→bb

Phys. Rev. D 89, 012003



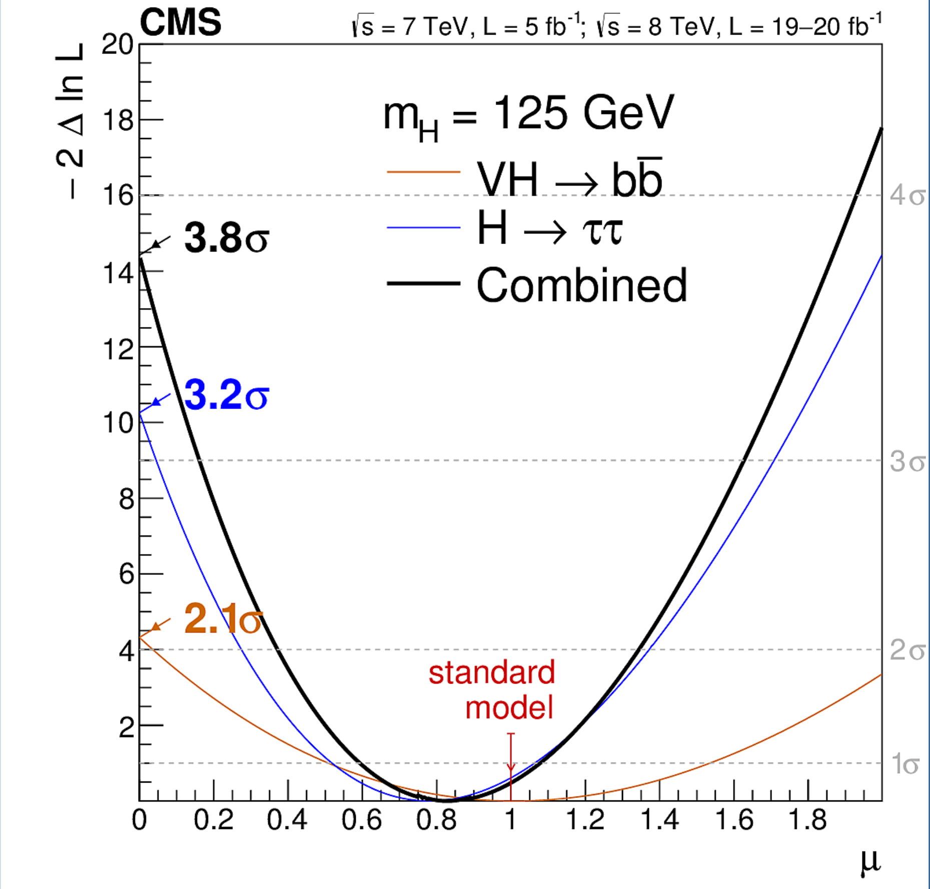
Significance of observation for ~125 GeV = 2.1σ (2.1σ) expected (observed)

- Despite having largest BR for m_H=125, H→bb is not easy
  - QCD backgrounds make observation through ggF infeasible
- Most sensitive channel is VH
  - exploit efficient+pure b-tagging
  - use MVAs to enhance sensitivity to signal
  - low resolution on m_H
- Analysis combines results from several independent V leptonic decay channels

Higgs Decay Modes: H→Fermions

- Combination of H→ττ and H→bb results
- Significance of observation for ~125 GeV = 4.4σ (3.8σ) expected (observed)
  - Evidence for Higgs coupling to fermions
- Published in Nature Physics 10, 557–560 (2014)
- Big news from the 2014 Winter Conferences

Channel ($m_H = 125$ GeV)	Significance (σ) Expected	Observed	Best-fit μ
$VH \rightarrow b\bar{b}$	2.3	2.1	1.0 ± 0.5
$H \rightarrow \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24



Summary of Individual Analyses

$M_H = 125$ GeV Decay Mode	Production Mechanism	Lumi (fb^{-1}) 7 + 8 TeV	Significance of Observation (σ = standard deviation) Expected	 Observed	Signal Strength $\mu = \sigma/\sigma_{SM}$
$H \rightarrow bb$	VH	5 + 19	2.1σ	2.1σ	1.0 ± 0.5
$H \rightarrow WW$	ggF, VBF	4.9 + 19.5	5.8σ	4.3σ	$0.72^{+0.20}_{-0.18}$
$H \rightarrow \tau\tau$	ggF, VBF, VH	5 + 19.7	3.7σ	3.2σ	0.78 ± 0.27
$H \rightarrow ZZ$	ggF, VBF	5.1 + 19.6	6.7σ	6.8σ	$0.93^{+0.26}_{-0.23}{}^{+0.13}_{-0.09}$
$H \rightarrow \gamma\gamma$	ggF, VBF	5.1 + 19.6	5.2σ	5.7σ	$1.14^{+0.26}_{-0.23}$

- **Significance of Observation:**
  - "3σ significance" implies only 1 in 740 probability for background-only data to fluctuate to produce observed excess.
  - "5σ significance" = 1 in 3.5 million
- **Signal Strength, μ:**
  - How much signal is observed, in units of the amount predicted from the Standard Model for each search channel **(μ = 1.0 implies SM level)**

Grand Combination: Signal Strengths

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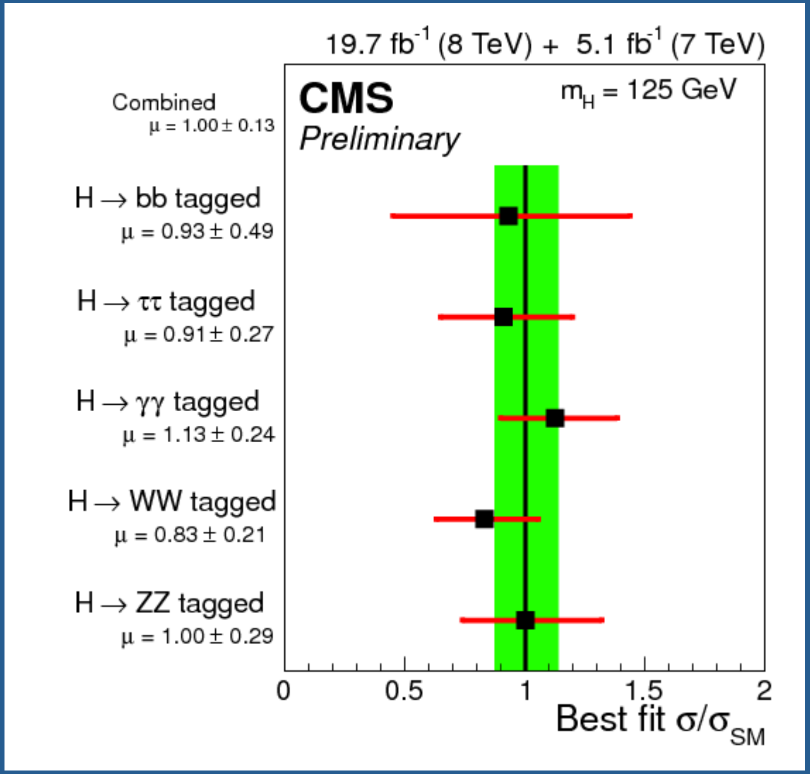
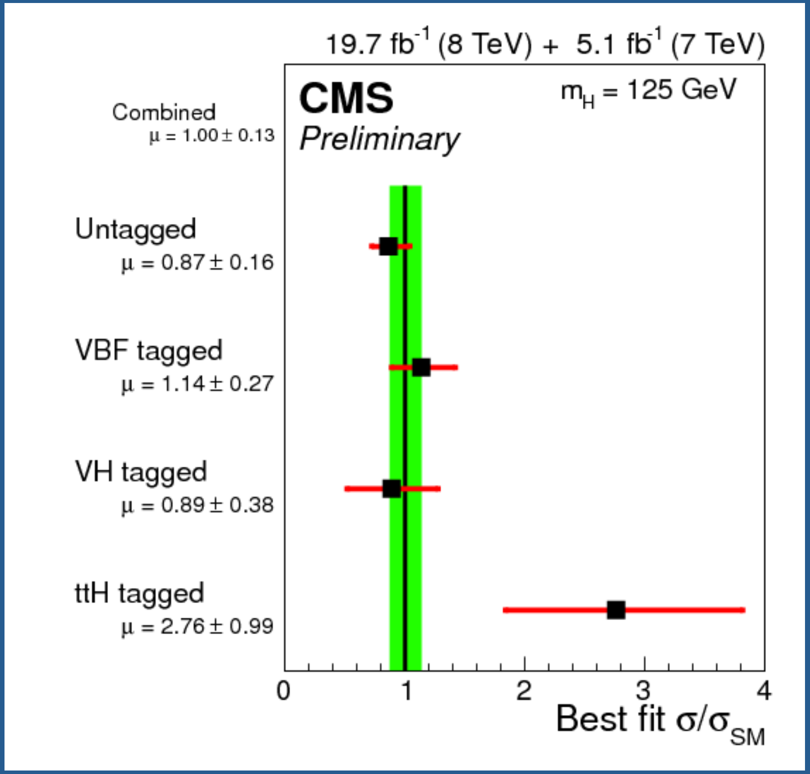




- Combine results from every channel accounting for stat and syst uncertainties, and their correlations
- Profile likelihood fits are performed with nuisance parameters profiled
- For $m_H = 125$,
  - $\mu = 1.0 \pm 0.13$ → very SM-like
  - All decay and most production signal strengths consistent with the SM

Grand Combination: Couplings to Particles of the SM

- Look for deviations from SM predictions for couplings to vector bosons and fermions

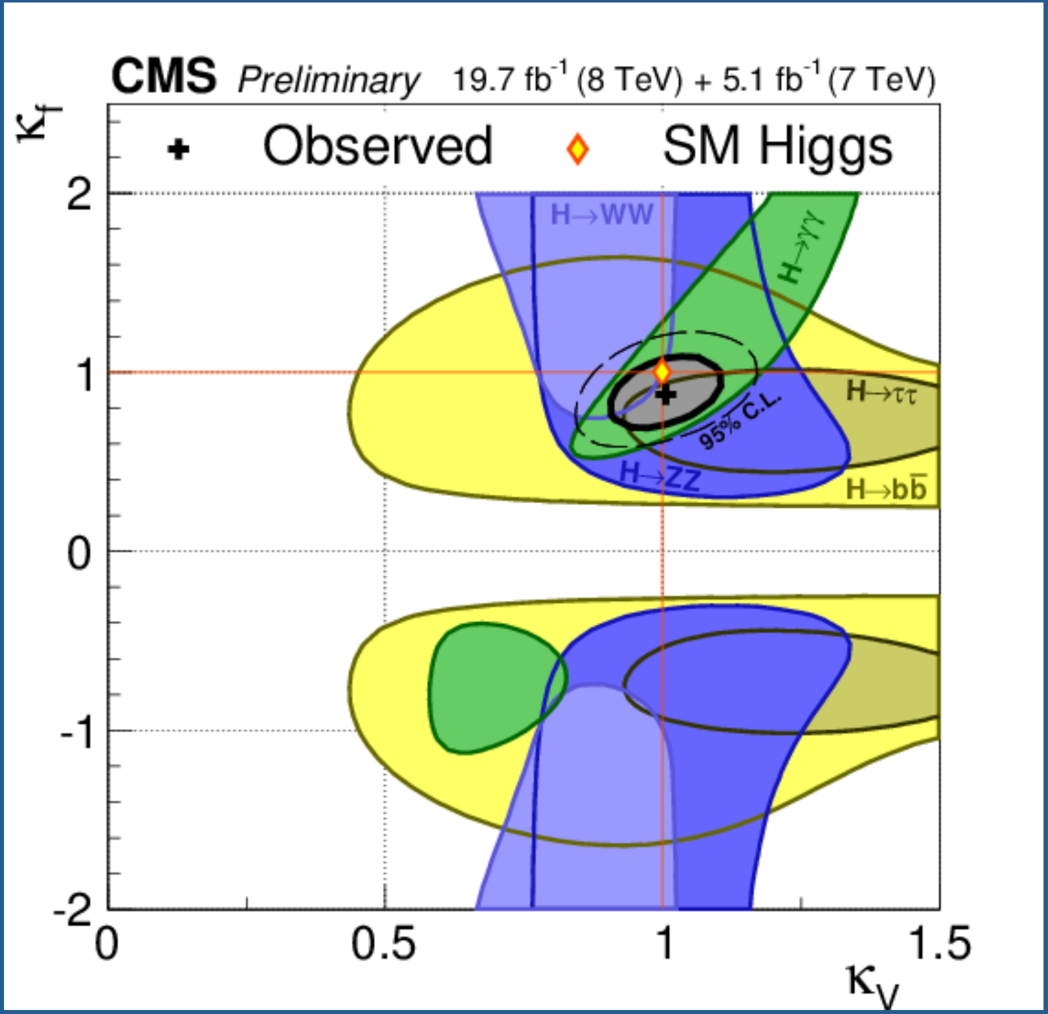
$$g_{HVV} = 2\frac{m_V^2}{v} \qquad g_{Hff} = \frac{m_f}{v}$$

↓

$$g_{HVV} = \kappa_V \left(2\frac{m_V^2}{v}\right) \qquad g_{Hff} = \kappa_f \left(\frac{m_f}{v}\right)$$

- Here assume same κ_V for each vector boson, and same κ_f for all fermions
- $(\kappa_V, \kappa_f) = (1.0, 1.0)$ is the SM
- Data prefers SM-like couplings – agreement within 1σ

CMS-PAS-HIG-14-009



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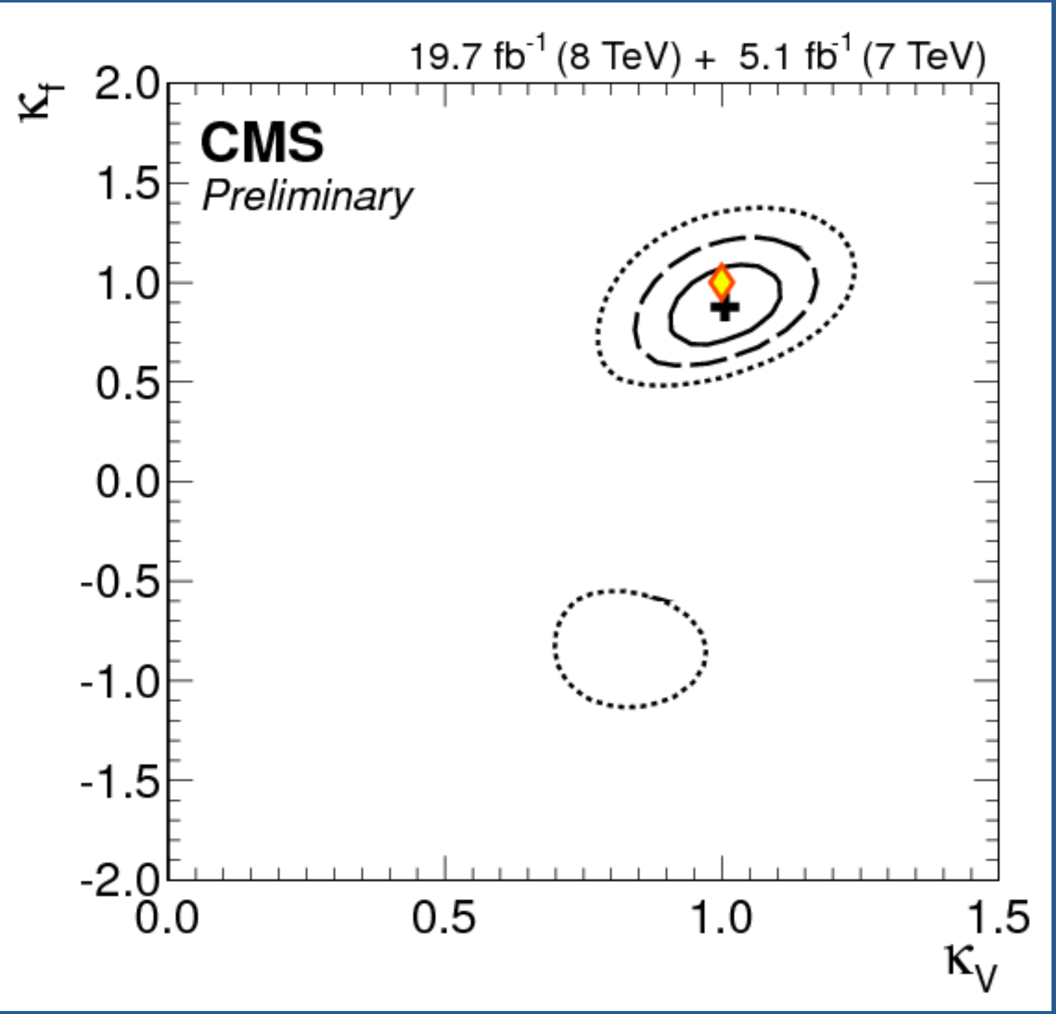

Grand Combination: Couplings to Particles of the SM

- Can test a variety of alternative coupling schemes to probe SM-like nature of this Higgs boson

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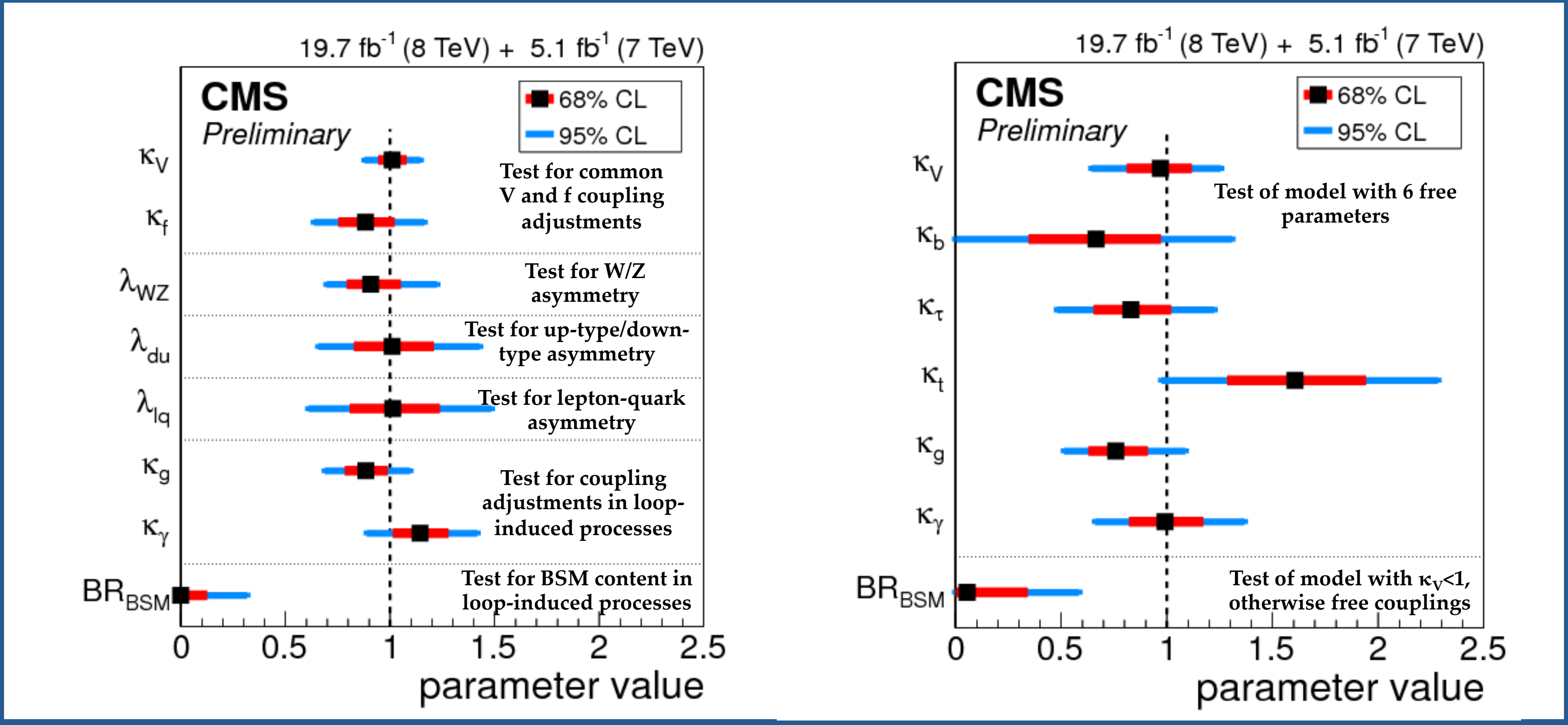


- Tests of all schemes are largely consistent with expectations from the SM
- Interesting:
  - Most general model tested sets limits on BR(H→BSM) < 0.58 at 95% CL
  - Still lots of room for BSM influence in Higgs couplings

More on the Higgs Couplings

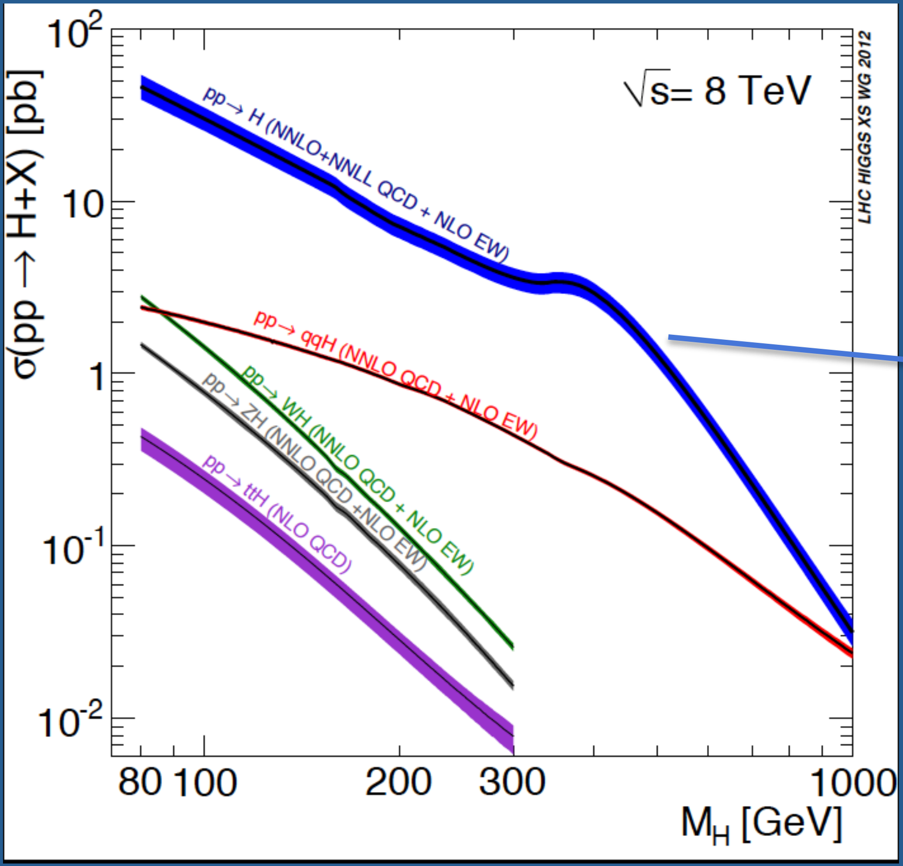
- **Fermionic couplings:**
  - LHC analyses have so far only been able to probe the Yukawa couplings Y_b and Y_τ directly

- Within the SM, the Higgs coupling to the top quark, Y_t, is predicted to be **by far the largest** of all the fermionic couplings
  - Large m_{top} implies relatively large coupling, $Y_t \sim 1$
    - ~x30 larger than Y_b
    - ~x100 larger than Y_τ
  - Strongest coupling among all known SM particles

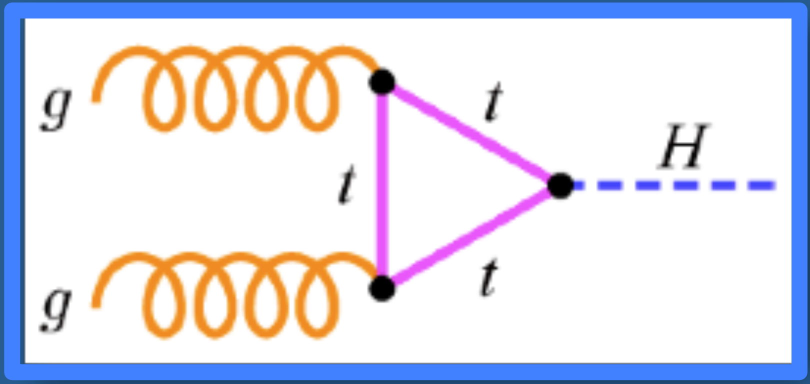
- Also Y_t will be the easiest (and perhaps only) up-type fermion coupling to probe

Imperative:
Absolutely need to measure Y_t directly to know the true nature of the couplings of the new boson.

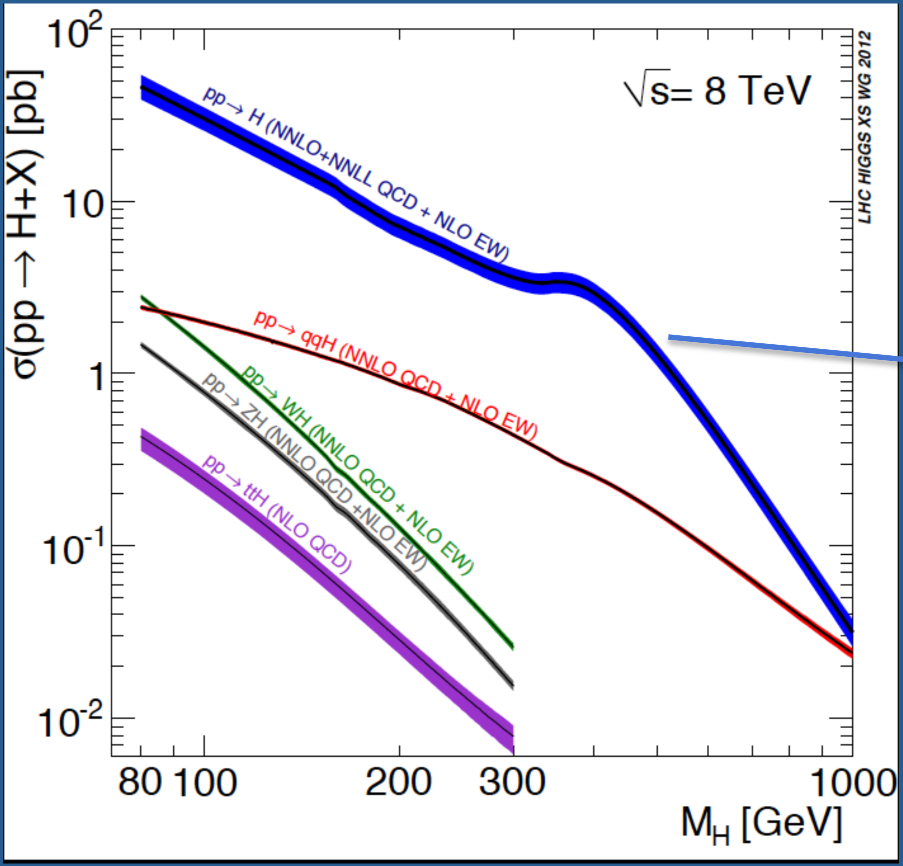
Higgs and Top



- Workhorse analyses already probe the top-Higgs coupling, though there are issues…
- Consider gluon fusion:



Higgs and Top



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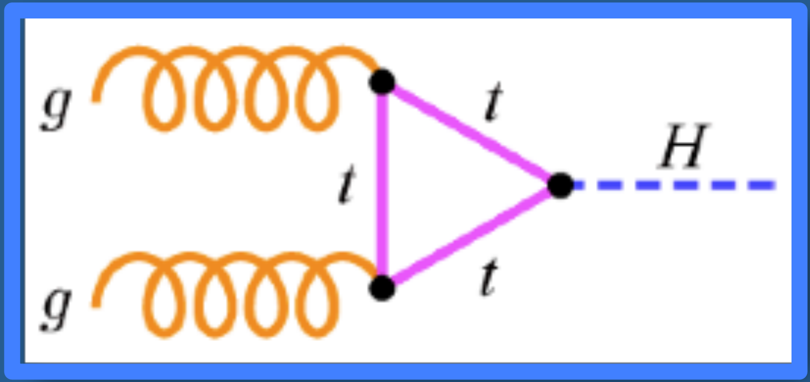
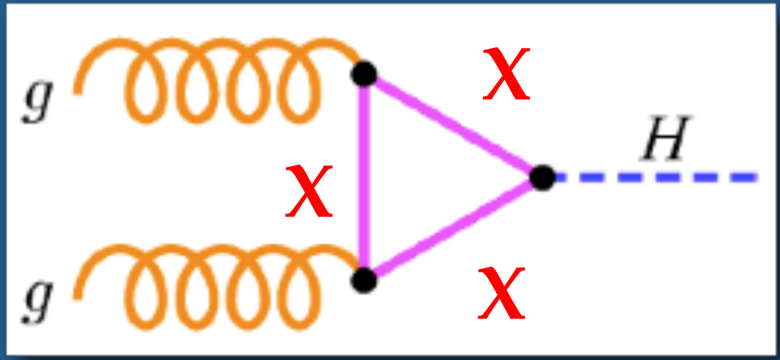
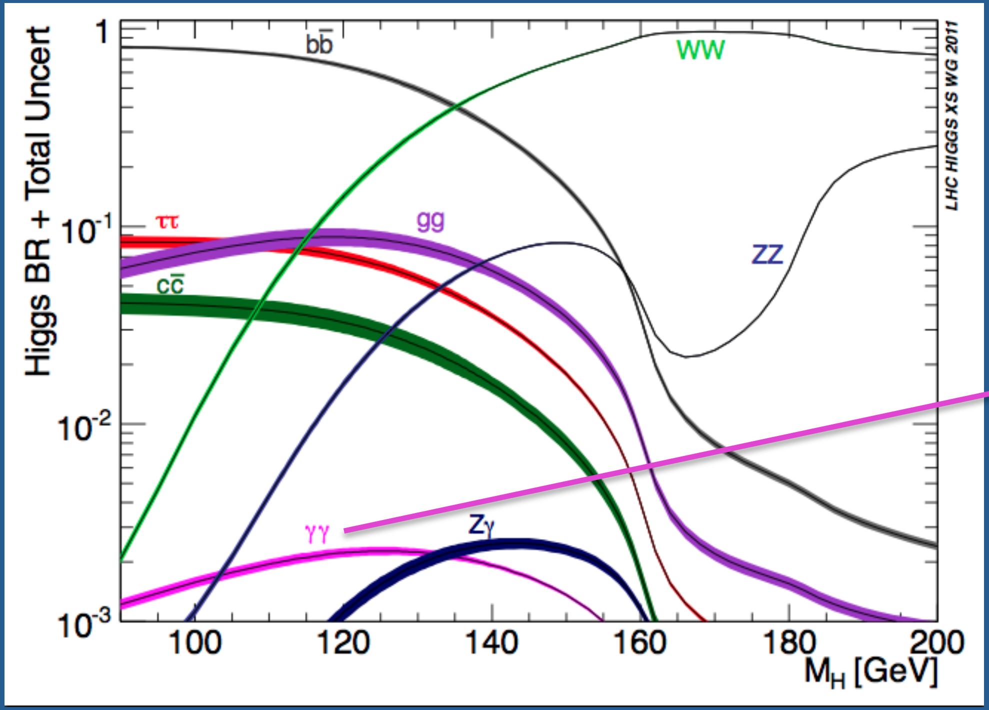


- But what about this?

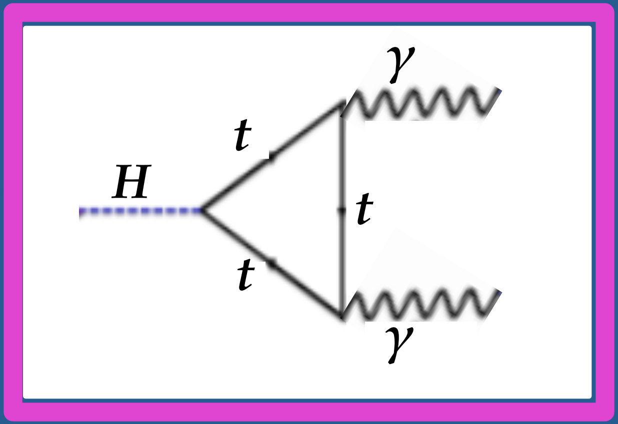


We assume gluon-fusion proceeds through a top-quark loop…but we don't really know!

Higgs and Top



- Similar problems on the decay side:



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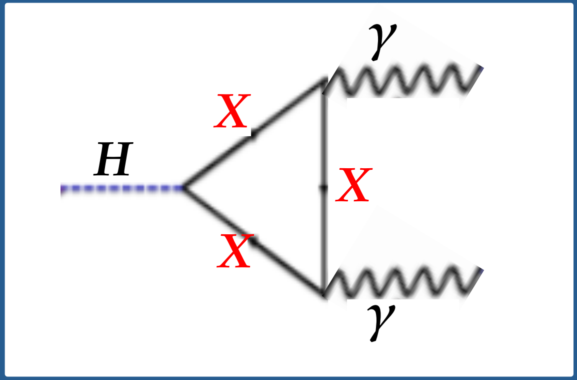
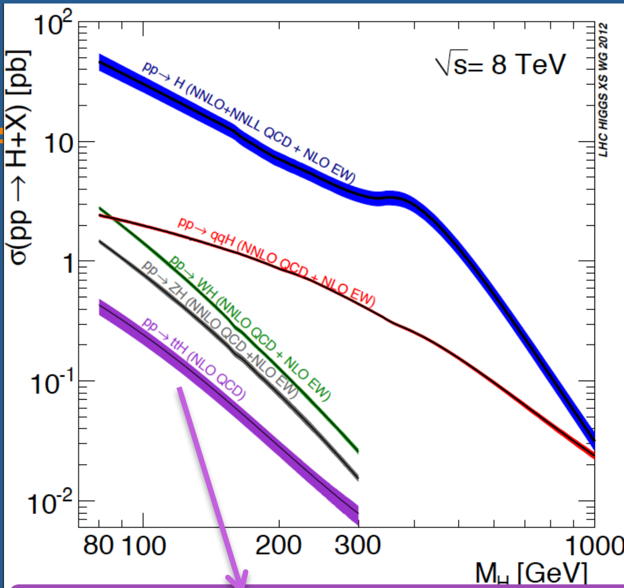
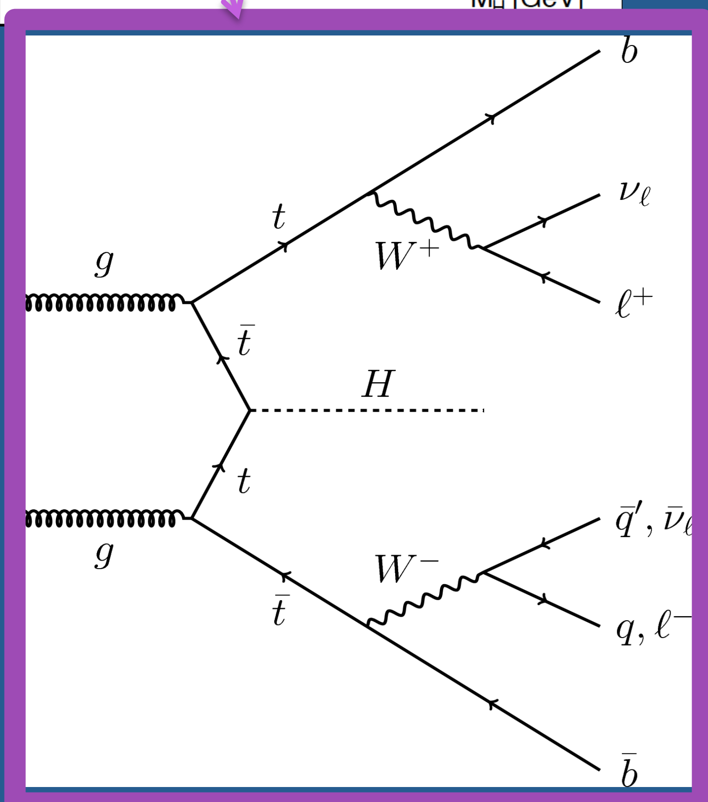


The results of the CMS grand combination say that the new boson has couplings that "are SM-like".

To really know what is going on, **we need a direct probe** of the top-Higgs coupling…





Y_t : Experimental Challenges

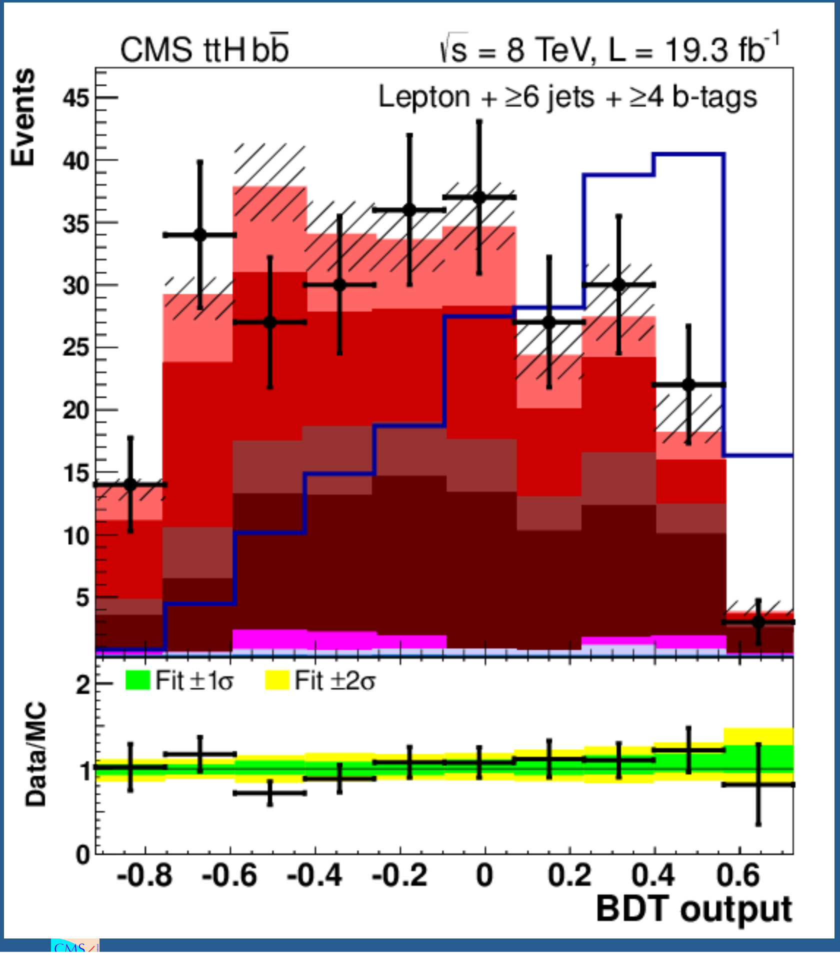
- Unlike b's and τ's, top-Higgs coupling not accessible through Higgs decay
  - Only insight comes from production-side dynamics
- Best chance: Higgs production in association with a top-quark pair
  - Comparatively small production cross section wrt other Higgs production channels
  - Spectacular signature – rich final state
- ttH production cross section dwarfed by main background, tt+jets:

root(s) [TeV]	7	8	14
σ (ttH (125)) [fb]	86	129	611
σ (tt+jets) [fb]	177000	253000	950000

Search for ttH Production, H→bb with BDTs

- Focus on two primary channels:
  - **Single-lepton channel:** one high p_T isolated e/μ, ≥4 jets, ≥2 b tags
  - **Dilepton channel:** two opposite-sign leptons, ≥2 jets, ≥2 b tags
- Backgrounds: a considerable problem
  - Irreducible: tt+b-jets
    - Poorly known, both theoretically and experimentally
  - Experimental:
    - False-positive b-tags in tt+LF-jets
- Split selected events into categories based on jet, b-tag multiplicities
- Exploit BDT discriminant in each category for signal extraction
- Perform simultaneous fit across all categories

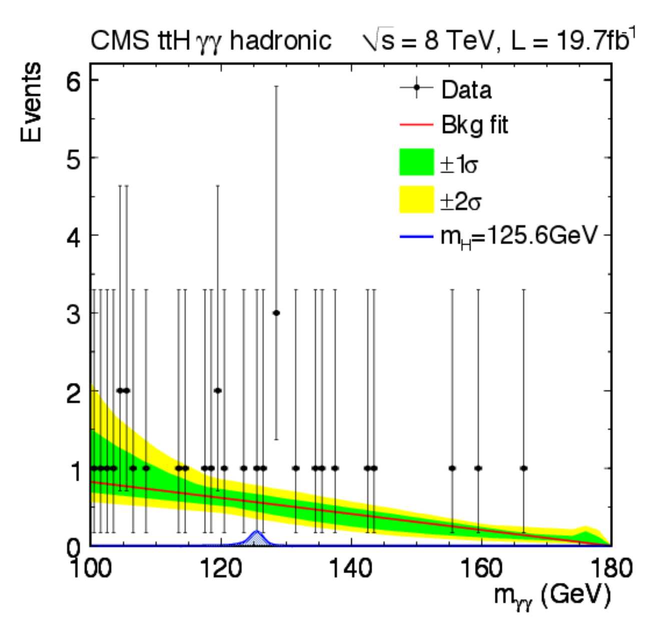
BDT inputs, discriminating signal from bkgd:
- Object kinematics
- Multi-object characteristics
- Angular variables
- Qualities of b-tagged jets
  - continuous b-tag discriminant

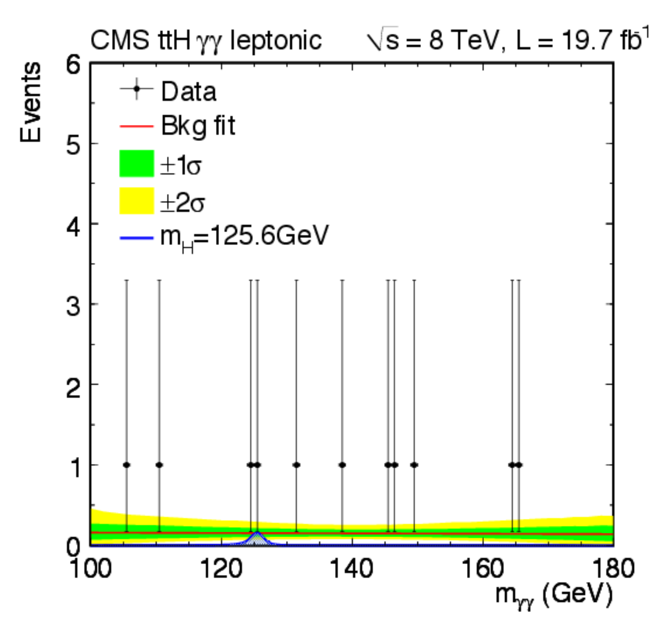


arXiv:1408.1682, Accepted by JHEP

Search for ttH Production, H→γγ

- Very low-rate process but
  - low background
  - distinctive diphoton peak $M_{\gamma\gamma} \sim M_H$
- Event selection:
  - Two reconstructed high p_T photons
  - Leptonic ttbar category:
    - ≥1 isolated high p_T e/μ
    - ≥2 high p_T jets, ≥1 b-tagged jet
  - Hadronic ttbar category:
    - ==0 e/μ
    - ≥5 high p_T jets, ≥1 b-tagged jet
- Look for a resonance in $M_{\gamma\gamma}$
  - Describe background as a falling exponential

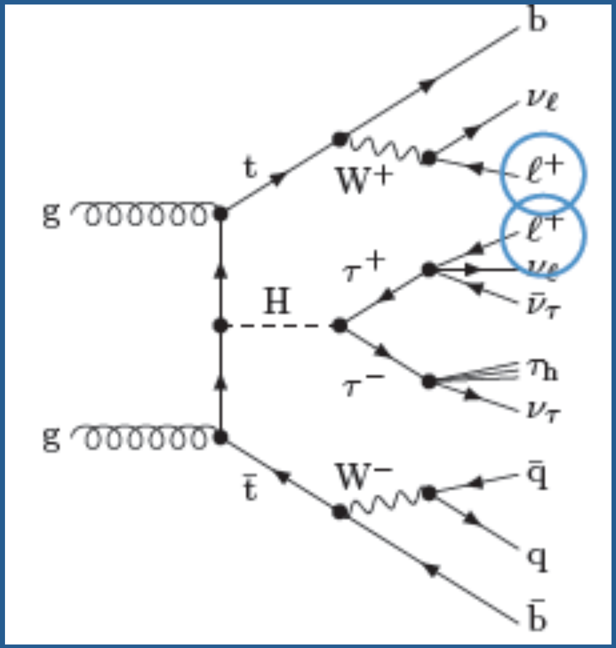




Search for ttH Production, H→Multileptons

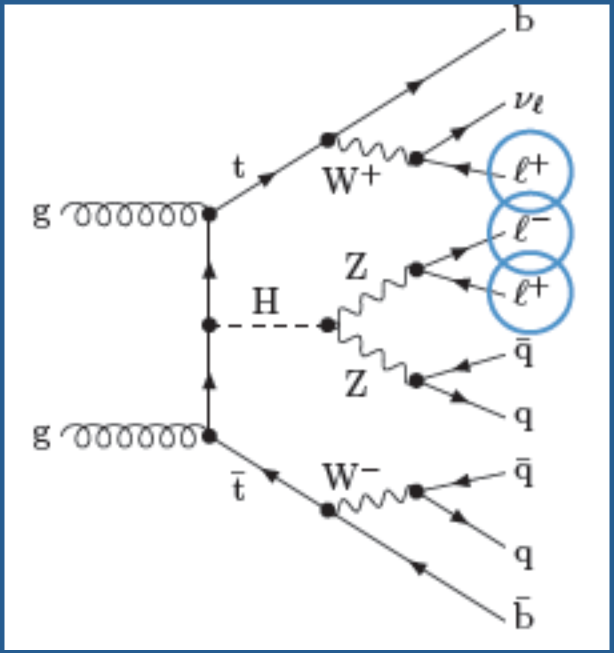
Same-sign dilepton

2 e/μ with $p_T > 20$
≥4 jets with $p_T > 25$
≥1 b-tagged jet



Three lepton

1 e/μ with $p_T > 20$
1 e/μ with $p_T > 10$
1 e(μ) with $p_T > 7(5)$
≥2 jets with $p_T > 25$
≥1 b-tagged jet
Veto $M_{ll} \sim M_Z$



Four lepton

1 e/μ with $p_T > 20$
1 e/μ with $p_T > 10$
2 e(μ) with $p_T > 7(5)$
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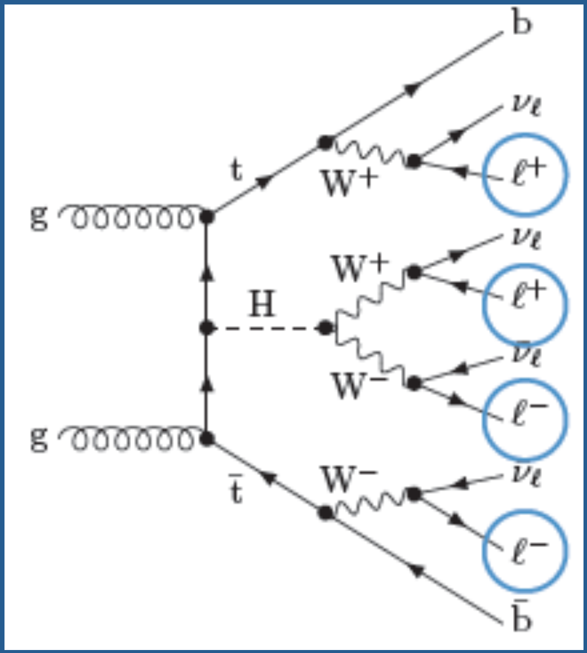


Low-rate but low-background signatures.

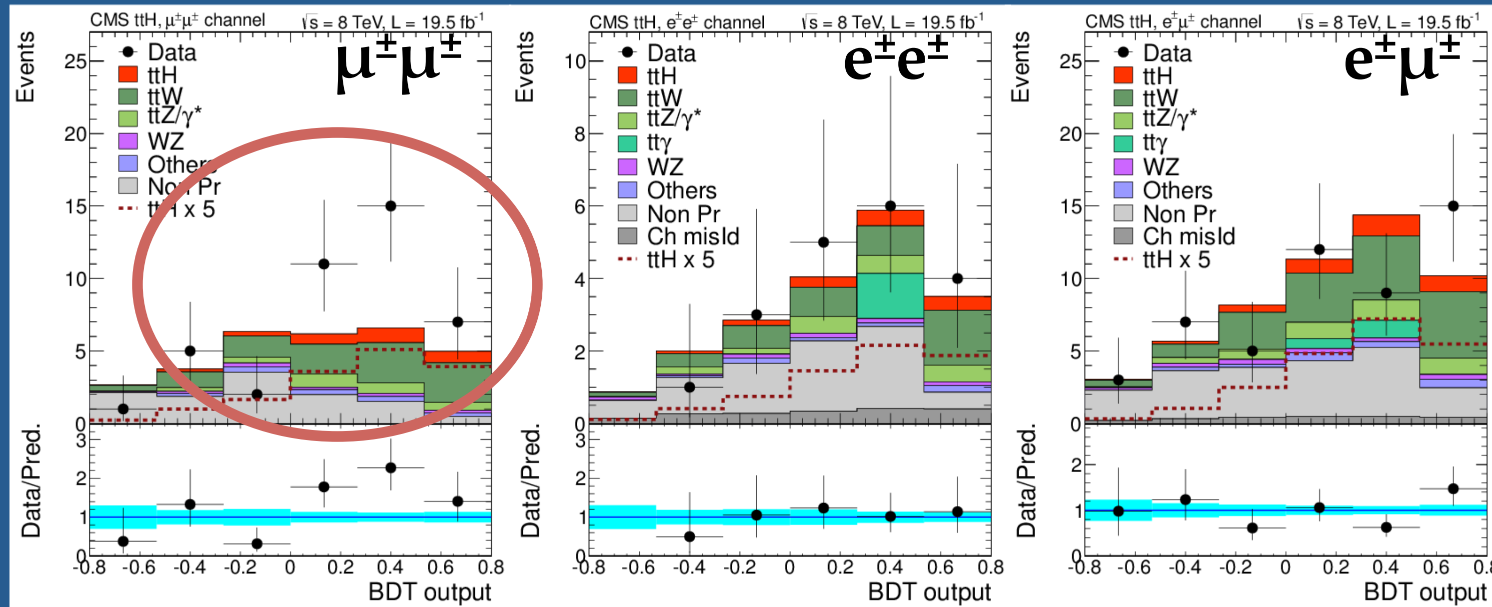
Search for ttH Production, H→Multileptons

Expected and observed yield in 19.6/fb at 8 TeV

	ee	$e\mu$	$\mu\mu$	3ℓ	4ℓ
$t\bar{t}H$, $H \to WW$	1.0 ± 0.1	3.2 ± 0.4	2.4 ± 0.3	3.4 ± 0.5	0.29 ± 0.04
$t\bar{t}H$, $H \to ZZ$	—	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H$, $H \to \tau\tau$	0.3 ± 0.0	1.0 ± 0.1	0.7 ± 0.1	1.1 ± 0.2	0.15 ± 0.02
$t\bar{t}\,W$	4.3 ± 0.6	16.5 ± 2.3	10.4 ± 1.5	10.3 ± 1.9	—
$t\bar{t}\,Z/\gamma^*$	1.8 ± 0.4	4.9 ± 0.9	2.9 ± 0.5	8.4 ± 1.7	1.12 ± 0.62
$t\bar{t}\,WW$	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\,\gamma$	1.3 ± 0.3	1.9 ± 0.5	—	2.6 ± 0.6	—
WZ	0.6 ± 0.6	1.5 ± 1.7	1.0 ± 1.1	3.9 ± 0.7	—
ZZ	—	0.1 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.47 ± 0.10
Rare SM bkg.	0.4 ± 0.1	1.6 ± 0.4	1.1 ± 0.3	0.8 ± 0.3	0.01 ± 0.00
Non-prompt	7.6 ± 2.5	20.0 ± 4.4	11.9 ± 4.2	33.3 ± 7.5	0.43 ± 0.22
Charge misidentified	1.8 ± 0.5	2.3 ± 0.7	—	—	—
All signals	1.4 ± 0.2	4.3 ± 0.6	3.1 ± 0.4	4.7 ± 0.7	0.54 ± 0.08
All backgrounds	18.0 ± 2.7	49.3 ± 5.4	27.7 ± 4.7	59.8 ± 8.0	2.07 ± 0.67
Data	19	51	41	68	1

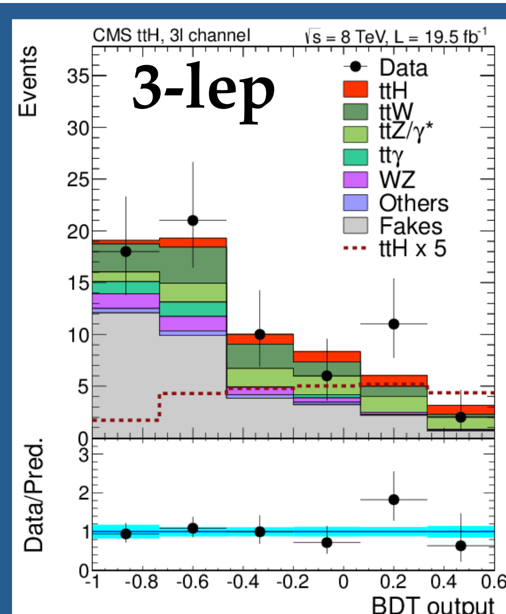
- Signal dominated in each category by H→WW mode
- Significant excess over expectation in SS 2lep μμ channel

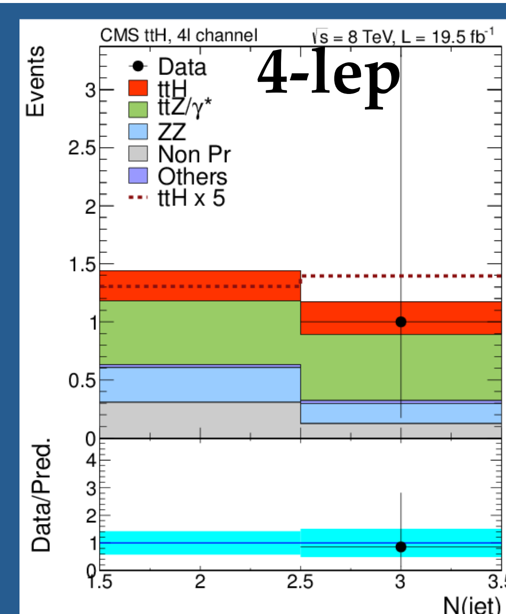
Search for ttH Production, H→Multileptons



Signal extraction:

- BDT used in SS 2-lep and 3-lep categories
- N_{jets} alone used for 4-lep category
- Excess in μμ channel

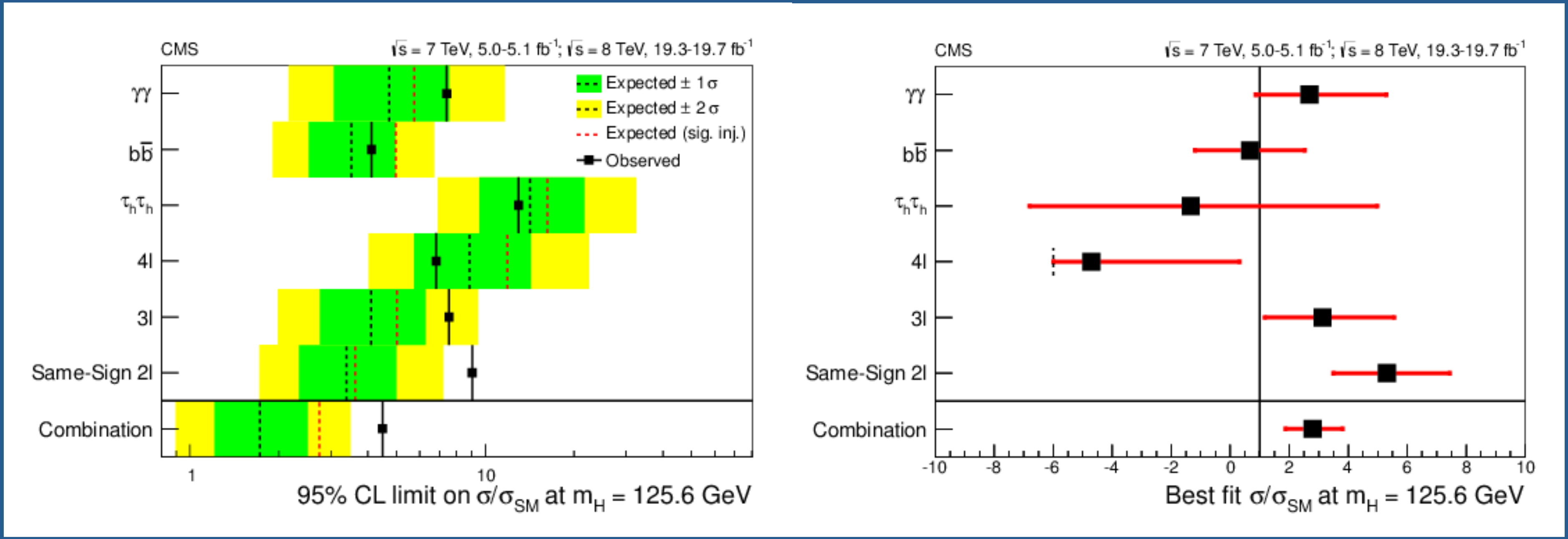




arXiv:1408.1682, Accepted by JHEP

Search for ttH Production: All Channels

arXiv:1408.1682, Accepted by JHEP

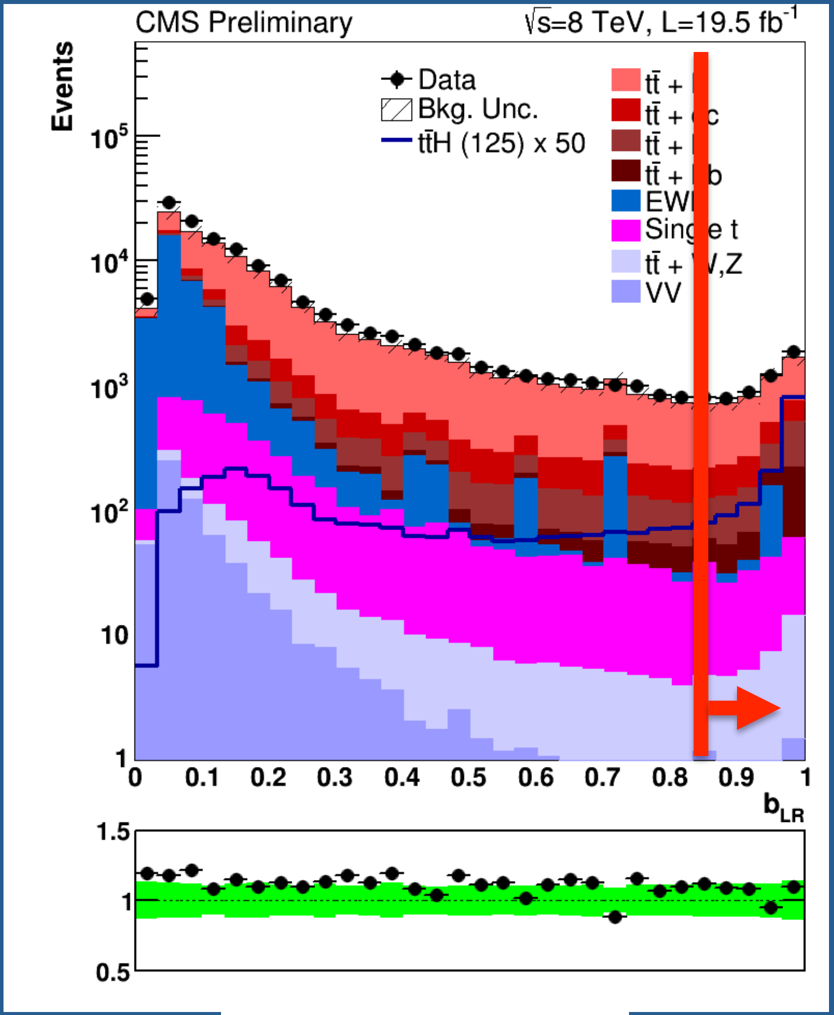


- Suite of ttH analyses not yet achieving sensitivity to level of ttH production predicted in the SM
- Place instead upper limits on the amount of ttH in the observed data
  - $\mu = \sigma/\sigma_{SM} < 2.7$ (4.5) expected (observed) at 95% CL
    - Driven by excess in SS dilepton channel
- Given the excess, data naturally prefers more signal than predicted by the SM
  - Combined $\mu = 2.8^{+1.0}_{-0.9}$ at 68% CL

ttH, H→bb with MEM

CMS-HIG-14-010

- Matrix-element method (MEM) provides a powerful device for signal discrimination
  - Integrate over unreconstructed or poorly measured particles
  - Marginalize over unknown quark-to-jet assignments
  - Assign event weight under ttH or tt+bb hypotheses
- Consider just events in which the S or B interpretation is feasible:
  - 1 lepton, ≥5 jets
  - 2 leptons, ≥4 jets
- Alternative event-level likelihood ratio b-jet ID selection



$$b_{LR} \equiv \frac{\mathcal{L}_{bbbb}}{\mathcal{L}_{bbbb} + \mathcal{L}_{bbjj}}.$$

ttH, H→bb with MEM

CMS-HIG-14-010

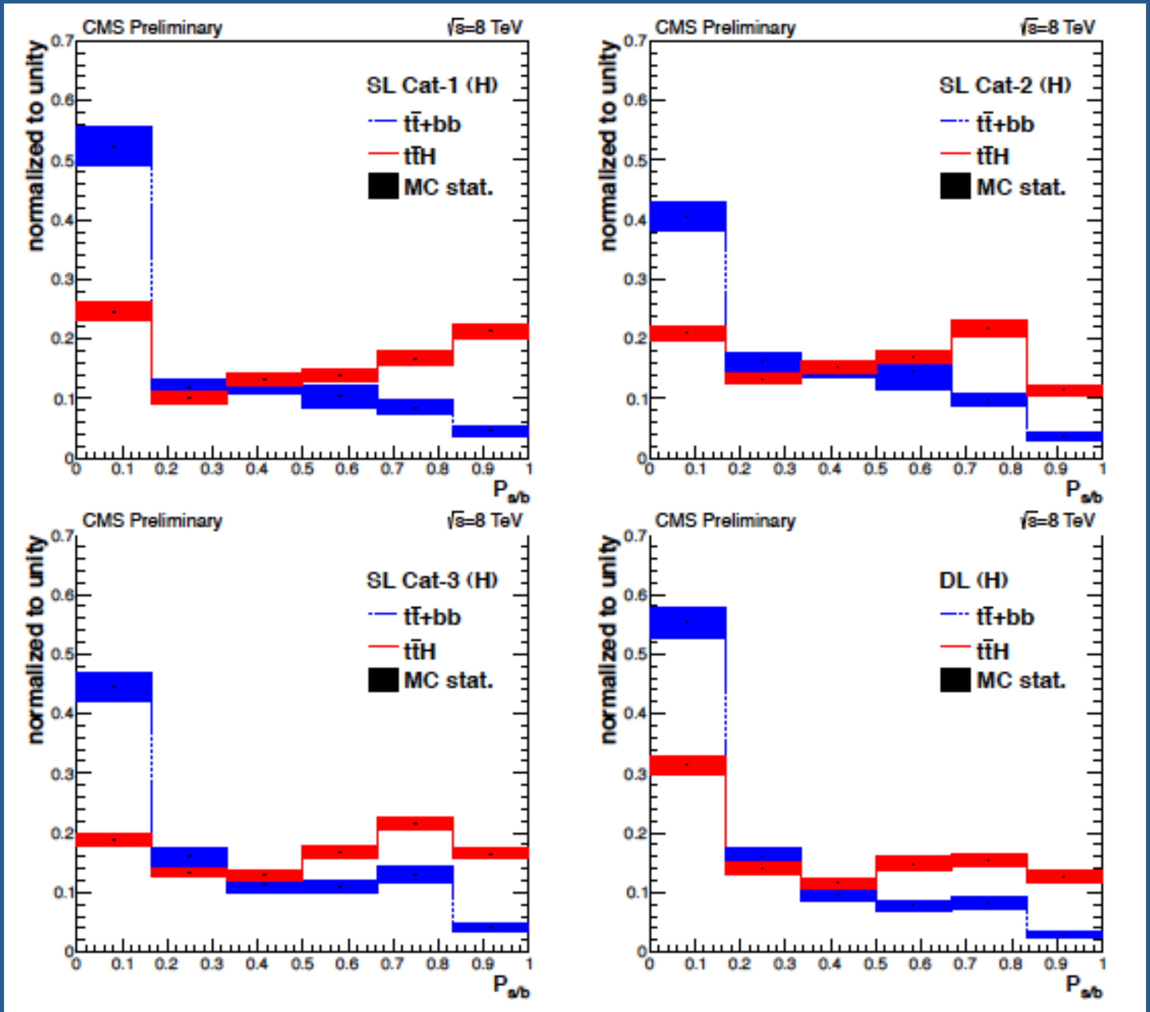
SL Cat 1 tt → blv bqq All quarks reconstructed	**SL Cat 2** tt → blv bq q + g All quarks reconstructed – except for one W daughter – and ≥1 gluon
SL Cat 3 tt → blv bq q All quarks reconstructed – except for one W daughter	**DIL** tt → blv blv All quarks reconstructed

- Categorize events according to what is reconstructed in the event – rather than just

  N_{jets} and N_{tags}

ttH, H→bb with MEM

CMS-HIG-14-010



- Categorize events according to what is reconstructed in the event – rather than just

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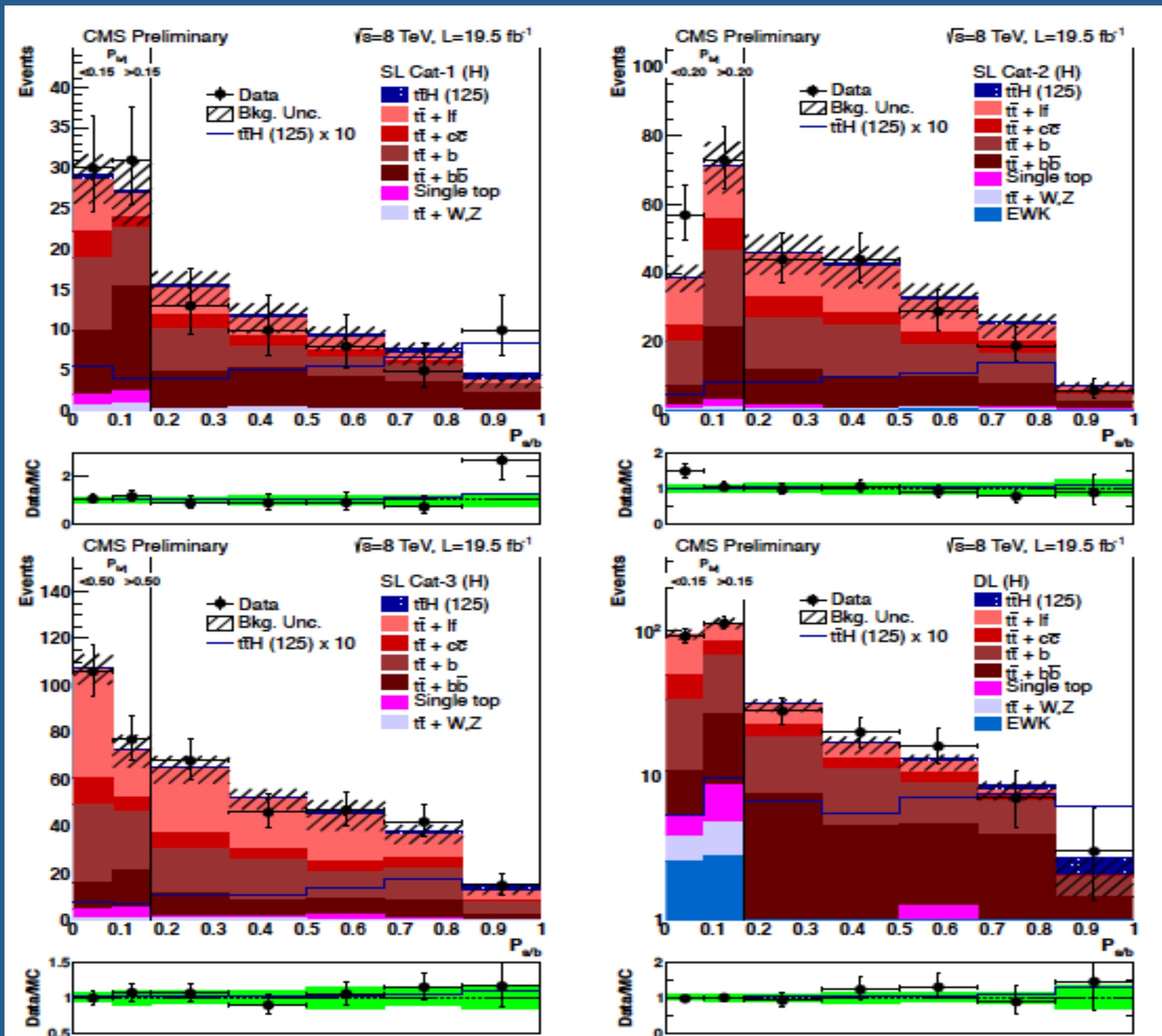
- Build probability densities for S,B from ME and likelihood used in b_{LR}
- **Final discriminant:**

  $P_{s/b}$ = ratio of ttH, ttbb probabilities

  - Good a priori separation

ttH, H→bb with MEM

CMS-HIG-14-010



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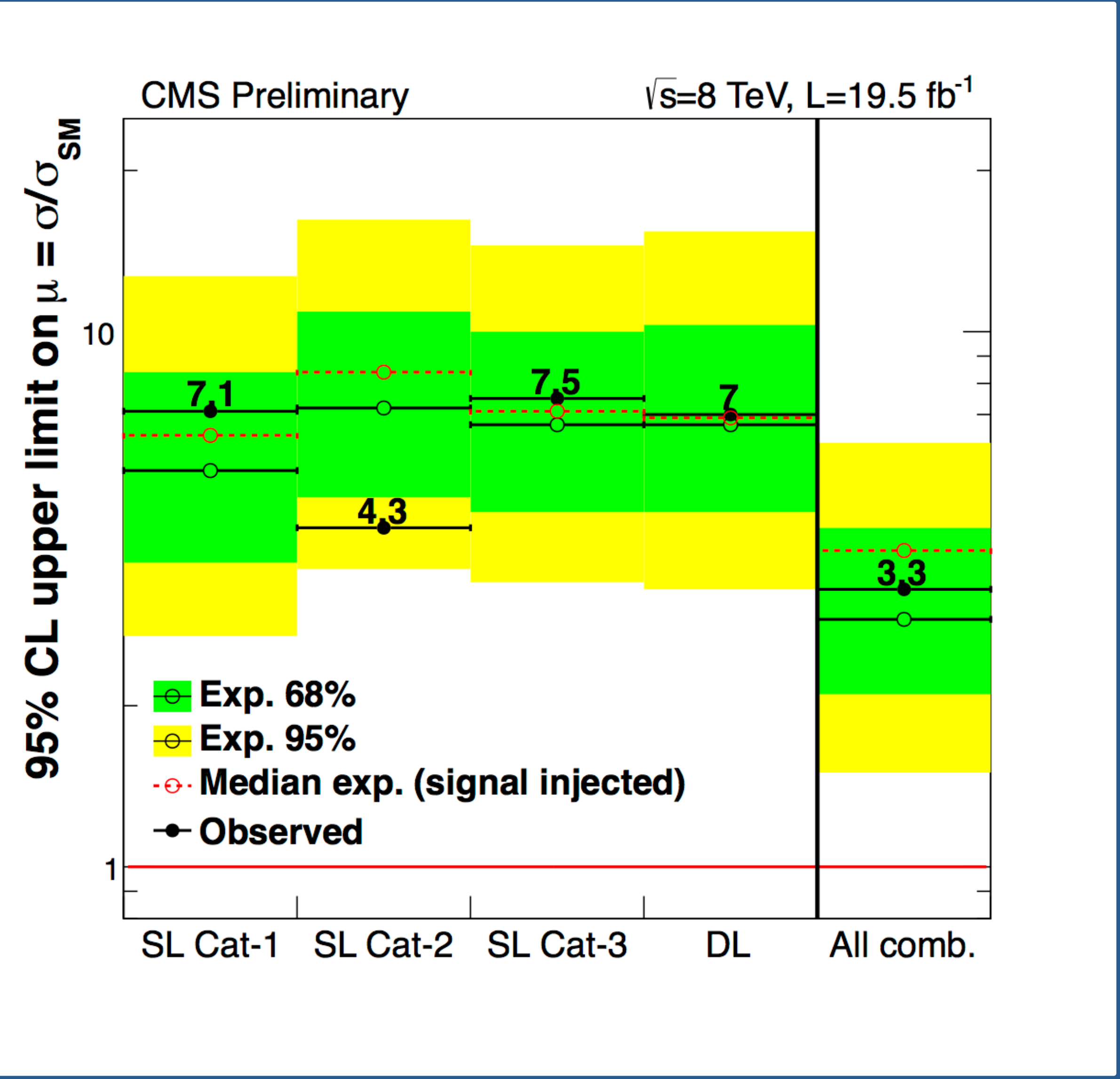
ttH, H→bb with MEM

CMS-HIG-14-010



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- **Final discriminant:**

  $P_{s/b}$ = ratio of ttH, ttbb probabilities
  - Good a priori separation
  - Well-behaved in data

- Perform simultaneous fit across categories and set upper limits

Characterizing the Higgs Boson: Spin and Parity

- The Higgs boson of the SM is a CP-even scalar, $J^P = 0^+$

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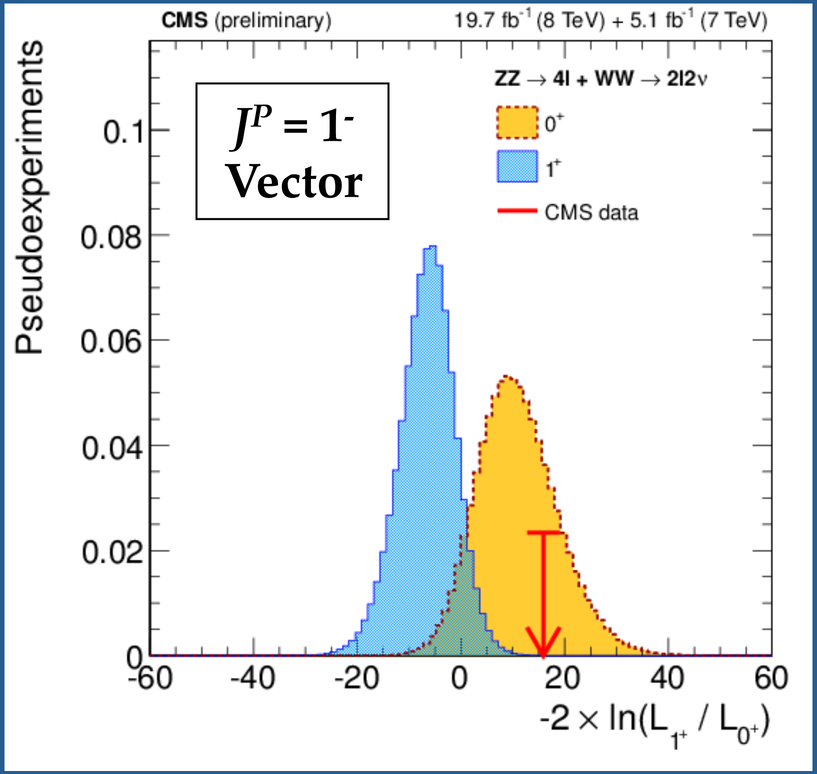
    - Spin 1 hypothesis disfavored by observation of H→γγ, but tested anyways

CMS-HIG-14-014



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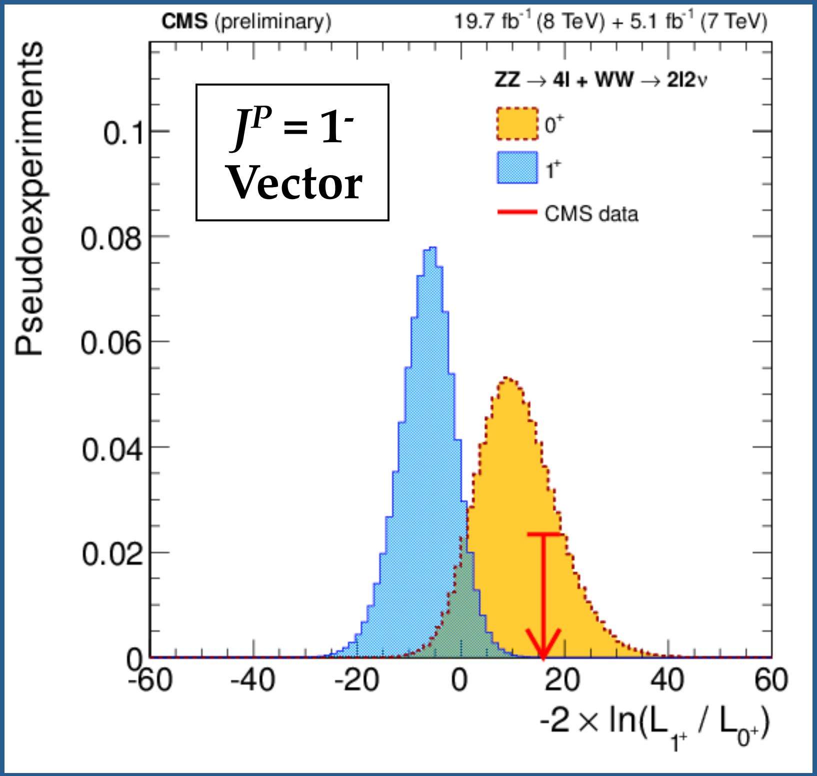
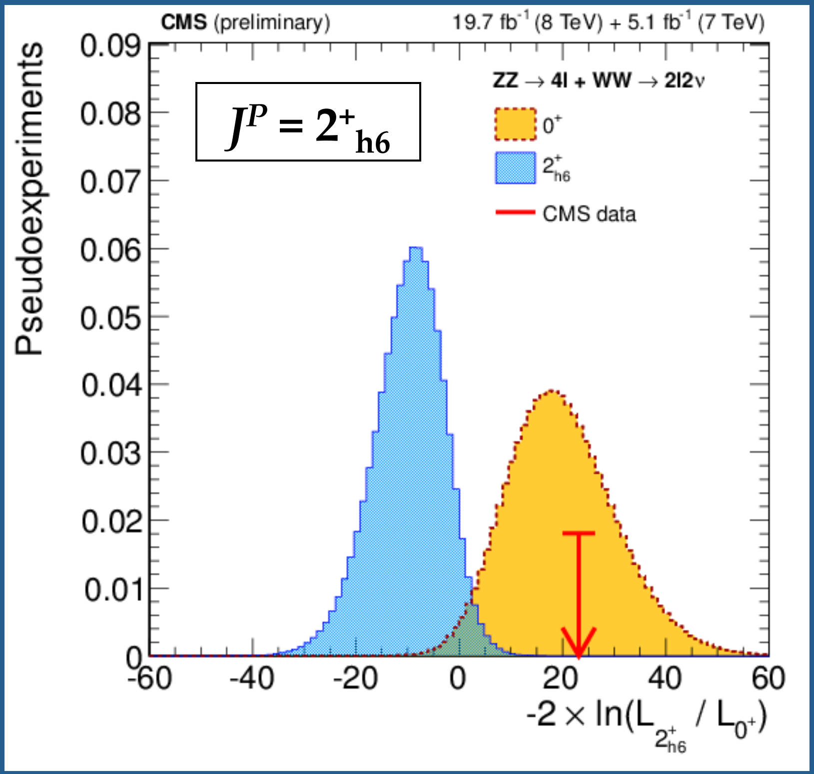
  - The spin and parity influence the Higgs decay kinematics
  - Alternative spin-parity models can be tested
    - Spin 1 hypothesis disfavored by observation of H→γγ, but tested anyways
    - No known fundamental particle has spin 2. Many models predict them, however.

CMS-HIG-14-014





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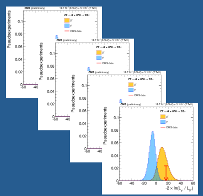
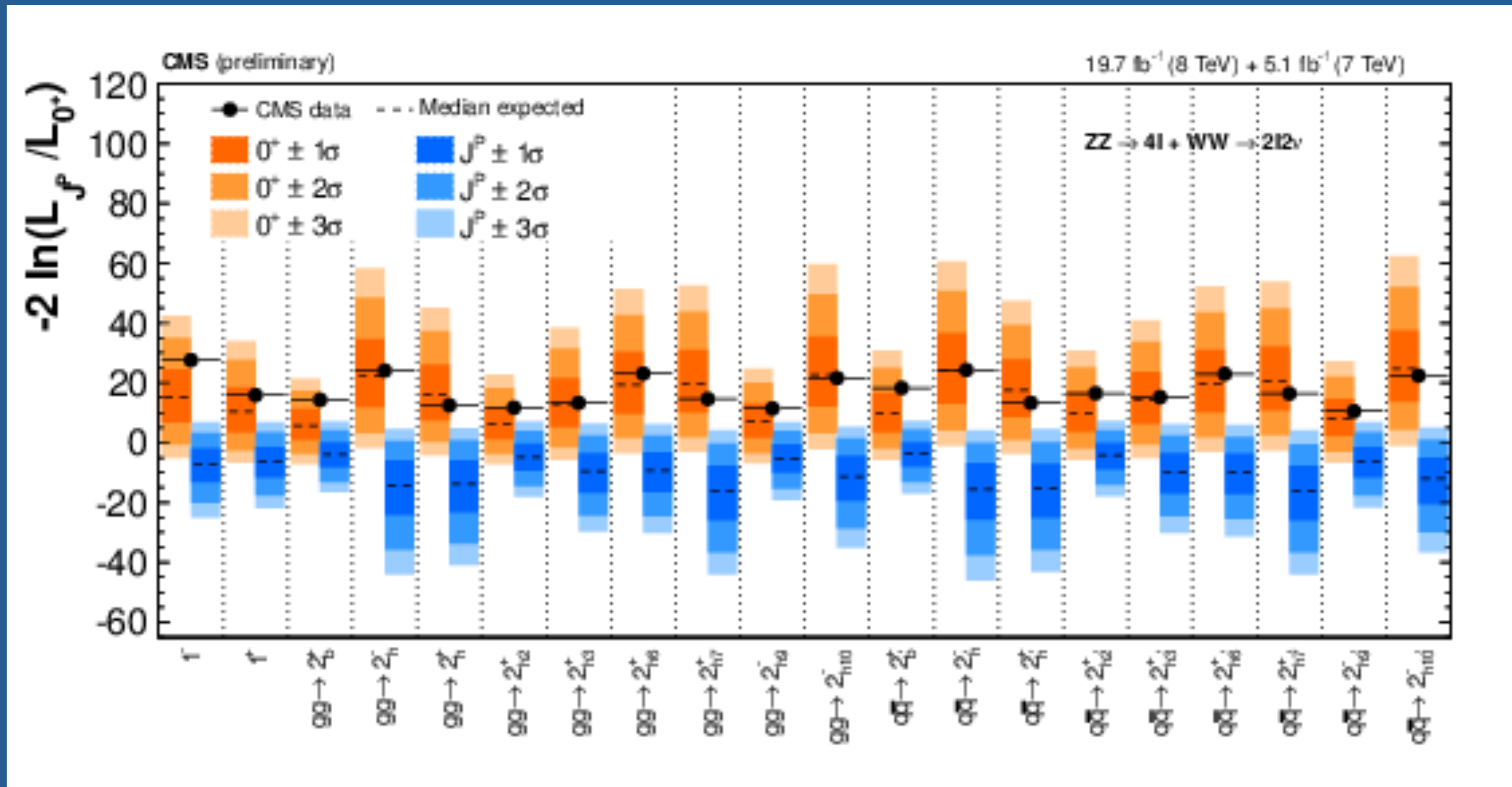


CMS-HIG-14-014



- $J^P = 0^-, 1^\pm, 2$ excluded at 99% CL

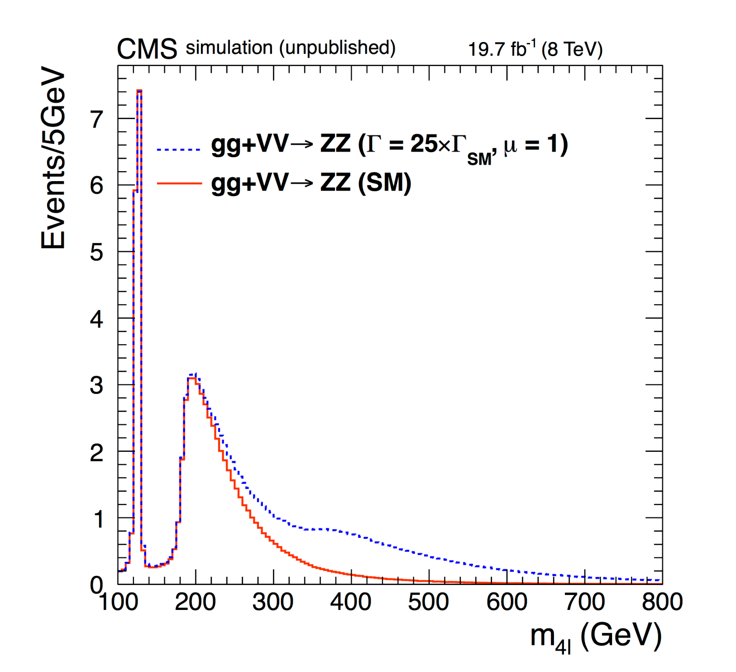
Characterizing the Higgs Boson: Width

- The narrow width approximation is not really adequate for H→ZZ

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}.$$

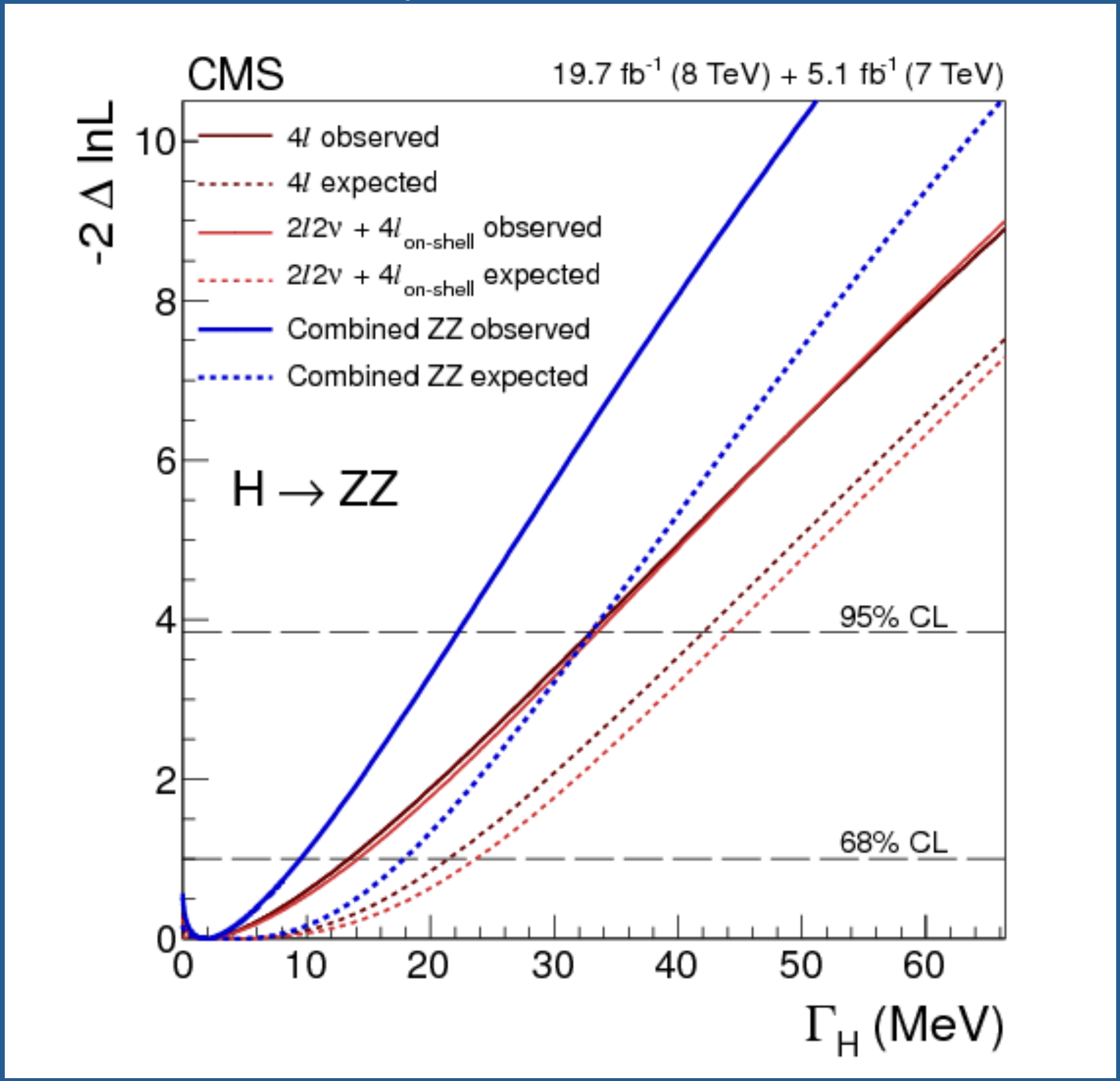


Phys. Lett.B 736 (2014)64

- Off-shell contribution is sizable
  - For $m_{ZZ} > 2\ m_Z$, the contribution is ~8%
- Can derive information on the Higgs width from on-shell / off-shell ratio

Characterizing the Higgs Boson: Width

Phys. Lett.B 736 (2014)64



- Combination of $H \rightarrow ZZ \rightarrow 4l\pm$ and $H \rightarrow ZZ \rightarrow 2l2\nu$ channels
- Results:

$\Gamma_H < 22$ MeV at 95%CL

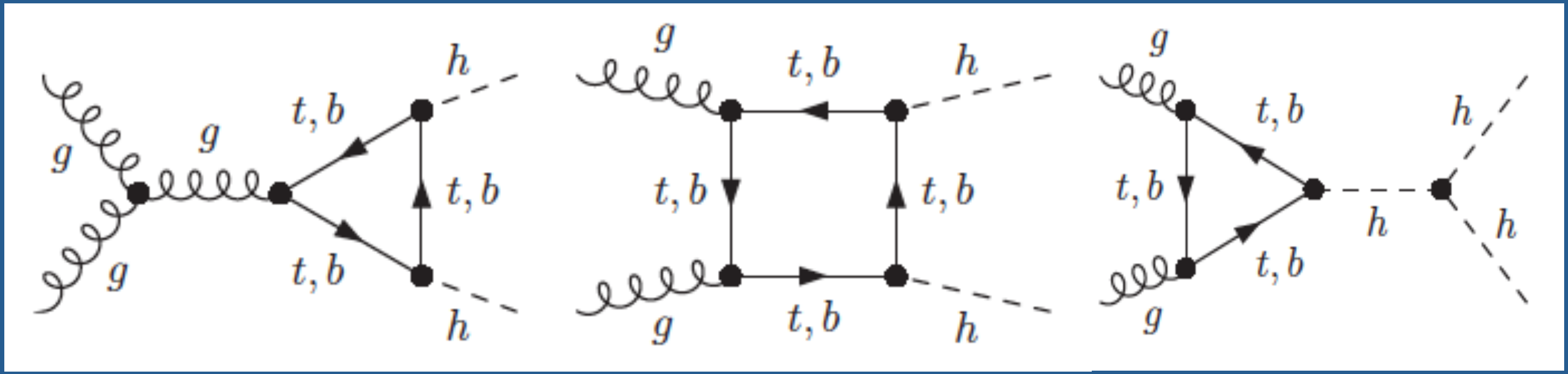
or, more clearly

$\Gamma_H / \Gamma_{SM} < 5.4$ at 95%CL

These results are ~100 times more precise than previous Higgs width limits.

Characterizing the Higgs Boson: Self-Coupling

http://arxiv.org/pdf/1206.5001v2.pdf



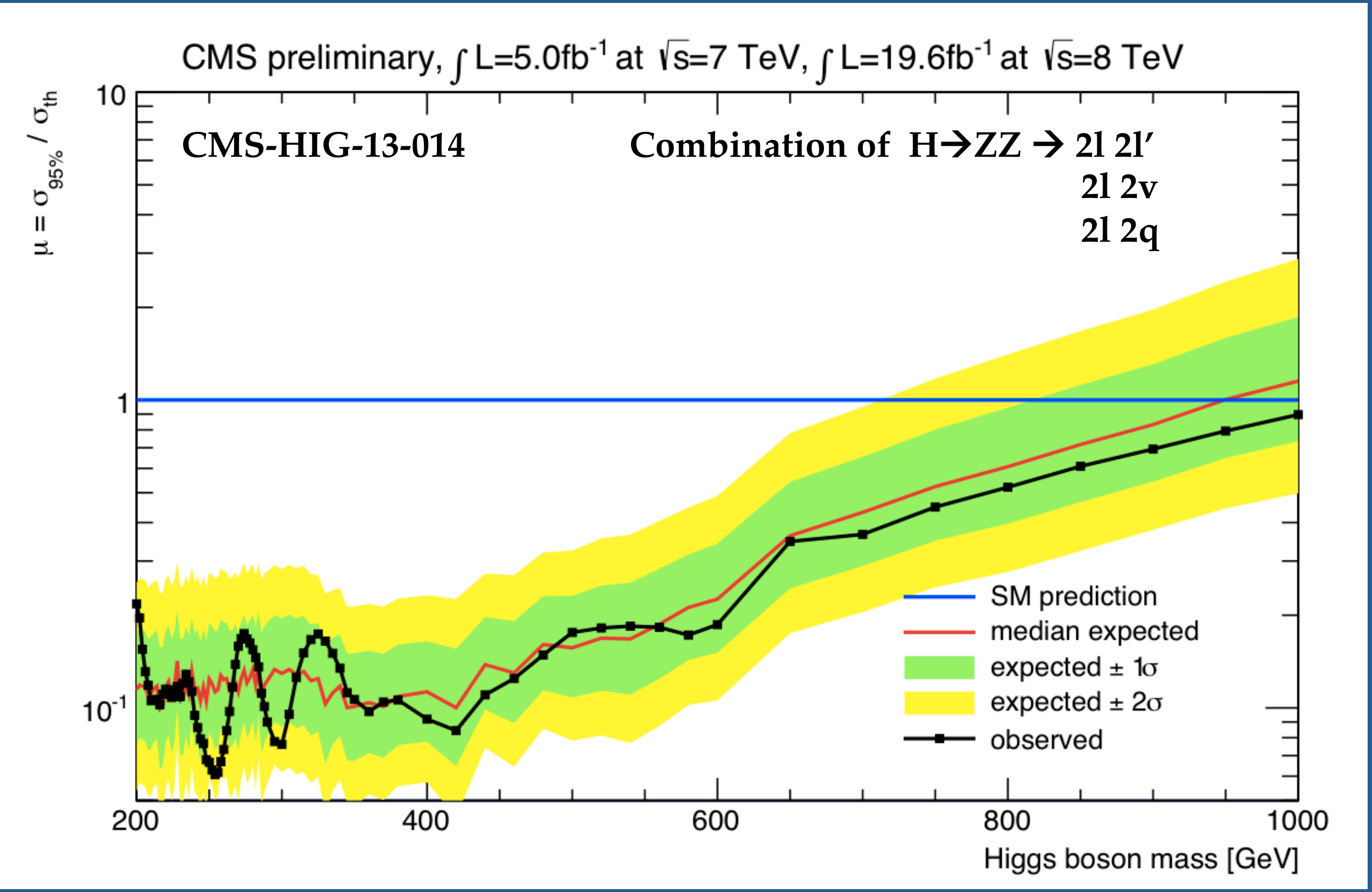
- Ultimate characterization will come through examination of the Higgs self-coupling
- Accessible through Higgs pair production searches
  - Very low production cross section
- Need significant increase in integrated luminosity:
  - **High-luminosity LHC era**

- In Run 1 era, can look for Higgs pair production in resonance searches
  - more on this in a few slides…

Are there other Higgs Bosons?

Search for Heavy SM-Like Higgs Bosons

- Several high-mass Higgs searches have been performed
- Look for SM-like Higgs production
- Exploit H→ZZ and H→WW decay modes (dominant at large m_H)



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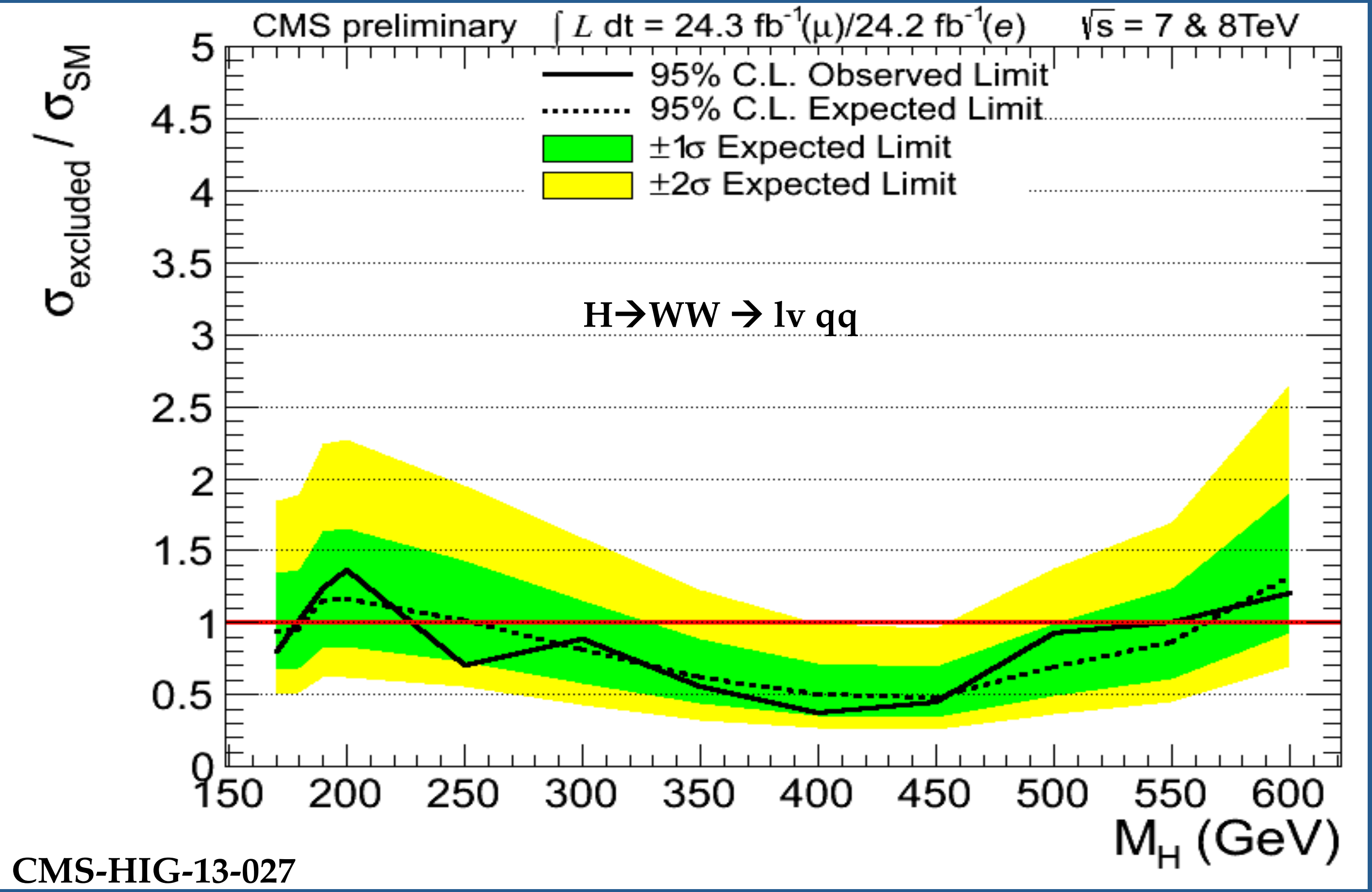
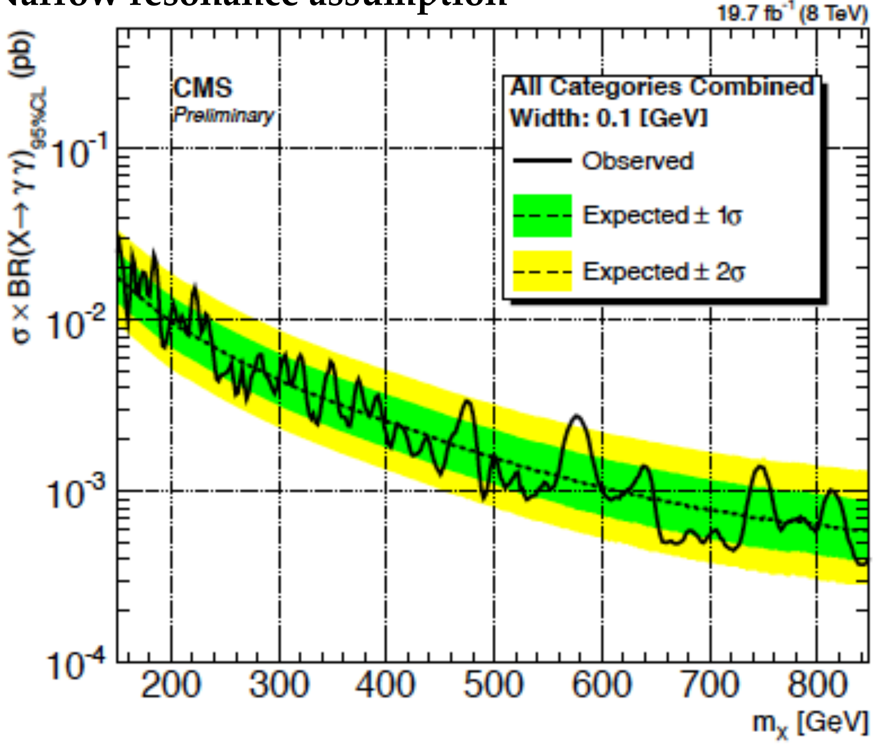


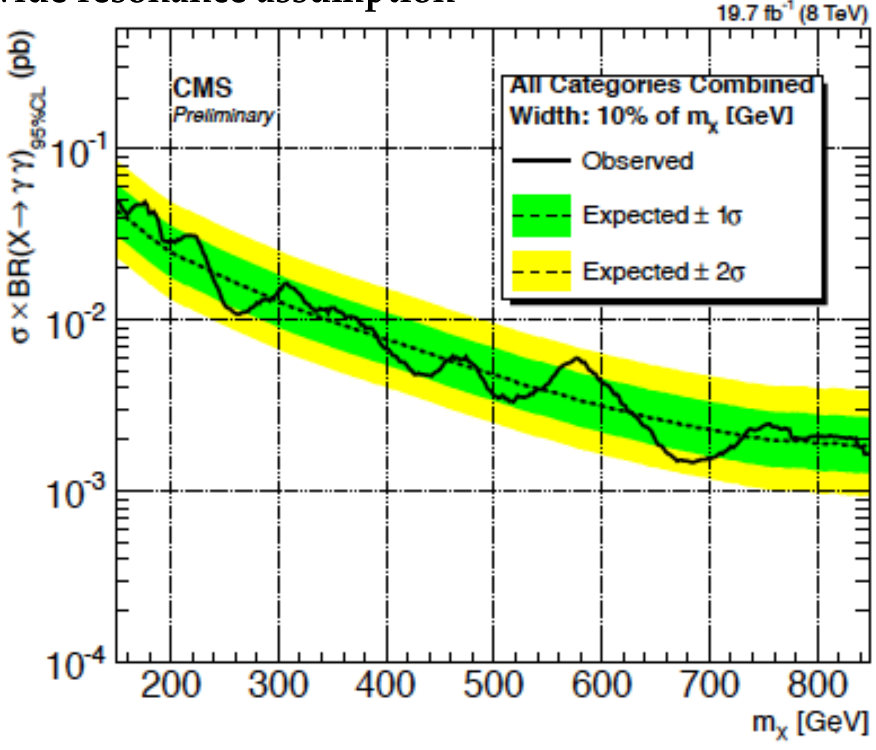
High-Mass Resonance Search in Diphoton Signature

CMS-HIG-14-006

Narrow resonance assumption



Wide resonance assumption

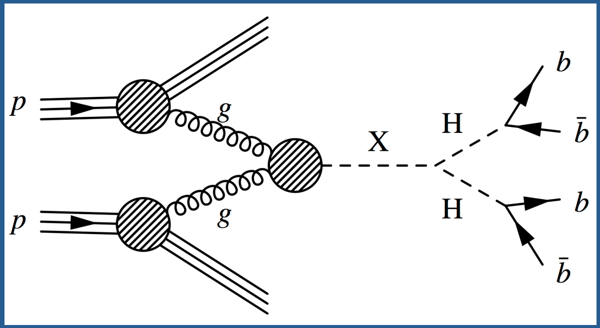


- Several BSM models predict high mass Higgs states
- Good mass resolution in diphoton signature allows for resonance scans

Is this Higgs a Window to New Physics?

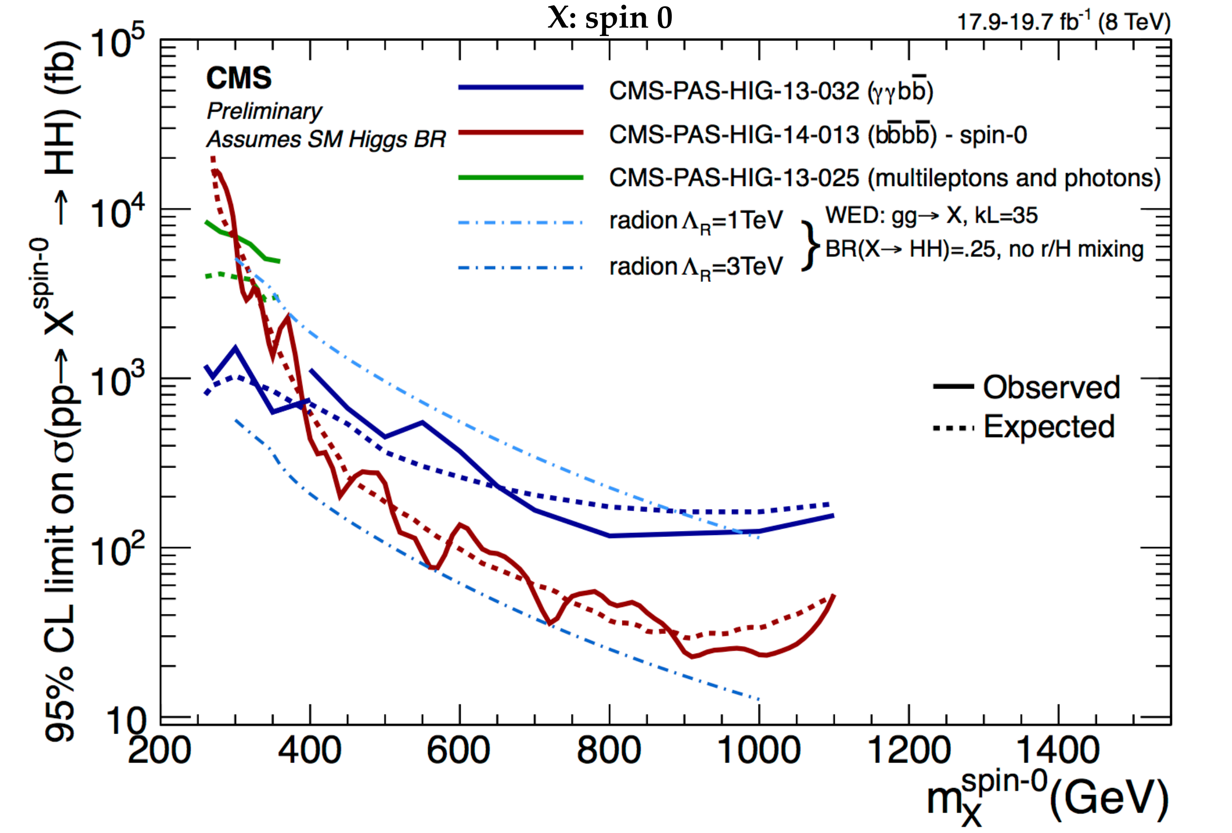
Search for Di-Higgs Production

- Recall, the Higgs self-coupling is an important remaining piece of the characterization campaign
  - Need the Run 2 dataset



- In the meantime, we can look for high mass BSM particles decaying to pairs of Higgs bosons

- Three such analyses at CMS
  - X→HH→bbγγ
  - X→HH→bbbb
  - X→HH→multileptons, photons



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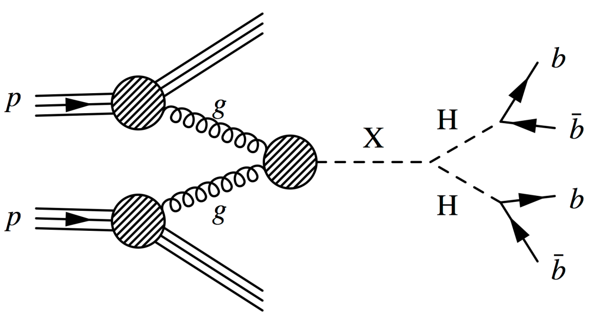

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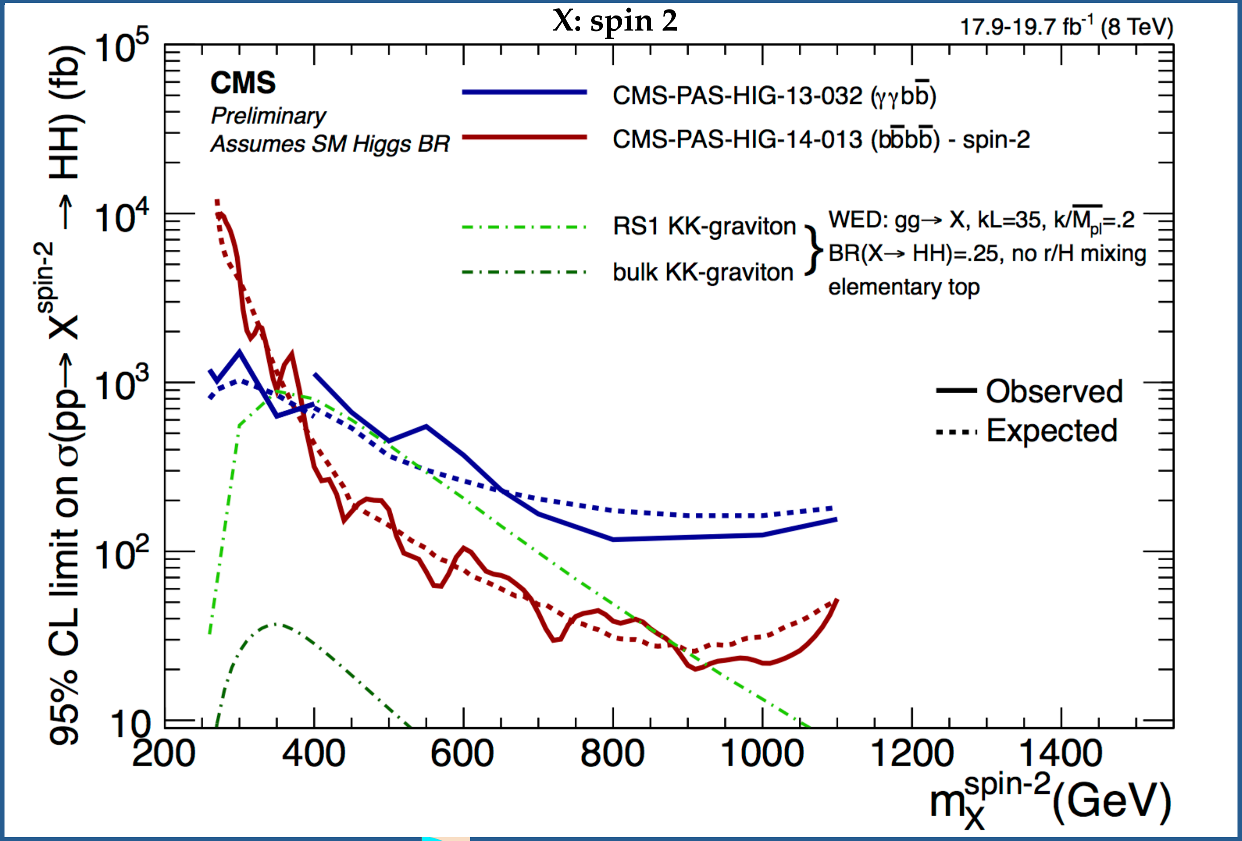
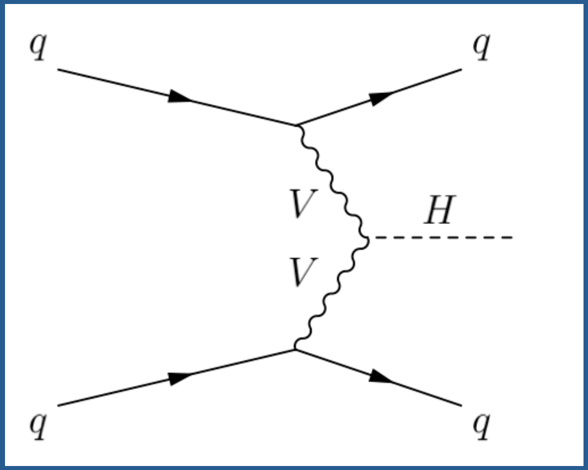


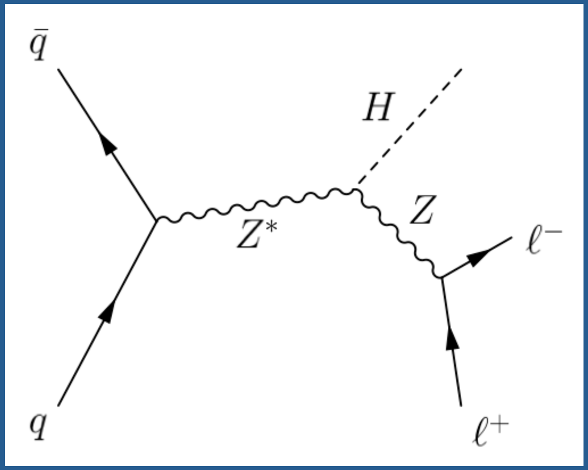
Search for Invisibly Decaying Higgs

- Since the Higgs couples to mass, it could decay to non-interacting massive particles that escape the detector without a trace: Examples:
  - The neutralino of SUSY if LSP
  - Dark matter particles – Higgs could be the conduit between SM and DM
- Signature characterized by large missing E_T
- Search performed in three channels exploiting VBF and ZH Higgs production

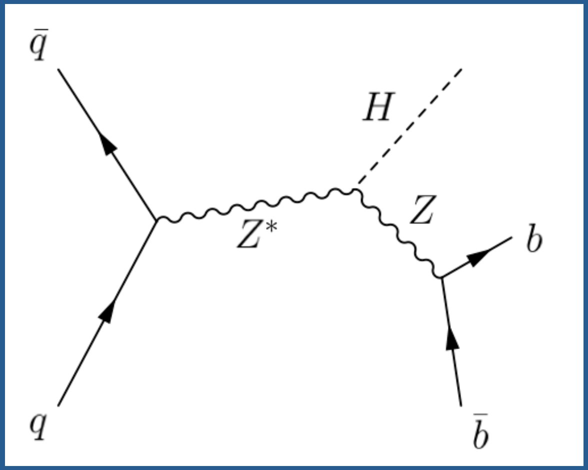
Vector Boson Fusion



Z (ll) H



Z (bb) H



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- Signature characterized by large missing E_T
- Search performed in three channels exploiting VBF and ZH Higgs production
- Different discriminating variables used in each case

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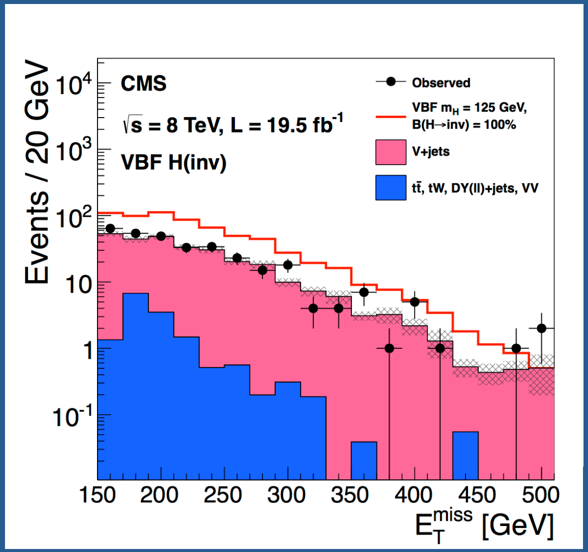
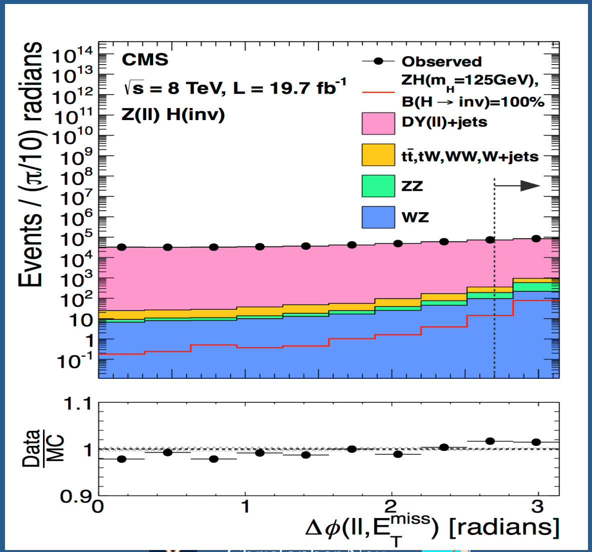


Z (ll) H



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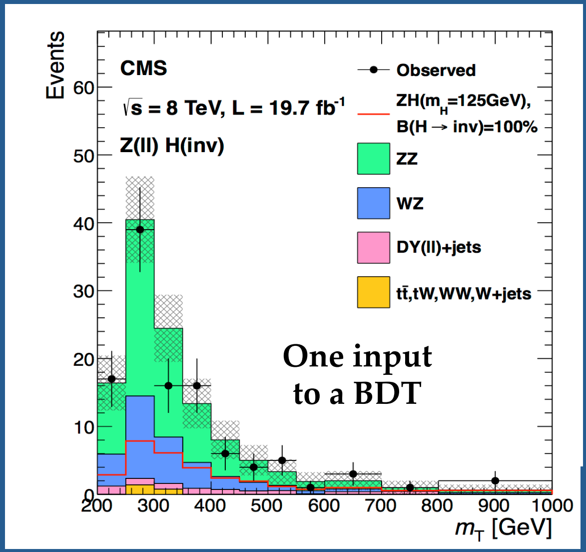
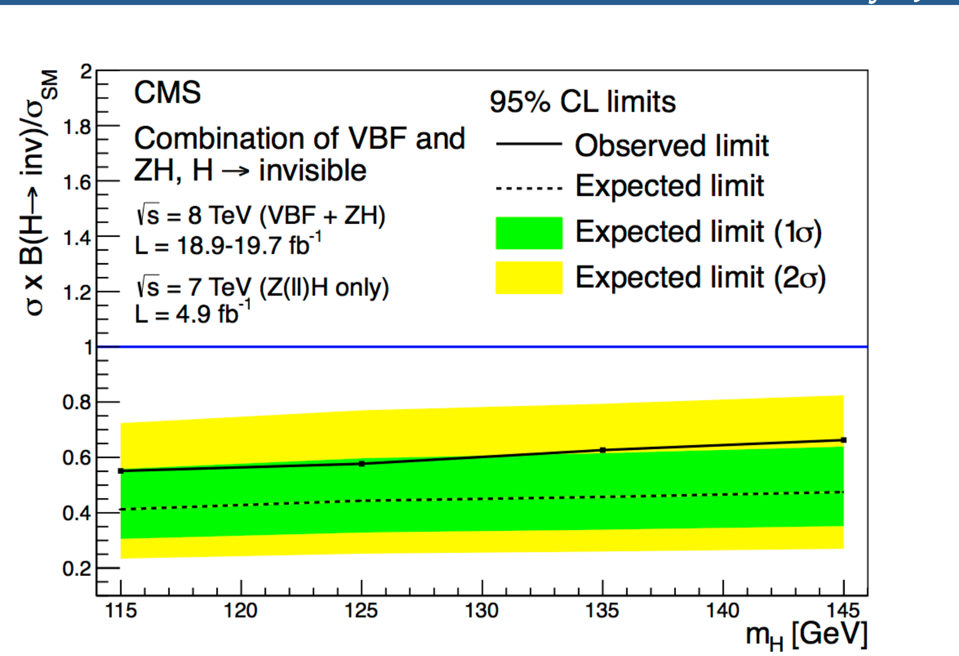
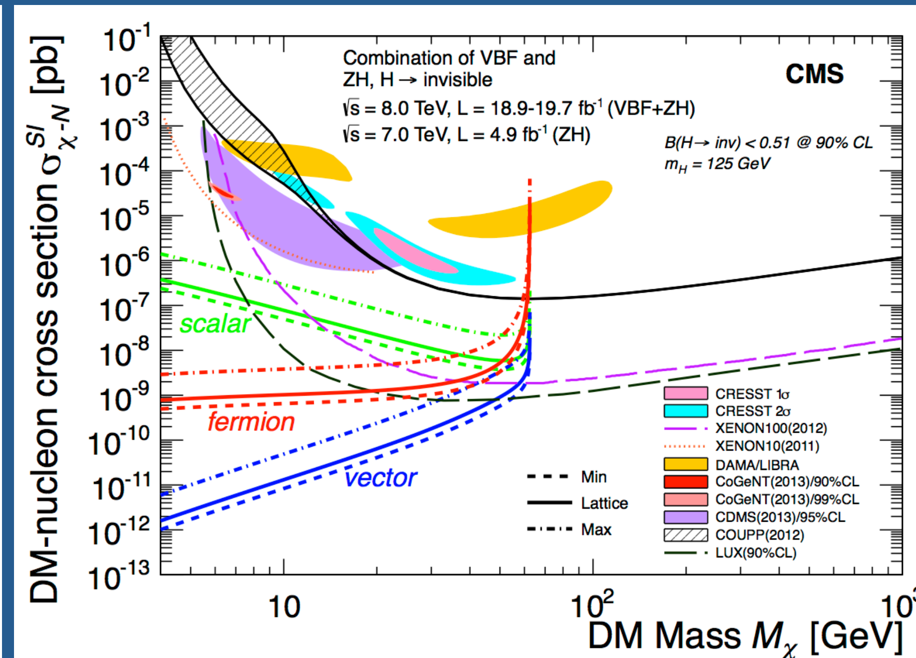


Search for Invisibly Decaying Higgs

Eur. Phys.J.C 74 (2014) 2980



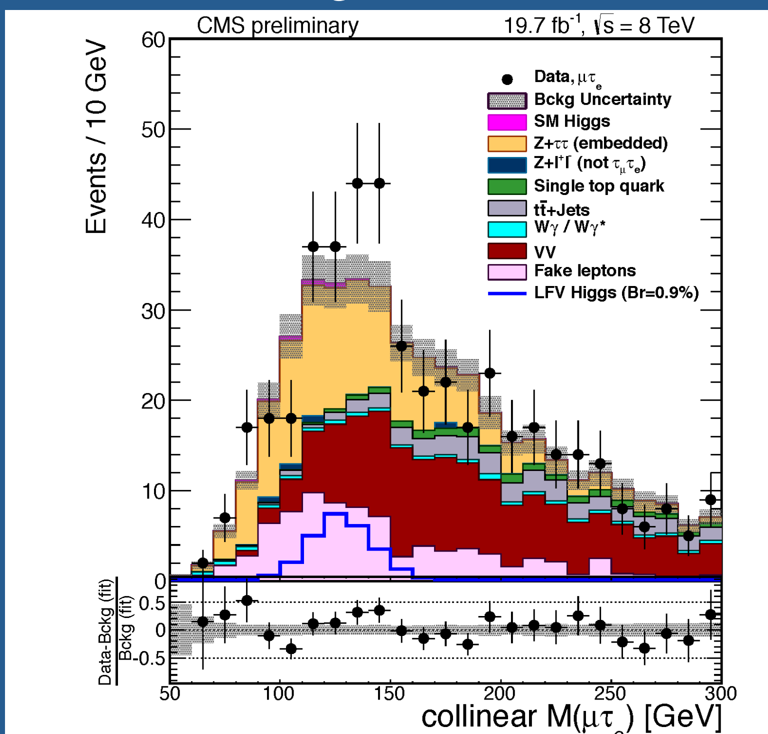


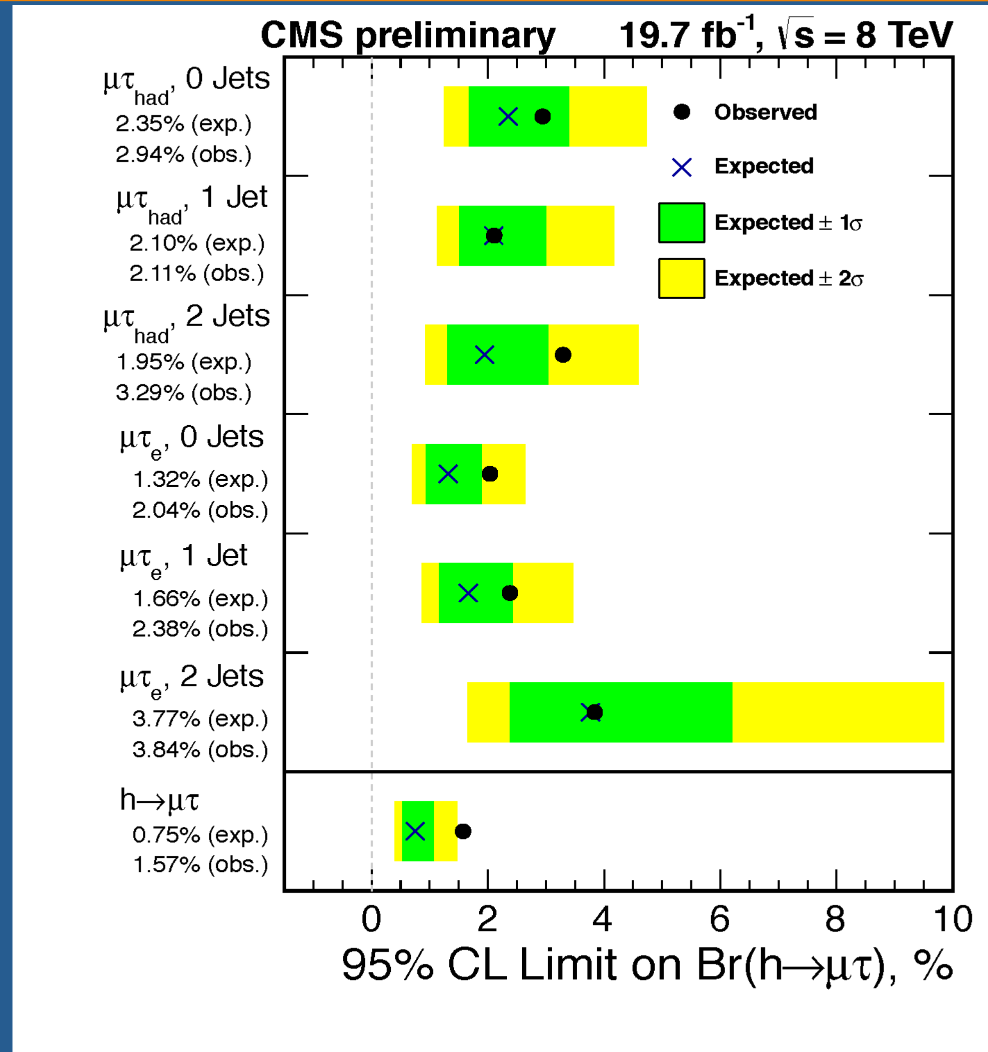
- Combined limit from all three channels:
  - $BR(H \rightarrow inv) < 0.58$ at 95% CL for $m_H = 125$
- "Higgs portal" DM interpretation:
  - $H \rightarrow \chi\chi$ possible if $m_\chi < m_H / 2$
  - Limits on χ-nucleon cross section as a function of m_χ for scalar, vector and Majorana fermion hypotheses for χ

Search for LFV Decaying Higgs

CMS-HIG-14-005

- Search performed looking for LFV decay $H \rightarrow \mu\tau$
  - Search for $\mu\tau_e$ and $\mu\tau_{had}$
  - Split analysis into categories based on jet multiplicity
- Max likelihood fit in $M(\mu\tau)$ across 6 categories



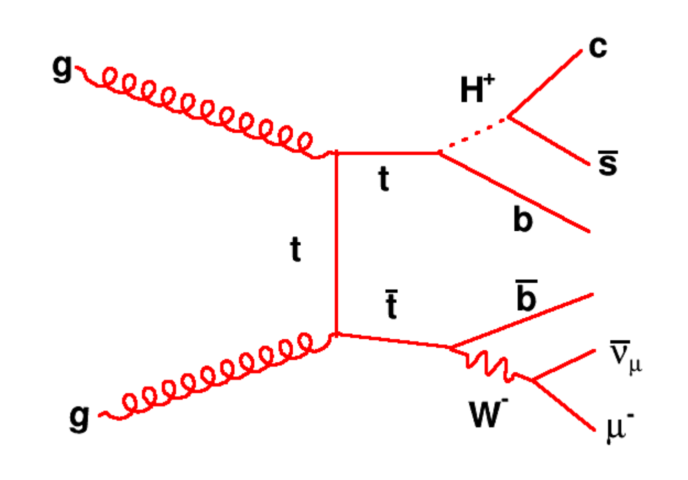


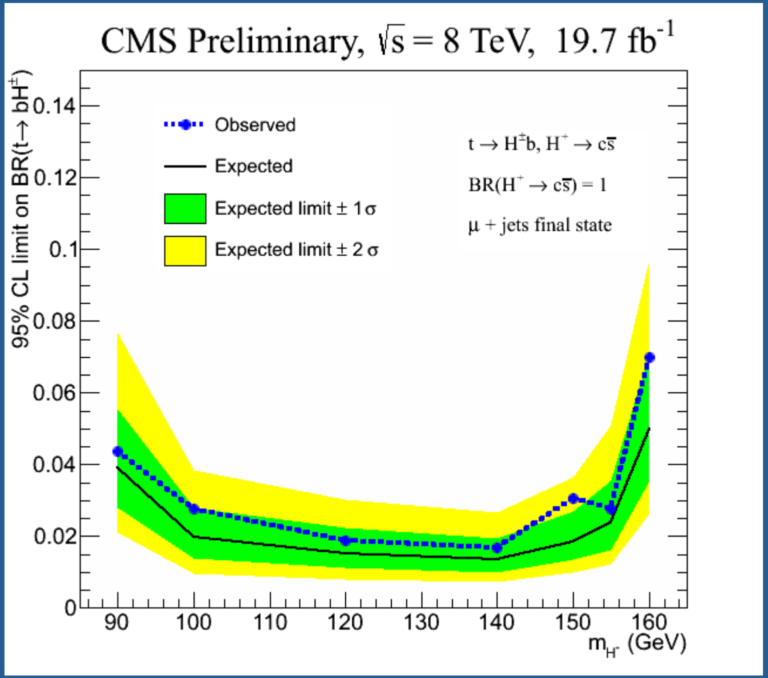
$BR(H \rightarrow \mu\tau) < 1.57\%$ at 95% CL for $m_H = 125$
Slight excess observed (2.5σ)

Search for Charged Higgs in top Decays

CMS-HIG-13-035

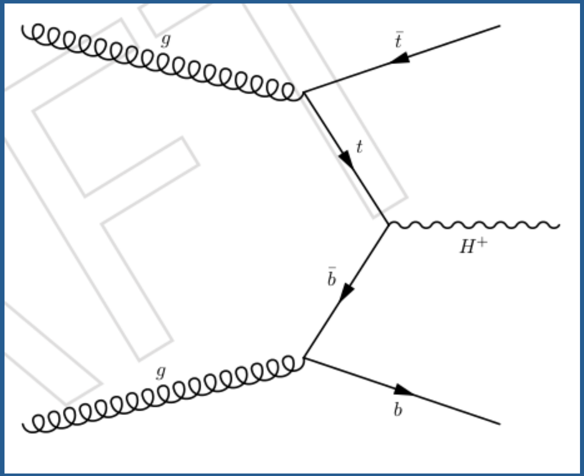
- Charged Higgs bosons play a role in several BSM models
- Look in decays of the top quark
  - SM: BR(t→Wb) ~ 100%
  - But given large m_t, this is a reasonable strategy to pursue
- Signature: standard ttbar selection
  - 1 isolated high p_T muon
  - ≥4 jets
  - MET
- Counting experiment, seeing no excess, set upper limit on BR(t→Hb)



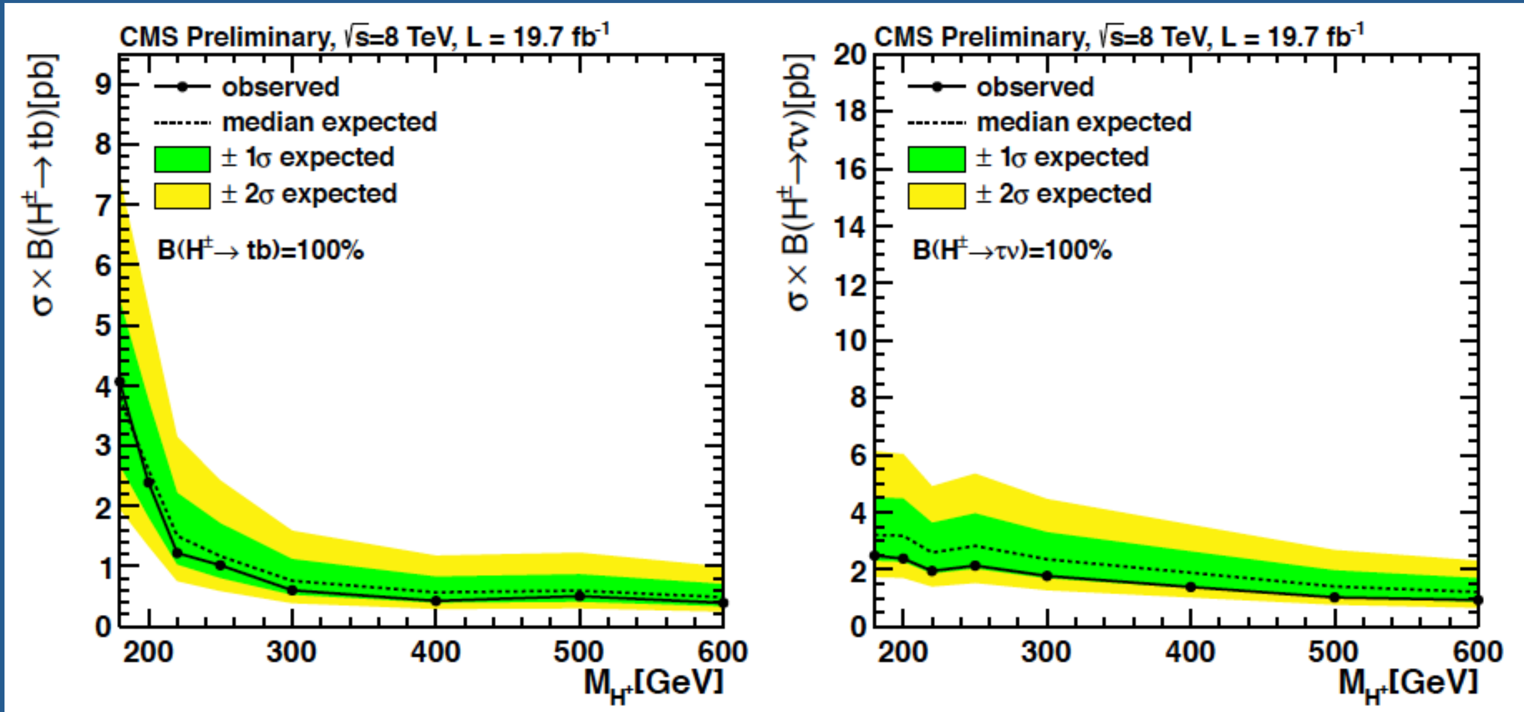


Search for Heavy Charged Higgs

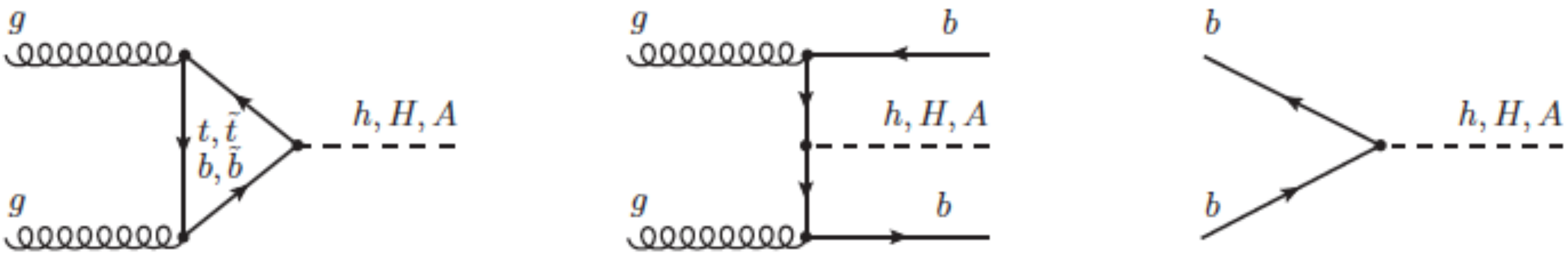
CMS-HIG-13-026
Just made public today!



- Search performed looking for heavy charged Higgs produced via gg→H^+tb
- Consider two decay modes:
  - H^+ → tb
  - H^+ → τν
- Significant synthesis with existing ttbar cross section measurements



Search for SUSY Higgs

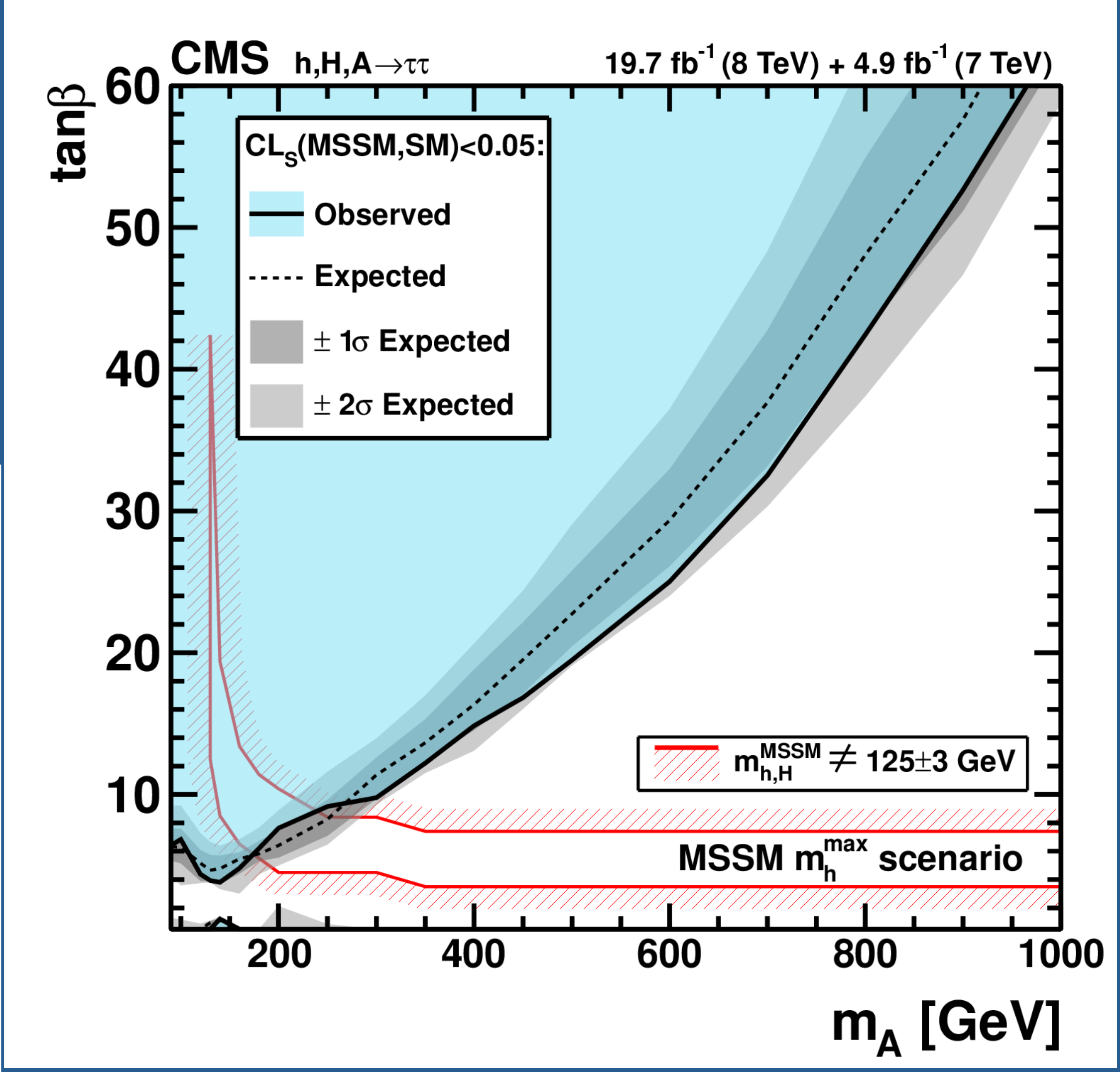


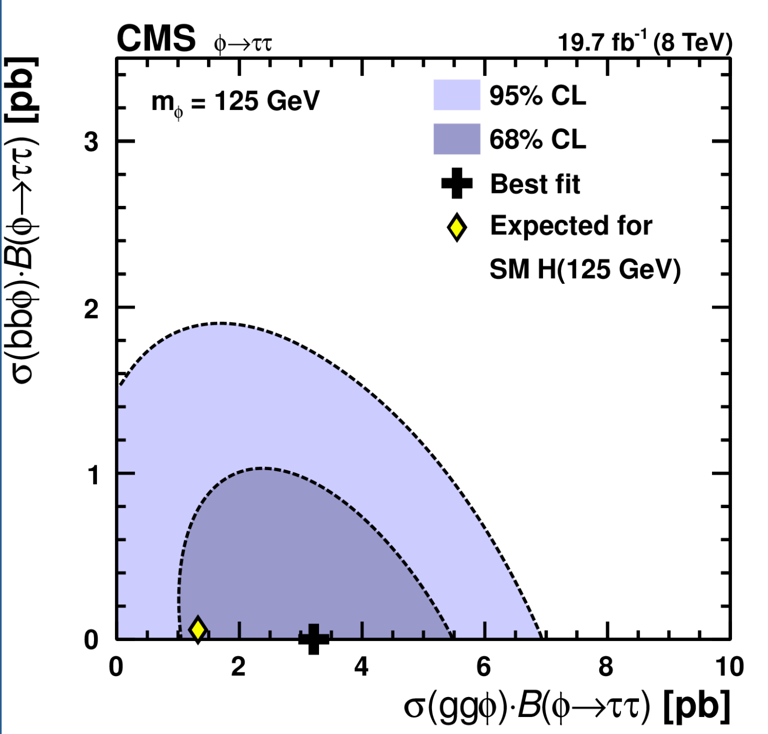
- Minimal supersymmetric extension of the standard model (MSSM)
  - Two Higgs doublets
  - Five physical observable Higgs bosons:
    - Light and heavy CP-even states, h and H
    - CP-odd state: A
    - Charged Higgs: $H^{\pm}$
  - Two free parameters, typically chosen to be m_A and tanB = ratio of vevs for two Higgs doublets
- Large tanB → enhanced Higgs coupling to down-type fermions
  - Hence associated b production and decay $H \rightarrow \tau\tau$ offer unique opportunities for MSSM-directed searches

Search for SUSY Higgs

- Test a variety of MSSM "benchmark" scenarios
  - Establish exclusion regions for each in m_A v. tanB plane
- Also examine ggϕ and bbϕ production cross sections to probe consistency w/ SM

arXiv:1408.3316, submitted to JHEP





Summary

- Higgs physics at CMS has now moved from the search and discovery phase into a precision measurement era
- Characteristics of this Higgs boson need to be measured with high precision. Some have been with the Run 1 data sample; a few crucial ones remain.
- The measurement campaign has so far revealed no significant deviations from the predictions of the SM
- Run 2 will afford us an unprecedented opportunity to study this new particle
  - Will the SM nature of this Higgs be confirmed?
  - Or are we in for some surprises?

Backup

Discovery of a New Particle


Celebrations on
4 July 2012

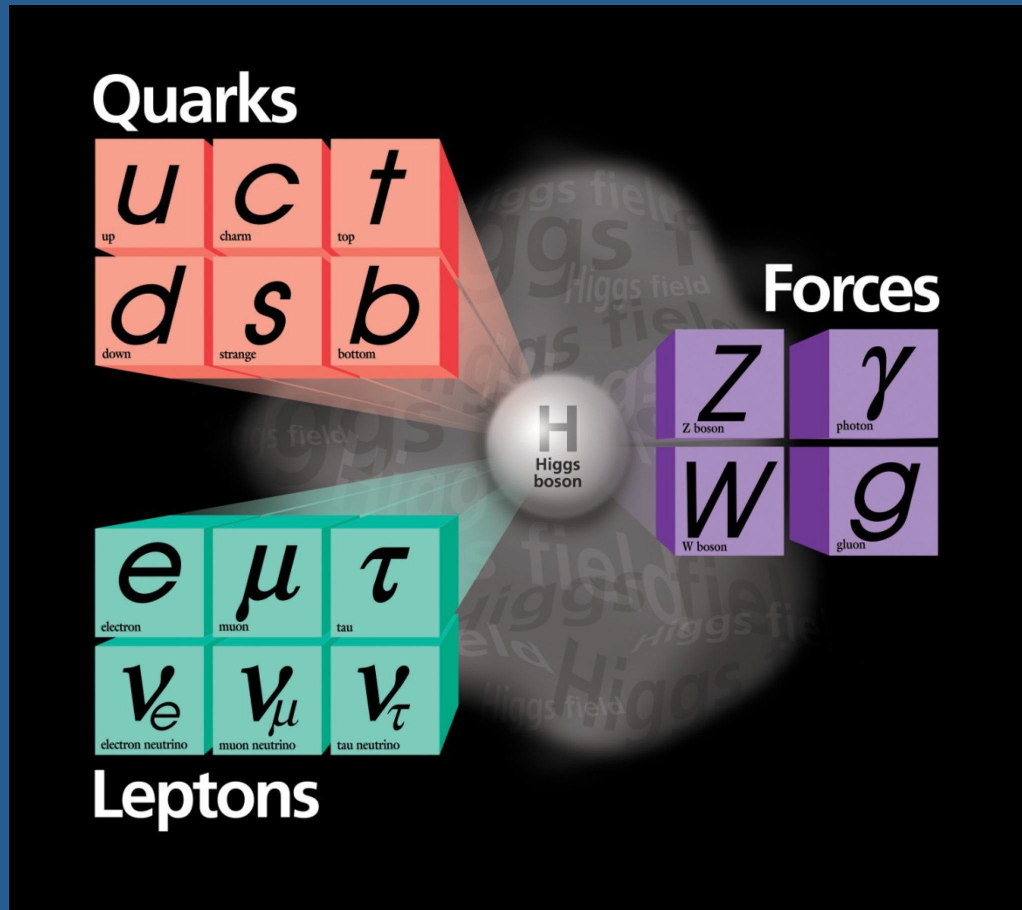
CERN and Melbourne and many other places around the globe


Both CMS and ATLAS reporting 5 sigma evidence for a new particle with mass ~ 125 GeV

2 March 1995: Discovery of a New Particle

http://www-visualmedia.fnal.gov/

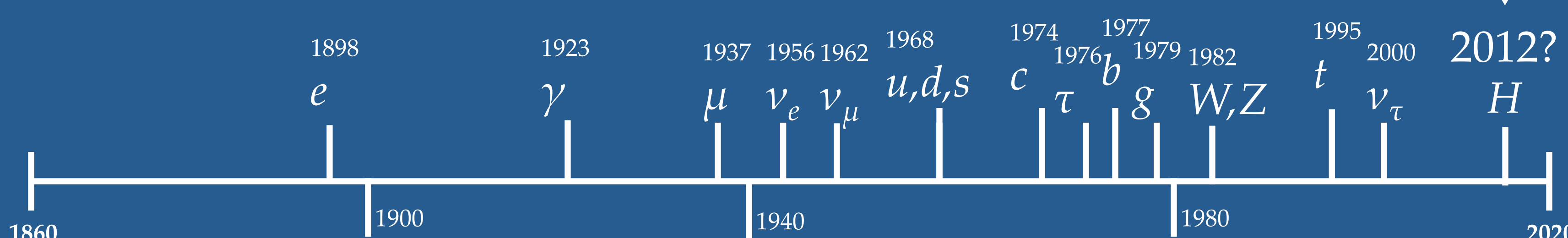
The History of Discoveries



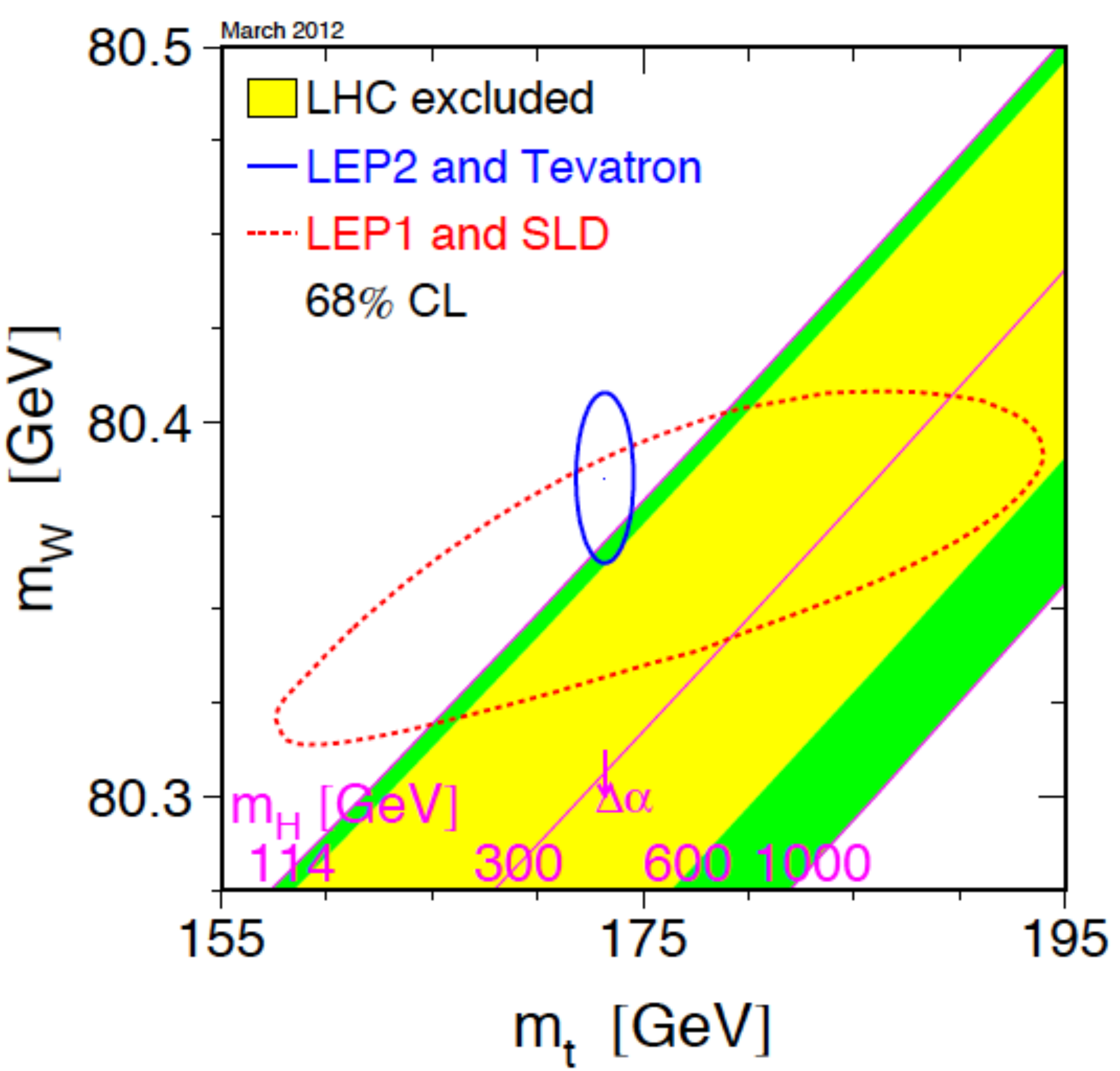
One remaining piece to complete the puzzle

H:

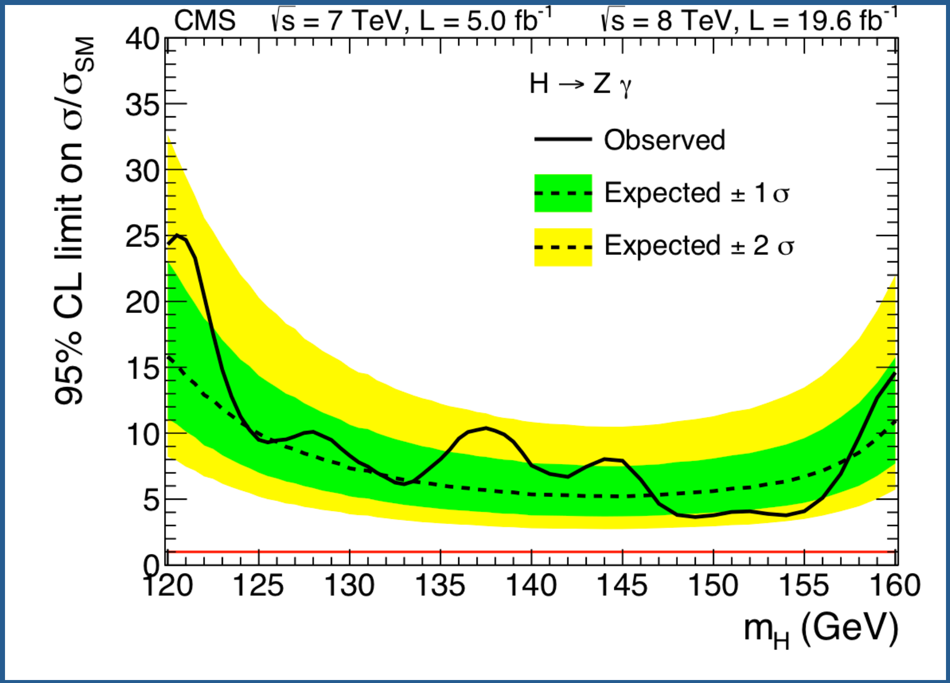
the Higgs boson -- the last piece of the standard model.

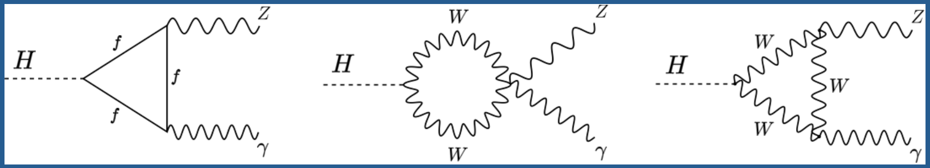


Higgs and Top



Higgs Decay Modes: Rare Decay Modes





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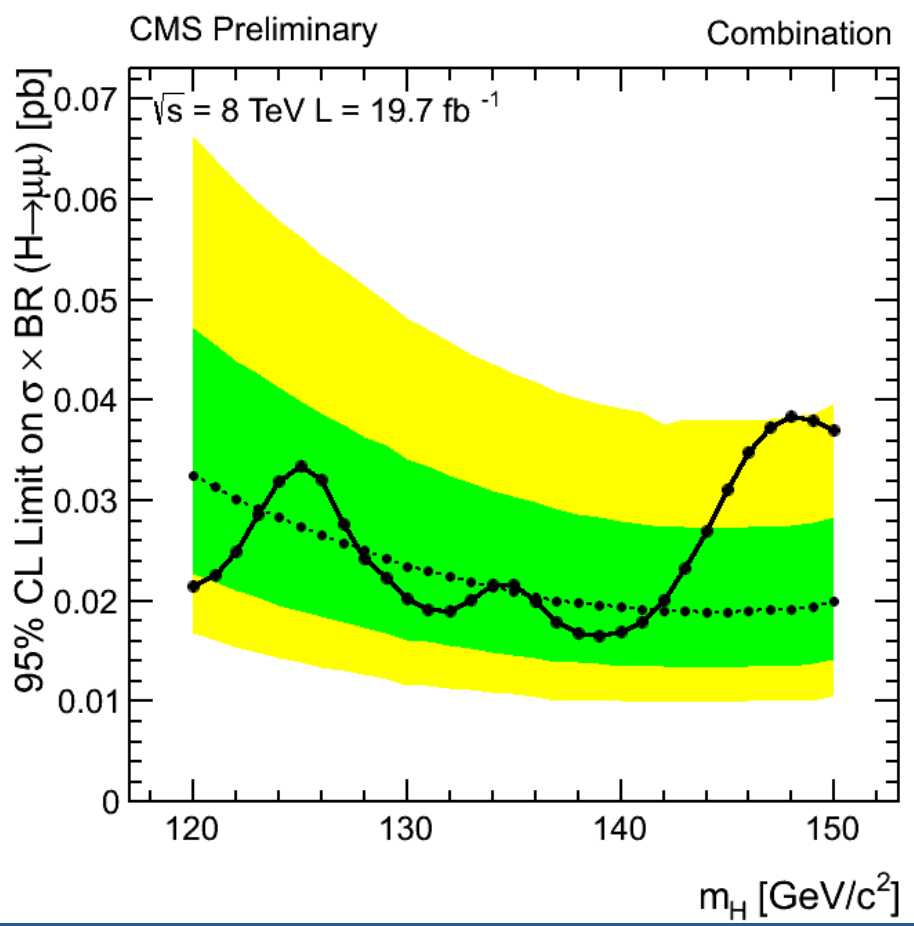
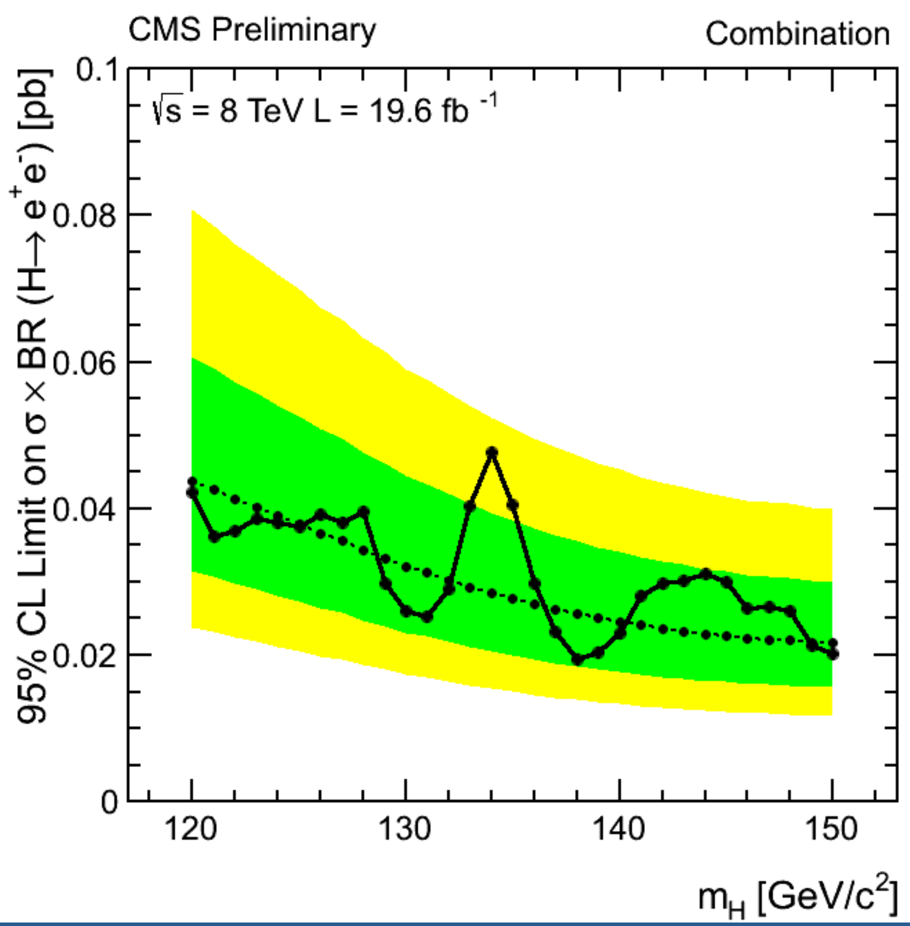
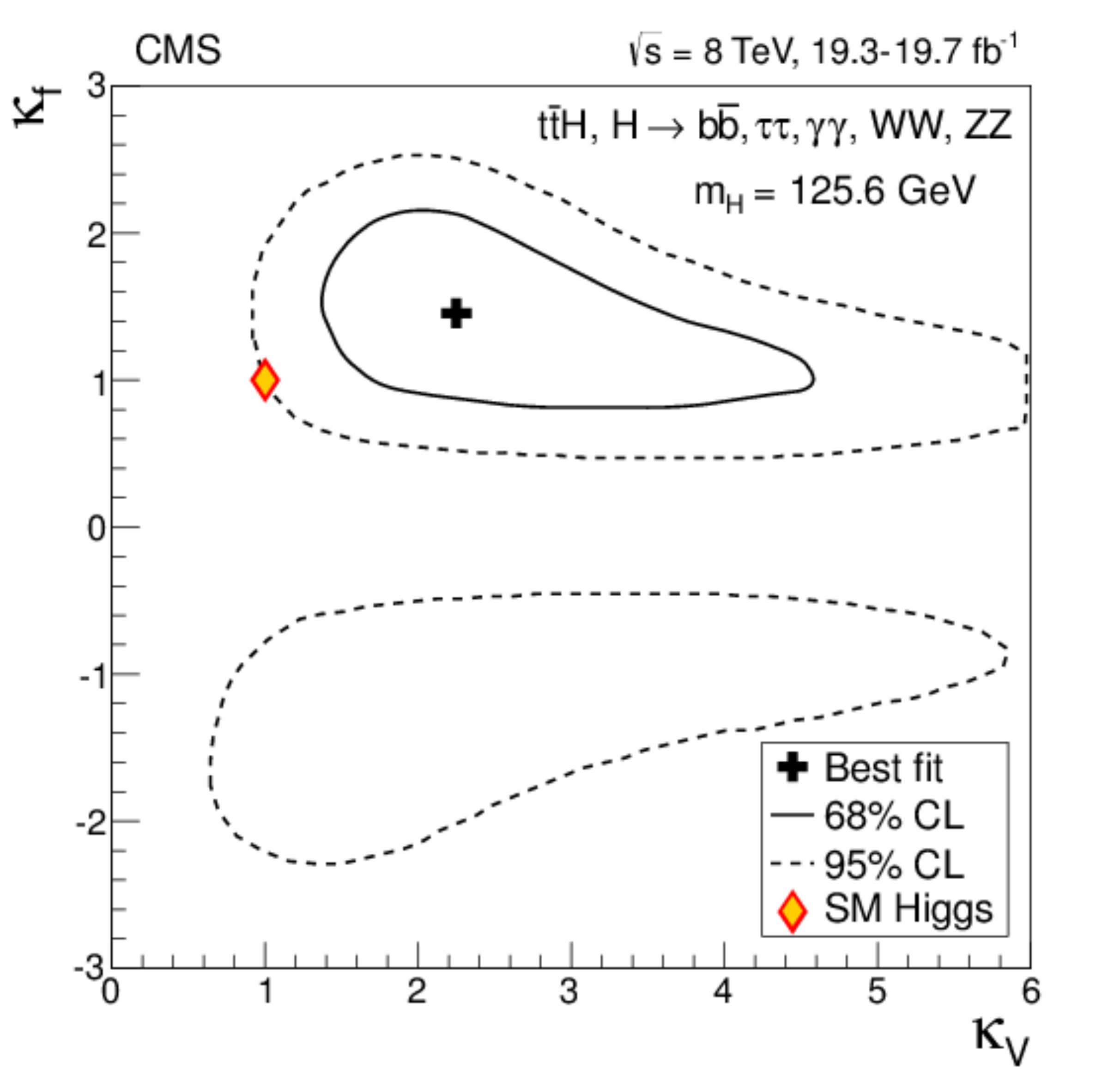




Search for ttH Production: All Channels

arXiv:1408.1682, Accepted by JHEP



- Can perform same kind of coupling-modifier study as described earlier
- Value in performing this solely within ttH analyses