

The Standard Model Higgs and beyond

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LIP Lisbon

BUE, December 5, 2016

- ✓ Standard Model and the Higgs boson
- ✓ The Higgs boson and beyond
- ✓ Neutral and charged Higgs
- ✓ BSM Higgs: light pseudo-scalar, non-SM Higgs decay
- ✓ Looking forward



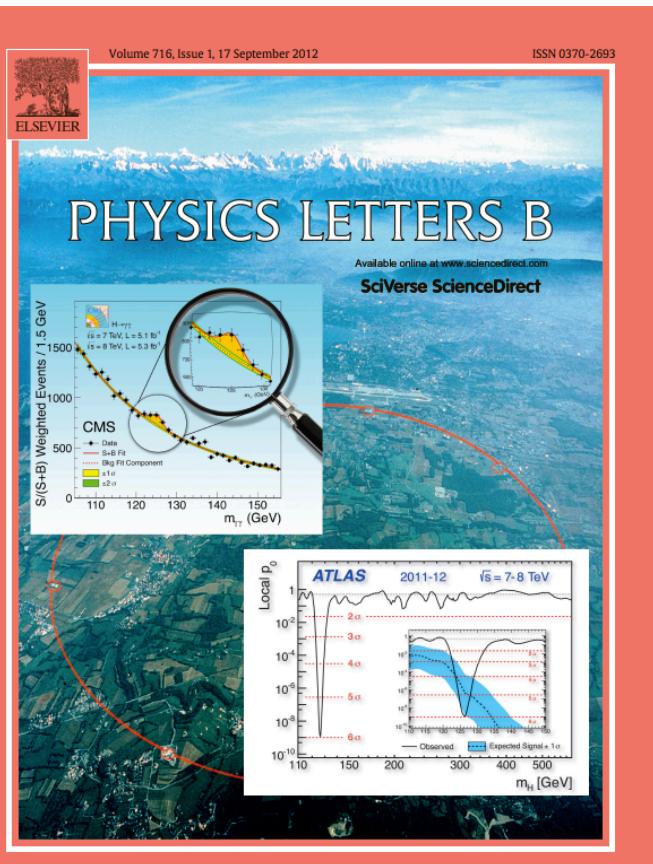
$H \rightarrow ZZ \rightarrow 4e, 4\mu, 2e2\mu$

- Signal: 4 isolated leptons from same vertex

- Small background
 - Fully reconstructed, mass resolution $\sim 1\%$

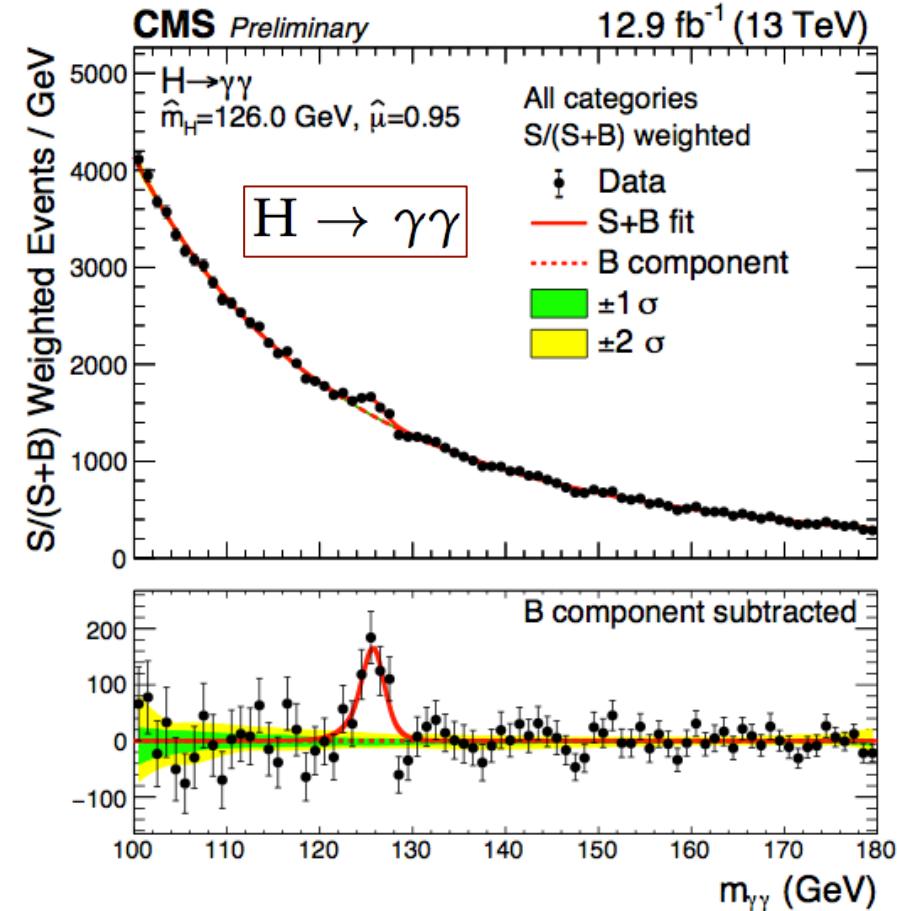
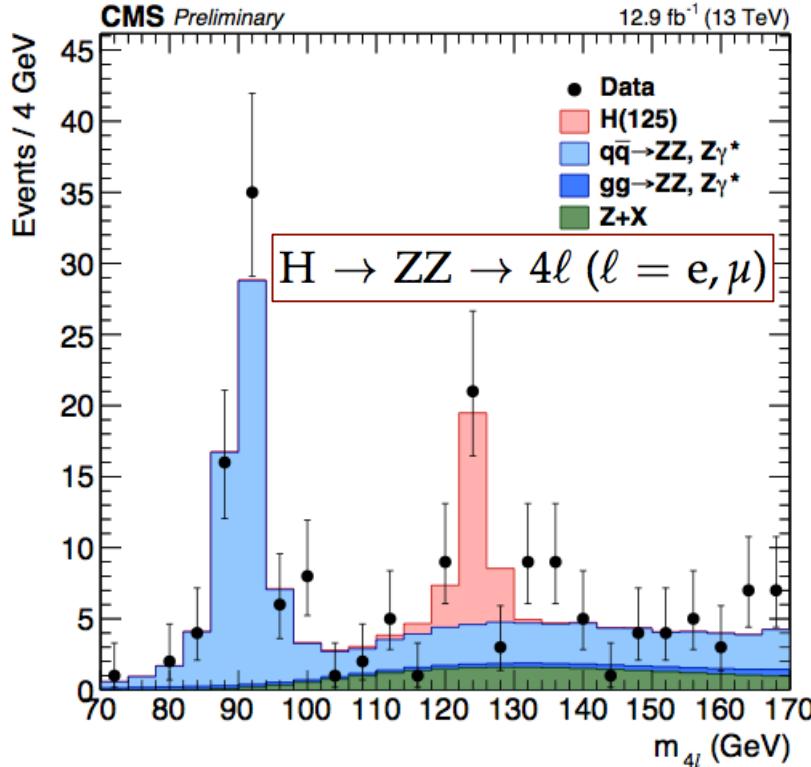
The golden channel

2012: A new boson discovery



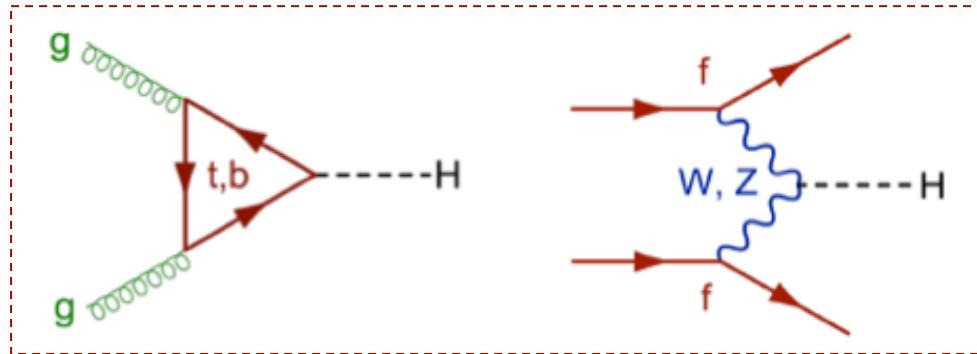
Higgs rediscovery (12.9/fb)

PRD 89 (2014) 092007, PLB726(2013)088, HIG-16-020, HIG-16-033

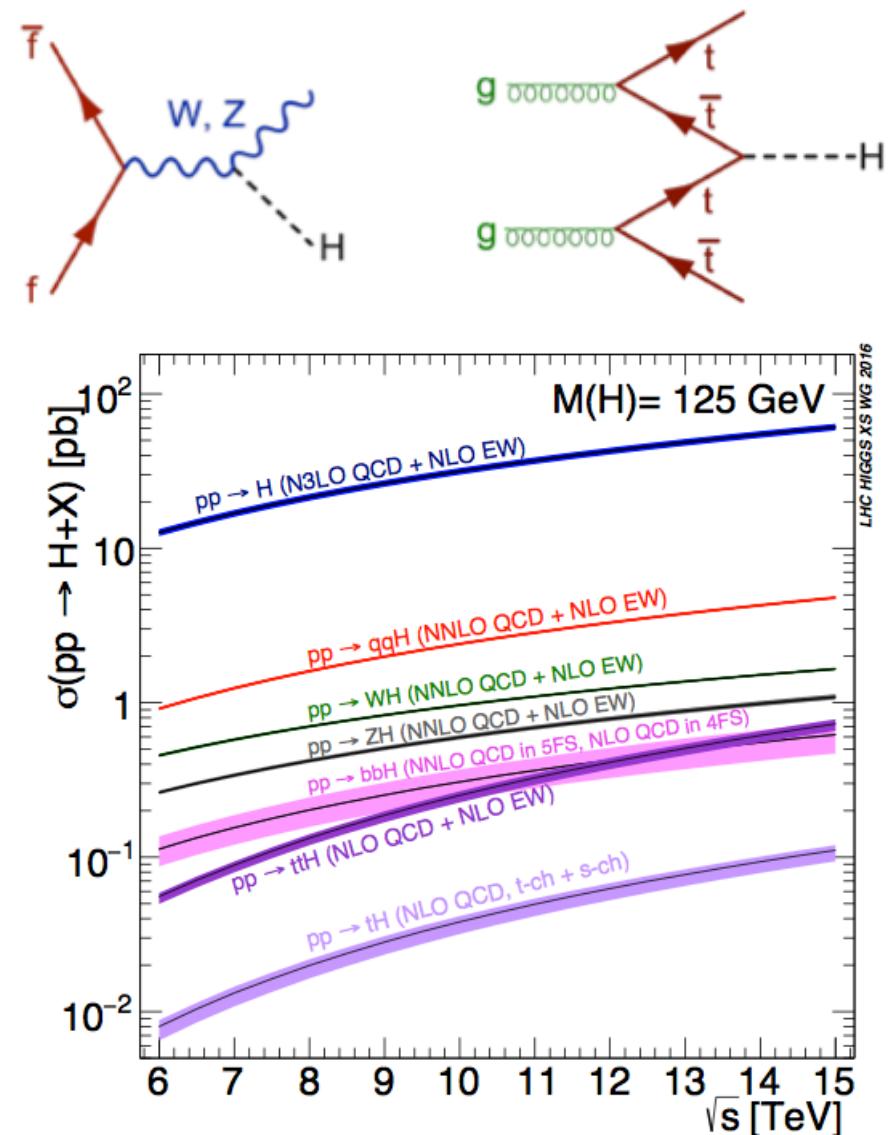


- Clear signal visible by eye
 - Observation in boson channels
 - Evidence for fermion couplings
 - Precision mass measurement ($\sim 125 \text{ GeV}$)
 - Spin determined

Higgs boson production

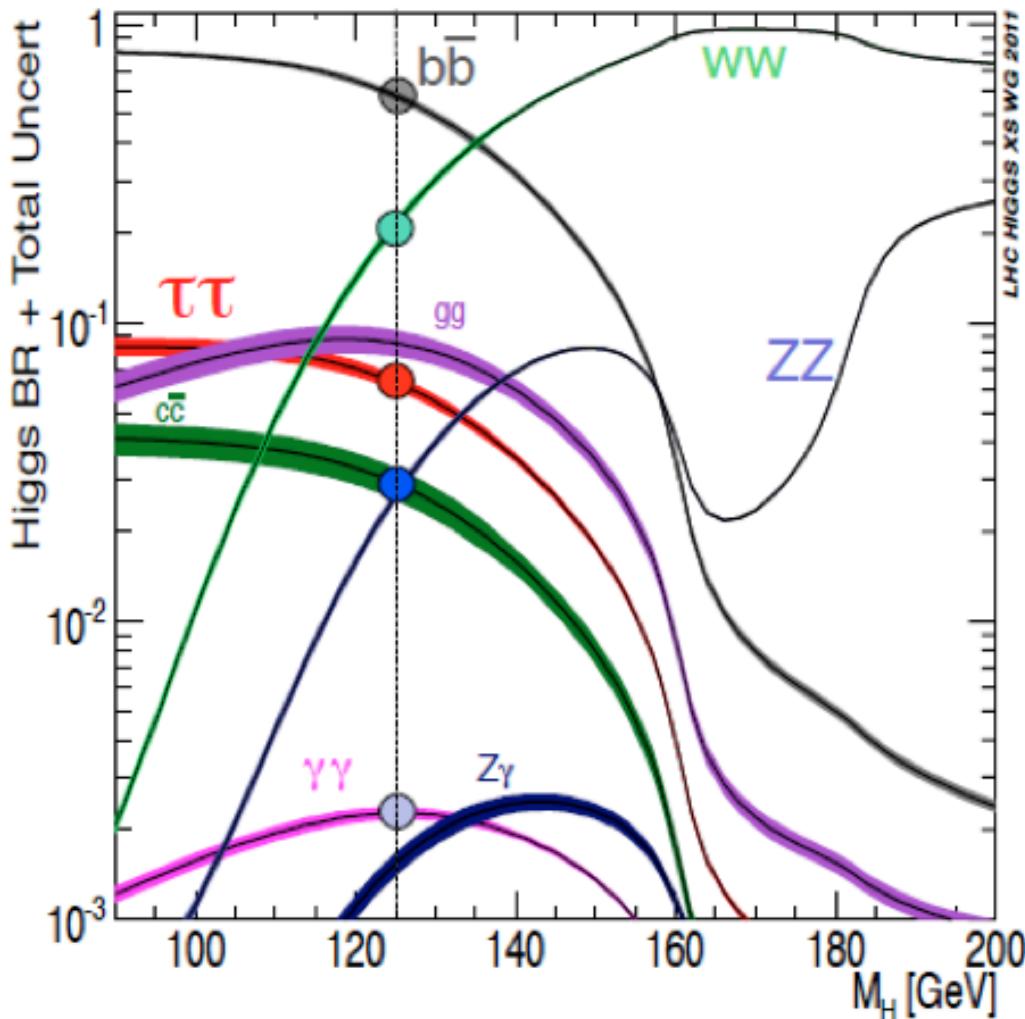


- Gluon-gluon fusion (ggF) 87.2%
- Vector boson fusion (VBF): 6.8%
- VH: 4.1%
- ttH: 0.9%
- Cross section increase of x2-4 btw Run1 and Run2
- Observed modes: ggF, VBF



Higgs boson decays

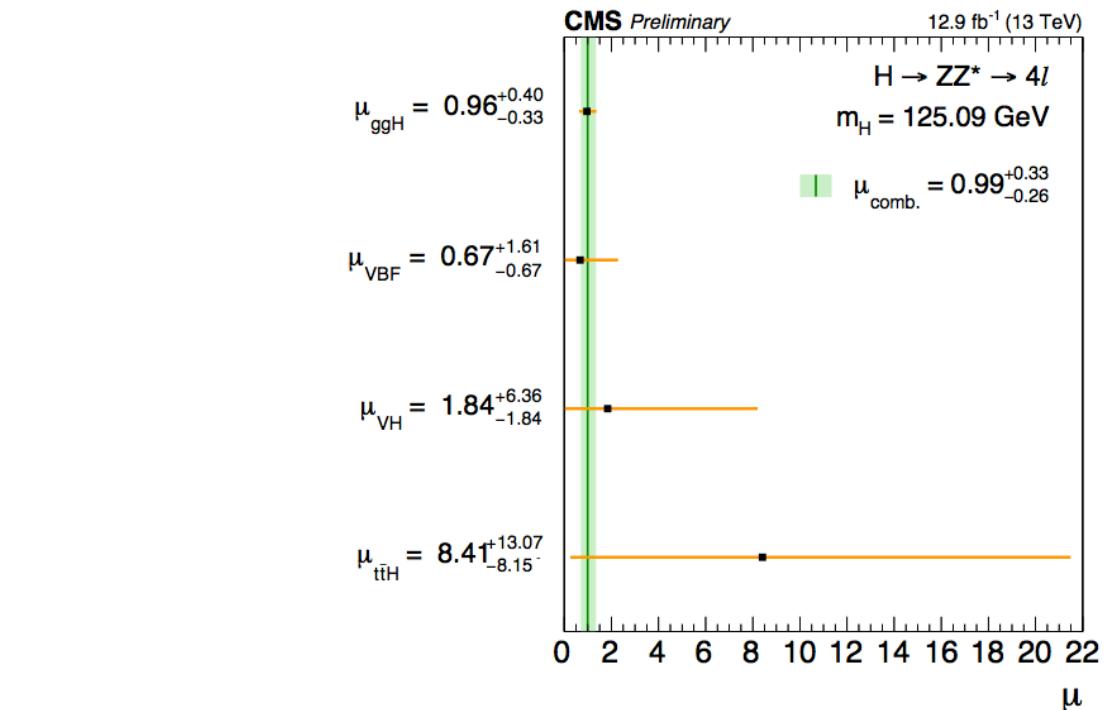
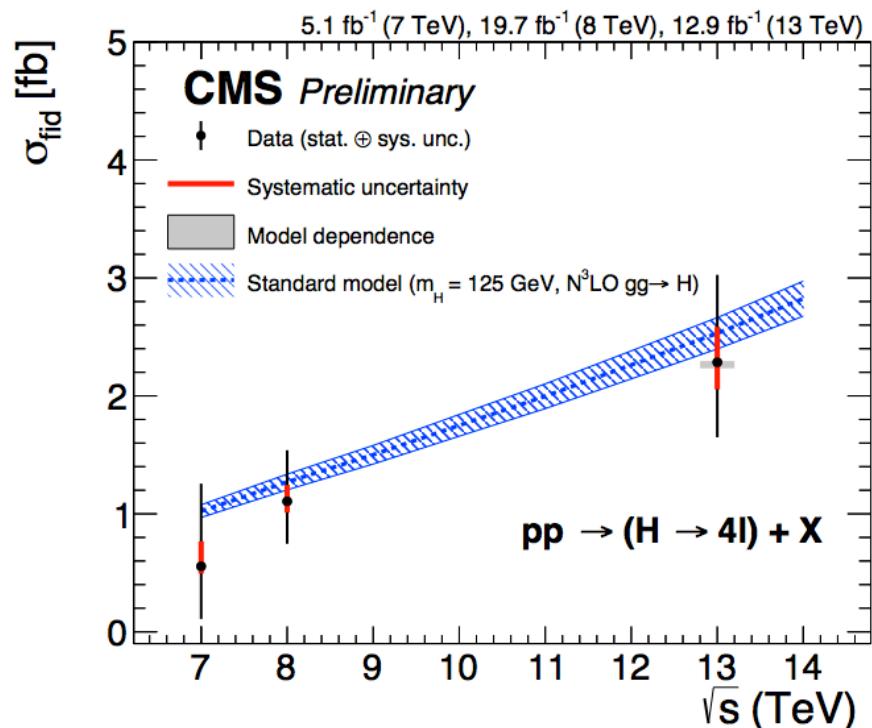
- 5 decay modes studied
- Low mass region is challenging
 - High sensitivity/high resolution: $\gamma\gamma$, ZZ
 - High sensitivity/low resolution: WW
 - Low sensitivity/low resolution: bb, $\tau\tau$



Higgs cross section: H \rightarrow ZZ

- No tension in signal strength

$$\mu = \sigma / \sigma_{SM} = 0.99^{+0.33}_{-0.26}$$



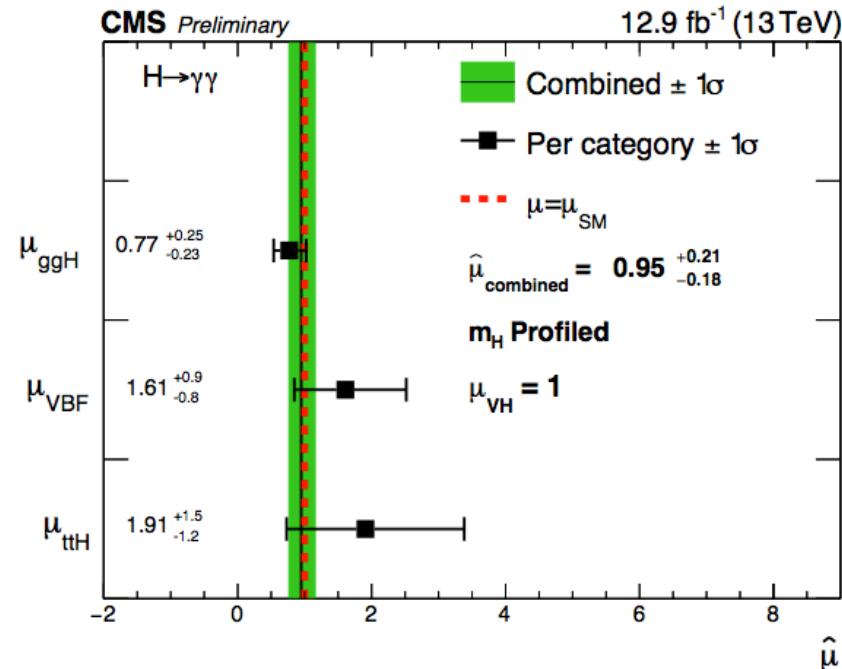
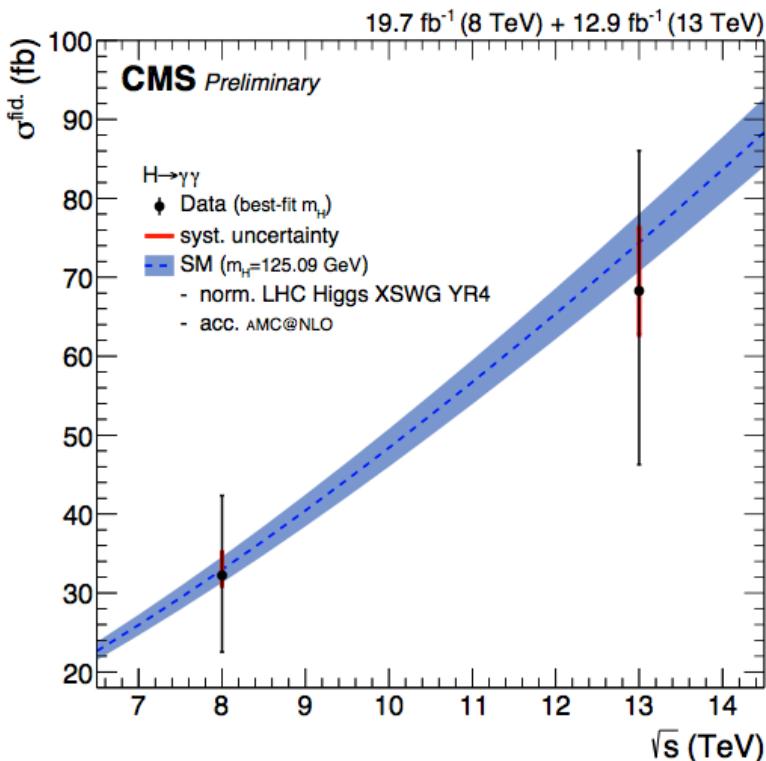
- Fiducial cross section is compatible with SM

$$\sigma_{fid.} = 2.29^{+0.74}_{-0.64} (\text{stat.})^{+0.30}_{-0.23} (\text{sys.})^{+0.01}_{-0.05} (\text{model dep.}) \text{ fb}$$

Higgs cross section: $H \rightarrow \gamma\gamma$

- No tension in signal strength

$$\mu = \sigma / \sigma_{SM} = 0.95 \pm 0.20$$



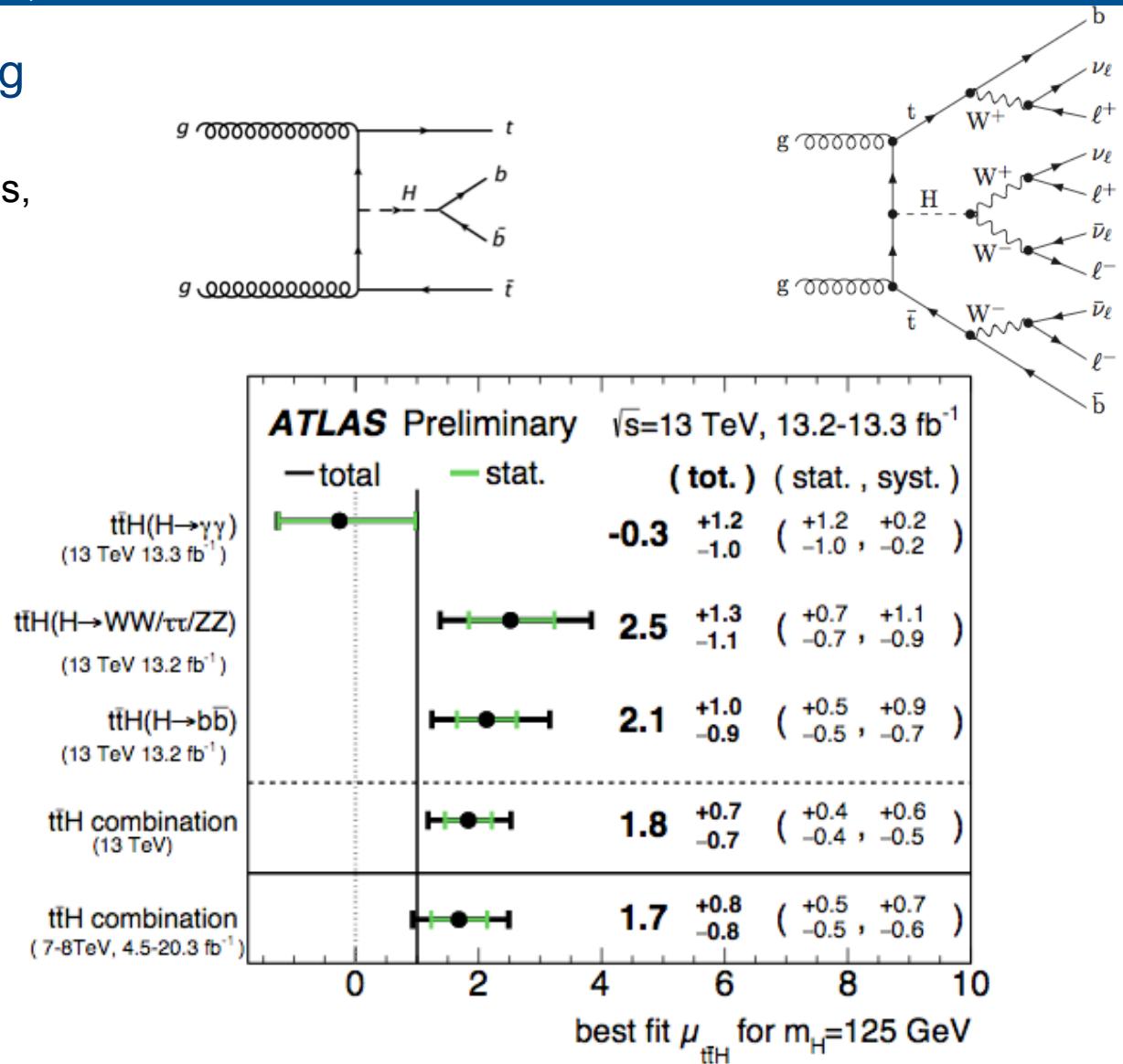
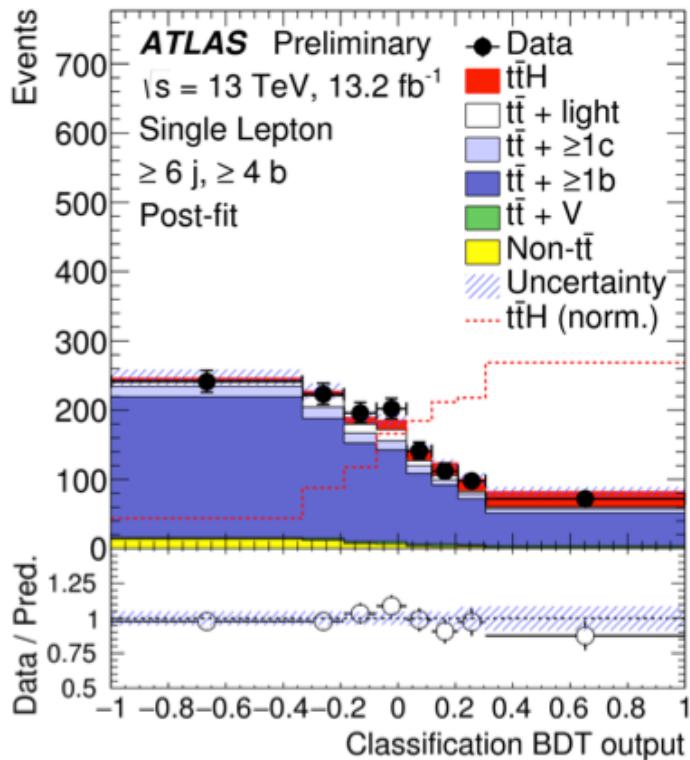
- Fiducial cross section is compatible with SM

$$\hat{\sigma}_{fid} = 69^{+18}_{-22} \text{ fb} = 69^{+16}_{-22} (\text{stat.})^{+8}_{-6} (\text{syst.}) \text{ fb}$$

ttH production

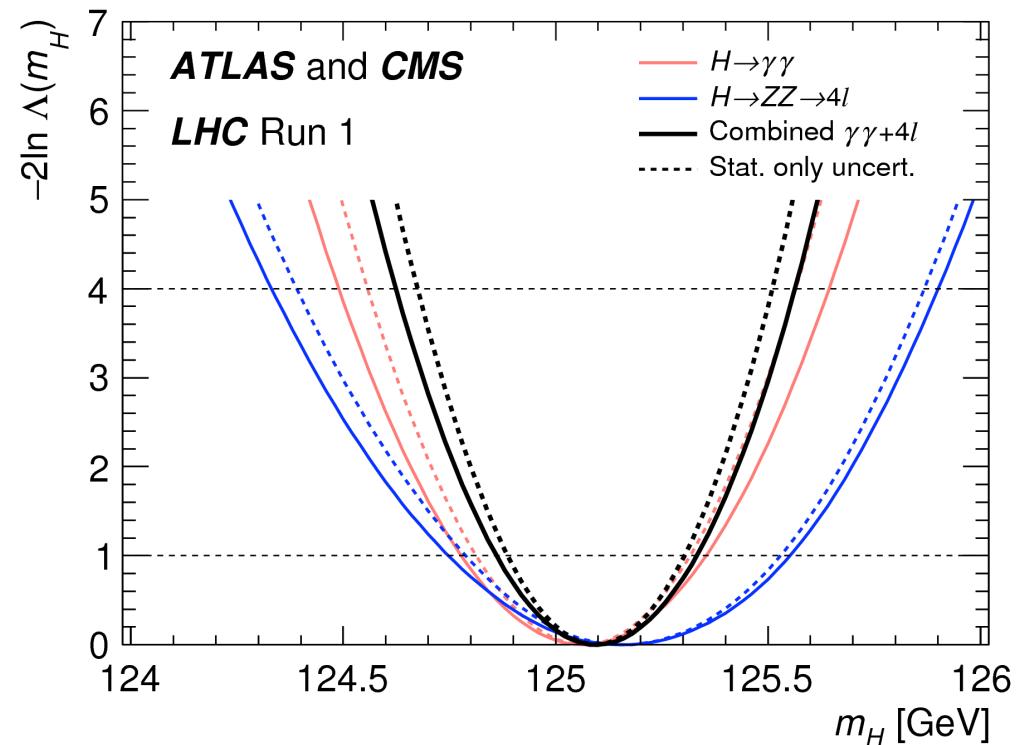
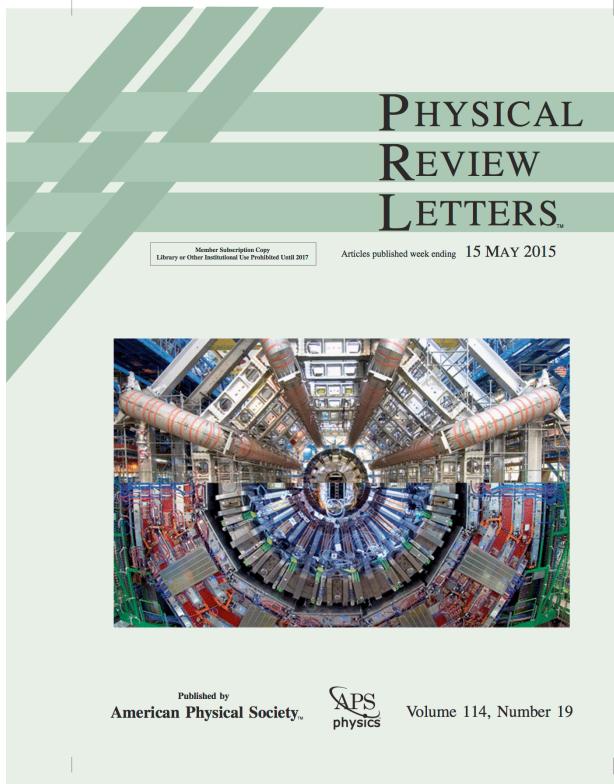
ATLAS-CONF-2016-080, ATLAS-CONF-2016-080, CMS-HIG-16-004

- Probe top-quark Higgs coupling
 - ttH (bb,multi-leptons, $\gamma\gamma$)
 - Categorize events based on #leptons, b-tags, etc.
 - Use BDT for S/B separation



Mass measurement

PRL 114(2015)191803



$$\begin{aligned} M_H &= 125.09 \pm 0.24 \text{ GeV} \\ &= \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.) GeV} \end{aligned}$$

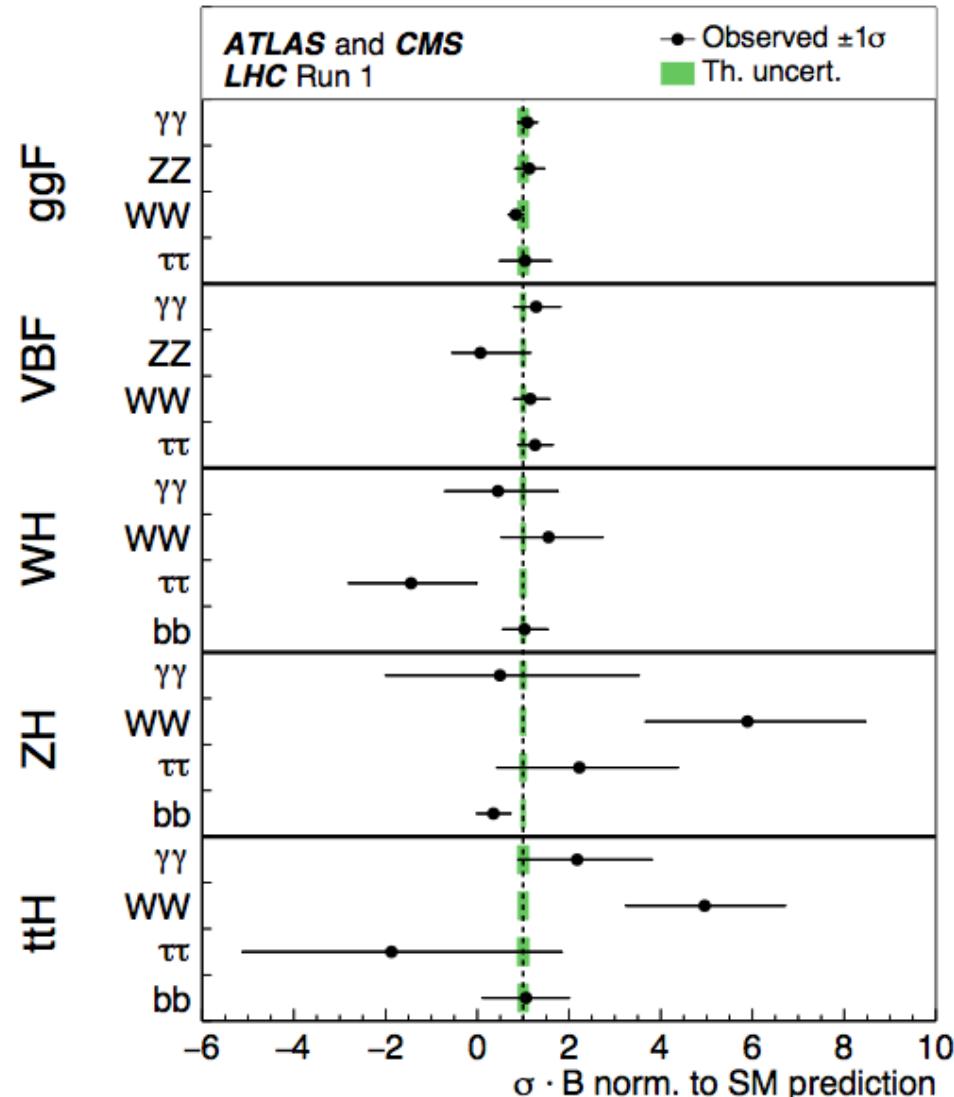
Higgs boson production and decays

PRL114, 191803, JHEP08(2016)045

- $m_H = 125.09 \pm 0.24$ GeV
- Consistent with spin 0 and even parity
- All couplings consistent with SM
- ggF precision close to theoretical uncertainties

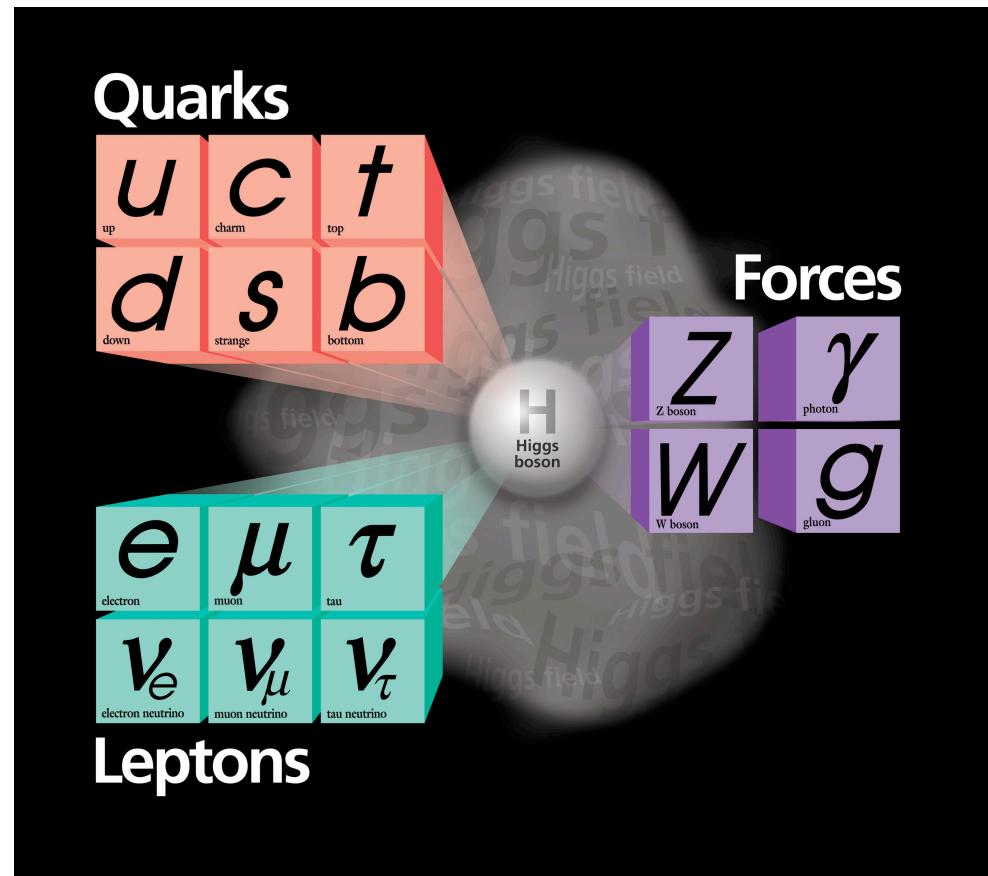
Combination papers:

- Mass: PRL 114, 191803
- Rate, couplings: JHEP08(2016)045



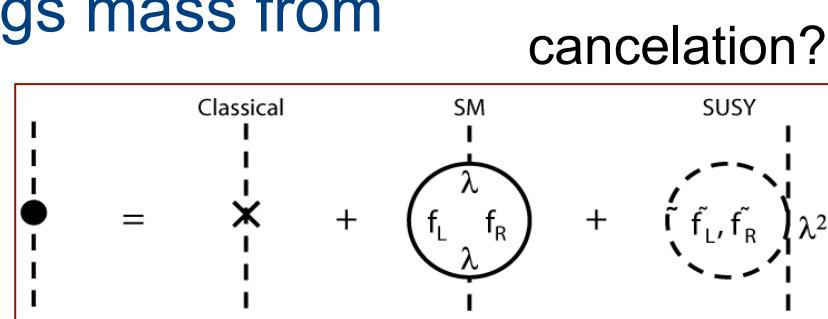
Standard Model theory of everything?

- Discovery of the Higgs boson marks the triumph of the SM
- However, even with the inclusion of the Higgs boson, SM is an incomplete theory
- Dark matter
- Asymmetry between matter and anti-matter
- Gravity and unification of forces
- Masses and neutrino hierarchy



Higgs and the SM

- SM is a successful theory
- Nothing prevents the SM to survive up to the Planck scale.
However, it is **unnatural**.
- Virtual particles in quantum loops contribute to the Higgs mechanism
 - Contributions grow with Λ (upper scale validity of the SM)
 - Higgs mass depends quadratically on Λ : $m^2 = m_0^2 + g^2 \Lambda^2$
- Miraculous cancellations are needed to keep $m_H < 1 \text{ TeV}$
- Is there a symmetry that protects the Higgs mass from receiving large corrections?



Higgs and the SM

- **Hierarchy problem**

- Low mass top-squarks cancel divergent SM contributions to Higgs mass

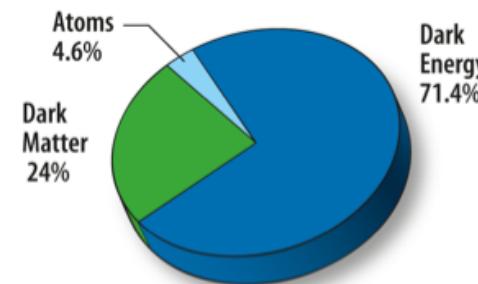
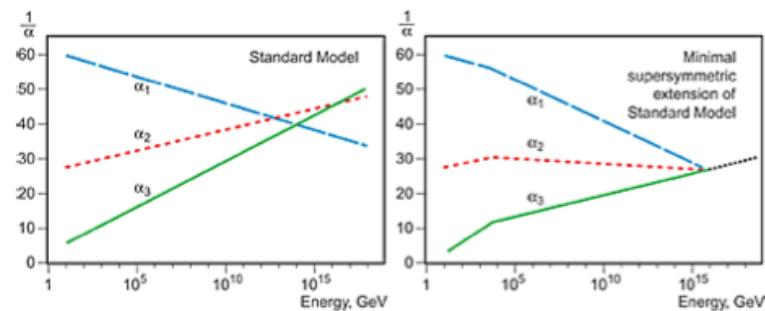
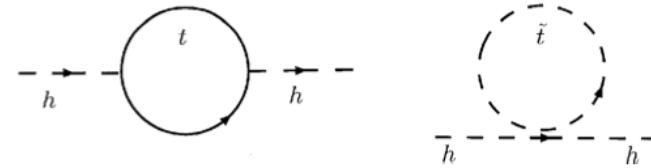
- **Unification of gauge couplings**

- “Sparticles” change running couplings and ensure unification

- **Dark matter**

- Lightest SUSY particle is a good candidate for DM

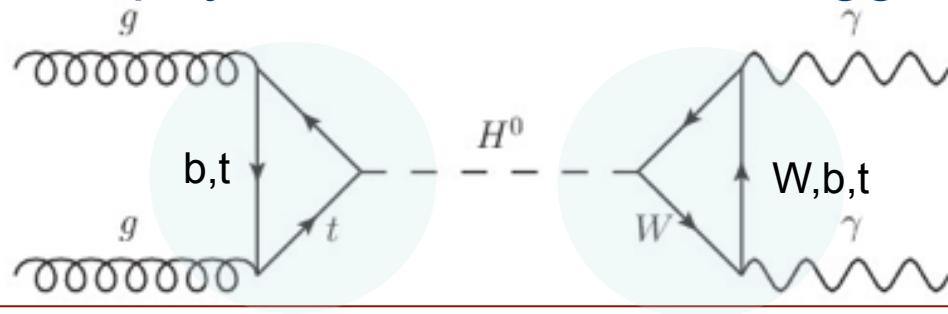
- **# experimental scenarios is large**



Higgs and BSM

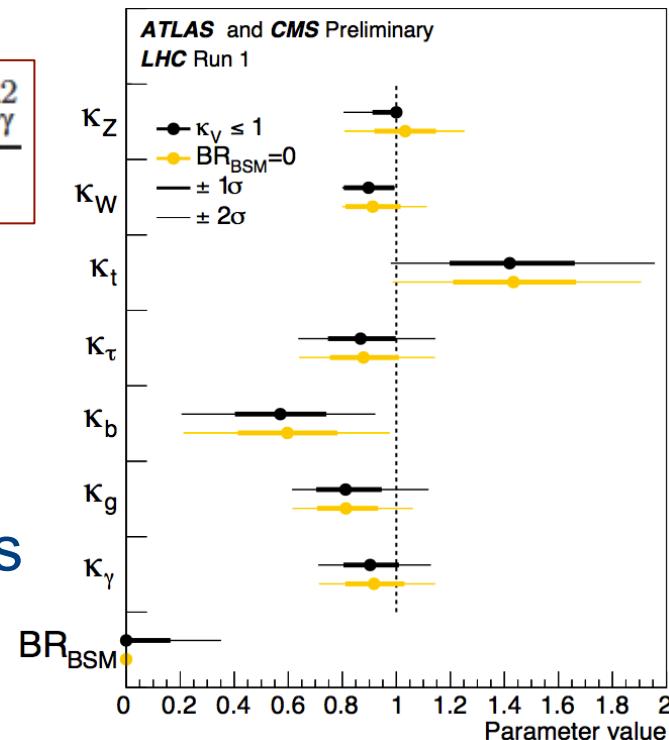
JHEP08(2016)045

- Is there BSM physics hidden in the “Higgs sector”?



$$(\sigma \cdot \text{BR}) (\text{gg} \rightarrow \text{H} \rightarrow \gamma\gamma) = \sigma_{\text{SM}}(\text{gg} \rightarrow \text{H}) \cdot \text{BR}_{\text{SM}}(\text{H} \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\text{H}}^2}$$

Strategy: parametrize deviations wrt SM in production and decay
 ⇒ loops are sensitive to BSM physics



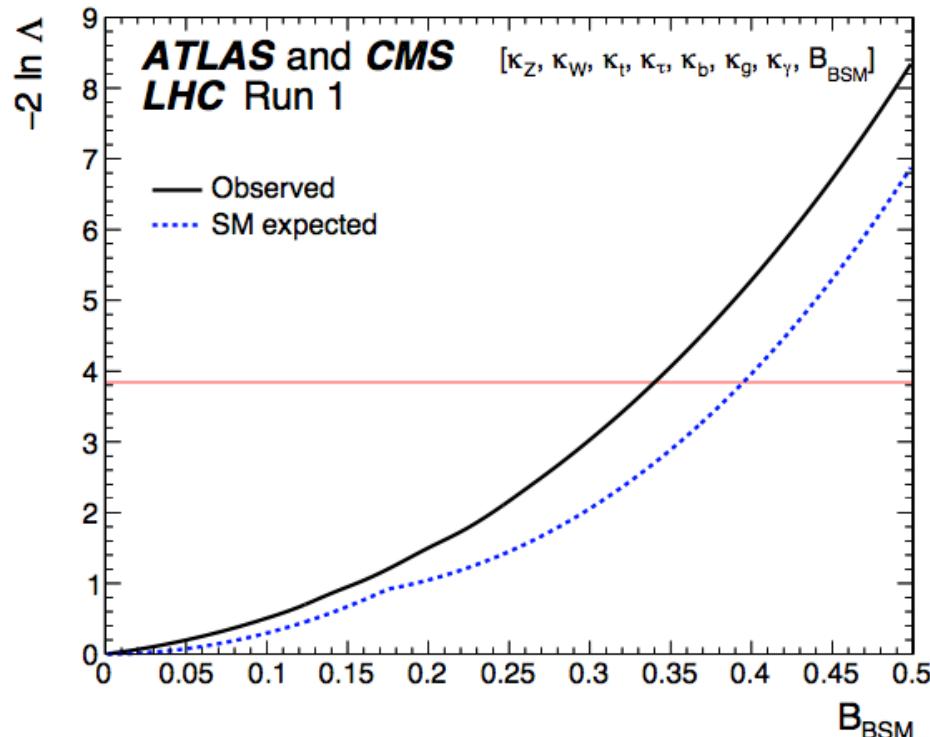
Experimental approach:

- Measure H(125) properties
- Search for additional Higgs bosons
- Search for BSM in signatures with Higgs bosons
- Search for BSM Higgs decays

Looking for new particles

JHEP08(2016)045

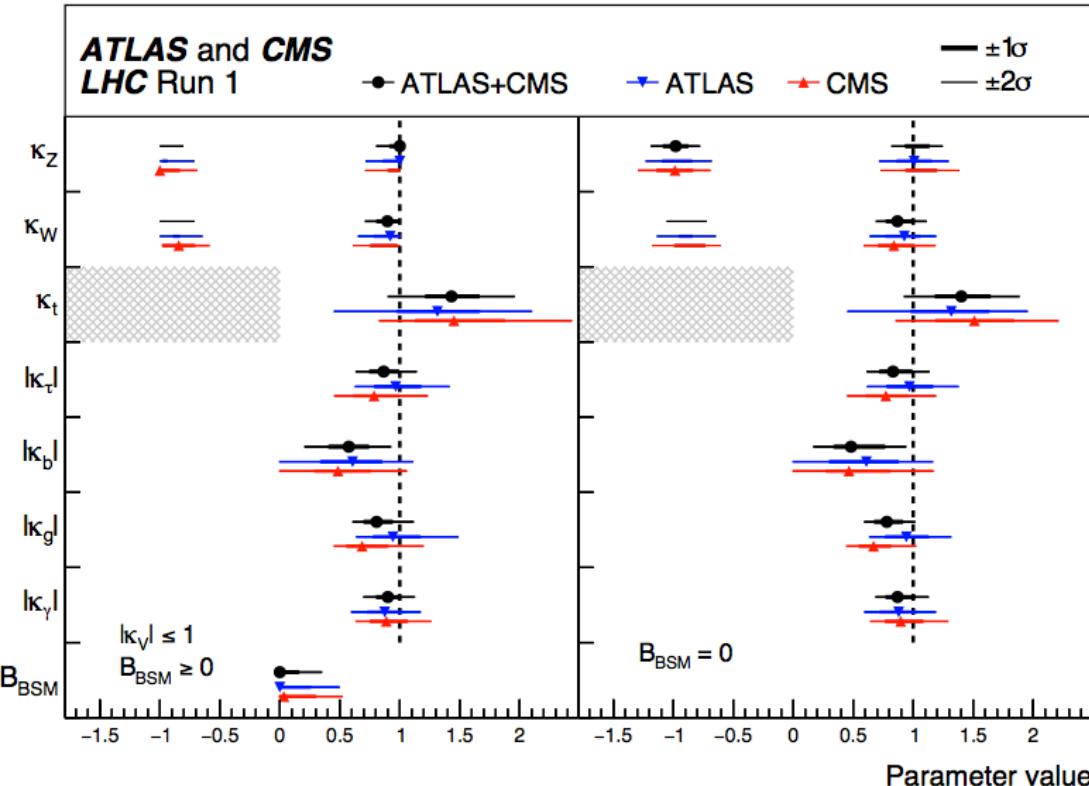
- Constrain BR_{BSM} in a scenario with free parameters
- $\Gamma_{\text{tot}} = \Gamma_{WW} + \Gamma_{ZZ} + \Gamma_{bb} + \dots + \Gamma_{\text{BSM}}$
- Likelihood scan vs BR_{BSM}
- Assuming couplings bound by SM expectations ($k_v < 1$)
- $0 \leq \text{BR}_{\text{BSM}} \leq 0.34$ at 95%CL



Couplings: decays

ATLAS-CONF-2015-044, CMS-HIG-15-002, JHEP08(2016)045

BSM physics in the loop



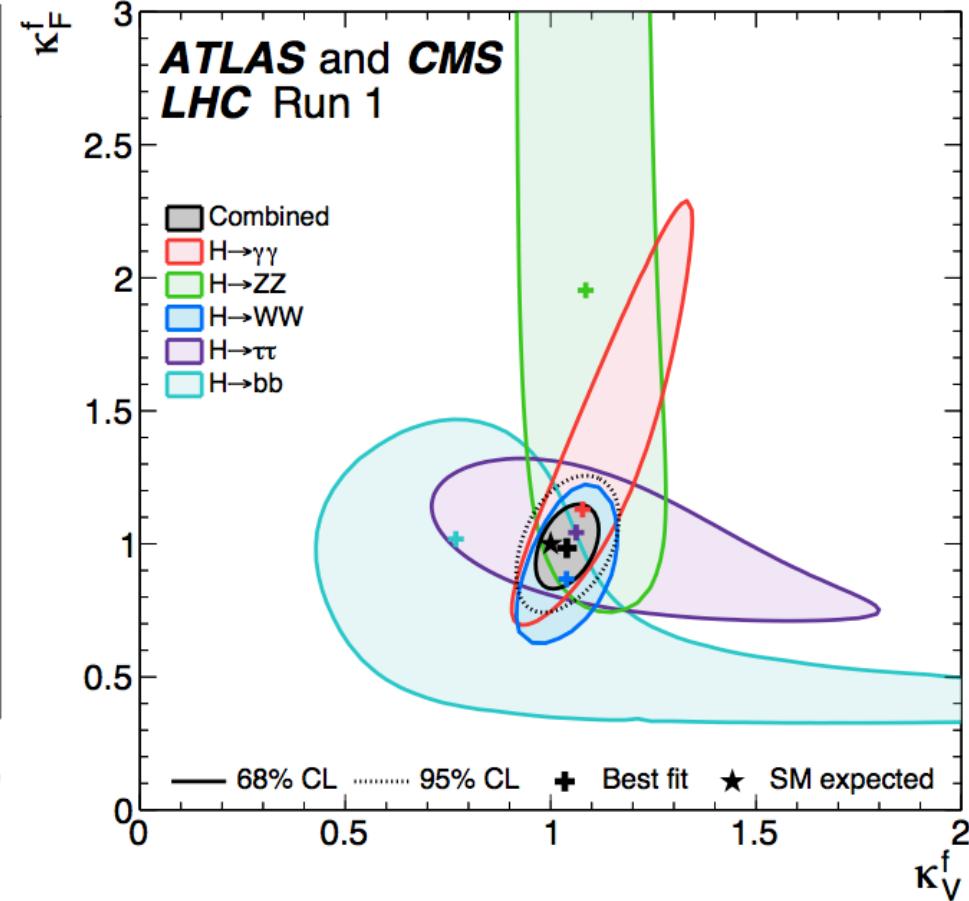
BR_{BSM} can be measured

$BR_{BSM} < 0.34$ at 95% C.L. (assuming $\kappa_V \leq 1$)

BR_{BSM} includes non standard decays, visible or invisible

⇒ Results in agreement with SM ($\kappa_V = \kappa_F = 1$) within 1σ

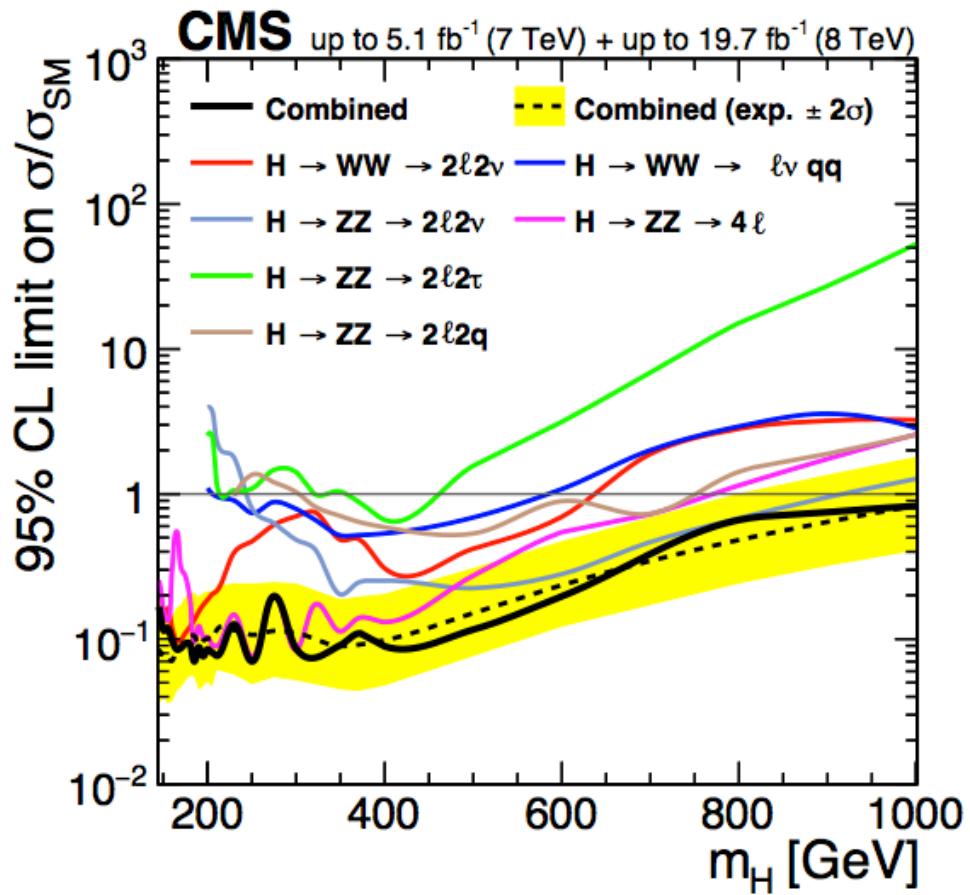
Vector and fermion couplings



High mass: $H \rightarrow WW/ZZ$

JHEP 10(2015)144

- Search for a heavy Higgs boson
 - $H \rightarrow ZZ \rightarrow 4\ell, 2\ell 2\nu, 2\ell qq$
 - $H \rightarrow WW \rightarrow 2\ell 2\nu, 2\ell qq$
- optimized separately for VBF and gluon fusion production processes
- SM-like Higgs boson excluded in 4ℓ and $2\ell 2\nu/\ell\nu qq$ channels at 95%CL in mass ranges up to 1000 GeV
- Search interpreted in BSM scenario (heavy Higgs, heavy EWK singlet state)
 - evolution of signal strength of the singlet state with modified couplings/width wrt SM.
 - assume new scalar does not decay to any new particle



Extending searches

- Minimal Supersymmetric SM (MSSM)
 - Neutral Higgs: $\phi \rightarrow \tau\tau/bb/\mu\mu$
 - Charged Higgs
- Next-to-MSSM
 - Light pseudoscalar: $h \rightarrow aa$
 - Non-SM decays: $h \rightarrow 2a \rightarrow 4\tau/4\mu$
 - Heavy Higgs: $H \rightarrow h_{125}h_{125}$ or $A \rightarrow Zh_{125}$
- FCNC: $t \rightarrow cH$

Higgs sector in the MSSM

Higgs sector in SUSY contains two scalar doublets:

- 5 physical Higgs bosons
 - 3 neutral: CP-even $\phi=h,H$ CP-odd A
 - 2 charged H^\pm

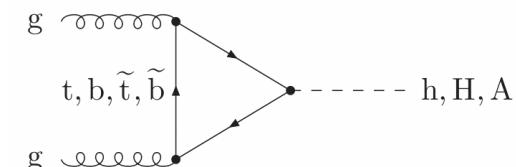
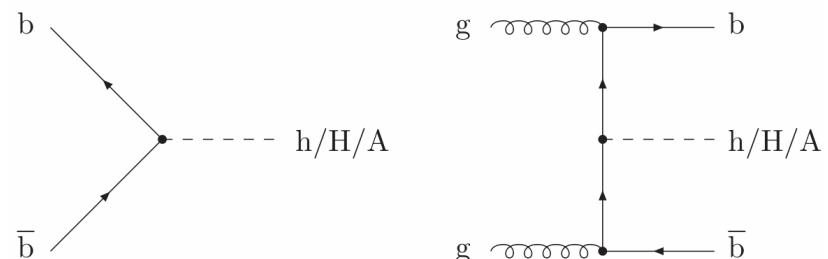
- SM-like Higgs boson: h

Neutral Higgs ϕ decay modes:

- $BR(\phi \rightarrow b\bar{b}) \sim 90\%$
- $BR(\phi \rightarrow \tau\tau) \sim 10\%$
- $BR(\phi \rightarrow \mu\mu) \sim 0.1\%$

Two main production modes:

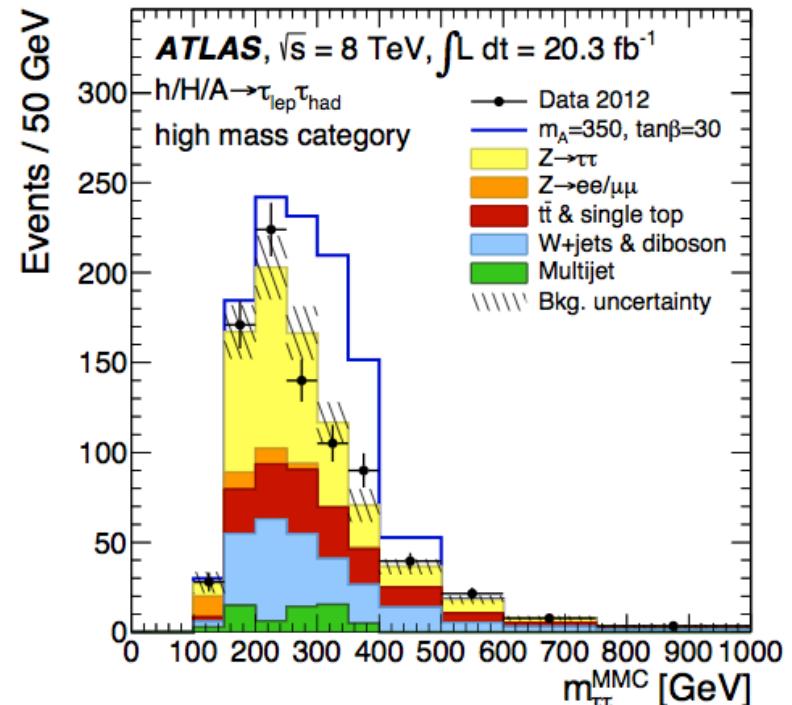
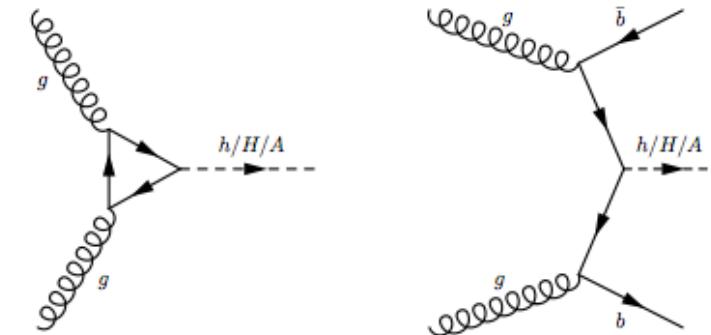
- $gg \rightarrow H$
- $b\bar{b}H$



Neutral MSSM Higgs

JHEP 10(2014)212, arXiv:1409.6064

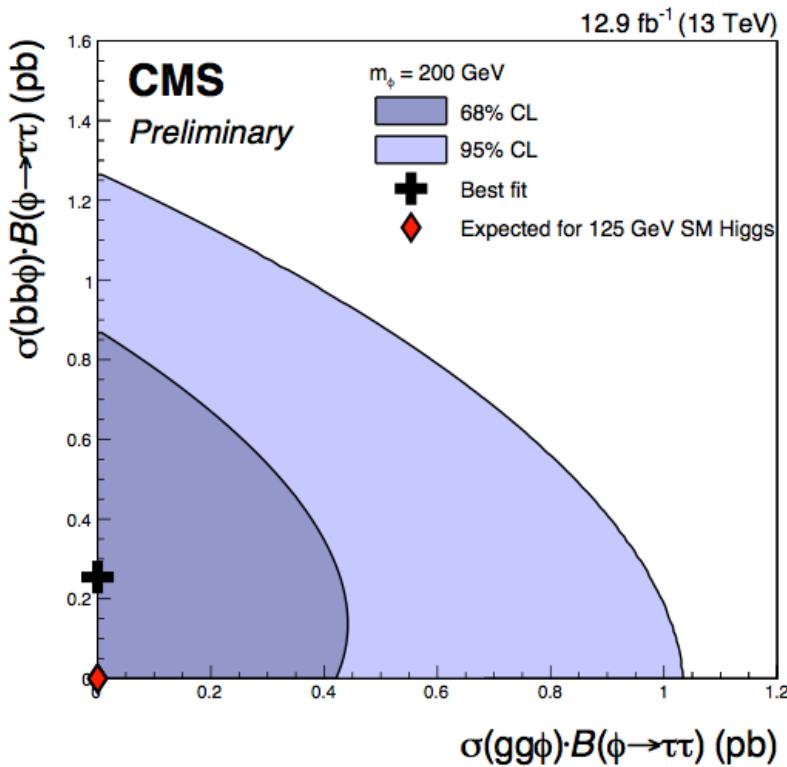
- Enhanced couplings of MSSM Higgs to down-type fermions (large $\tan\beta$)
⇒ increased BR to τ leptons and b-quarks
- Search for neutral MSSM Higgs boson
- 5 final states used: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$, $\mu\mu$
 - Reconstruct tau-pair invariant mass
 - Split in b-tag/no b-tag categories to enhance sensitivity
- Main backgrounds: $Z \rightarrow \tau\tau$, QCD/W+jets, DY, ttbar, dibosons



Neutral MSSM Higgs: $\phi \rightarrow \tau\tau$

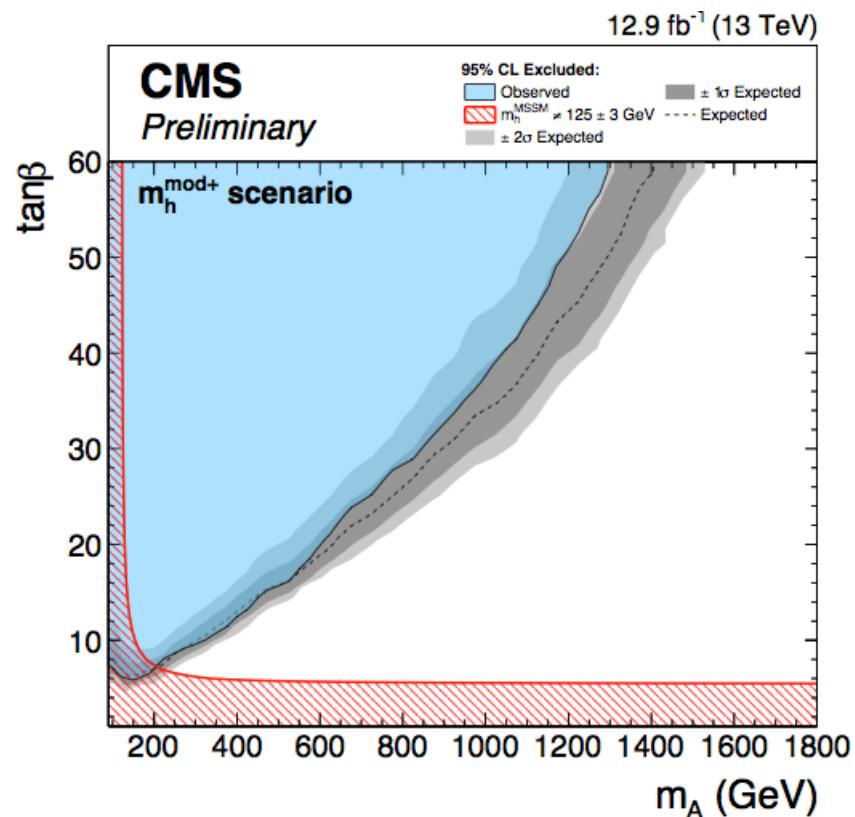
JHEP 10(2014)212, arXiv:1409.6064, CMS-HIG-16-037

- Direct search: inclusive and b-tagged
- τ in both leptonic and hadronic decays



Model-independent limits by separating production modes

$\tan\beta$ vs m_A window becoming smaller

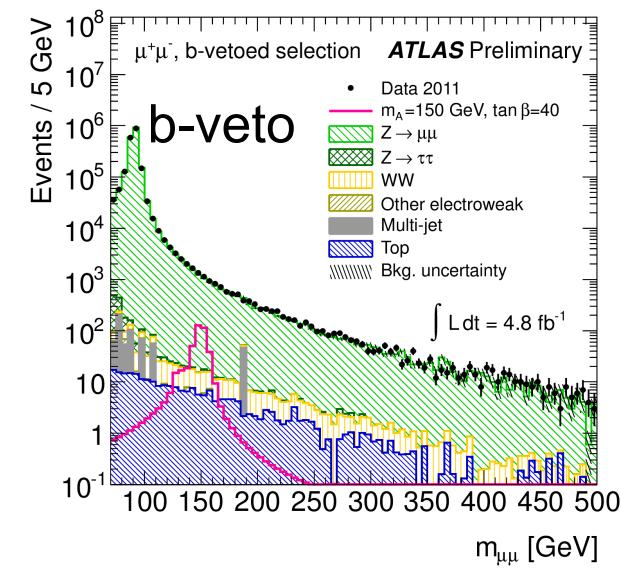
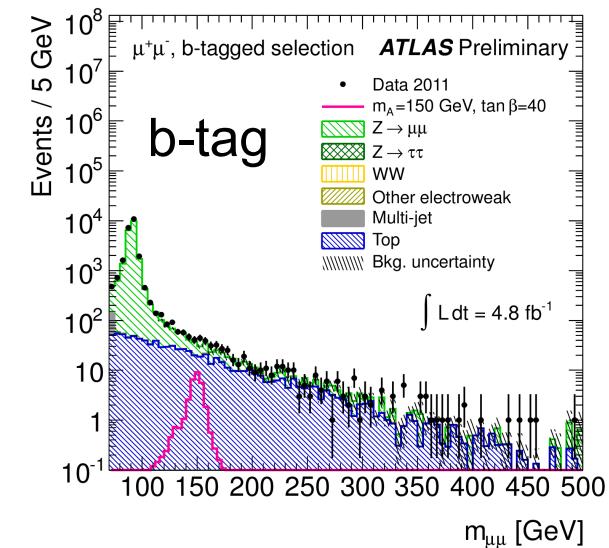
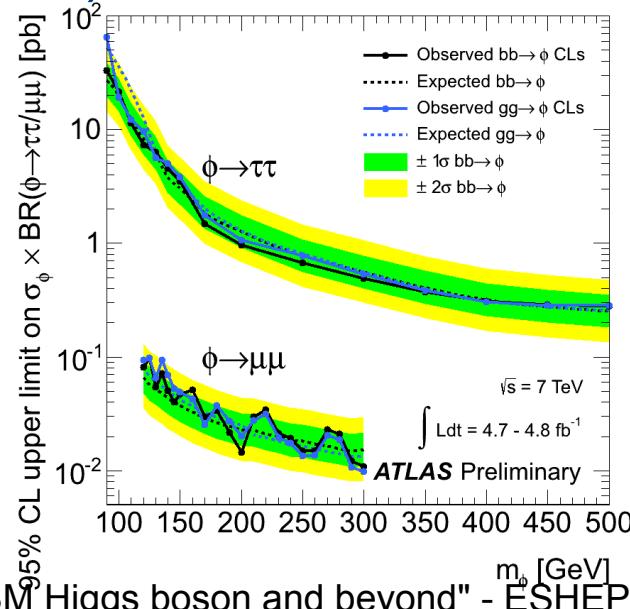
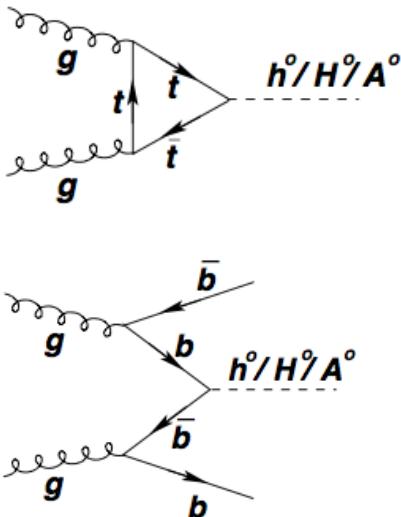


No significant excess over bkg expectations

Neutral MSSM Higgs: $\phi \rightarrow \mu\mu$

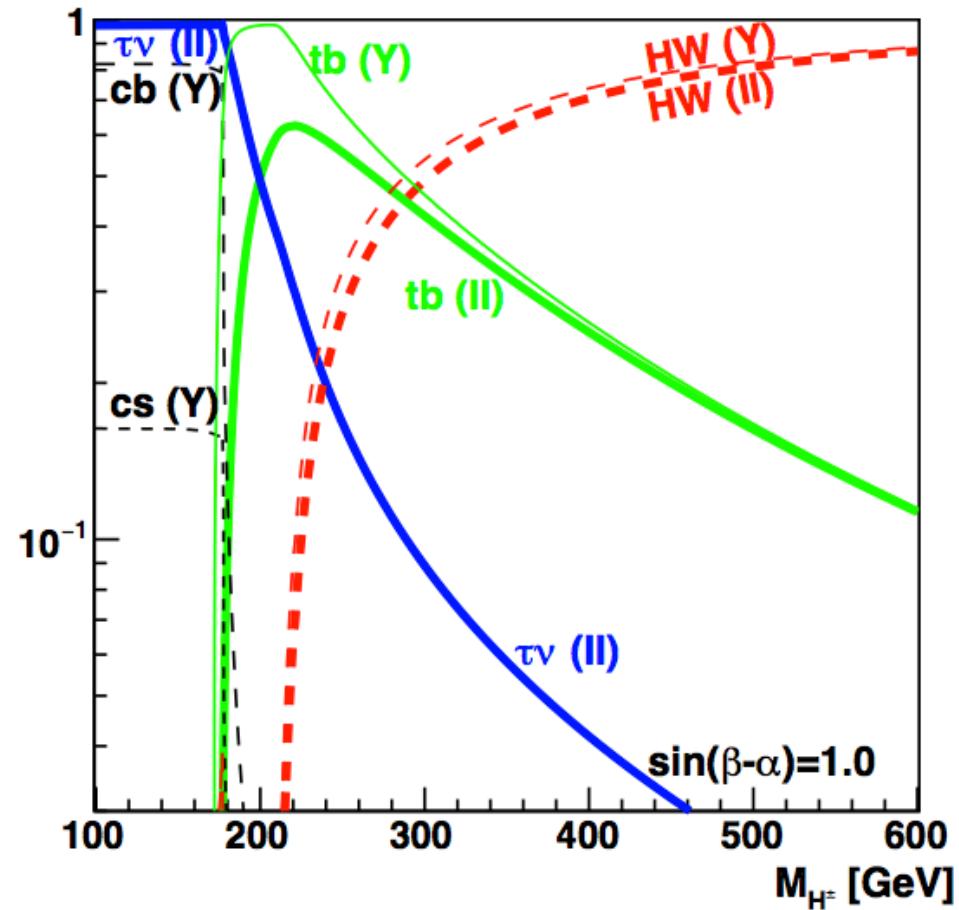
arXiv:1508.01437, ATLAS-CONF-2012-094

- Search for a $\mu\mu$ mass resonance
- Good mass resolution
 - full and clean reconstructed final state
- Split in b-tagged and non b-tagged categories to be sensitive to $gg \rightarrow \phi$ and $bb\phi$ production modes
- Main backgrounds: $Z(b\bar{b})$, $t\bar{t}$, WW



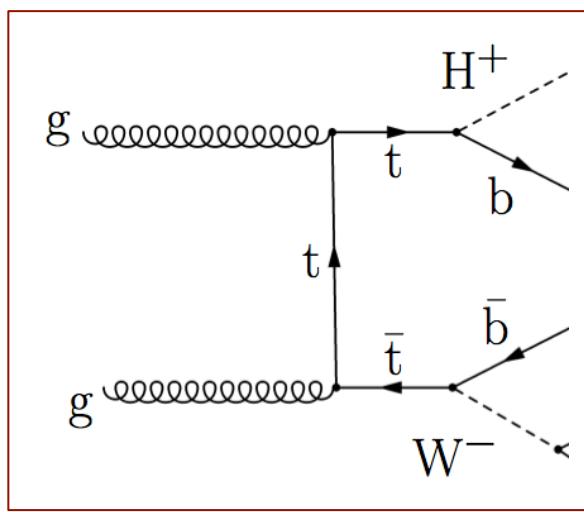
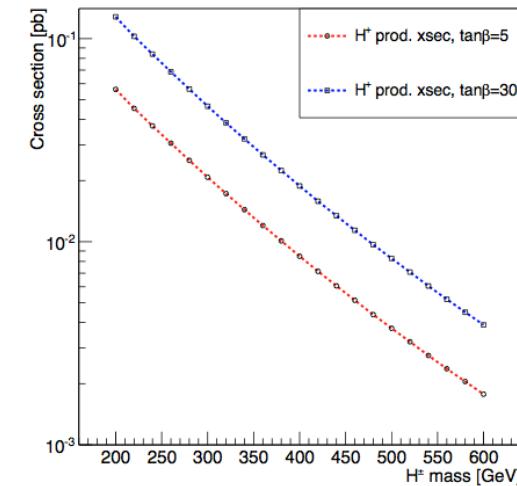
Charged Higgs

- If found, a clear indication of BSM
- Study non-SM Higgs in two mass regimes:
- $m_H < m_{top}$
 - Mostly produced in top quark decays
 - Large $\tan\beta$: $H^\pm \rightarrow \tau^\pm \nu$
 - Small $\tan\beta$ (< 1): $H^\pm \rightarrow c\bar{s}$
- $m_H > m_{top}$
 - Produced in gluon-gluon fusion
 - Main decays: $H^\pm \rightarrow tb$, $H^\pm \rightarrow \tau^\pm \nu$
- Main backgrounds: ttbar, W+jets

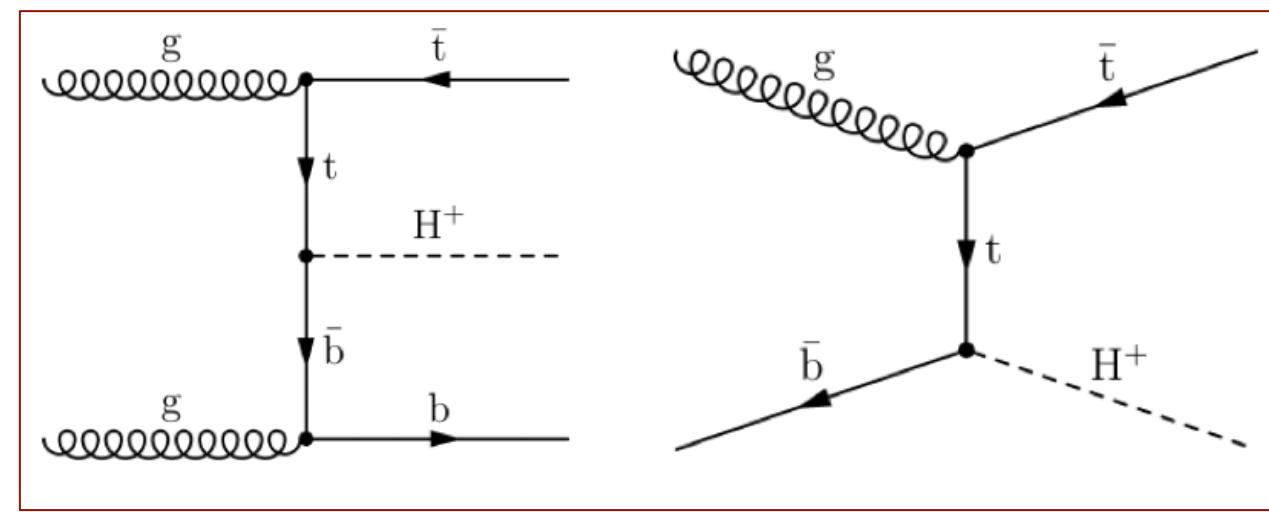


Charged Higgs (cont.)

- Different strategies for low- and high-mass searches
- tau+lepton, lep+jets, and eμ final states
- b-tagged jet categorization
- limited by statistics at high-mass



$m_H < m_{top}$

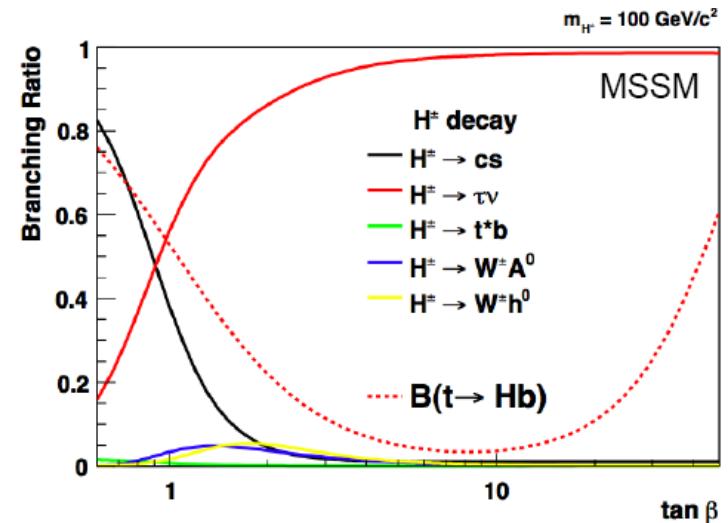


$m_H > m_{top}$

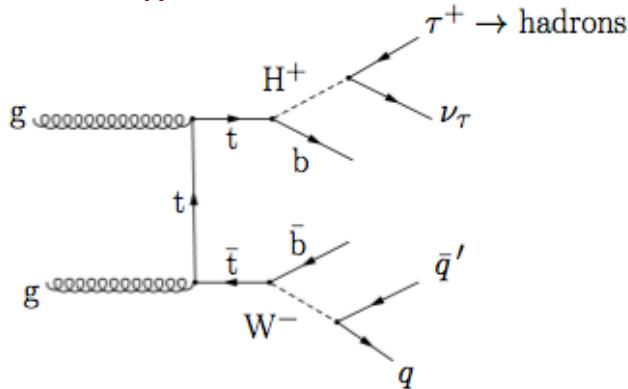
Charged Higgs and top quark decays

JHEP 07(2012)143, arXiv:1508.07774, HIG-16-031

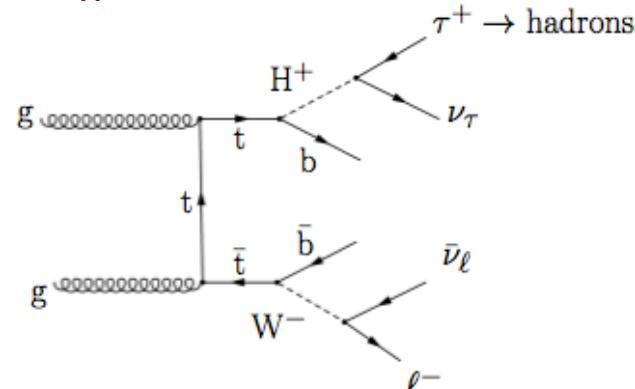
- Look for charged Higgs in four final states:
 - Tau+lepton (electron or muon)
 - Dilepton (tau decays leptonically)
 - lepton+jets
 - Fully hadronic: tau+jets



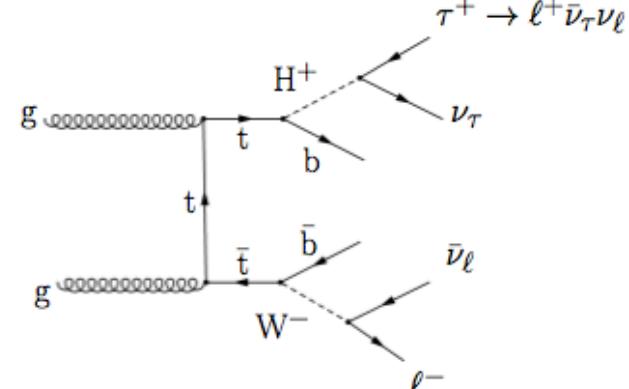
$\tau_h + \text{jets}$



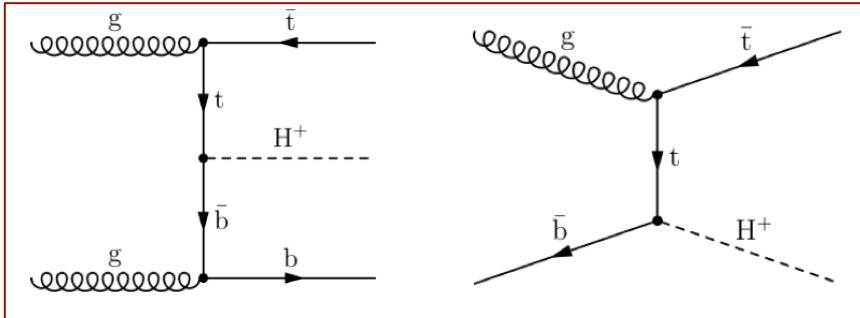
$\tau_h + \text{lepton (e/\mu)}$



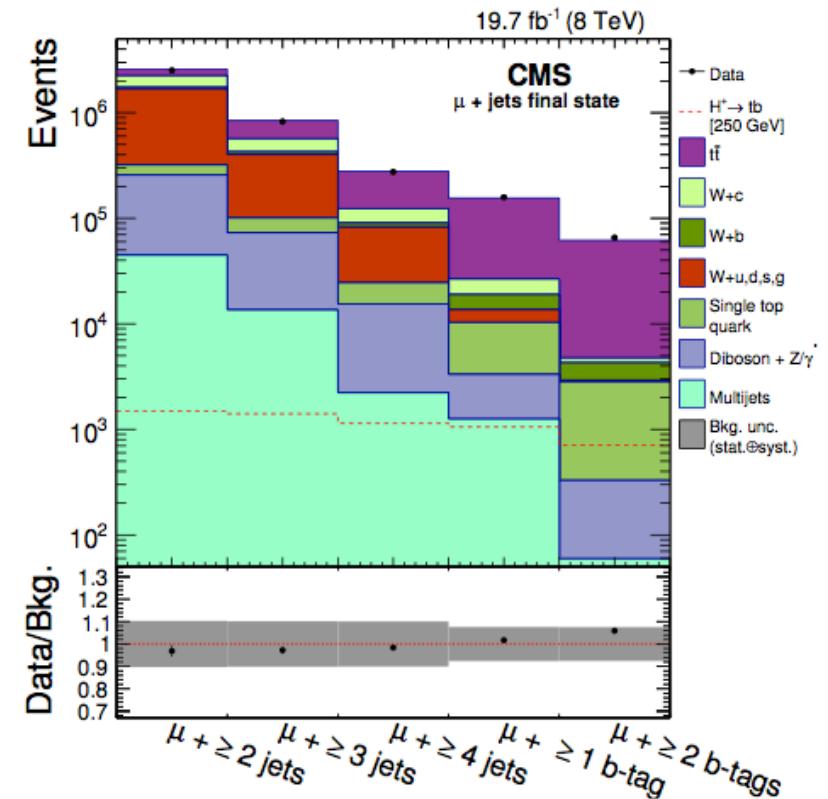
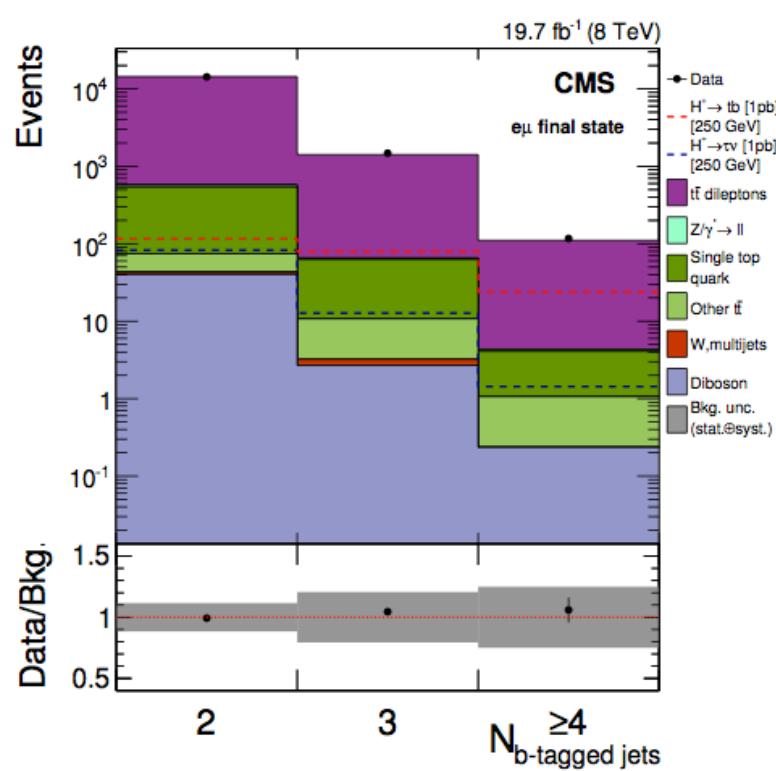
di-lepton ($e\mu$)



Number of b-tagged jets



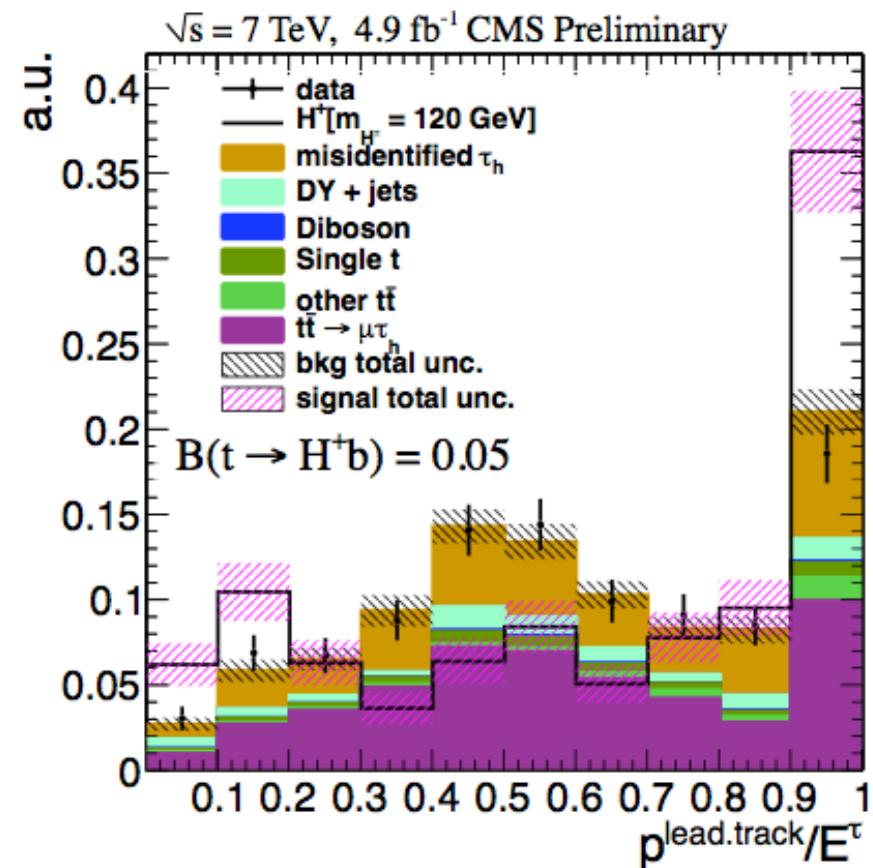
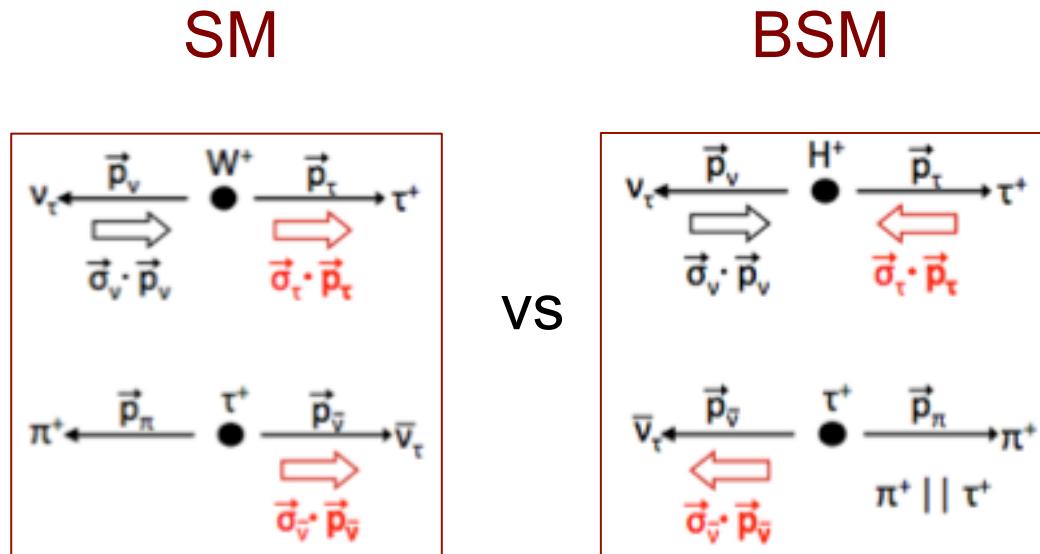
High-mass H^+ search:
look at b-tag multiplicity



Looking at tau decays

CMS-HIG-12-052

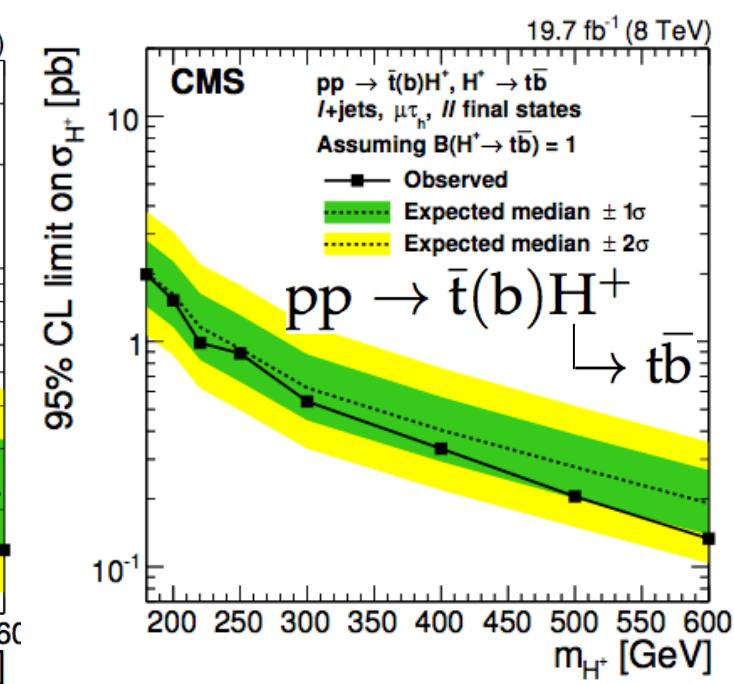
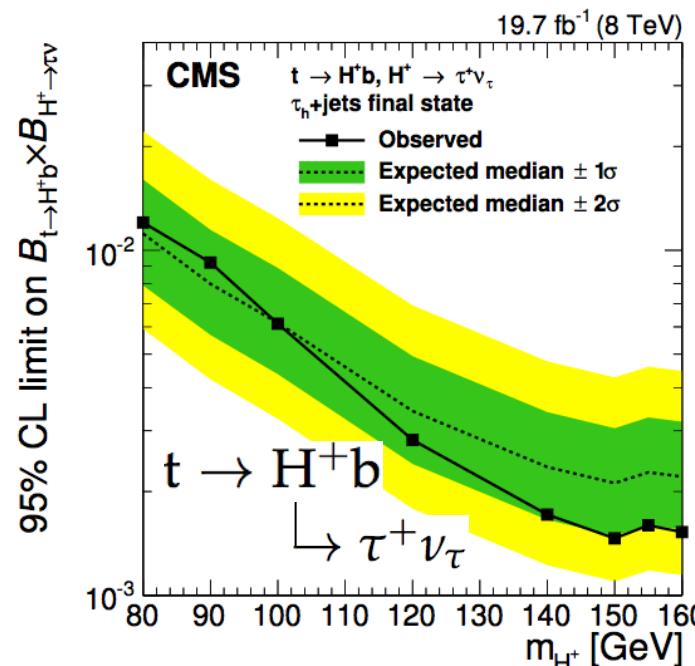
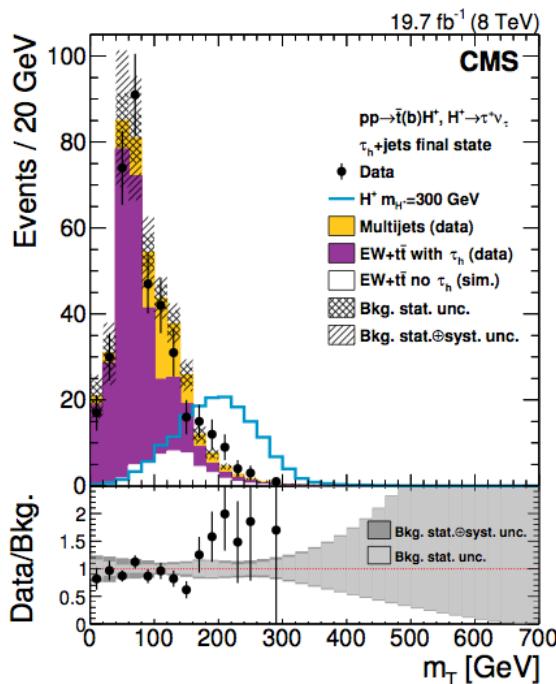
- Use R variable in the limit extraction: binned maximum-likelihood fit
- Tau fake component is data-driven, includes uncertainties



Is there a charged Higgs?

JHEP 07(2012)143, CMS-HIG-12-052, arXiv:1508.07774

- If anomalous tau-lepton production in ttbar decays there may be contribution from H^+
Yields in agreement with expectations \Rightarrow set limits



At 13TeV, expect improvement
with 5-10/fb for $m_{H^+} > 300\text{GeV}$

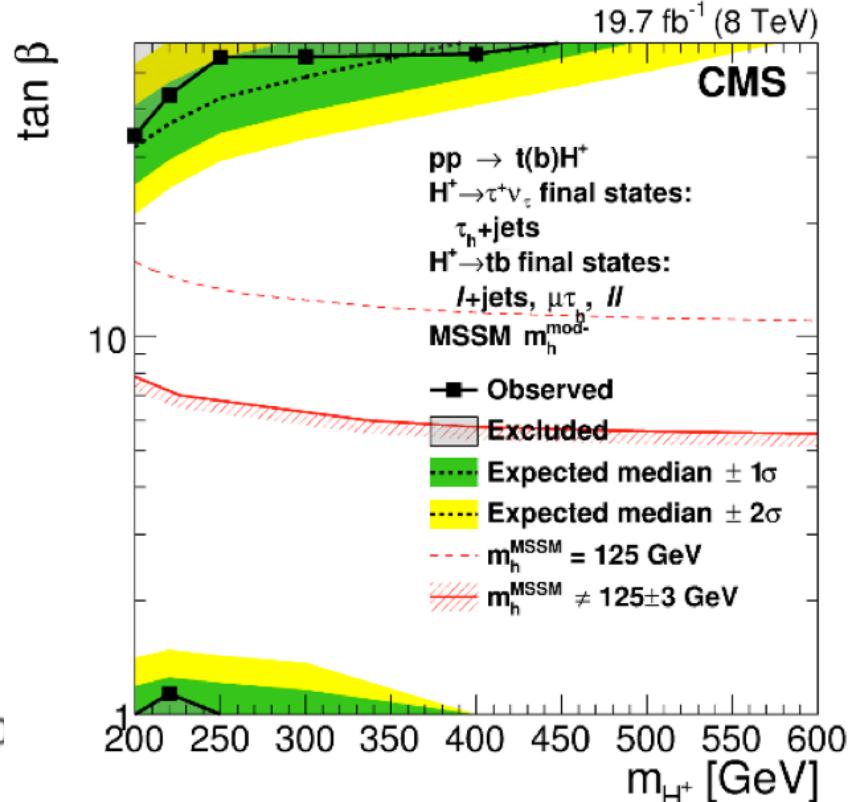
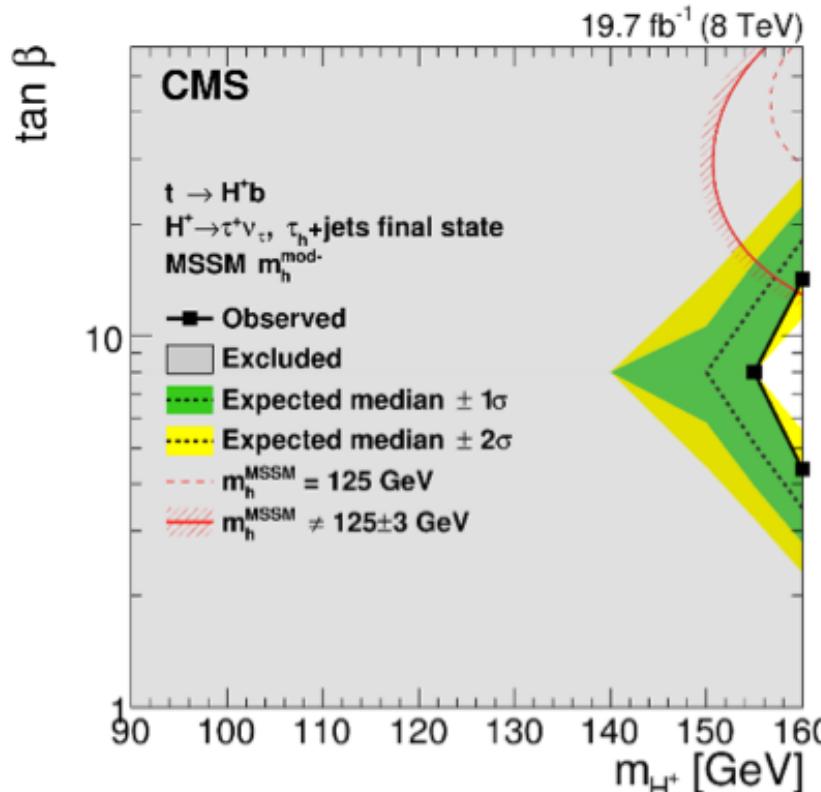


- ttbar xsection increases x3.3
- signal increases x6(x7) for $m_{H^+} = 500(600)\text{GeV}$

Still hope for MSSM?

JHEP 07(2012)143, CMS-HIG-12-052, arXiv:1508.07774

- A new modified MSSM scenario: m_h^{mod} (arXiv:1302.7033)
- Reduce amount of mixing in the stop sector (X_t/M_{SUSY})
- A/H decays to chargino/neutralinos allowed (arXiv:0709.1029)
- Allows for reduction of decays into $\tau\tau$ and bb



Cross section ratios

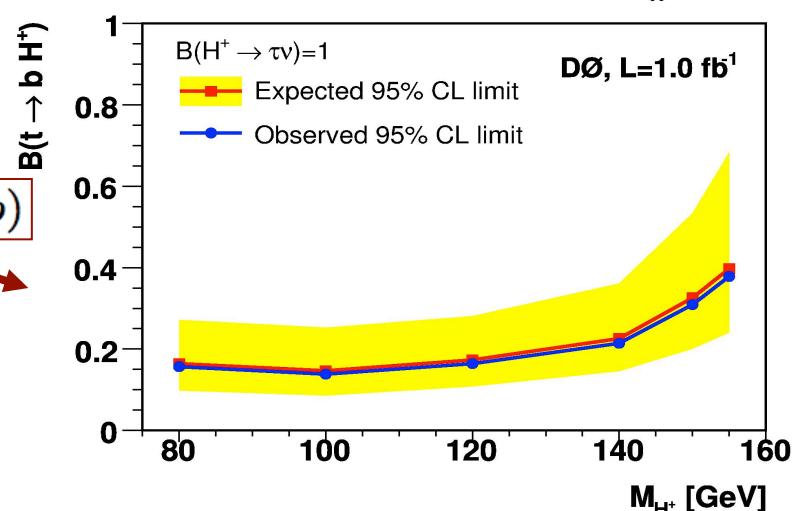
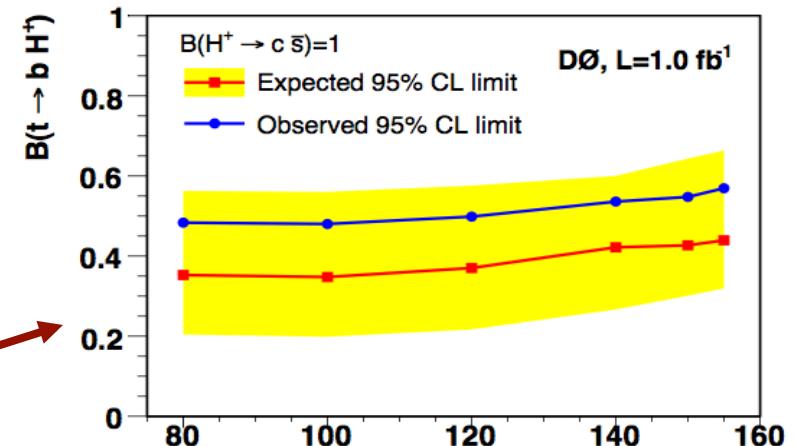
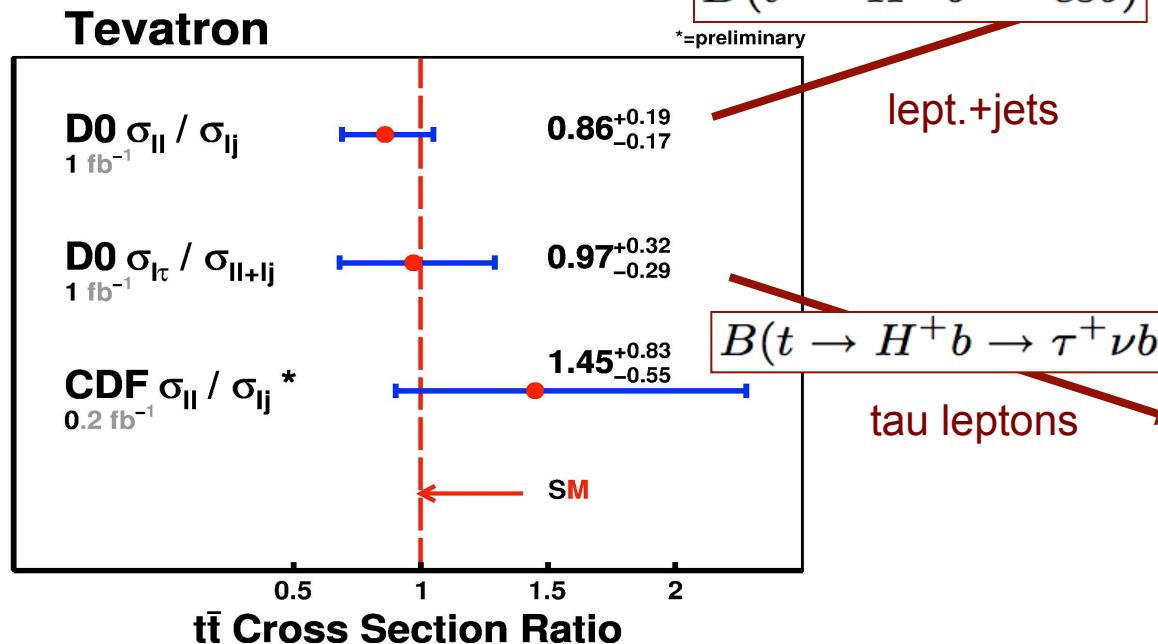
PRD 80(2009) 071102

Many systematic unc. cancel in the ratio

Study of cross section ratios

⇒ sensitive to BSM

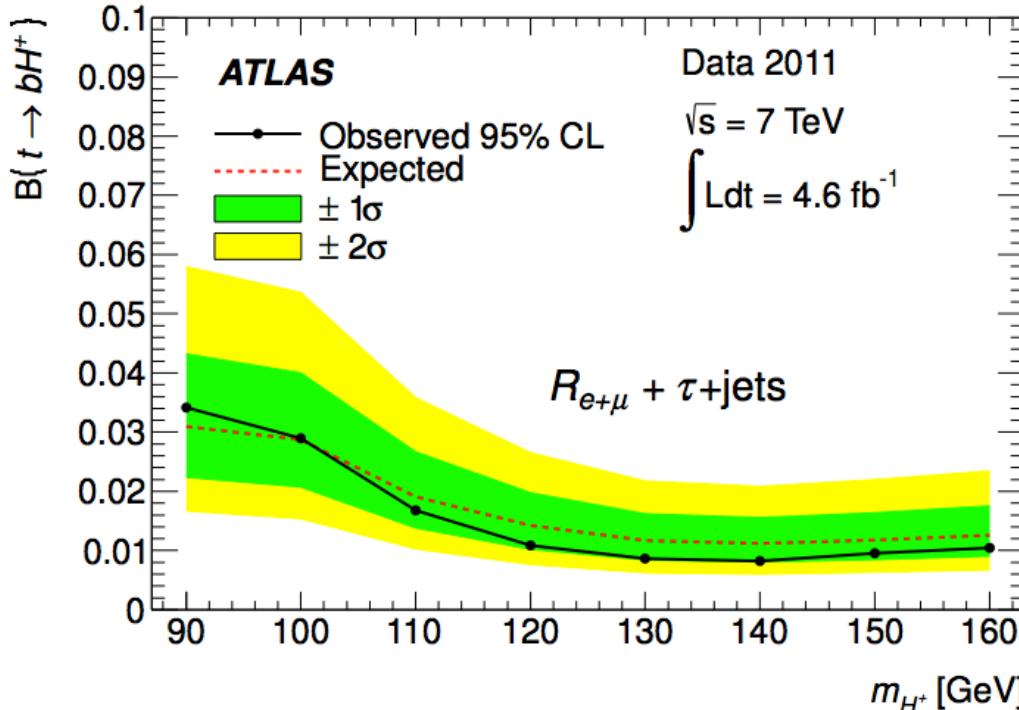
1. BR(I+jets)/BR(II)
2. BR(I+tau)/BR(II)



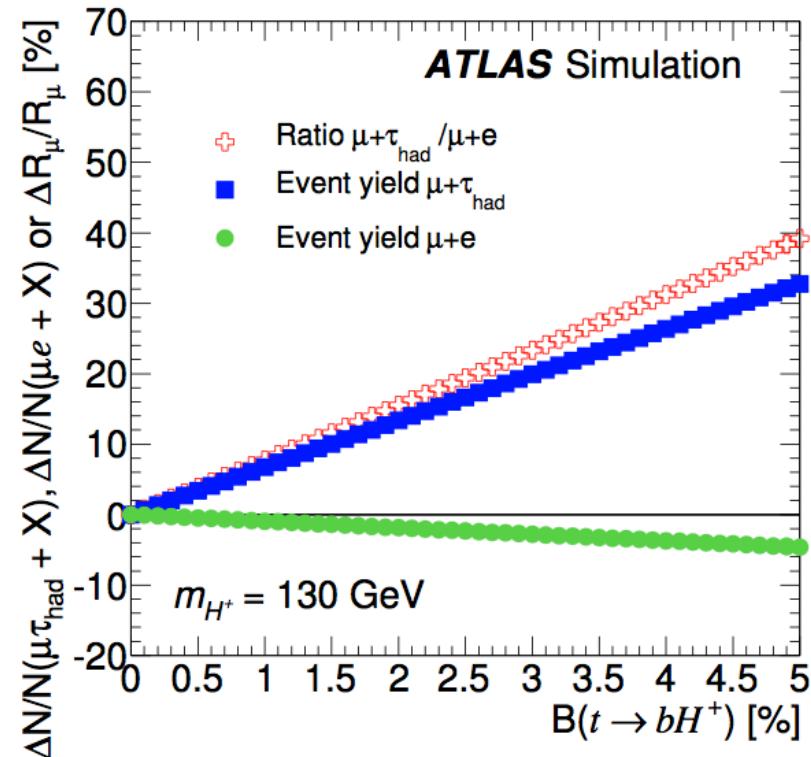
Combination of more channels

JHEP 03(2013)076

- Search for charged Higgs boson
- Use $\tau_{\text{had}} + \text{lep}$ and $\tau_{\text{had}} + \text{jets}$ final states
 - compare to $e\mu$ yields
- Search for anomalous decays



M. Gallinaro - "The SM Higgs boson and beyond" - ESHEP2016 - Dec. 3-8, 2016

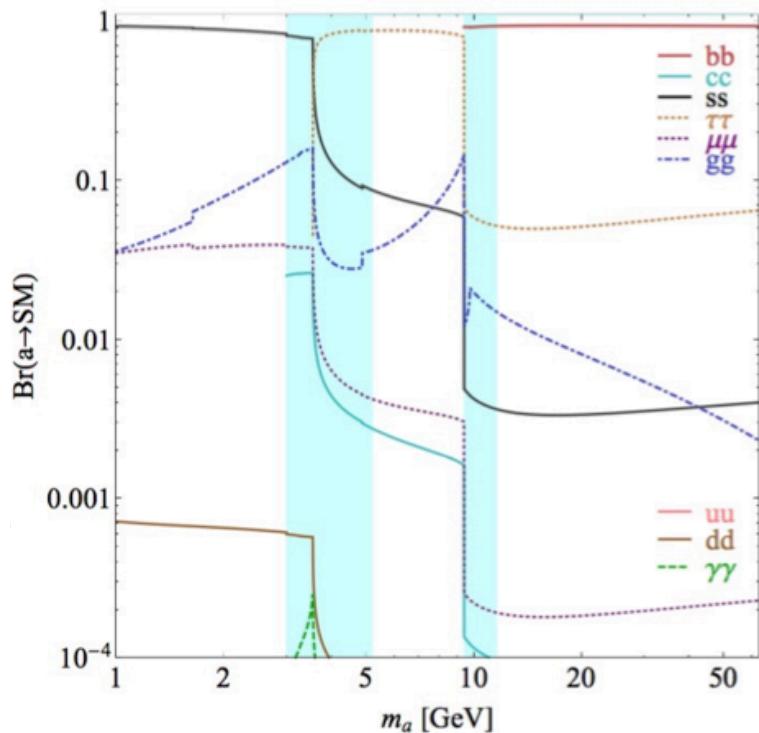
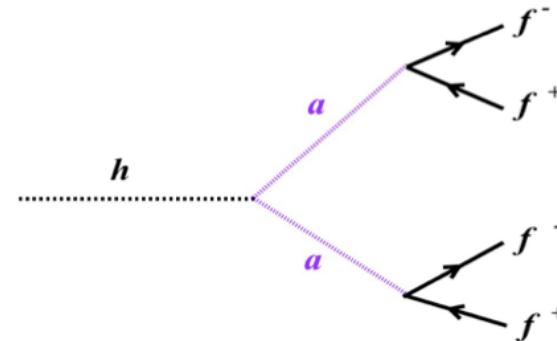


Set limits on:

$$\mathcal{B}(t \rightarrow bH^+)$$

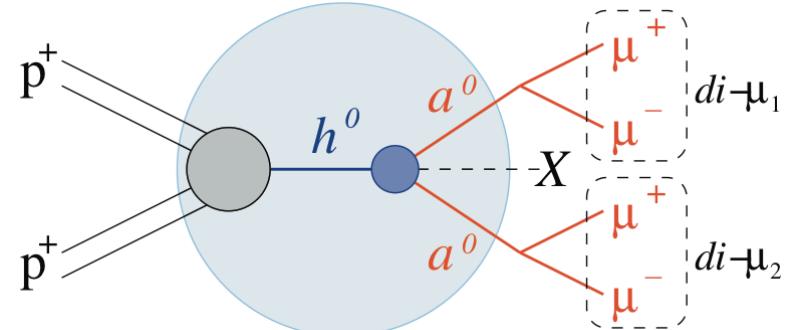
non-SM Higgs decay: $h \rightarrow aa \rightarrow 4X$

- Standard search for light (pseudo)- scalar Higgs with $m_a < m_h/2$
 - generic prediction of BSM theories (extended Higgs sector, NMSSM, etc)
 - Final states go to fermions (b, τ, μ, \dots)
 - BR depends on boson mass, model parameters

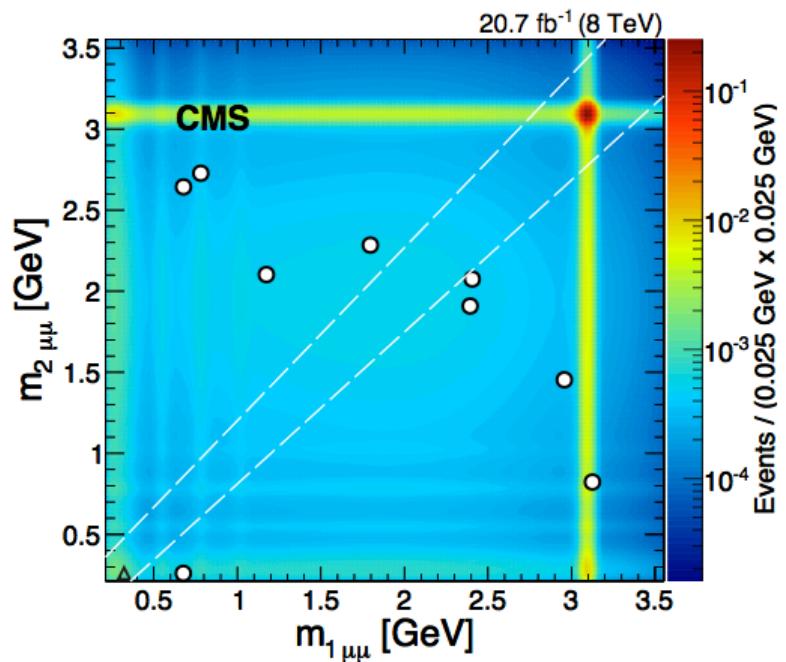


non-SM Higgs decay: $h \rightarrow aa \rightarrow 4\mu$

PLB 726(2013)564, arXiv:1506.00424, HIG-16-035



- Explore non-SM decays of a Higgs boson (h)
 - Higgs boson (h) can be SM or not
 - include production of two new light boson (a^0)
- Search for generic Higgs decays: $h \rightarrow 2a + X \rightarrow 4\mu + X$
 - Require two dimuon pairs with consistent masses
 - Observe 9 events in off-diagonal region
 - Signal region: **1 event** (2.2 ± 0.7 bkg)
 - Limits on production rates, benchmark models



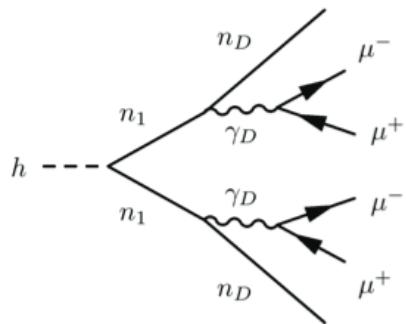
NMSSM and Dark SUSY Limits

PLB 726(2013)564, arXiv:1506.00424, HIG-16-035

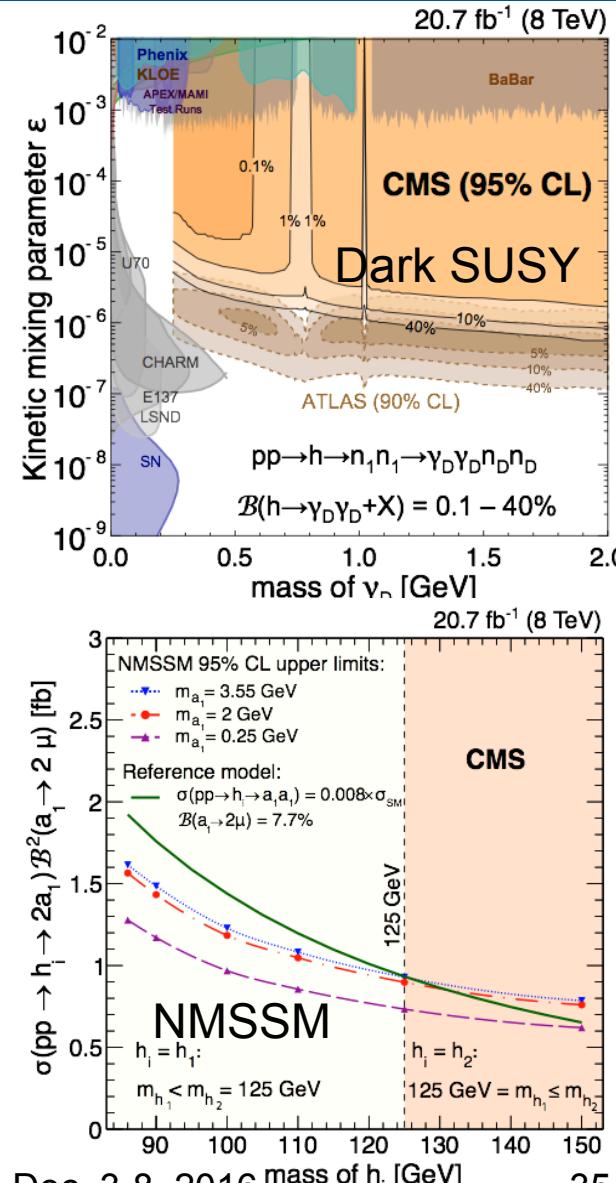
Results interpreted in NMSSM and dark SUSY

- Dark SUSY: h decay to pair of neutralinos (n_1): LSP

$$n_1 \rightarrow n_D \gamma_D \text{ decays} \quad \begin{cases} \mu^+ \mu^- \\ \text{invisible} \end{cases}$$



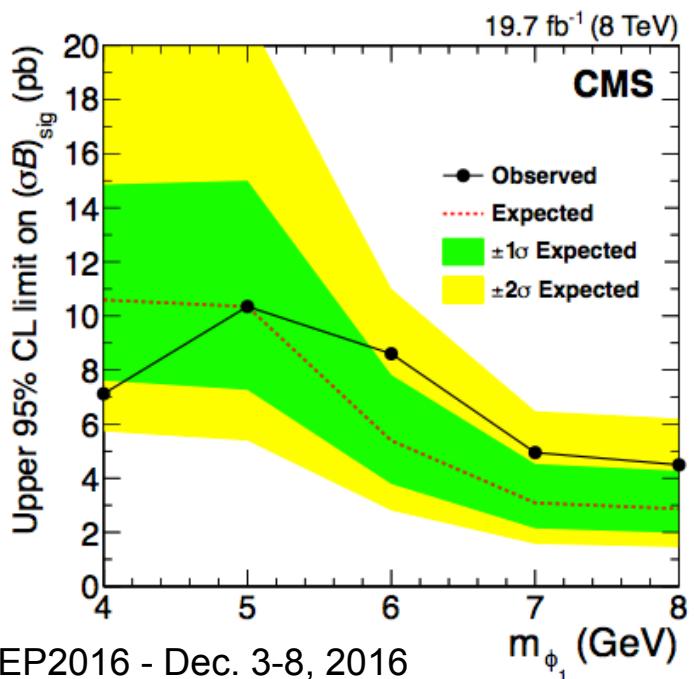
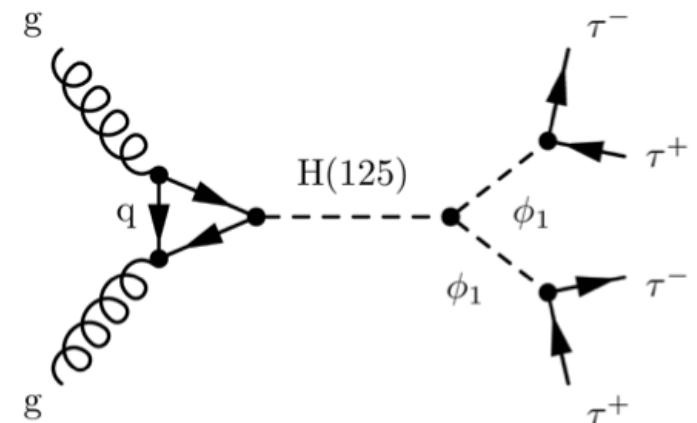
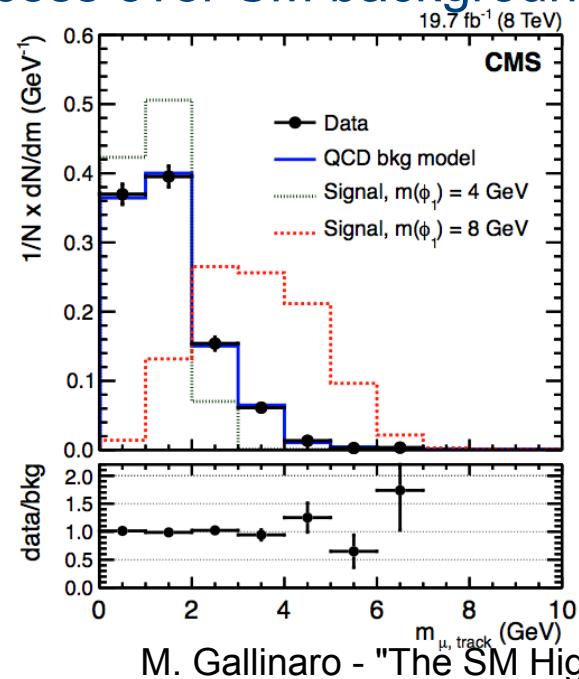
- NMSSM: Extend MSSM by adding a complex singlet field (1 CP-even+1 CP-odd boson)
- NMSSM: $h_{1,2} \rightarrow 2a_1; a_1 \rightarrow 2\mu$
- Compare to SM Higgs cross section



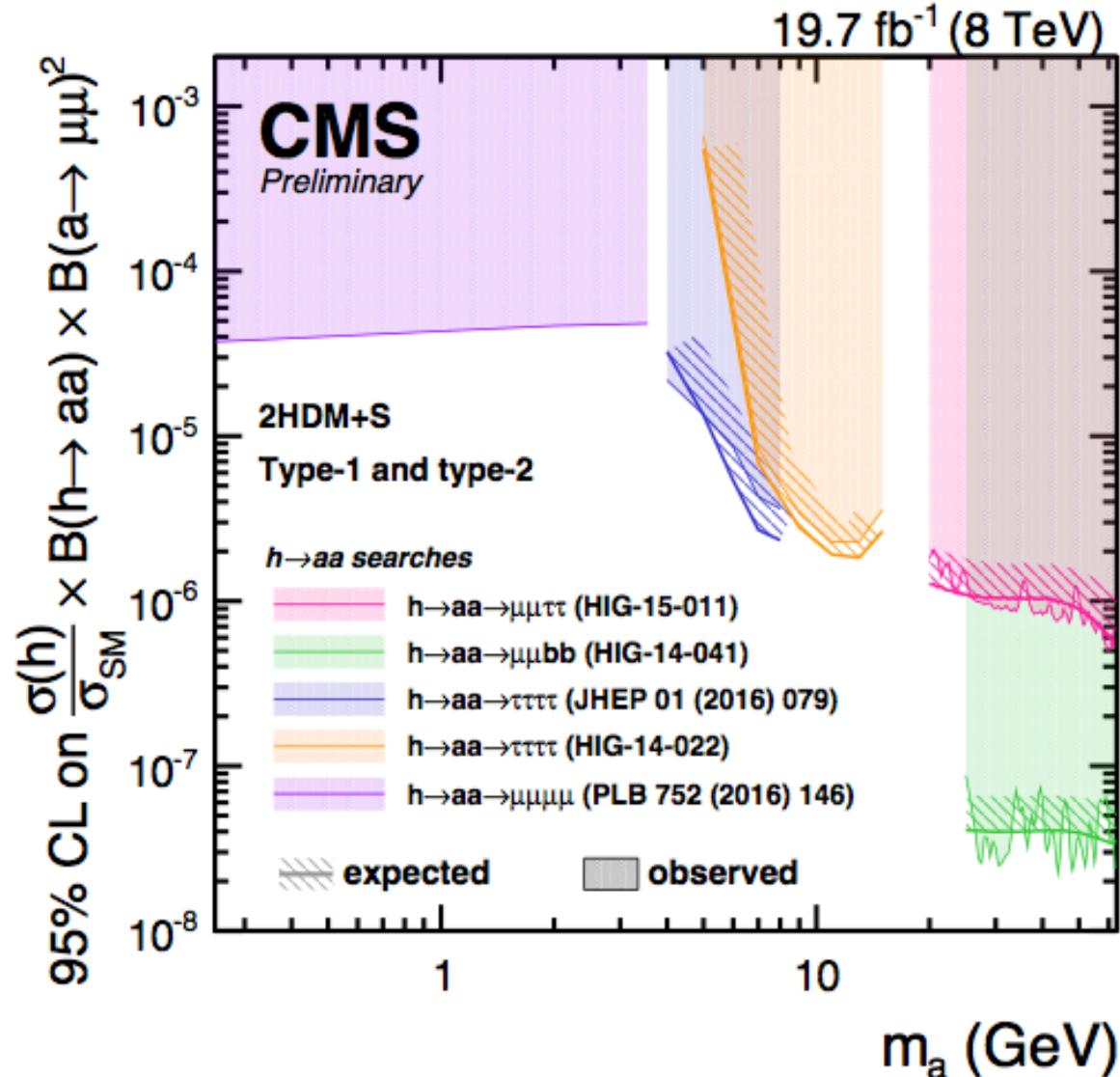
non-SM Higgs decay: $H_{125} \rightarrow 2h(a) \rightarrow 4\tau$

JHEP01(2016)079

- Search for very light Higgs in NMSSM
 - $h_{1,2}$ (CP-even), $a_{1,2}$ (CP-odd) to a pair of τ leptons
 - $H(125) \rightarrow h_1 h_2 (a_1 a_2) \rightarrow 4\tau$
- Reconstruct μ -track invar. mass (m_1, m_2)
 - SS dimuon sample (removes DY)
 - bin in 2-dim distribution, fit signal and bkg
 - QCD bkg from control region
- No excess over SM backgrounds



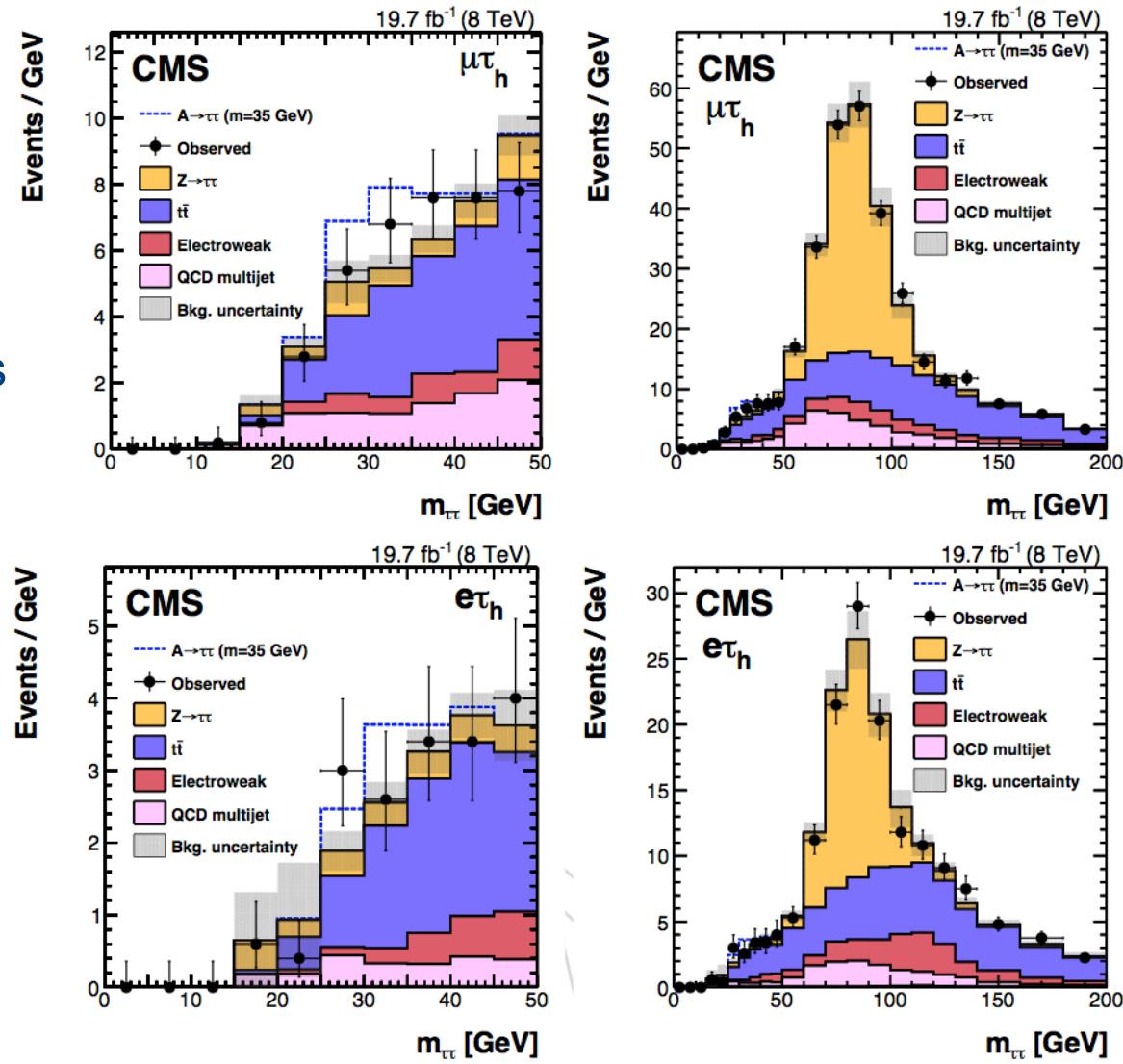
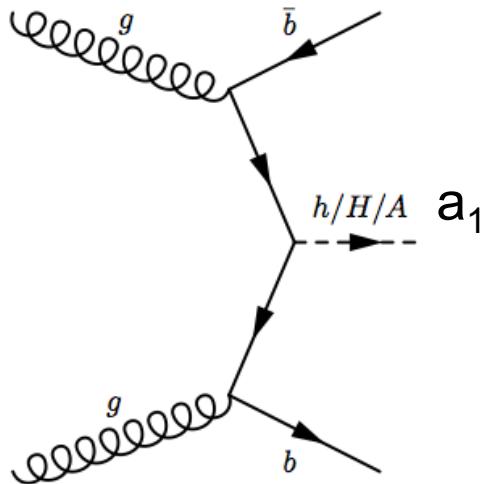
Summary for Higgs exotic decays



Low mass Higgs: $a_1(\rightarrow\tau\tau)bb$

PLB758(2016)296

- Low mass Higgs in the NMSSM
- Low mass pseudo-scalar ($a_1 \rightarrow \tau\tau$) in association with bbar: $a_1 bb \rightarrow \tau\tau bb$
- Similar strategy to $H \rightarrow \tau\tau$
- Search for a_1 masses below Z mass
- No evidence for signal
- Set limits: $\sigma x B \sim 9-39$ pb

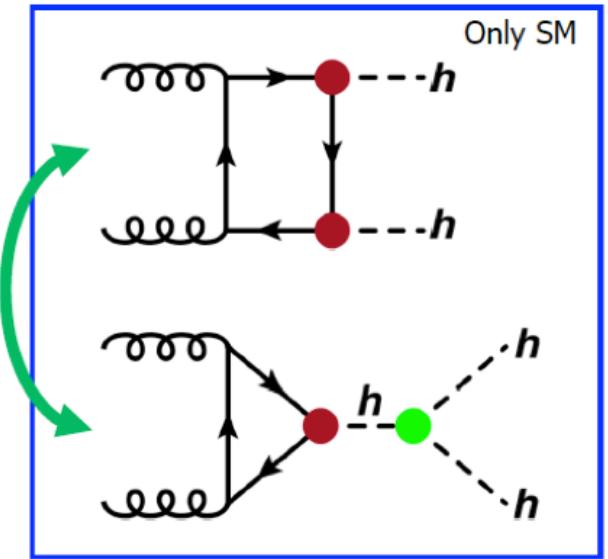


di-Higgs searches

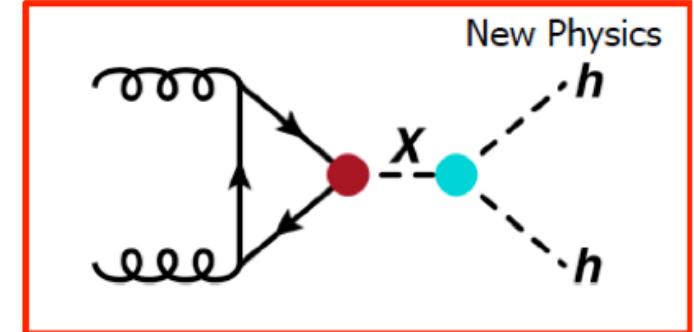
- Destructive interference in SM
- Could be altered in BSM
- If constructive, it could be large enhancement
- In SM, only $\sigma=38\text{fb}$ at 13 TeV
- Study different final states

	BR	Mass scale
$b\bar{b}bb$	34%	
$b\bar{b}\tau\tau$	7.3%	High
$b\bar{b}WW$	27%	
$b\bar{b}\gamma\gamma$	0.26%	Low

non-resonant production

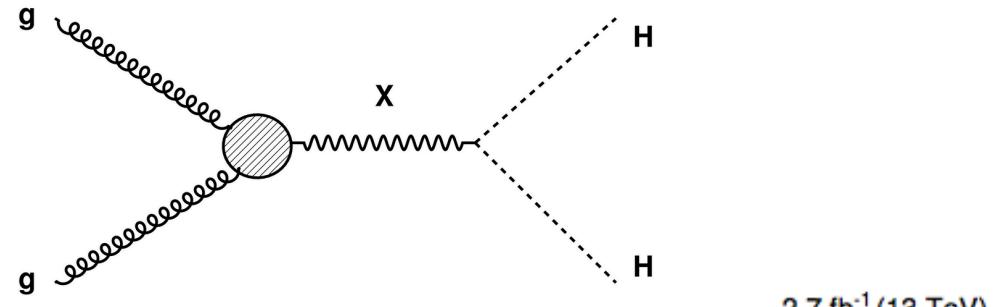
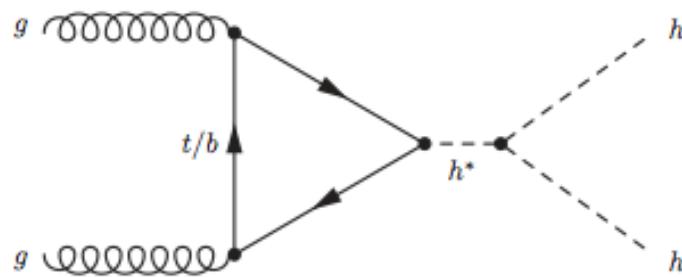


resonant production

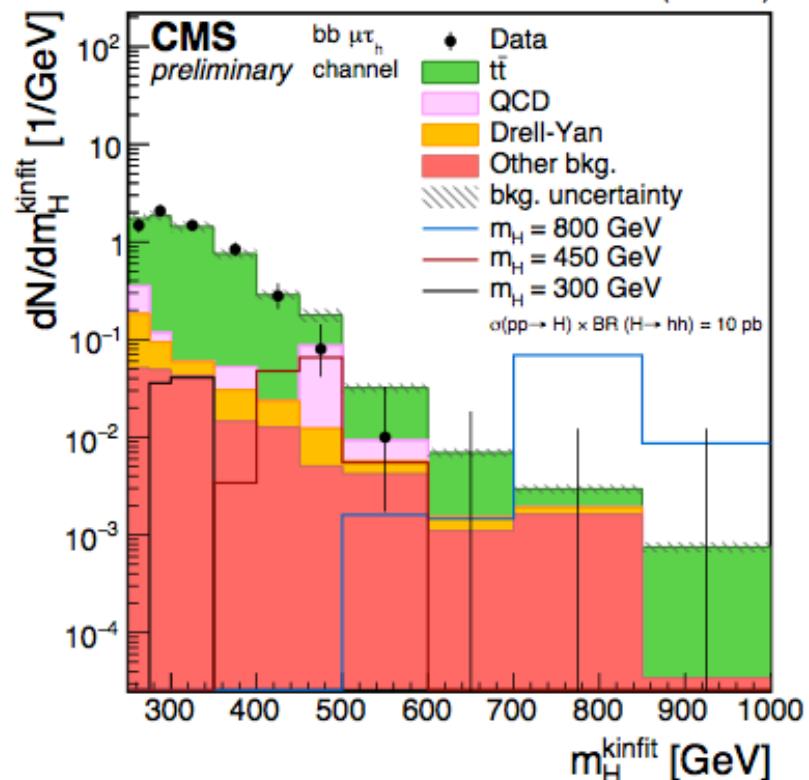


Heavy Higgs to $h_{125} h_{125} \rightarrow \tau\tau bb$

CMS-EXO-15-008, CMS-HIG-16-012, CMS-HIG-16-013



- Resonant and non-resonant production
 - Double Higgs production to determine λ_{hhh}
 - BSM models could enhance non-resonant hh production
 - $H \rightarrow h_{125} h_{125} \rightarrow bb\tau\tau$
- h_{125} decay products nearly collinear
- boosted “single” merged jet ($\rightarrow bb$)
- use $\tau_e \tau_h$, $\tau_\mu \tau_h$, and $\tau_h \tau_h$ final states
- sidebands/inverted isolation to determine bkg
- set limits on spin-0 resonance at 850-30fb for $M_X=0.8-2.5$ TeV



Heavy Higgs: $H \rightarrow h_{125} h_{125}$, $A \rightarrow Z h_{125}$

PRD90(2014)112013, PLB755(2016)217

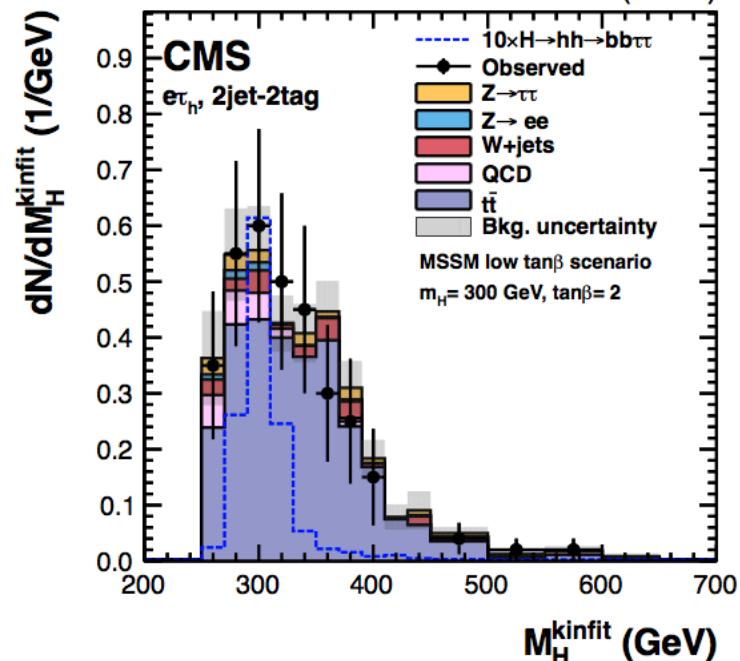
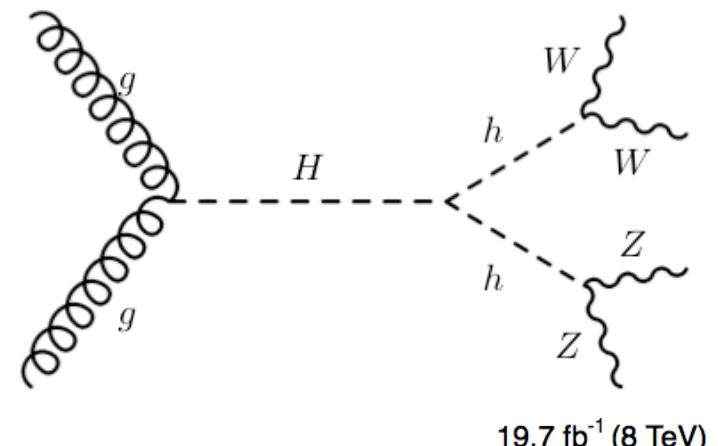
- MSSM: Heavy Higgs searches
 - Search for $A \rightarrow Z h_{125}$ and $H \rightarrow hh$
- Exclusive search in multilepton and diphoton +lepton channels
 - Also $bb\tau\tau$ (hh), or $ll\tau\tau$ (Zh)
 - exclusive channels (leptons, taus, photons, $N_{b\text{tags}}$, etc.)

⇒ No excess in data, set limits

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \rightarrow u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \rightarrow uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \rightarrow uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \rightarrow c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \rightarrow cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \rightarrow cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

FCNC decays

- Also search for $t\bar{t} \rightarrow (bW)(ch)$
 - Not forbidden but highly suppressed
 - enhanced w/some parameter models
- $\text{BR}(t \rightarrow cH) < 0.56\% \text{ (0.65\%) @95\% CL}$

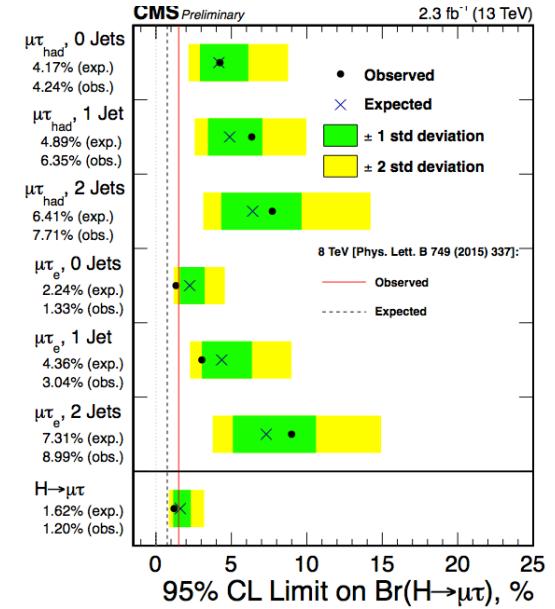
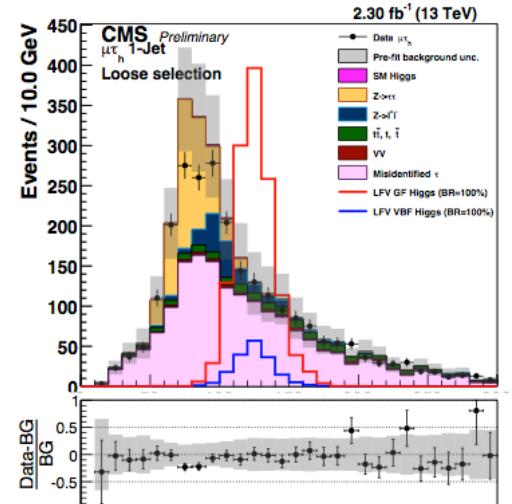


LFV in Higgs decays

CMS-HIG-14-040, CMS-HIG-16-005

- Some BSM models allow for LFV Higgs decays
- Search for $H \rightarrow e\tau, e\mu, \mu\tau$ final states
- Categories: N_{jet} , lepton kinematics
 - N_{jet} to target ggH and VBF production
- Main background from DY, ttbar, WW
- Mild excess in Run1 not confirmed in Run2

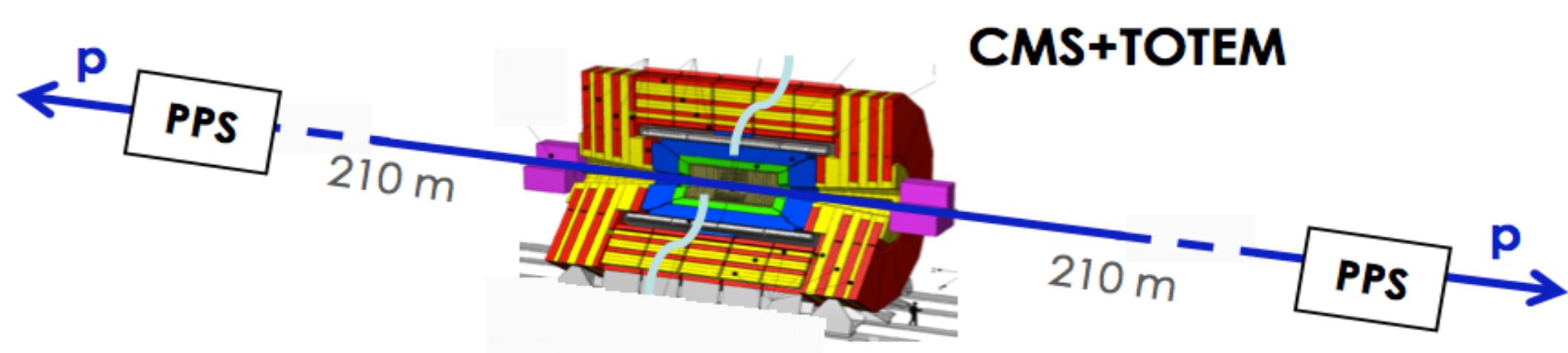
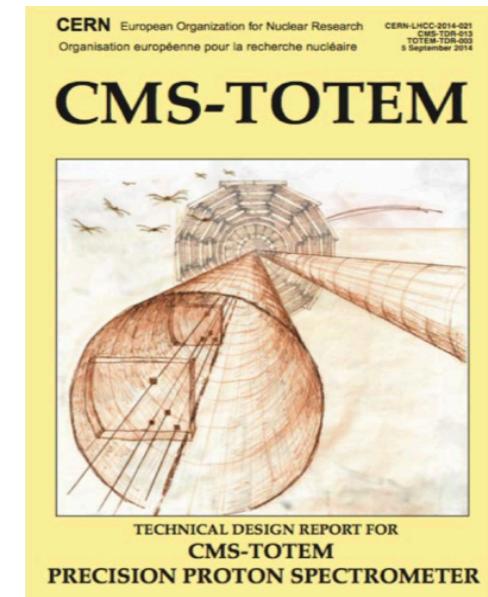
	95%CL (obs/exp)	Best fit
$h \rightarrow \mu\tau$ (run1)	$<1.51/0.75\%$	$0.84^{+0.39}_{-0.37}\%$
$h \rightarrow \mu\tau$ (run2)	$<1.20/1.62\%$	$-0.76^{+0.81}_{-0.84}\%$



Looking forward: CT-PPS

CERN-LHC-2014-021

- The Precision Proton Spectrometer is a joint CMS and TOTEM project that aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
- Tracking and timing detectors inside the beam pipe at ~210m from IP5
- Project approved in Dec. 2014 by LHCC
- Data taking started in 2016 (full scope from 2017)



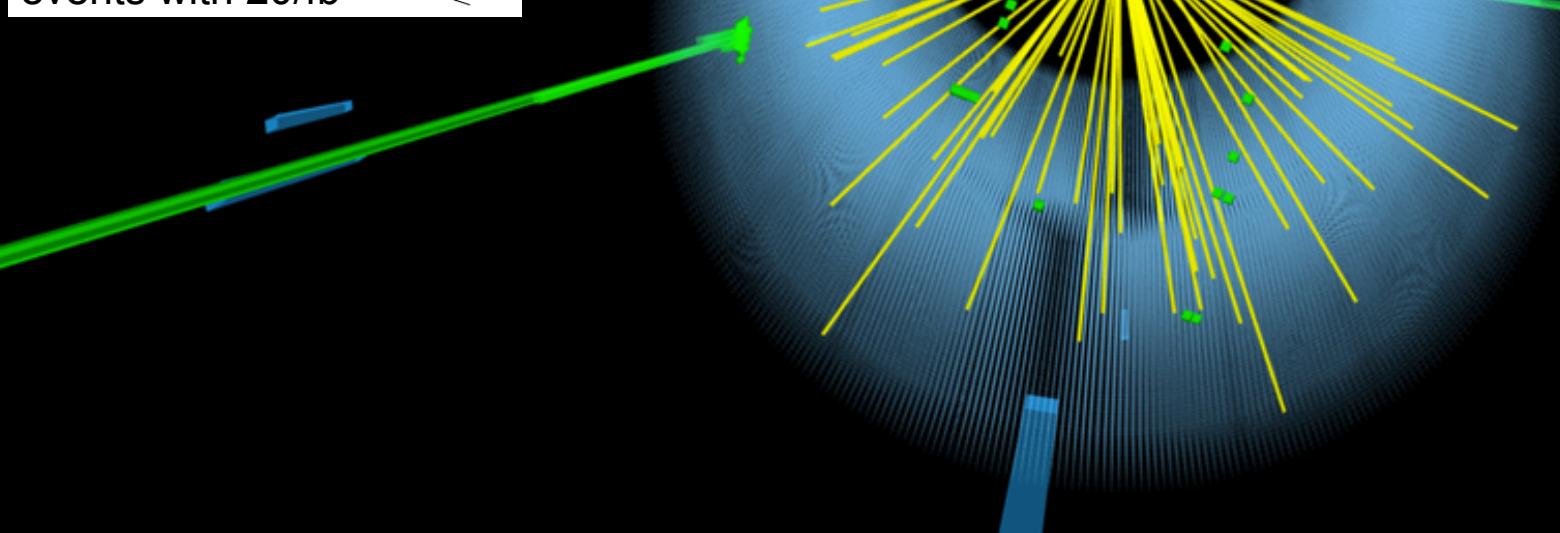
BSM searches: resonances, etc.

CMS-EXO-15-004, CERN-LHC-2014-021

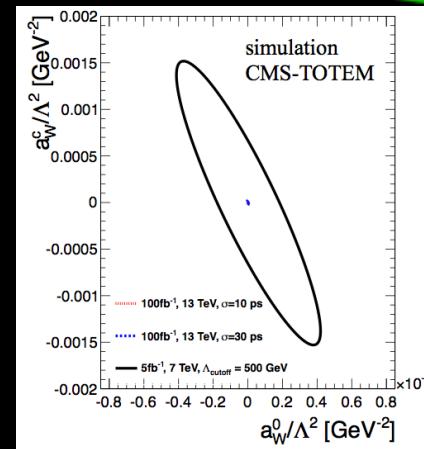
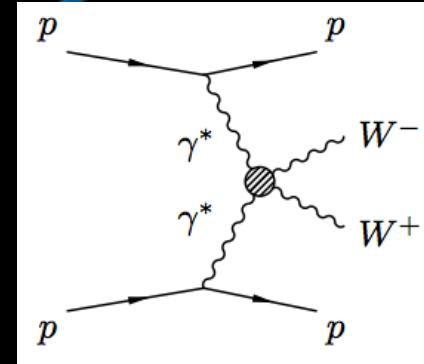


CMS Experiment at the LHC, CERN
Data recorded: 2015-Sep-11 22:46:54.589056 GMT
Run / Event / LS: 256353 / 437637379 / 244

diphotons at PPS
 $\sigma \sim 0.3 \text{ fb}$ a few 'clean' events with 20/fb

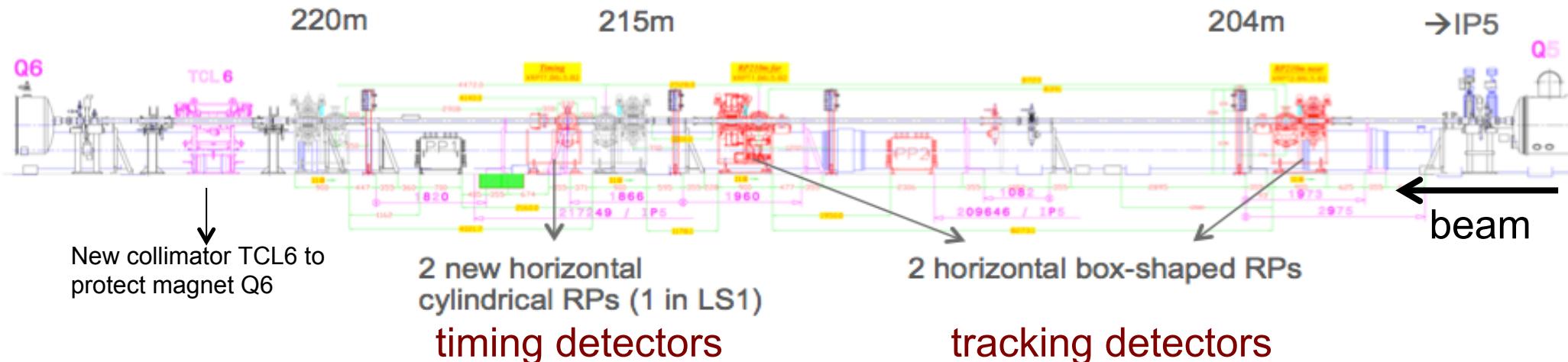


exclusive WW production



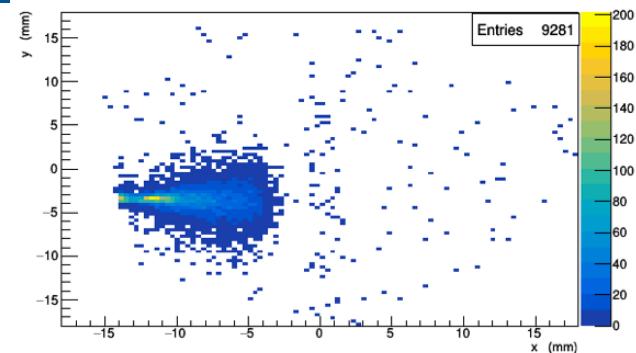
Experimental challenges

- Ability to operate the detectors close to beam ($15-20\sigma$) to maximize acceptance for low momentum loss (ξ) protons
- Limit impedance introduced by beam pockets
 - improved RF shielding of RPs
- Sustain high radiation levels
 - For 100/fb, proton flux up to $5 \times 10^{15} \text{ cm}^{-2}$ in tracking detectors, $10^{12} n_{\text{eq}}/\text{cm}^2$ and 100Gy in photosensors and readout electronics
- Reject background in the high-pileup ($\mu=50$) of normal LHC running

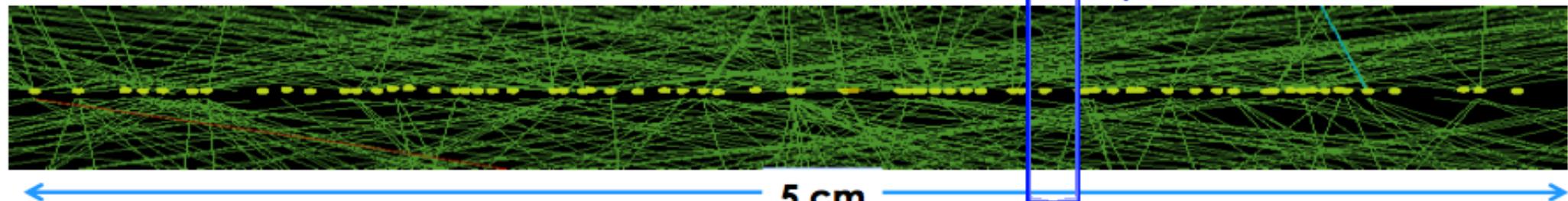
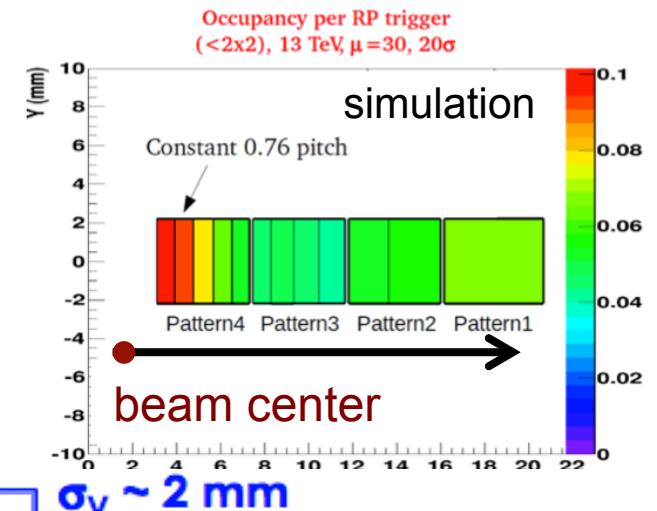


Detectors

- Tracking detectors
 - Goal: measure proton momentum
 - Technology: silicon 3D pixels (6 planes per pot)



- Timing detectors
 - Goal: identify primary vertex, reject “pileup”
 - $\sigma_{\text{time}} \sim 10\text{ps} \Rightarrow \sigma_z \sim 2\text{mm}$
 - Technology: silicon/diamond



Summary

- Excellent consistency but SM is incomplete
- Top quark physics as a probe to BSM
- Extensions foresee existence of additional bosons
 - Searches for BSM bosons natural companion to precision SM Higgs boson measurements
 - Neutral, charged, light, heavy, di- Higgs searches
- Excellent performance of the LHC
 - After LS1, increased energy to 13 TeV
- Searches provide no hints for BSM physics yet



backup

Constraining Higgs width

PLB 736(2014)64

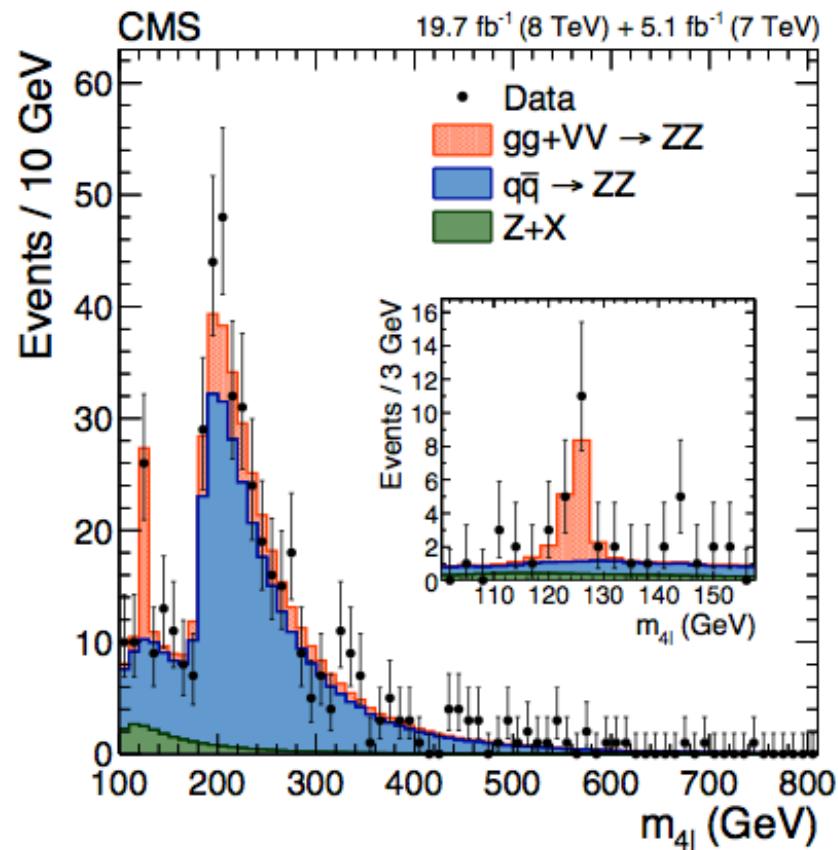
- couplings and width sensitive probes to BSM
- indirectly constrained in coupling fits
- off-peak to on-peak ratio proportional to Γ_H
- constrain Higgs boson width by using off-shell production/decay
- measure ratio of $\sigma^{\text{off-peak}}$ to $\sigma^{\text{on-peak}}$

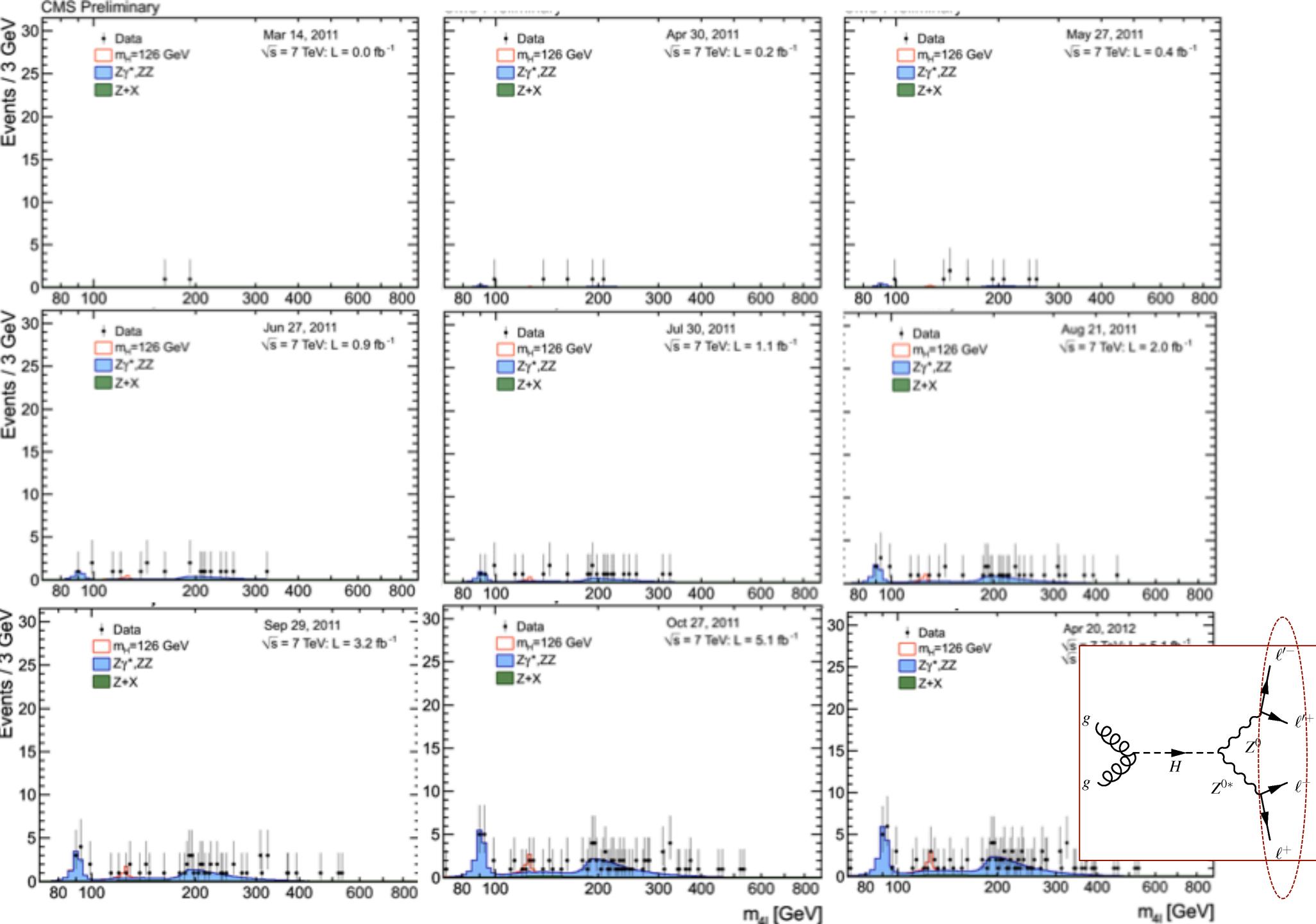
$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-peak}} \propto \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}, \quad \sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-peak}} \propto g_{ggH}^2 g_{HZZ}^2$$

F. Caola, K. Melnikov PRD88(2013)054024
J. Campbell et al. arXiv:1311.3589

- g_{ggH} and g_{HZZ} : couplings to gluons and bosons
- measurement of Γ_H

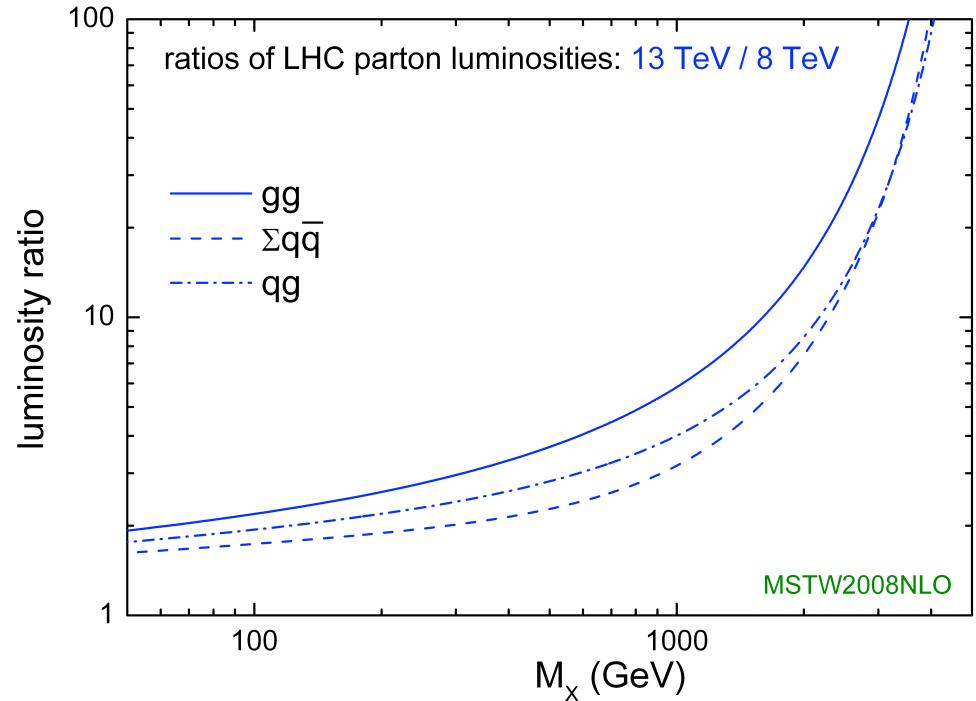
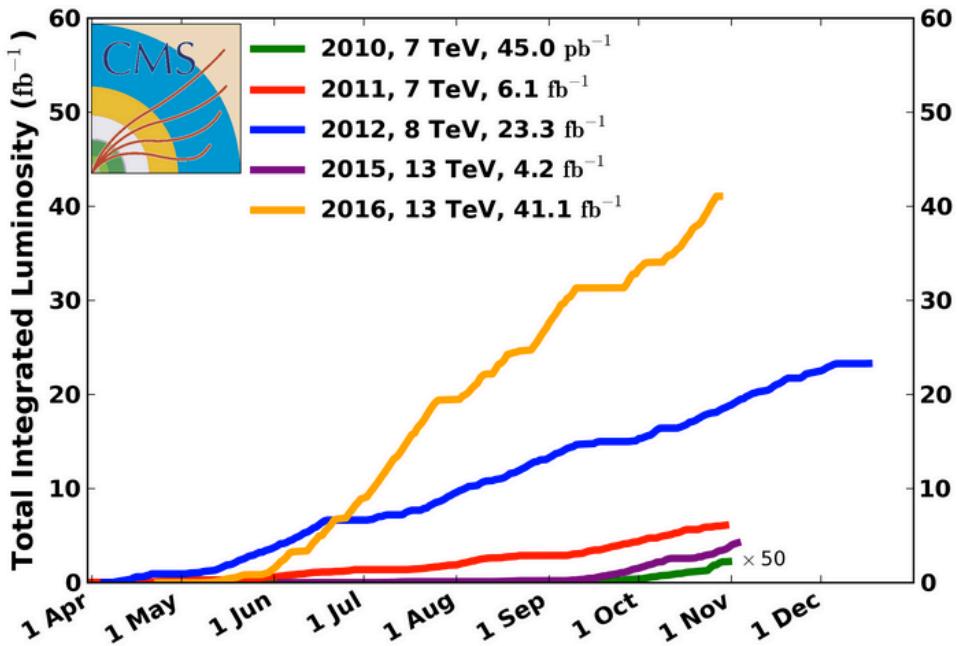
obs.(exp.) @95%CL:
 $\Gamma_H < 5.4(8.0)\Gamma_H^{\text{SM}}$
 $\Gamma_H < 22(33)\text{MeV}$





The Large Hadron Collider

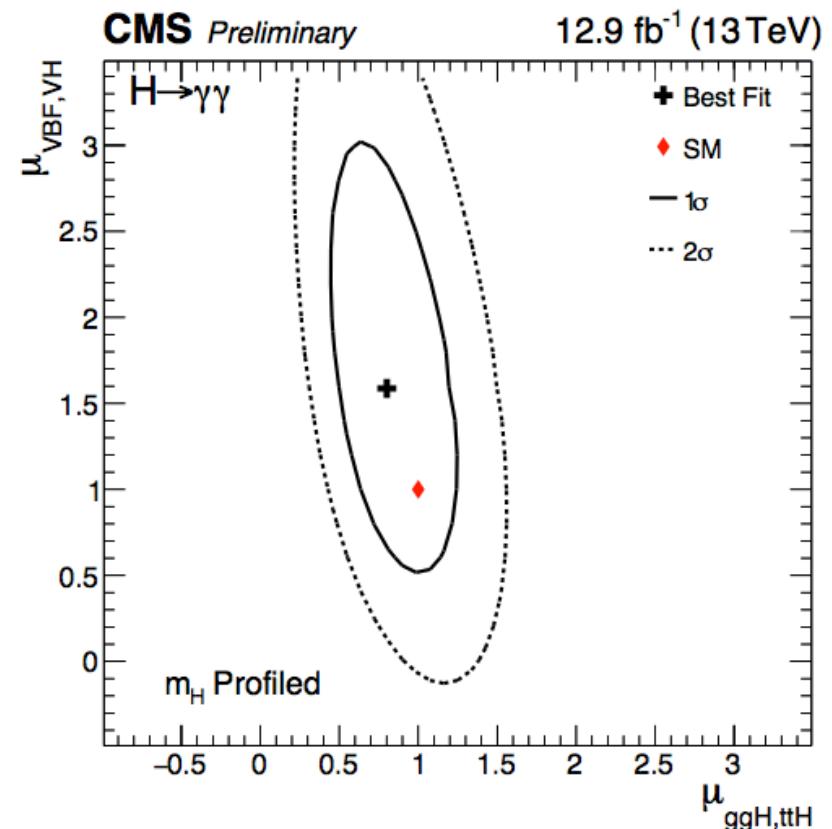
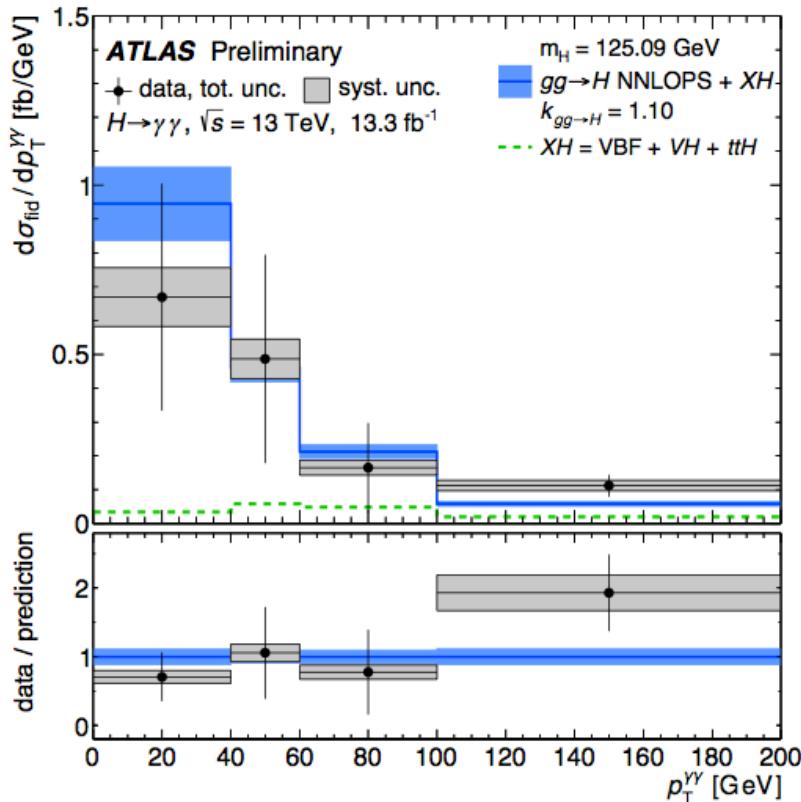
- Built to explore new energy frontiers
- First colliding beams in 2009



- re-establish SM measurements
- access to new physics processes

Higgs cross section: $H \rightarrow \gamma\gamma$ (cont.)

- Differential cross section

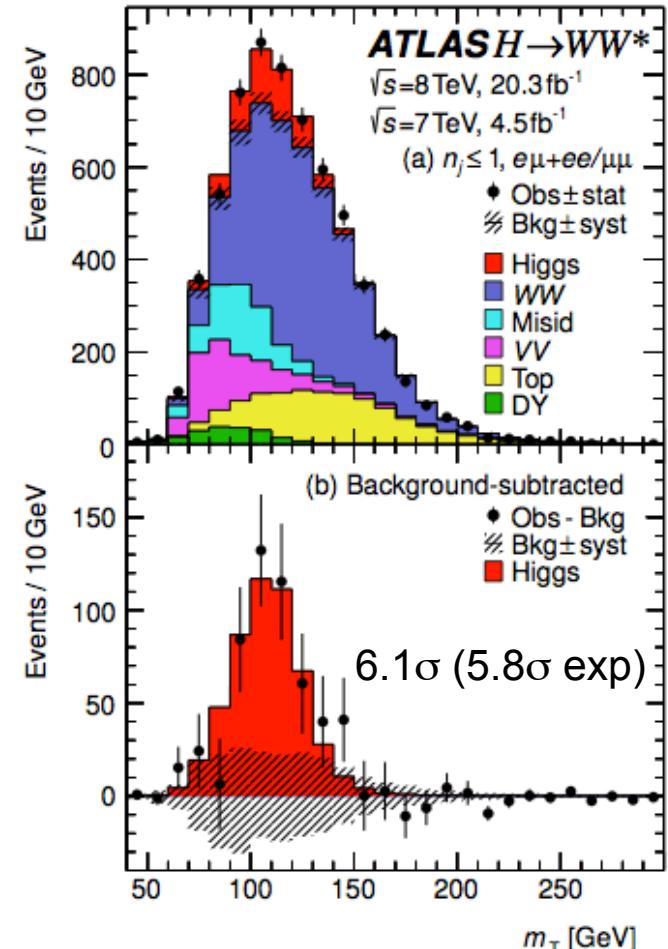
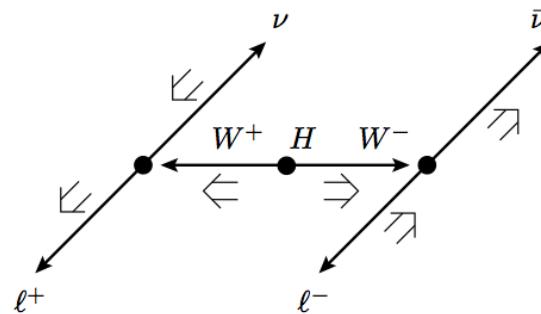
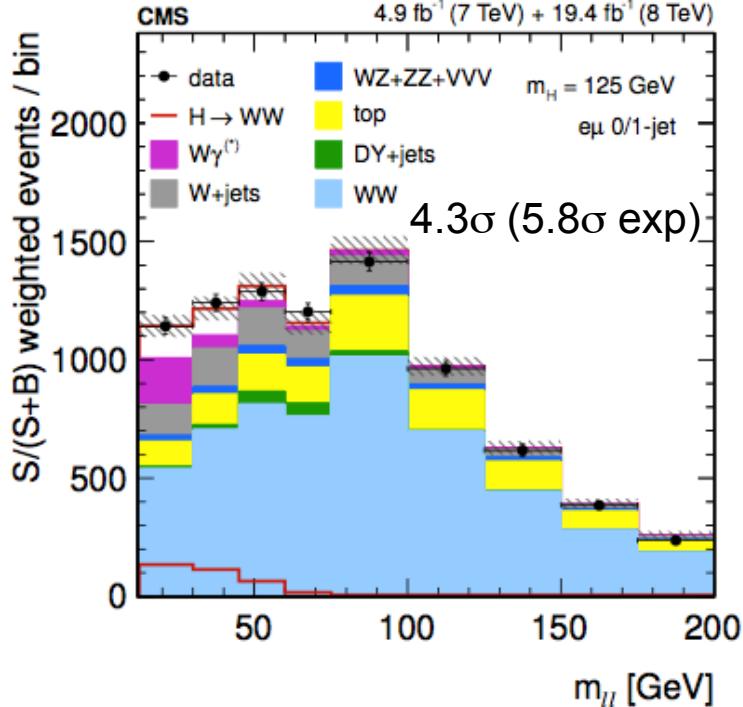


- Also a 2-parameter fit:

$$\mu = 0.91 \pm 0.20 \text{ for } m_H = 125.09 \text{ GeV}$$

Higgs to WW

JHEP 01(2014)096, PRD 92(2015)012006



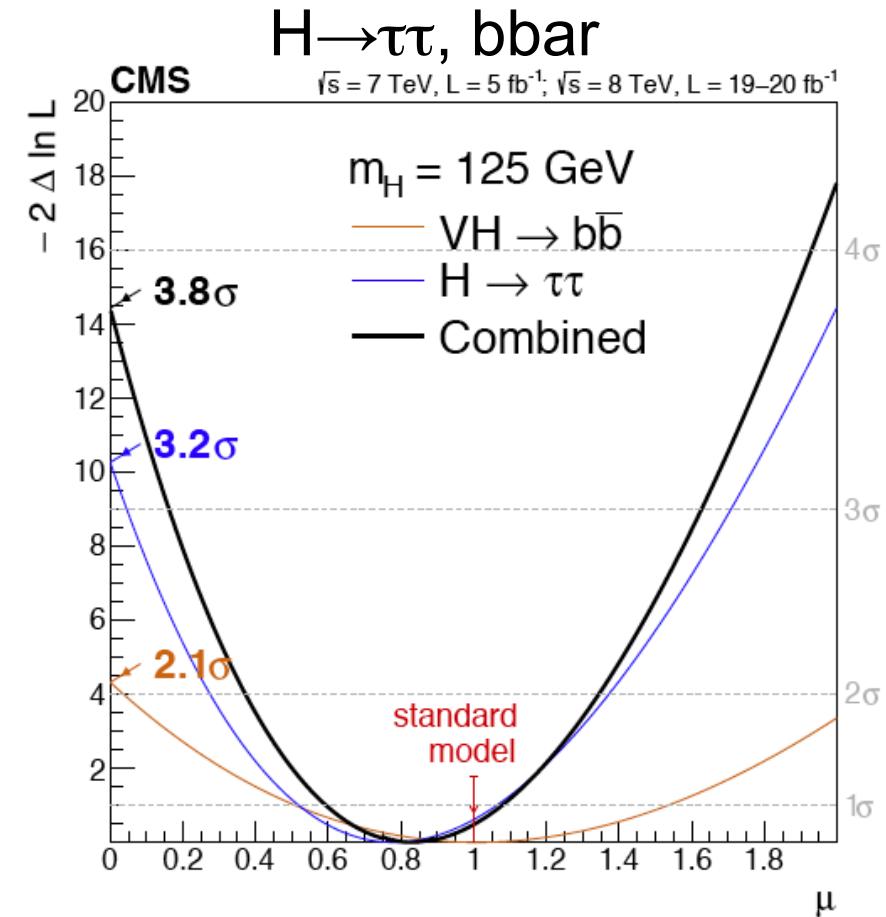
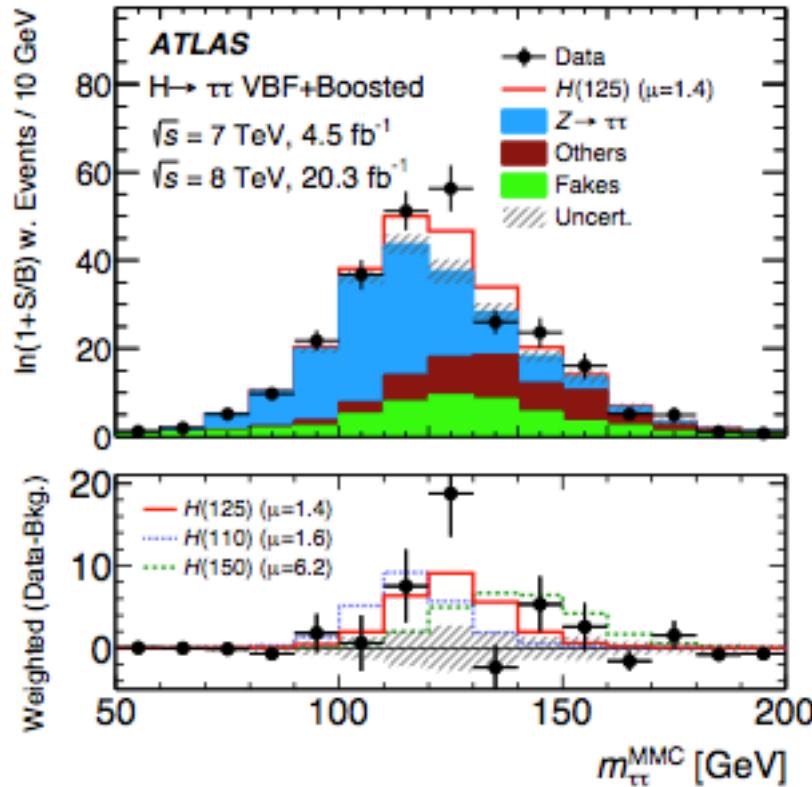
- Large branching fraction $\sim 22\%$
- High sensitivity, low mass resolution
- Not fully reconstructible → observables:
 m_H , $\Delta\phi_{jj}$, m_T
- Backgrounds: WW, W+jets, top
- 5 exclusive event categories

- All categories consistent with SM

Higgs decays to fermions

JHEP08(2016)045, JHEP04(2015)117, JHEP05(2014)104

$H \rightarrow \tau\tau$



significance ($\tau\tau$)
 significance ($b\bar{b}$)

ATLAS obs(exp)

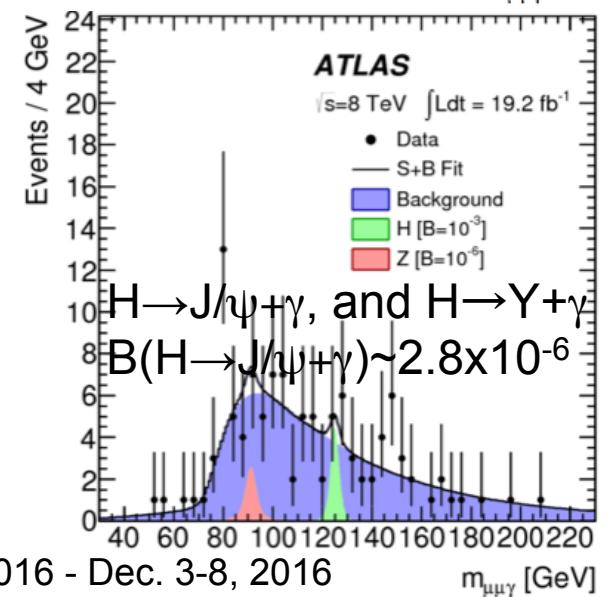
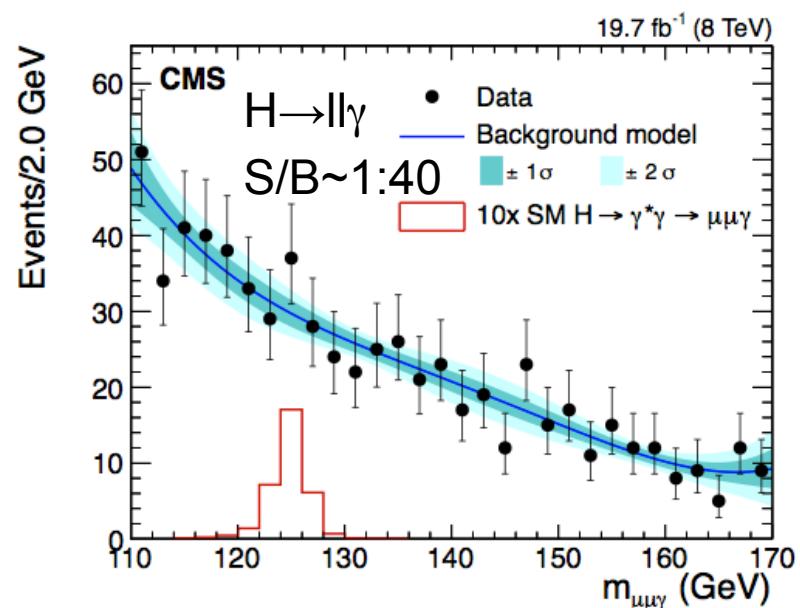
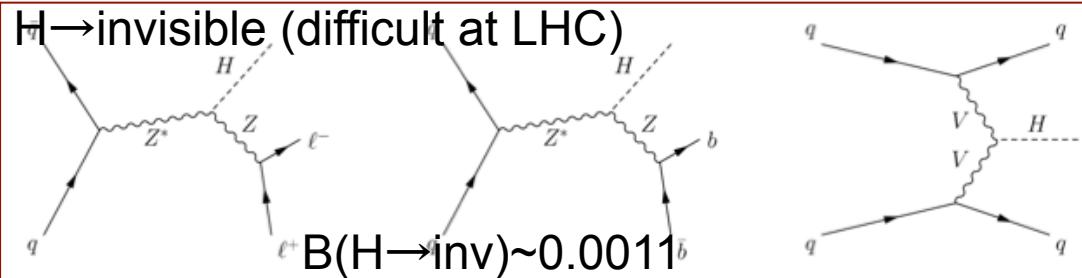
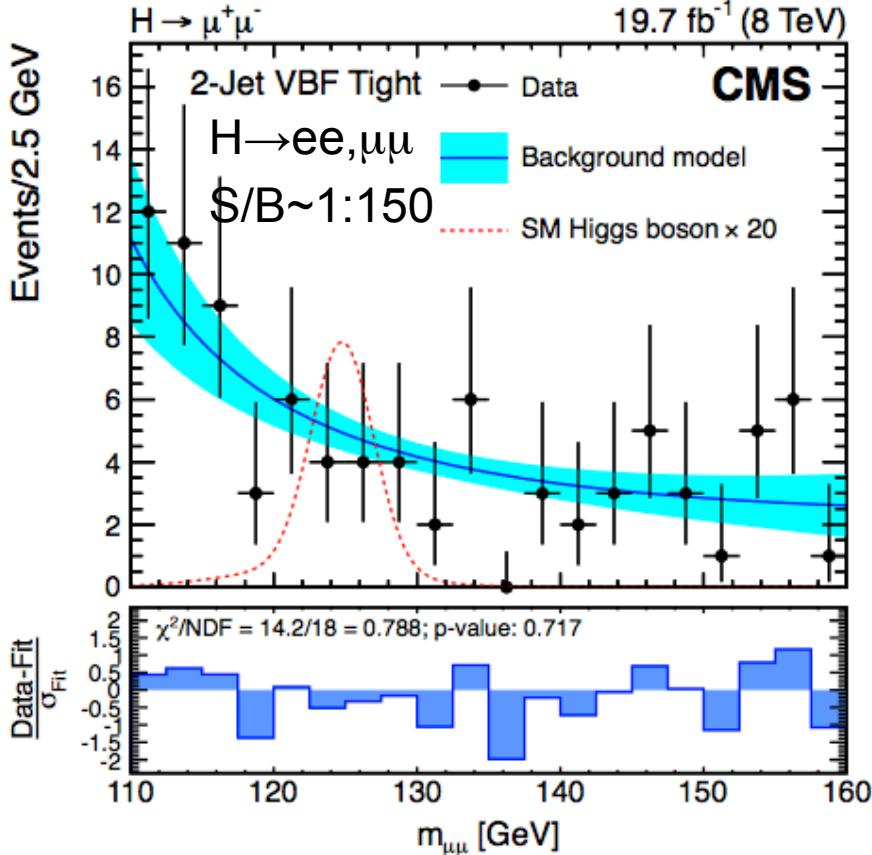
$4.4\sigma (3.3\sigma)$
 $1.4\sigma (2.6\sigma)$

CMS

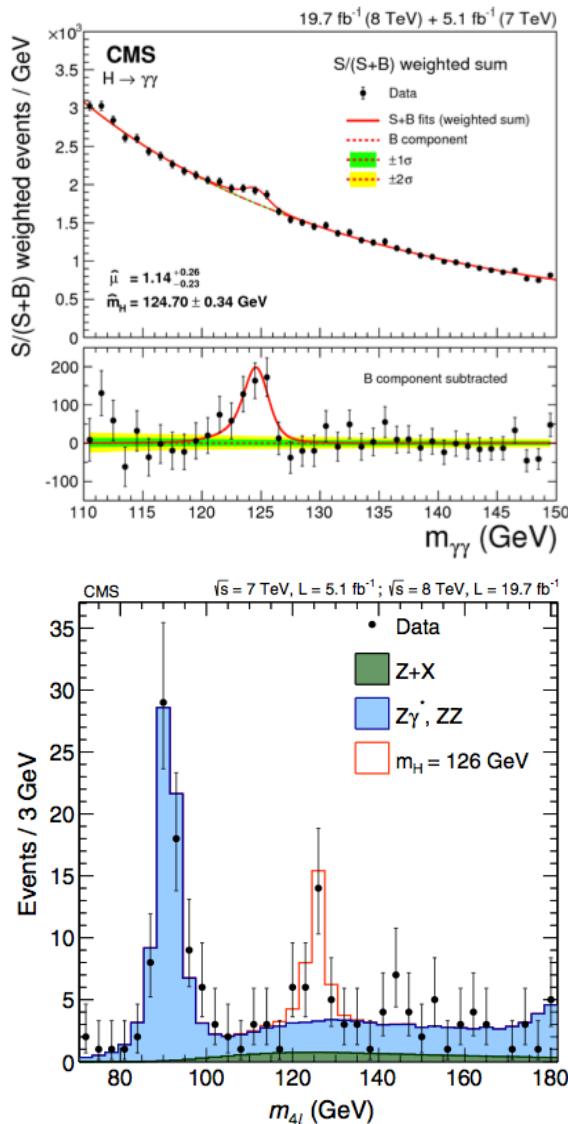
$3.4\sigma (3.7\sigma)$
 $2.1\sigma (2.5\sigma)$

Search for rare decays

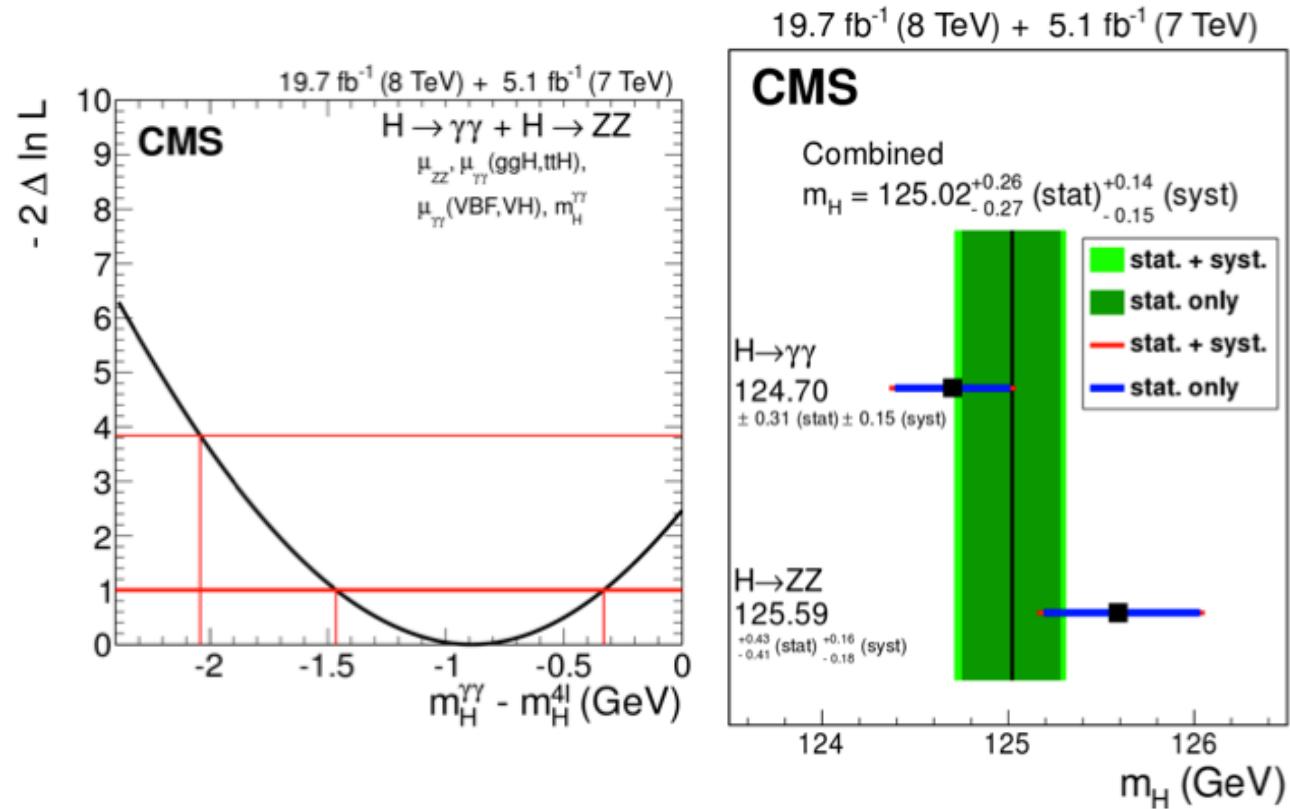
PLB 726(2013)587, arXiv:1507.03031, JPLB 03(2015)048, CMS-HIG-15-012, PRL 114(2015)121801, ATLAS-CONF-2016-041



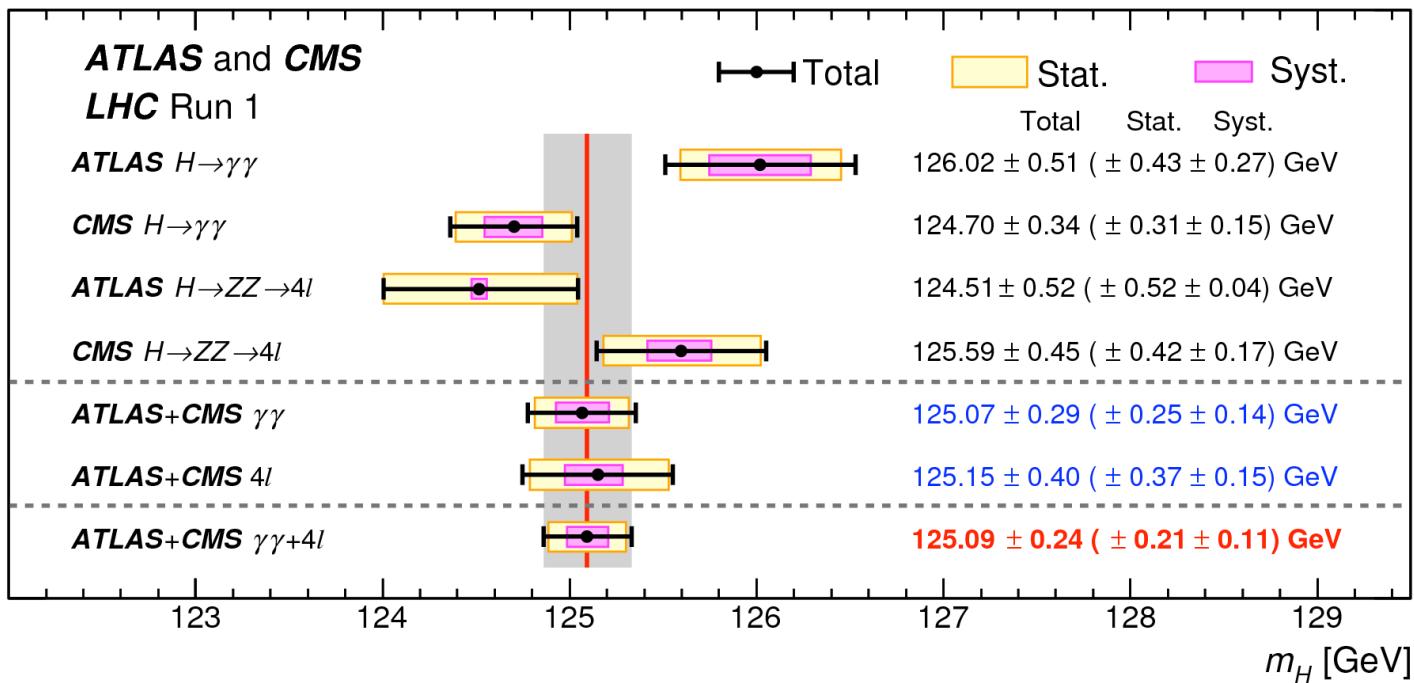
Higgs mass



- Best resolution expected in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$
- WW and $\tau\tau$ measurements are compatible



Mass in the individual channels

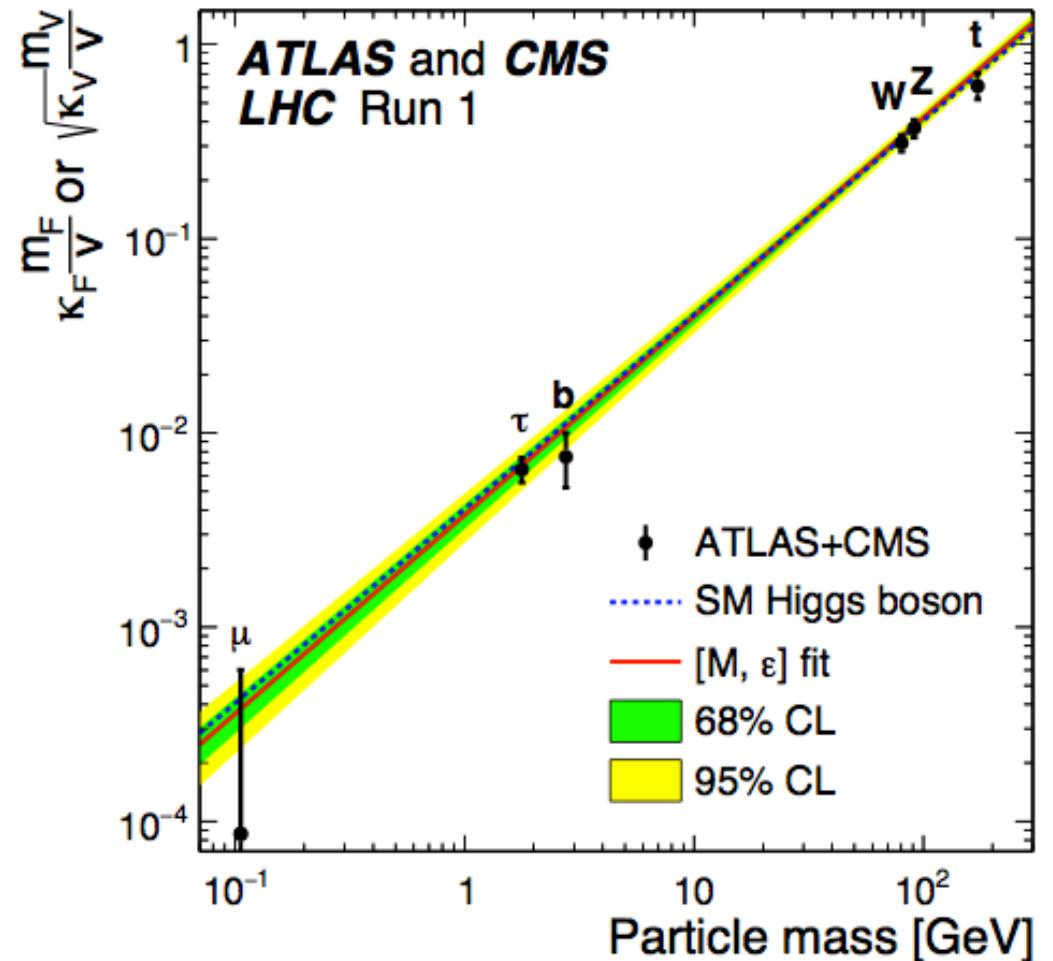


- Most accurate measurement in the $\gamma\gamma$ and $4l$ channels
- Some “tension” between the four measurements (p -value $\sim 10\%$)

Particle mass coupling dependency

PLB726(2013)88, JHEP08(2016)045

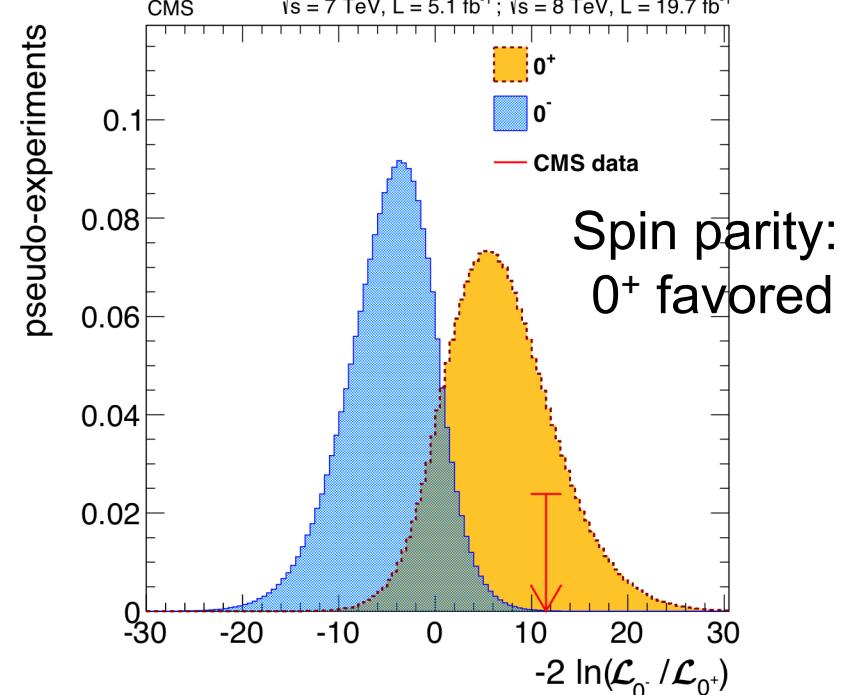
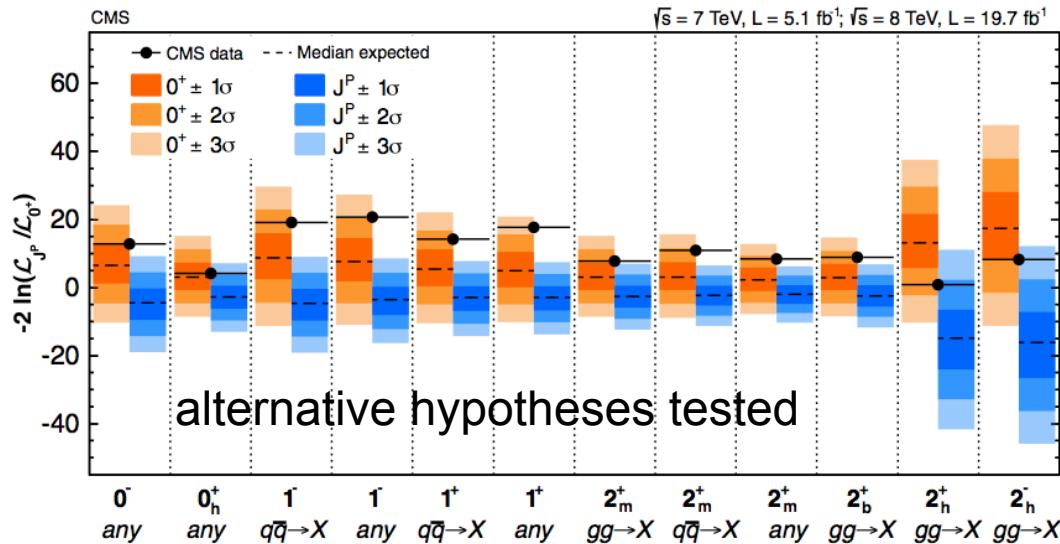
- Fitting the 5 main tree level coupling modifiers and resolving all loops
- Within current precision, couplings scale with particle mass



Spin

PRD 89(2014)092007

- it may be the first BSM particle produced/observed
- Does it have SM couplings and decays?
- Is it part of an extended scalar sector?
- Does it have exotic properties?



⇒ it is compatible with the SM Higgs boson