



Second Topical Meeting From Higgs to Dark Matter 2014

Dr Holms Hotel, Geilo, Norway

14 - 17 December

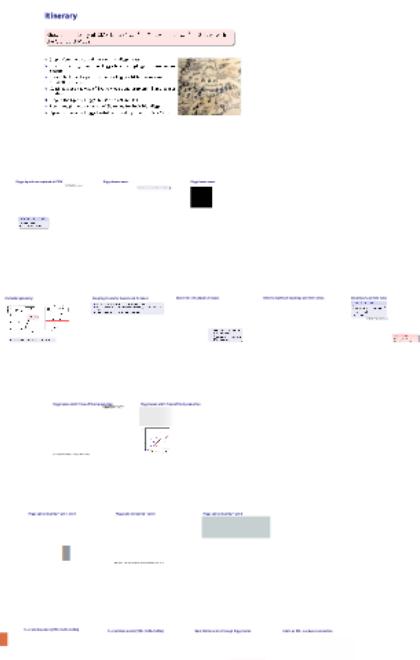
Marry Christmas and Happy new Year

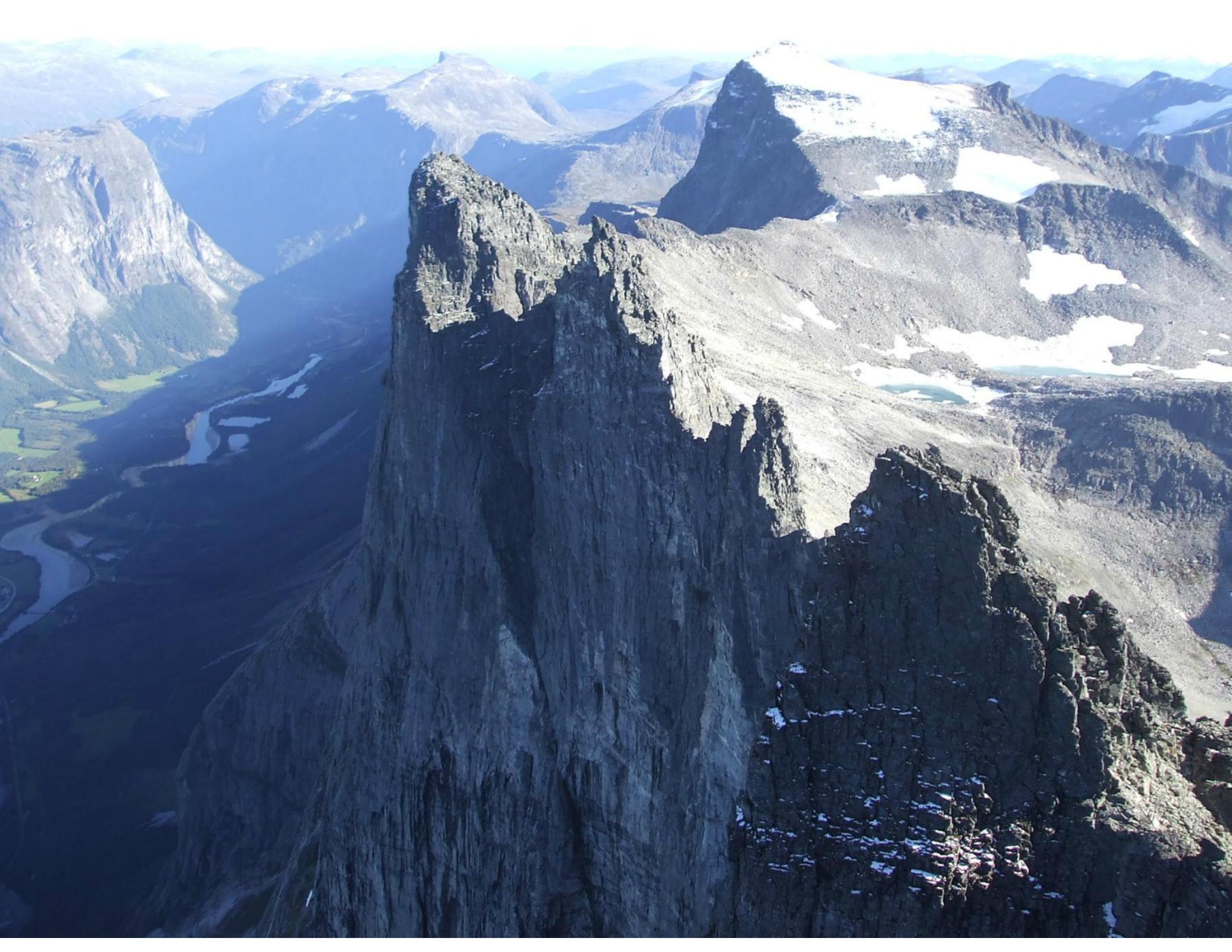


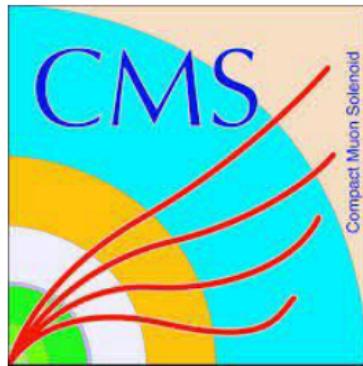
Overview of SM Higgs measurements at CMS and constraints on DM from Higgs searches

Roko Plestina for the CMS collaboration

From Higgs to Dark Matter







Overview of SM Higgs measurements at CMS and constraints on DM from Higgs searches

Roko Pleština for the CMS collaboration

From Higgs to Dark Matter
2nd Topical Meeting, Geilo, Norway – 14-17 December 2014



中国科学院高能物理研究所
*Institute of High Energy Physics
Chinese Academy of Sciences*

Itinerary

Show compatibility of CMS Data (5 fb^{-1} at 7 TeV and 20 fb^{-1} at 8 TeV) with the Standard Model

- Stop before the gate and measure the **Higgs mass**
- Enter to the Bright World of **Higgs boson couplings to fermions and bosons**
- Turn right from the peak and do the **Higgs width measurement from off-shell production**
- Continue along the way of Exotic Models and **drop spin-1 and spin-2 models**
- Stop in the **Spin-0 Higgs Tensor Structure Hall**
- Pass through the dark tunnel of **Searches for Invisible Higgs**
- Open the luminous **Higgs Portal**, and shed light on the Dark World



Higgs signatures explored at CMS

m_H fixed to 125.0 GeV

Decay tag	incl.(ggH)	VBF tag	VH tag	ttH tag		Obs.	Exp.
H \rightarrow ZZ	✓	✓			→	6.5	6.3
H \rightarrow $\gamma\gamma$	✓	✓	✓	✓	→	5.6	5.3
H \rightarrow WW	✓	✓	✓	✓	→	4.7	5.4
H \rightarrow $\tau\tau$	✓	✓	✓	✓	→	3.8	3.9
H \rightarrow bb		✓	✓	✓	→	2.0	2.3
H \rightarrow Z γ	✓	✓					
H \rightarrow $\mu\mu$	✓	✓					
H \rightarrow inv.		✓	✓				

CMS-PAS-HIG-14-009

207 subcategories,
2519 nuisance parameters

Tags are never 100% pure

e.g. VBF-tagged events are expected to contain 20-50% gg \rightarrow H, depending on the analysis and subcategory

Higgs boson mass

Analysis with good mass resolution

Using only analysis with **good mass resolution** and with **fully reconstructed** final state:

- $H \rightarrow ZZ^* \rightarrow 4l$
- $H \rightarrow \gamma\gamma$

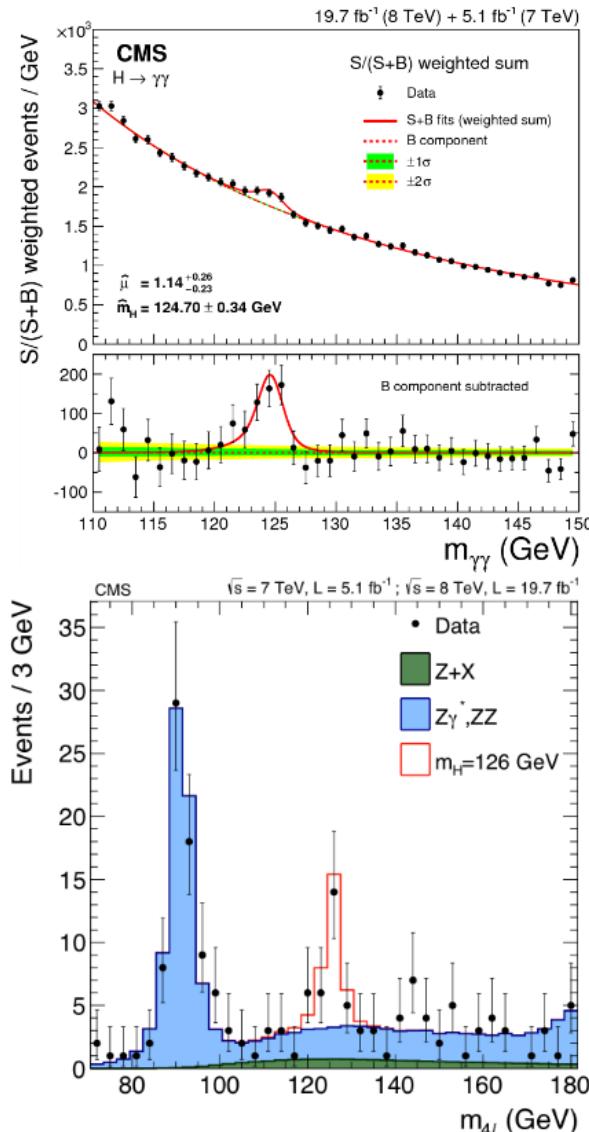
$H \rightarrow \gamma\gamma$

- Two isolated, high p_T photons
- Events categorized by $m_{\gamma\gamma}$ resolution, kinematics and production mode
- Same as measurement of the couplings
- Simultaneous S+B fit to all categories
- Background from fit to data
- Analytic signal model accounting for data/MC corrections and associated uncertainties

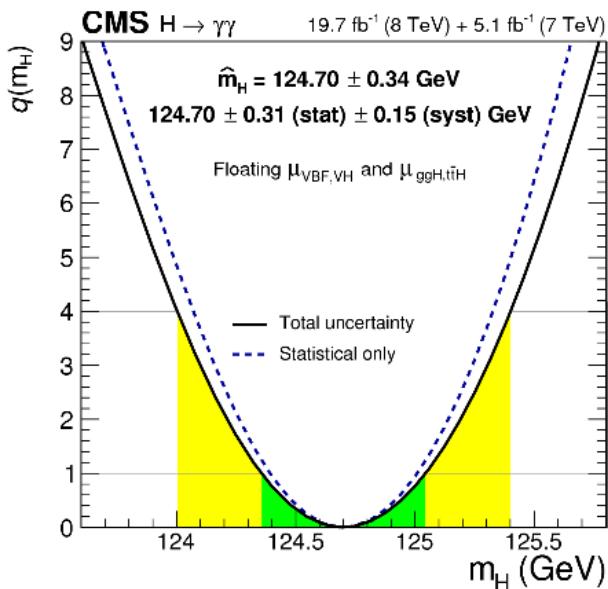
$H \rightarrow ZZ^* \rightarrow 4l$

- Four isolated leptons
- Only lepton flavor categorization ($4e$, 4μ , $2e2\mu$)
- Unbinned maximum likelihood fit
- Use m_{4l} vs kin. discriminant (KD) for S/B separation
- Use information on event-by-event mass resolution

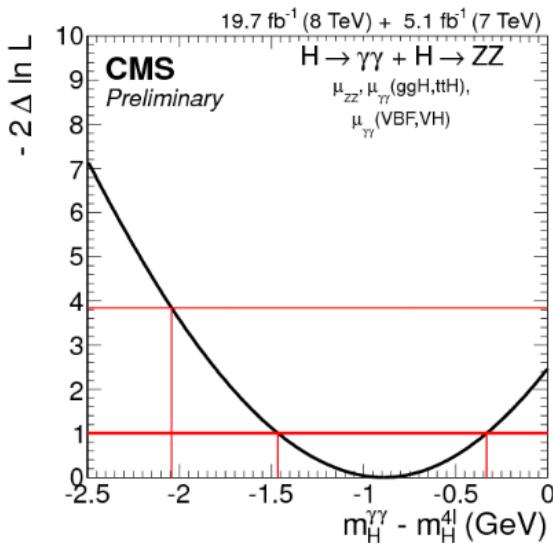
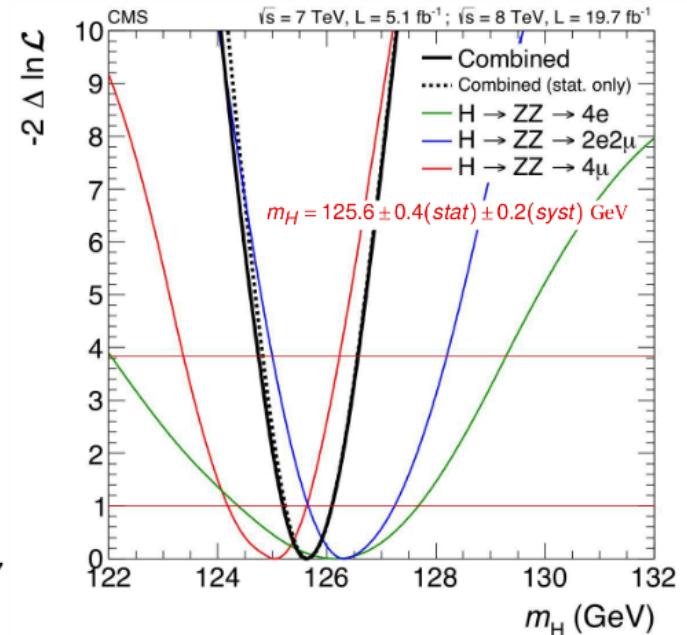
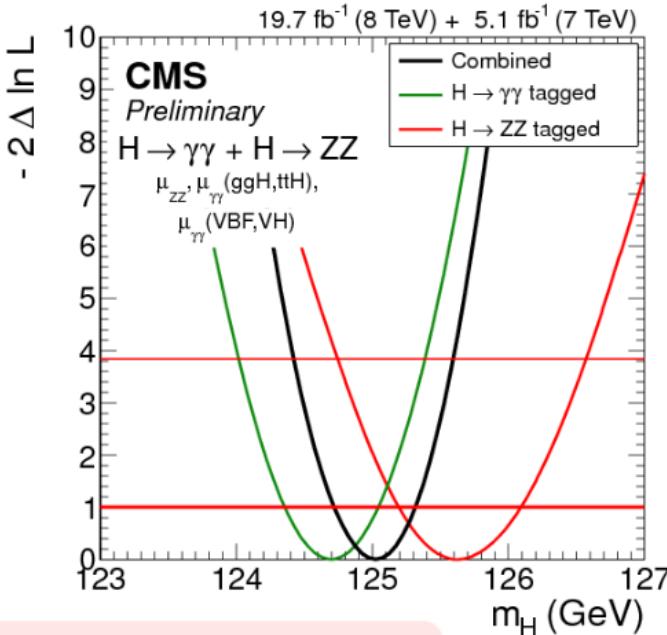
Energy scale is dominant systematic.



Higgs boson mass



$$m_H = 125.03^{+0.26}_{-0.27}(\text{stat.})^{+0.13}_{-0.15}(\text{syst.}) \text{ GeV}$$



- Reduce model dependence of the mass estimate by allowing signal strengths of Higgs production mechanisms to float independently
- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ results compatible at the 1.6σ level
- Statistical uncertainty still dominates the measurement (wait for Run2)

Global signal strength

Overall signal strength

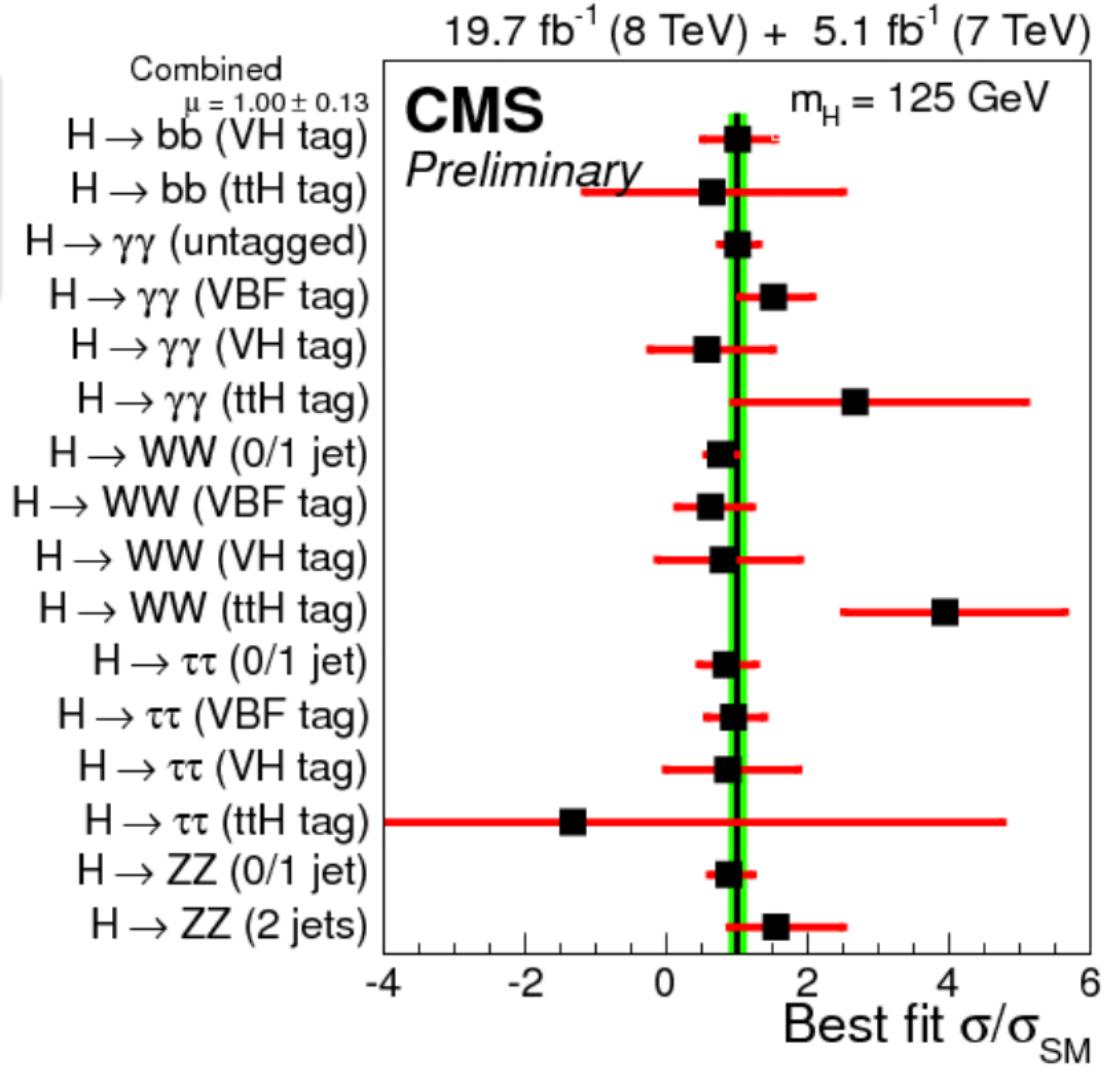
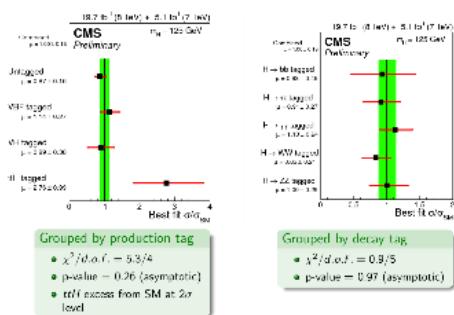
$$1.00 \pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})$$

- theo. includes QCD scales, PDF+ α_S , UEPS, and BR

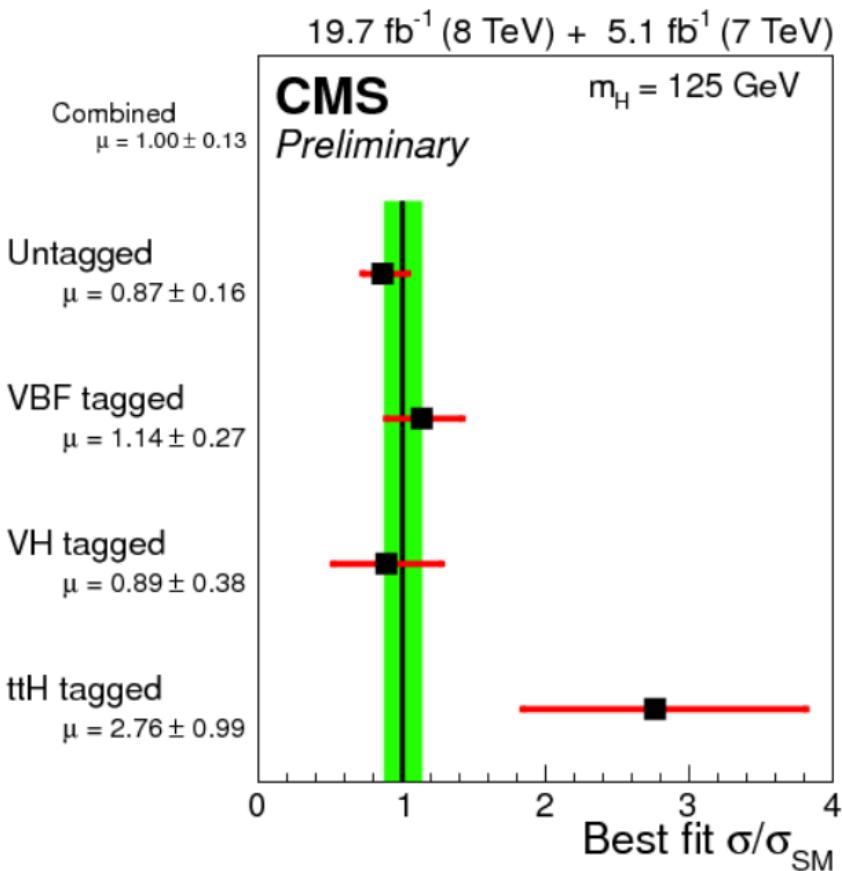
Production and decay tag

- $\chi^2/d.o.f. = 10.5/16$
- p-value = 0.84 (asymptotic)

Signal strength grouped by production and decay

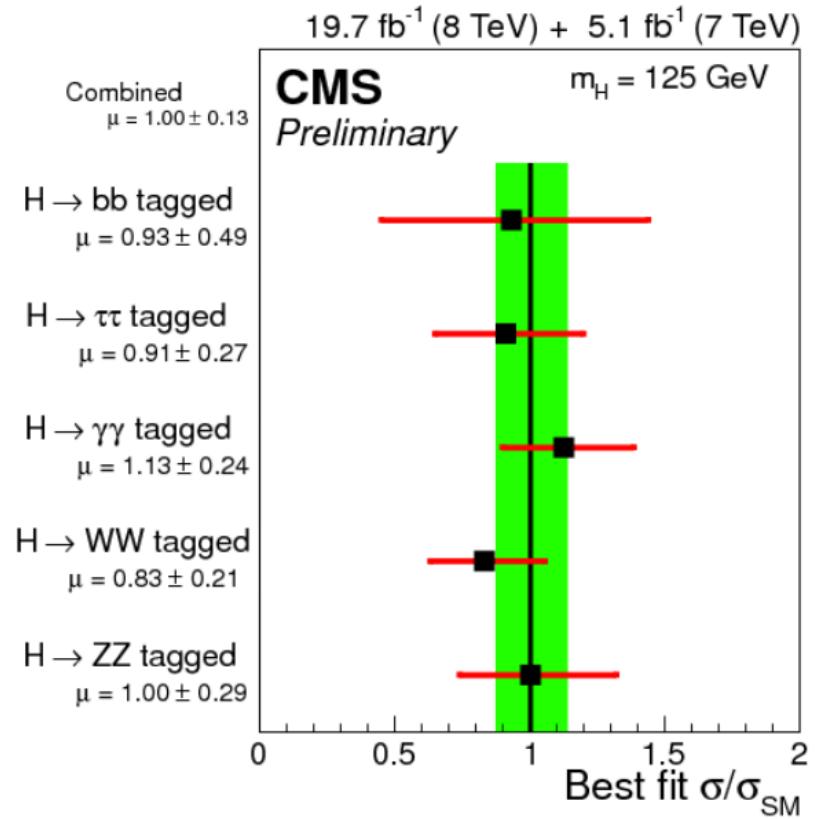


Signal strength grouped by production and decay



Grouped by production tag

- $\chi^2/d.o.f. = 5.3/4$
- p-value = 0.26 (asymptotic)
- ttH excess from SM at 2σ level



Grouped by decay tag

- $\chi^2/d.o.f. = 0.9/5$
- p-value = 0.97 (asymptotic)

Tests of Higgs boson couplings

Prescription from LHCHXSWG [arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{ see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

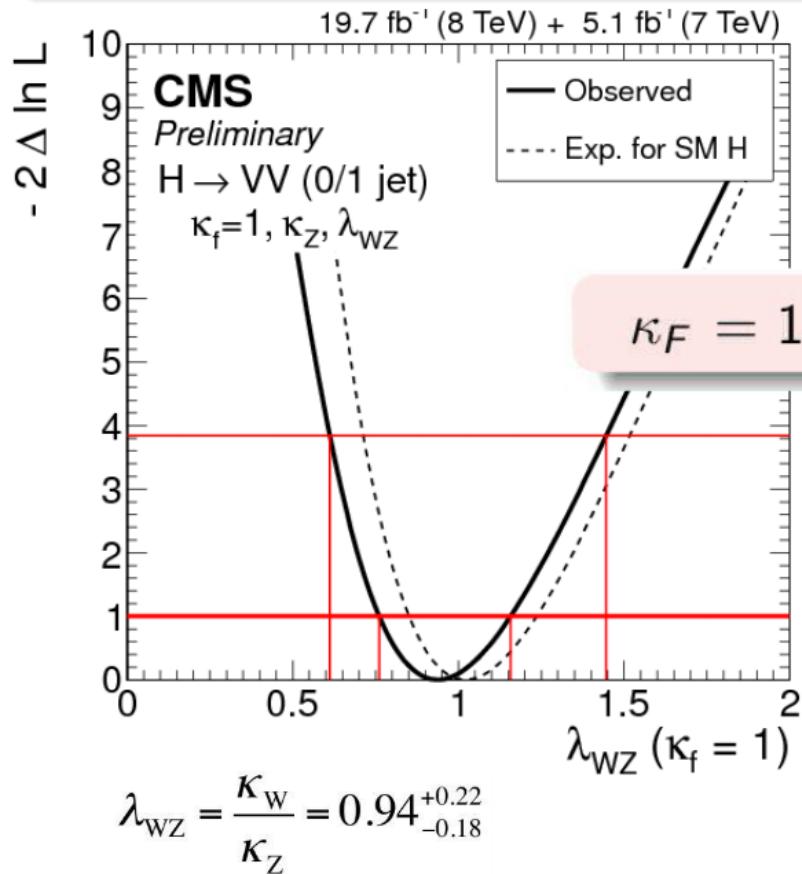
Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Assume single resonance
- Zero-width approximation: $(\sigma \times BR)(i \rightarrow H \rightarrow f) = \frac{\sigma_i \times \Lambda_f}{\Lambda_H}$
- SM tensor structure

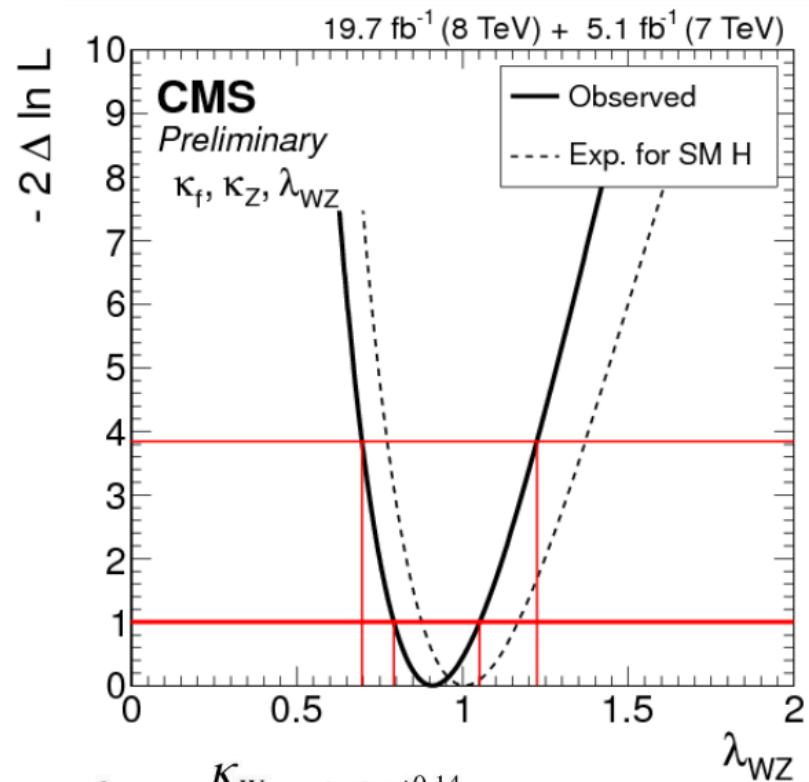
Custodial symmetry

Only WW and ZZ channels (0/1 jet)



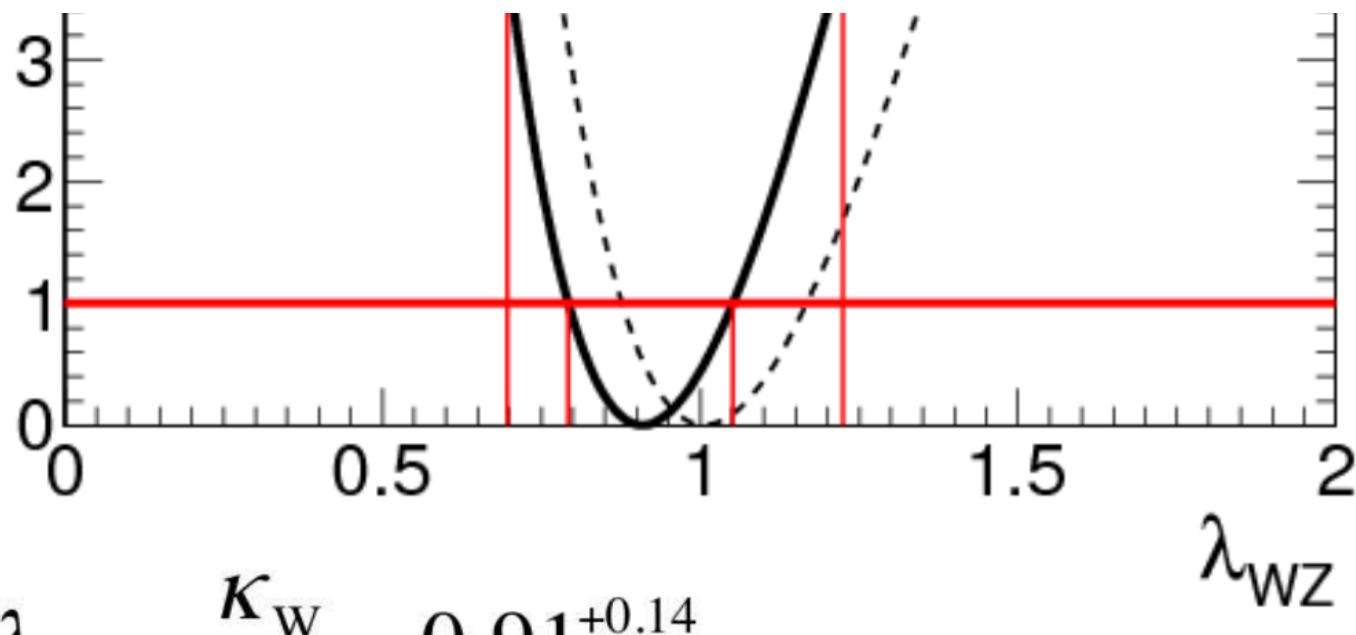
No deviation → treat Z and W as V

Full combination



Custodial Symmetry

- The SM Higgs sector symmetry $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$ (due to Higgs vev)
- Result: m_W/m_Z , and their couplings to the Higgs, g_W/g_Z , protected against large rad



$$\lambda_{WZ} = \frac{K_W}{K_Z} = 0.91^{+0.14}_{-0.12}$$

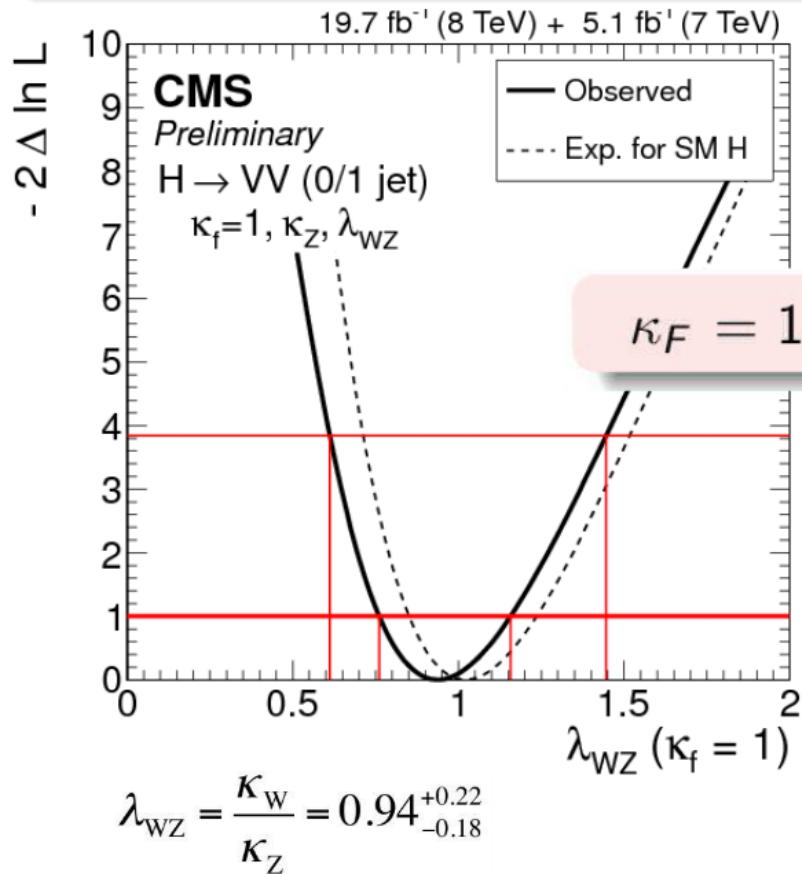
and W as V

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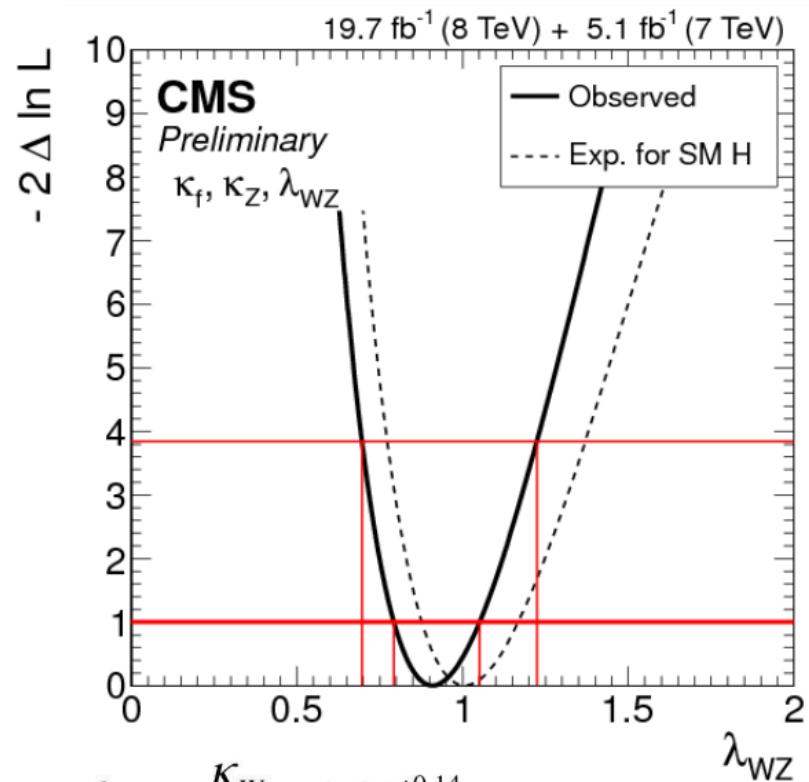
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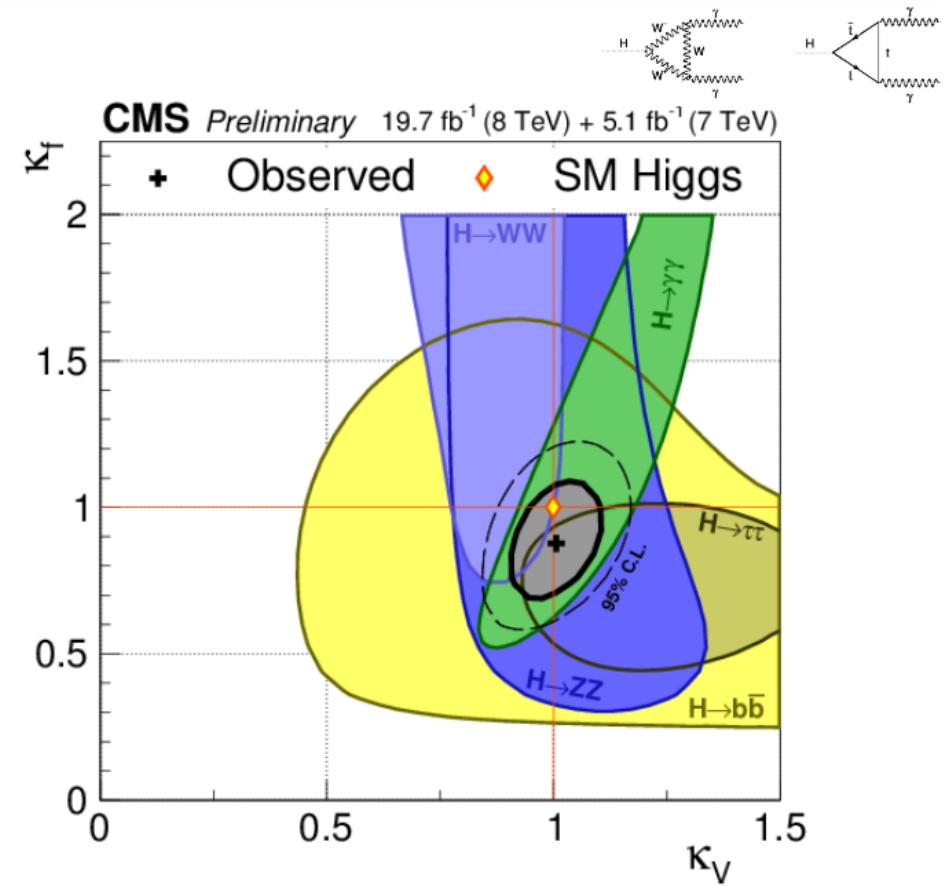
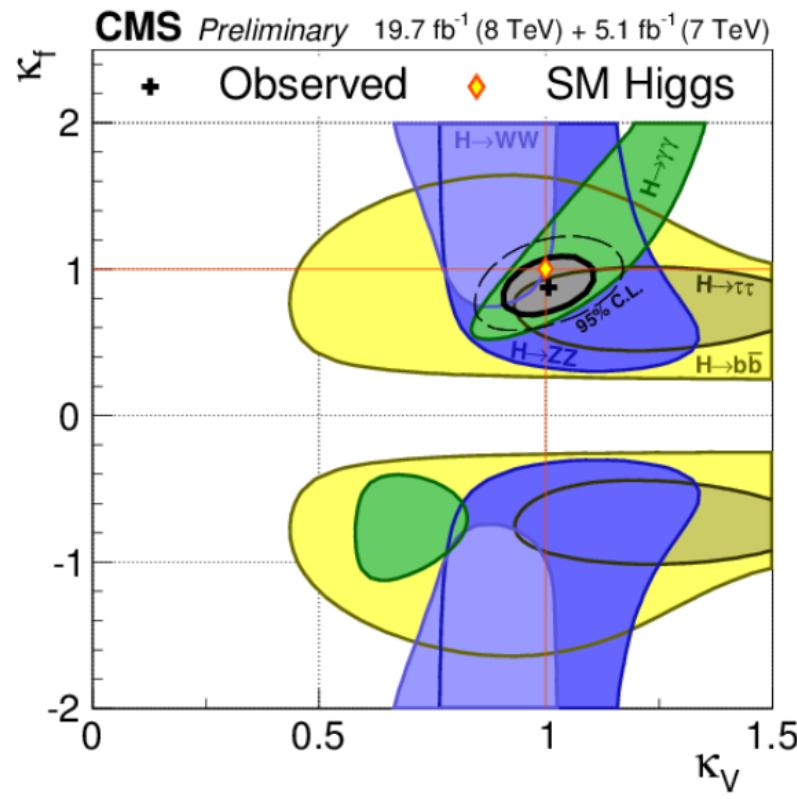


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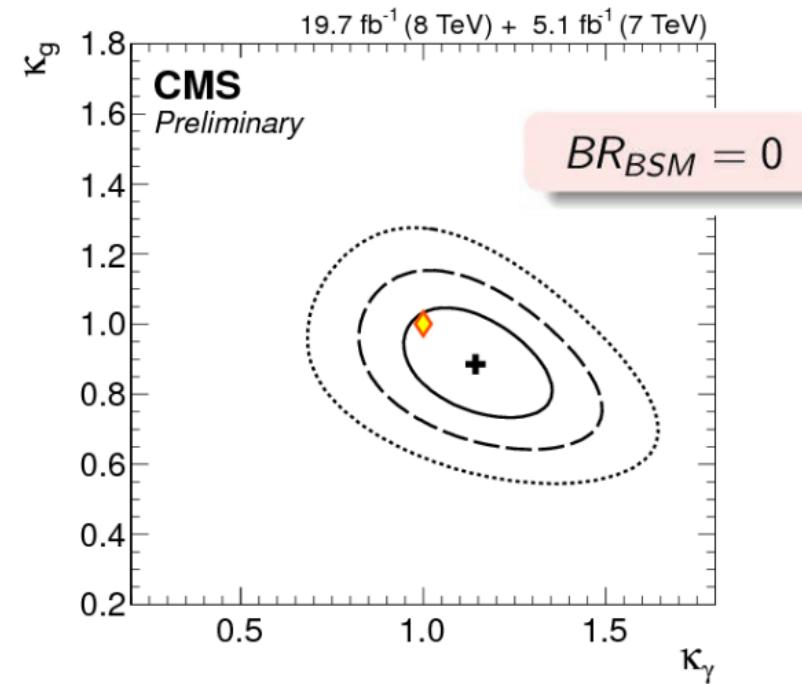
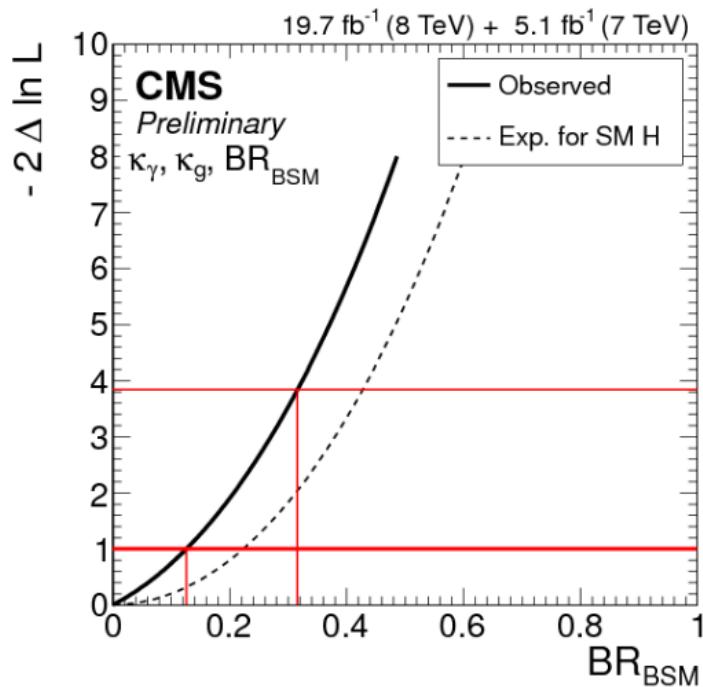
Couplings to vector bosons and fermions

- Map vector-boson and fermionic couplings into κ_V and κ_f plane
- $H \rightarrow \gamma\gamma$ (through the loops) sensitive to relative sign (–) of couplings to W and top
- interference between W and top loops plays a role



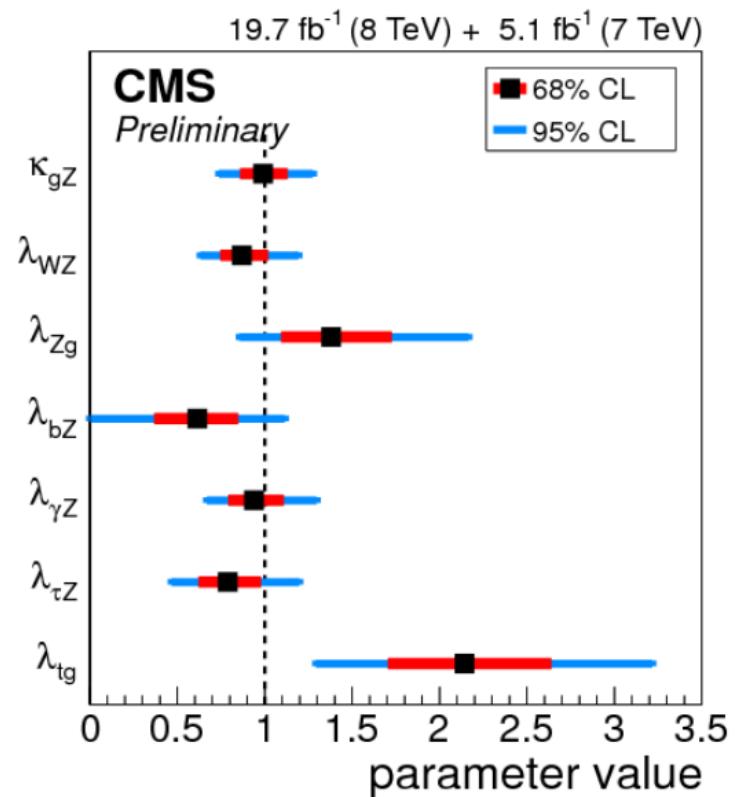
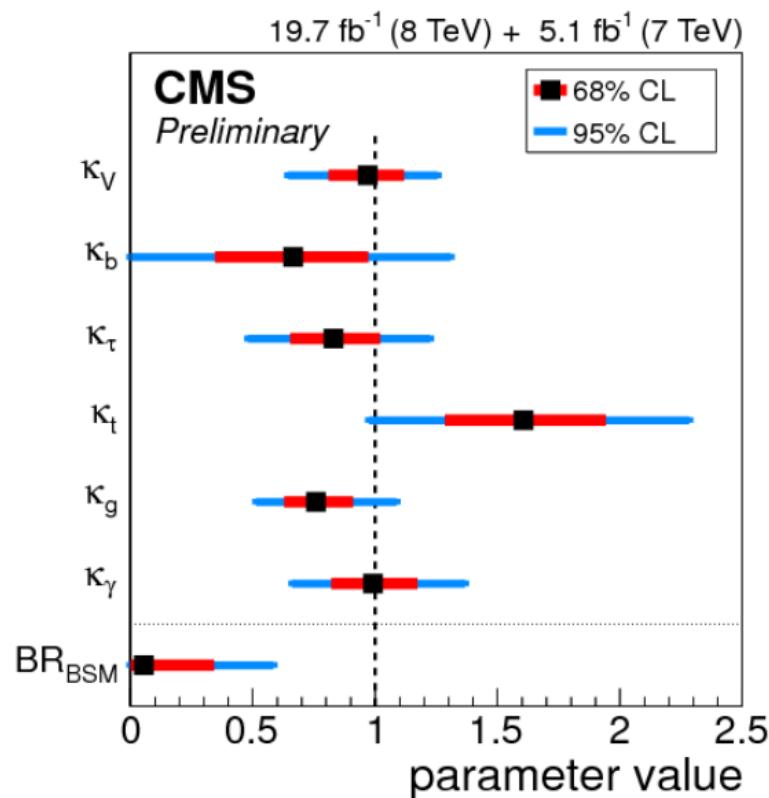
Search for new physics in loops

- New particles can potentially hide in the loop-mediated couplings ($H\gamma\gamma$ and ggH)
- The photons and gluons are treated tree-level effective couplings



- New particles can contribute to the total width
- Allow total width to scale as $1/(1 - BR_{BSM})$

Generic models of couplings and their ratios



Six-parameter model + free width

Allow beyond-SM decays and restricting the tree-level effective couplings to vector bosons to $\kappa_V \leq 1.0$

Couplings ratio model

All gauge and third generation fermion couplings are floated allowing for invisible (undetectable) widths

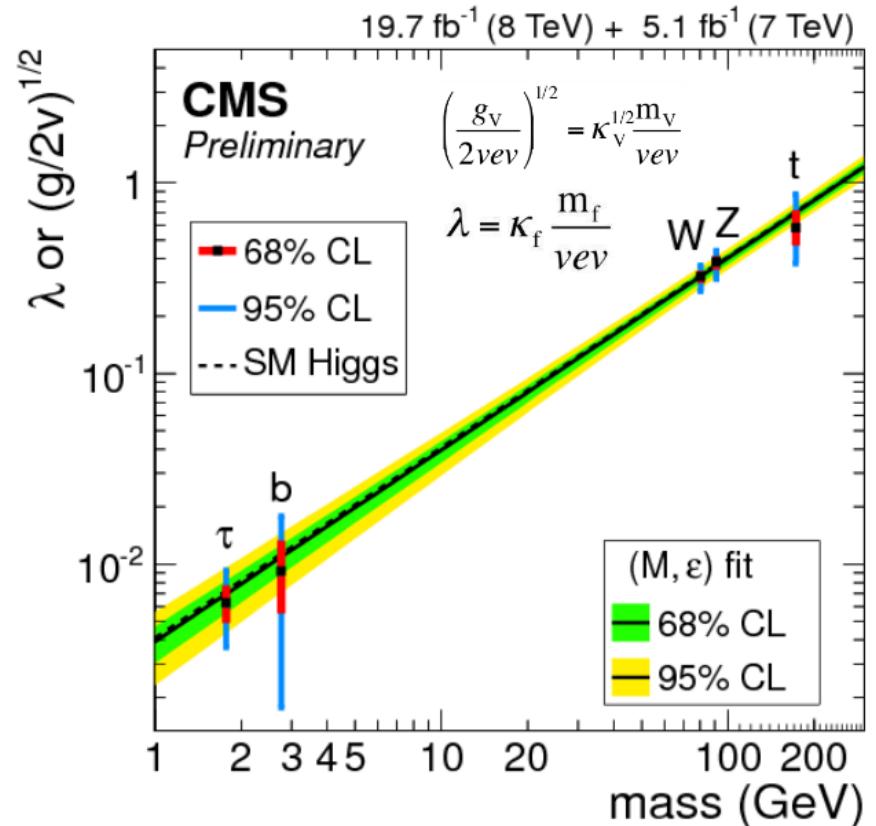
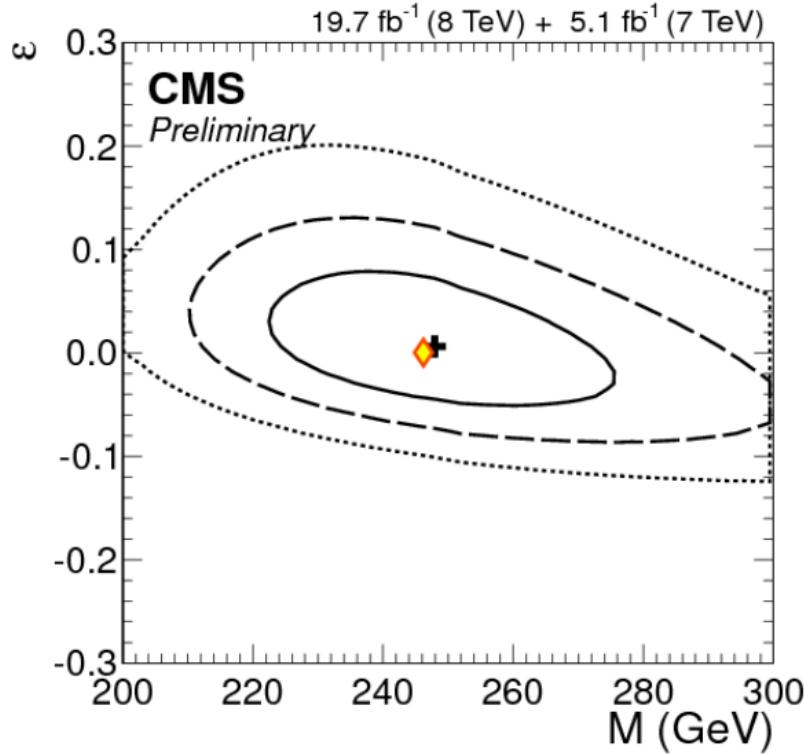
Coupling vs. particle mass

Generic M and ϵ model

Parametrized in terms of a mass scaling parameter ϵ and a vev parameter M :

- $\kappa_f = vev \cdot \frac{m_f^\kappa}{M^{1+\epsilon}}$
- $\kappa_V = vev \cdot \frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$

[J. Ellis and T. You, arXiv:1207.1693]



Standard Model

$vev = 246$ GeV and $\kappa_f = \kappa_V = 1$
recovered for $M = vev$ and $\epsilon = 0$

Higgs boson width from offshell production

$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}^2} \propto g_{ggH}^2 g_{HZZ}^2 \frac{F(m_{ZZ})}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

On-shell/Off-shell ratio

- SM predicts $\Gamma_{tot} = 4.2$ MeV, direct measurement yields $\Gamma_{tot} = 3.4$ GeV, 3 orders of magnitude
- Γ_H can indirectly be extracted from On-shell/Off-shell ratio
- Mild model dependence — works for BSM models if the ratio is not altered by new physics (i.e. top loop still dominates in ggH)
- Signal - background destructive interference through fermion box diagrams

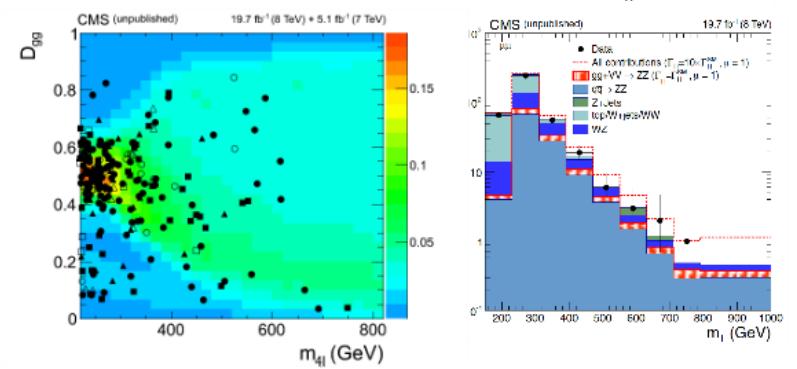
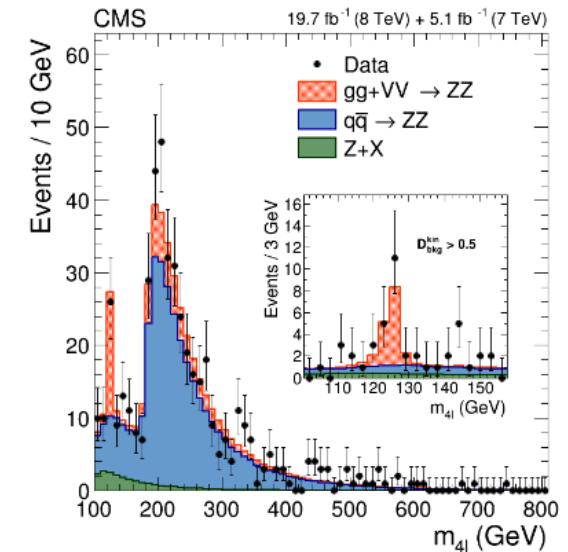
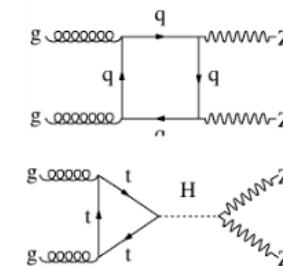
Analysis

- The $H \rightarrow ZZ^* \rightarrow 4l$ analysis uses the m_{4l} distribution near the peak and above the ZZ production threshold as well as a kinematic discriminant to separate the Higgs boson production from the ZZ continuum background
- The $H \rightarrow ZZ^* \rightarrow 2l2\nu$ analysis relies on the transverse mass or missing transverse energy distributions, depending on the jet categories.

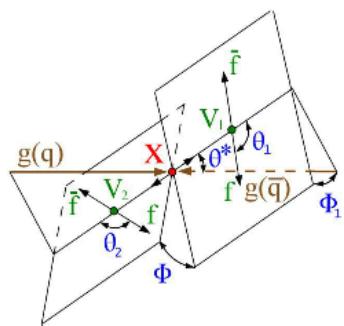
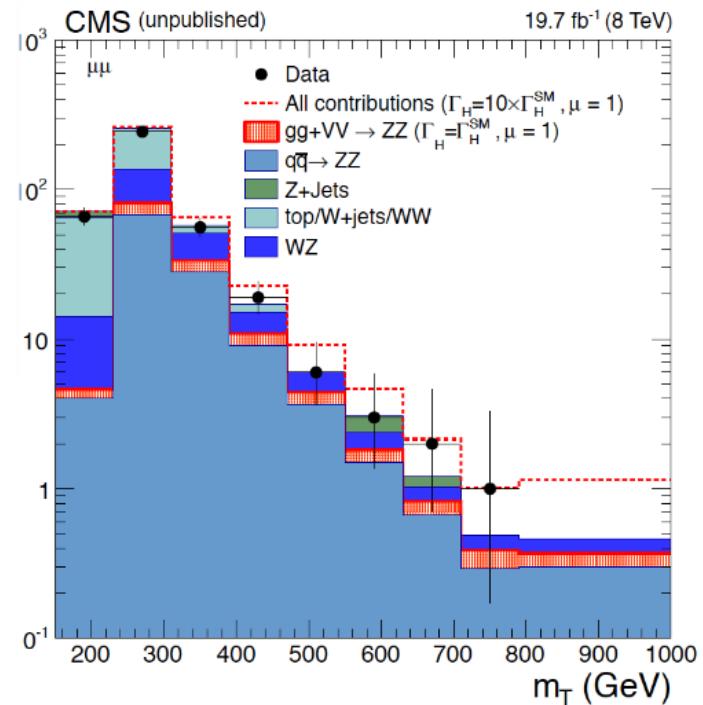
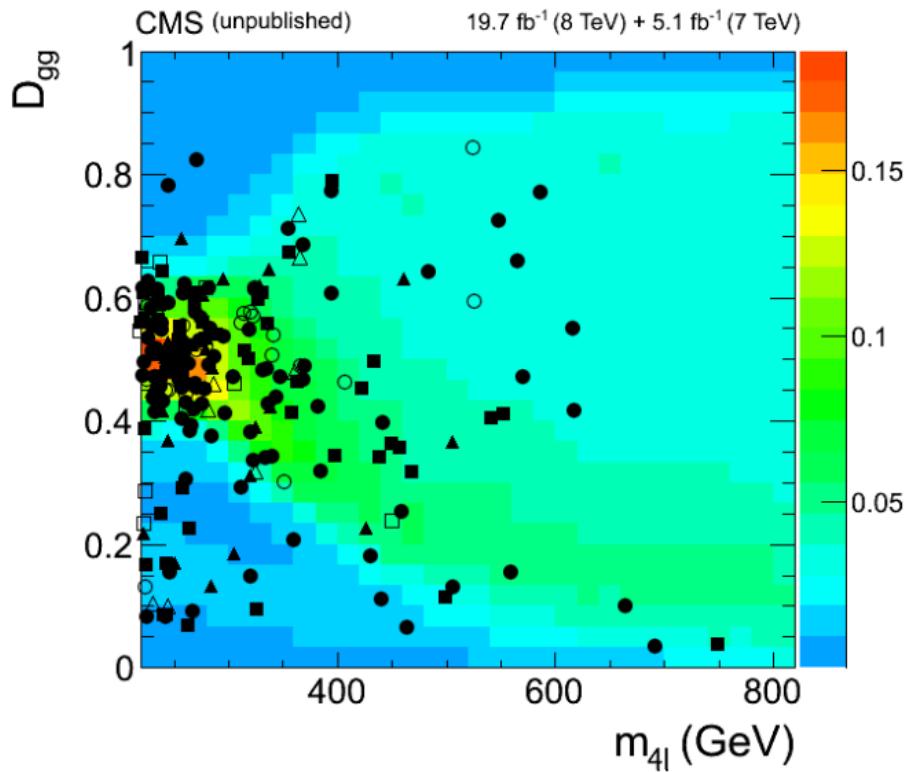
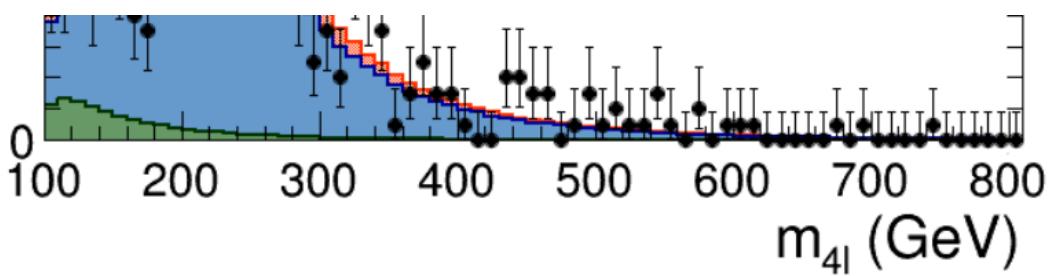
$$\begin{aligned}\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-peak}} &\propto \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H} \\ \sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-peak}} &\propto g_{ggH}^2 g_{HZZ}^2\end{aligned}$$

F. Caola, K. Melnikov (Phys. Rev. D88 2013)
J. Campbell et al. (arXiv:1311.3589)

on-shell: $m_{ZZ} \approx m_H$
off-shell: $m_{ZZ} - m_H \gg \Gamma_H$



$$\begin{aligned}D_{gg} &\equiv \frac{\mathcal{P}_{gg}}{\mathcal{P}_{gg} + \mathcal{P}_{qq}} = \left[1 + \frac{\mathcal{P}_{bg}^M}{a \times \mathcal{P}_{sig}^{gg} + \sqrt{a \times \mathcal{P}_{int}^{gg} + \mathcal{P}_{bg}^{gg}}} \right]^{-1} \\ m_T^2 &= \left[\sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \sqrt{E_T^{\text{miss}}{}^2 + m_{\ell\ell}^2} \right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{\text{miss}} \right]^2\end{aligned}$$



$$\mathcal{D}_{gg} \equiv \frac{\mathcal{P}_{gg}}{\mathcal{P}_{gg} + \mathcal{P}_{q\bar{q}}} = \left[1 + \frac{\mathcal{P}_{bkg}^{q\bar{q}}}{a \times \mathcal{P}_{sig}^{gg} + \sqrt{a} \times \mathcal{P}_{int}^{gg} + \mathcal{P}_{bkg}^{gg}} \right]^{-1}$$

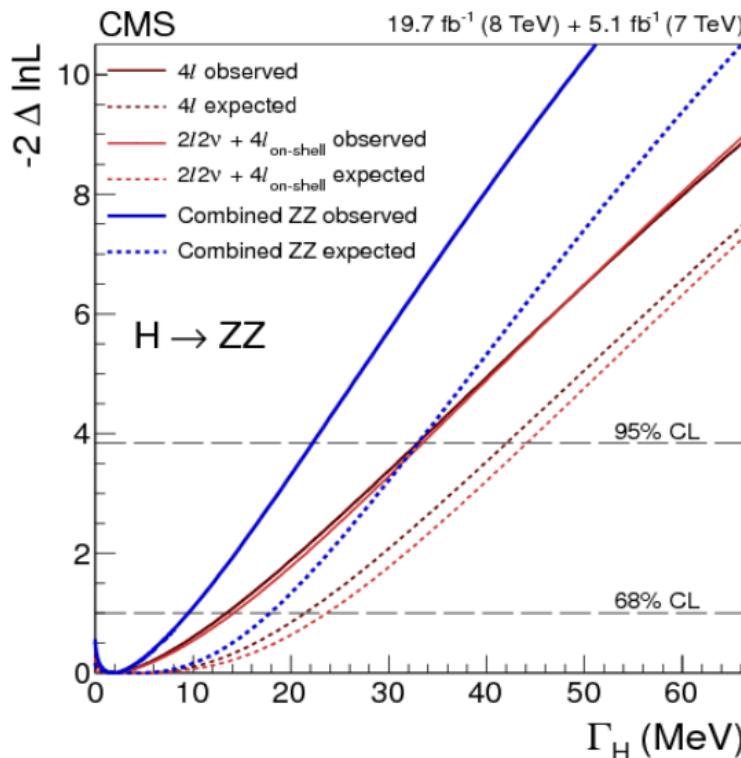
$$m_T^2 = \left[\sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \sqrt{E_T^{\text{miss}}^2 + m_{\ell\ell}^2} \right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{\text{miss}} \right]^2$$

Higgs boson width from offshell production

Likelihood fits

3 parameters are unconstrained in the likelihood fit:

- μ_{ggH} and μ_{VBF} : Signal strength scale w.r.t SM prediction (driven by the on-shell analysis — $4l$ analysis dominates)
- Γ_H/Γ_0 : Higgs width scale w.r.t SM prediction (Γ_H extracted from the off-shell analysis)



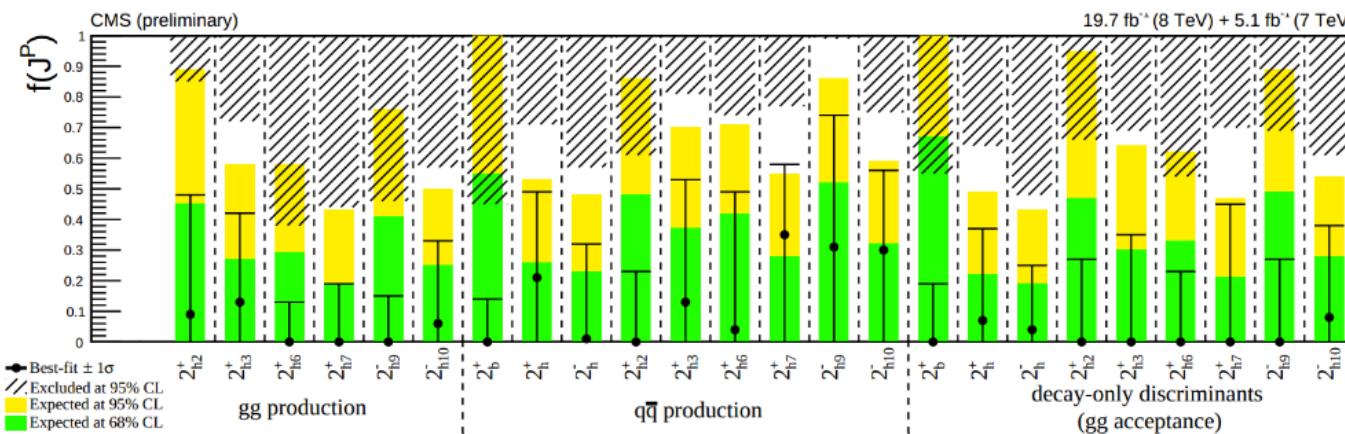
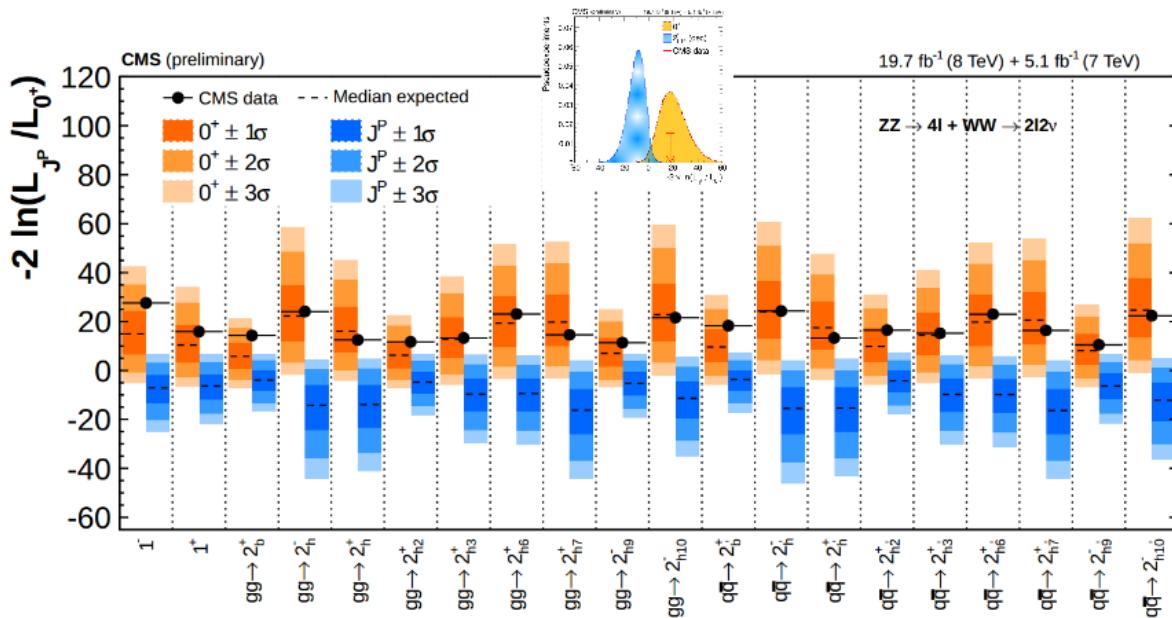
Γ_H Measurement

- expected: $\Gamma_H = 4.2^{+13.5}_{-4.2}$ MeV
- measured: $\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV

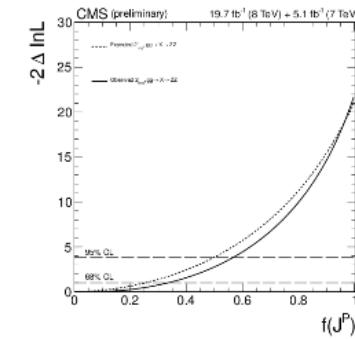
Γ_H 95% limits

- expected: 33 MeV
- measured: 22 MeV

Higgs spin and parity – spin 1 and 2



- Combination of ZZ+WW channels excludes all pure alternative models at 99.9 % CL
- Case of nearly degenerated states — testing for mixture of SM Higgs (0^+) and spin 1 or 2 models



Higgs spin and parity – spin 0

$$A(HV_1V_2) \sim \left[a_1^{V_1V_2} + \frac{\kappa_1^{V_1V_2} q_{V_1}^2 + \kappa_2^{V_1V_2} q_{V_2}^2}{\left(\Lambda_1^{V_1V_2}\right)^2} \right] m_V^2 \epsilon_{V_1}^* \epsilon_{V_2}^* + \underline{a_2^{V_1V_2} f_{\mu\nu}^{*(V_1)} f^{*(V_2),\mu\nu}} + \underline{a_3^{V_1V_2} f_{\mu\nu}^{*(V_1)} \tilde{f}^{*(V_2),\mu\nu}}$$

Λ_1 term
leading momentum expansion

a₂ term
CP even state

a₃ term
CP odd state

Phenomenology of HVV interactions

Interaction between a spin 0 Higgs and two gauge bosons V_1, V_2 (Z, W, γ, g):

- Expansion up to q^2
- assume small anomalous couplings — q^4 and h.o. not considered

Analysis strategy

- Use sensitive channels $H \rightarrow ZZ$ and $H \rightarrow WW$
- Test exotic spin-parity states using hypothesis testing
- Measure tensor structure parameters using likelihood fits

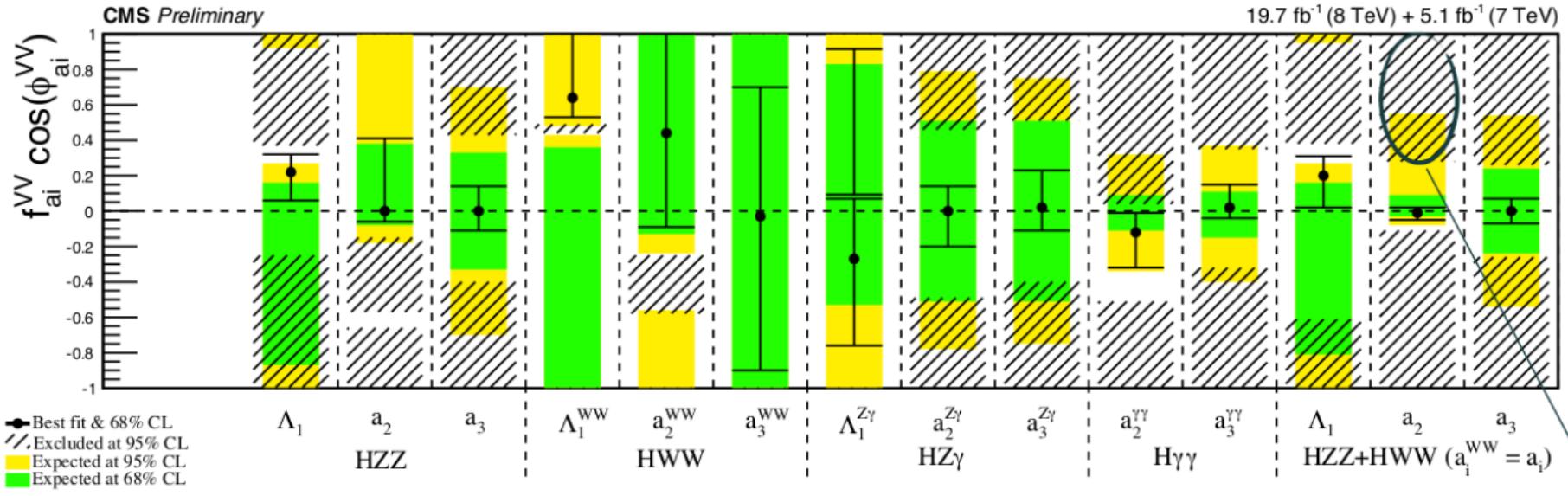
$$f_{a2} = \frac{|a_2|^2 \sigma_2}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4}$$

SM values

	a_1	q^2/Λ_1^2	a_2	a_3
HZZ(WW)	2	$10^{-3} - 10^{-2}$	$10^{-3} - 10^{-2}$	$< 10^{-10}$
HZ γ	-	$10^{-3} - 10^{-2}$	~ 0.0035	$< 10^{-10}$
H $\gamma\gamma$	-	-	~ -0.004	$< 10^{-10}$

Interaction	Anomalous coupling	Coupling phase	Effective fraction	Translation constant
HZZ	Λ_1	ϕ_{Λ_1}	f_{Λ_1}	$\sigma_1 / \tilde{\sigma}_{\Lambda_1} = 1.45 \times 10^{-8} \text{ GeV}^{-4}$
	a_2	ϕ_{a2}	f_{a2}	$\sigma_1 / \sigma_2 = 2.68$
	a_3	ϕ_{a3}	f_{a3}	$\sigma_1 / \sigma_3 = 6.36$
HWW	Λ_1^{WW}	$\phi_{\Lambda_1}^{WW}$	$f_{\Lambda_1}^{WW}$	$\sigma_1^{WW} / \tilde{\sigma}_{\Lambda_1}^{WW} = 1.87 \times 10^{-8} \text{ GeV}^{-4}$
	a_2^{WW}	ϕ_{a2}^{WW}	f_{a2}^{WW}	$\sigma_1^{WW} / \sigma_2^{WW} = 1.25$
	a_3^{WW}	ϕ_{a3}^{WW}	f_{a3}^{WW}	$\sigma_1^{WW} / \sigma_3^{WW} = 3.01$
HZ γ	$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda_1}^{Z\gamma}$	$f_{\Lambda_1}^{Z\gamma}$	$\sigma_1 / \tilde{\sigma}_{\Lambda_1}^{Z\gamma} = 5.76 \times 10^{-9} \text{ GeV}^{-4}$
	$a_2^{Z\gamma}$	$\phi_{a2}^{Z\gamma}$	$f_{a2}^{Z\gamma}$	$\sigma_1 / \sigma_2^{Z\gamma} = 22.4 \times 10^{-4}$
	$a_3^{Z\gamma}$	$\phi_{a3}^{Z\gamma}$	$f_{a3}^{Z\gamma}$	$\sigma_1 / \sigma_3^{Z\gamma} = 27.2 \times 10^{-4}$
H $\gamma\gamma$	$a_2^{\gamma\gamma}$	$\phi_{a2}^{\gamma\gamma}$	$f_{a2}^{\gamma\gamma}$	$\sigma_1 / \sigma_2^{\gamma\gamma} = 28.2 \times 10^{-4}$
	$a_3^{\gamma\gamma}$	$\phi_{a3}^{\gamma\gamma}$	$f_{a3}^{\gamma\gamma}$	$\sigma_1 / \sigma_3^{\gamma\gamma} = 28.8 \times 10^{-4}$

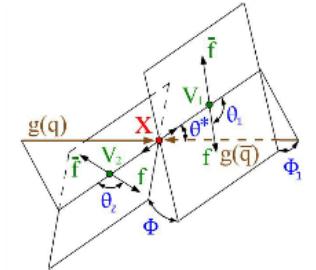
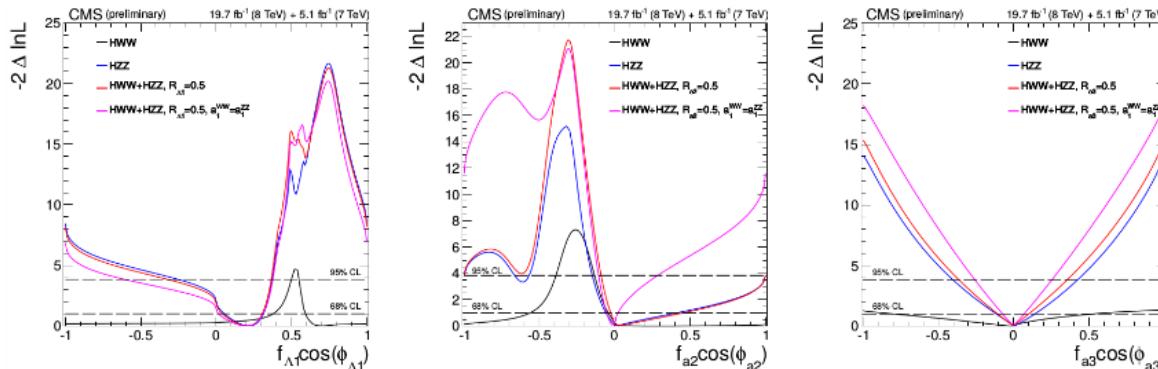
Higgs spin and parity – spin 0



Likelihood fits

- Use suitable Kinematic Discriminants for each measurement
- Construct multidimensional signal and background pdf templates from discriminants
- Perform likelihood function scans over complex couplings ratios (exotic/SM)

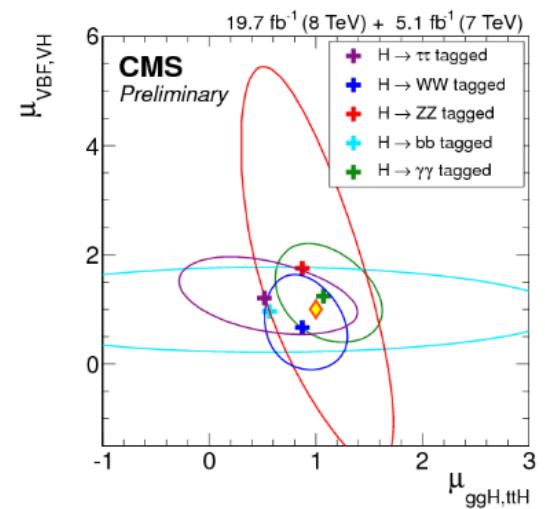
Region not excluded in either HZZ or HWW .
Constraint from $HZZ - HWW$ correlation



Higgs \rightarrow invisible decays

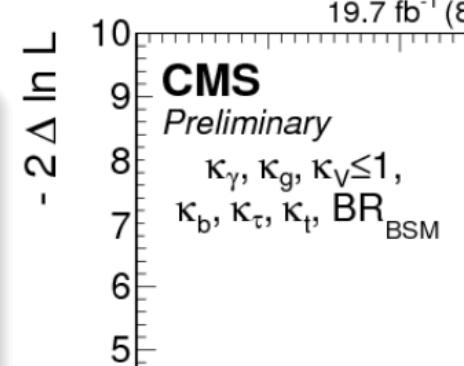
Recent measurements of the branching fractions of the 125 GeV Higgs boson are **compatible with the SM** expectations, but with **large uncertainties**.

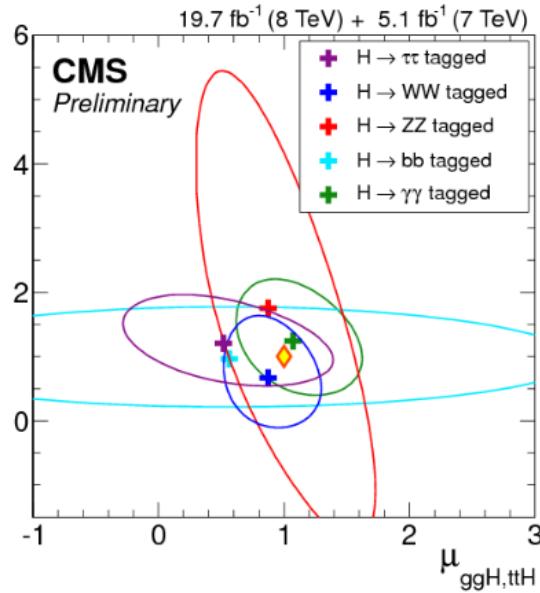
- Can still accommodate significant non-SM decays
- Additional Higgs bosons with exotic decays are still possible



Indirect constraints

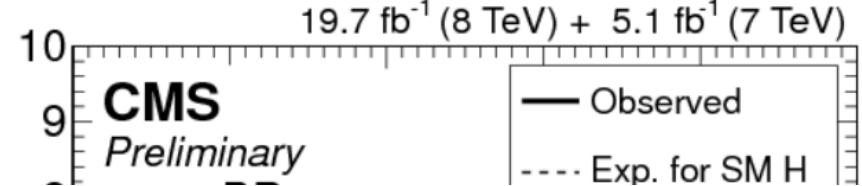
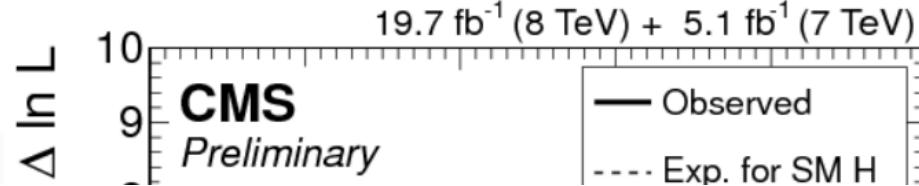
B_{BSM} can be inferred by fitting the observed decay modes:





Many models predict Higgs boson(s) decaying to heavy, undetectable particles

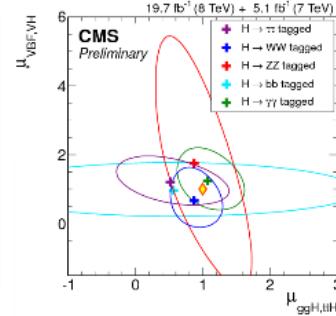
- 4th-generation neutrinos, neutralinos, graviscalars in extra-dimensions, etc.
- Some of these constitute viable dark matter (DM) candidates
- In “Higgs portal” models, the DM does not couple to any SM particles but the Higgs — a mediator between the SM and DM sectors



Higgs \rightarrow invisible decays

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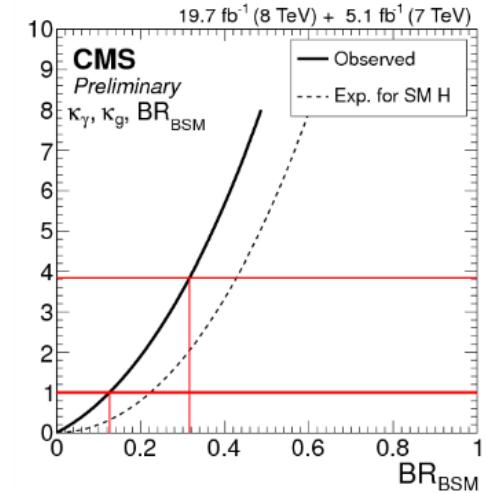
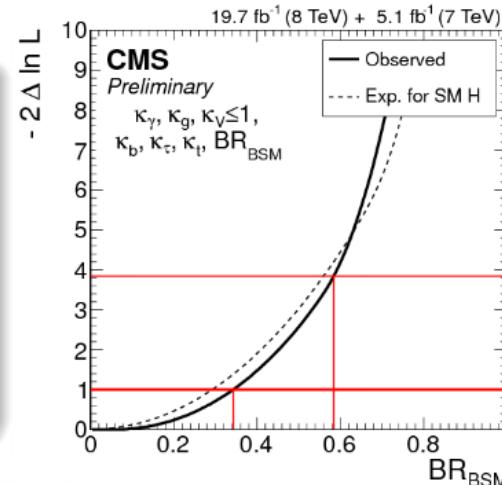
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Indirect constraints

B_{BSM} can be inferred by fitting the observed decay modes:

$B_{BSM} < 0.58$ (0.32 from more constrained model)



Direct searches

In production channels where the Higgs boson recoils against a visible system:

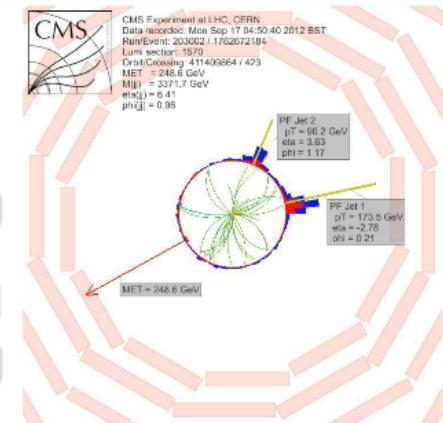
- Vector boson fusion (VBF)
- Associated production with a Z boson, decaying to a pair of leptons or $b\bar{b}$

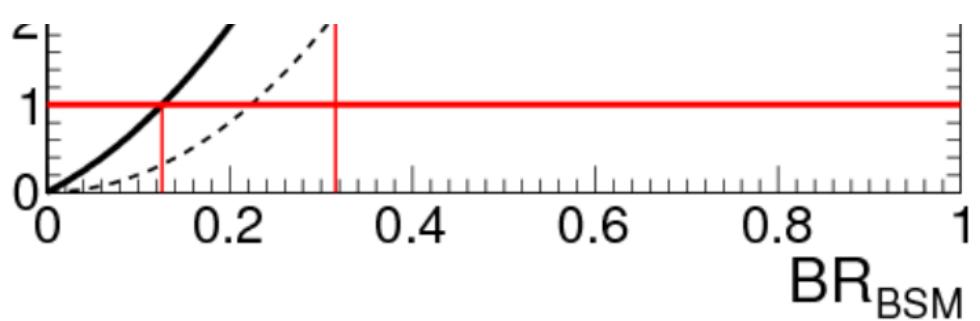
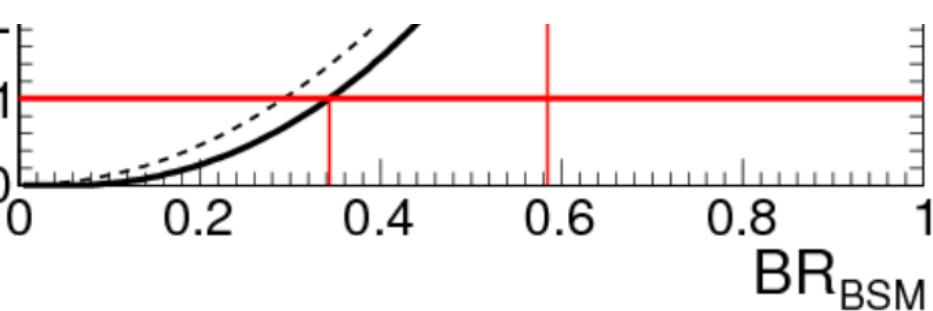
[arXiv:1404:1344]

$qq \rightarrow qqVV \rightarrow qqH \rightarrow 2\text{jets} + \text{MET}$

$qq \rightarrow Z^* \rightarrow ZH \rightarrow l^+l^- + \text{MET}$

$qq \rightarrow Z^* \rightarrow ZH \rightarrow b\bar{b} + \text{MET}$



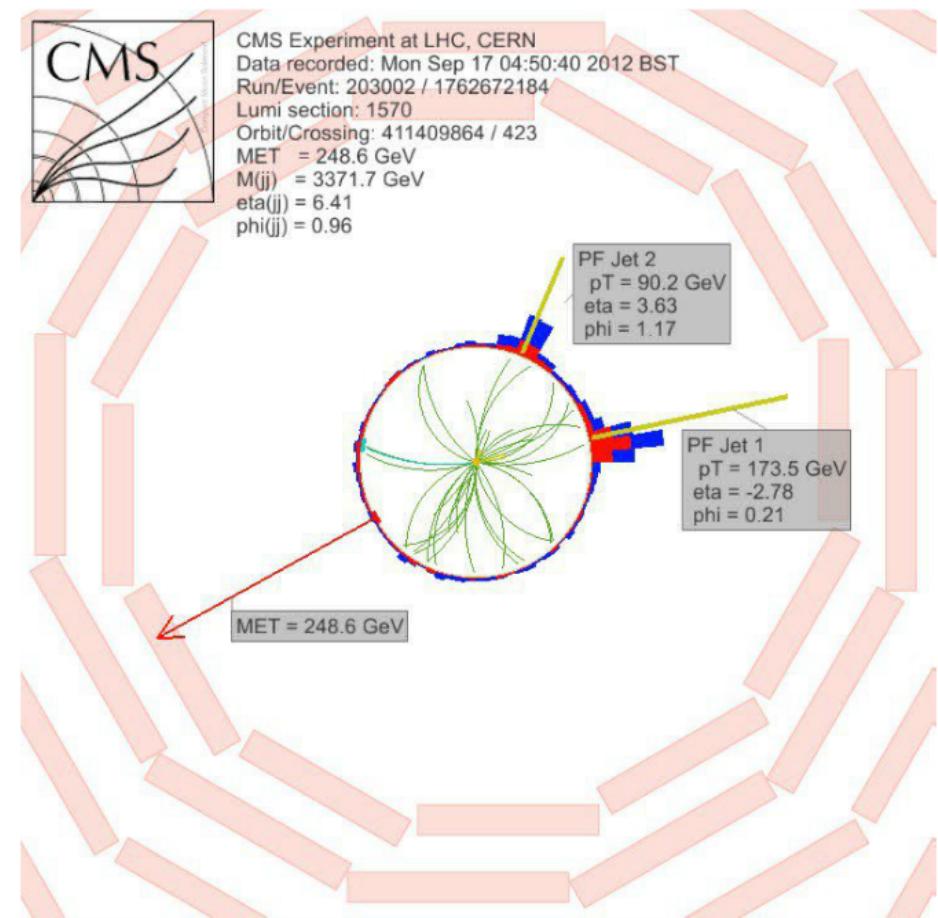


[arXiv:1404:1344]

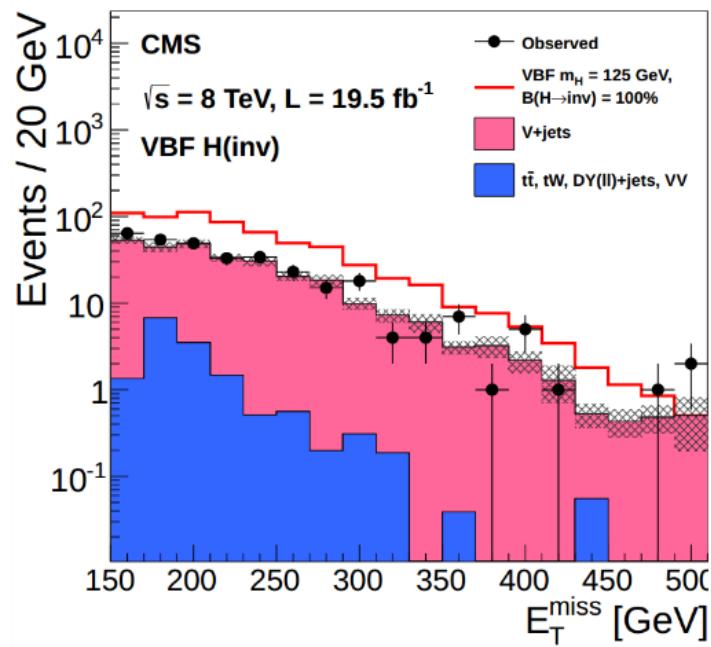
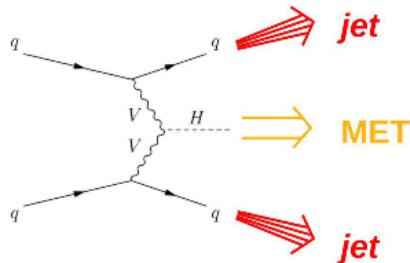
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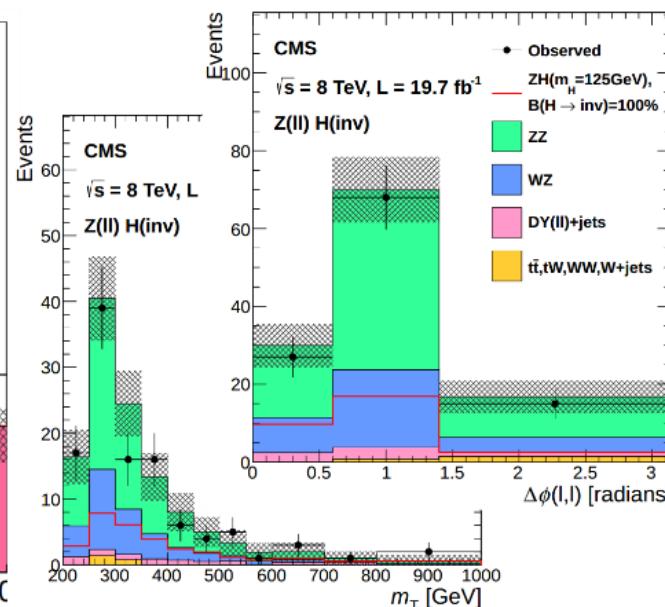
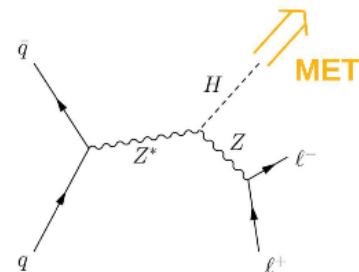


H → invisible pillars [VBF, H+Zll, H+Zbb]



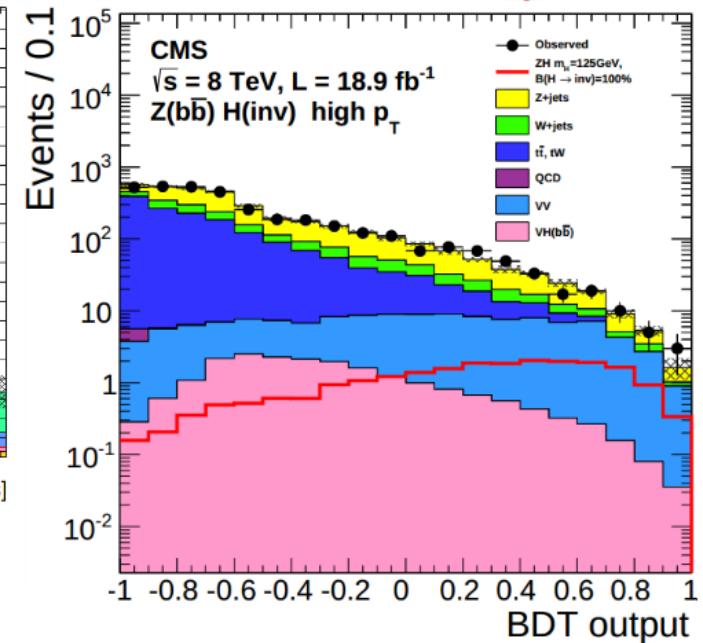
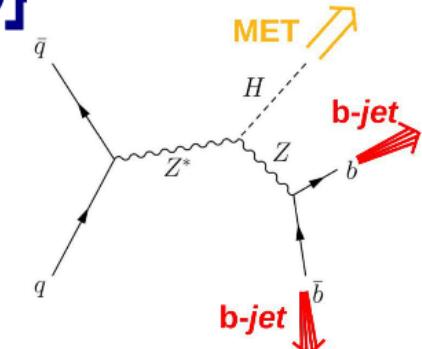
VBF production

- Two forward jets, separated by a large rapidity gap, high invariant mass
- Large missing transverse energy (MET, E_T^{miss})
- Backgrounds: $Z(\nu\bar{\nu}) + \text{jets}$, $W(l\nu) + \text{jets}$, $DY(II) + \text{jets}$, Single top, $t\bar{t}$, dibosons, QCD multijets
- Rates from data control regions: $Z(\nu\bar{\nu}) + \text{jets}$, $W(l\nu) + \text{jets}$, QCD multijets



Associated H(inv.) + Z(II)

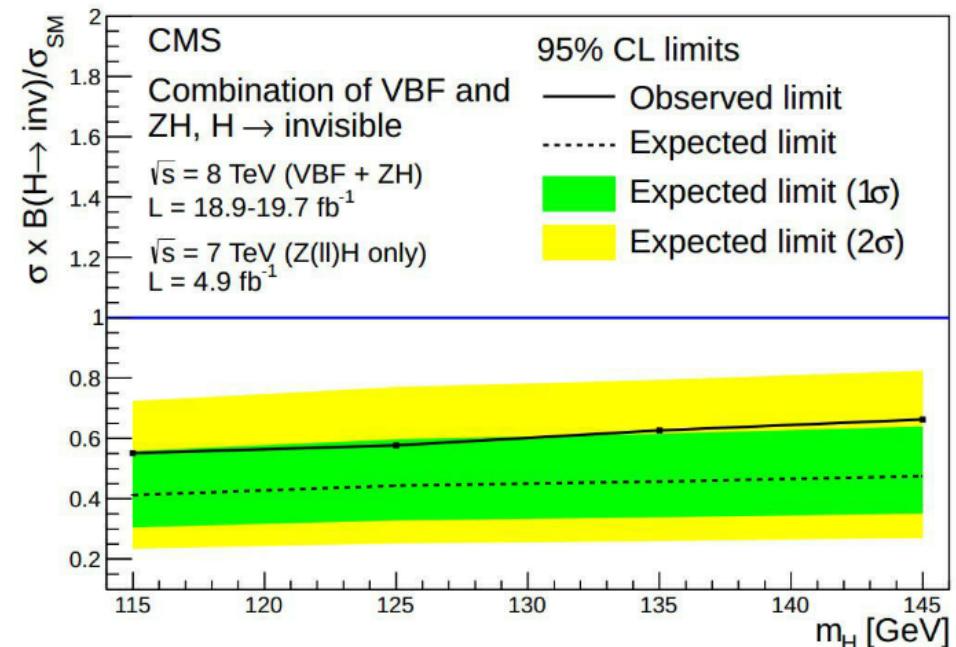
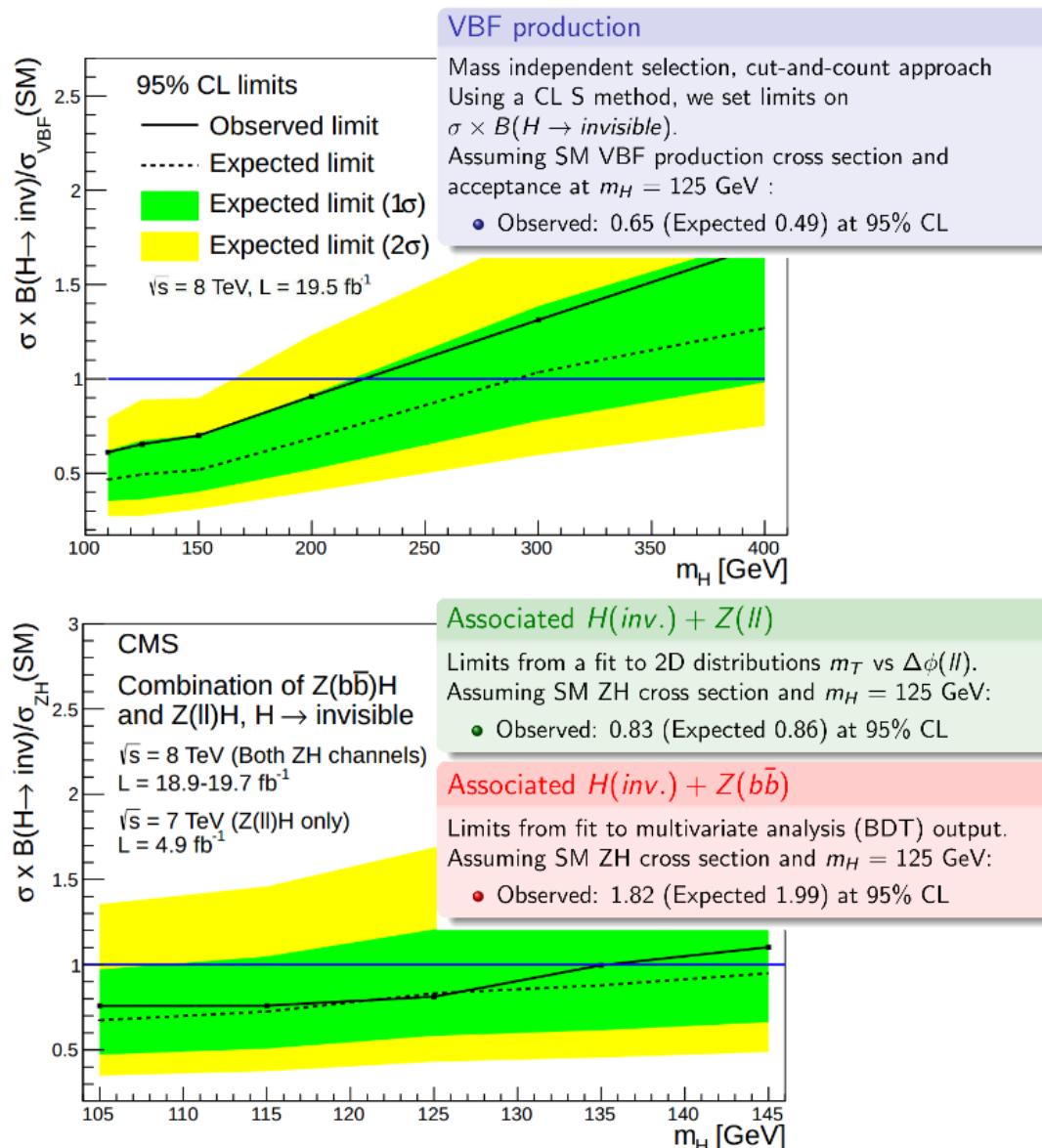
- Two isolated leptons from Z decay, large MET
- Backgrounds: $ZZ(l\nu\nu\nu) + \text{jets}$, $WW(l\nu\nu\nu) + \text{jets}$, $WZ(l\nu\nu\nu) + \text{jets}$, $DY(II) + \text{jets}$, $t\bar{t}$, single top, $W(l\nu) + \text{jets}$, QCD
- Data control regions: $ZZ(\tau\tau) + \text{jets}$, $WW(l\nu\nu\nu) + \text{jets}$, $DY(II) + \text{jets}$, $t\bar{t}$, single top



Associated H(inv.) + Z(bb)

- Two b-jets from Z decay, large MET
- Backgrounds: $Z(\nu\bar{\nu}) + \text{jets}$, $W(l\nu) + \text{jets}$, $ZZ(b\bar{b}\nu\nu) + \text{jets}$, $WZ(l\nu b\bar{b}) + \text{jets}$, $t\bar{t}$, Single top, $t\bar{t}$, dibosons, QCD multijets
- Background modeled with MC, normalized from data

H → invisible results [VBF, H+Zll, H+Zbb]



Combination of VBF and ZH production

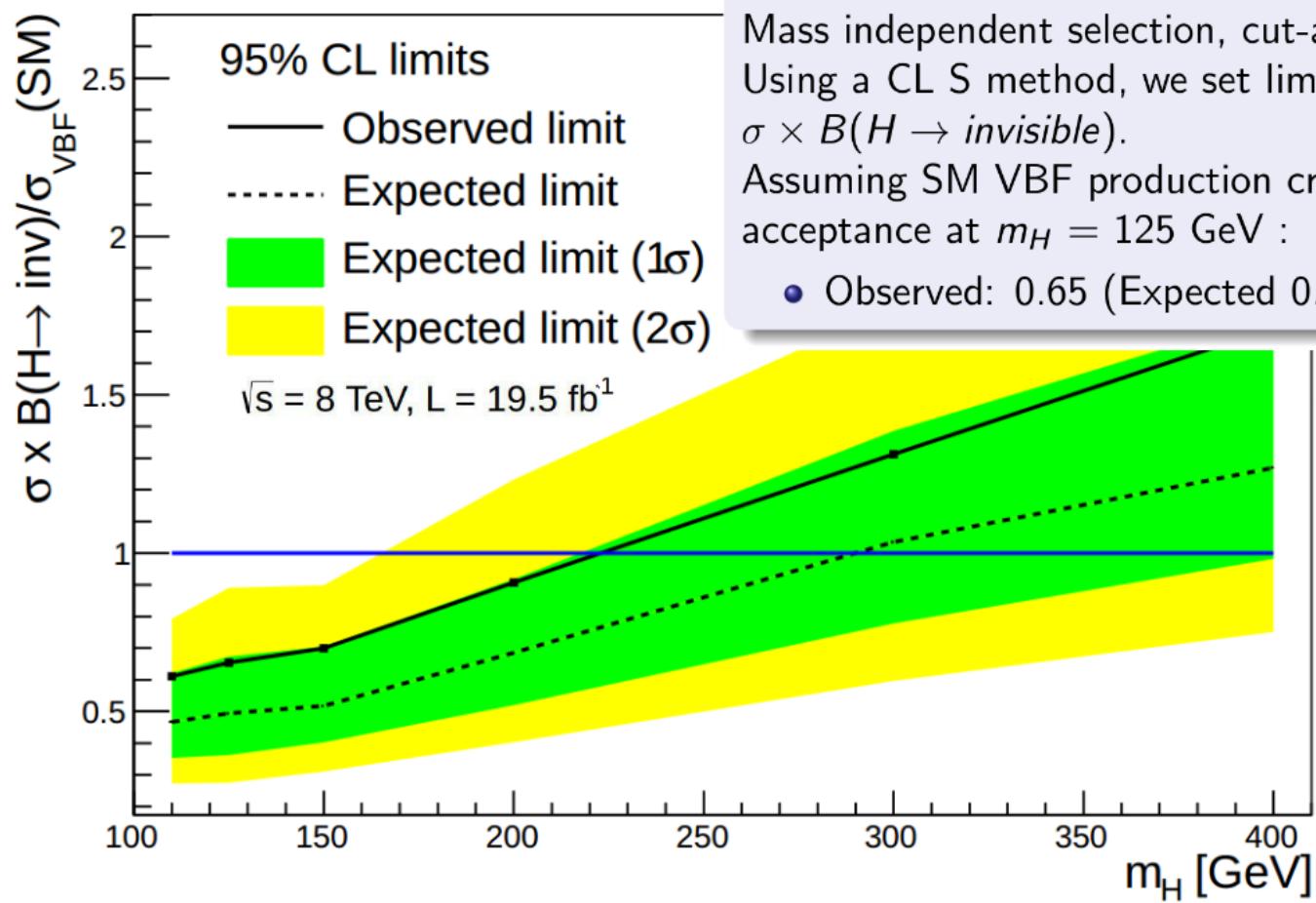
Individual limits on $\sigma \times B(H \rightarrow \text{invisible})/\sigma_{SM}$ from VBF and ZH channels are combined.
Assuming SM VBF and ZH cross sections, they are interpreted as limits on $B(H \rightarrow \text{invisible})$

- Observed: 0.58 (Expected 0.44) at 95% CL
- Comparable to indirect constraints

Main systematic uncertainties

- Jet energy scale
- PDF renormalization/factorization scale
- Total integrated luminosity
- Lepton momentum scale
- Jet energy resolution
- MET scale/resolution

$H \rightarrow$ invisible results [VBF, $H+Z$]



VBF production

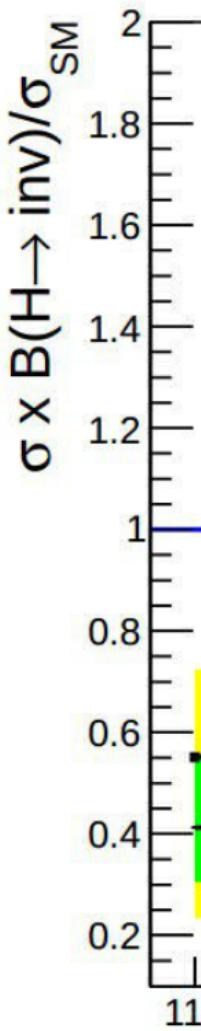
Mass independent selection, cut-and-count approach
 Using a CL S method, we set limits on
 $\sigma \times B(H \rightarrow \text{invisible})$.
 Assuming SM VBF production cross section and
 acceptance at $m_H = 125 \text{ GeV}$:

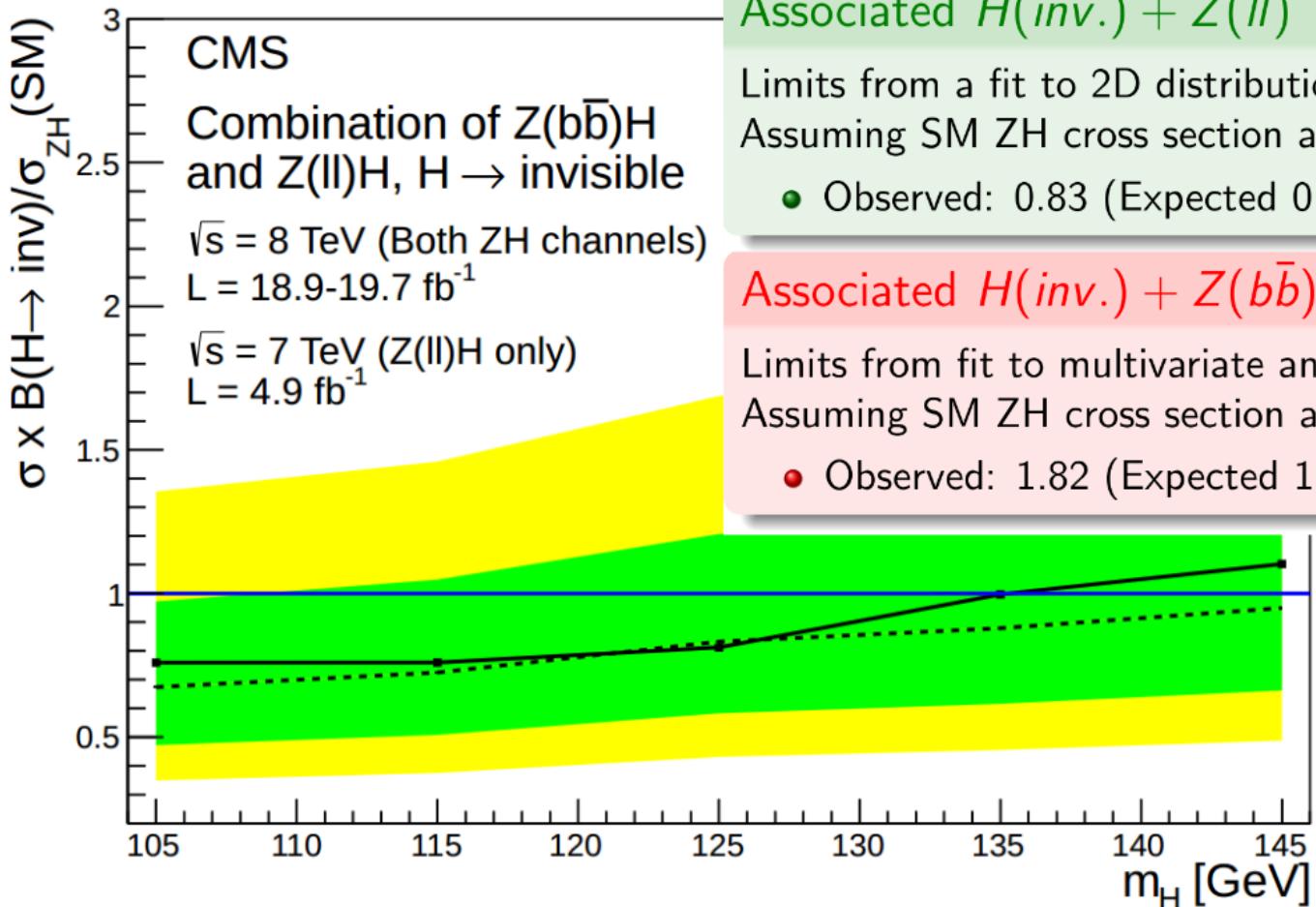
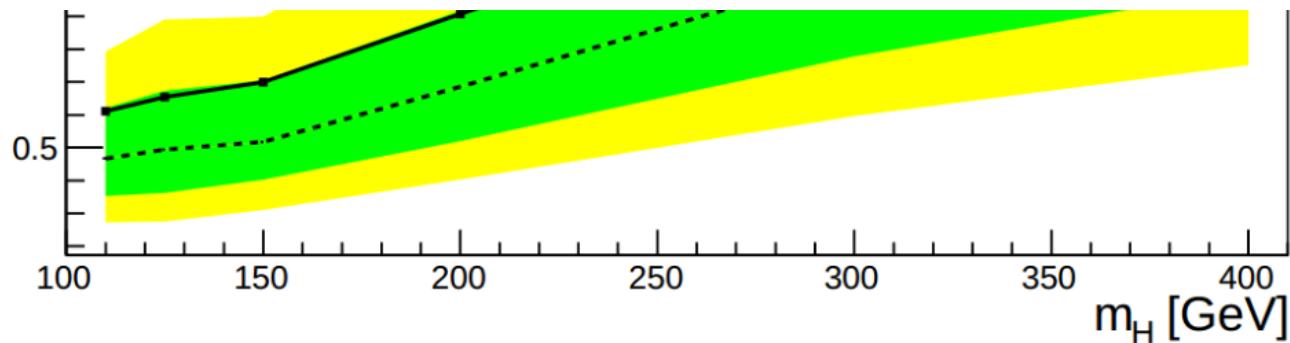
- Observed: 0.65 (Expected 0.49) at 95% CL



Associated $H(\text{inv.}) + Z(\text{ll})$

Limits from a fit to 2D distributions m_T vs $\Delta\phi(\text{ll})$.
 Assuming SM ZH cross section and $m_H = 125 \text{ GeV}$:





Associated $H(\text{inv.}) + Z(l\bar{l})$

Limits from a fit to 2D distributions m_T vs $\Delta\phi(l\bar{l})$.
Assuming SM ZH cross section and $m_H = 125 \text{ GeV}$:

- Observed: 0.83 (Expected 0.86) at 95% CL

Associated $H(\text{inv.}) + Z(b\bar{b})$

Limits from fit to multivariate analysis (BDT) output.
Assuming SM ZH cross section and $m_H = 125 \text{ GeV}$:

- Observed: 1.82 (Expected 1.99) at 95% CL

ction, cut-and-count approach
we set limits on

production cross section and
25 GeV :
Expected 0.49) at 95% CL

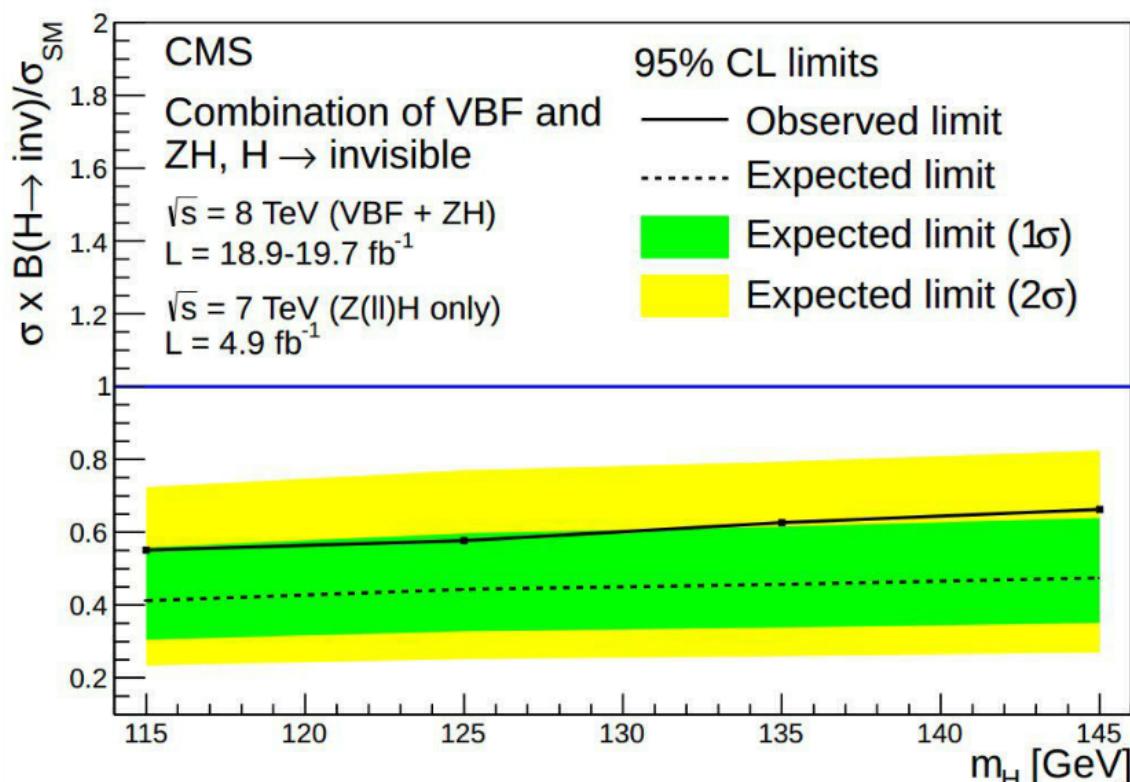


+ $Z(l\bar{l})$

distributions m_T vs $\Delta\phi(l\bar{l})$.
Cross section and $m_H = 125$ GeV:
Expected 0.86) at 95% CL

+ $Z(b\bar{b})$

bivariate analysis (BDT) output.
Cross section and $m_H = 125$ GeV:
Expected 1.99) at 95% CL



Combination of VBF and ZH production

Individual limits on $\sigma \times B(H \rightarrow \text{invisible})/\sigma_{SM}$ from VBF and ZH channels are combined.

Assuming SM VBF and ZH cross sections, they are interpreted as limits on $B(H \rightarrow \text{invisible})$

- Observed: 0.58 (Expected 0.44) at 95% CL
- Comparable to indirect constraints

Main systematic uncertainties

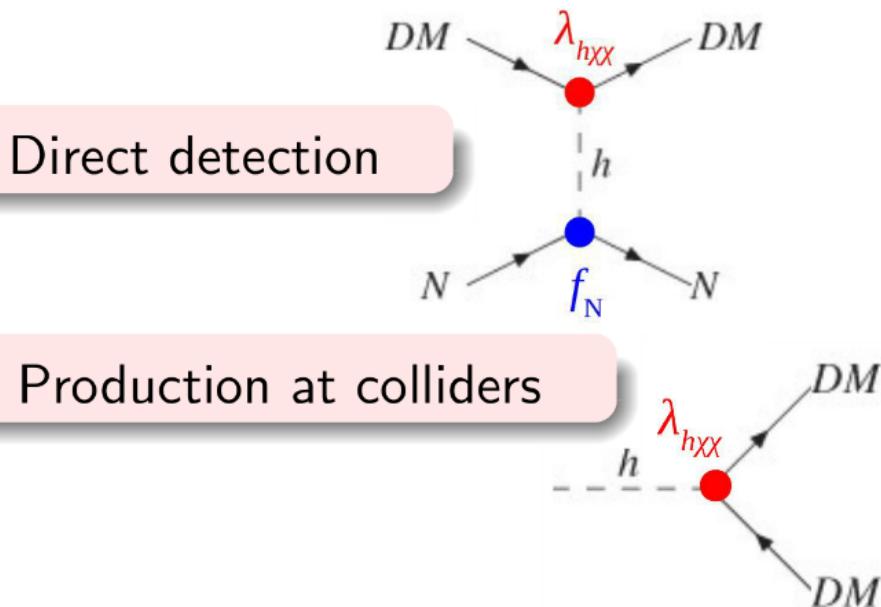
- Jet energy scale
- PDF renormalization/factorization scale
- Total integrated luminosity
- Lepton momentum scale
- Jet energy resolution
- MET scale/resolution

Dark Matter enters through Higgs Portal

Combination of VBF and ZH production

Limits on the Higgs invisible branching fraction can be interpreted in the context of **Higgs portal DM models**

- Direct-detection experiments measure the DM-nucleon elastic interaction, mediated by a Higgs
- If the DM has mass below $m_H/2$, the decay width Γ_{inv} can be translated to spin-independent DM-nucleon elastic cross section and compared to results from direct detection



$$\sigma_{S-N}^{SI} = \frac{\lambda_{hSS}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2} \quad \text{scalar DM}$$

$$\sigma_{V-N}^{SI} = \frac{\lambda_{hVV}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2} \quad \text{vector DM}$$

$$\sigma_{f-N}^{SI} = \frac{\lambda_{hff}^2}{4\pi \Lambda^2 m_h^4} \frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2} \quad \text{fermion DM}$$

Higgs-nucleon coupling f_N

$f_N = 0.326$ from lattice calculation
(min/max from MILC Collaboration)

Some Higgs portal related talks:
[hep-ph/0609004](http://arxiv.org/abs/hep-ph/0609004)
[hep-ph/0703160](http://arxiv.org/abs/hep-ph/0703160)
[hep-ph/0705.0303](http://arxiv.org/abs/hep-ph/0705.0303)
[hep-ph/0709.1202](http://arxiv.org/abs/hep-ph/0709.1202)
[hep-ph/0711.1002](http://arxiv.org/abs/hep-ph/0711.1002)
[hep-ph/0801.0211](http://arxiv.org/abs/hep-ph/0801.0211)
[hep-ph/0803.0301](http://arxiv.org/abs/hep-ph/0803.0301)
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Some Higgs portal related talks

First order electroweak phase transition and dark matter in (non)conformal Higgs portal models

Session: Higgs Portal Models

We study the electroweak phase transition in class of classically (non)conformal Higgs portal models, with and without Veltman conditions imposed for the scalar sector. Some of the models include also fermionic type dark sector, which can be related to dark matter or neutrino masses. We find, by scanning the model parameter spaces, many realizations of the models, where the electroweak phase tran ... [More](#)

Presented by Jussi VIRKAJÄRVI on 16 Dec 2014 at 09:45

The Higgs Portal

Session: Higgs Portal Models

I will discuss some aspects of the Higgs portal models, in particular, their cosmological implications as well as possible signatures at the LHC.

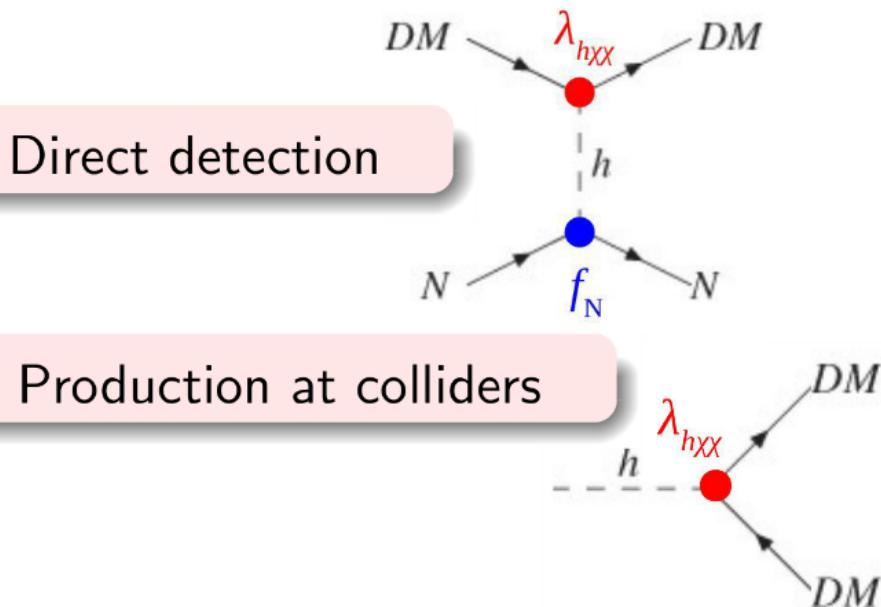
Presented by Oleg LEBEDEV on 16 Dec 2014 at 09:00

Dark Matter enters through Higgs Portal

Combination of VBF and ZH production

Limits on the Higgs invisible branching fraction can be interpreted in the context of **Higgs portal DM models**

- Direct-detection experiments measure the DM-nucleon elastic interaction, mediated by a Higgs
- If the DM has mass below $m_H/2$, the decay width Γ_{inv} can be translated to spin-independent DM-nucleon elastic cross section and compared to results from direct detection



$$\sigma_{S-N}^{SI} = \frac{\lambda_{hSS}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2} \quad \text{scalar DM}$$

$$\sigma_{V-N}^{SI} = \frac{\lambda_{hVV}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2} \quad \text{vector DM}$$

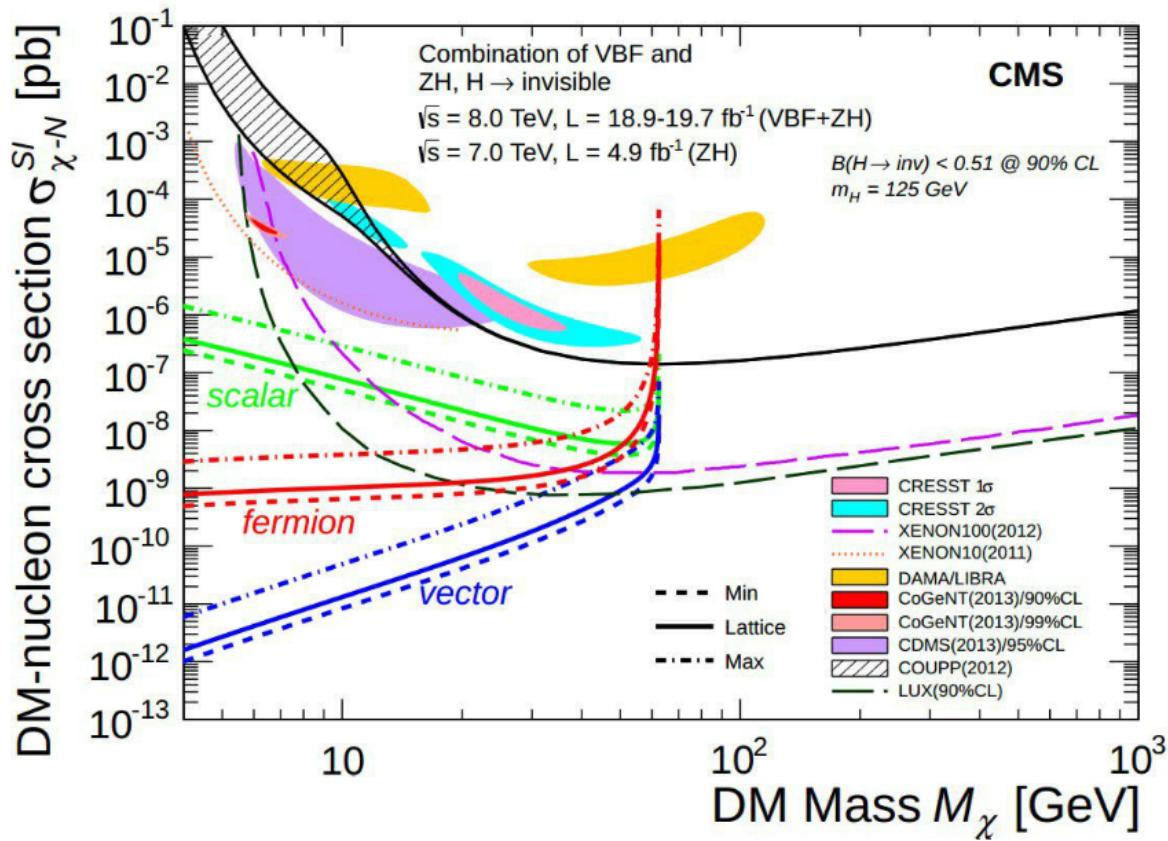
$$\sigma_{f-N}^{SI} = \frac{\lambda_{hff}^2}{4\pi \Lambda^2 m_h^4} \frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2} \quad \text{fermion DM}$$

Higgs-nucleon coupling f_N

$f_N = 0.326$ from lattice calculation
(min/max from MILC Collaboration)

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Limits on DM – nucleon cross section



$$\mathcal{B}(H \rightarrow inv) = \frac{\Gamma_{inv}}{\Gamma_{SM} + \Gamma_{inv}}$$

Competitive results

Use the combined limits from VBF, $Z(H)H$, and $Z(b\bar{b})H$ searches for $m_H = 125$ GeV:
 $B(H \rightarrow inv) < 0.51$ at 90% CL

- Set limits on the spin-independent DM-nucleon cross section for **3 scenarios: scalar, fermion, vector DM**
- Results competitive with current results from direct-detection experiments in the low DM mass region

Conclusions

- Higgs boson couplings to fermions and bosons measured
- Higgs mass precisely determined — statistical uncertainty still dominates (Run2)
- Higgs width measurement boosted to the realm of SM expectation using off-shell production
- Excluded at $> 99\%$ CL models with Higgs boson of spin-1 and spin-2
- Set stringent limits on effective fractions and phases from spin-0 tensor structure allowing for mixture of multiple spin-0 models
- Indirect measurements and direct searches set consistent limits on $B(H \rightarrow \text{invisible})$
- Under Higgs Portal model interpretation, CMS sets concurrent limits on low mass dark matter

All consistent with SM with the back door left open for some DM to enter.



Second Topical Meeting From Higgs to Dark Matter 2014

Dr Holms Hotel, Geilo, Norway

14 - 17 December

Marry Christmas and Happy new Year

