Second Topical Meeting
From Higgs to Dark Matter 2014

Dr Holms Hotel, Geilo, Norway

14 - 17 December

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

Itinerary

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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→ZZ	✔	✔			→	6.5	6.3
H→γγ	✔	✔	✔	✔	→	5.6	5.3
H→WW	✔	✔	✔	✔	→	4.7	5.4
H→ττ	✔	✔	✔	✔	→	3.8	3.9
H→bb		✓	✔	✔	→	2.0	2.3
H→Zγ	✓	✓					
H→μμ	✓	✓					
H→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→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:

- $H \to ZZ^\star \to 4l$
- $H \to \gamma\gamma$

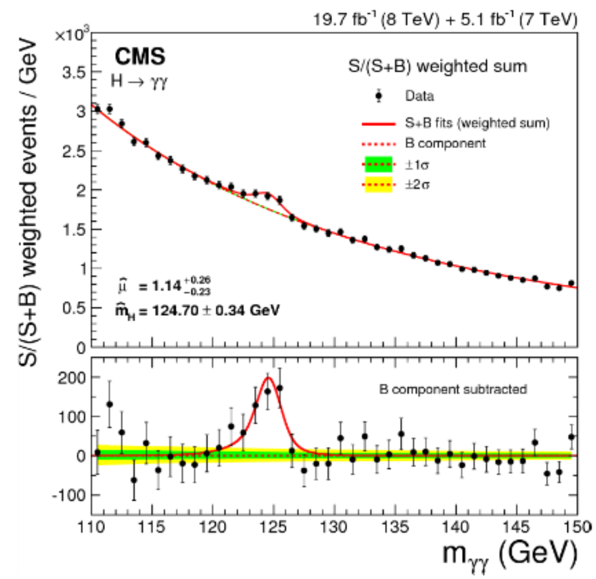
$H \to \gamma\gamma$

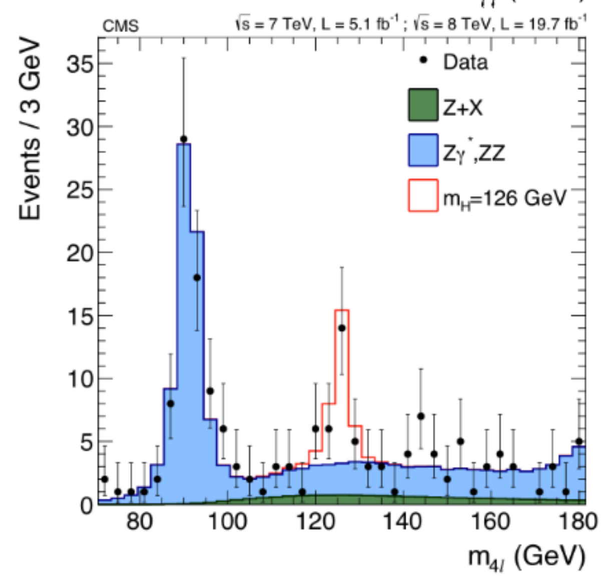
- Two isolated, high p_T photons
- Events categorized by $m_{\gamma\gamma}$ resolution, kinematics and production mode
- Same as measurement of the couplings
- Simultaneous S+B fit to all categories
- Background from fit to data
- Analytic signal model accounting for data/MC corrections and associated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

$H \to ZZ^\star \to 4l$

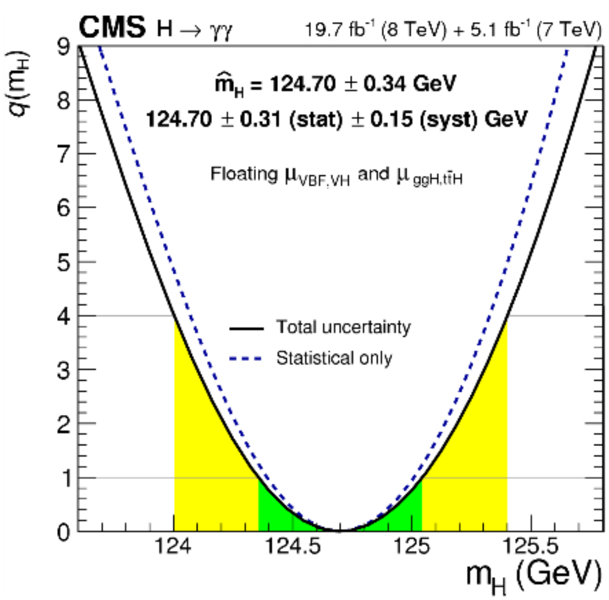
- Four isolated leptons
- Only lepton flavor categorization ($4e$, 4μ , $2e2\mu$)
- Unbinned maximum likelihood fit
- Use m_{4l} vs kin. discriminant (KD) for S/B separation
- Use information on event-by-event mass resolution

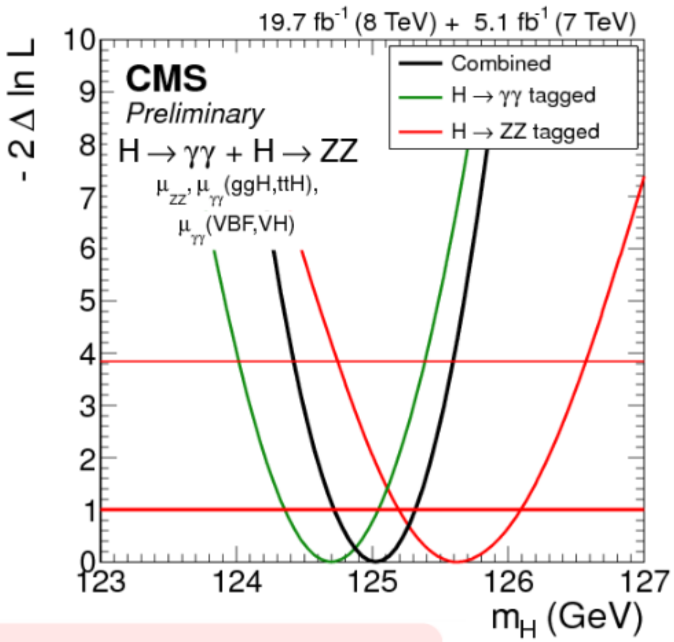
Energy scale is dominant systematic.

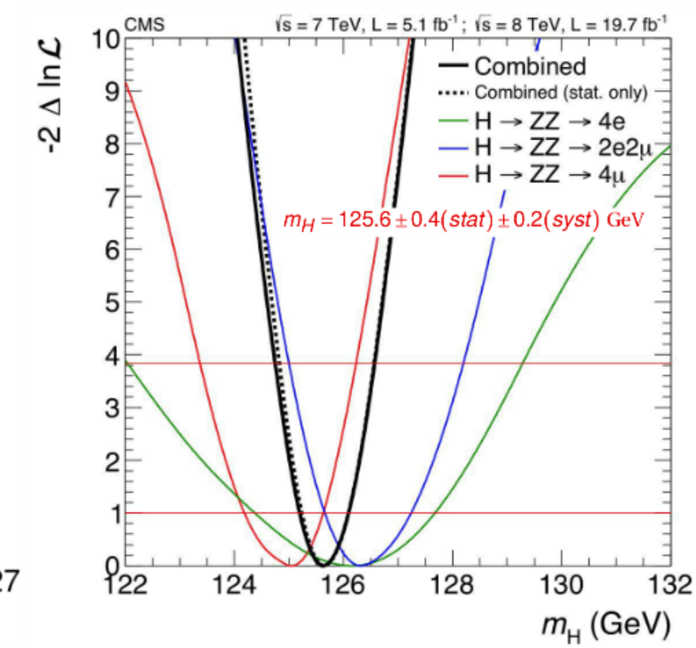




Higgs boson mass

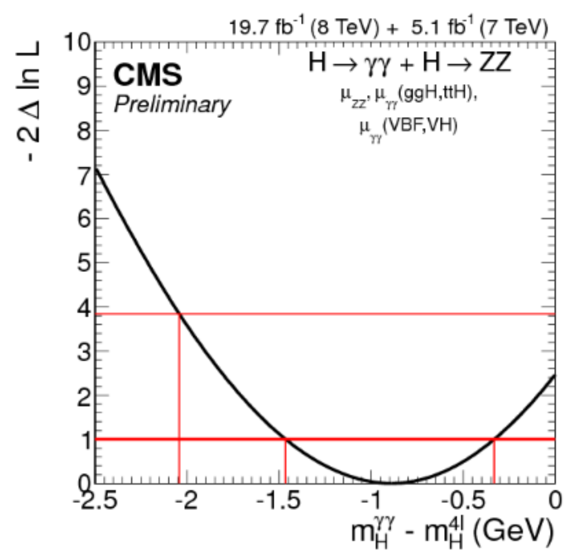






$$m_H = 125.03^{+0.26}_{-0.27}(stat.)^{+0.13}_{-0.15}(syst.)\ \mathrm{GeV}$$

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



Global signal strength

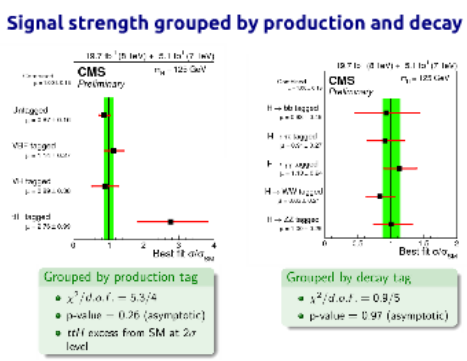
Overall signal strength

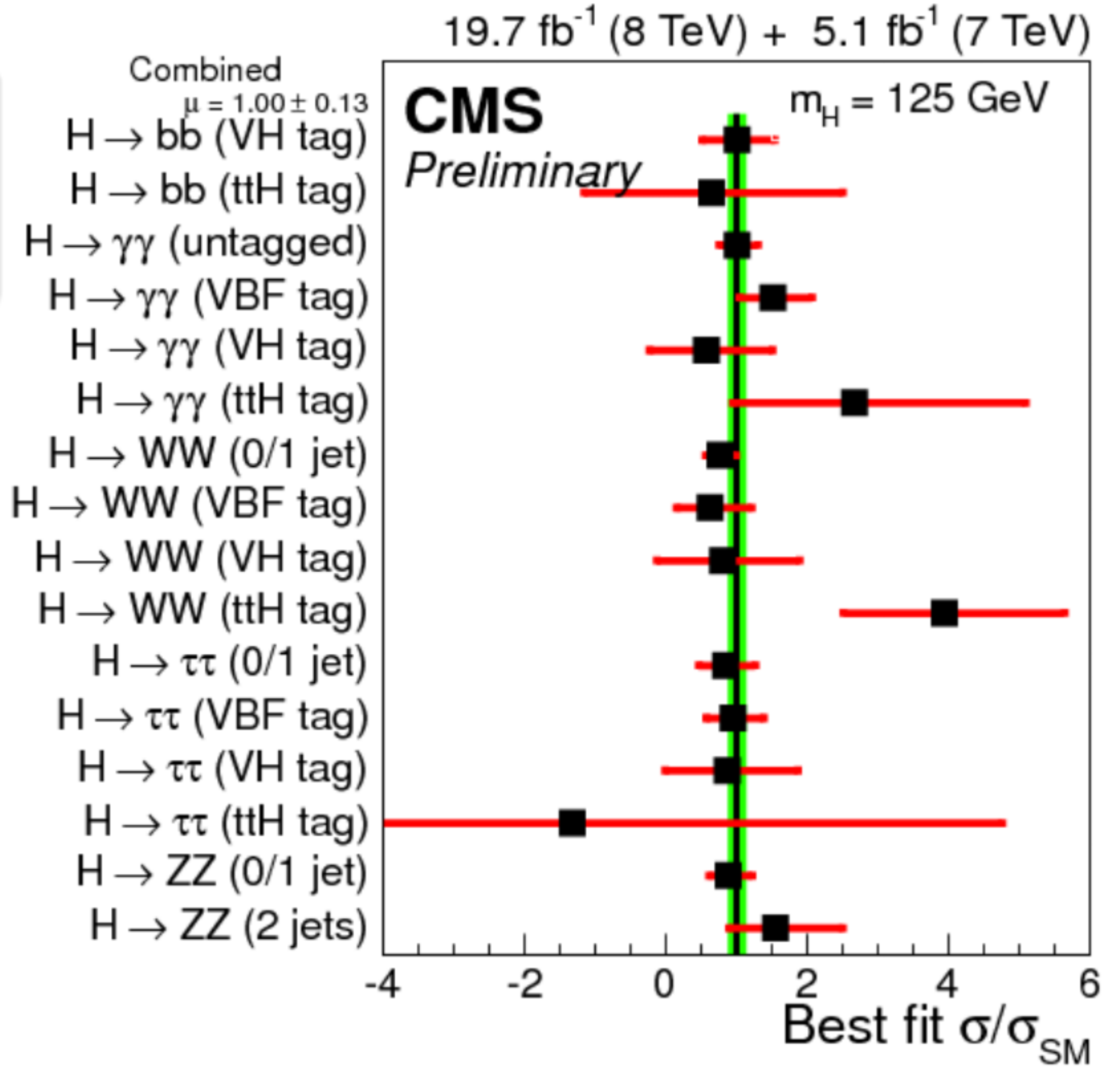
$1.00 \pm 0.09(stat.)^{+0.08}_{-0.07}(theo.) \pm 0.07(syst.)$

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

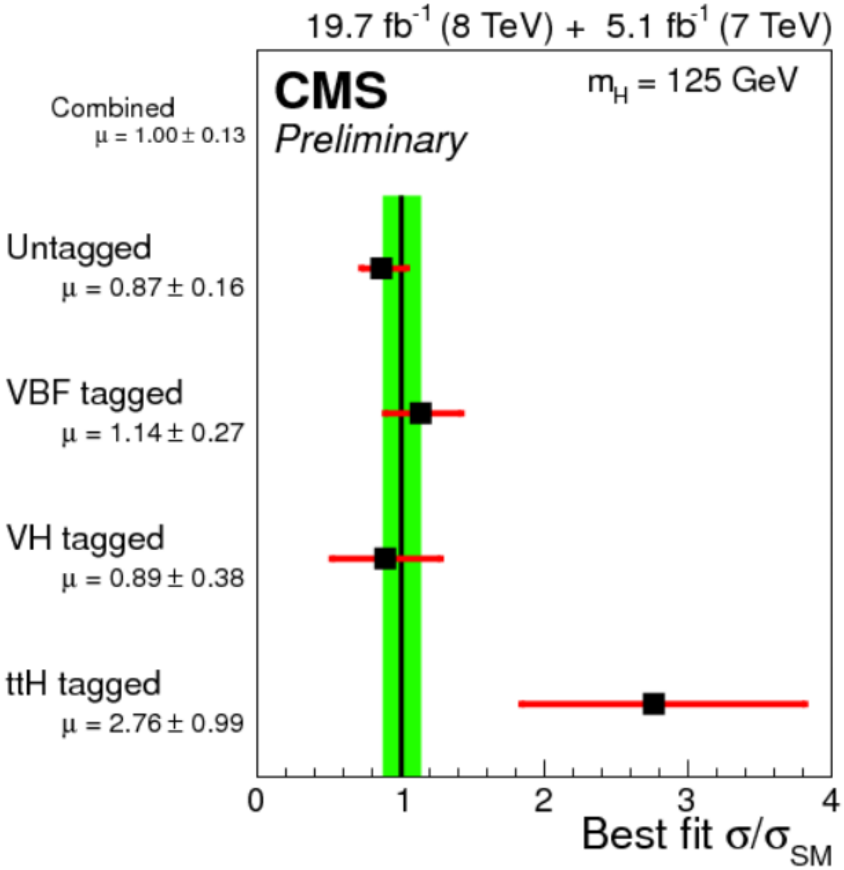
Production and decay tag

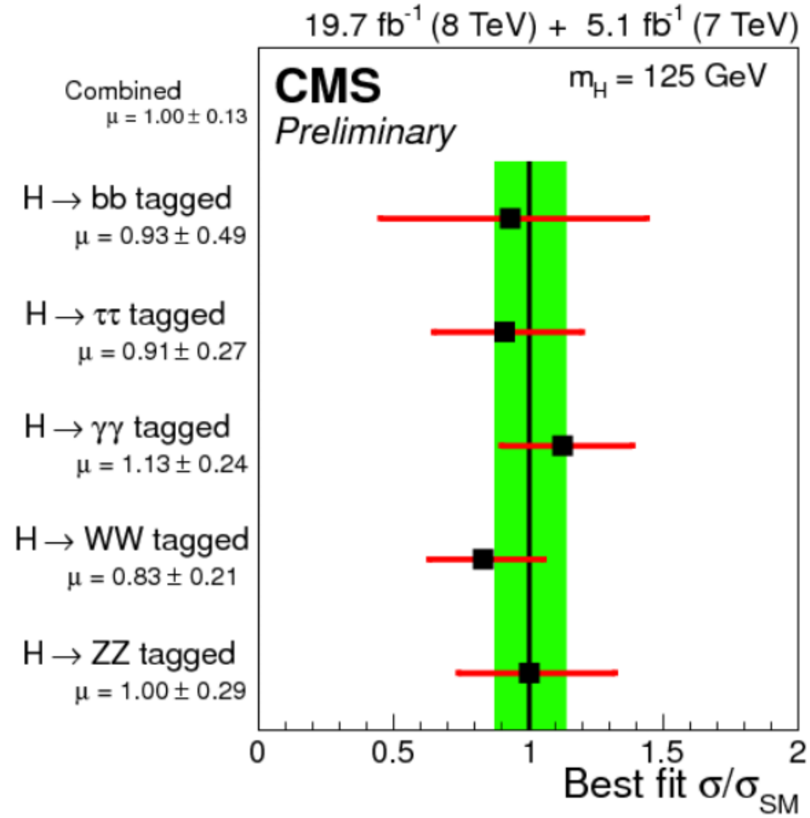
- $\chi^2/d.o.f. = 10.5/16$
- p-value = 0.84 (asymptotic)





Signal strength grouped by production and decay





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

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

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

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

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

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

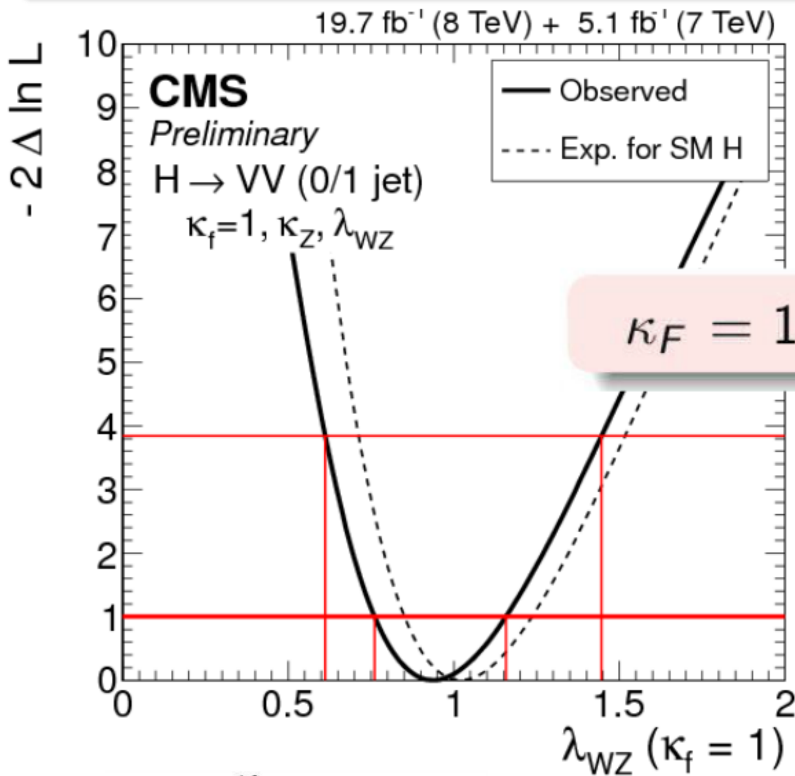
Total width

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

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

Custodial symmetry

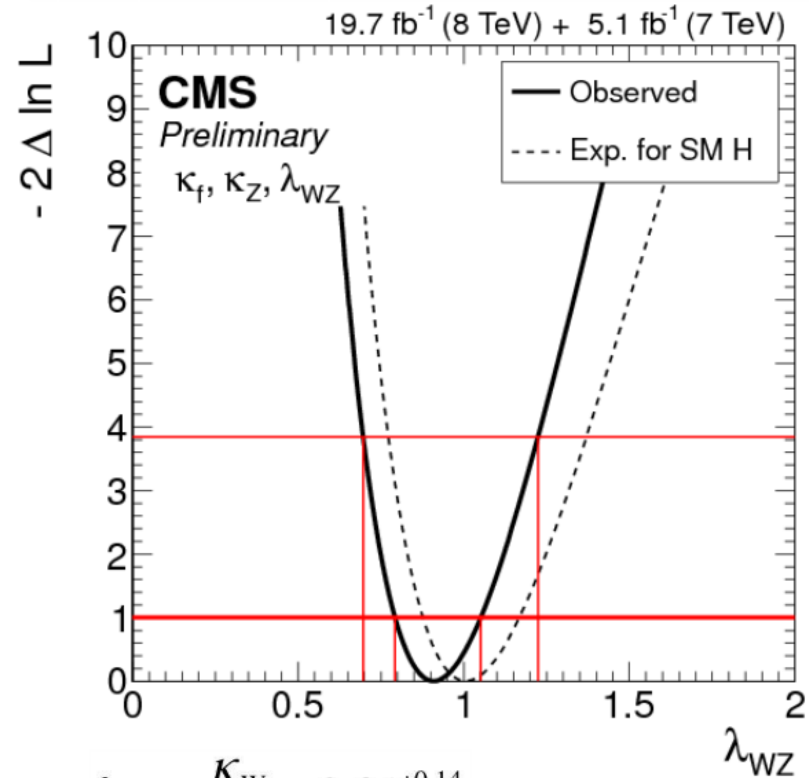
Only WW and ZZ channels (0/1 jet)



$\kappa_F = 1$

$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 0.94^{+0.22}_{-0.18}$$

Full combination

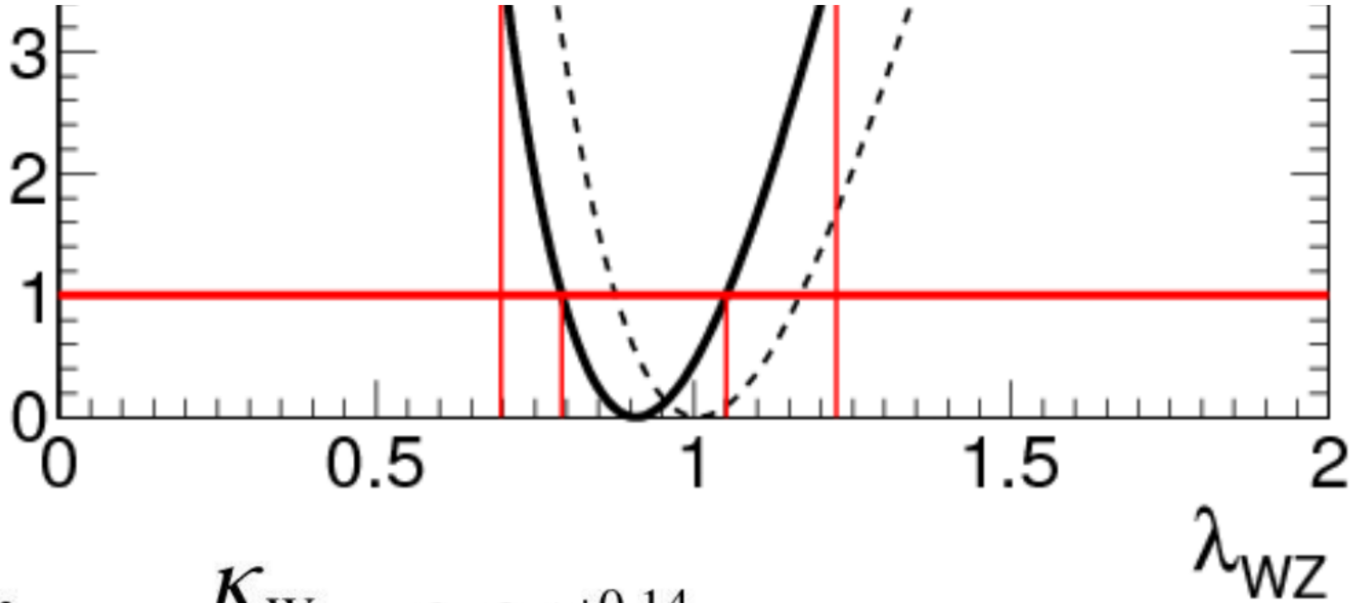


$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 0.91^{+0.14}_{-0.12}$$

No deviation $\rightarrow$ treat Z and W as V

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



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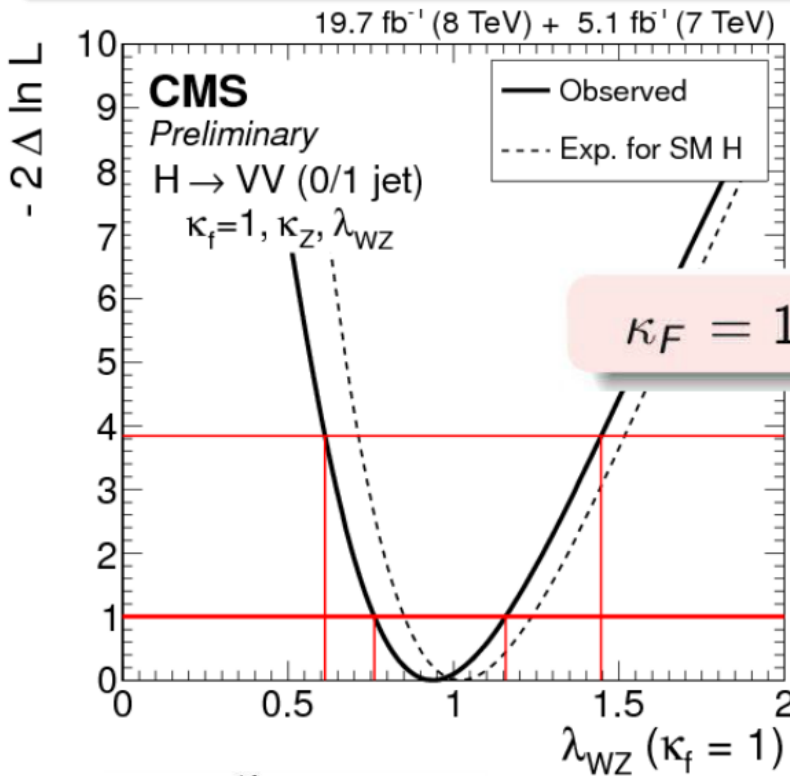

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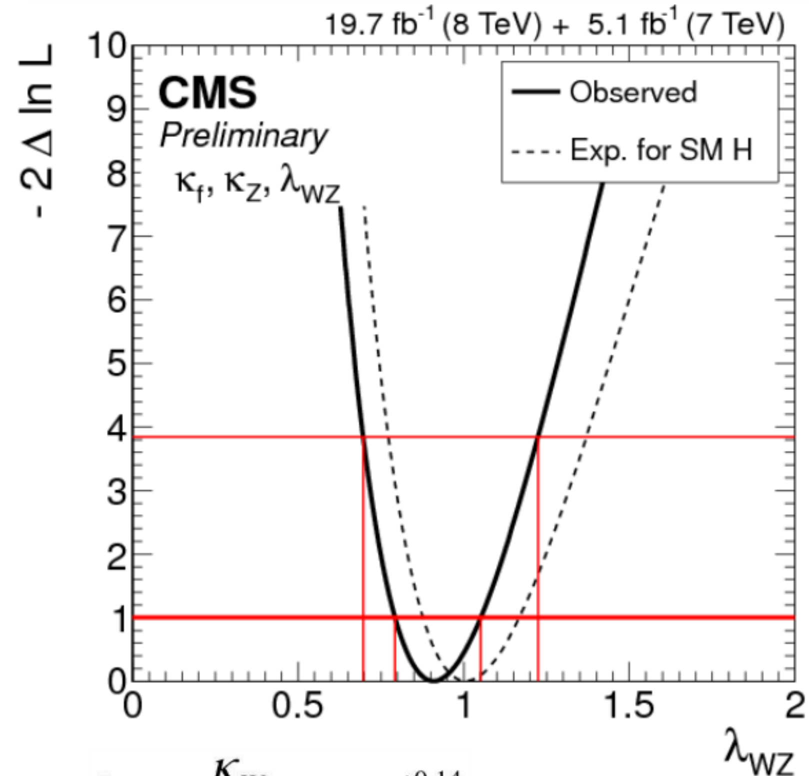

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No deviation → treat Z and W as V

Custodial Symmetry

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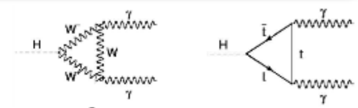
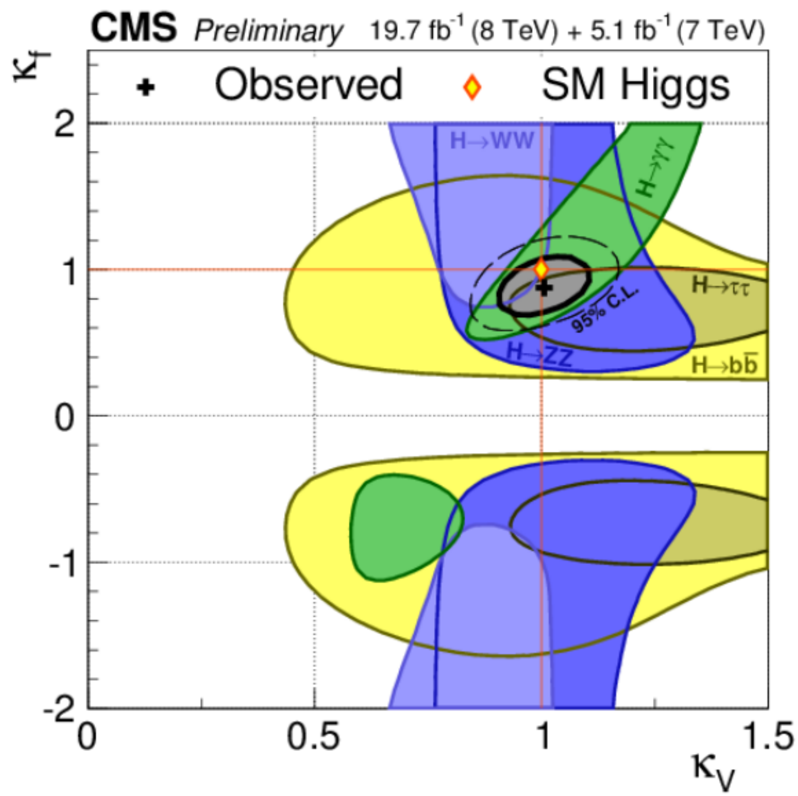
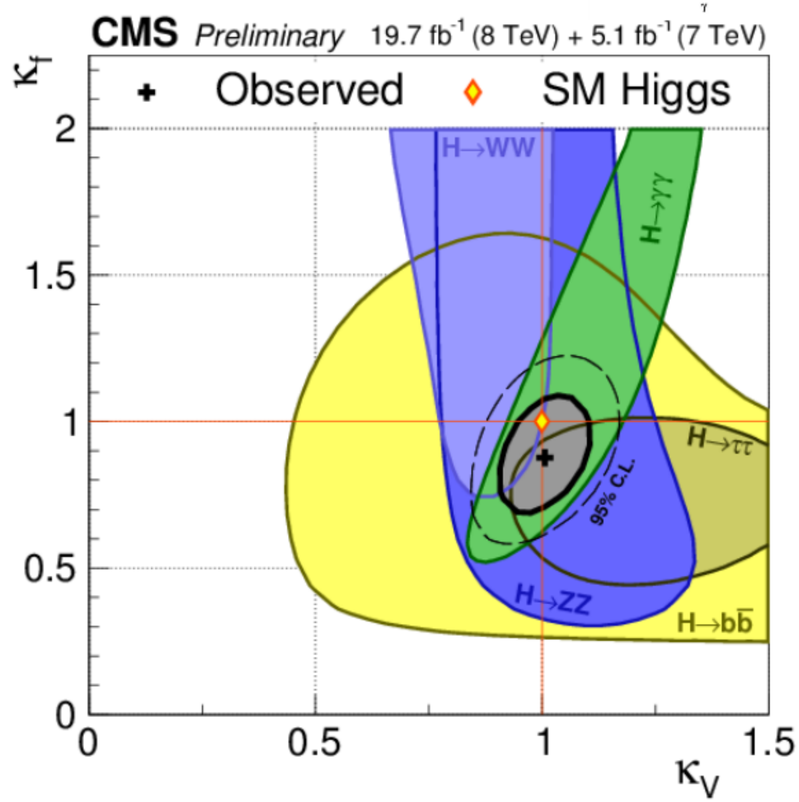
- Result: m_W/m_Z , and their couplings to the Higgs, g_W/g_Z , protected against large rad

Couplings to vector bosons and fermions

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

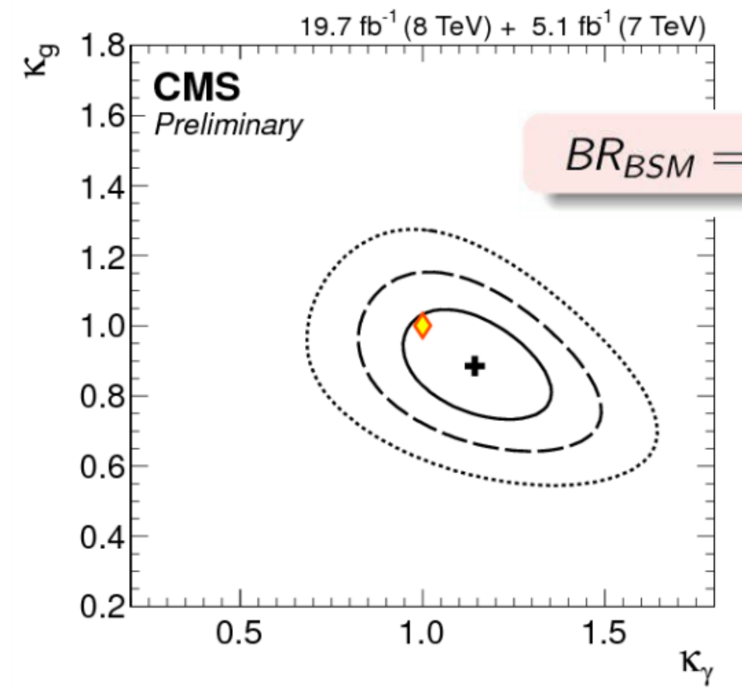


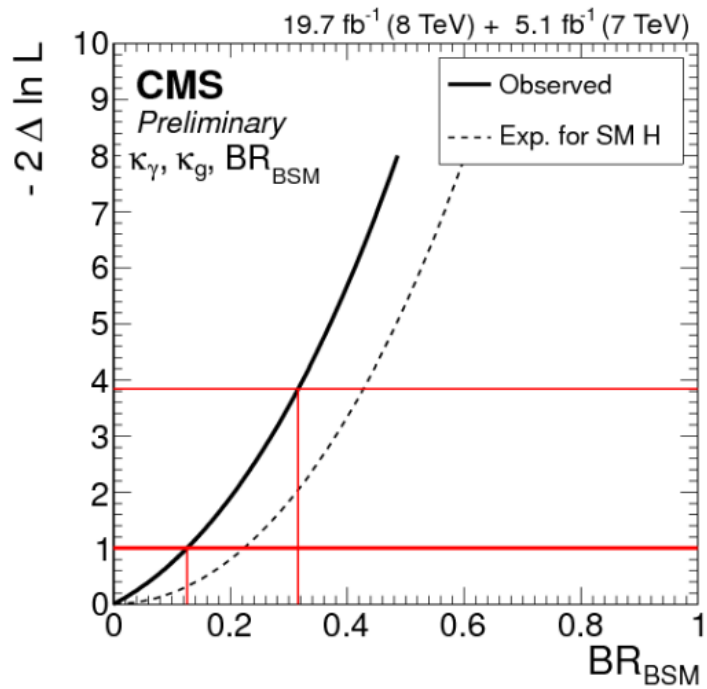




Search for new physics in loops

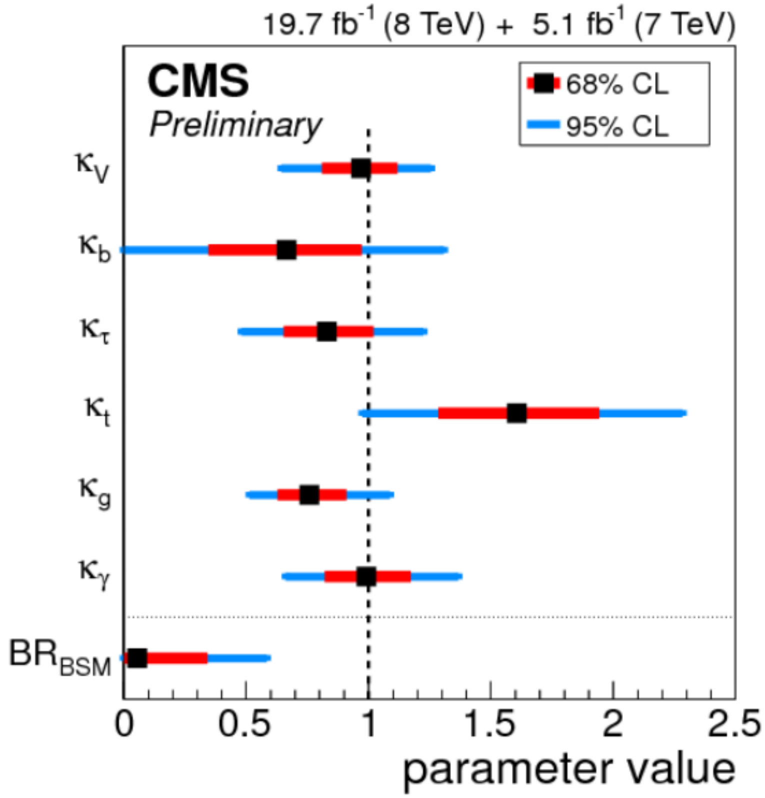
- New particles can potentially hide in the loop-mediated couplings ($H\gamma\gamma$ and ggH)
- The photons and gluons are treated tree-level effective couplings

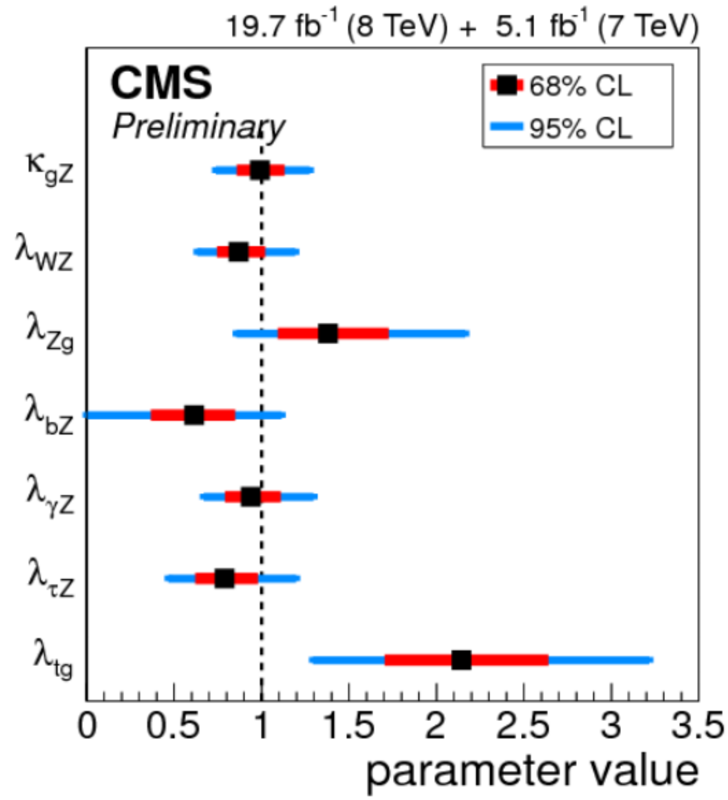




- New particles can contribute to the total width
- Allow total width to scale as $1/(1 - BR_{BSM})$

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

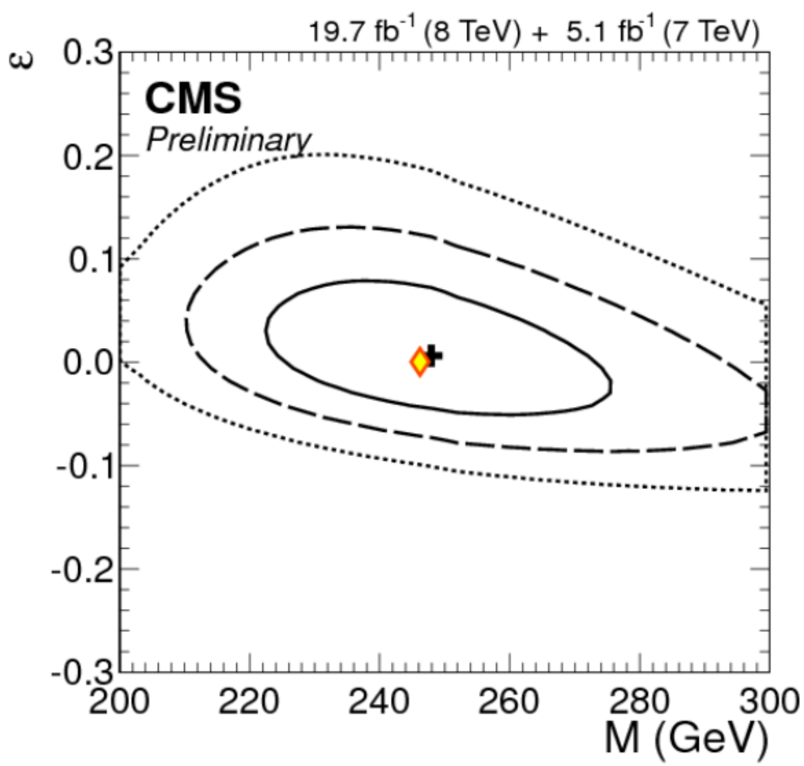
Coupling vs. particle mass

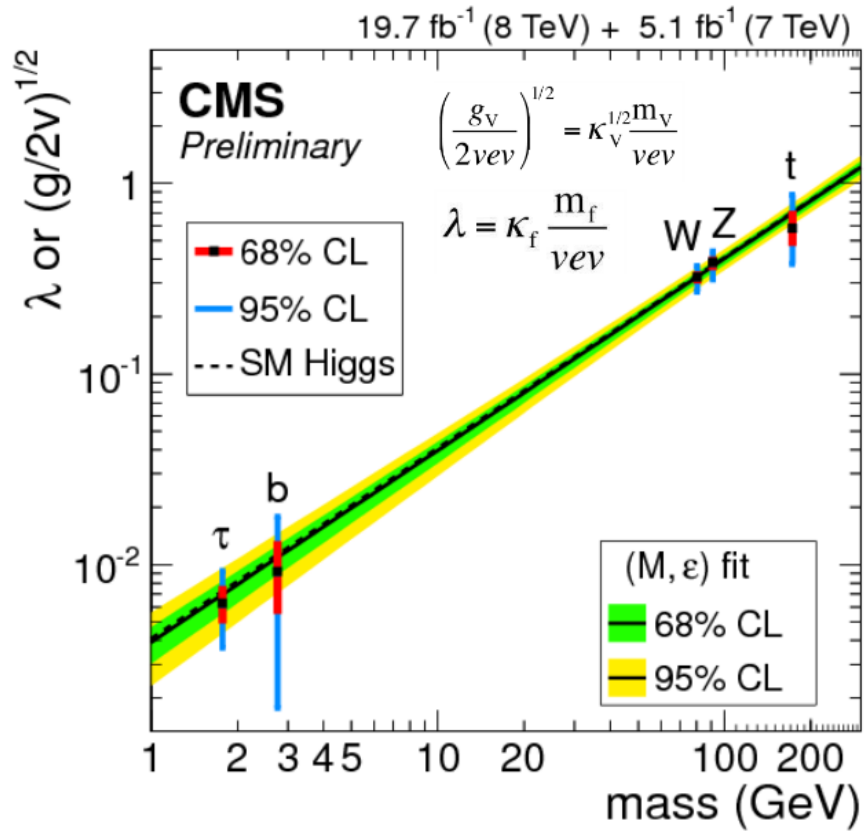
Generic M and ϵ model

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

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

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

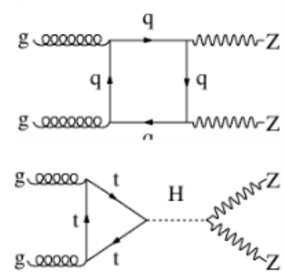
$$\sigma^{on-peak}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}$$

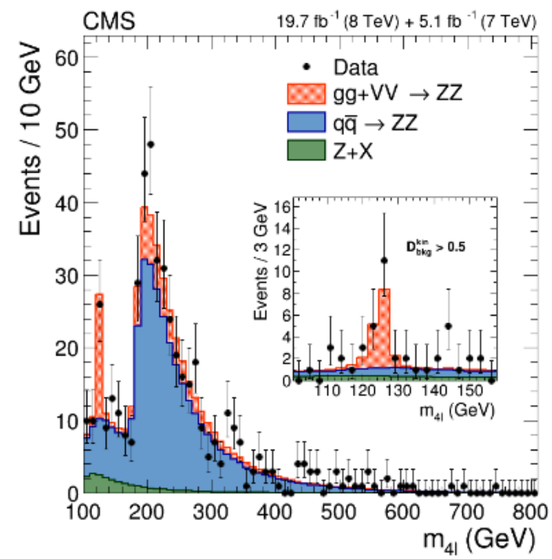
$$\sigma^{off-peak}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

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

On-shell/Off-shell ratio

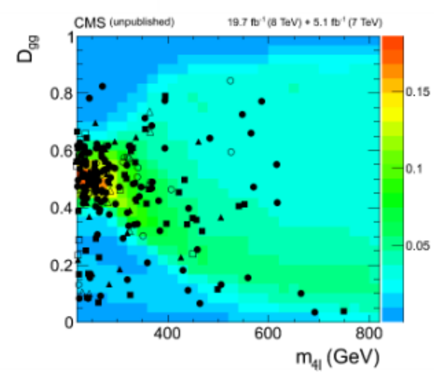
- SM predicts $\Gamma_{tot} = 4.2$ MeV, direct measurement yields $\Gamma_{tot} = 3.4$ GeV, 3 orders of magnitude
- Γ_H can indirectly be extracted from On-shell/Off-shell ratio
- Mild model dependence — works for BSM models if the ratio is not altered by new physics (i.e. top loop still dominates in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

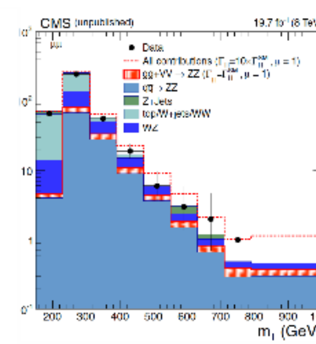


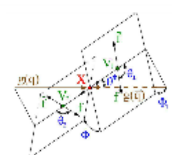


Analysis

- The $H \to ZZ^{\star} \to 4l$ 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 $H \to ZZ^{\star} \to 2l2\nu$ analysis relies on the transverse mass or missing transverse energy distributions, depending on the jet categories.



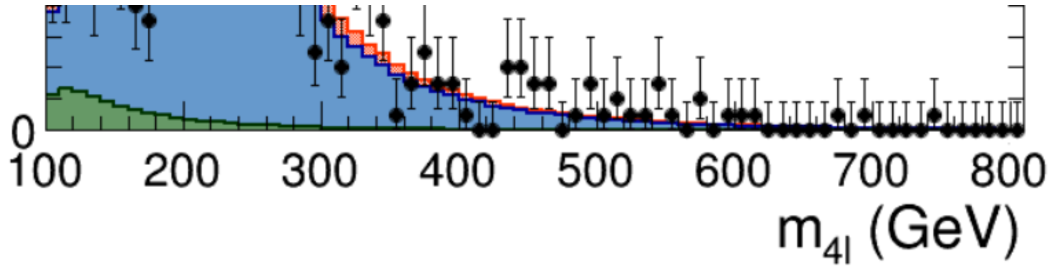


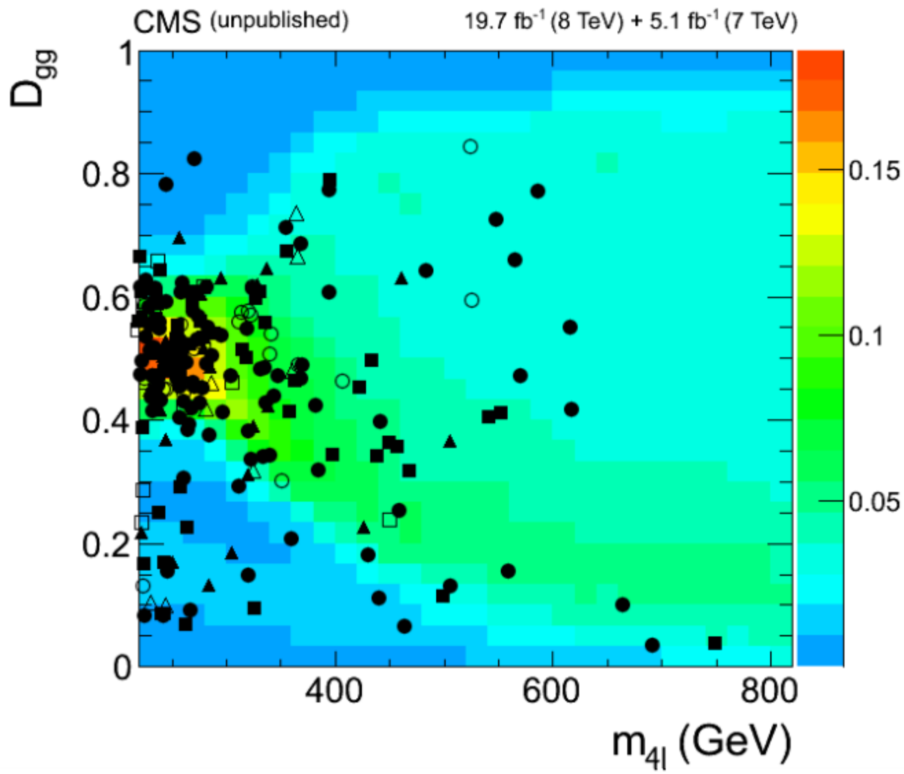


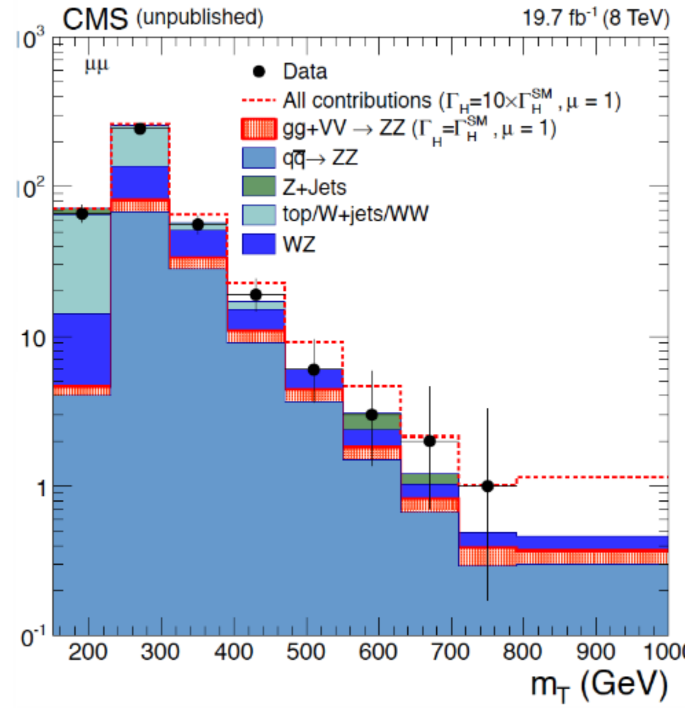
$$\mathcal{D}_{gg} = \frac{\mathcal{P}_{gg}}{\mathcal{P}_{gg}+\mathcal{P}_{q\bar{q}}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{bkg}}{a\times\mathcal{P}^{gg}_{sig} + \sqrt{a}\times\mathcal{P}^{gg}_{int} + \mathcal{P}^{gg}_{bkg}}\right]^{-1}$$

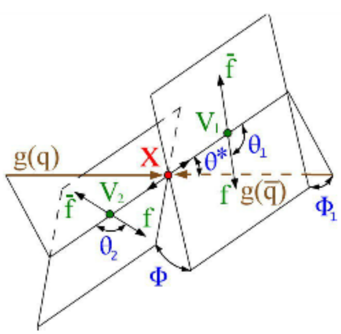
$$m^2_T = \left[\sqrt{p_{T,\ell\ell}{}^2 + m_{\ell\ell}{}^2} + \sqrt{E^{miss}_T{}^2 + m_{\ell\ell}{}^2}\right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}^{miss}_T\right]^2$$

[10.1103/PhysRevD.89.092007, 10.1140/epjc/s10052-013-2469-8]









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

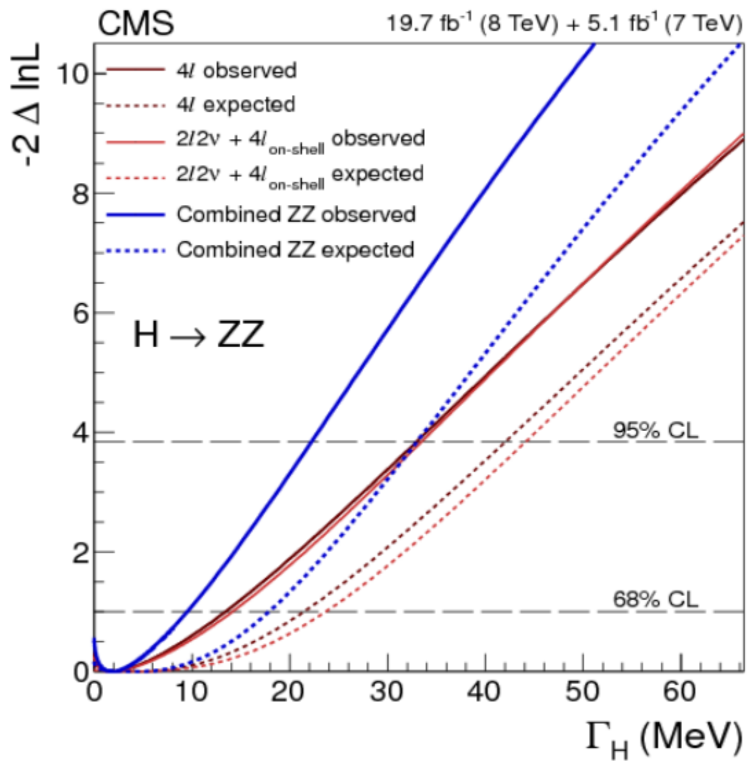
$$m_T^2 = \left[\sqrt{p_{T,\ell\ell}{}^2 + m_{\ell\ell}{}^2} + \sqrt{E_T^{miss\,2} + m_{\ell\ell}{}^2} \right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{miss} \right]^2$$

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 scal w.r.t SM prediction (Γ_H extracted from the off-shell analysis)



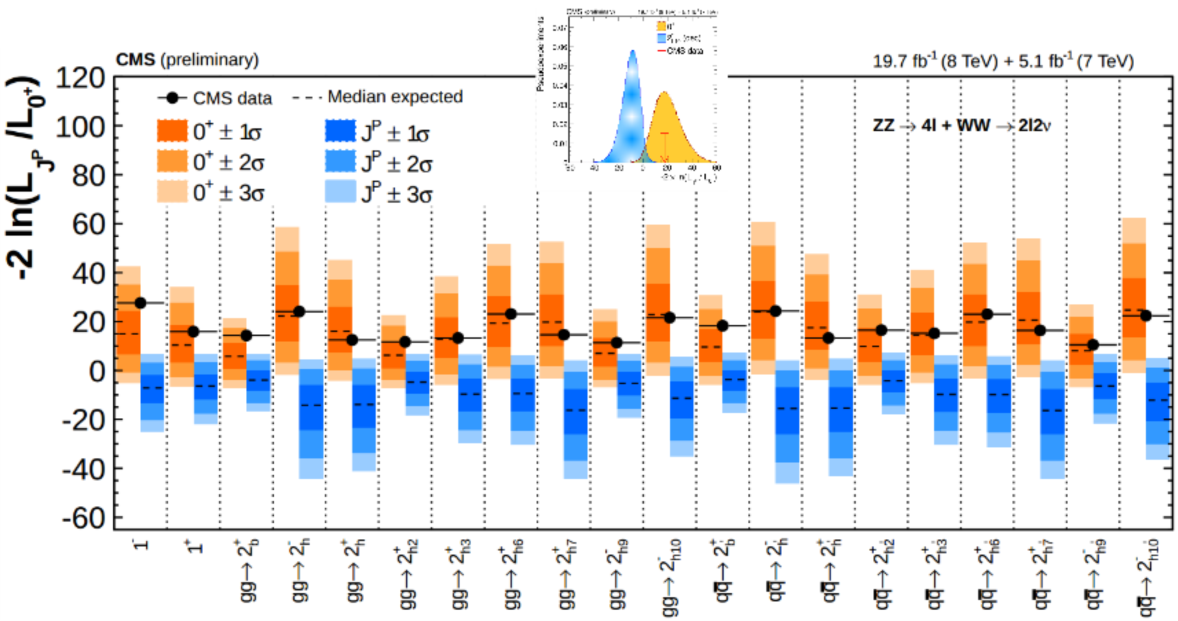
Γ_H Measurement

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

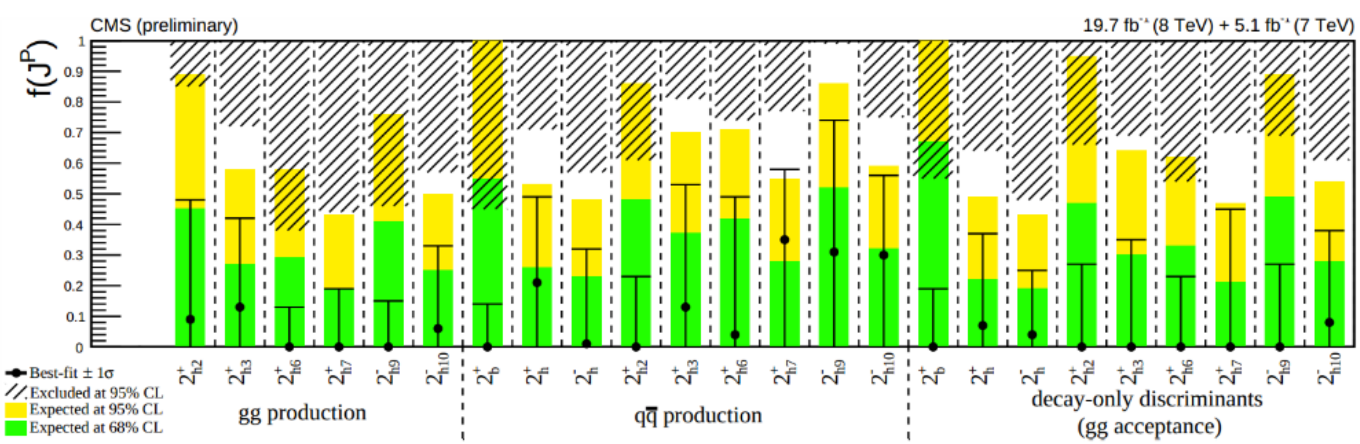
Γ_H 95% limits

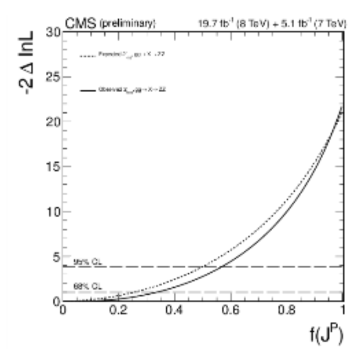
- expected: 33 MeV
- measured: 22 MeV

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

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu} + a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}$$

Λ_1 term
leading momentum expansion

a_2 term
CP even state

a_3 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 $H \to ZZ$ and $H \to WW$
- Test exotic spin-parity states using hypothesis testing
- Measure tensor structure parameters using likelihood fits

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4}$$

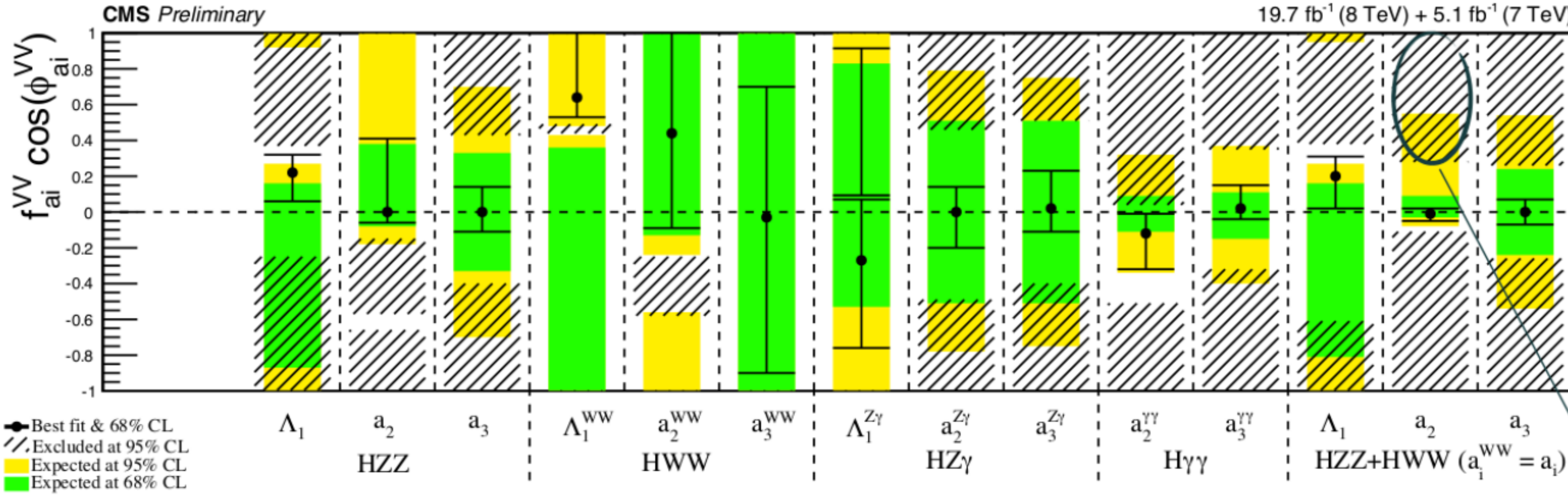
SM values

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

Interaction	Anomalous coupling	Coupling phase	Effective fraction	Translation constant
HZZ	Λ_1	$\phi_{\Lambda 1}$	$f_{\Lambda 1}$	$\sigma_1/\tilde{\sigma}_{\Lambda 1} = 1.45 \times 10^{-8}$ 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}	$\phi_{\Lambda 1}^{\mathrm{WW}}$	$f_{\Lambda 1}^{\mathrm{WW}}$	$\sigma_1^{\mathrm{WW}}/\tilde{\sigma}_{\Lambda 1}^{\mathrm{WW}} = 1.87 \times 10^{-8}$ GeV^{-4}
	a_2^{WW}	ϕ_{a2}^{WW}	f_{a2}^{WW}	$\sigma_1^{\mathrm{WW}}/\sigma_2^{\mathrm{WW}} = 1.25$
	a_3^{WW}	ϕ_{a3}^{WW}	f_{a3}^{WW}	$\sigma_1^{\mathrm{WW}}/\sigma_3^{\mathrm{WW}} = 3.01$
HZγ	$\Lambda_1^{\mathrm{Z}\gamma}$	$\phi_{\Lambda 1}^{\mathrm{Z}\gamma}$	$f_{\Lambda 1}^{\mathrm{Z}\gamma}$	$\sigma_1/\tilde{\sigma}_{\Lambda 1}^{\mathrm{Z}\gamma} = 5.76 \times 10^{-9}$ GeV^{-4}
	$a_2^{\mathrm{Z}\gamma}$	$\phi_{a2}^{\mathrm{Z}\gamma}$	$f_{a2}^{\mathrm{Z}\gamma}$	$\sigma_1/\sigma_2^{\mathrm{Z}\gamma} = 22.4 \times 10^{-4}$
	$a_3^{\mathrm{Z}\gamma}$	$\phi_{a3}^{\mathrm{Z}\gamma}$	$f_{a3}^{\mathrm{Z}\gamma}$	$\sigma_1/\sigma_3^{\mathrm{Z}\gamma} = 27.2 \times 10^{-4}$
H$\gamma\gamma$	$a_2^{\gamma\gamma}$	$\phi_{a2}^{\gamma\gamma}$	$f_{a2}^{\gamma\gamma}$	$\sigma_1/\sigma_2^{\gamma\gamma} = 28.2 \times 10^{-4}$
	$a_3^{\gamma\gamma}$	$\phi_{a3}^{\gamma\gamma}$	$f_{a3}^{\gamma\gamma}$	$\sigma_1/\sigma_3^{\gamma\gamma} = 28.8 \times 10^{-4}$

[Phys.Rev.Lett. 110 (2013) 081803, Phys.Rev. D89 (2014) 092007, CMS-PAS-HIG-14-014]

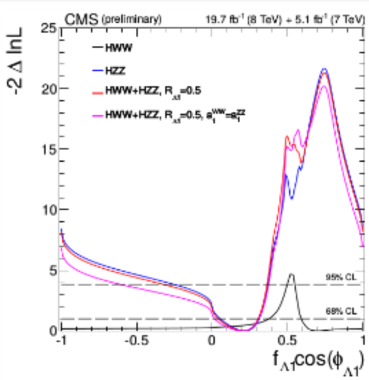
Higgs spin and parity – spin 0

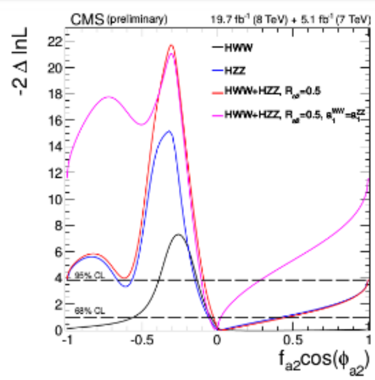


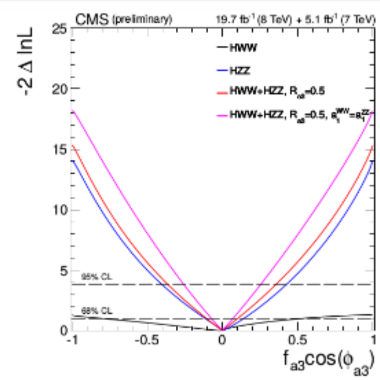
Region not excluded in either *HZZ* or *HWW*. Constraint from *HZZ* – *HWW* correlation

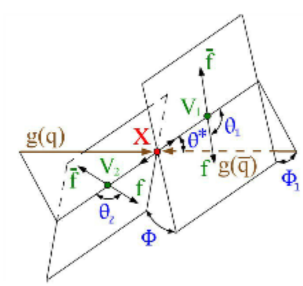
Likelihood fits

- 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)





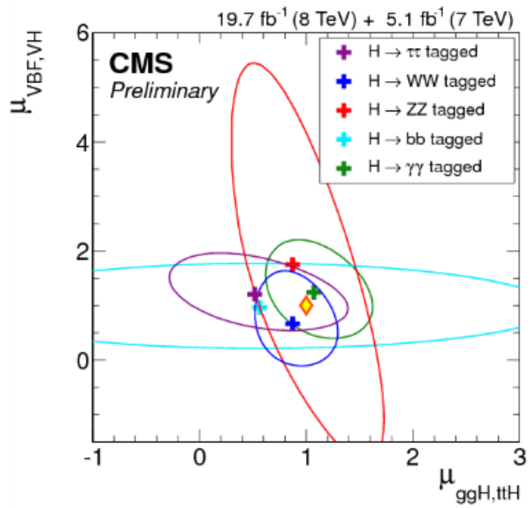




Higgs → invisible decays

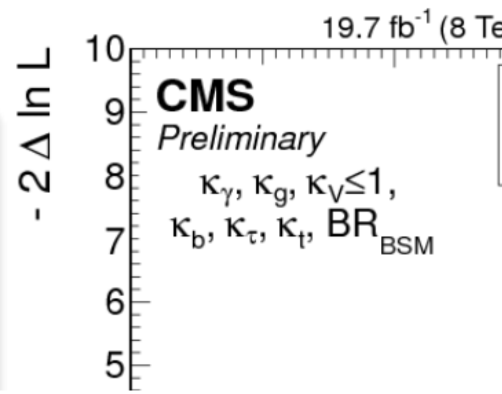
Recent measurements of the branching fractions of the 125 GeV Higgs boson are **compatible with the SM** expectations, but with **large uncertainties**.

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

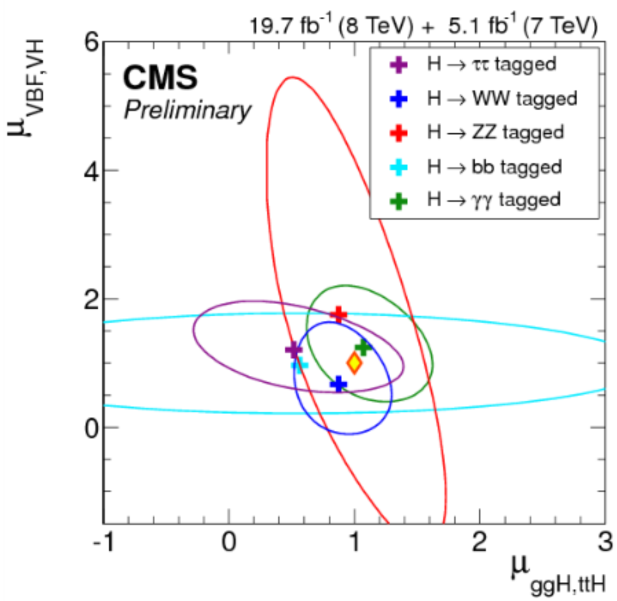


Indirect constraints

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

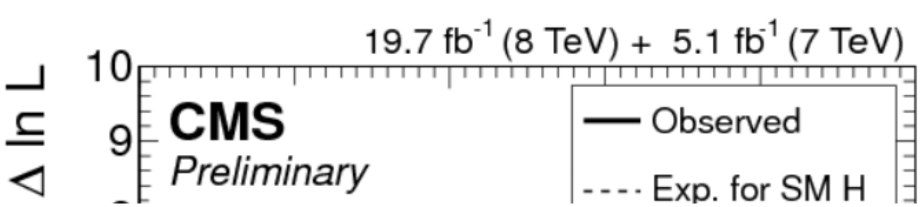


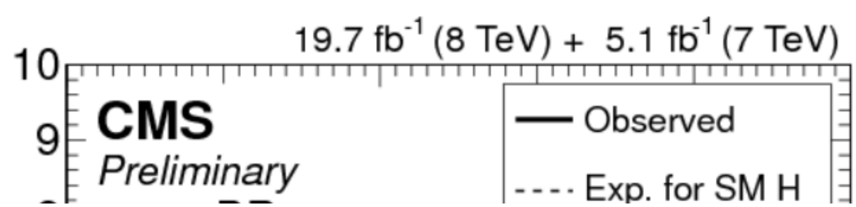
ys



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

- 4^{th}-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





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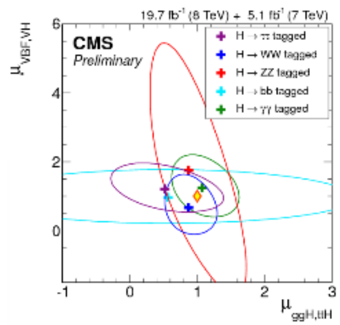
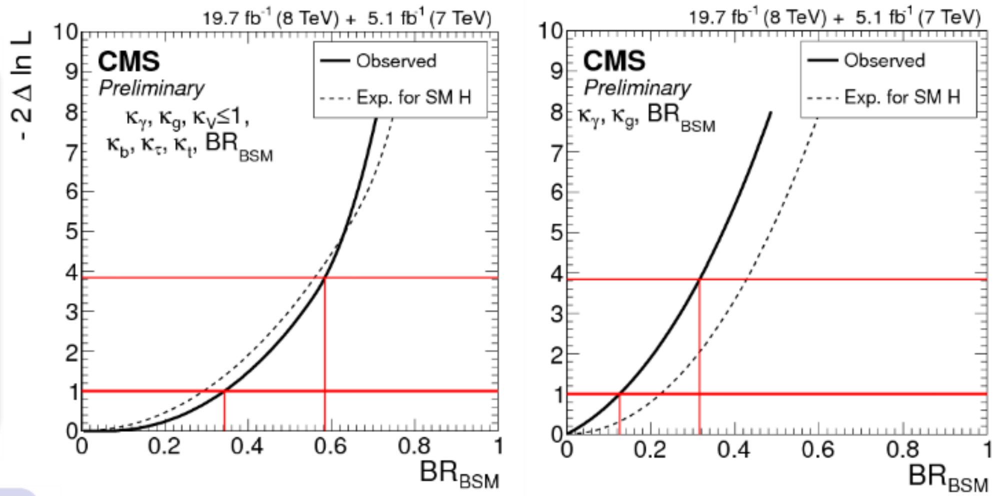


Many models predict Higgs boson(s) decaying to heavy, undetectable particles

- 4^{th}-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

Indirect constraints

B_{BSM} can be inferred by fitting the observed decay modes: $B_{BSM} < 0.58$ (0.32 from more constrained model)



[arXiv:1404:1344]

Direct searches

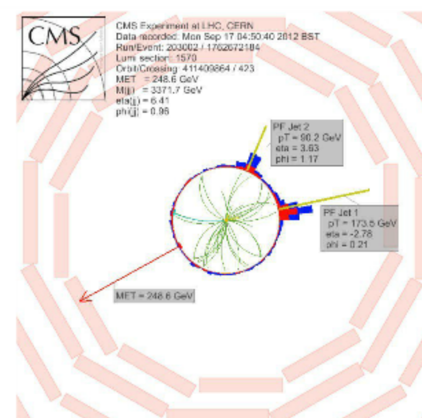
In production channels where the Higgs boson recoils against a visible system:

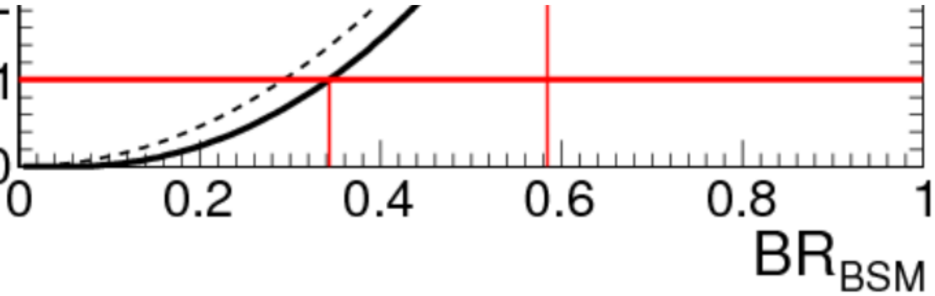
- Vector boson fusion (VBF)
- Associated production with a Z boson, decaying to a pair of leptons or $b\bar{b}$

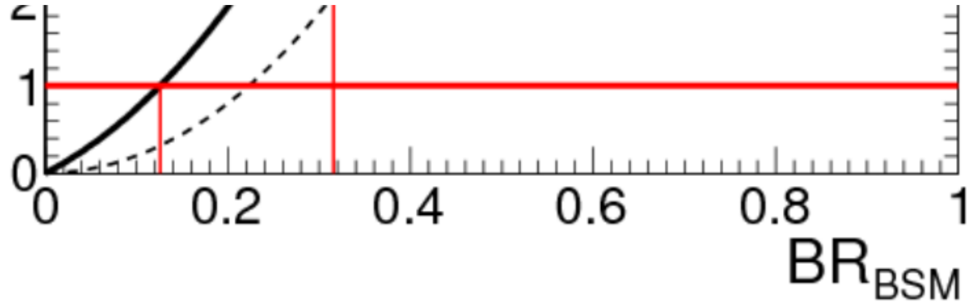
$qq \to qqVV \to qqH \to 2\text{jets} + \text{MET}$

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

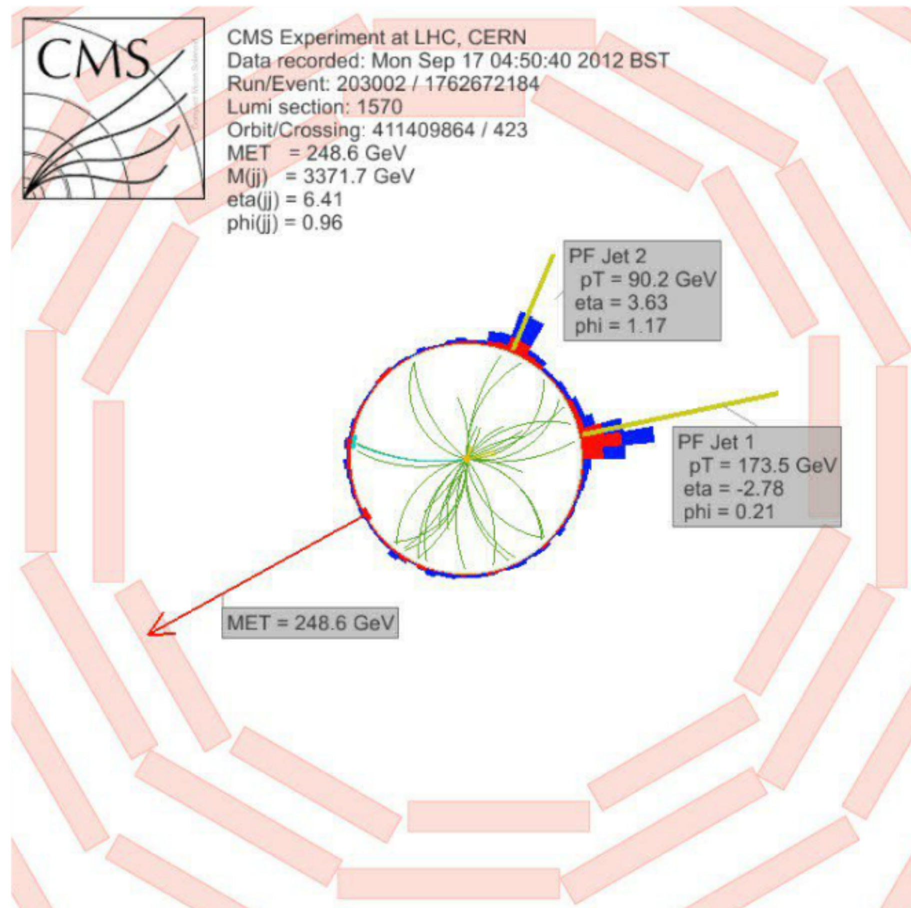
$qq \to Z^{*} \to ZH \to b\bar{b} + \text{MET}$







[arXiv:1404:1344]

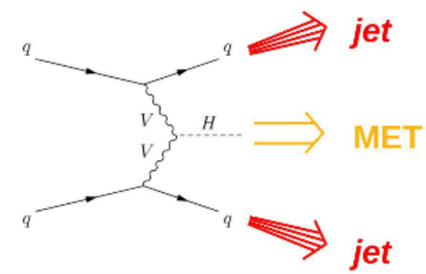


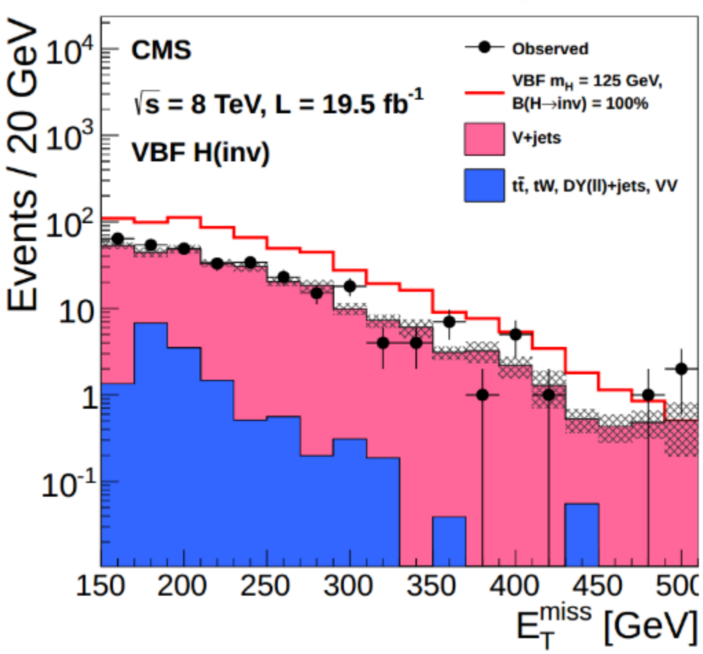
$$qq \to qqVV \to qqH \to 2\text{jets} + \text{MET}$$

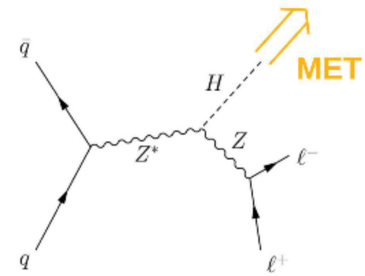
$$qq \to Z^\star \to ZH \to l^+l + \text{MET}$$

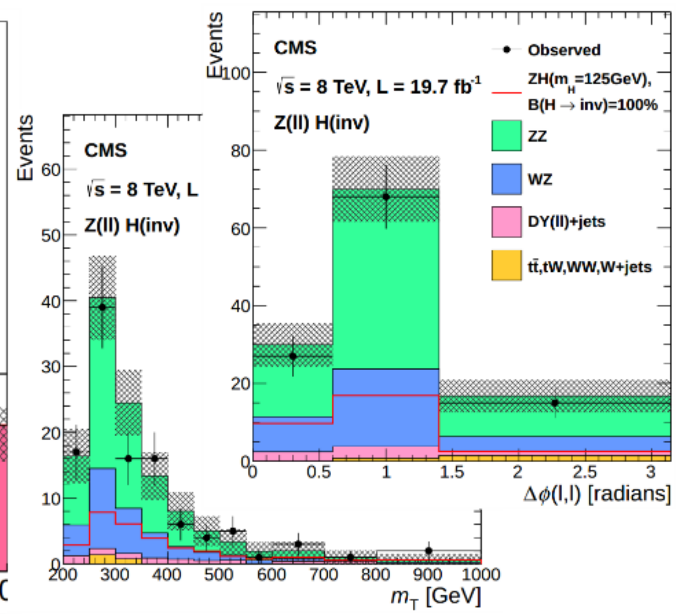
$$qq \to Z^\star \to ZH \to b\bar{b} + \text{MET}$$

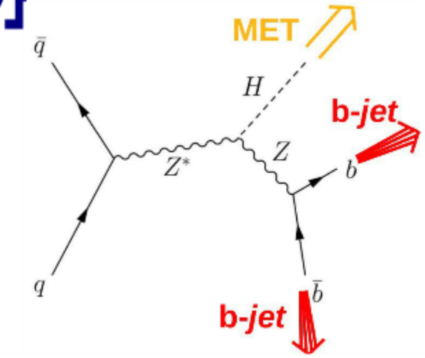
H → invisible pillars [VBF, H+Zll, H+Zbb]

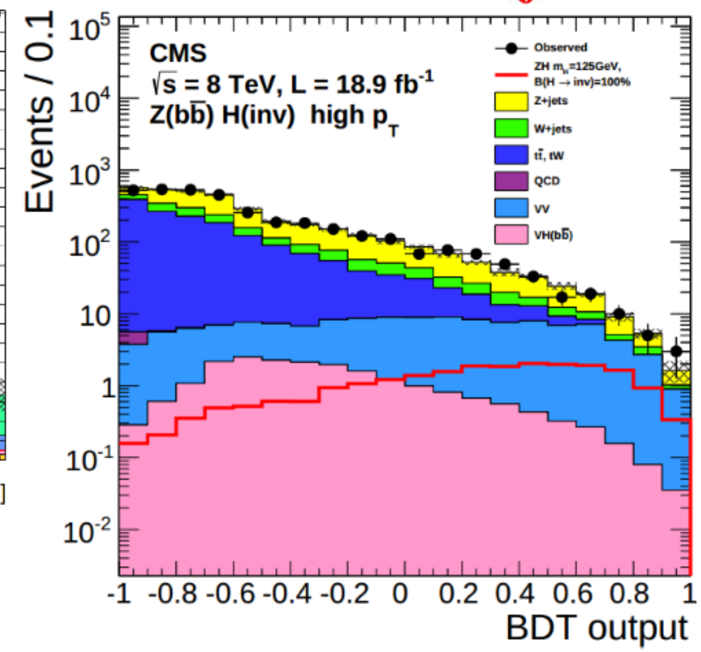












VBF production

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

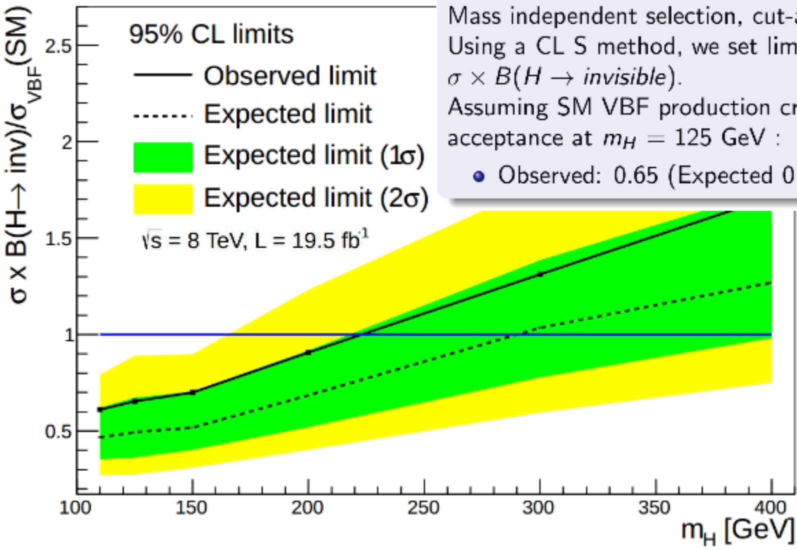
Associated $H(inv.) + Z(ll)$

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

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

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

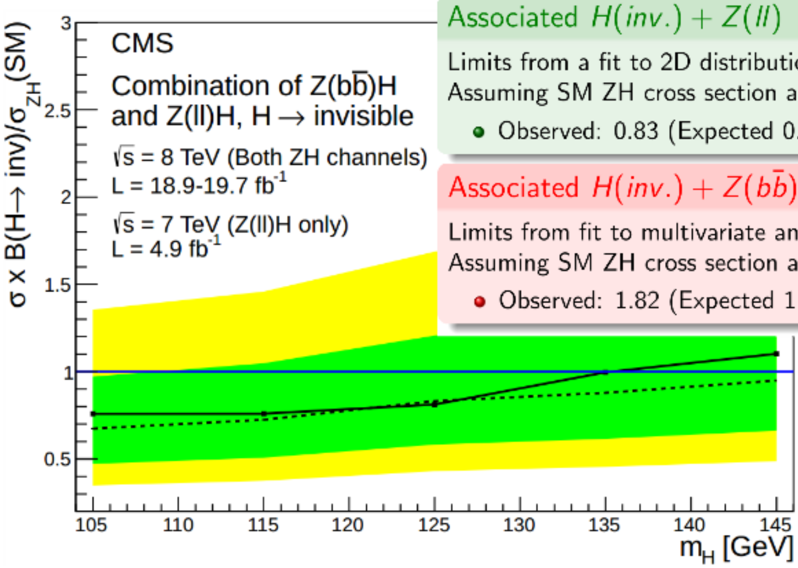
H → invisible results [VBF, H+Zll, H+Zbb]



VBF production

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

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



Associated $H(inv.) + Z(ll)$

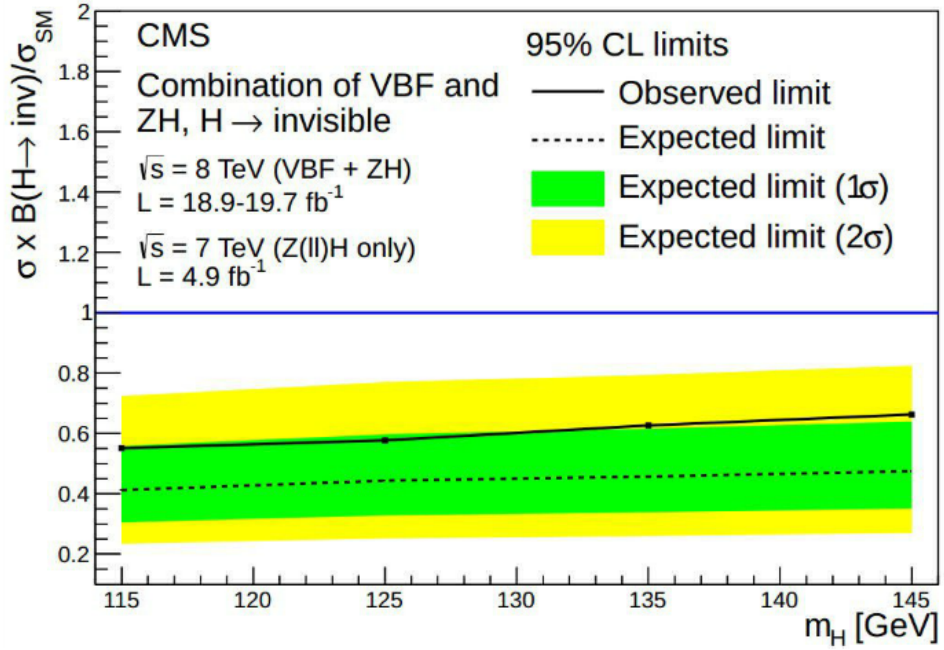
Limits from a fit to 2D distributions m_T vs $\Delta\phi(ll)$.
Assuming SM ZH cross section and $m_H = 125$ GeV:

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

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

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

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



Combination of VBF and *ZH* production

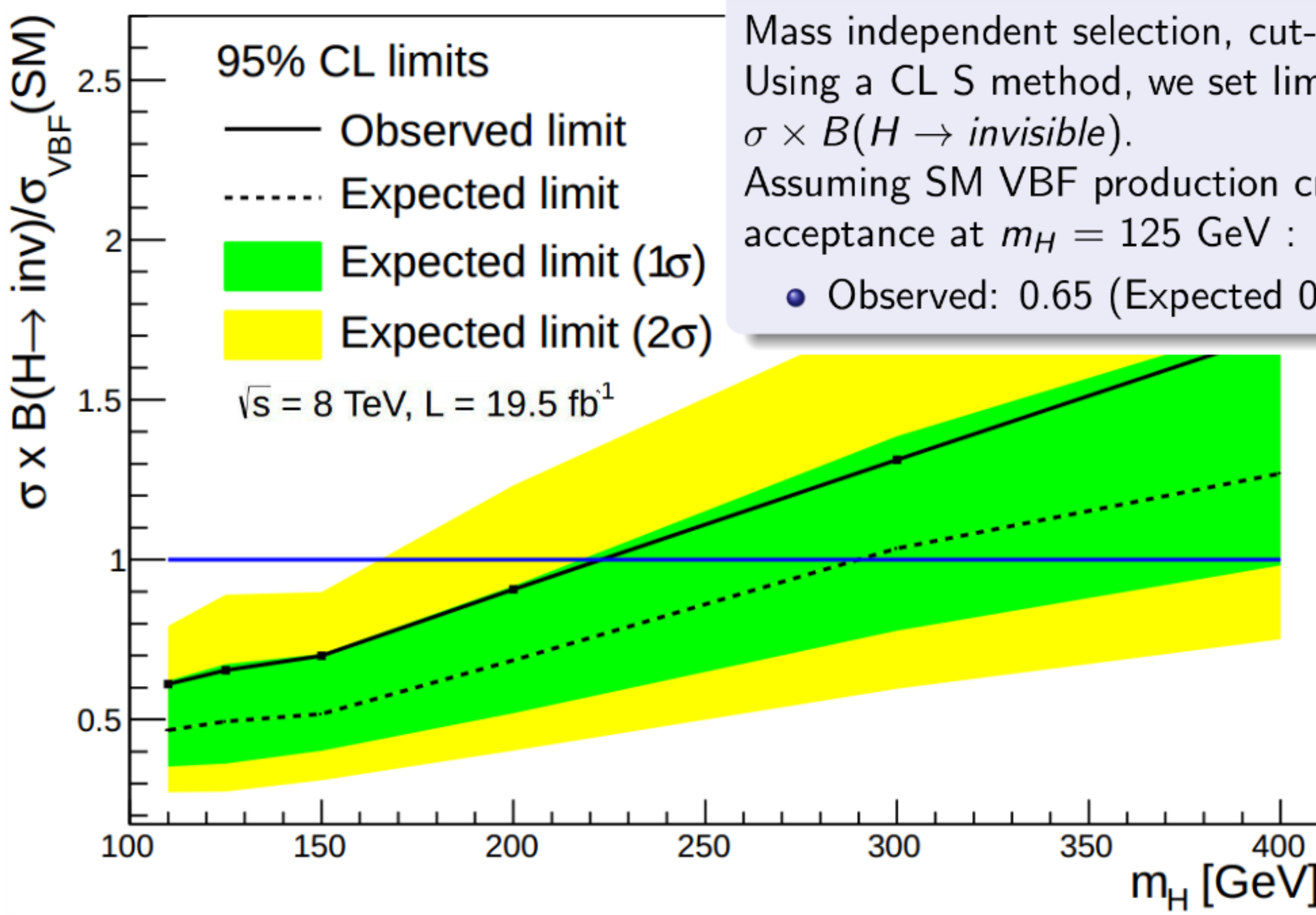
Individual limits on $\sigma \times B(H \to invisible)/\sigma_{SM}$ from VBF and *ZH* channels are combined.
Assuming SM VBF and ZH cross sections, they are interpreted as limits on $B(H \to invisible)$

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

Main systematic uncertainties

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

H → invisible results [VBF, H+Z



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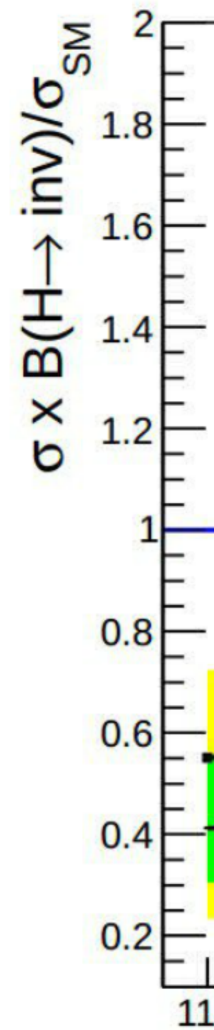

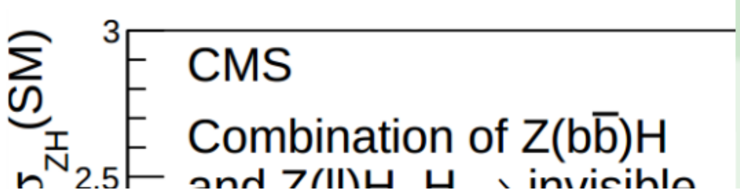

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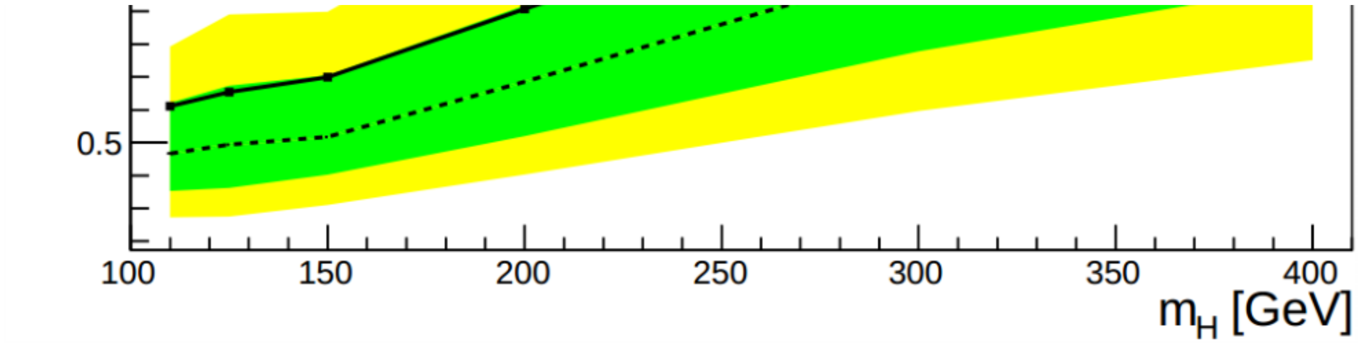

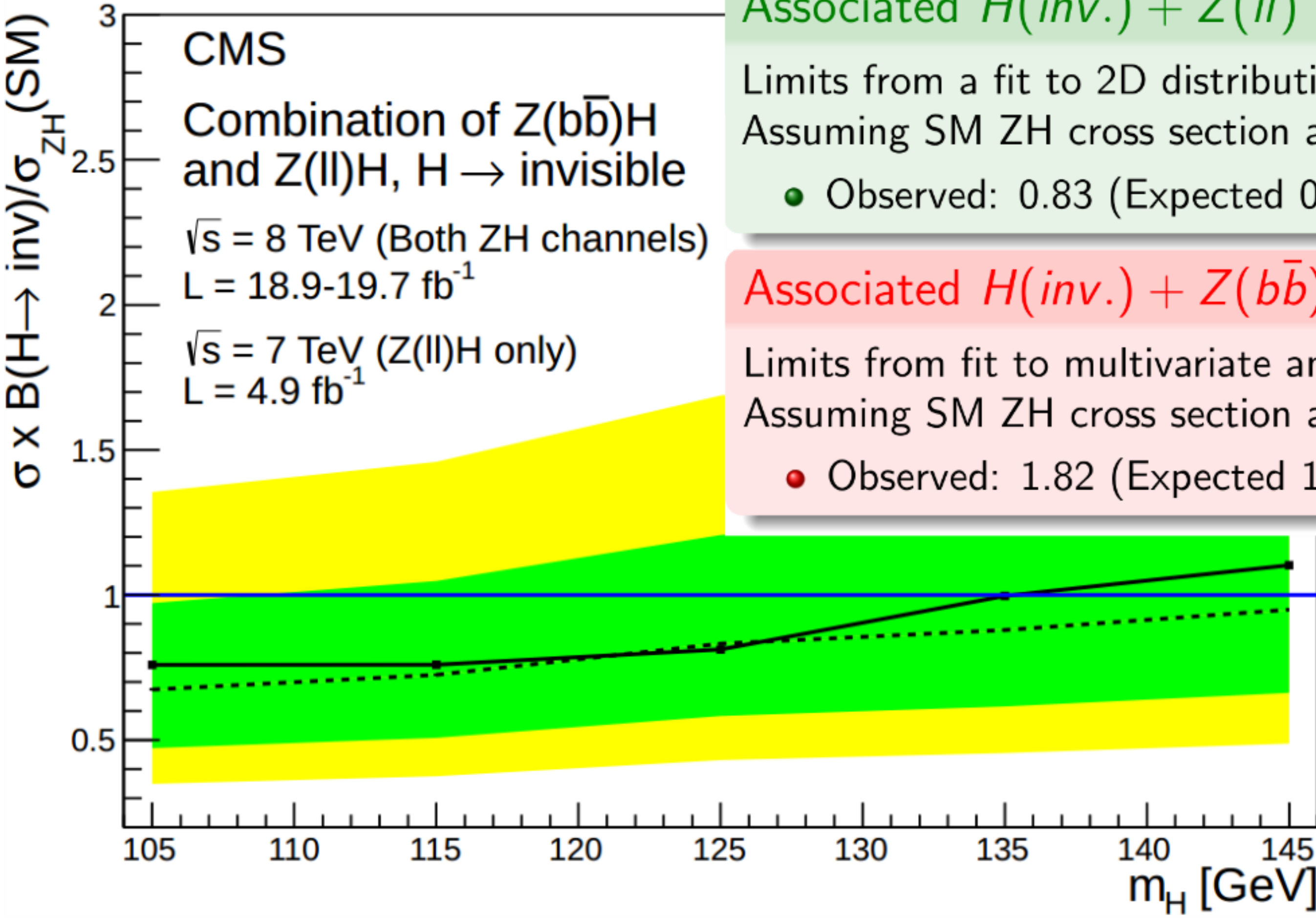

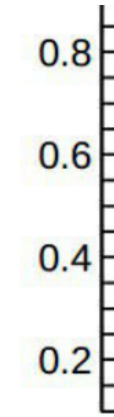

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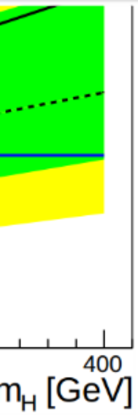

$+ Z(ll)$

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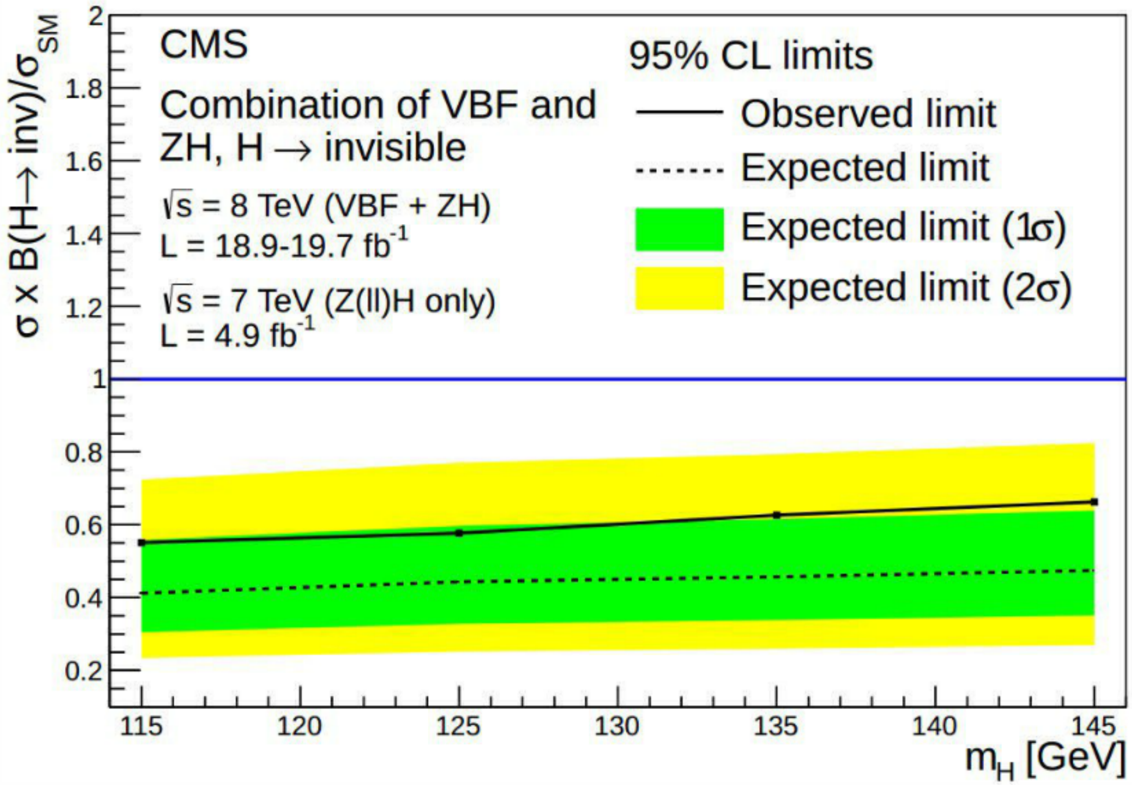

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- Lepton momentum scale
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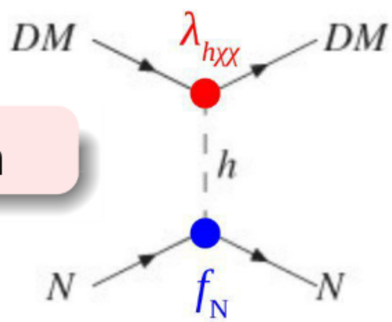
Dark Matter enters through Higgs Portal

Combination of VBF and ZH production

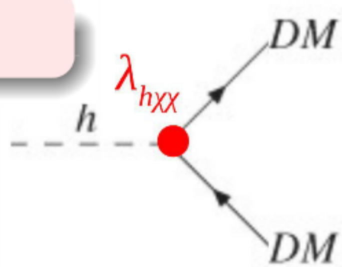
Limits on the Higgs invisible branching fraction can be interpreted in the context of **Higgs portal DM models**

- 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

Direct detection



Production at colliders



$$\sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_S + m_N)^2}$$ scalar DM

$$\sigma^{SI}_{V-N} = \frac{\lambda^2_{hVV}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_V + m_N)^2}$$ vector DM

$$\sigma^{SI}_{f-N} = \frac{\lambda^2_{hff}}{4\pi \Lambda^2 m_h^4}\frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2}$$ fermion DM

Higgs-nucleon coupling f_N

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

Phys. Rev. Lett. 103 (2009) 122002

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**

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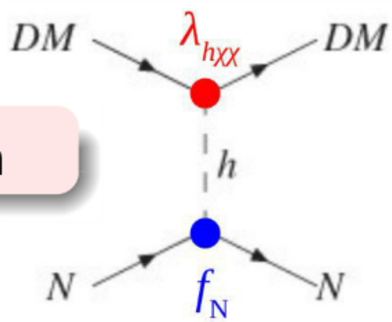

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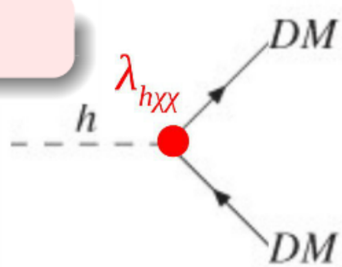


$$\sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2} \quad \text{scalar DM}$$

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

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

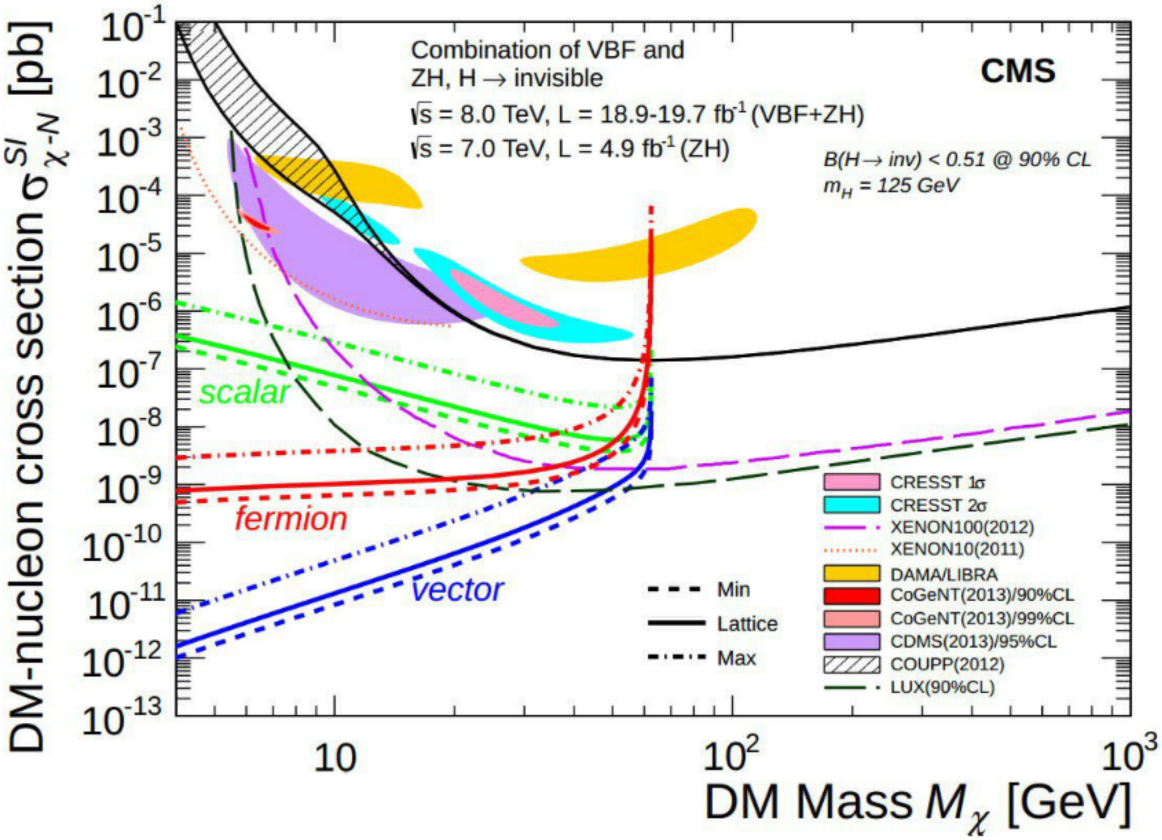
Higgs-nucleon coupling f_N

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

Phys. Rev. Lett. 103 (2009) 122002


Some Higgs portal related talks

Limits on DM – nucleon cross section



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

Competitive results

Use the combined limits from VBF, $Z(ll)H$, and $Z(b\bar{b})H$ searches for $m_H = 125$ GeV: $B(H \to inv) < 0.51$ 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 $B(H \to invisible)$
- 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