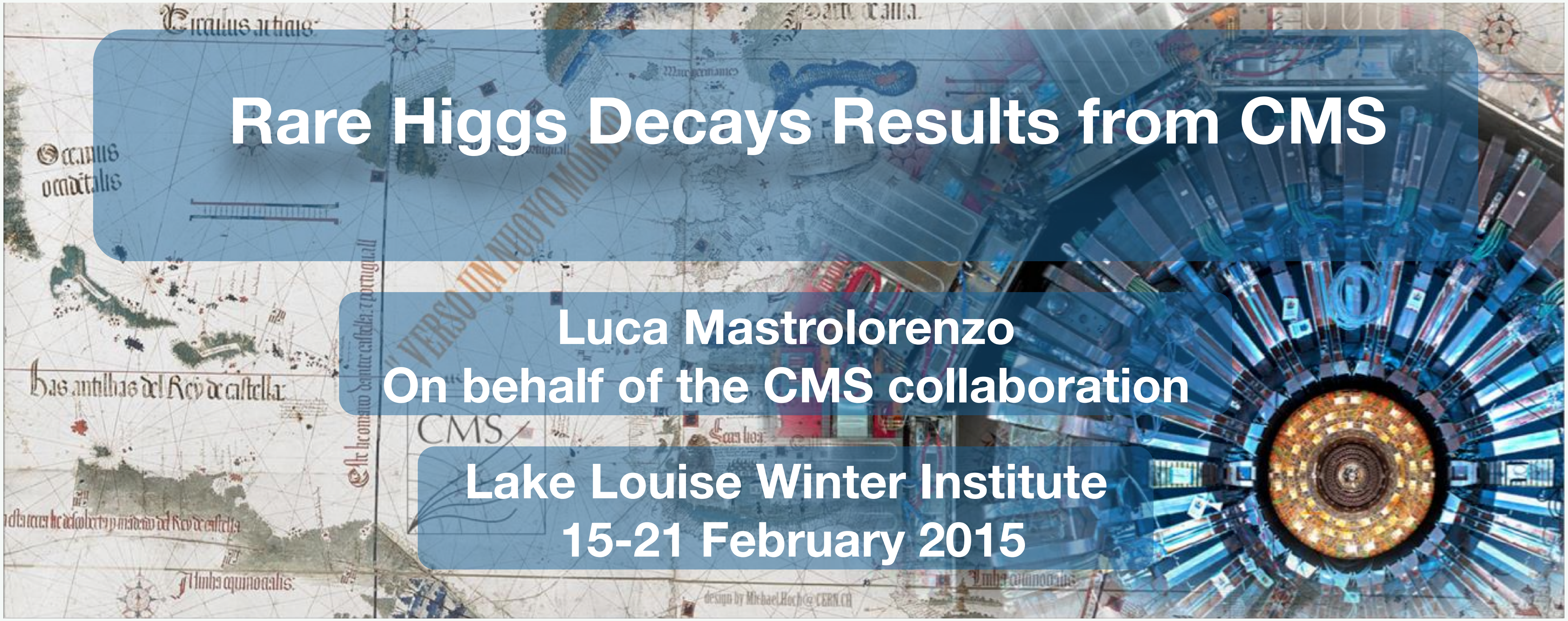


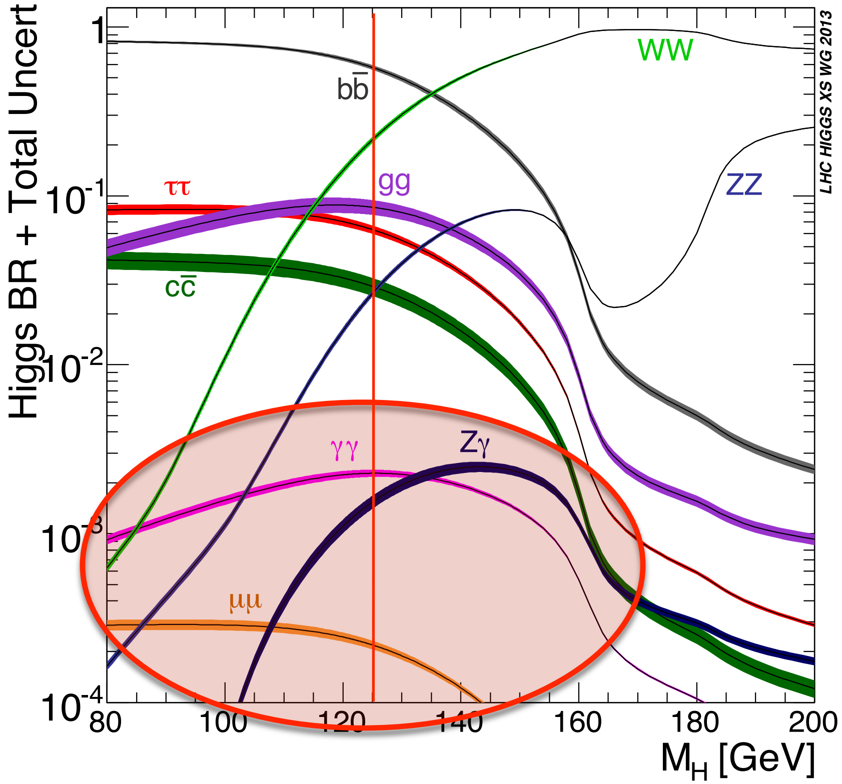
Rare Higgs Decays Results from CMS

Luca Mastrolorenzo
On behalf of the CMS collaboration

Lake Louise Winter Institute
15-21 February 2015

Introduction:

- Overview of H rare decays searches performed by CMS



The talk deals with Higgs boson decays having a very low σxBR predicted by the SM:

- H → μμ

This talks also addresses decays of the Higgs boson strongly suppressed by the SM:

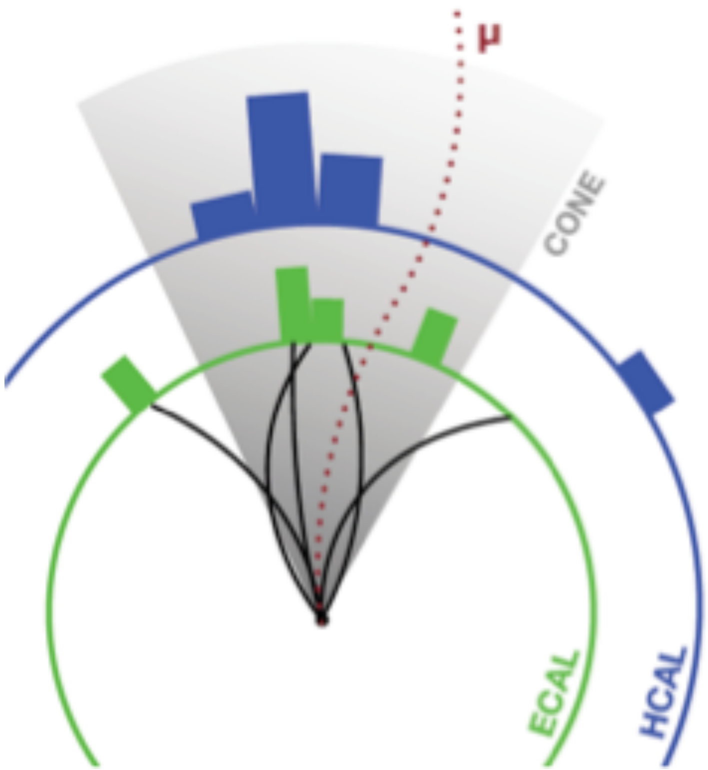
- LFV H → τμ
- H→Invisible

Event reconstruction – overview:

Particle Flow (PF)

Most of the analyses presented rely on the use of the PF

- Combining all the information from the different CMS sub-systems to identify all the stable particles in the event: $e^{\pm}$, $\mu^{\pm}$, γ, $h^{\pm}$, h^{0}



Inputs to build

Jets, E_T^{miss}, τ_h, Lepton/photon Isolation

$H \rightarrow \mu\mu$ (BR ~ $2.19 \cdot 10^{-4}$)

http://arxiv.org/pdf/1410.6679v1.pdf

Motivation:

- After the Higgs boson discovery, we need to measure the Higgs boson properties: among them its **couplings to fermions**!
- Check non-universality of Higgs boson couplings to fermions
  - ➢ Confront $H \rightarrow \mu\mu$ and $H \rightarrow \tau\tau$ decay rates (already observed by CMS)
- $H \rightarrow \mu\mu$:
  - ➢ Only LHC-accessible test of Higgs couplings to 2nd generation fermions
  - ➢ Very clean final state, but very small expected rate and non-negligible background

Analysis strategy:

- Search for a resonance peak in the di-μ invariant mass spectrum on top of a falling DY dominated (+tt, ZZ, WW) background
- Analysis sensitivity increased by an extensive categorization:
  - ➢ The categorization is based on Jet-multiplicity, $p_T^{\mu\mu}$, m_{jj}

H→μμ

Event selection:

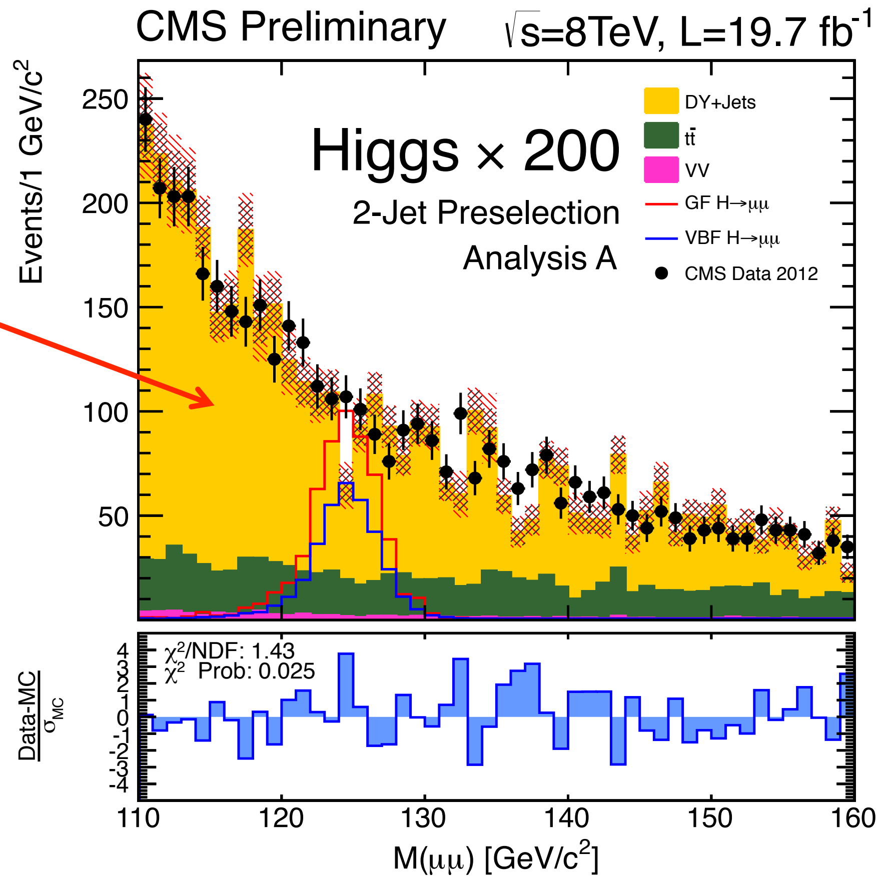
- Opposite sign, isolated muons with p_T > 25 GeV

2-Jet category	**Jet-p_T^{lead} > 40 + Jet $p_T^{sublead}$ > 30 + p_T^{miss} < 40**		
	VBF-tight	**GF-tight**	**Loose**
	M_{jj}>650 +|$\Delta\eta_{jj}$|>3.5	**$p_T^{\mu\mu}$ > 50 + M_{jj}>250**	**No-VBF && no-GF**
0/1-Jet category	! (2-Jet category)		
	Tight	**Loose**	**-**
	$p_T^{\mu\mu}$ > 10	**$p_T^{\mu\mu}$ < 10**	**-**

The above categories are further subdivided to further improve the sensitivity exploiting the expected $m_{\mu\mu}$ resolution

Sig. and Bkg. estimation:

DY: Z→μμ is
The main background

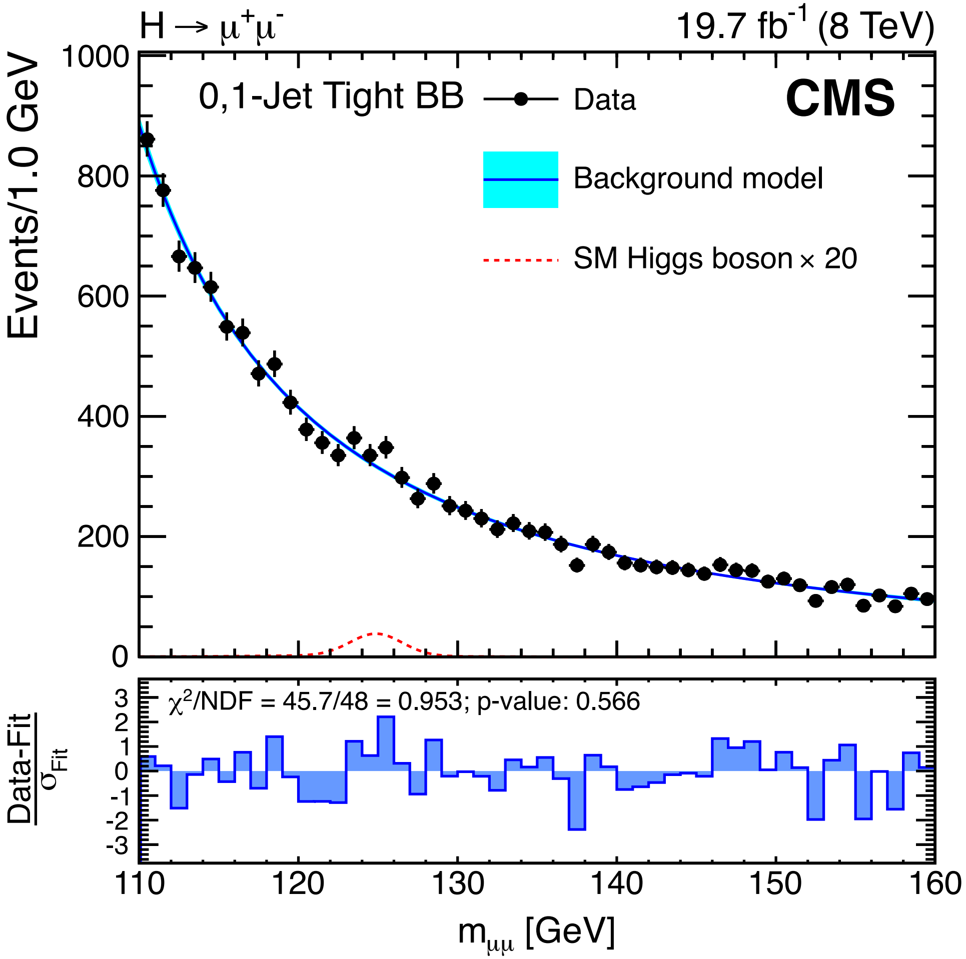


- Bkg shape & normalization → from data
- Selection ε + Sig. estimation → from MC

$H \rightarrow \mu\mu$

Results:

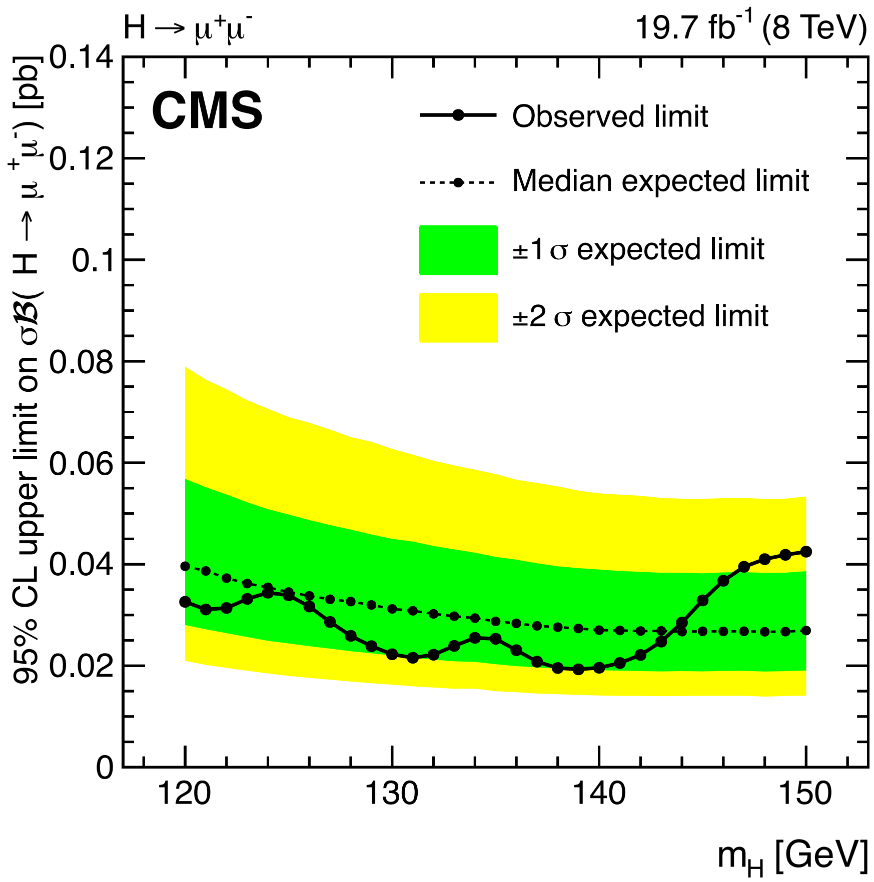
- Fit to $m_{\mu\mu}$ with parametrized Sig+Bkg shape



H→μμ

Results:

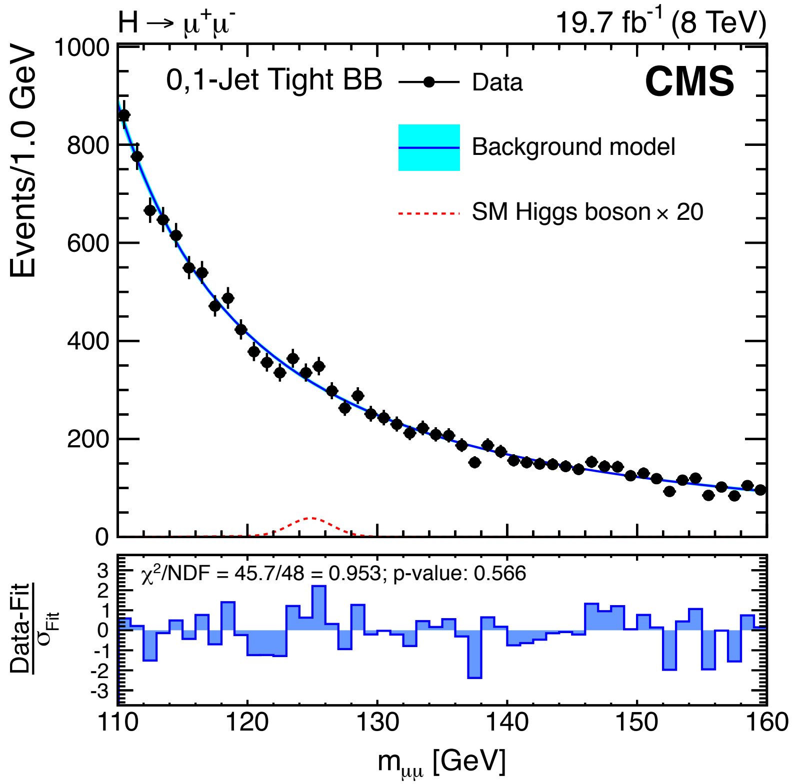
- Simultaneous fit in all the categories and extraction of upper limit on σxBR(H→μμ)

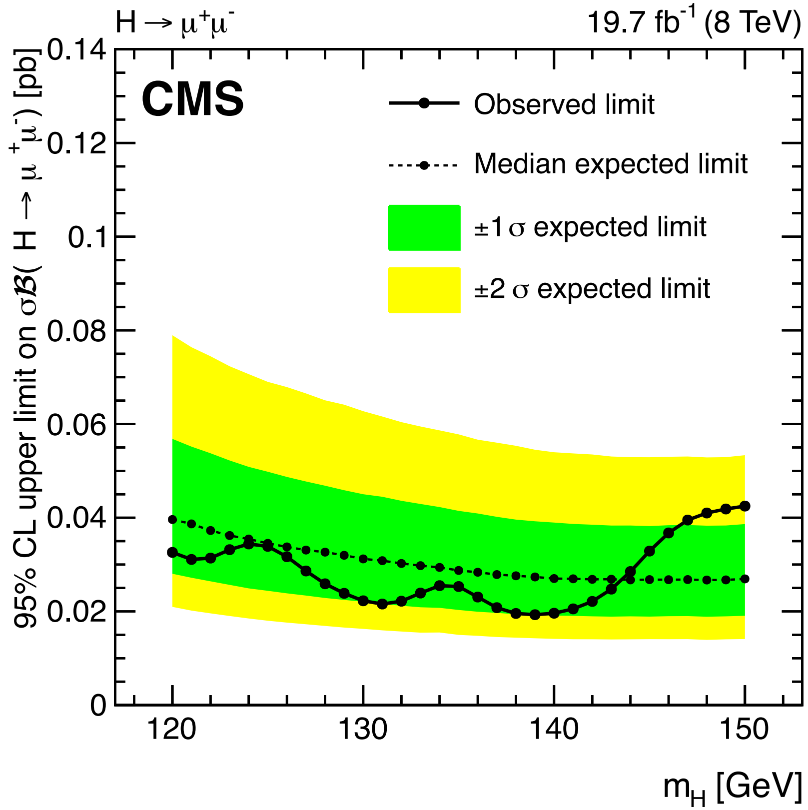


No Signal→Upper Limit on σxBR(H→μμ) @95% CL:

Exp. @m_H=125 GeV: $6.5^{+2.8}_{-1.9}$ x σ_{SM}

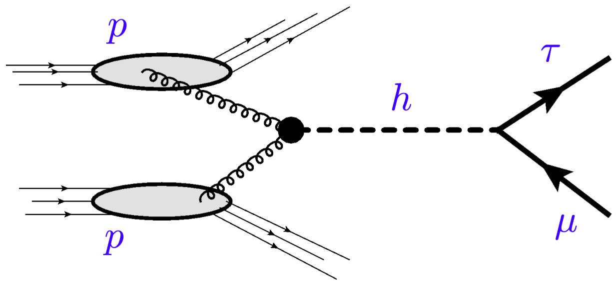
Obs. @m_H=125 GeV: 7.4 x σ_{SM}





Motivation:

• In the SM LFV decays are forbidden. Nevertheless they are admitted if SM is considered an effective theory



• LFV decays of the Higgs boson can also "naturally" occur in BSM , e.g.:

- ➢ Models that predict more than 1 Higgs boson
- ➢ Composite Higgs models

Current constraints

• Indirect searches so far: LFV mediated by a virtual Higgs

• μ → *e* strongly constrained by μ → *eγ* searches: BR(H->μ*e*) < O(10^{-8})

• τ → μ, τ → *e* less stringent ⟹ BR(H->μ*e*) < O(10%)

Observation of Higgs Boson ⟹ Possibility of direct search LFV H→μτ!

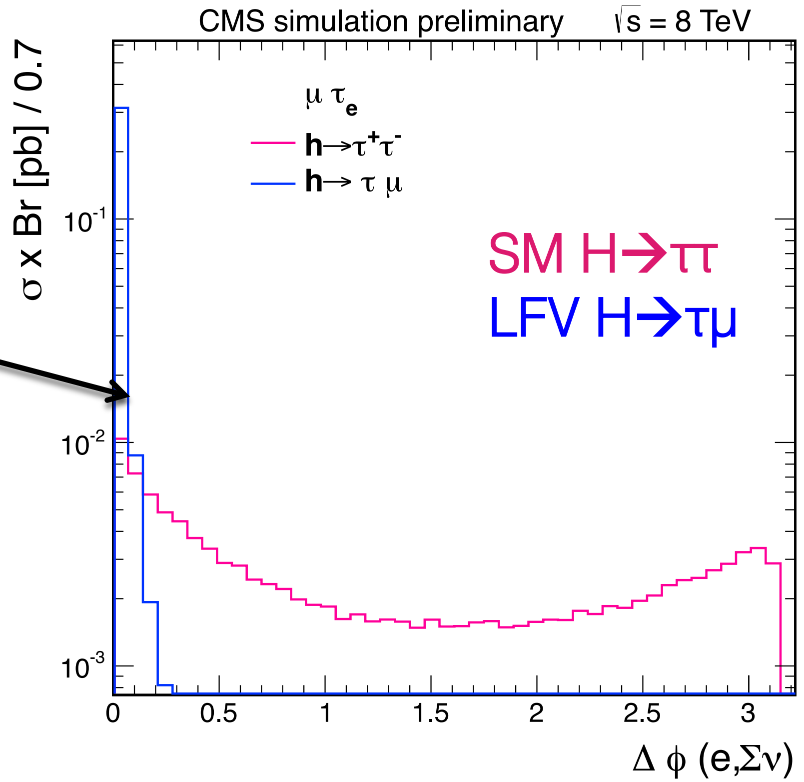
CMS presents the first direct search for LFV H→μτ

H→τμ (LFV)

Analysis strategy:

- Search performed in 2 channels: $\mu\tau_e$ and $\mu\tau_{had}$
- Final state signature similar to the SM H→ττ. But there are some kinematical differences

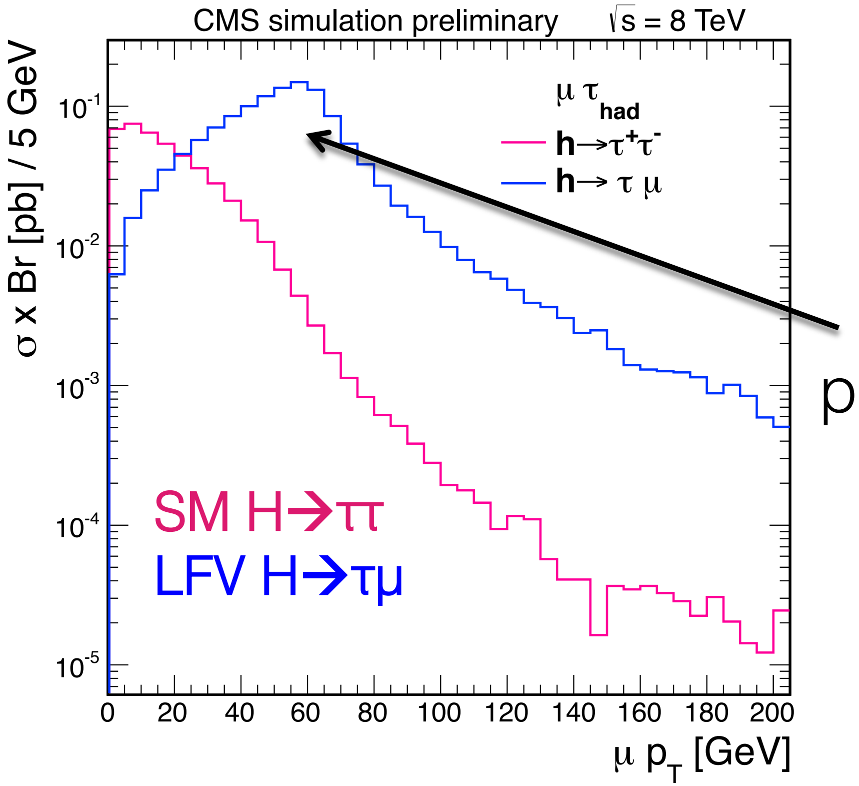
In LFV H→τμ neutrinos are collinear with the τ



H→τμ (LFV)

Analysis strategy:

- Search performed in 2 channels: $\mu\tau_e$ and $\mu\tau_{had}$
- Final state signature similar to the SM H→ττ. But there are some kinematical differences



In LFV H→τμ muon comes promptly from the H

- Categories: 0-Jet / 1-Jet / 2-Jets

H→τμ (LFV)

- The sensitive variable is the **collinear mass**, defined as:

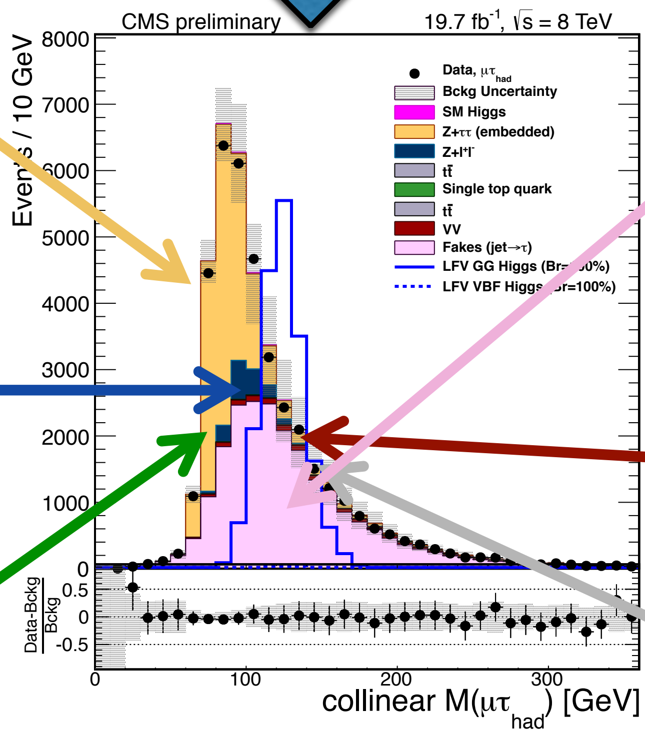
$$\begin{cases} \vec{p}_T^{\,\upsilon} = E_T^{miss} \cdot \hat{p}_T^{\tau-vis} \\ x_{\tau-vis} = \dfrac{\left|\vec{p}_T^{\,\tau-vis}\right|}{\left|\vec{p}_T^{\,\tau-vis}\right| + \left|\vec{p}_T^{\,\upsilon}\right|} \end{cases} \Rightarrow \quad M_H \equiv M_{coll} = \frac{M_{vis}}{\sqrt{x_{\tau-vis}}}$$

Estimator of the reconstructed Higgs boson mass using the observed decay products

Z→ττ
- Embedded technique
- Simulated tau →Zμμ
- Normalization from MC

Z→ll
- From MC

Single top
- From MC



Fakes
- Jets → lepton in QCD/Wj
- Estimated from data
- WW, ZZ removed by MC
- e.g. mis-id muon

VV
- From MC

tt
- From MC

H→τμ (LFV)

M_{coll} independent systematics:

- Electron and tau ε/ID/iso~2%-9%
- ZZ+Jets and WW bkg:10%-30%

M_{coll} dependent systematics:

- Tau Energy Scale ~3%
- Jet Energy Scale ~3%-7%

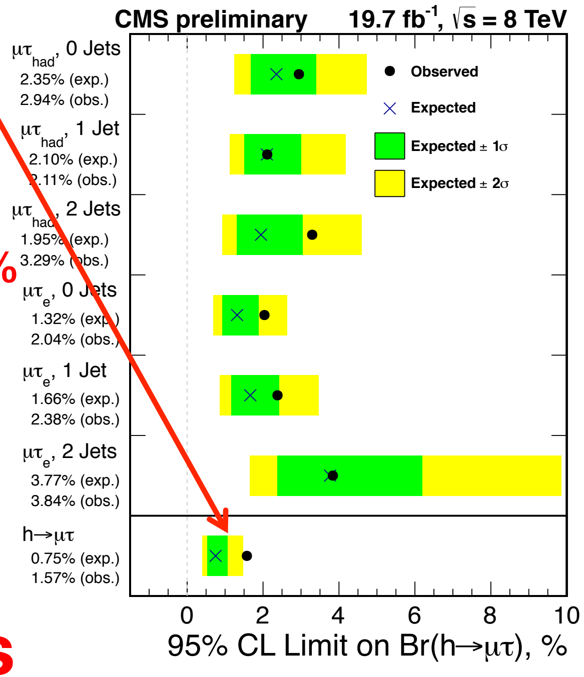
If the excess is interpreted as a signal Best Fit:
$BR(H\rightarrow\tau\mu)<(0.89_{-0.37}^{+0.40})\%$

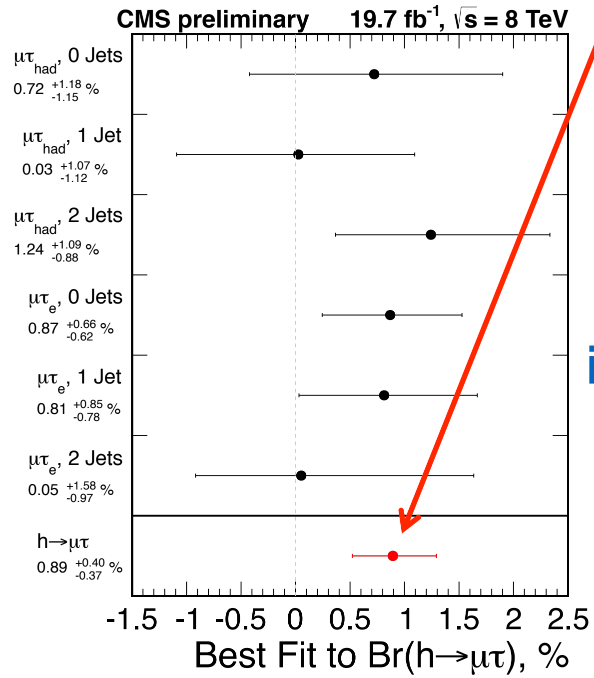
Combining all the channels

Exp Up.Lim
$B(H\rightarrow\tau\mu)<(0.75\pm0.38)\%$

Obs. Up.Lim
$B(H\rightarrow\tau\mu)<1.57\%$

Slight excess





The results could be interpreted as limits on the Yukawa coupling

H→Invisible

doi:10.1140/epjc/s10052-014-2980-6.

All measurements of the H(125) indicate the compatibility with the SM Higgs boson

Uncertainties on σxBR are large ⟹ H→inv is not excluded

Non-SM H→inv. decays:

- H→neutralinos in SUSY models
- H→graviscalars (extra-dim.)
- H interaction with Dark Matter
  (D.M. portal theory: the Higgs boson as mediator between SM particles and DM)

Indirect search constraints

- Inferred by visible decay modes adding a Γ_{inv} term in the combined fit.
- CMS result: upper limit on H(inv.) BR = 0.89 @95% CL

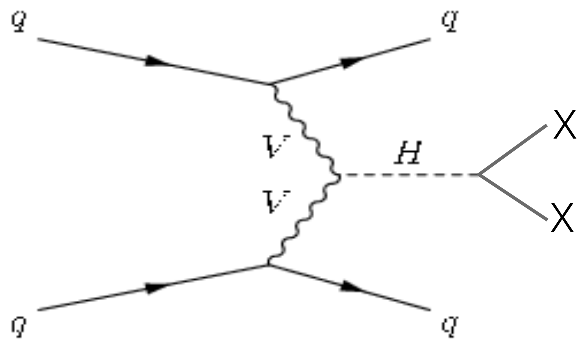
Direct search constraints

- H boson recoiling against a visible system

CMS direct search

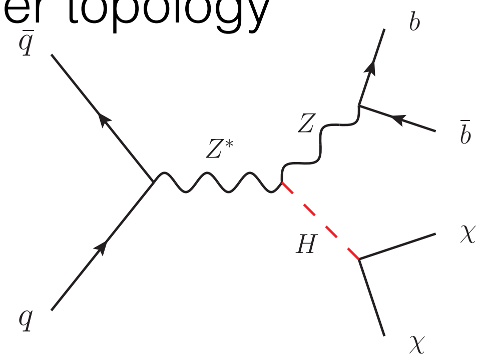
VBF production mode

- First search for H(inv.) in the VBF production mode!
- Relatively large σ_{SM} but 2Jets + E_T^{miss} suffers from large background
- Major Backgrounds:
  - Z(νν)+Jets
  - W(eν)+Jets + W(τν)+Jets
  - QCD multijet + tt
- VBF topology help to reduce the background: The event selections ask for 2 forward jets with high m_{jj} and high rapidity gap + large E_T^{miss}



VH production

- Lower σ_{SM} respect VBF but Z boson + E_T^{miss} provides a clearer topology
- Z(ℓℓ)H(inv): hight p_T isolated leptons from Z, high E_T^{miss}
  - Major bkg: Z(ℓℓ)Z(inv) and W(νℓ)Z(inv)
- Z(bb)H(inv): jet pair consistent with Z→bb, large E_T^{miss}
  - Major bkg: Z(bb)Z(inv), W(νb)Z(inv), Z+bb, tt

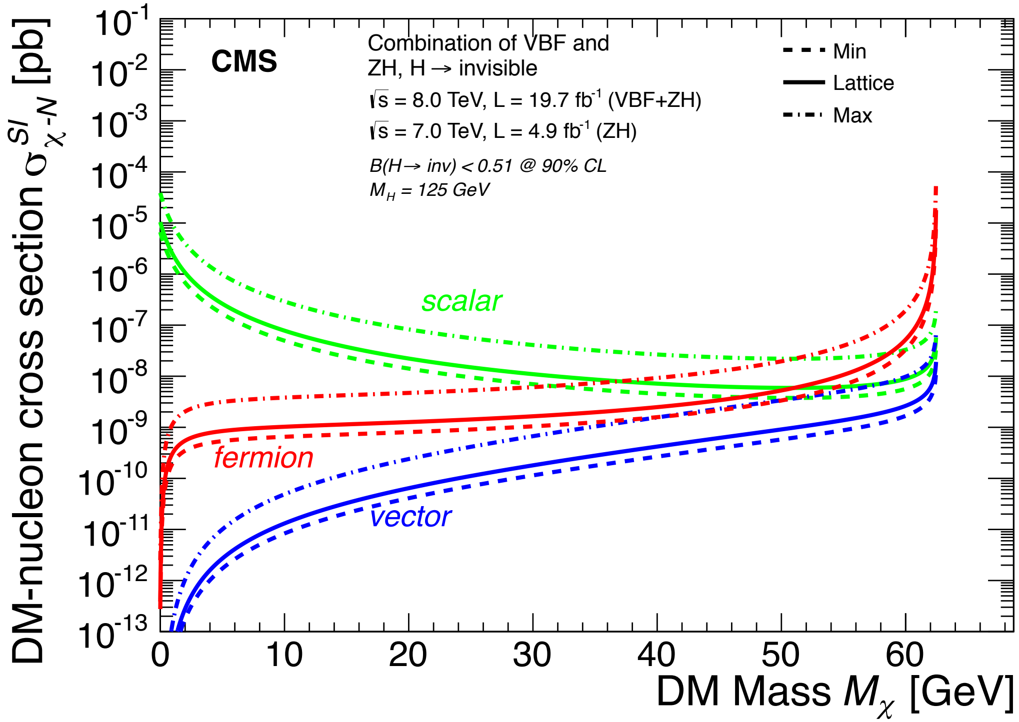


H→Invisible

Results:

No evidence for a signal in any of the 3 decay channel

- Assuming σ_{SM} Exp.(Obs.) Lim. on σ_H X BR(H→inv) = 0.58 (0.44)@95% CL
- Better constraint than the one given by indirect searches
- Interpretation of the result in terms of dark-matter portal theory:
  - ➢ If $m_\chi < M_H/2$ it is possible to relate the Γ_{inv} to σ(DM-nucleon) scattering



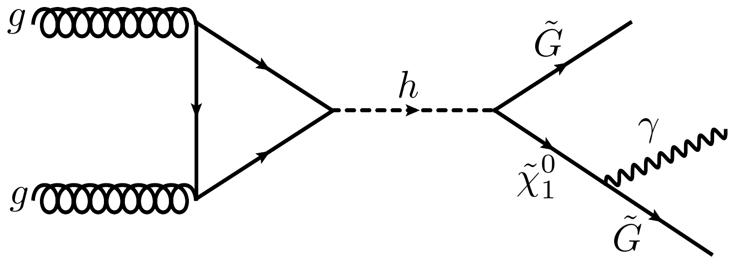
H→Invisible **NEW!! (Jan 2015)** HIG-14-024-pas

Search for new physics with low-E_T γ + E_T^{miss} final state

DM-particle

- In some SUSY scenarios, the H_{125} boson can decay into a gravitino($\tilde{G}$) and a neutralino($\tilde{X}_1^0$)
- In these models $\tilde{G}$ is the lightest supersymmettric particles while the $\tilde{X}_1^0$ is the next-to-lightest: so $\tilde{X}_1^0 \rightarrow \tilde{G} + \gamma$

The monophoton final state can constrain extensions of the SM



- This decay mode produces a single isolated photon + E_T^{miss} from the undetected $\tilde{G}$
- If $m_{X_1^0} < m_H/2$ the decay $h \rightarrow X_1^0 X_1^0 \rightarrow \gamma\gamma$ would dominate ⟹ interesting region

$m_H/2 < m_{X_1^0} < m_H$ ⟹ and since m_H =125 the $E_T(\gamma)$ and E_T^{miss} are relatively low

Required $E_T(\gamma)>45$ and $E_T^{miss}>40$

First CMS search in this low-energy regime

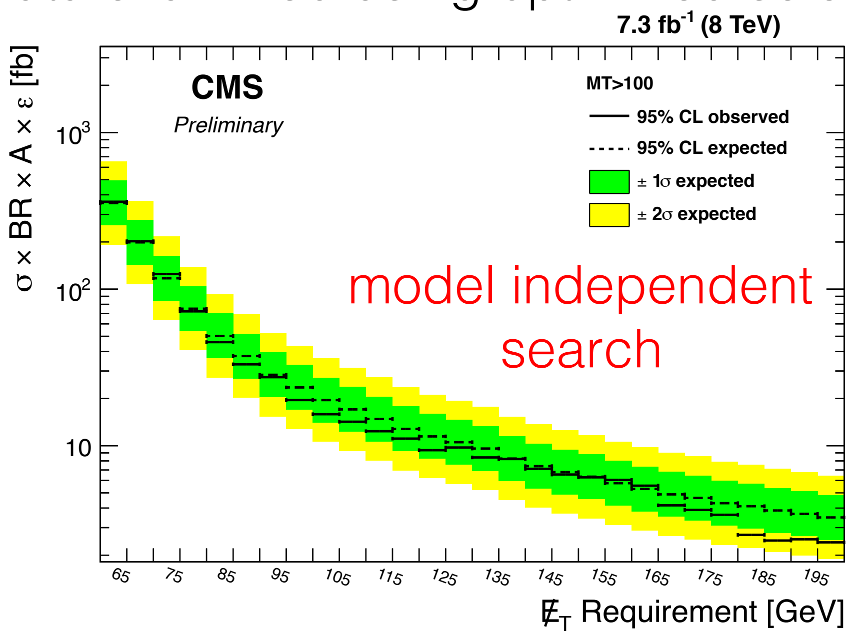
H→Invisible NEW!! (Jan 2015)

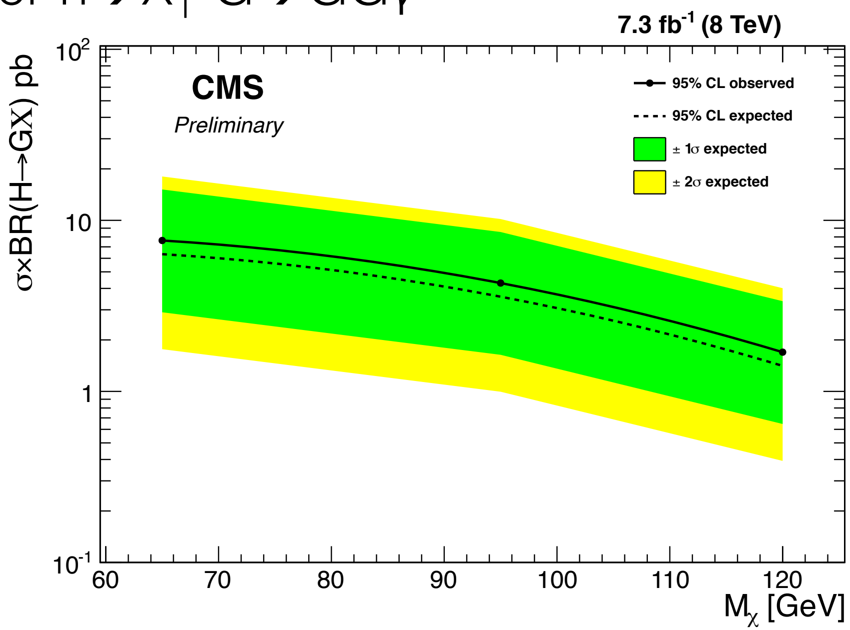
Major background:

- Irreducible from SM $Z\gamma \rightarrow \nu\nu\gamma$

Results:

- Search for new physics in the $\gamma+E_T^{miss}$ final state has been performed with an integrated luminosity of 7.3 fb^{-1}@8TeV
- No evidence for new physics ⟹ upper limits have been placed as function of E_T^{miss}
- Data examined using optimized selections for $h \rightarrow \tilde{X}_1^0 G \rightarrow GG\gamma$





Conclusion:

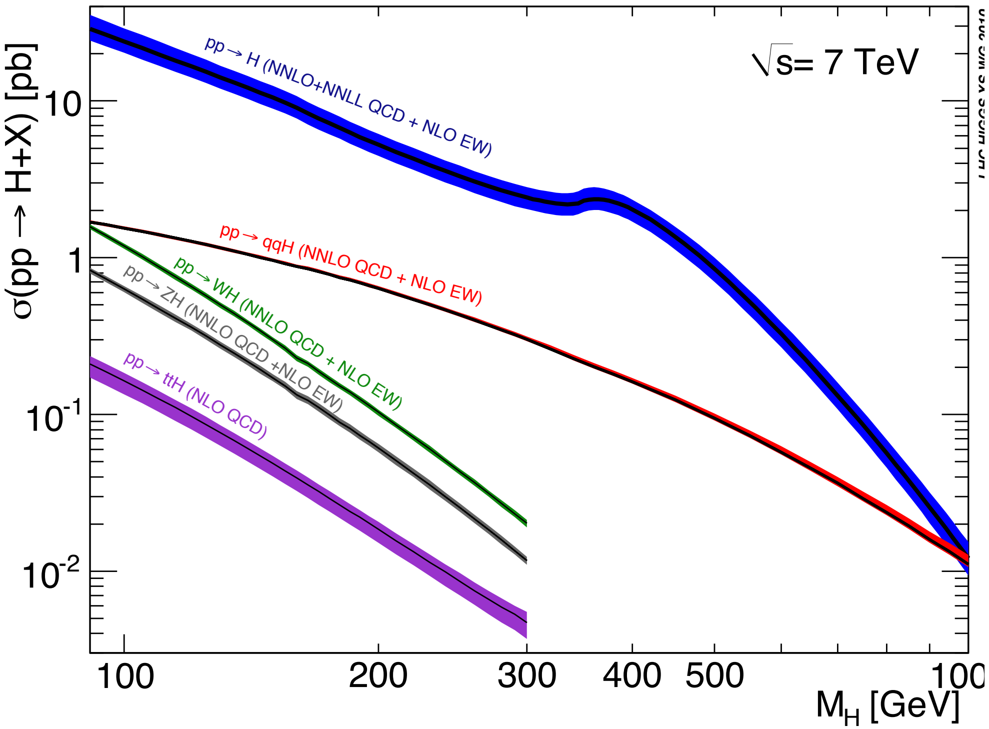
- Different searches for Higgs boson rare decays have been performed in CMS using the whole LHC Run-1 dataset ($5fb^{-1}$@7TeV + $19fb^{-1}$@8TeV) :
  - H→μμ: **NO EXCESS FOUND → UPPER LIMIT ON BR~0.0016**
    will reach 3σ(5σ) sensitivity with 450(1200) fb^{-1}
  - H→μτ (LFV): **SLIGHT EXCESS of 2.5σ → local p-value 0.007 @ mH = 126 GeV**
    The constraints on BR(H→μτ) could be interpreted as constraints on the Yukawa couplings
  - H→invisible: **NO EXCESS FOUND → LIMIT ON BR ~0.44 @ 95% CL**
    - **search for new physics in low-ET(γ) + E_T^{miss} : first limits for $h \to X_1 G \to GGg$ in pp-coll.**

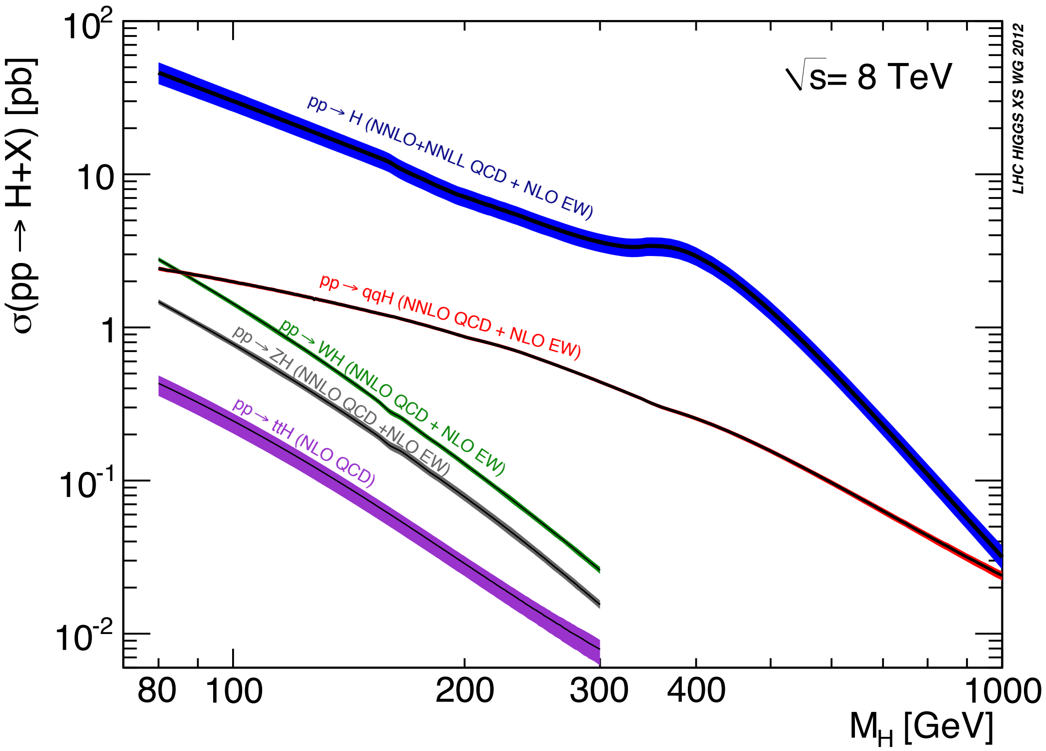
    The constraints on BR(H→inv) have been interpreted as constraints on the σ(Dark-Matter->nucleon) scattering

BACK-UP

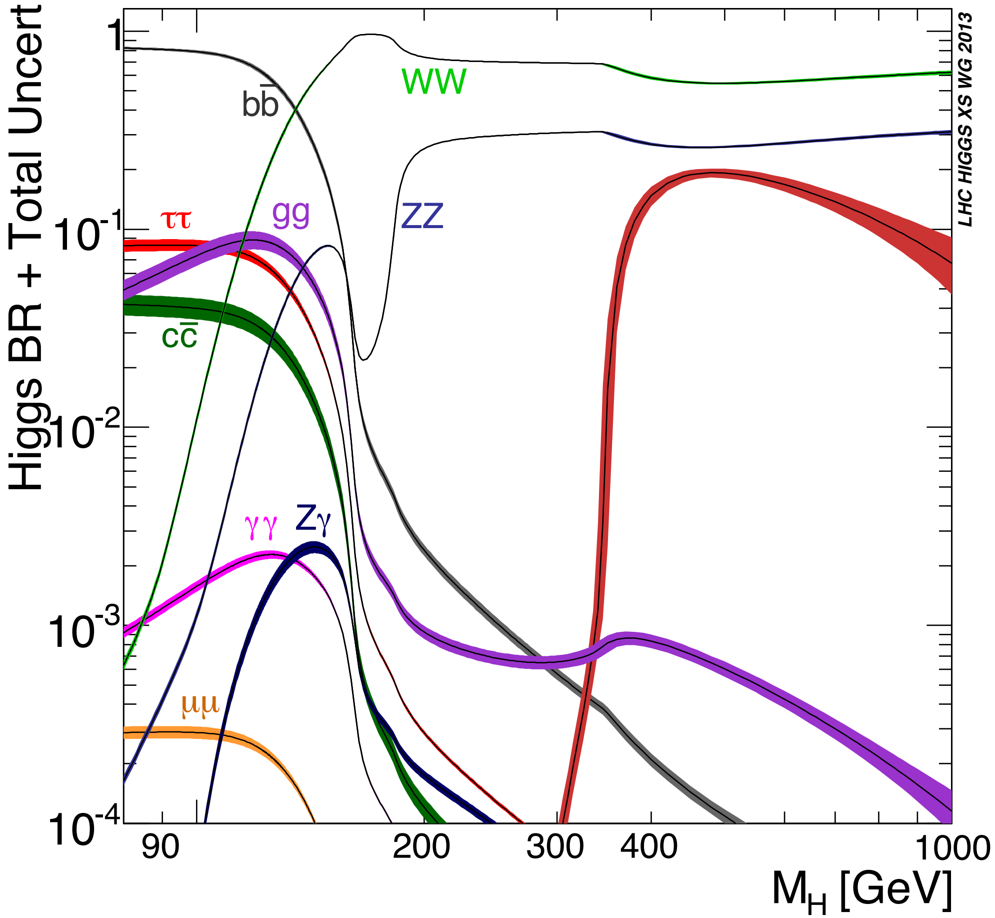
BACK-UP

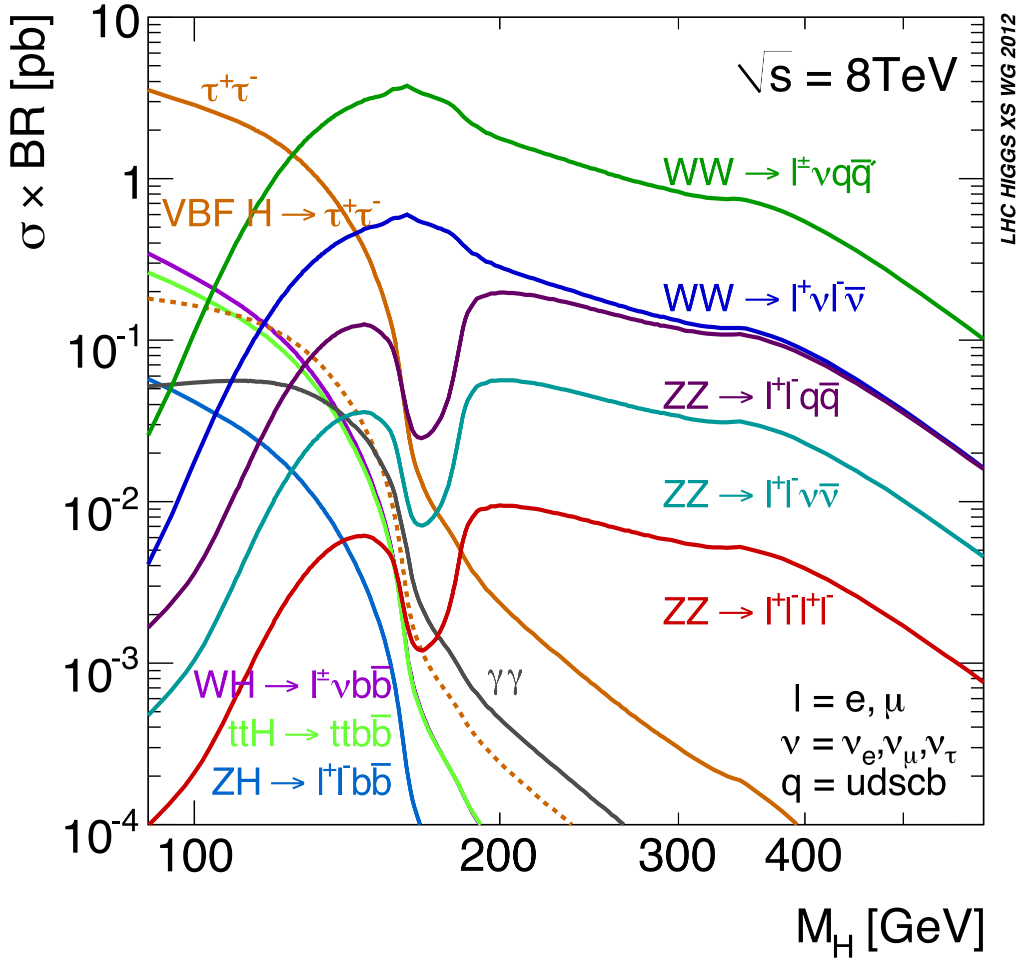
Higgs cross sections





BACK-UP


Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
bb̄
WW
ZZ
ττ
gg
cc̄
γγ
Zγ
μμ
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
90
200
300
400
1000
M_H [GeV]

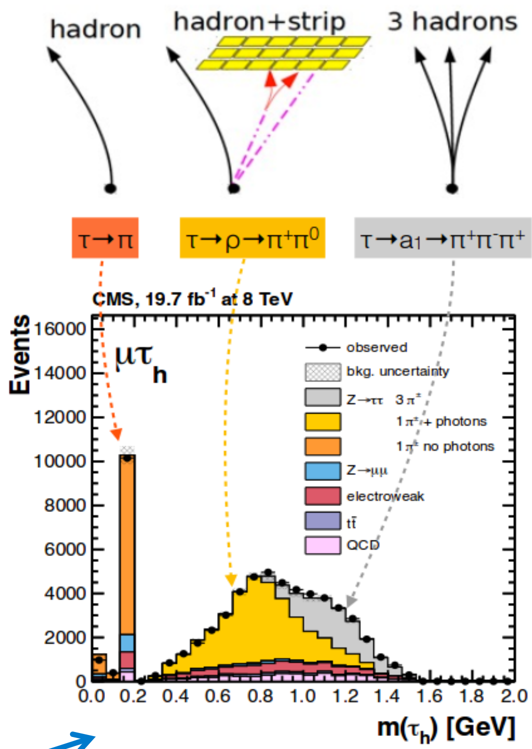

σ × BR [pb]
LHC HIGGS XS WG 2012
√s = 8TeV
τ⁺τ⁻
VBF H → τ⁺τ⁻
WW → l±νqq̄'
WW → l⁺νl⁻ν̄
ZZ → l⁺l⁻qq̄
ZZ → l⁺l⁻νν̄
ZZ → l⁺l⁻l⁺l⁻
WH → l±νbb̄
ttH → ttbb̄
ZH → l⁺l⁻bb̄
γγ
l = e, μ
ν = νe,νμ,ντ
q = udscb
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
100
200
300
400
M_H [GeV]

Ingredients of the reconstruction common to the following analyses:

- **Vertex:**
  → Ordered by $\sum_{tracks} p_T^2$
- **Jets:**
  → PFJets reconstructed using collinear/infrared safe algorithm anti-kt R=0.5
  → correction for the Pile-Up (PU), |η| and p_T dependences
- **E_T^{miss}:**
  → Evaluated from the list of reconstructed PF candidates
  → Corrected propagating the JES corrections

$$\vec{E}_T^{miss} = -\sum_{PF-cand} \vec{p}_T$$

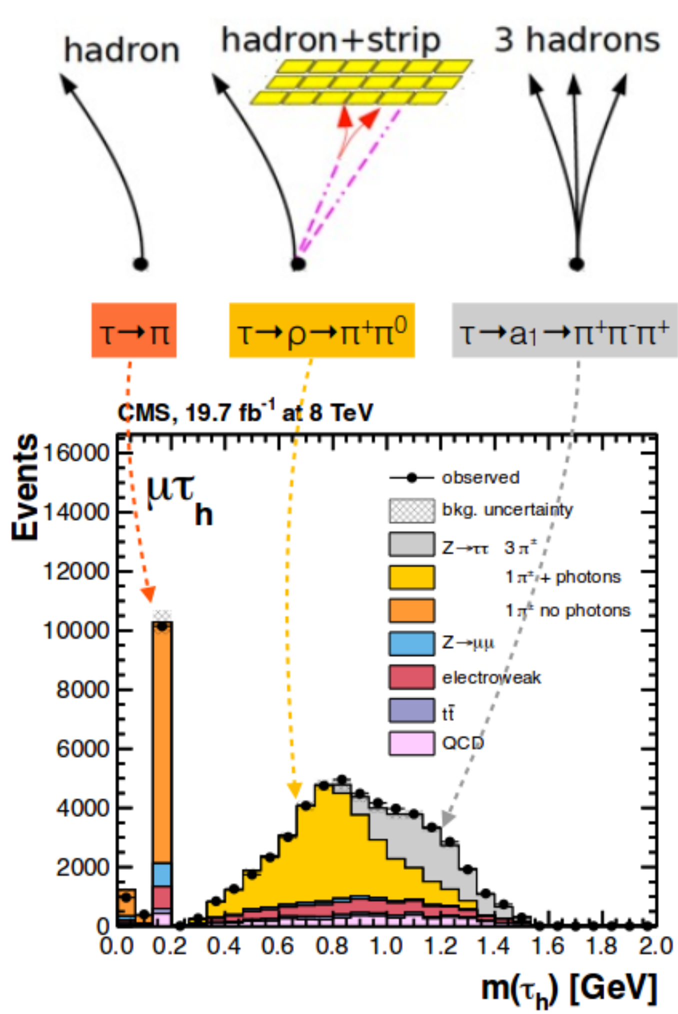
- **Hadronic Taus:**
  → Hadron Plus Strip algorithm (PF based)



HPS algorithm for tau ID

τ decay mode		resonance	Branching Ratio [%]
leptonic	$\tau^- \to \ell^- \nu_\tau \bar{\nu}_e$	-	17.83 pm 0.04
leptonic	$\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$	-	17.41 pm 0.04
TOTAL leptonic			35.24 ± 0.11
1-Prong	$\tau^- \to \pi^- \nu_\tau$	-	10.83 ± 0.06
1-Prong + π^0s	$\tau^- \to \pi^- \pi^0 \nu_\tau$	$\rho^-(770)$	25.52 ± 0.09
1-Prong + π^0s	$\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$	$a1^-(1260) \to \rho^-(770)$	9.30 ± 0.11
3-Prongs	$\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau$	$a1^-(1260) \to \rho^0(770)[\sigma^0(500)]$	9.31 ± 0.06
TOTAL hadronic			54.96 ± 0.82

Table summarizing the τ decay modes considered in the analysis.



H→τμ (LFV)

Results:

Constraint on BR(H→μτ) —interpreted→ Constraint on Yukawa couplings

- At tree-level the LFV decays are:

$$L_V = -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h$$

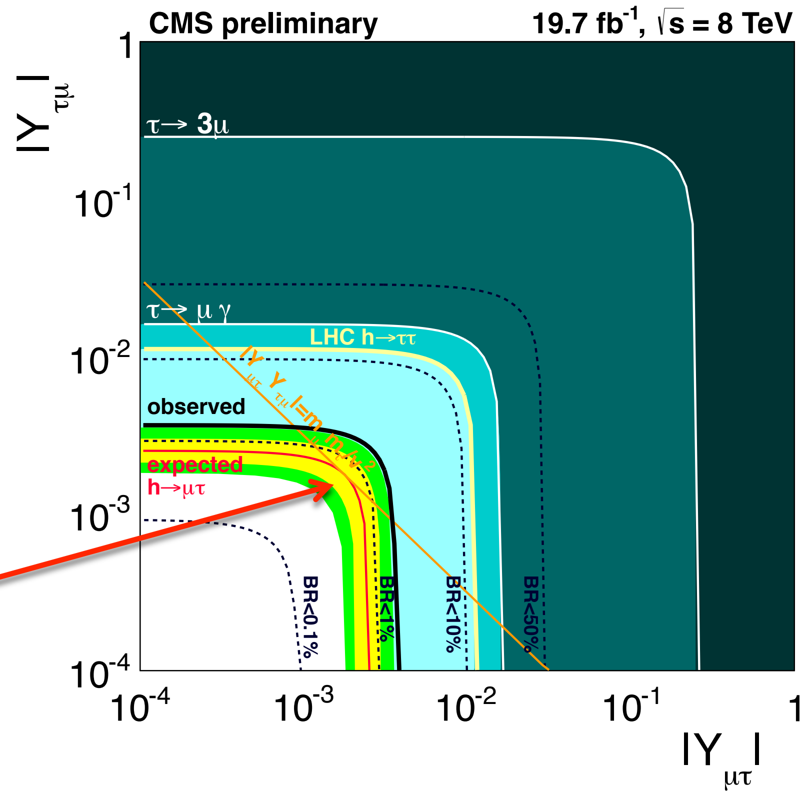
- The BF in term of Yukawa couplings is:

$$BR(H \to \ell^\alpha \ell^\beta) = \frac{\Gamma(H \to \ell^\alpha \ell^\beta)}{\Gamma(H \to \ell^\alpha \ell^\beta) + \Gamma_{H-SM}}$$

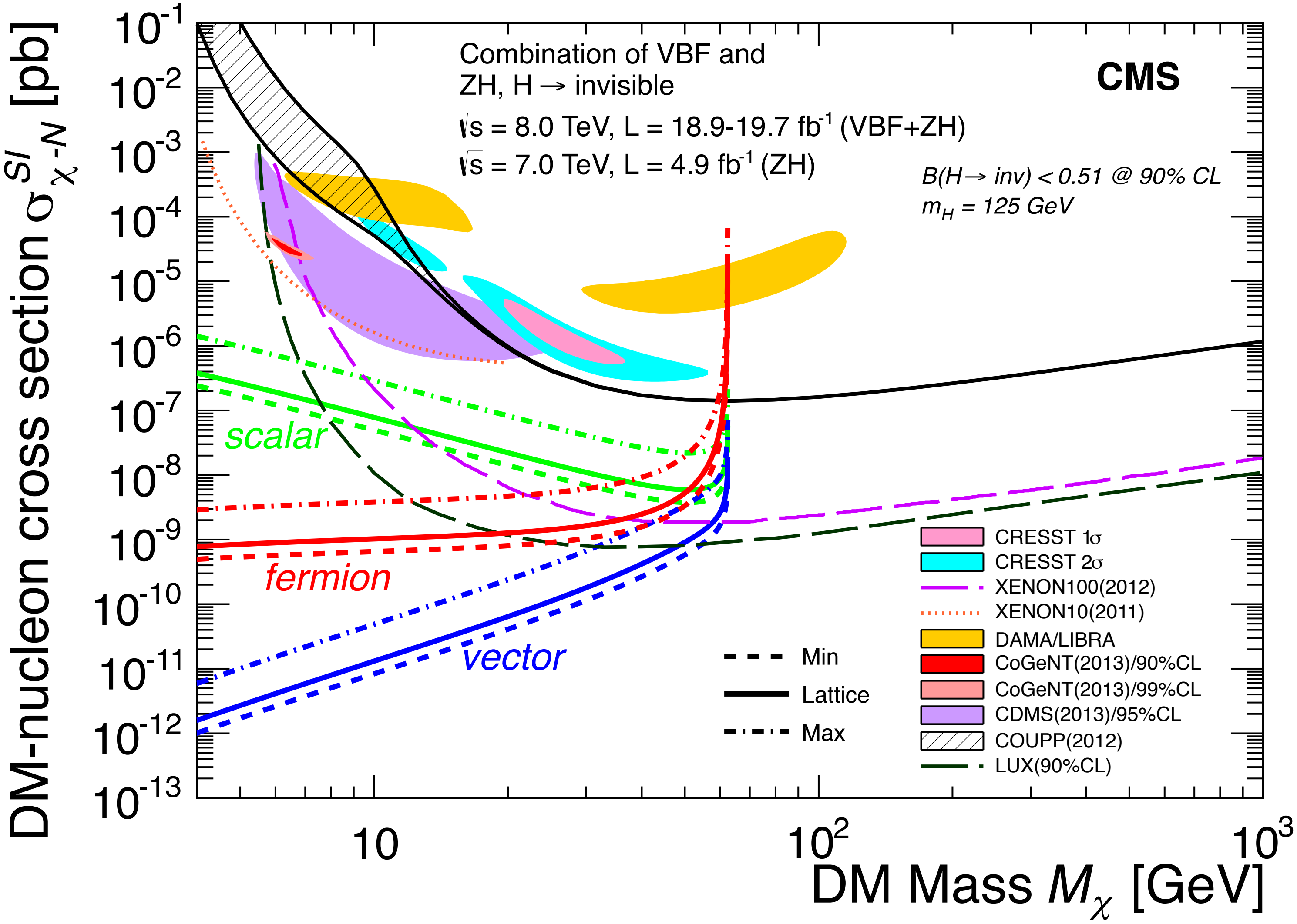
$$\ell^\alpha, \ell^\beta = e, \mu, \tau \quad \wedge \quad \ell^\alpha \neq \ell^\beta$$

- The $\Gamma(H \to l^\alpha l^\beta)$ makes the link with $Y_{\alpha\beta}$:

$$\Gamma(H \to \ell^\alpha \ell^\beta) = \frac{m_H}{8\pi}\left(\left|Y_{\ell^\alpha \ell^\beta}\right|^2 + \left|Y_{\ell^\beta \ell^\alpha}\right|^2\right)$$



H→inv.


Combination of VBF and
ZH, H → invisible
√s = 8.0 TeV, L = 18.9-19.7 fb-1 (VBF+ZH)
√s = 7.0 TeV, L = 4.9 fb-1 (ZH)
CMS
B(H→ inv) < 0.51 @ 90% CL
mH = 125 GeV
scalar
fermion
vector
Min
Lattice
Max
CRESST 1σ
CRESST 2σ
XENON100(2012)
XENON10(2011)
DAMA/LIBRA
CoGeNT(2013)/90%CL
CoGeNT(2013)/99%CL
CDMS(2013)/95%CL
COUPP(2012)
LUX(90%CL)
DM-nucleon cross section σSI χ-N [pb]
DM Mass Mχ [GeV]
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10
10^2
10^3

H→Invisible

Results:

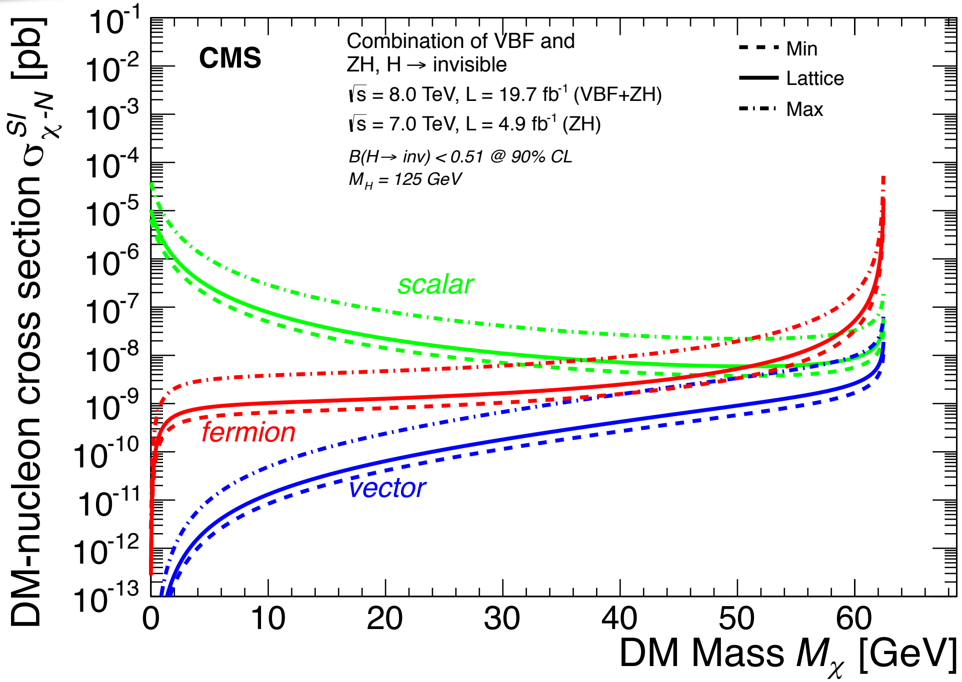
No evidence for a signal in any of the 3 decay channel

- Assuming σ_{SM} Exp.(Obs.) Lim. on σ_H X BR(H→inv) = 0.58 (0.44)@95% CL
- Better constraint than the one given by indirect searches
- Interpretation of the result in terms of dark-matter portal theory:
  - ➢ If $m_\chi < M_H/2$ it is possible to relate the Γ_{inv} to σ(DM-nucleon) scattering

$$\sigma_{S-Nucl.} \propto \frac{4\Gamma_{inv}}{M_H^3 \upsilon^2 \beta} \frac{m_N^4 f_N^2}{\left(m_\chi + m_N\right)^2}$$

$$\sigma_{V-Nucl.} \propto \frac{16\Gamma_{inv} m_\chi^4}{M_H^3 \upsilon^2 \beta \left(M_H^4 - 4m_\chi^2 + 12 m_\chi^4\right)^2} \frac{m_N^4 f_N^2}{\left(m_\chi + m_N\right)^2}$$

$$\sigma_{f-Nucl.} \propto \frac{8\Gamma_{inv} m_\chi^2}{M_H^5 \upsilon^2 \beta^3} \frac{m_N^4 f_N^2}{\left(m_\chi + m_N\right)^2}$$

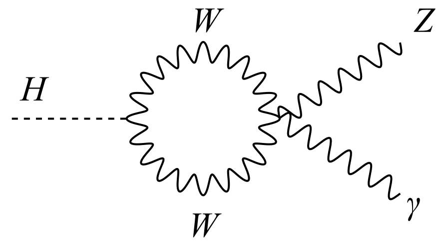


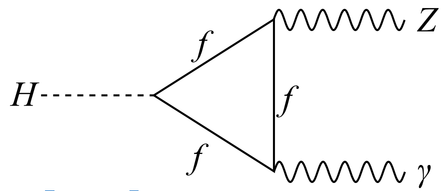
H→Zγ (BR ~$1.54 \cdot 10^{-3}$)

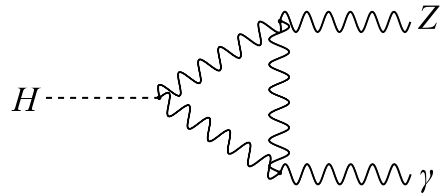
doi:10.1016/j.physletb.2013.09.057

Theoretical motivation

- Loop-induced process:
  - ➢ Small BR
  - ➢ Sensitive to new particles potentially running in the loops







- Could be substantially modified by new charged particles without affecting the ggH production cross section

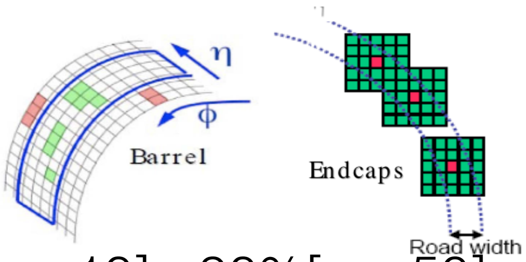
Analysis strategy:

- Z→ μμ/ee decays considered
  - ➢Clean final state topology
  - ➢3-body M_{inv} resol. ~1-3%
  - ➢Low level of background
- Categorization according to mass resolution and S/B

H→Zγ

Principal Bkg:

IRREDUCIBLE: Zγ from SM production
REDUCIBLE: FSR from Z, Z+Jets where Jet/lepton fake γ



Object Selection:

γ: **ECAL supercluster** + PF isolation → ε ≈ 90%
e: **ECAL supercluster** + track in the tracker → ε ≈ 60%[p_T~10] - 90%[p_T~50]
μ: Global fit to trajectory using tracker + muon system → ε ≈ 95%

Event pre-selection:

- 2 opposite sign, same flavour leptons consistent with Z decay + 1γ

Final kinematic selection

+ $m_{ll} > 50$ GeV → reject H→γγ*→*llγ* + $m_{ll\gamma}$ in [100, 180] GeV/c²
+ΔR_{ll}, $\Delta R_{l\gamma} > 0.4$ → reject ISR + $(m_{ll} + m_{ll\gamma}) > 185$ → reject FSR

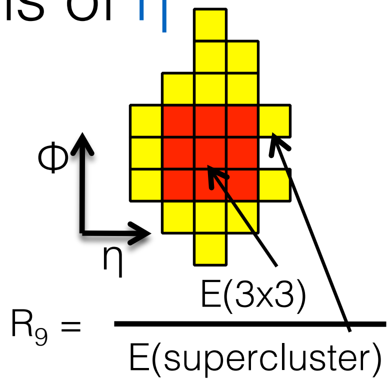
Event Classes:

**Resolution much better in the BARREL than in the ENDCAPS

- → Enhanced analysis sensitivity
- → Categorization made on expected $m_{ll\gamma}$ resolution** and S/B

4 mutually exclusive event classes defined in terms of η and shower shape of γ (R_9)

Class 1	Class2
l/γ all in the BARREL + high R_9 ***Signal: 34% - Data: 20%**	**l/γ all in the BARREL + low R_9** ***Signal: 31% - Data: 31%**
Class 3	**Class 4**
At least 1 l in the ENDCAP ***Signal: 18% - Data: 20%**	**γ in the ENDCAP** ***Signal: 17% - Data: 29%**



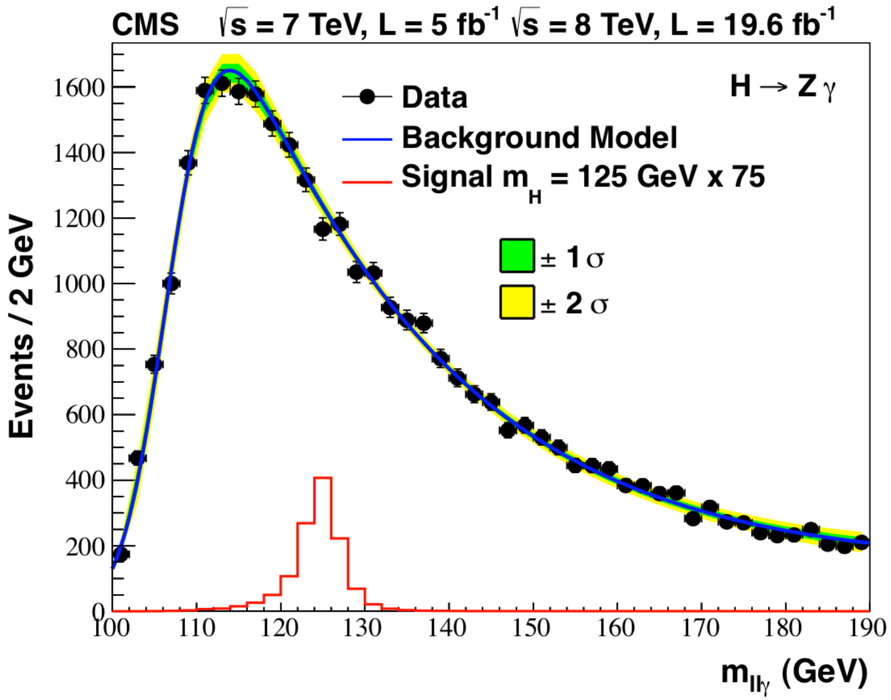
Not converted γ:
$R_9 > 0.94$

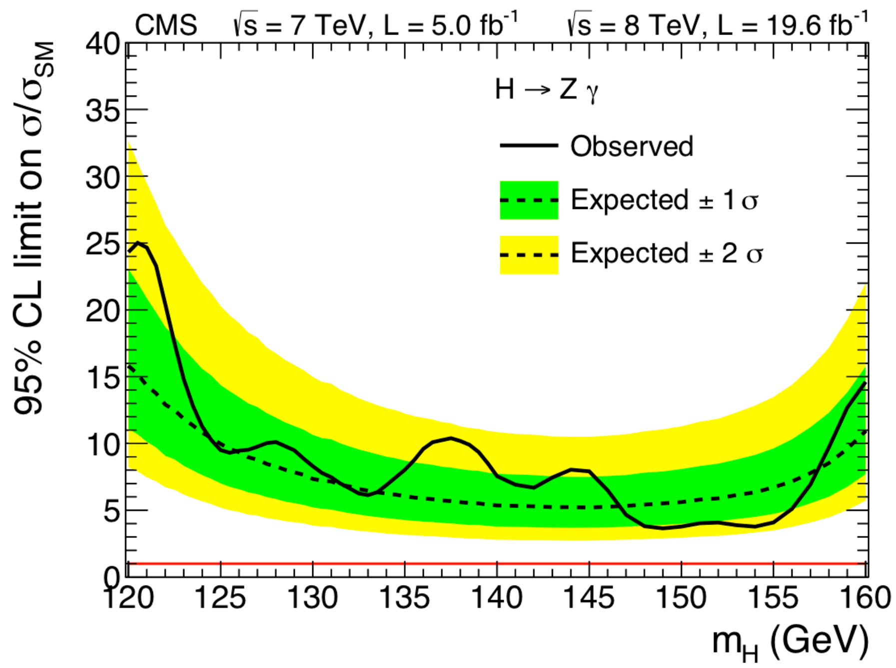
*this is when Z→Zμμ

H→Zγ

Results:

- Background model: fit with polynomial function the $m_{ll\gamma}$ distribution in [100, 180] GeV
- Signal is described using a NLO ME monte carlo generator





No excess has been found → σ upper limit 4-25 x σ_{SM} @95% CL