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Searches for Exotic Higgs decays in CMS

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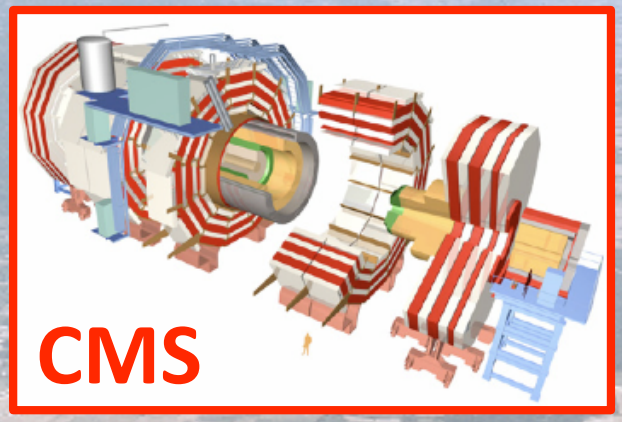
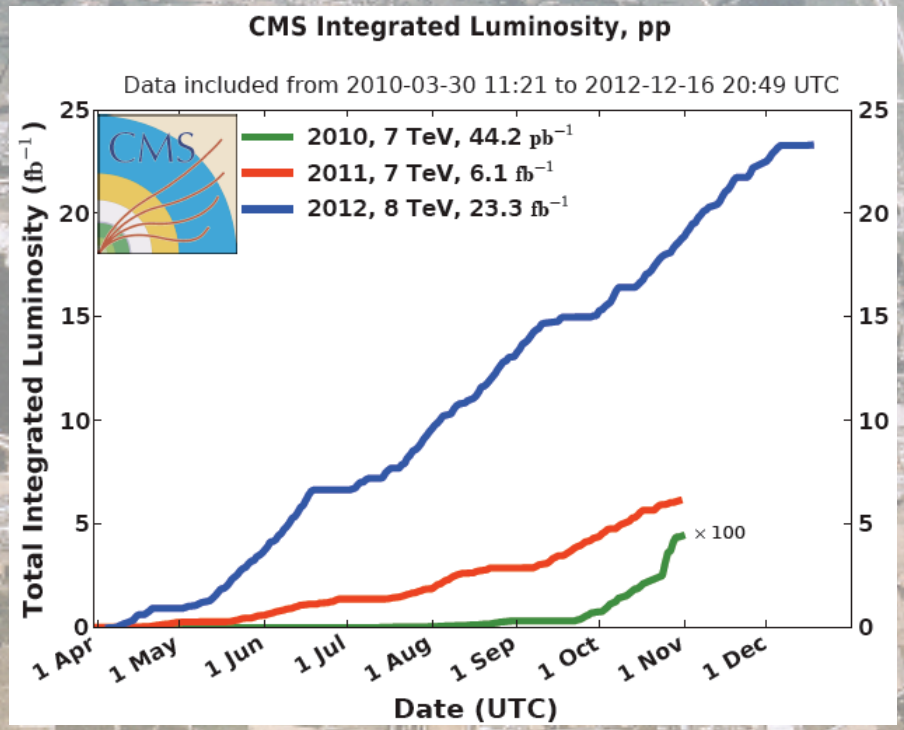


Outline:

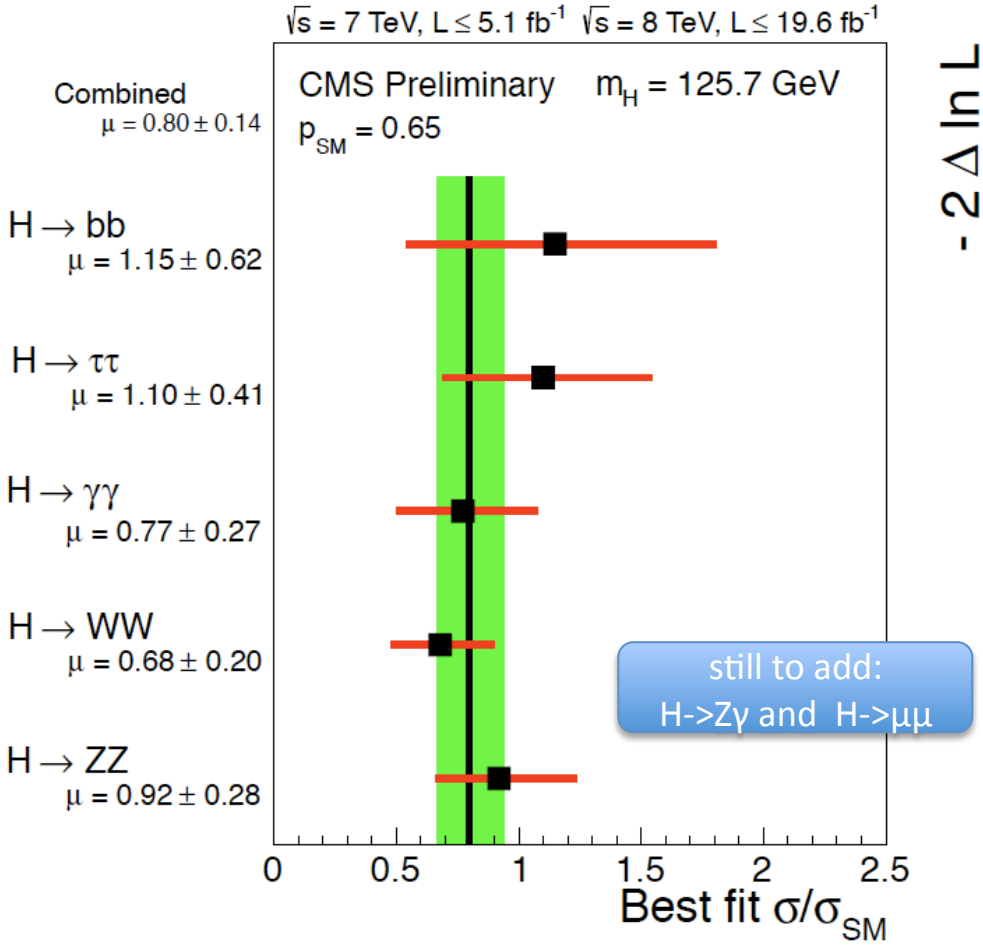
- Motivation
- CMS detector
- Higgs Beyond Standard Model: MSSM & NMSSM
- Higgs rare decays



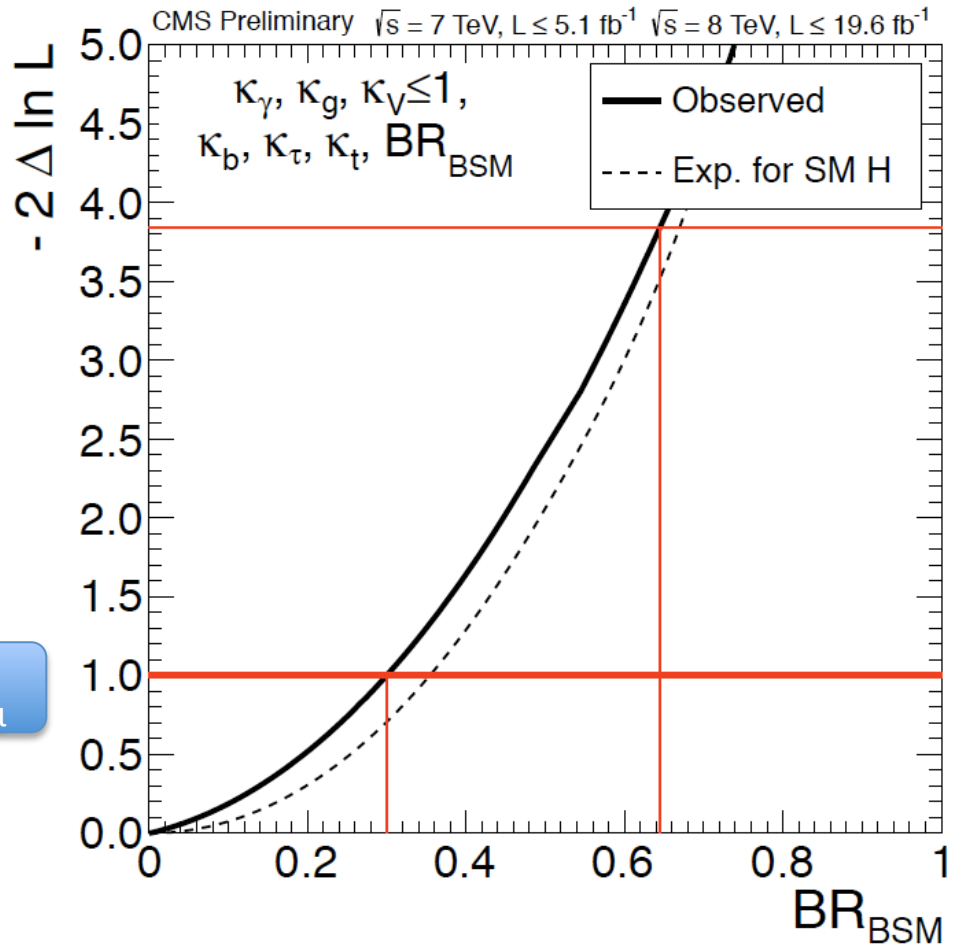
what is driving us

combining all CMS approved results for Moriond'13:

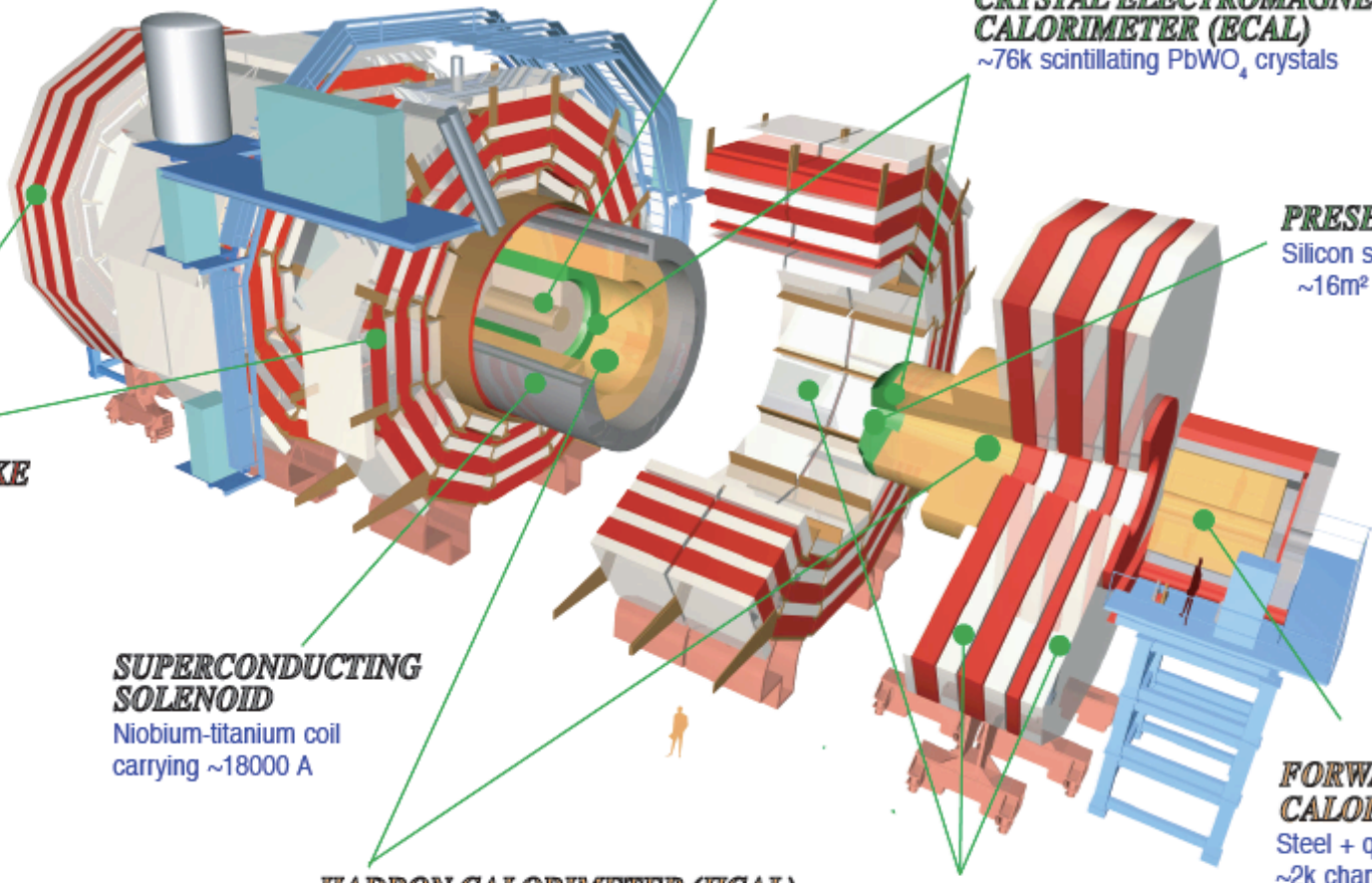
- $BR_{BSM}=\Gamma_{BSM}/\Gamma_{tot}$ assuming that couplings to the electroweak bosons are bound by the SM expectation ($\kappa_V \leq 1$)
- $0 \leq BR_{BSM} \leq 0.64$ at 95% C.L. (more details in CMS-PAS-HIG-13-005)



still to add:
H->Zγ and H->μμ



CMS Detector

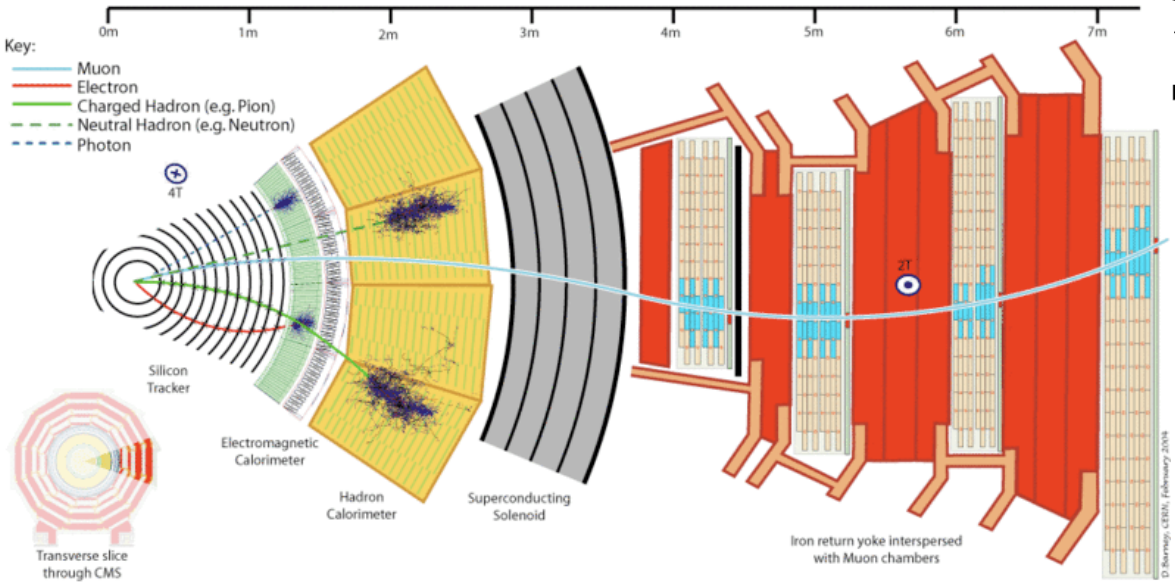


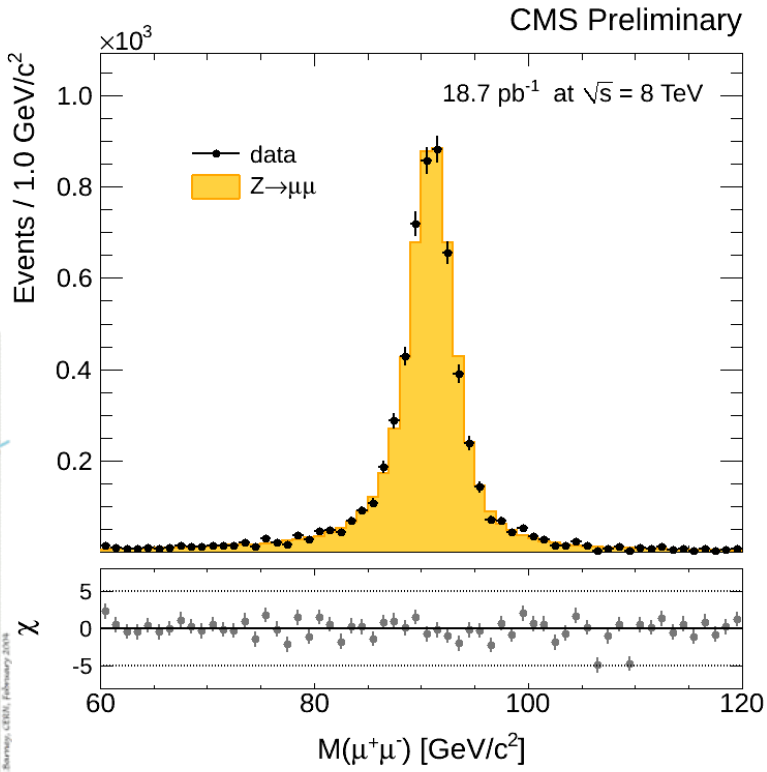
Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

before we go for physics we need to understand the physics objects (e, μ, τ, jets and E_T^{miss})

physics objects: muons

Muons in CMS:
track segment reconstructed in the muon chambers matched with track in silicon tracker





- **coverage:** $|\eta| < 2.4$, $\eta = -\ln[\theta/2]$
- **momentum resolution**:

$\sigma_{p_T}/p_T \approx 0.015\% \, p_T \oplus 0.5\%$

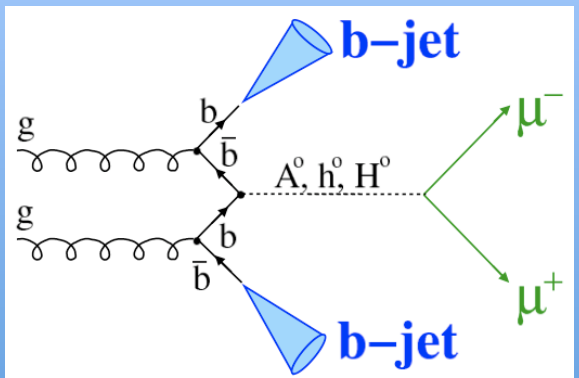
- good agreement between Monte Carlo simulation and data
- there is a reason why we are called CMS ☺

Minimal Supersymmetric SM

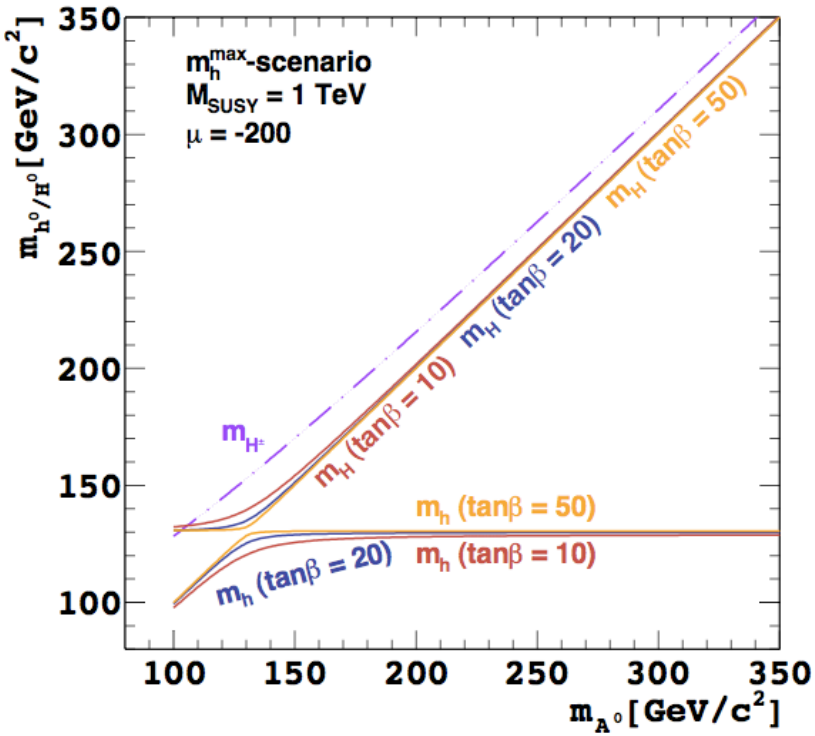
MSSM: Φ^0 (h^0, H^0, A^0), $H^\pm$

- Higgs sector can be described by: tanβ and m_A
- $\tan\beta = v_1/v_2$ where v_1 and v_2 – vacuum expectation values
- A^0 (CP odd): m_A
- h^0, H^0 (CP even): $m_{H,h}=\{1/2\{m_A^2+m_Z^2 \pm [(m_A^2+m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta\,]^{1/2}\}\}^{1/2}$
- $H^\pm$: $m_H=(m_A^2+m_W^2)^{1/2}$

- enhancement at large tanβ
- bbH: $g^{MSSM} = \tan\beta\, g^{SM}$



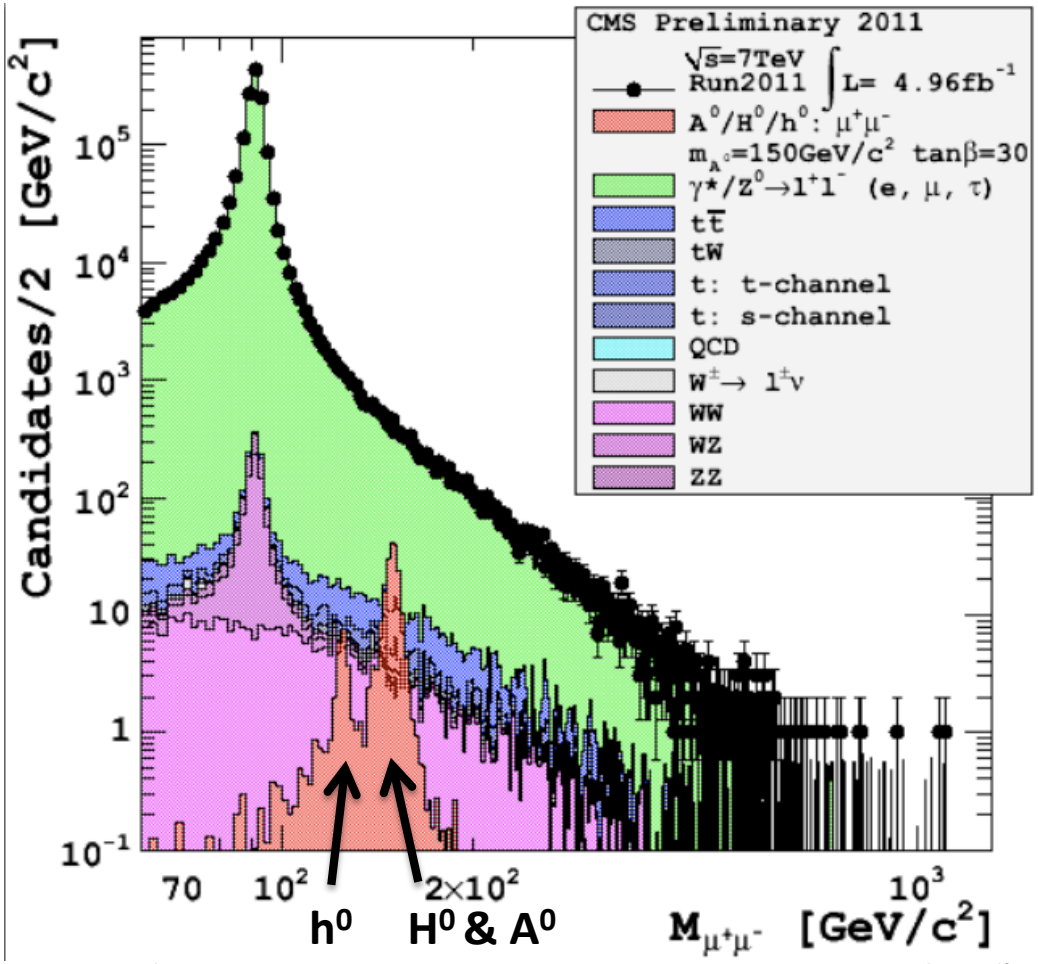
- two isolated μ with high p_T
- at least a b-jet with relatively low p_T
- low missing transverse energy E_T^{miss}
- irreducible background: bb γ*/Z

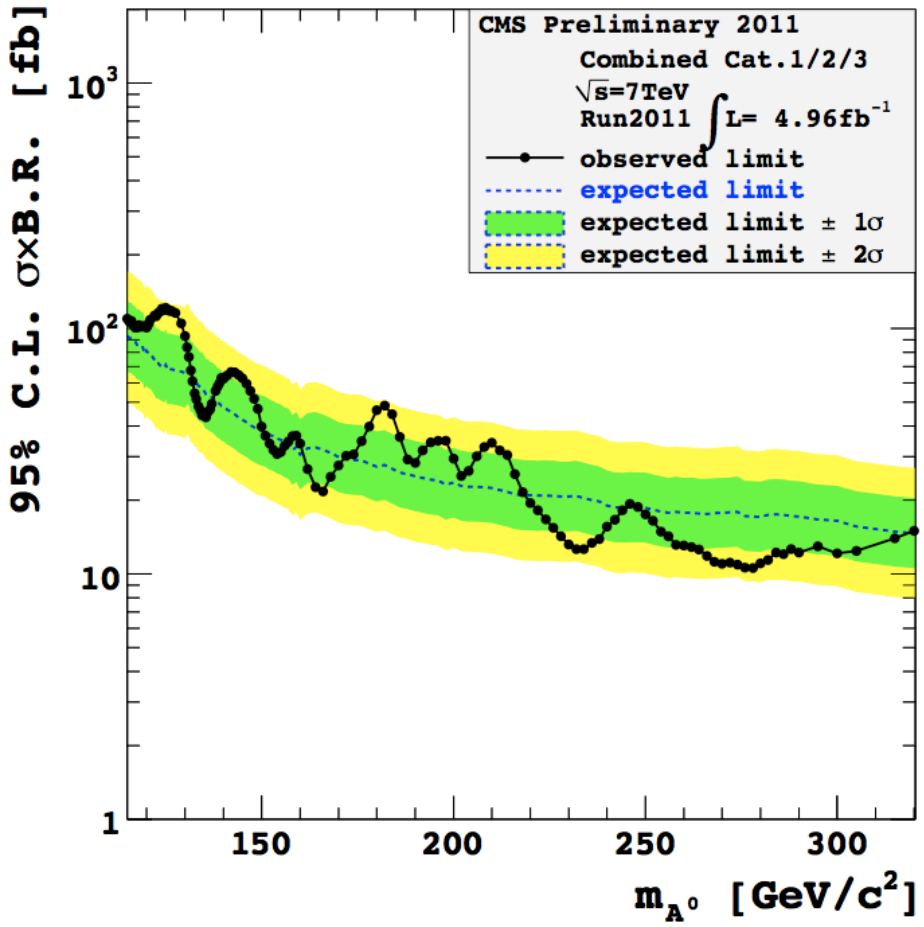


MSSM $H^0 \rightarrow \mu^+\mu^-$

MSSM analysis of $\sqrt{s}$ = 7 TeV

- made public during last summer **CMS PAS HIG-12-011**
- analysis of $\sqrt{s}$ = 8 TeV about to be finished, more results soon



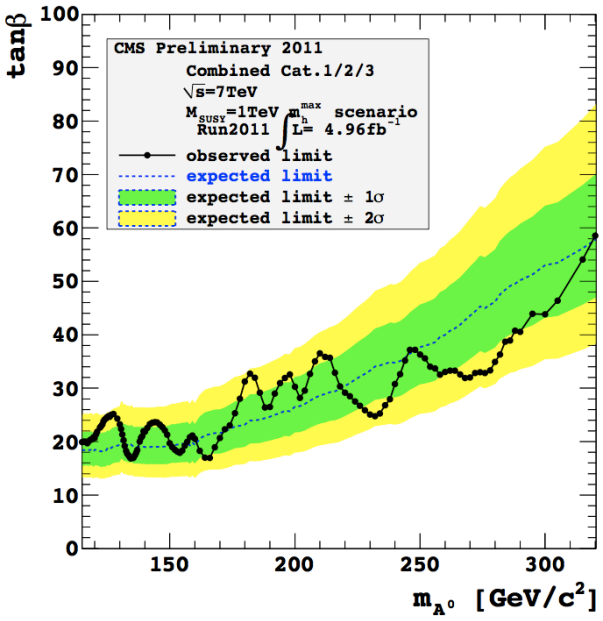


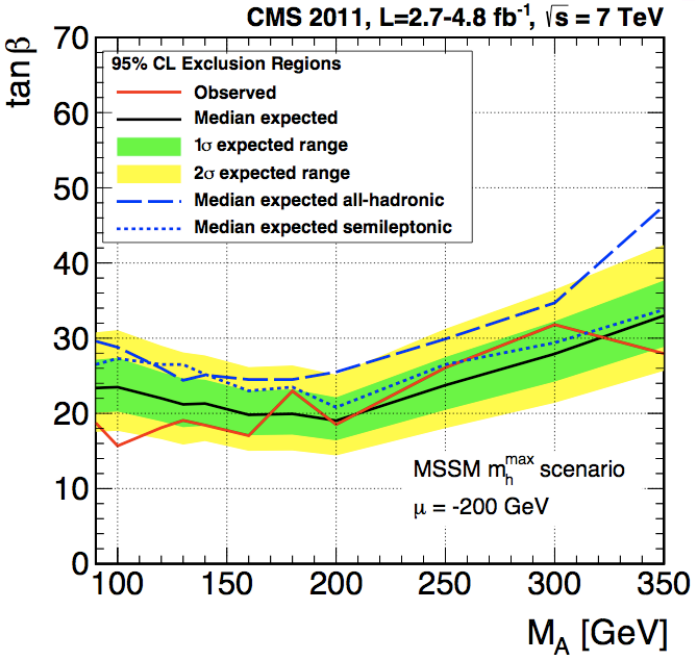
MSSM

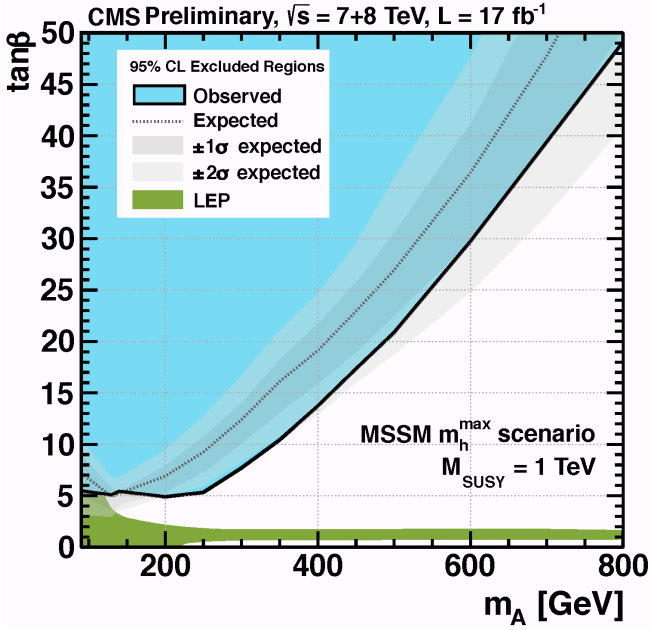
channel: μμ
- even with a BR of ≈10^{-4} good sensitivity is achieved
- best channel for a precise measurement of tanβ

channel: bb
- good BR
- challenging background
- more details in **arXiv:1302.2892**

channel: ττ
- better background conditions and ditau mass parameterization
- **CMS PAS HIG-12-050**



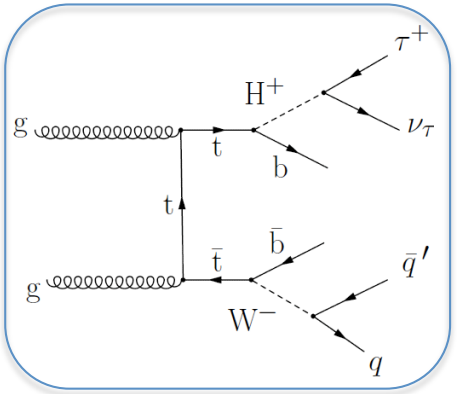




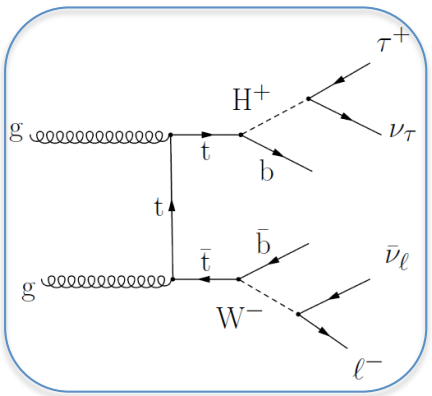
- there is an ongoing effort in CMS to combine all analyses and complete the analysis of the √s = 8 TeV data (plan to be ready by summer)

charged Higgs

low Higgs mass:
• production via t-quark decays:
gg -> H^+W^- and gg -> H^+H^-
• τ final states (sensitive for tanβ≥ 2):
- fully hadronic
- τ_{had} & W(e/μ)
- τ(μ/e) & W(e/μ)

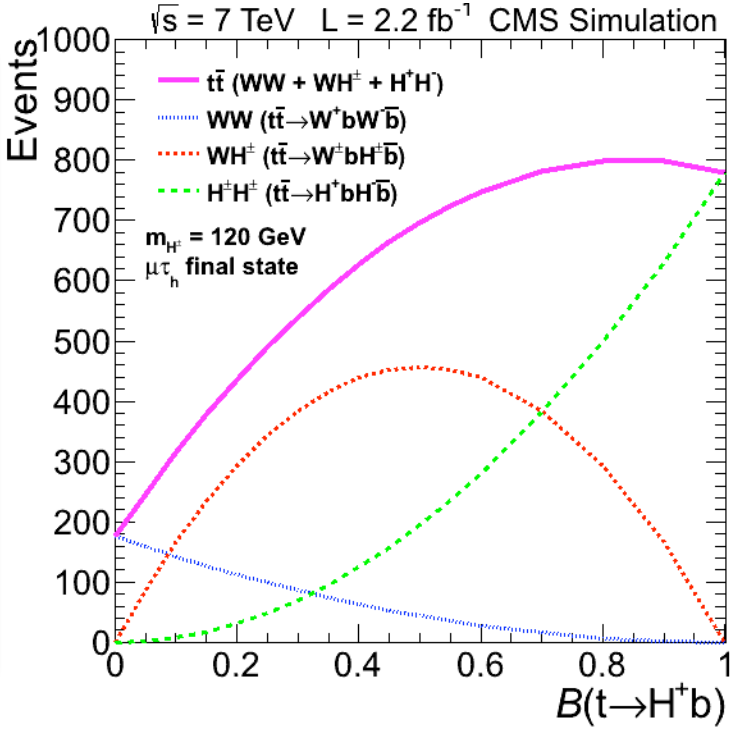


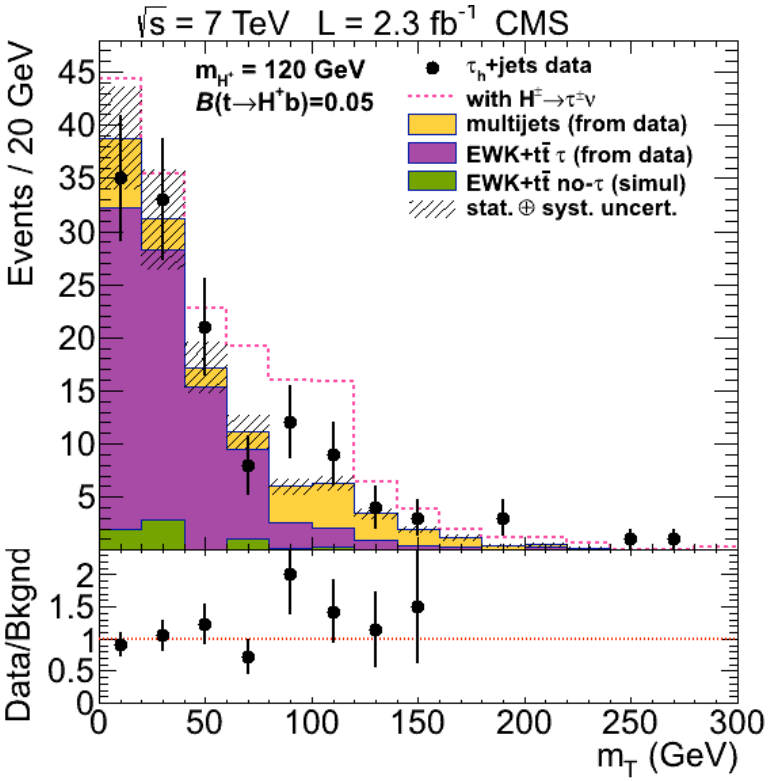
fully hadronic final state



leptonic final state (eμ)

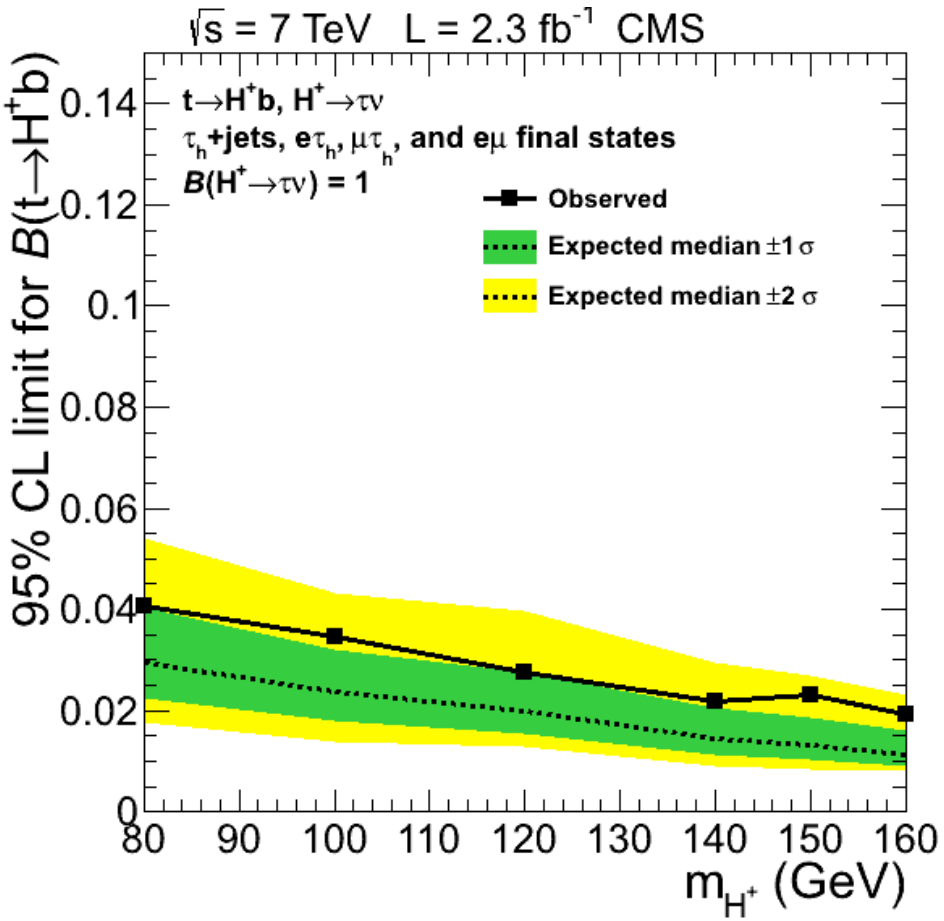
fully hadronic:
• isolated τ
• 4 high p_T jets
• one b tagged jet
• missing energy in transverse plane
e/μ:
• 2 high p_T jets
• isolated high p_T lepton
eμ:
• 2 isolated high p_T leptons

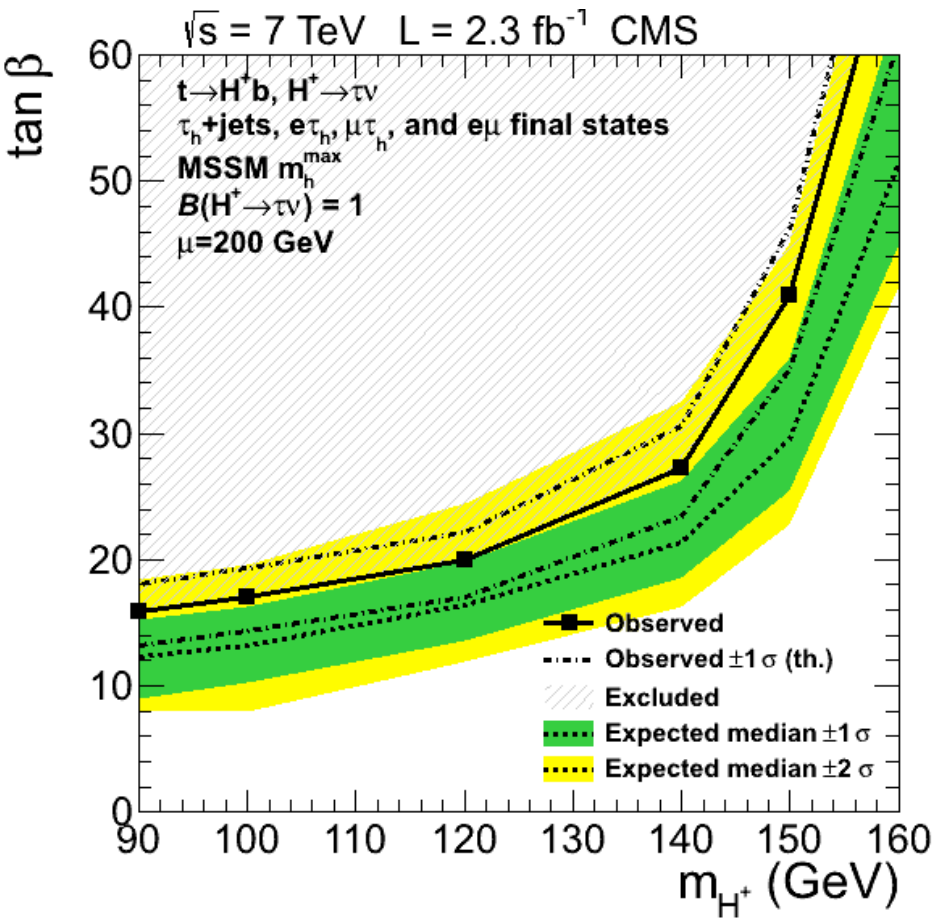




charged Higgs

the combined limits:



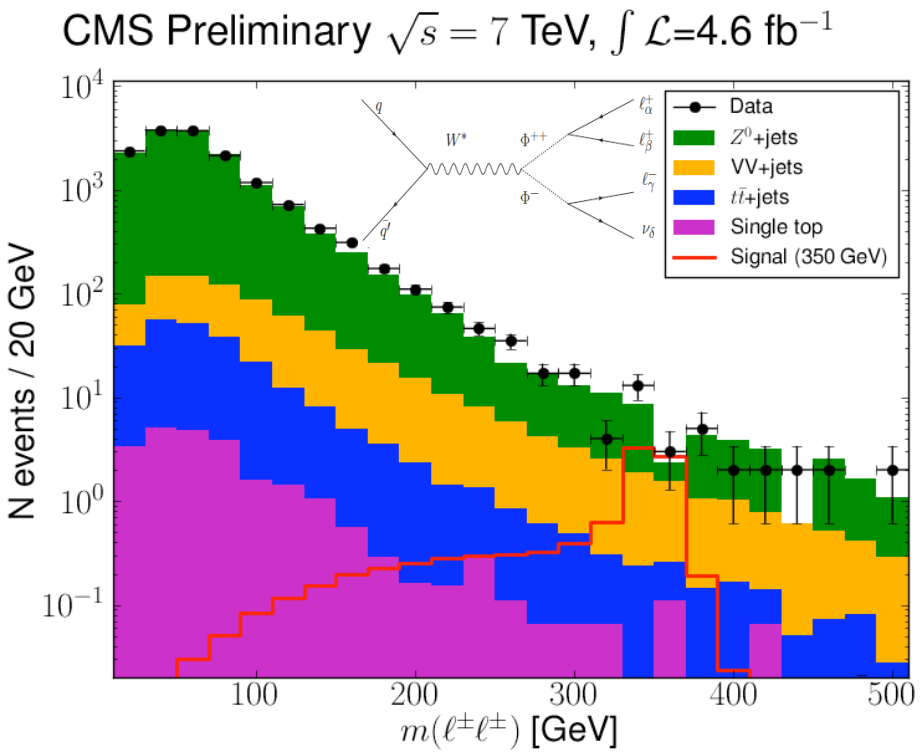


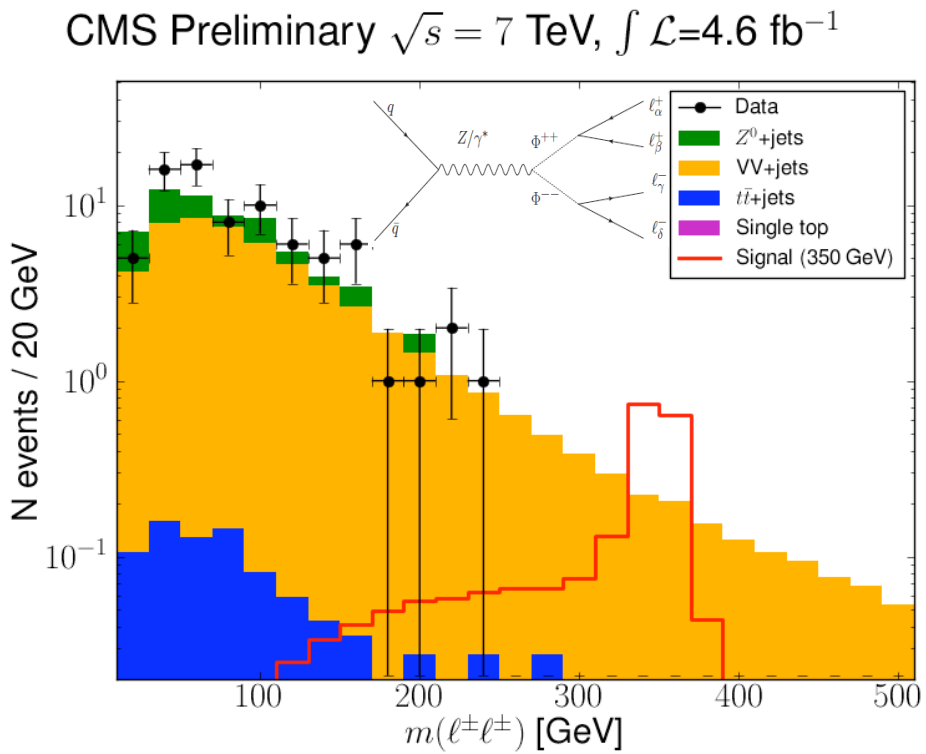
more details in **arXiv:1205.5736**

double charged Higgs

minimal type II seesaw model:
- an additional scalar field, triplet under $SU(2)_L$: Φ^{++}, Φ^{+} and Φ^{0} with $U(1)_Y$ hypercharge Y = 2
- test neutrino mass generation mechanism

selection:
- Σp_T leptons as function of m_Φ
- Z^0 veto
- missing energy in transverse plane
- $\Delta\phi$ for $\ell^{\pm}\ell^{\pm}$
- data driven methods to estimate bkg.: side bands, ABCD (4τ and 3τ final state)





double charged Higgs

- BP1: a massless neutrino, normal mass hierarchies
- BP2: a massless neutrino, inverted mass hierarchies
- BP3: degenerate neutrino mass spectrum (0.2 eV)
- BP4: Φ^{++} with equal BR to each lepton generation.

Branching fractions of Φ^{++} for the 4 benchmark points

Benchmark point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

observed limits:

Benchmark point	Combined 95% CL limit [GeV]	95% CL limit for pair production only [GeV]
$\mathcal{B}(\Phi^{++} \to e^+e^+) = 100\%$	444	382
$\mathcal{B}(\Phi^{++} \to e^+\mu^+) = 100\%$	453	391
$\mathcal{B}(\Phi^{++} \to e^+\tau^+) = 100\%$	373	293
$\mathcal{B}(\Phi^{++} \to \mu^+\mu^+) = 100\%$	459	395
$\mathcal{B}(\Phi^{++} \to \mu^+\tau^+) = 100\%$	375	300
$\mathcal{B}(\Phi^{++} \to \tau^+\tau^+) = 100\%$	204	169
BP1	383	333
BP2	408	359
BP3	403	355
BP4	400	353

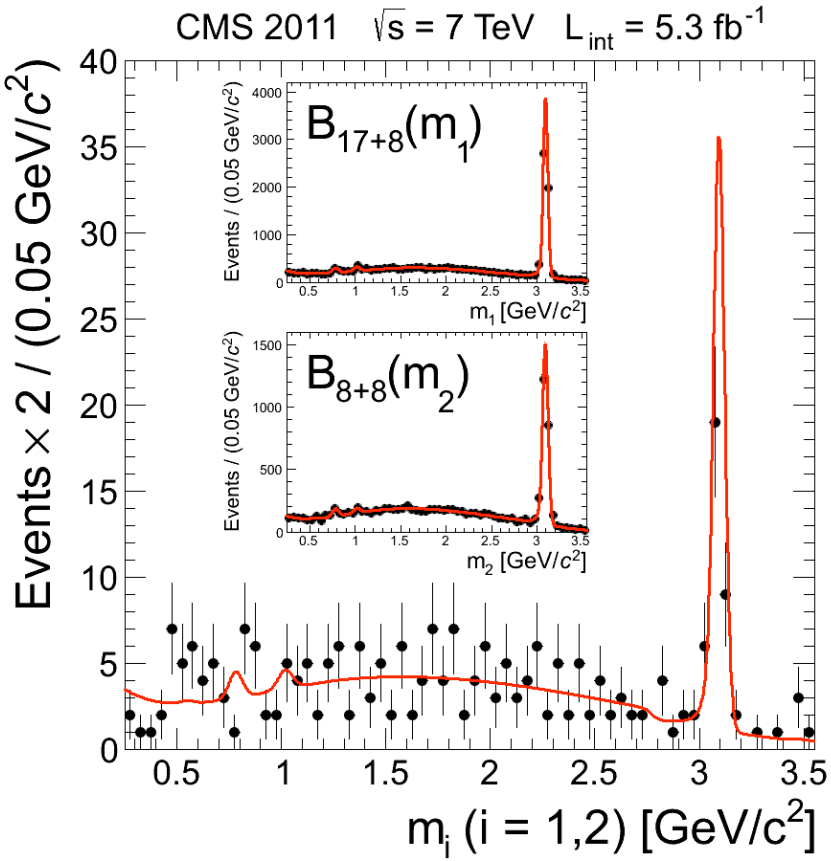
more details in **arXiv:1207.2666**

Next-to-**MSSM** $h_{1,2} \rightarrow a_1 a_1 \rightarrow 4\mu$

- **NMSSM:** Higgs can decay into an intermediate pair of bosons (a_1)
- CP-even Higgs bosons: h_1, h_2 (one is SM-like Higgs boson)
- CP-odd light Higgs boson: $h_{1,2} \rightarrow 2a_1$
- large BR($a_1 \rightarrow 2\mu$) for $2m_\mu < m_{a1} < 2m_\tau$

- background templates: obtained from bb enriched samples (no isolation criteria for muons)
- m_i: dimuon mass
- B_{17+8} for m_1
- B_{8+8} for m_2
- red curve: predicted bkg. shape model

- double muon trigger
- at least 4 isolated μ with $p_T > 8$ GeV and $|\eta| < 2.4$, one of them with $p_T > 17$ GeV and $|\eta| < 0.9$
- data driven background estimation
- more details can be found in **arXiv:1210.7619**



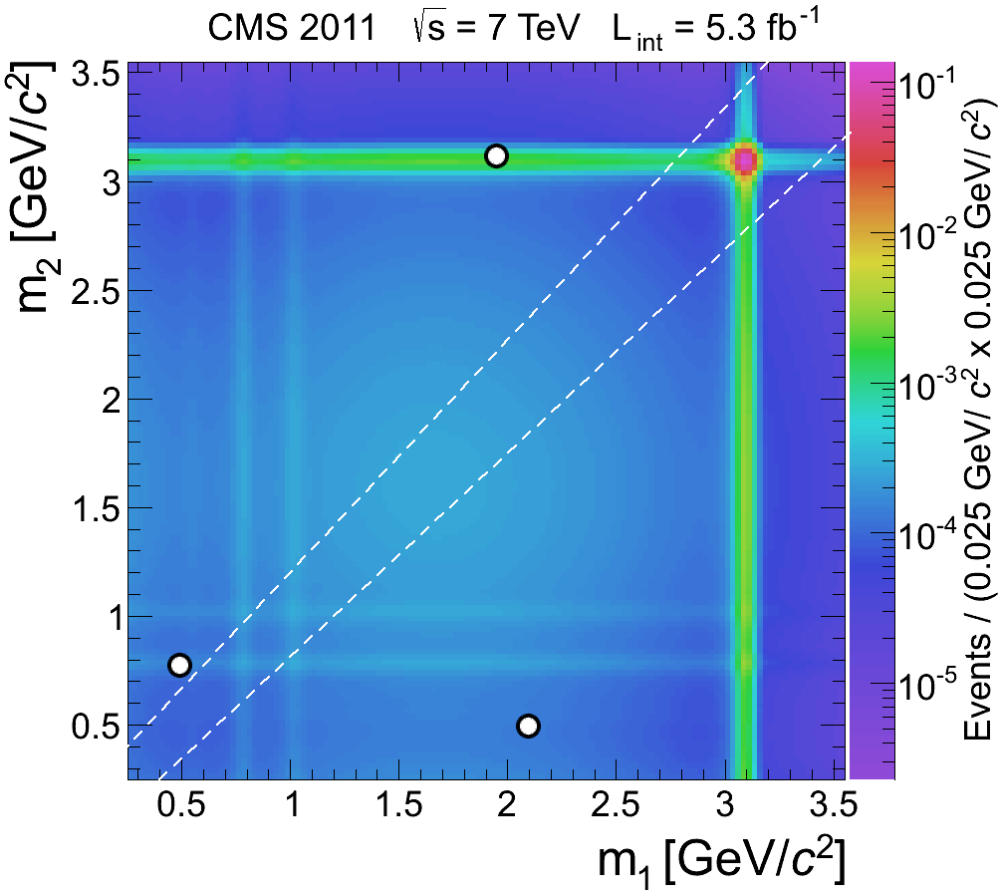
Next-to-**MSSM** $h_{1,2} \rightarrow a_1 a_1 \rightarrow 4\mu$

background expectation:
- sum of bb and direct J/ψ pair production
- including muon isolation
- $m_{1,2} = m_{\mu\mu}$

m_1: a muon with $p_T > 17$ GeV

- **3 events** in the data (empty circles) that all selections except signal requirement:

$m_1 \approx m_2$



interpretations

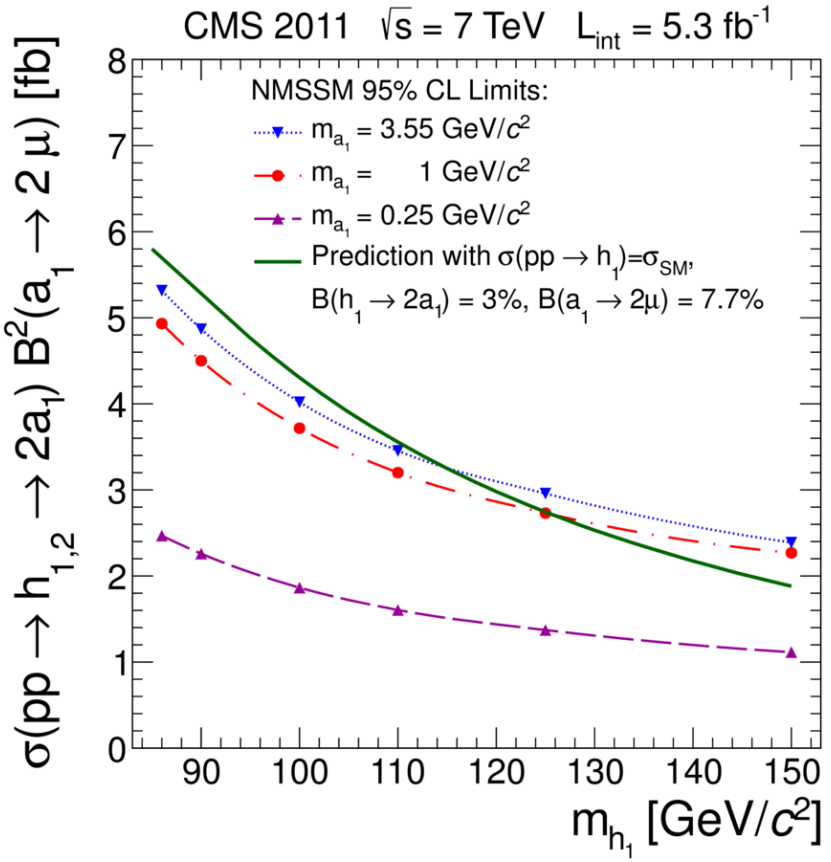
- **NMSSM:**
- CP-odd light Higgs boson: $h_{1,2} \rightarrow 2a_1$
- $2m_\mu < m_{a1} < 2m_\tau$

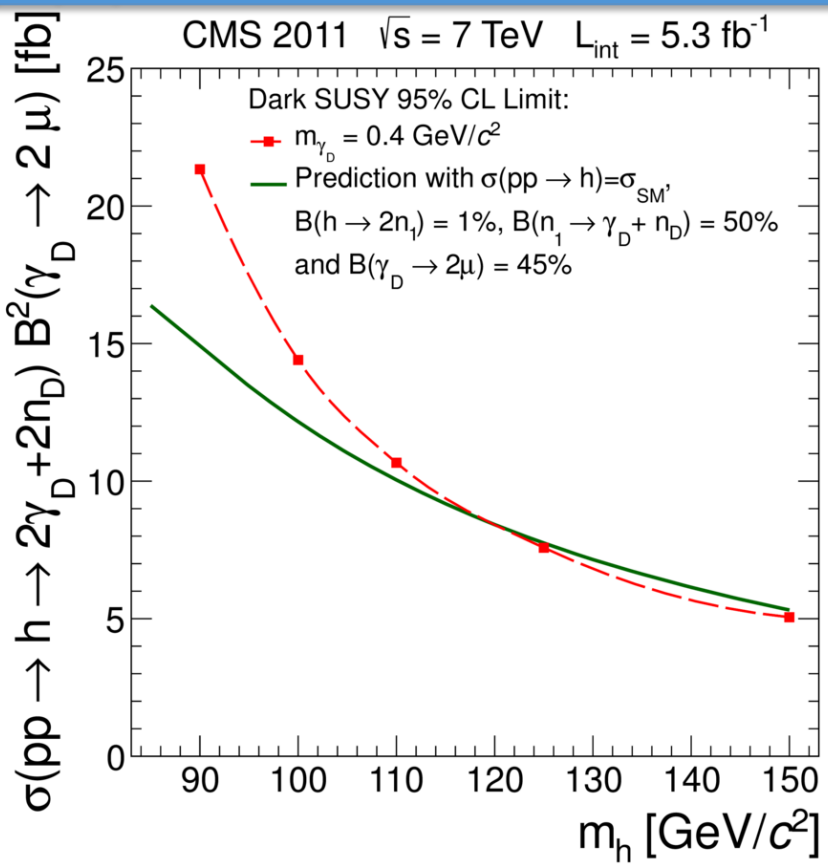
- analysis of 2012 data will be released soon

DARK SUSY:
- lightest neutralino n_1 no longer stable: $n_1 \rightarrow \gamma_D\, n_D$

γ_D – dark photon, n_D – dark fermion

- assumption γ_D decays only in SM particles: $\gamma_D \rightarrow \mu^+\mu^-$ with BR.$\approx$45%

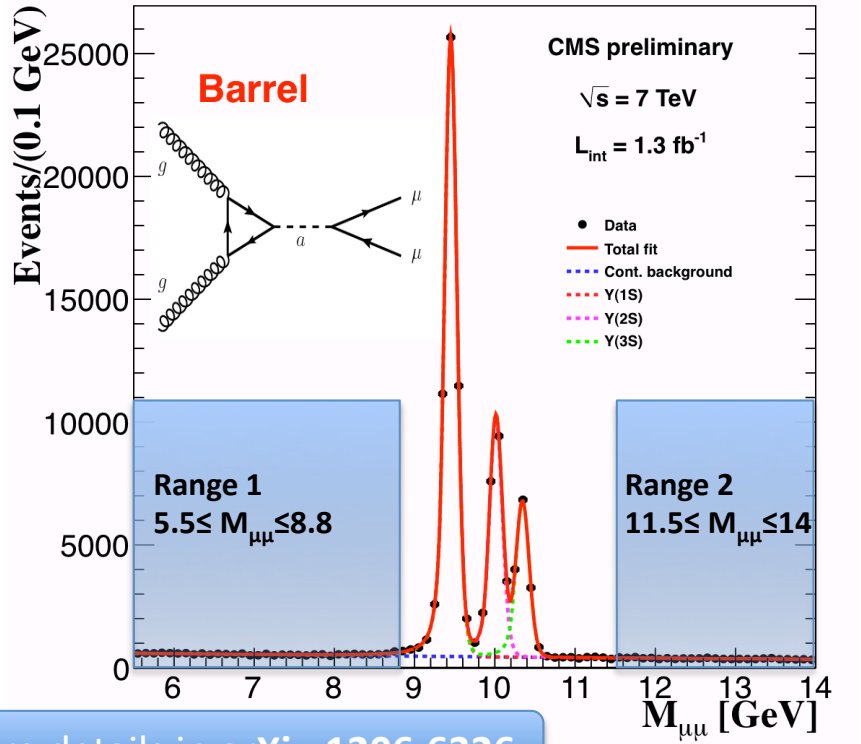




Next-to-MSSM $a_1 \rightarrow \mu^+\mu^-$

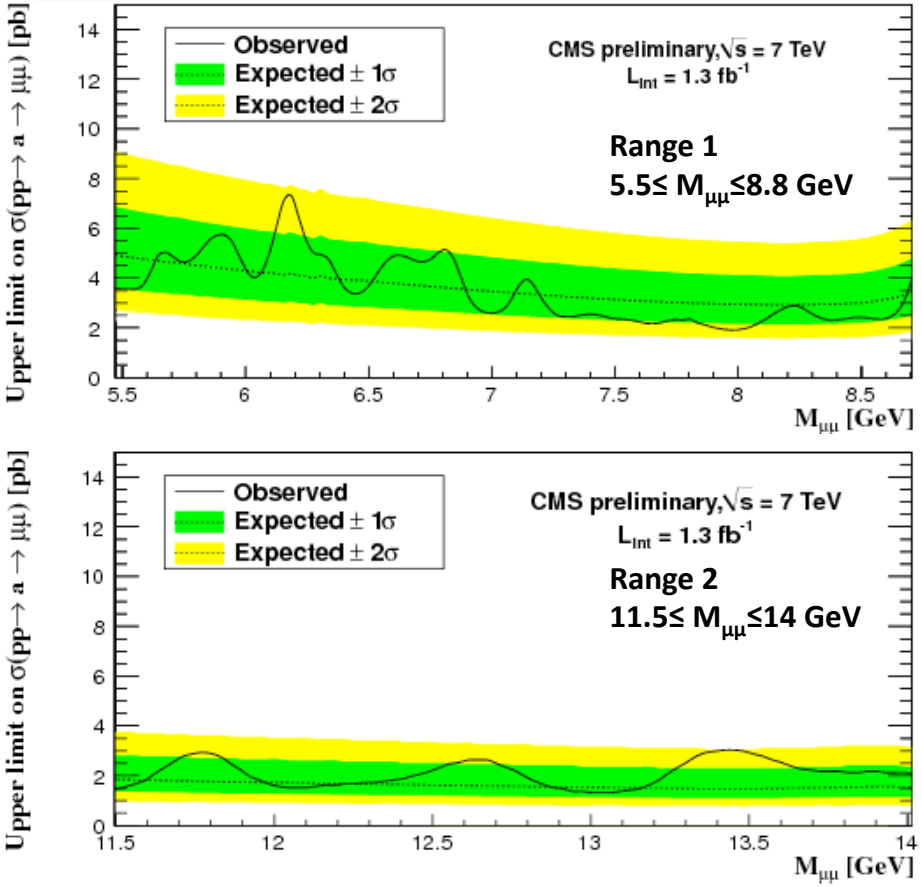
with a_1 is superposition of
- MSSM double pseudoscalar: a_{MSSM}
- additional NMSSM single pseudoscalar: a_S

$a_1 = a_{MSSM} * \cos\theta_A + a_S * \sin\theta_A$
θ_A: mixing angle



more details in **arXiv:1206.6326**

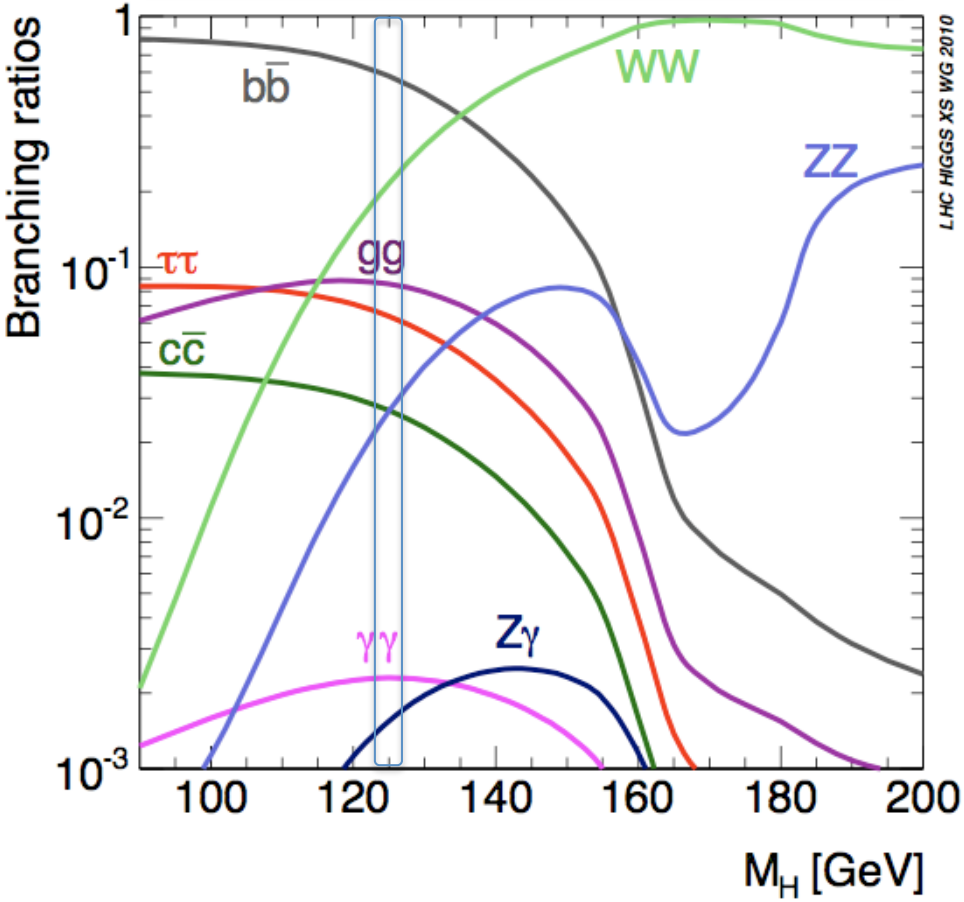
selection:
- dimuon trigger with muons $p_T > 3.5$ GeV, $p_T(\mu\mu) > 6$ GeV and $5.5 \le M_{\mu\mu} \le 14$ GeV
- two isolated and opposite charged muons $p_T > 5.5$ GeV and $|\eta| < 2.4$

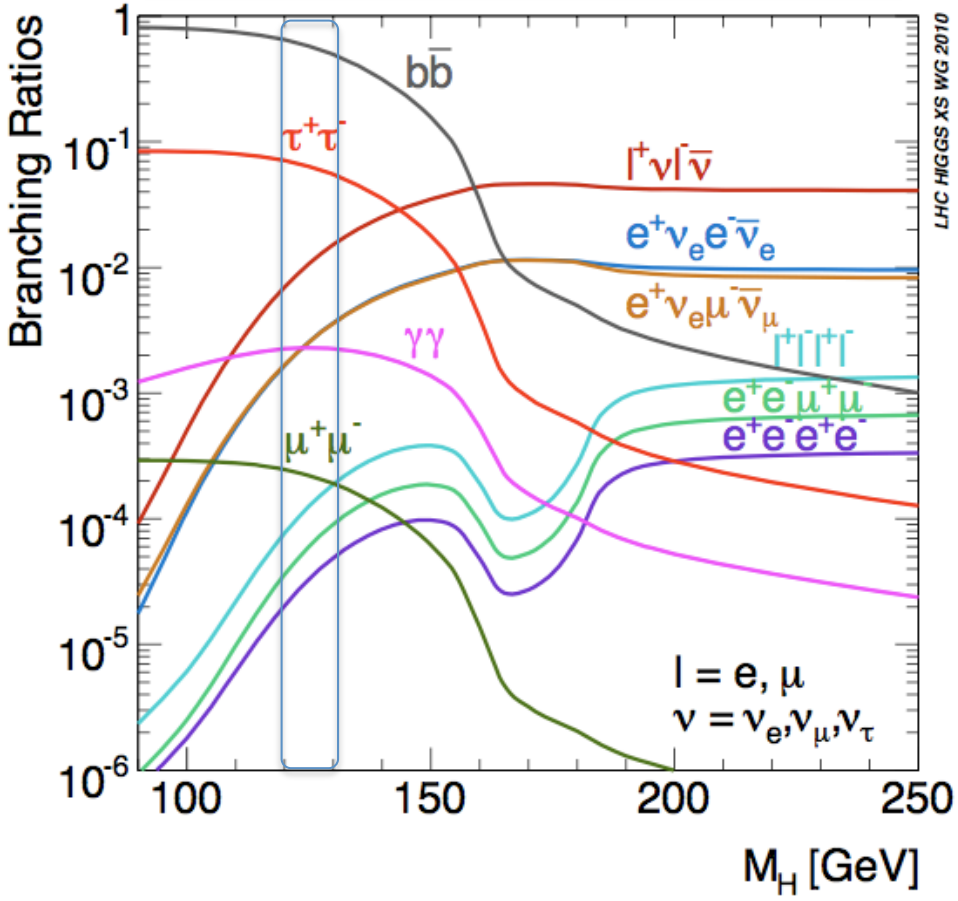


Higgs rare decays:

for m_H = 125.5 GeV everything below
predicted BR(H^0->$\gamma\gamma$):
2.28 ± 0.11 * 10^{-3}

- BR(H^0->$Z^0\gamma$): 1.58± 0.14 * 10^{-3}
- BR(H^0->$\mu^+\mu^-$): 2.17± 0.13 * 10^{-4}
- BR(H^0->e^+e^-): ≈5 * 10^{-9}





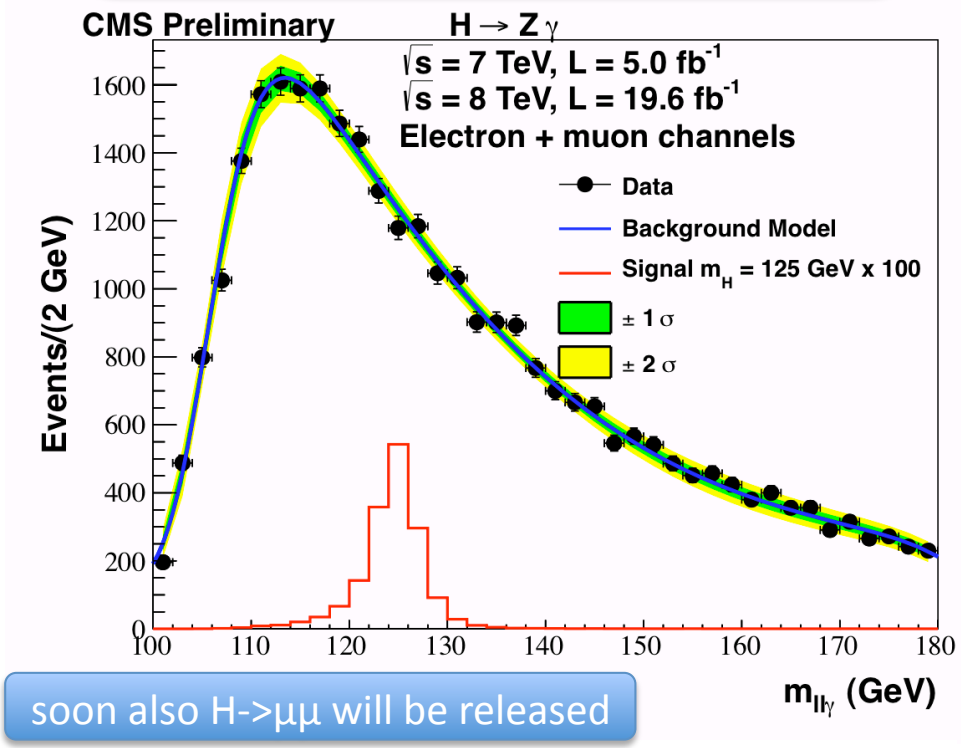
more details at https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR2

Higgs rare decays: $Z^0\gamma$

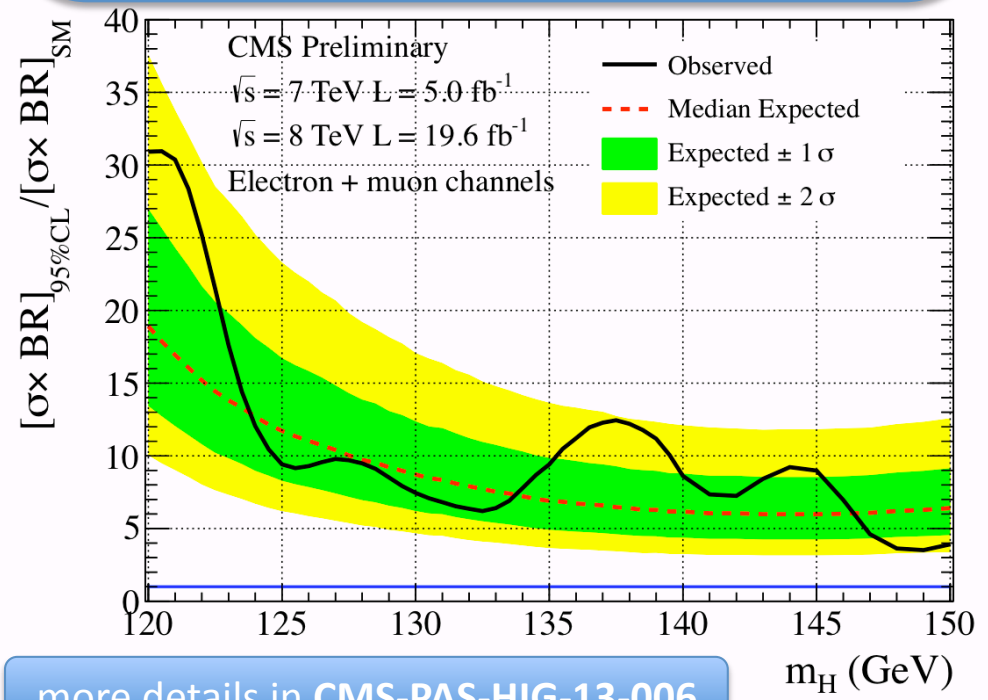
selection:
- dilepton triggers
- two opposite charge, same flavor and isolated leptons with $p_T > 20$ (10) GeV and $|\eta|<2.4$ (2.5) for μ (e)
- isolated photon $p_T > 15$ GeV & $|\eta|<2.5$

event classes:
- both leptons and γ in barrel region:
  - c1: high R_9 (best S/B)
  - c2: low R_9

  with R_9: ΣE of 3x3 ECAL crystals around most energetic one
- c3: one lepton in endcap, γ in barrel region
- c4: both leptons and γ in endcap region



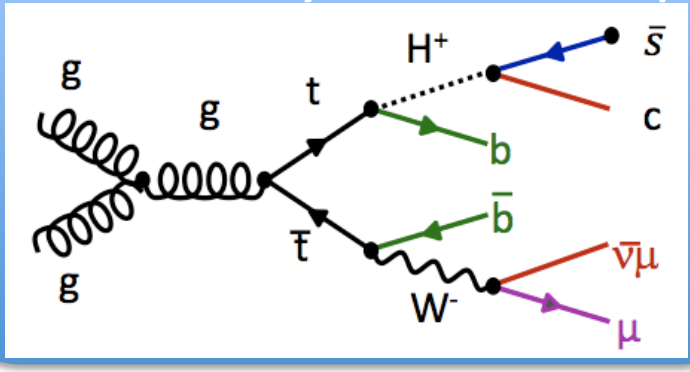
soon also H->μμ will be released



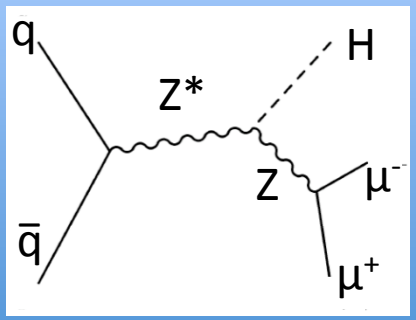
more details in **CMS-PAS-HIG-13-006**

going for more exotic

$H^+ \rightarrow c\bar{s}$:
dominant decay channel for tan β <1



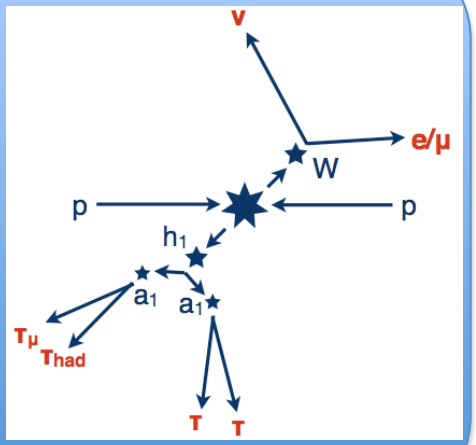
ZH with H inv.



- Higgs decaying to Dark Matter candidates
- MSSM h^0 decaying to LSP
- extra-dimension Higgs decaying to neutrinos

dedicated new group in CMS:
Higgs Exotic
- Radion→hh→γγbb
- h→μτ and h→eτ (LFV)
- heavy H→hh
- VBF with H inv.
- …

NMSSM: $h \rightarrow a_1 a_1 \rightarrow \tau_\mu \tau_h + X$
- τ_h reconstruction to be re-thought due to the boost from a_1
- together with final state topologies as 4τ, 2τ2b and 4γ will complete the NMSSM picture



summary

• **combination of the CMS results presented at Moriond sets the limits at $0 \leq BR_{BSM} \leq 0.64$ at 95% C.L**

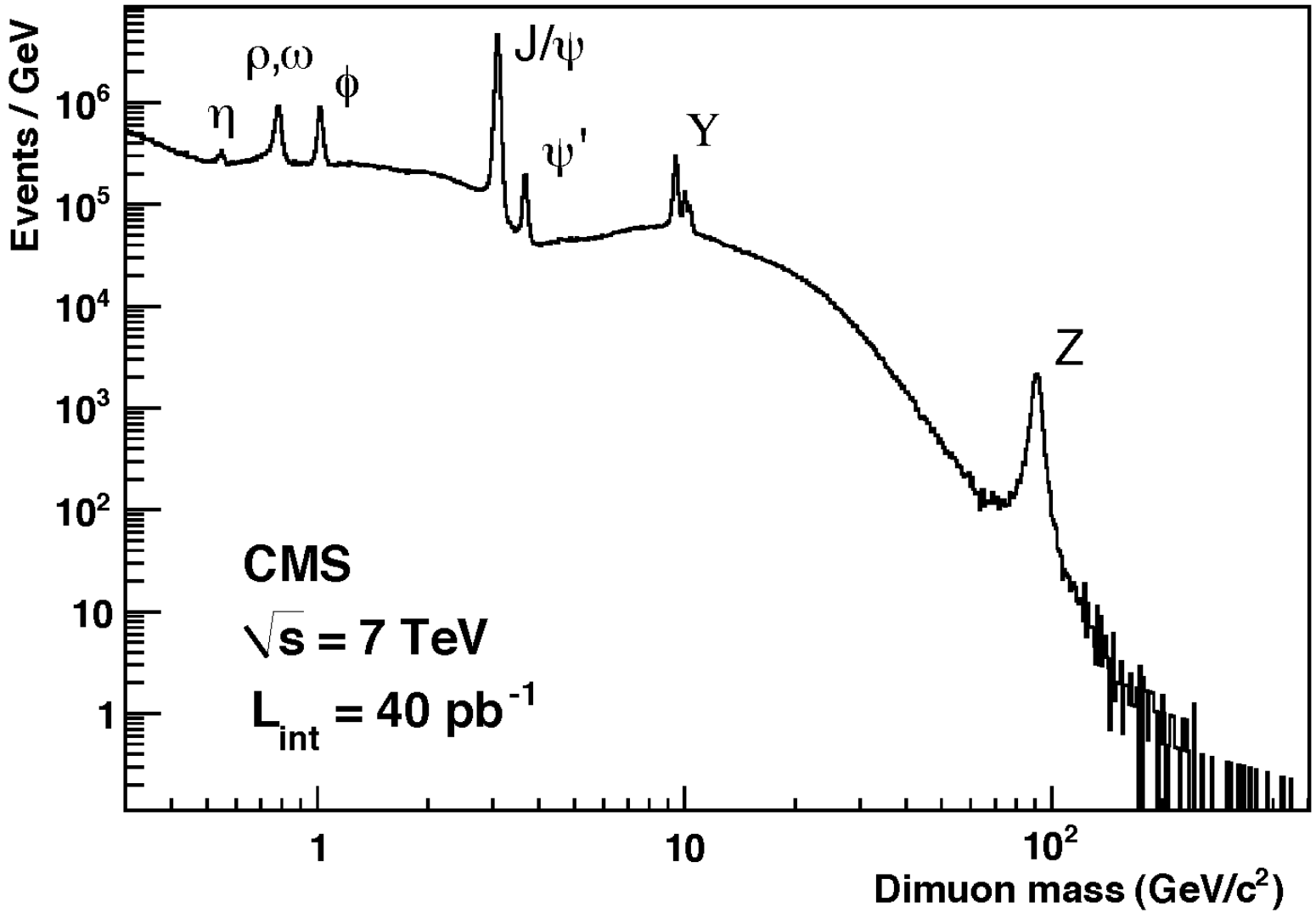
• so far **no signal** was observed in Higgs exotic and rare decays, but:

- in **MSSM: tanβ vs. m_A** allowed plane is getting smaller and smaller
- **MSSM charged Higgs** from t->bH^+, sensitive to tanβ > 2, observed limit within one standard deviation consistent with the expected limits
- **double charged Higgs** search excludes the benchmark points of the type II seesaw model for masses from 383 to 408 GeV
- searches for **additional bosons**, e.g. a_1, directly produced or via SM Higgs decays set upper limits cross-section and branching ratios
- also for **rare decays** as $Z^0\gamma$ we could set only upper limits

• still to come from the new **CMS Higgs Exo group:**
- searches on dimuon channel, H^+->cs (tanβ<1), VBF and Z H(inv.), LFV, …

back-up

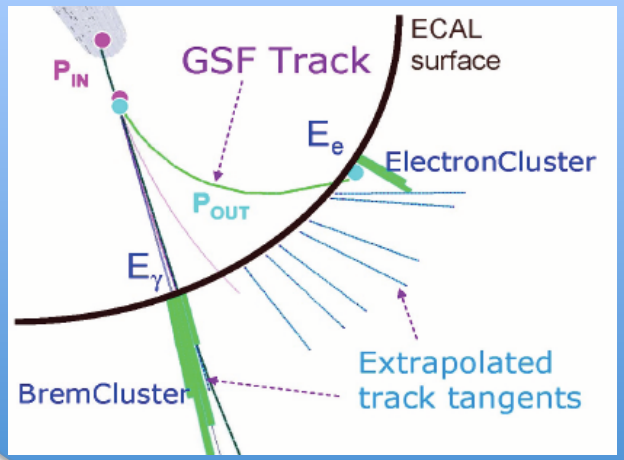
dimuon spectrum



we can reconstruct dimuon resonances from η to Z and beyond…

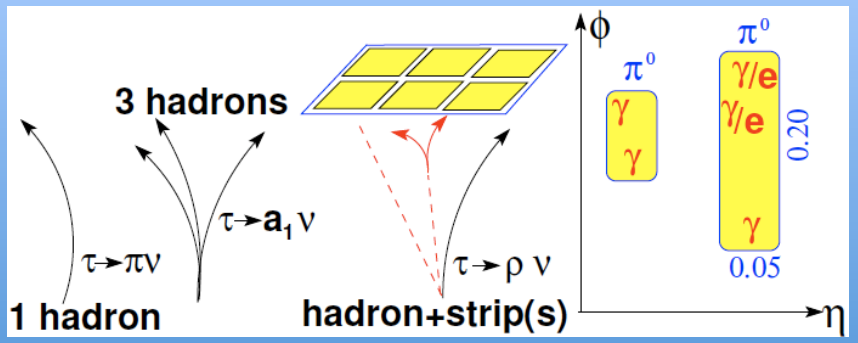
physics objects: e, τ, jets and E_T^{miss}

electron



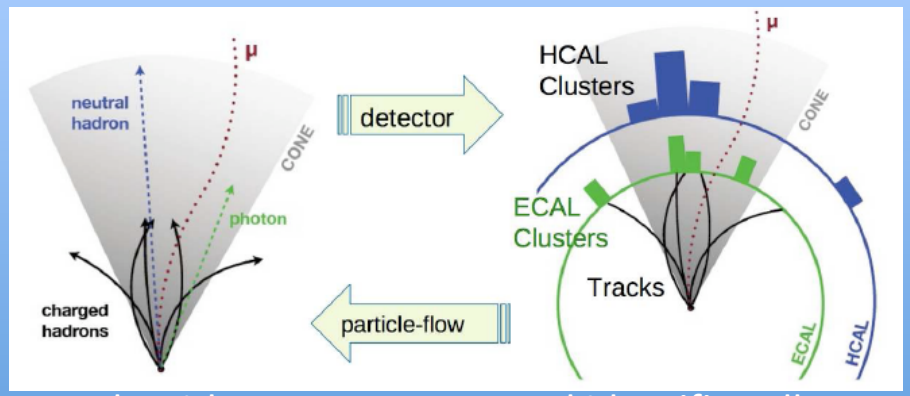
- Gauss Sum Function
- **coverage:** $|\eta| < 1.442$ & $1.556 < |\eta| < 2.5$
- **energy resolution:** $3\%/\sqrt{E\ /\mathrm{GeV}}$

τ lepton: hadronic decays

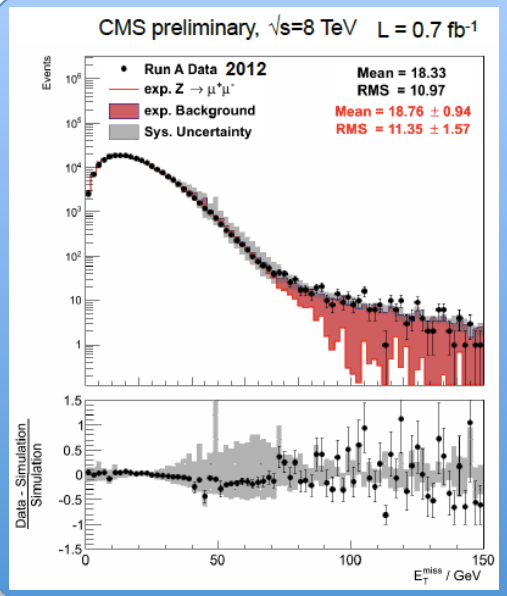


- **coverage:** $|\eta| < 2.3$
- **energy scale:** < 3 %

Particle Flow Jets in CMS:



- PF algorithm reconstructs and identifies all stable particles within the detector
- builds jets with the *anti*-k_T alg. which are infrared & collinear safe



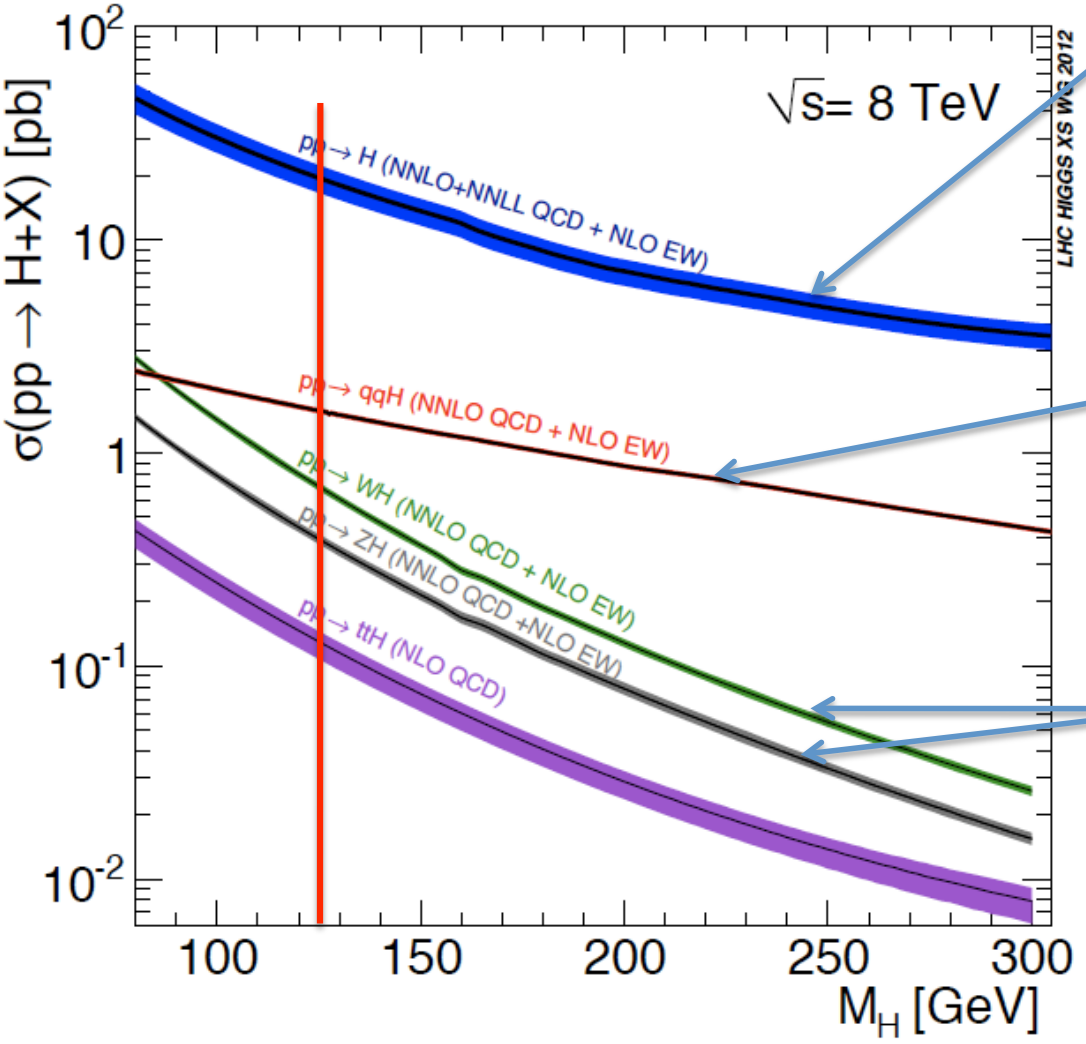
Missing Energy in Transverse plane

E_T^{miss}

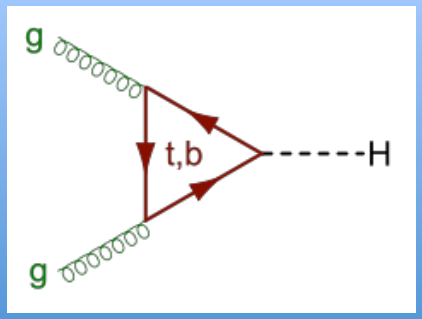
- **in CMS:** negative vector sum of all particle candidates reconstructed with the PF algorithm

SM production channels

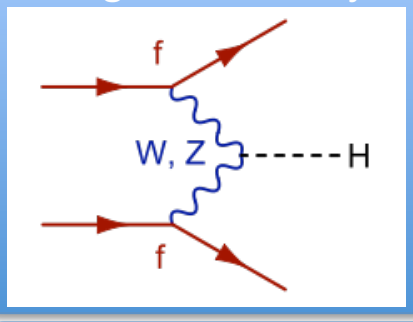
• cross-section expectations for $\sqrt{s}$ = 8 TeV



• gluon-gluon fusion



• VBF production
(2 energetic forward jets)



• associated production
(additional W or Z boson)