Bundesministerium
für Bildung
und Forschung

RWTH RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Search for Higgs and other bosons in beyond standard model physics with CMS

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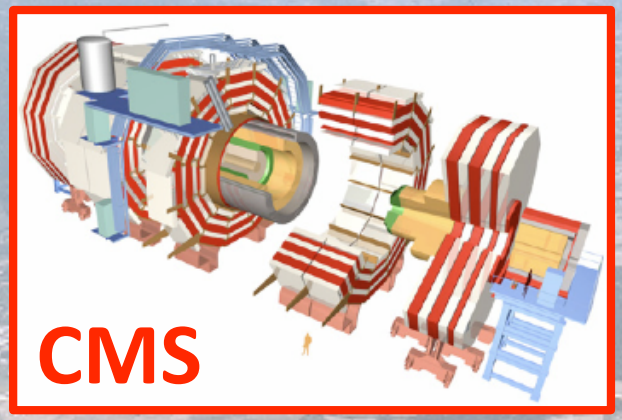
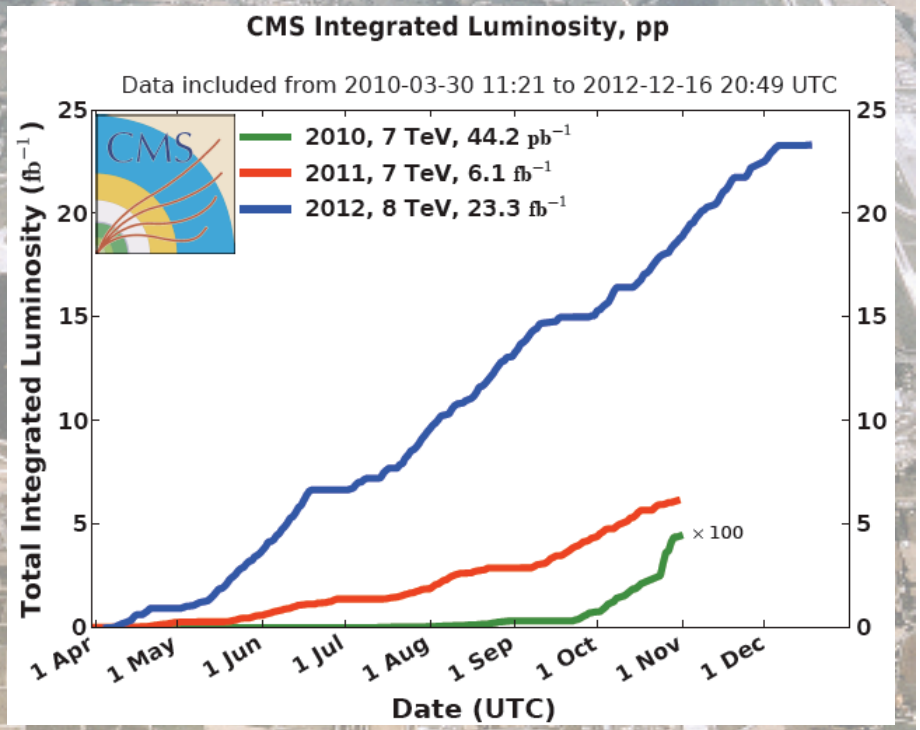


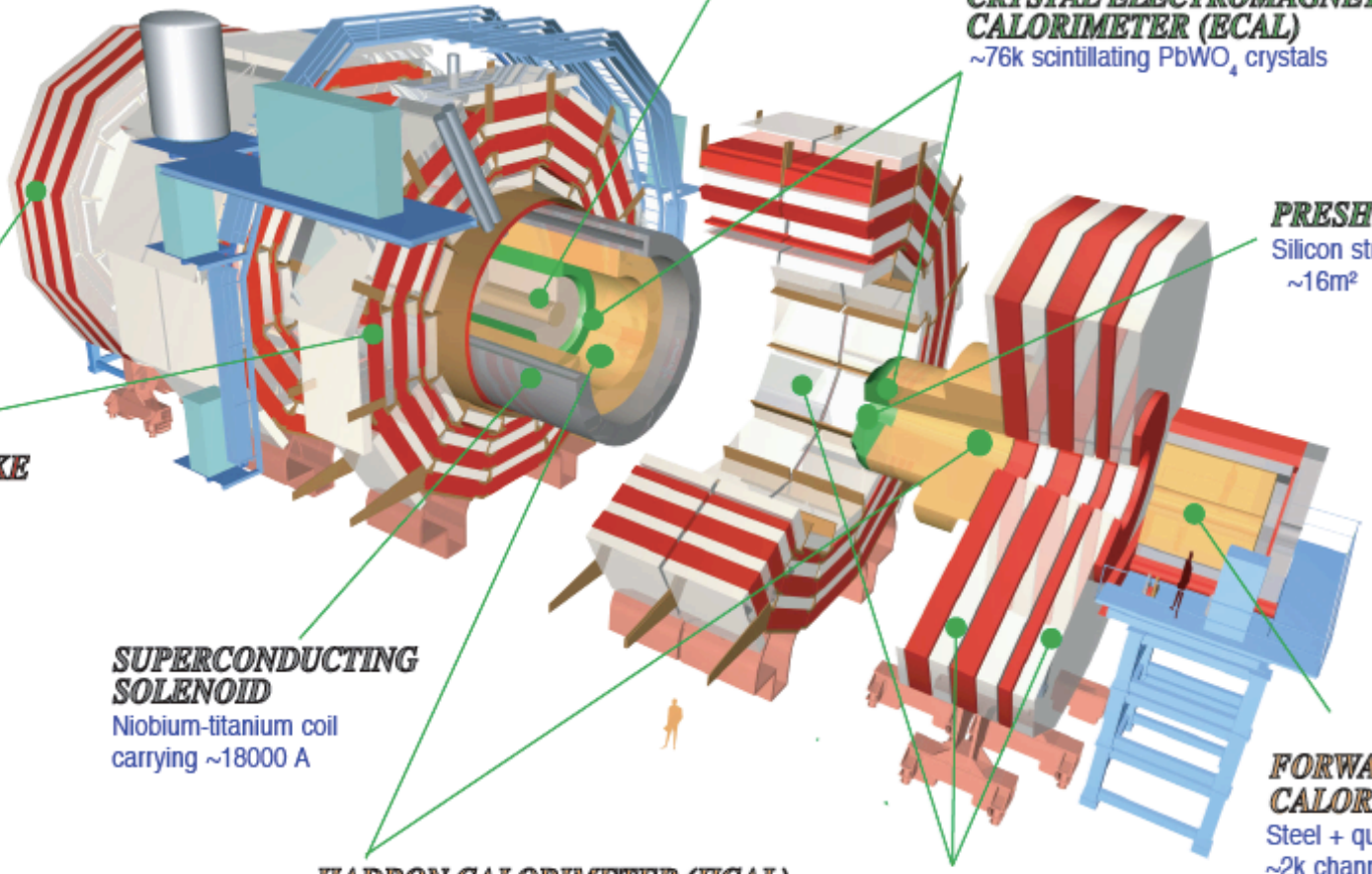
Outline:

- CMS detector
- Rare Higgs decays
- Beyond Standard Model
- Exotic bosons
- Higgs exotic decays



CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

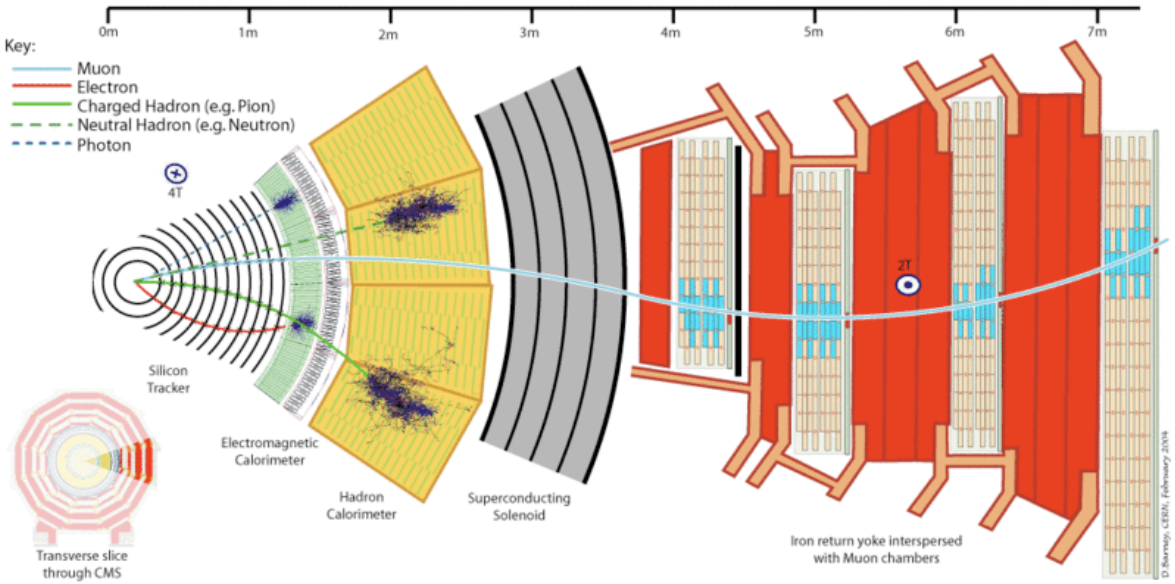
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

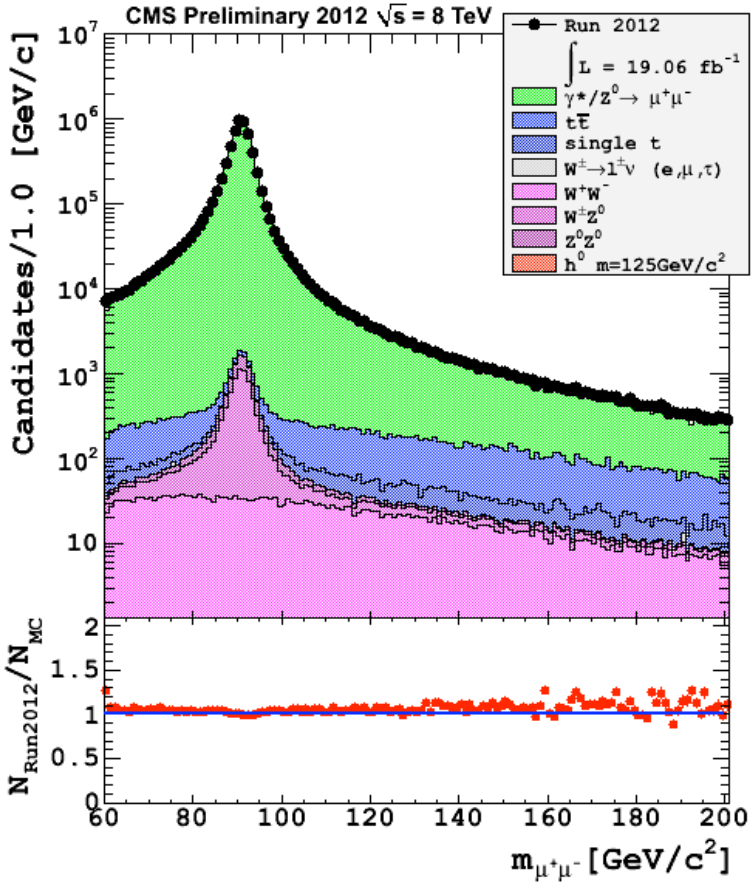
Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

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





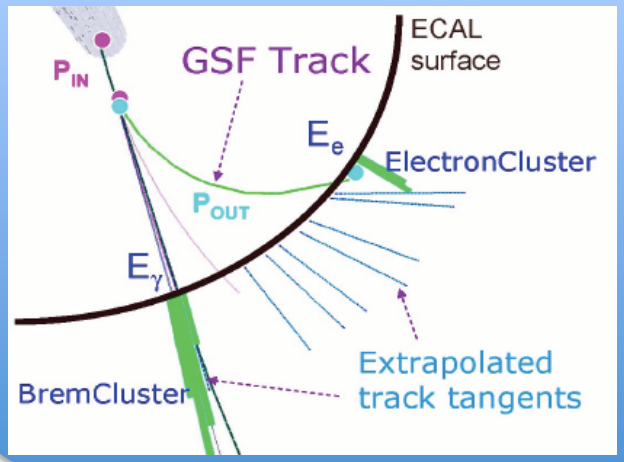
- **coverage:** $|\eta| < 2.4$, $\eta = -\ln[\theta/2]$
- **momentum resolution**:

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

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

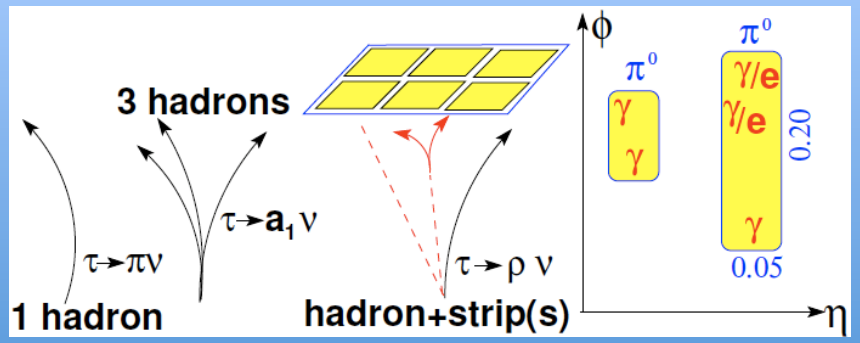
physics objects: e, τ, jets and E_T^{miss}

electron



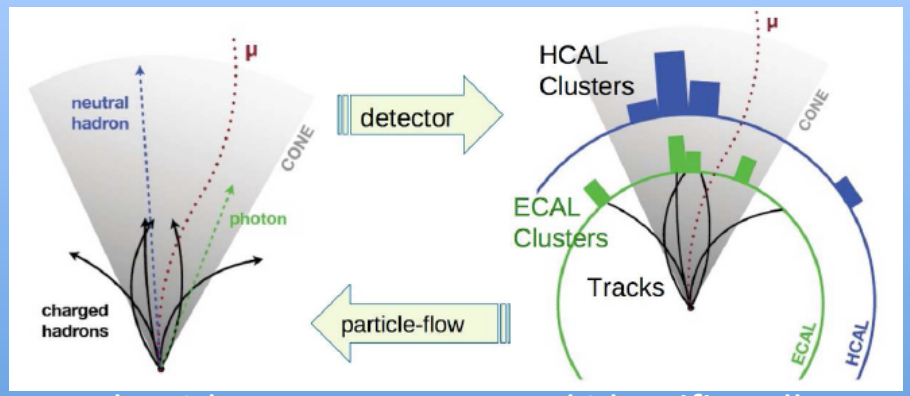
- Gauss Sum Function
- **coverage:** $|\eta| < 1.442$ & $1.556 < |\eta| < 2.5$
- **energy resolution:** $3\%/\sqrt{E\ /\mathrm{GeV}}$

τ lepton: hadronic decays

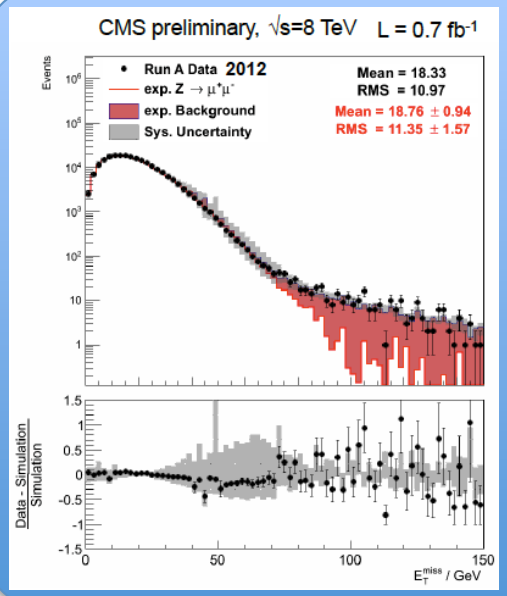


- **coverage:** $|\eta| < 2.3$
- **energy scale:** < 3 %

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

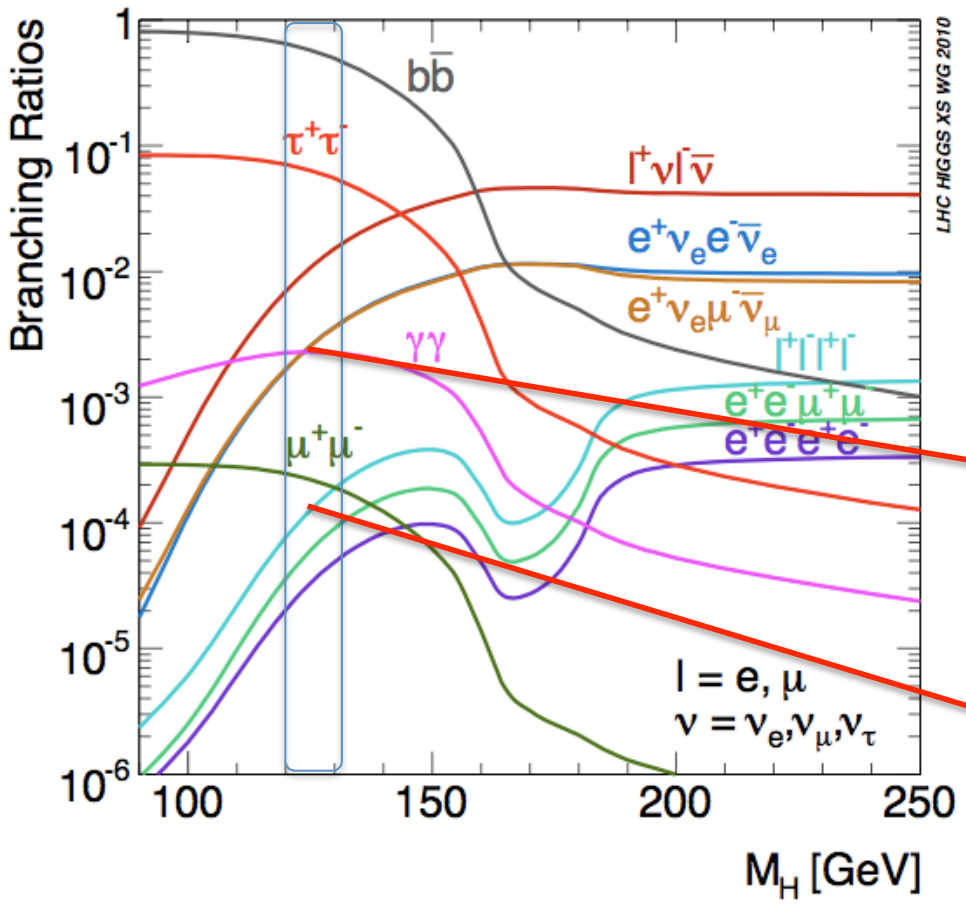
E_T^{miss}

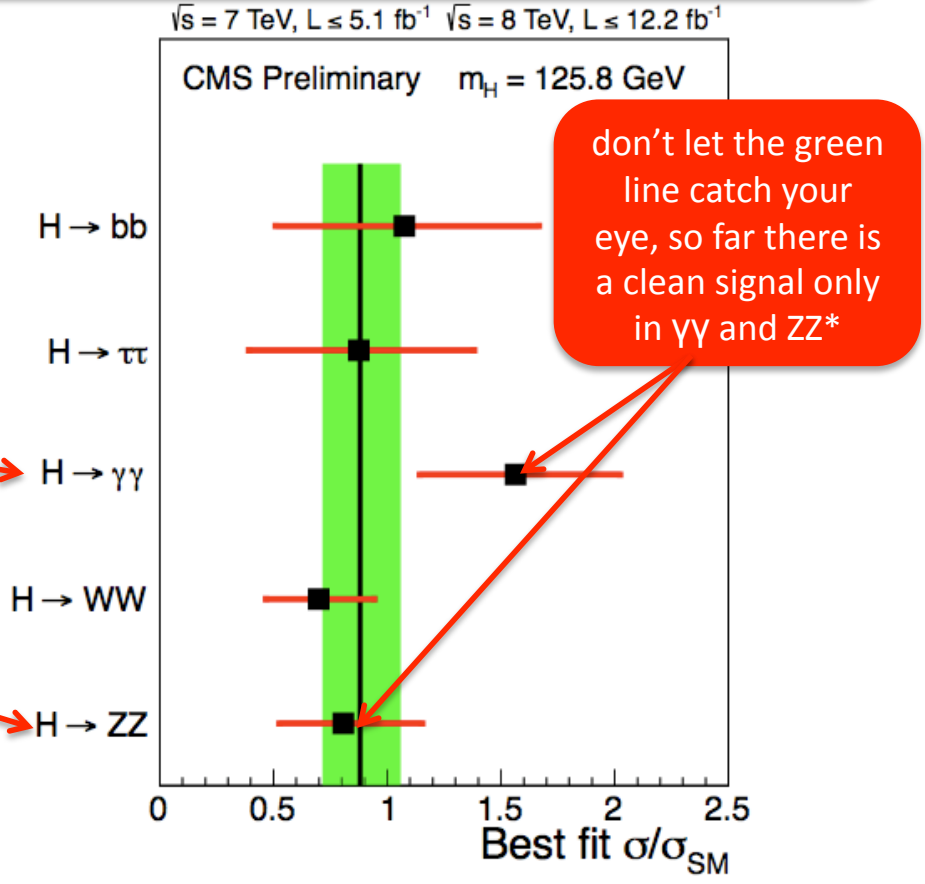
- **in CMS:** negative vector sum of all particle candidates reconstructed with the PF algorithm

Higgs boson in Standard Model

until July 4th in 2013 we were thinking (had on our tee/coffee cups):

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c. + \Psi_i y_{ij}\Psi_j\Phi + h.c. + \left|D_\mu\Phi\right|^2 - V(\Phi)$$



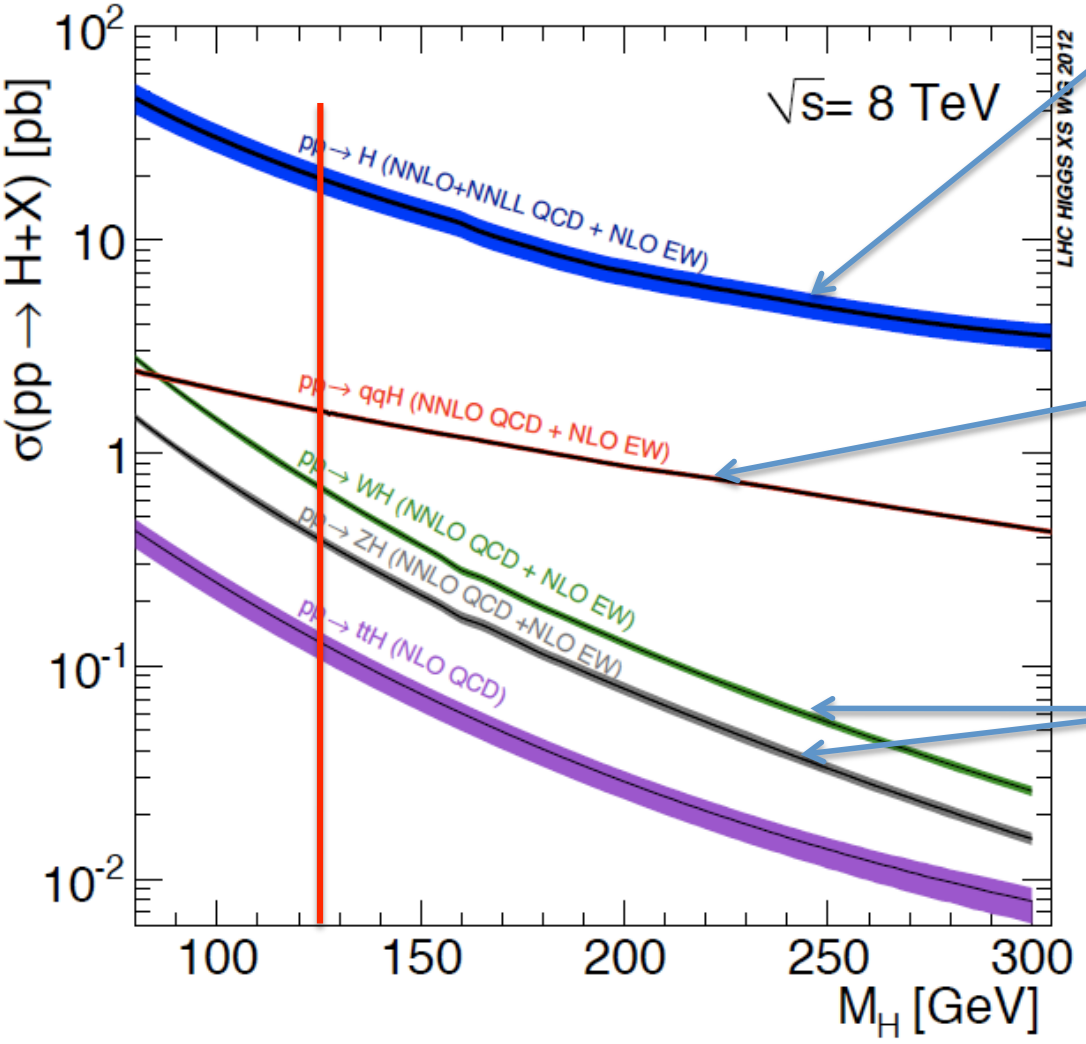


don't let the green line catch your eye, so far there is a clean signal only in γγ and ZZ*

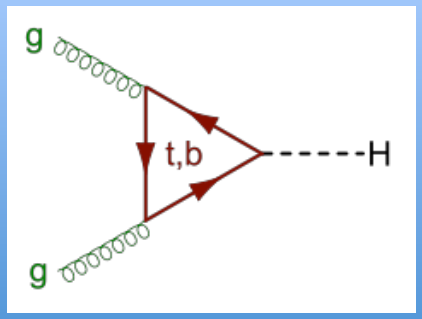
- now we know it and soon we might want to change it…

SM production channels

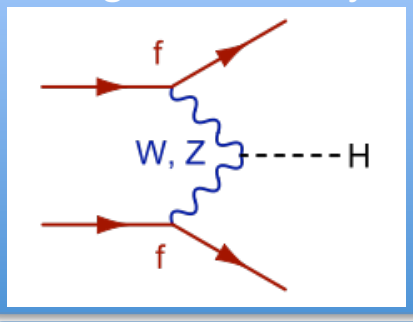
• cross-section expectations for $\sqrt{s}$ = 8 TeV



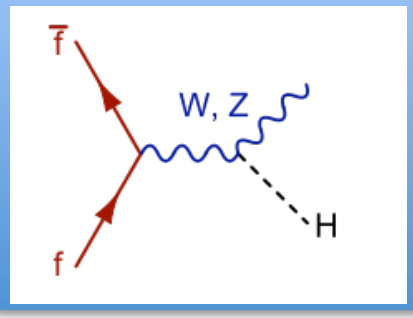
• gluon-gluon fusion



• VBF production
(2 energetic forward jets)

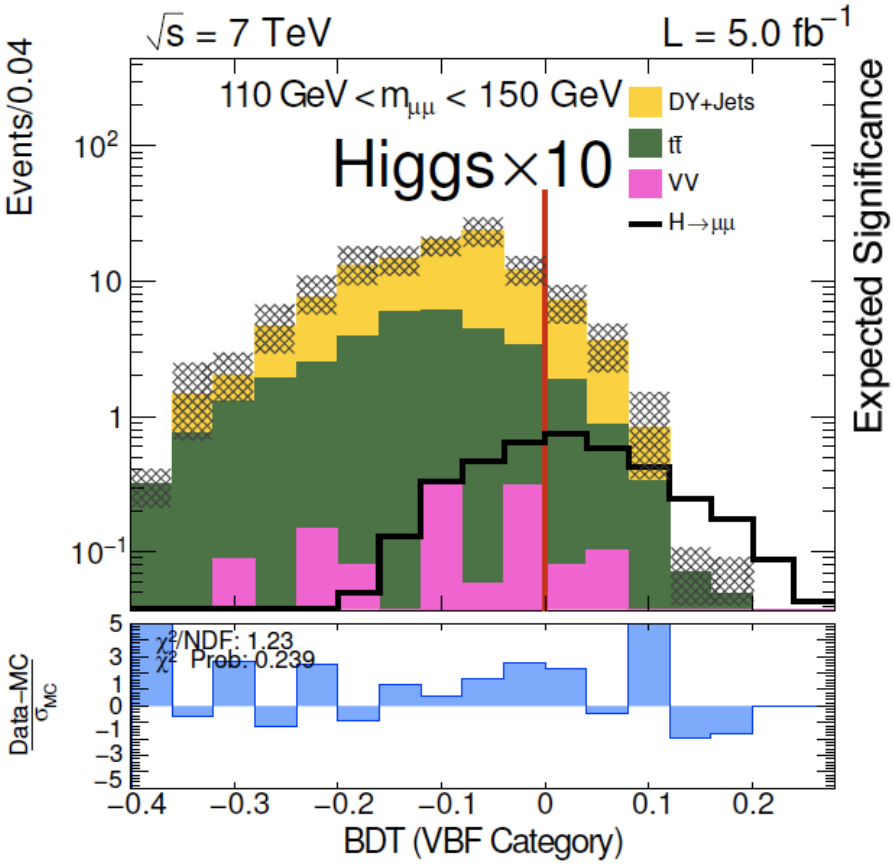


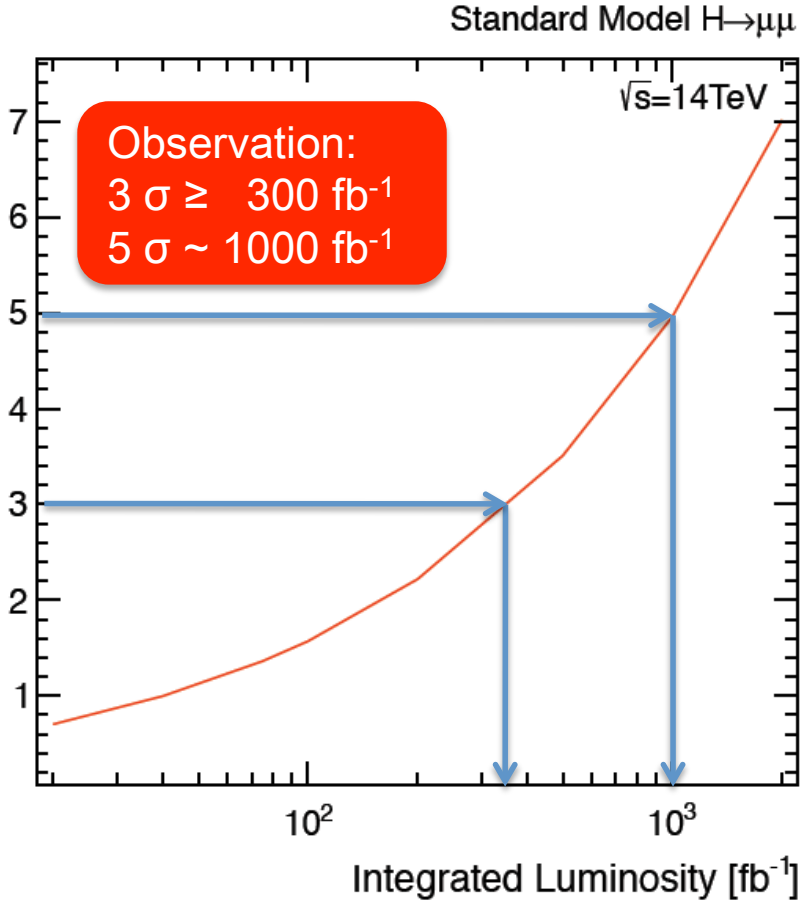
• associated production
(additional W or Z boson)



how SM becomes exotic

- the μμ decay channel has the BR between γγ and 4l (ZZ*) channel, but
- main difference is given by the Drell-Yan process contribution (dominant bkg.)
- seeing something in the dimuon channel with < 200 fb^{-1} is more than "exotic"
- same applies to the associated production channels



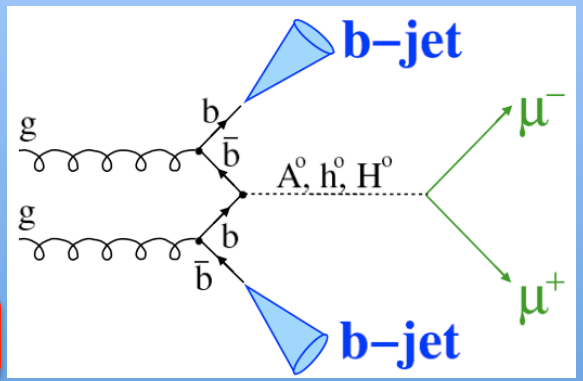


Minimal Supersymmetric SM

MSSM: Φ^0 (h^0, H^0, A^0), $H^\pm$

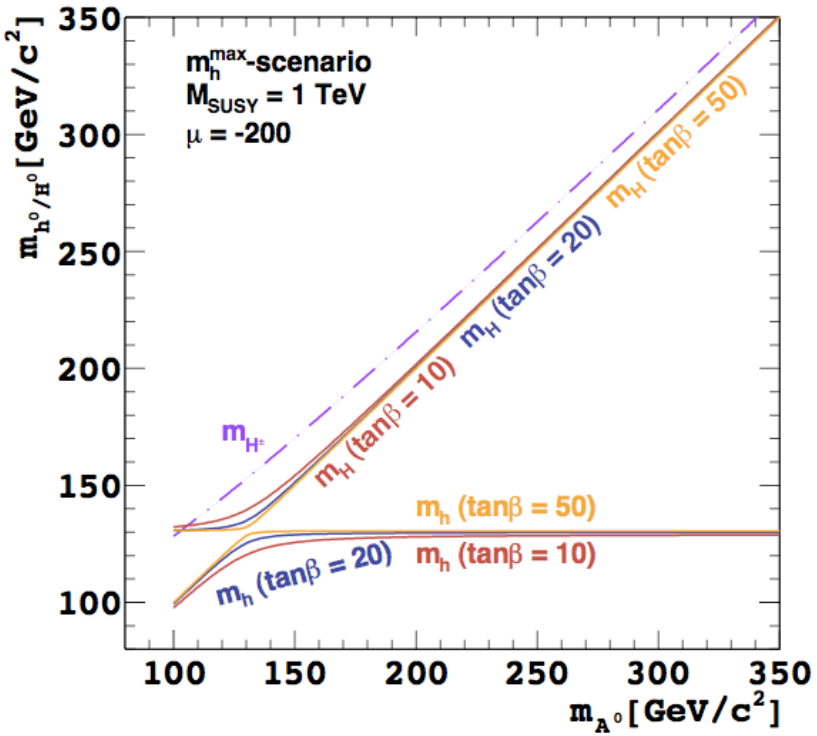
- Higgs sector can be described by: tanβ and m_A
- $\tan\beta = v_1/v_2$ where v_1 and v_2 – vacuum expectation values
- A^0 (CP odd): m_A
- h^0, H^0 (CP even): $m_{H,h}=\{1/2\{m_A^2+m_Z^2 \pm [(m_A^2+m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta\,]^{1/2}\}\}^{1/2}$
- $H^\pm$: $m_H=(m_A^2+m_W^2)^{1/2}$

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



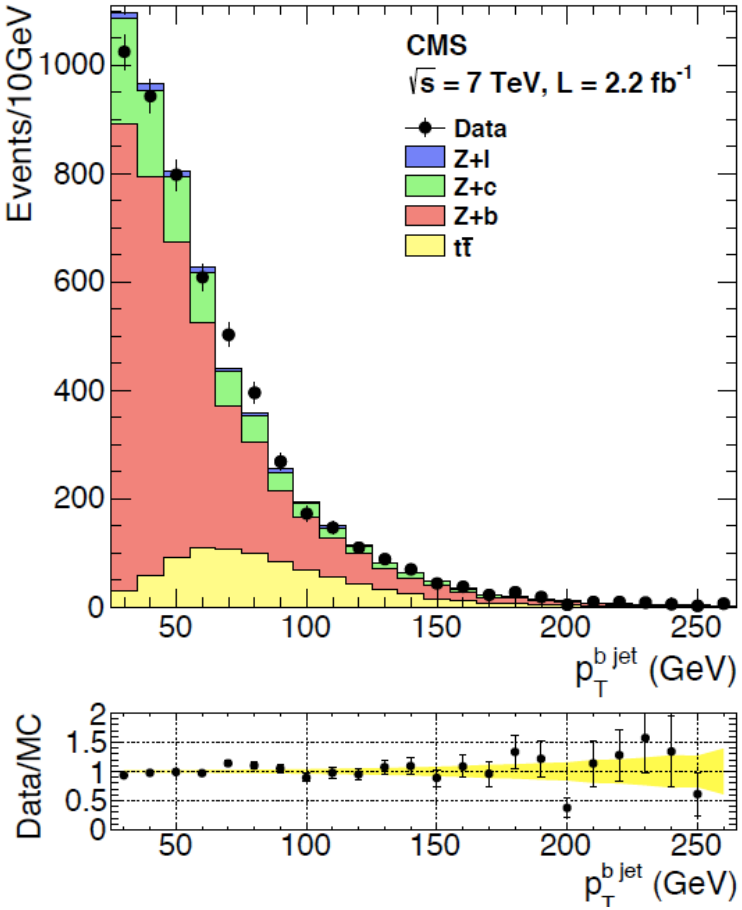
first thing to measure:

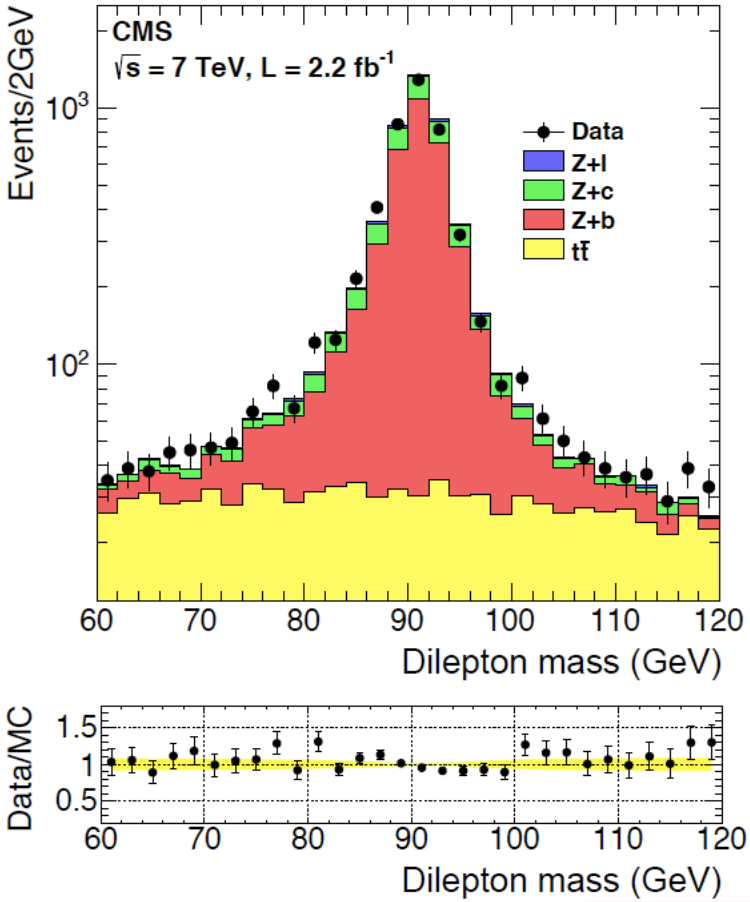
- two isolated μ with high p_T
- at least a b-jet with relatively low p_T
- low missing transverse energy E_T^{miss}
- irreducible background: bb γ*/Z



Z + b-jets

- same event topology as for $bb\Phi^0$, published in J. High Energy Phys. 06 (2012) 126





cross section:

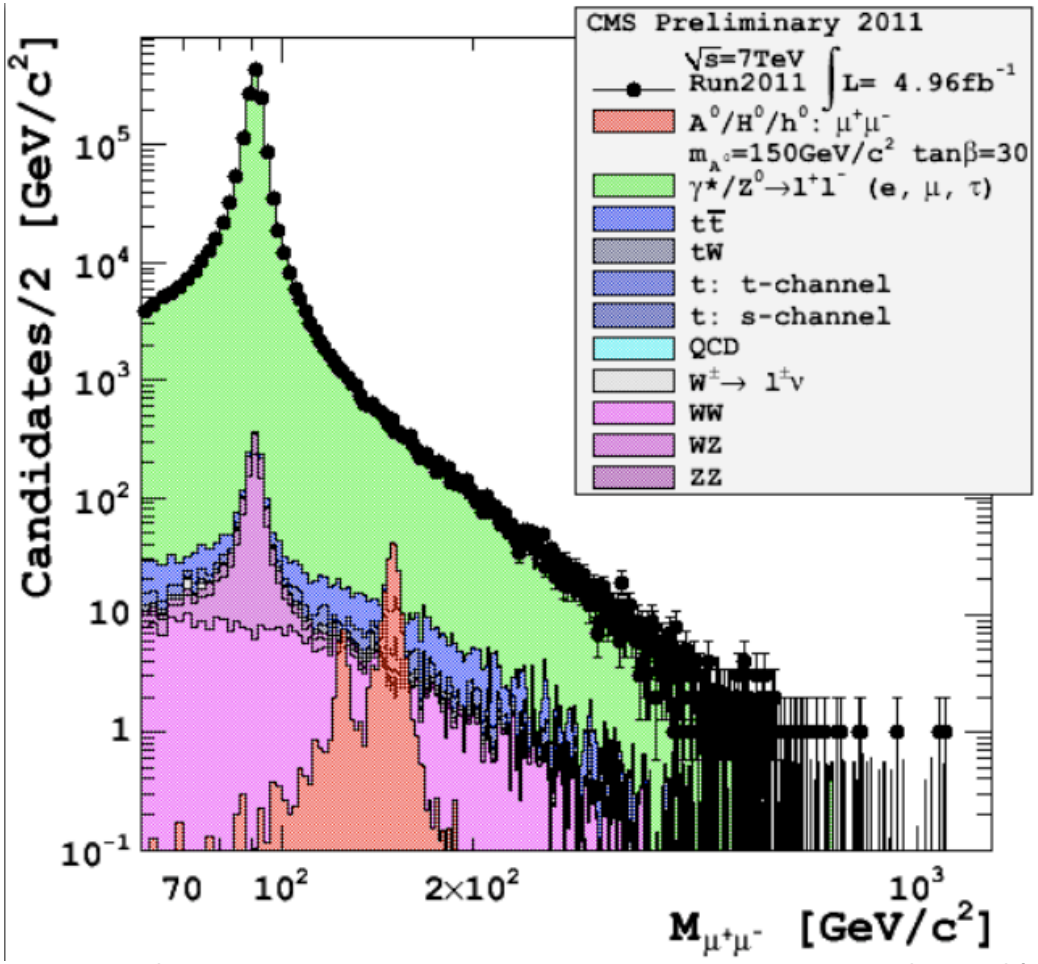
- measured 5.84 ± 0.08 (stat.) ± 0.72 (syst.) $^{+0.25}_{-0.55}$ (theory) pb
- theory (NLO) 4.73 ± 0.54 pb

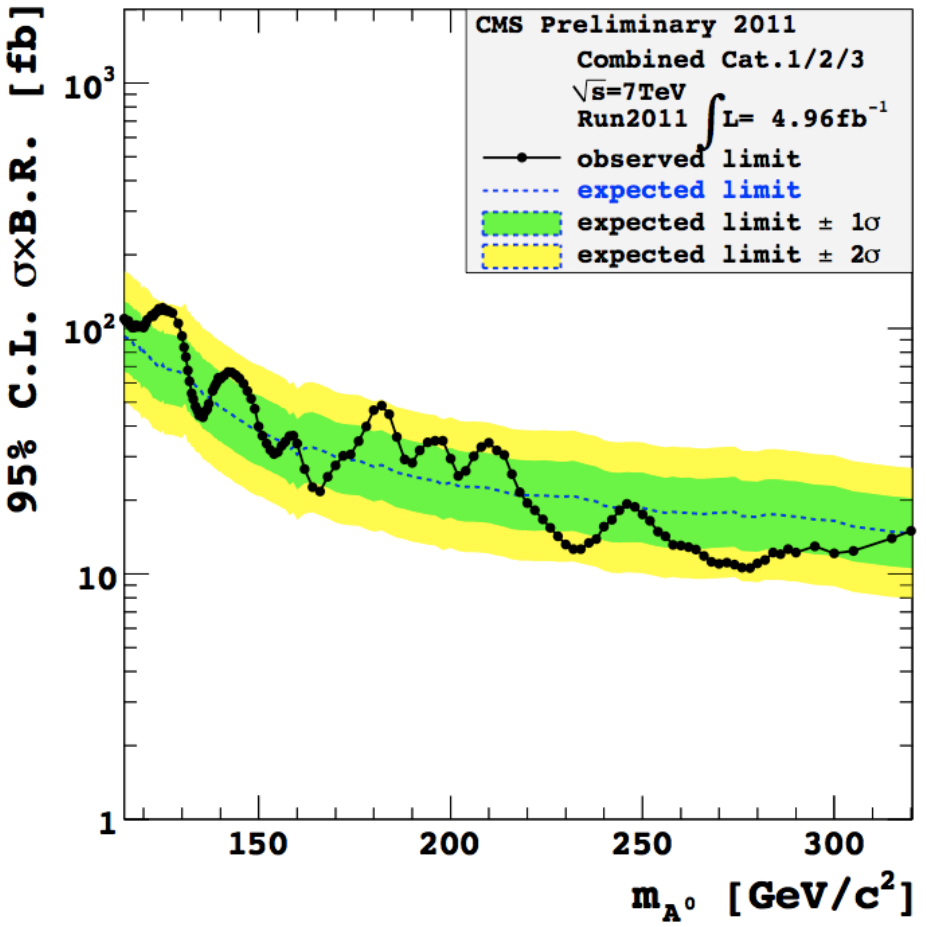
no surprise here

back to MSSM

I would go to see it

MSSM analysis of $\sqrt{s}$ = 7 TeV
- made public during last summer **CMS PAS HIG-12-011**
- analysis of $\sqrt{s}$ = 8 TeV and more highlights are shown in Hendrik Weber's talk



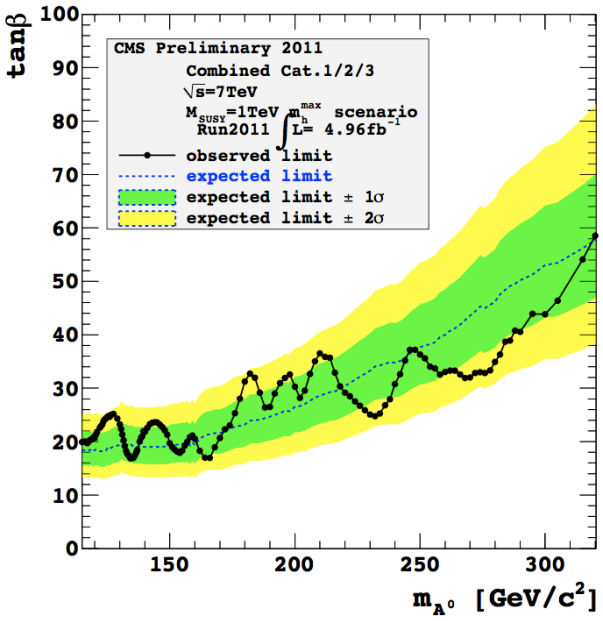


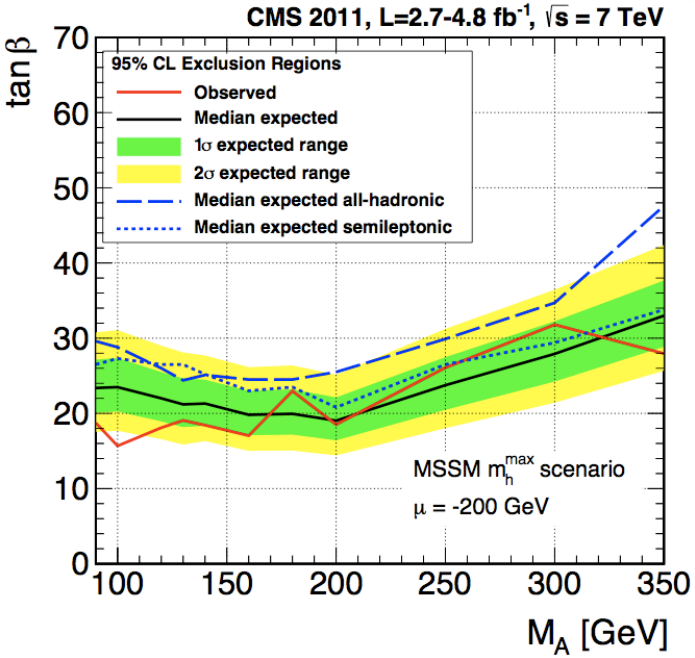
MSSM

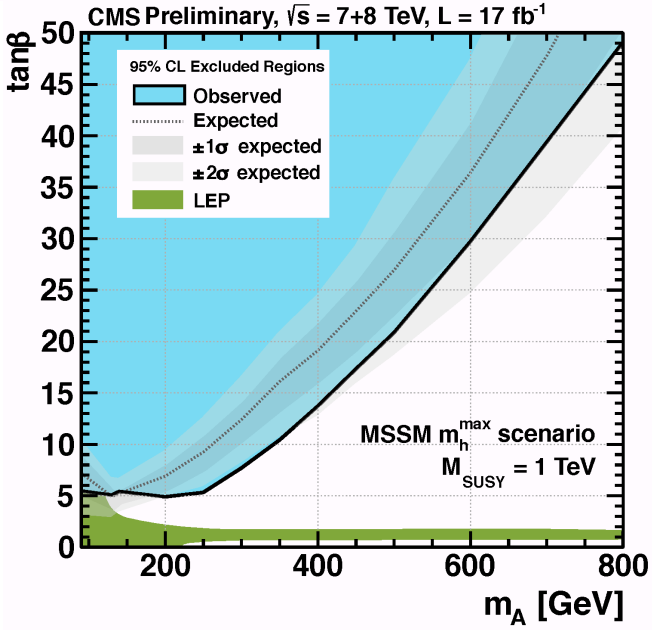
channel: μμ
- even with a BR of ≈10^{-4} good sensitivity is achieved
- best channel for a precise measurement of tanβ

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**

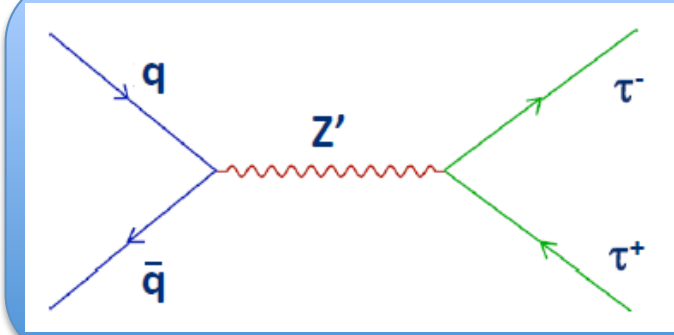






- there is an ongoing effort in CMS to combine all analyses and complete the analysis of the √s = 8 TeV data (plan to be ready by summer)

exotic bosons: Z'(ττ)



Sequential SM (SSM):
- neutral boson Z'_{SSM}

Superstring-inspired E_6 model:
- neutral boson Z'_{ψ}

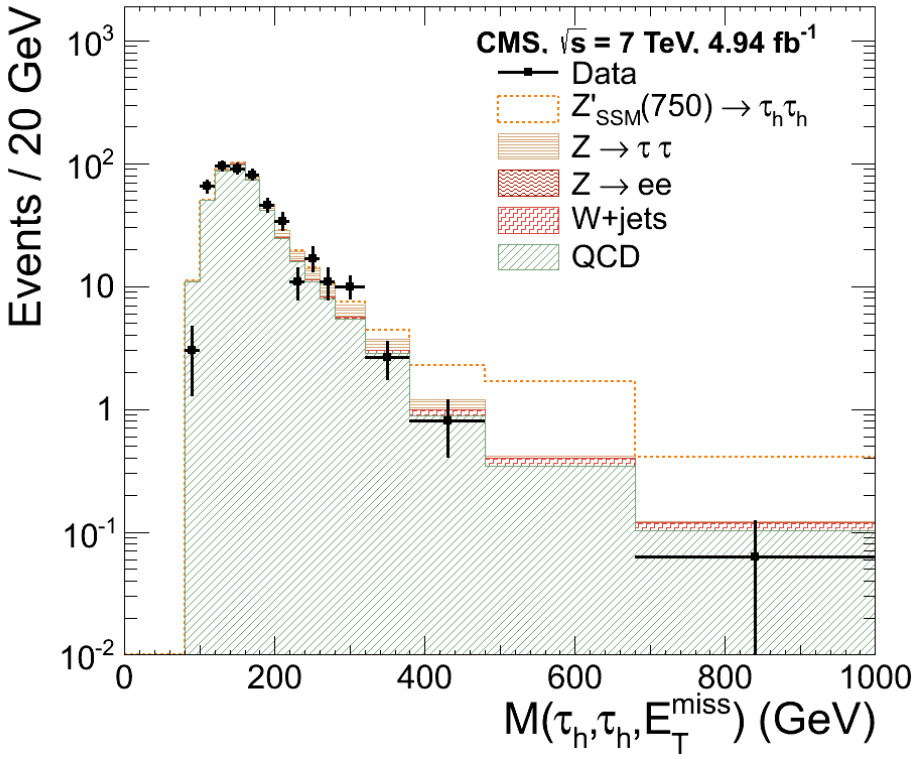
it was a hard time to understand our $\tau_h\tau_h$ trigger

most challenging decay channel: τ_h τ_h
- dedicated trigger: ditau hadronic
- offline selection:

- 2 opposite charged τ_h (1 prong)
- each with $p_T > 35$ GeV and $|\eta| < 2.1$
- isolated
- veto candidates passing: e and μ selection

- limit calculated using:

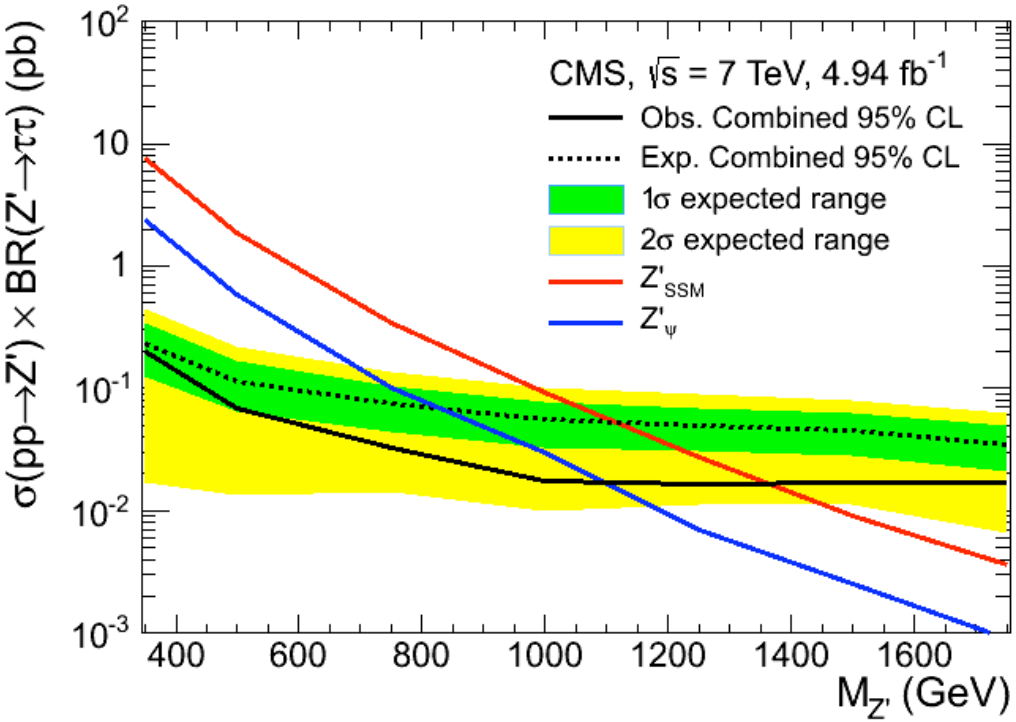
$$M(\tau_1, \tau_2, E_T^{miss}) = \sqrt{(E_{\tau_1} + E_{\tau_2} + E_T^{miss})^2 - (\vec{p_{\tau_1}} + \vec{p_{\tau_2}} + \vec{E_T^{miss}})^2}$$



“same procedure as every year…”

- these ττ final states were analyzed:
  $\tau_\mu \tau_e$, $\tau_\mu \tau_h$, $\tau_e \tau_h$, $\tau_h \tau_h$
- no signal was seen, so we setup limits:
  $M(Z'_{SSM}) > 1.4$ TeV and $M(Z'_\psi) > 1.1$ TeV
- more details can be found in
  Phys. Lett. B 716, 2012, 82-102

one thing to see is how we suppressed the W+jets contribution

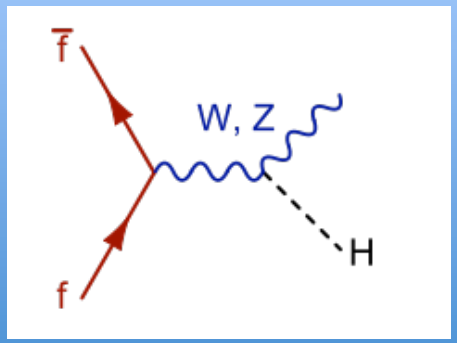


and this is how I have start enjoying the τ_h (delicate objects ☺)

back to SM: WH with $H(\tau_h\tau_h)$

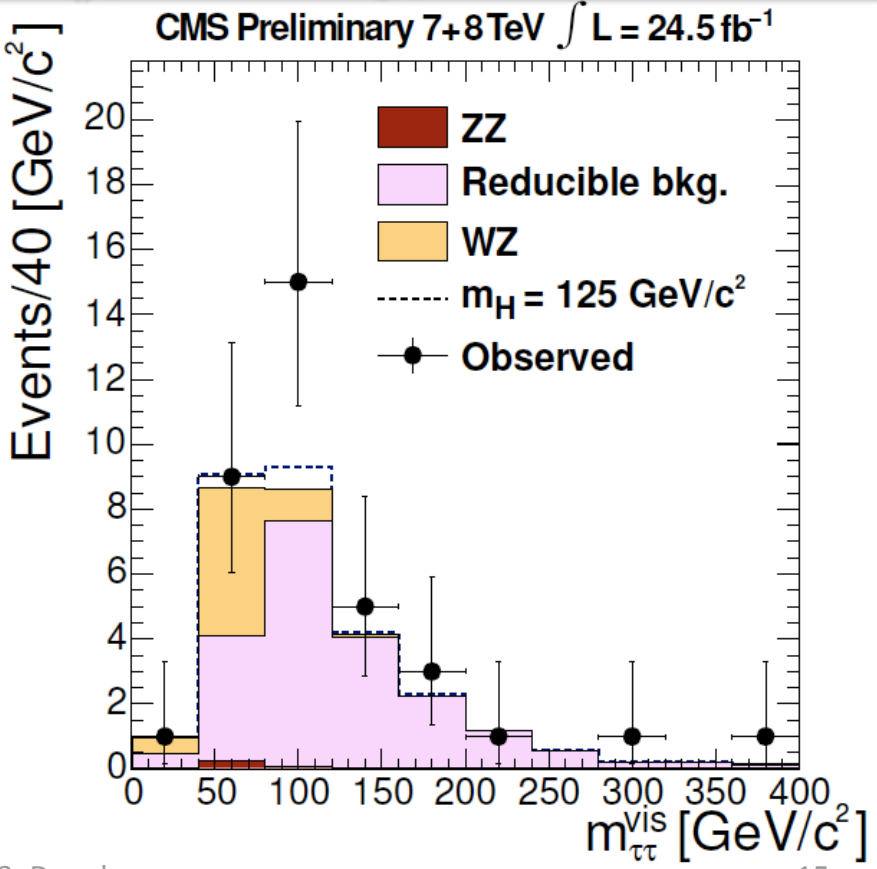
your remember the:

• **associated production** (additional W or Z boson)



events selected with:

- 2 isolated and opposite charge τ_h (1 or 3 prongs)
- one isolated e or μ
- vetoes against: Z(ee), Z(μμ), Z(ττ), tt (b-jets)
- in the end: the dominant background was given by fake τ_h (Reducible bkg.)



• ditau hadronic trigger had to use higher p_T thresholds to cope with lumi

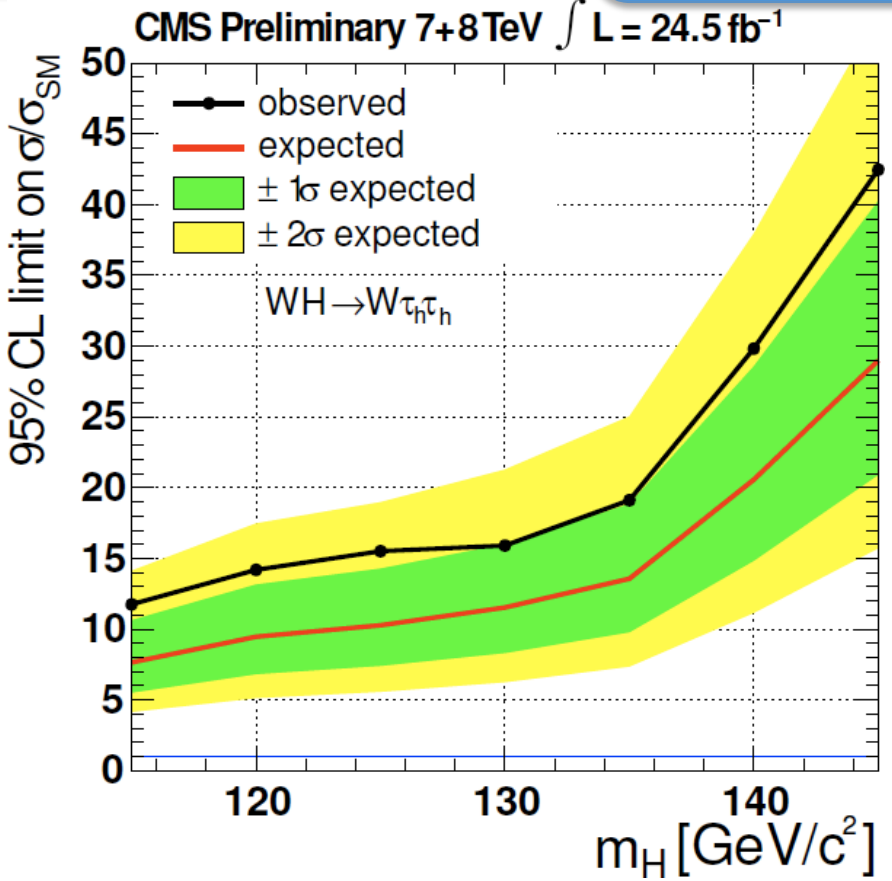
• to keep the advantage of a large BR for τ, but still have a good trigger:
next stop was to look for WH where the W decays via an e or μ

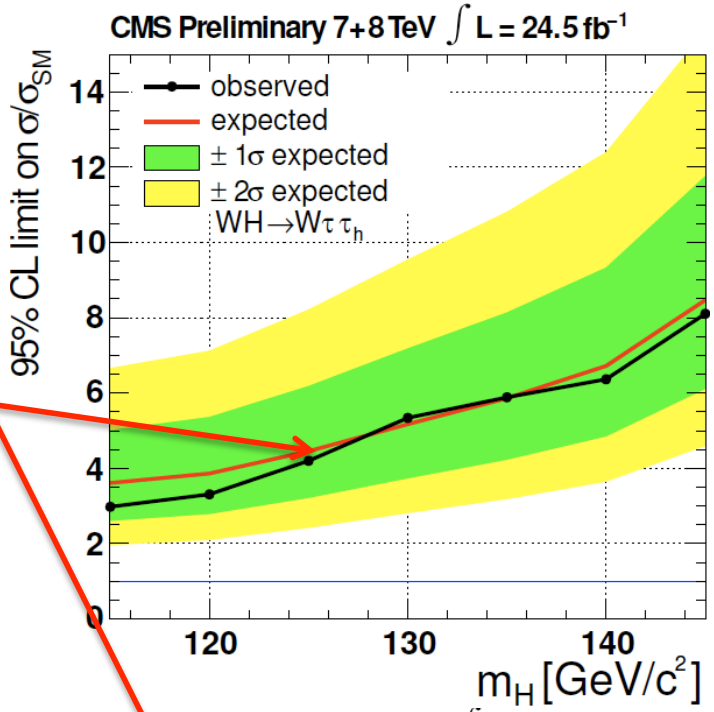
• single isolated muon and electron-tau cross triggers

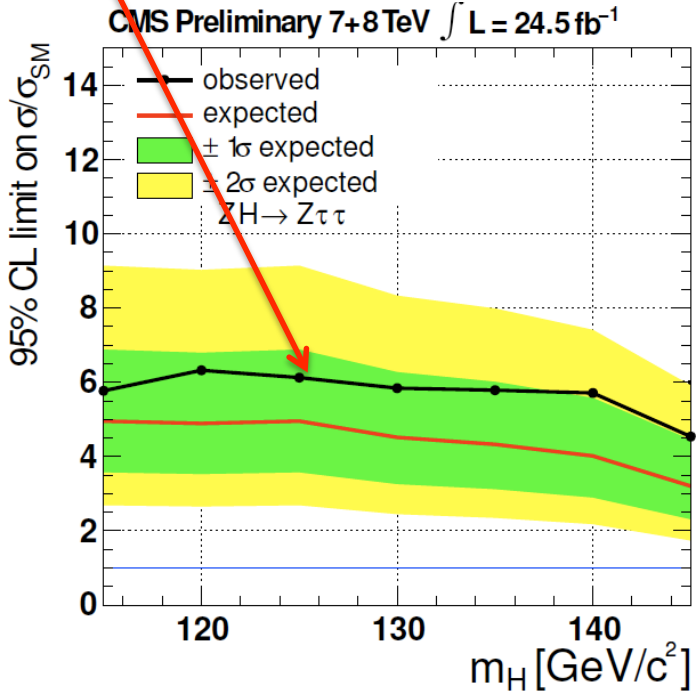
WH with $H(\tau_h\tau_h)$
vs.
$WH(\tau_{e/\mu}\tau_h)$ and $ZH(\tau\tau)$

before one starts jumping

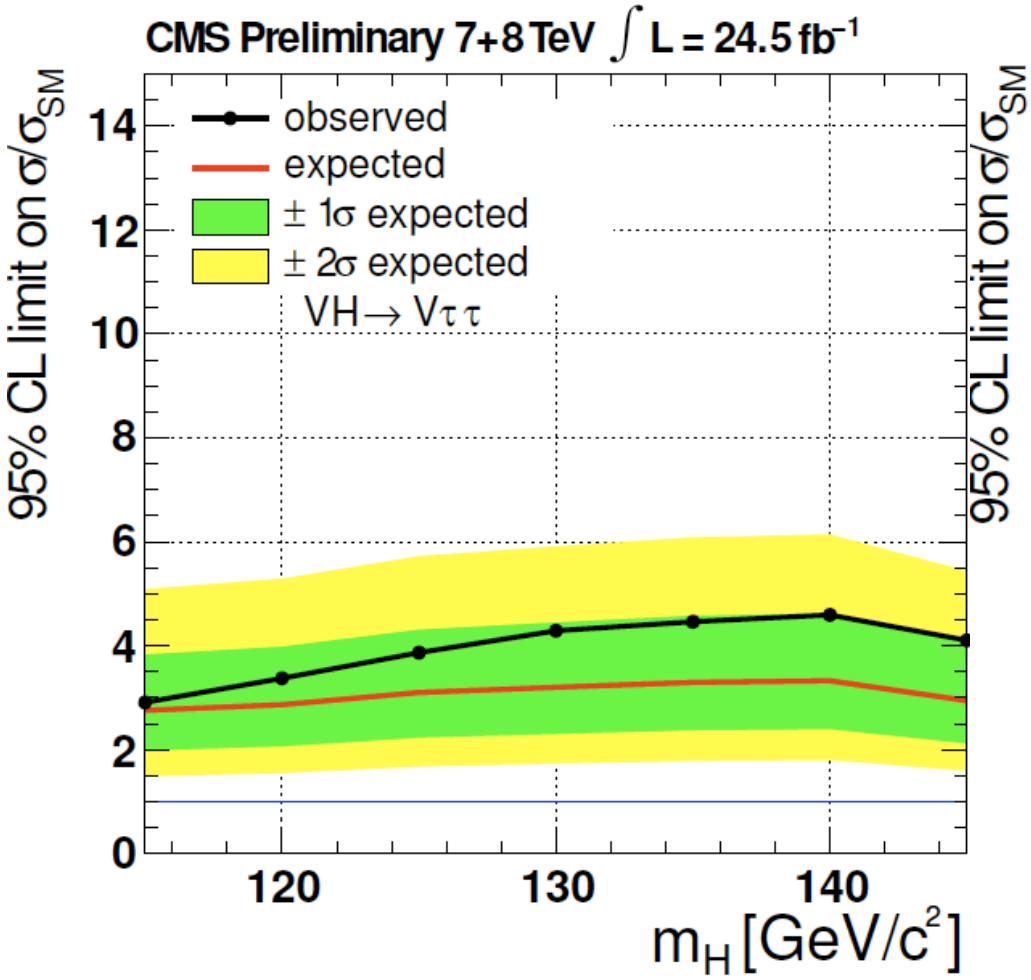
everything is within the one sigma band in the other two channels (independent analyses)

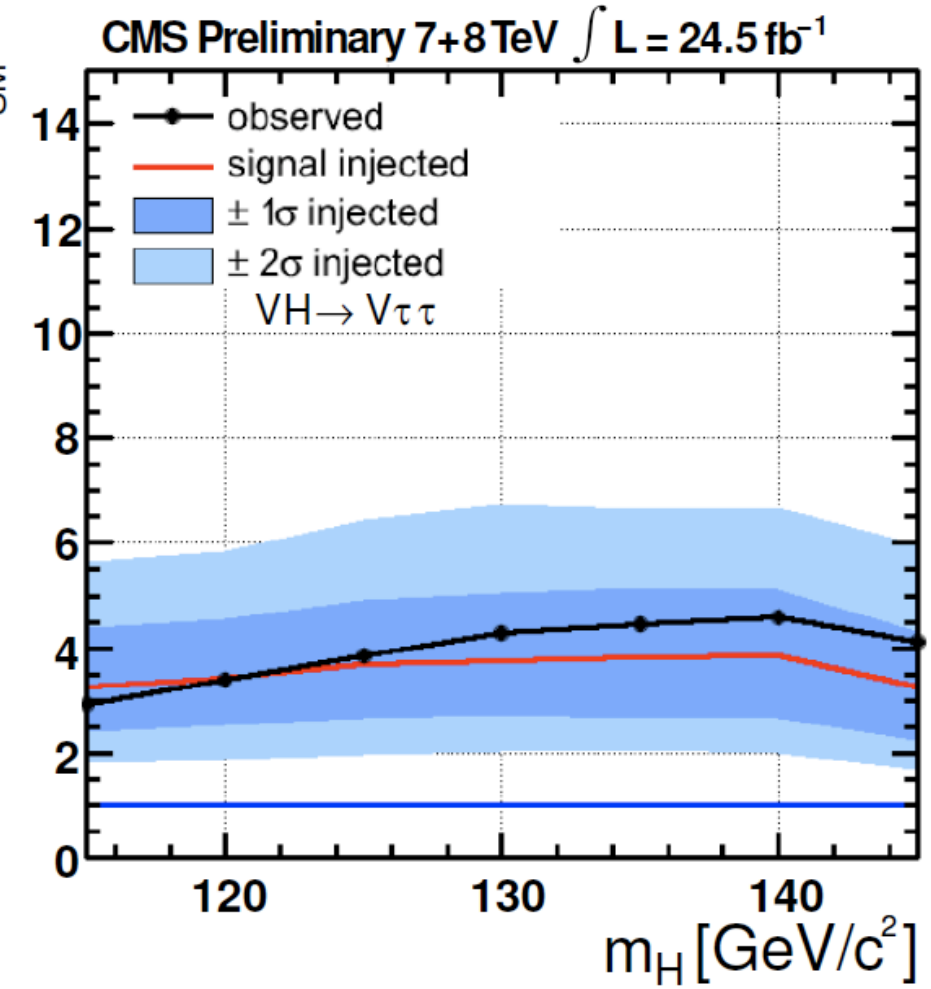






all combined: VH





• more details about this analysis can be found in **CMS PAS HIG-12-053**

it is time to look for something more "exotic"

new CMS Higgs group:

Higgs Exo

since December last year, together with Sasha Nikitenko, we convene the new started Higgs Exo group in CMS

purpose:

- set up analyses for rare and exotic Higgs decays with 2011/2012 data and prepare for the √s = 14 TeV ones for first data in 2015
- offer the needed space for analysis and new ideas other than we have done so far (we are now at the stage when we need to turn every "stone" remained untouched)

on Feb 4th we had a first workshop where we gathered together our theoretician colleagues and show them where we stand so far

14:00 - 20:00 **Higgs-Exo Workshop** Join Vidyo | Connect Salle Anderson

Convener: Alexandre Nikitenko (Imperial College Sci., Tech. & Med. (GB)), Adrian Perieanu (Rheinisch-Westfaelische Tech. Hoch. (DE))

Location: 40-S2-A01 - Salle Anderson

14:00 **Introduction** *10'*
Speakers: Alexandre Nikitenko (Imperial College Sci., Tech. & Med. (GB)), Adrian Perieanu (Rheinisch-Westfaelische Tech. Hoch. (DE))
Material: Slides

14:10 **Non standard/invisible Higgs channels in the MSSM** *40'*
Speaker: Abdelhak Djouadi (Universite de Paris-Sud 11 (FR))
Material: Slides

14:50 **CMS VBF H->invisible** *20'*
Speaker: Jim Brooke (University of Bristol (GB))
Material: Slides

15:10 **CMS ZH, H->invisible** *20'*
Speaker: Daniele Trocino (Northeastern University (US))
Material: Slides

15:30 **LHC Higgs(es) beyond the standard paradigms** *40'*
Speaker: Sabine Kraml (Centre National de la Recherche Scientifique (FR))
Material: Slides

16:10 **Break** *20'*

16:30 **Non-SM NMSSM Higgs channels favored by LHC Higgs mH=125 GeV** *40'*
Speaker: Prof. Margarete Muehlleitner (Institut für Theoretische Physik, Karlsruher Institut für Technologie KIT)
Material: Slides

17:10 **CMS H->aa->tau_mu + tau_h + X** *20'*
Speaker: Rachel Yohay (University of California Davis (US))
Material: Slides

17:30 **Break** *20'*

17:50 **A Systematic Search For Unexpected Higgs Decays** *40'*
Speaker: Prof. Matthew Strassler (Rutgers University,)
Material: Slides

18:30 **CMS triggers for some "Unexpected Higgs Decays"** *10'*
Speaker: Zeynep Demiragli (Brown University)
Material: Slides

18:40 **Conclusion** *20'*

we had 4 good talks regarding the theory (some of them we still need to fully digest ☺)

maybe in 3 or 4 months we can sit together again and give/take more input to/from theory

one example: NMSSM $h_{1,2} \rightarrow a_1 a_1 \rightarrow 4\mu$

it stands for:
Next-to-MSSM

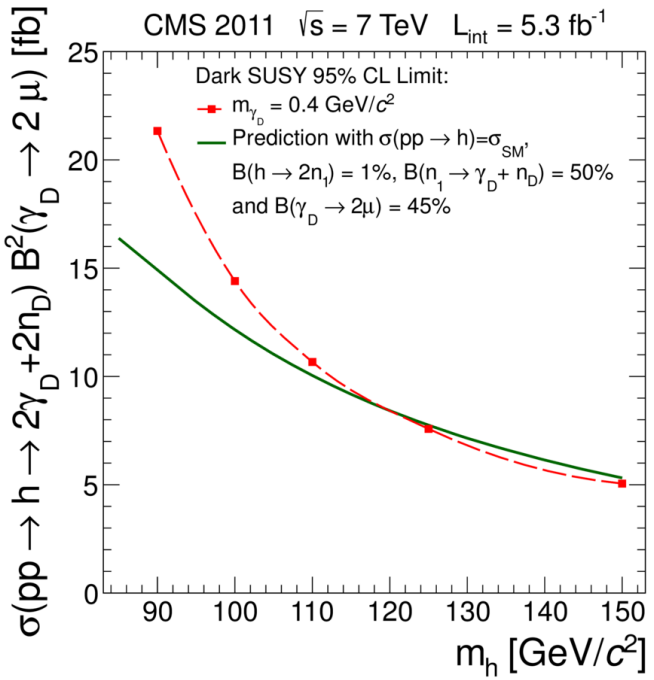
- analysis coordinated by Yuriy Pakhotin & Alexei Safonov (TEXAS A & M)
- scrutinized in Higgs Exo group for 2012 data

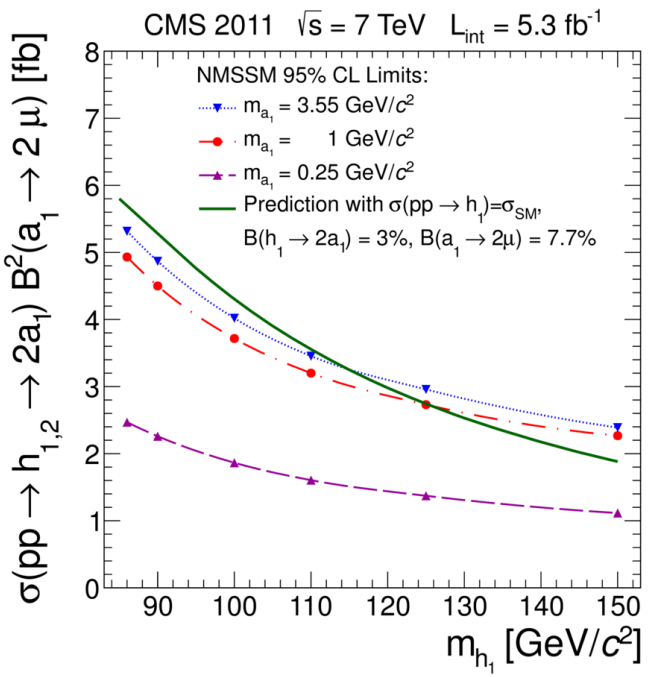
- **NMSSM:** Higgs can decay into an intermediate pair of bosons (a)
- **DARK SUSY:** analysis can be interpreted also considering lightest neutralino n_1 no longer stable:

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

$n_1 \rightarrow \gamma_D\, n_D$
γ_D – dark photon
n_D – dark fermion
- assumption γ_D decays only in SM particles:
$\gamma_D \rightarrow \mu^+\mu^-$ with BR.≈45%

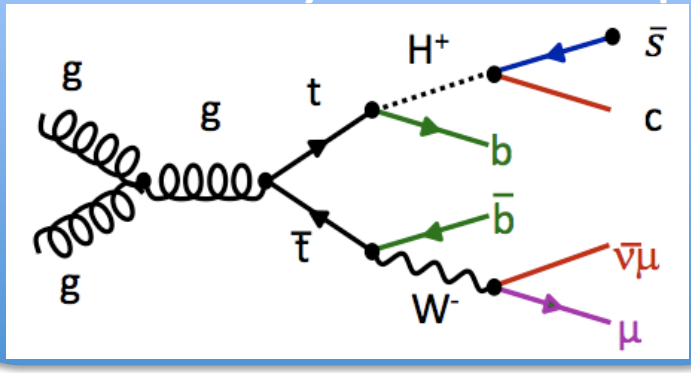
- analysis of 2012 data in NMSSM scenario already in approval procedure (expected to be released in few weeks)



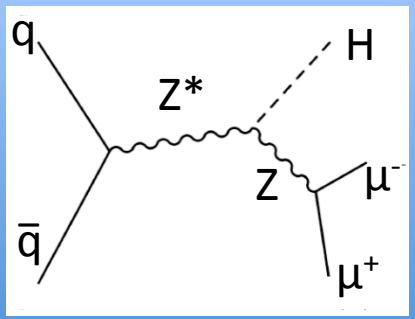


even more exotic:

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



ZH with H inv.

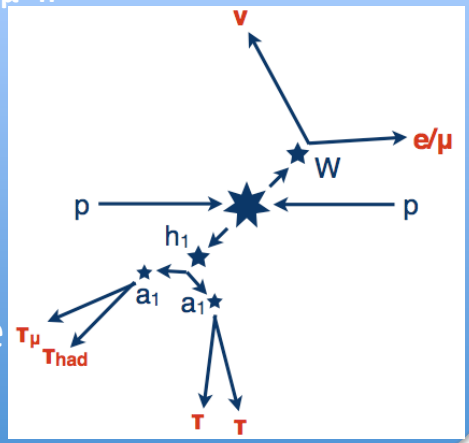


- Higgs decaying to Dark Matter candidates
- MSSM h^0 decaying to LSP
- extra-dimension Higgs decaying to neutrinos

- Radion→hh→γγbb
- h→μτ and h→eτ
- heavy H→hh
- …

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 and 2τ2b will complete the NMSSM picture



Daniele, Gouranga, Rachel, Alexandra, Shruti, Daniel, Colin…
only few names that you will hear more in the near future

instead of conclusions

where to go from here…

MET	γ+MET	Z+MET	ττ	ee	μμ(μμ)	qq/gg	bb	γγ (γγ)
h->inv VBF	h->GGγ	h->inv hZ, Z->ll	NMSSM h->τ(μ)τ(had)X $2m_\tau < m_X < 2m_b$		SM h->2μ	h+->cs	RS/G->hh->γγbb	
			h->μτ, h->eτ		MSSM h->2μ	gg->h+jet	h->inv hZ, Z->bb, jj	h->XY->4γ
			NMSSM h->2μ 2τ		NMSSM h->4μ		H->XX->2τ 2b $m_X > 2m_b$	h->XY->2τ2γ
			H->XX->4τ $m_X > 2m_b$				H->XX->4b $m_X > 2m_b$	

we (theorists, Sasha and me) thought about many topologies…
but as you can see there are still many empty cells to fill in
until the new data at √s=14 TeV arrive in 2015

join us!