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Direct searches for heavy Higgs bosons

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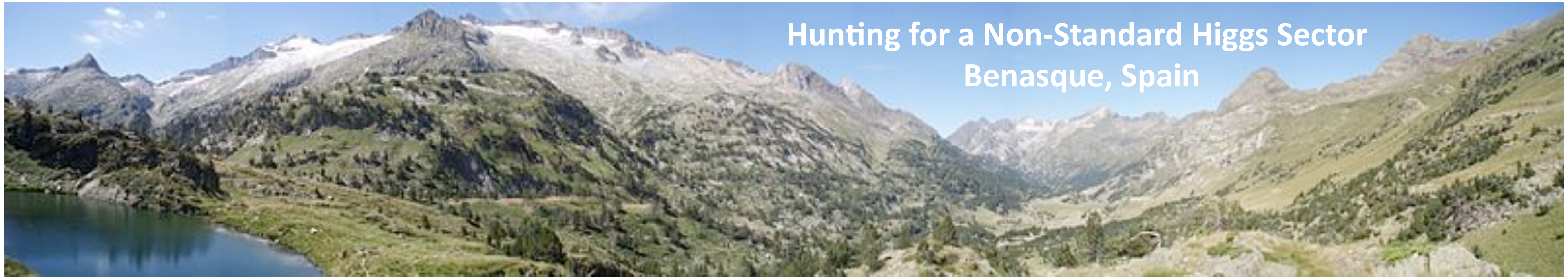
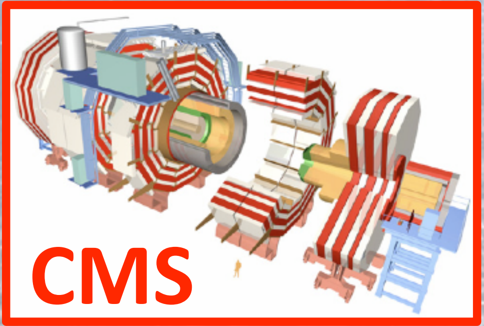
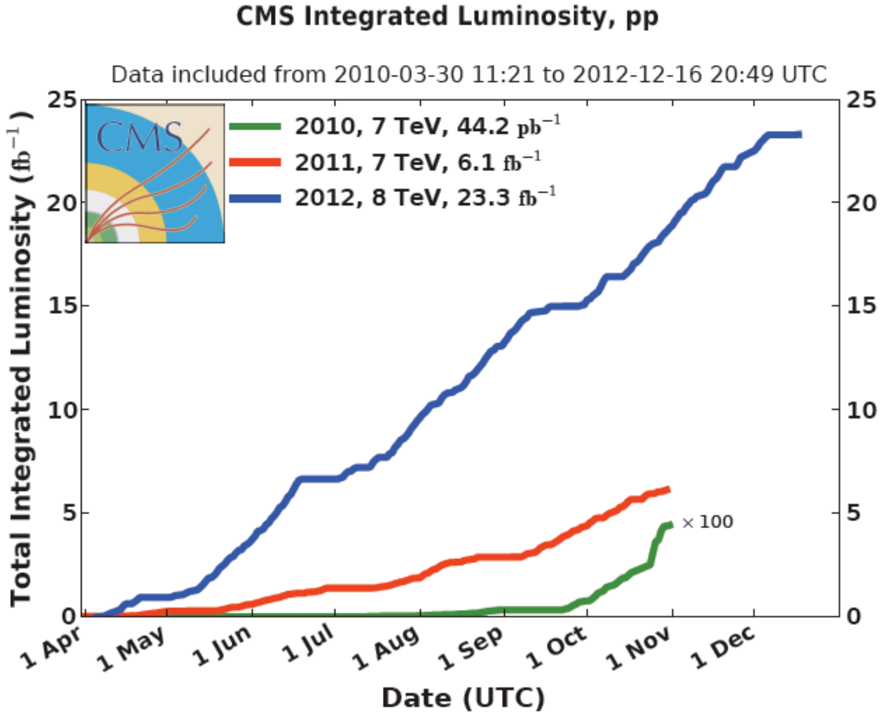


Hunting for a Non-Standard Higgs Sector
Benasque, Spain





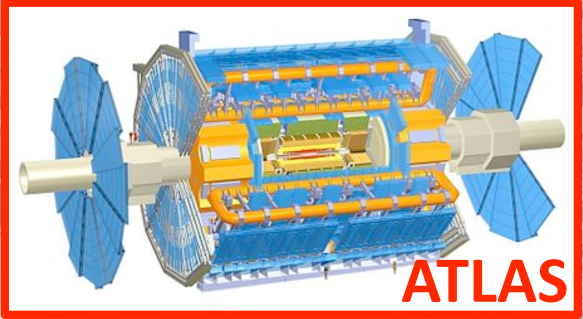
Outline:

- Motivation
- CMS & ATLAS detector
- Heavy Higgs:

2HDM

Higgs++

- Other searches at high mass
- Perspectives



what is driving us
- always problems -

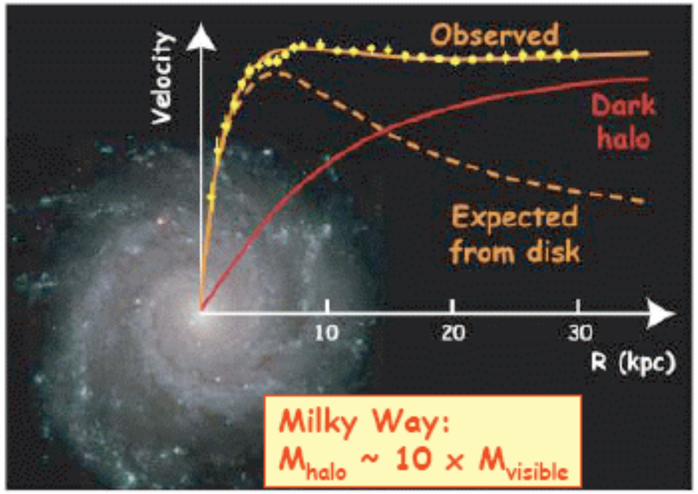
purely experimentalist point of view

hierarchy problem:
- electro-weak scale is at 10^2 GeV
- Plank-scale is at 10^{19} GeV

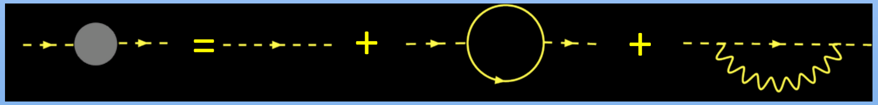
$M_W / M_P \sim 10^{-17}$ GeV

galaxies movement problem:
- we like solving by introducing a new type of matter:

dark (because we do not see it)
matter particles => they are not in SM



fine tuning problem:
- Higgs mass: $M_{meas.} = M_0 + \delta M$



M_0 : bare mass
δM : quantum mass correction (loops)
- $\delta M^2 \approx - 2\Lambda^2_{UV} / 16 \pi^2$

not a problem if Λ_{UV} would not be M_P (10^{19} GeV)
=> we need a correction with a precision of 10^{-17}

so far we can reach 0.05 nm (10^{-11}m) space resolution with Transmission Electron Microscope and hope to reach 10 fs (10^{-14}s) with XFEL (Free Electron Laser)

because of my experimental nature
let me see what I cannot see…

what is driving us

CMS combination:

- $BR_{BSM}=\Gamma_{BSM}/\Gamma_{tot}$ 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**)

searches for Higgs invisible decays:

- assuming SM production cross section

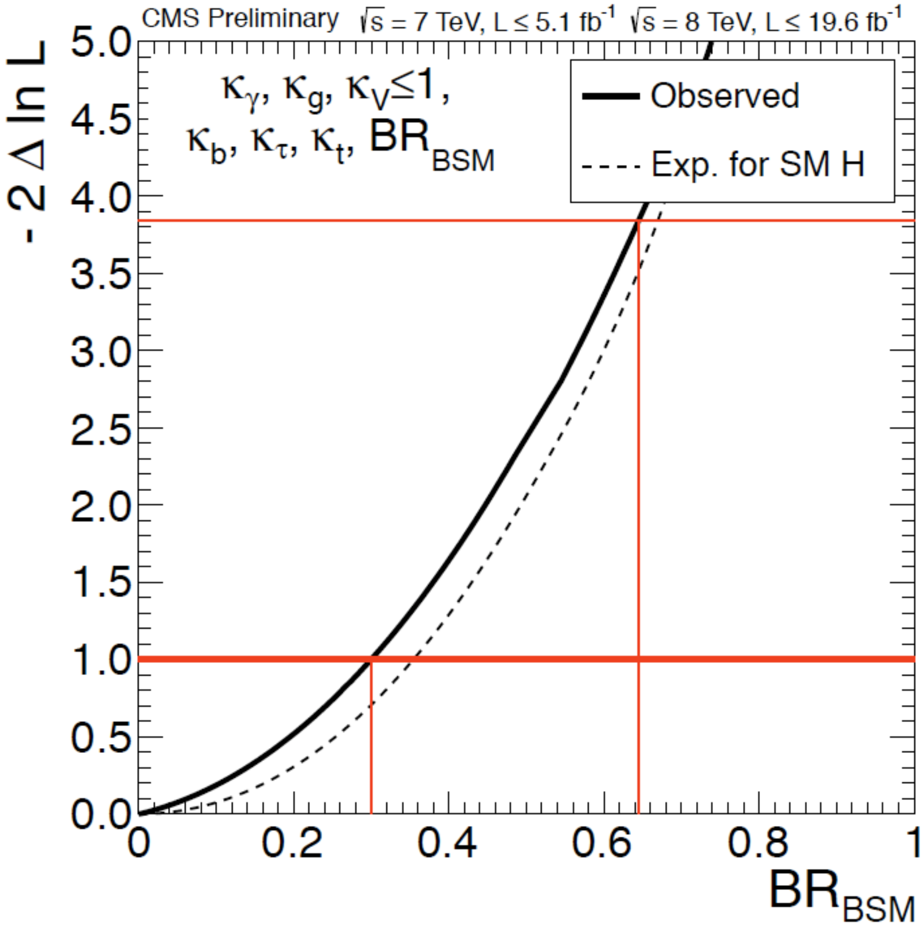
observed (expected) 95% CL limits

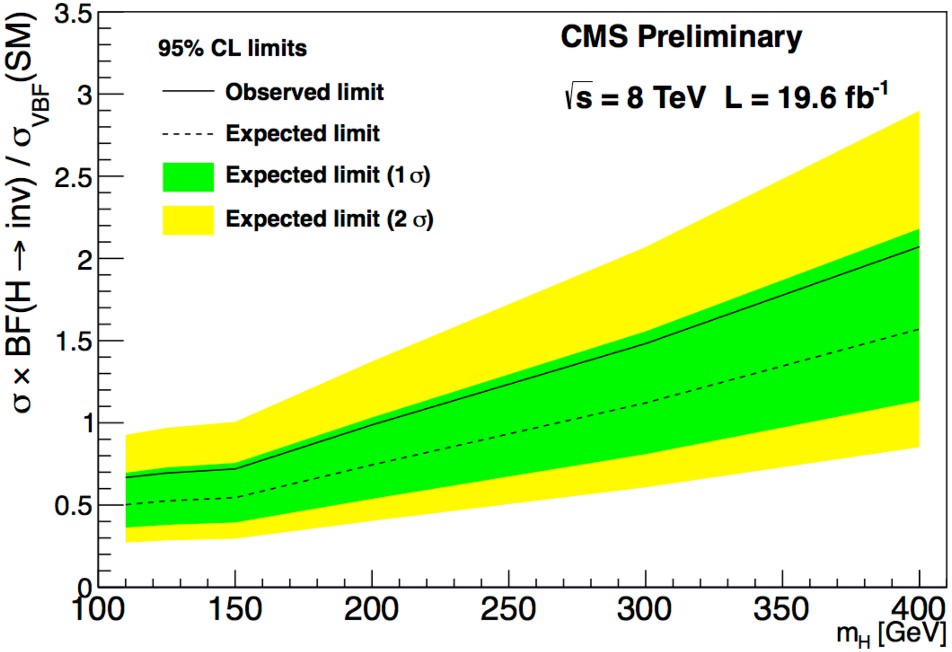
for Z($\ell\ell$)H **ATLAS: BR_{inv} < 65% (81%)**

CMS: BR_{inv} < 81% (83%)

for VBF H **CMS: BR_{inv} < 67% (52%)**

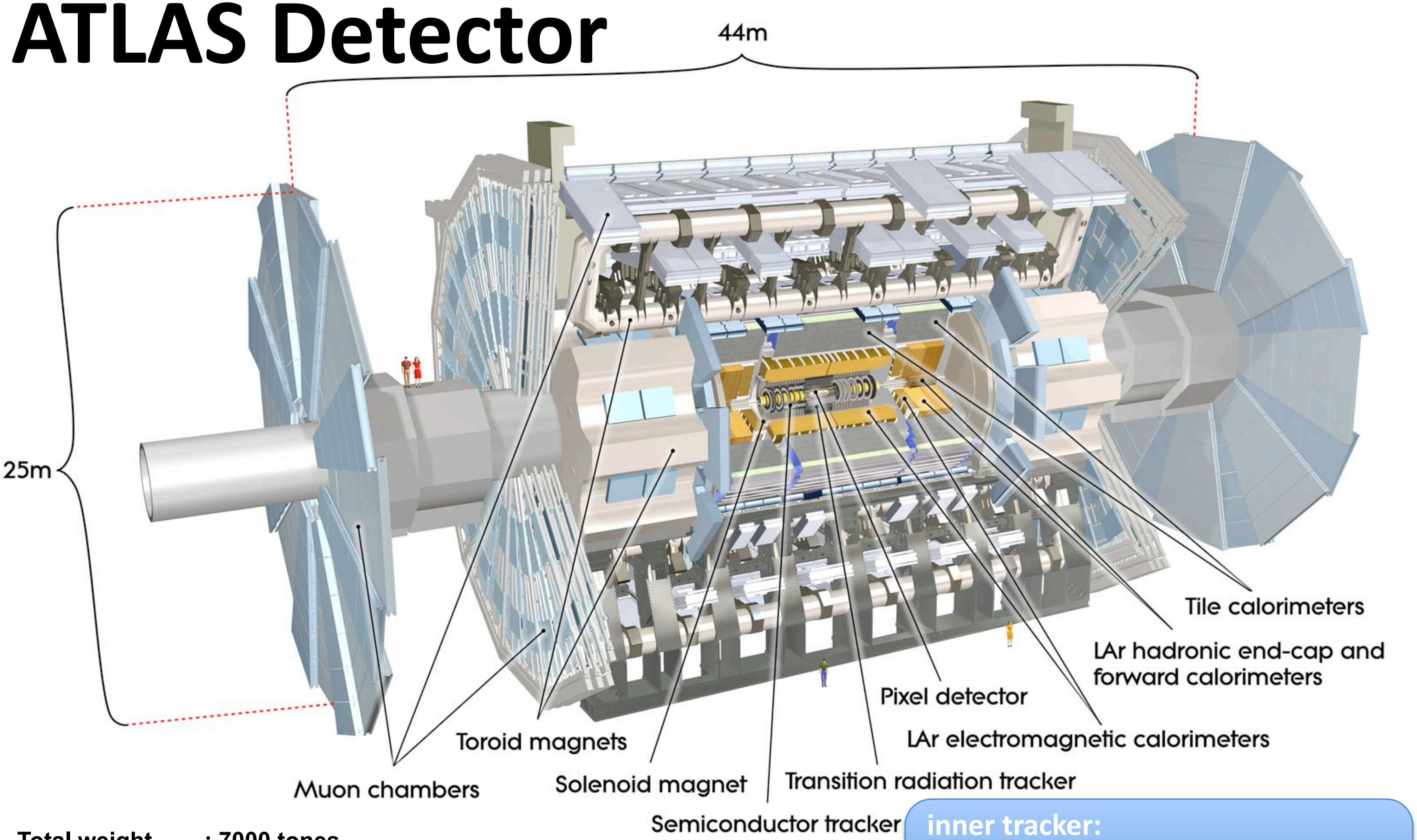
from combination **CMS: BR_{inv} < 58% (46%)**





there must be something out there

ATLAS Detector



Total weight : 7000 tones
Overall diameter : 25.0 m
Overall length : 46.0 m
Magnetic field : 2.0 T

inner tracker:

- **coverage:** $|\eta| < 2.5$, $\eta = - \ln [\theta/2]$
- **transverse momentum resolution**:

$\sigma_{p_T} / p_T \approx 0.05\% \, p_T \oplus 1.0\%$

physics objects: electrons

Electrons in ATLAS:

- energy clusters formed within a dedicated ΔηxΔϕ area and matched to a track (e – γ separation)

- track checked for a match to a secondary vertex (e – converted γ separation)

- use **G**auss **S**um **F**unction alg. to account for bremsstrahlung

EM calorimeter:

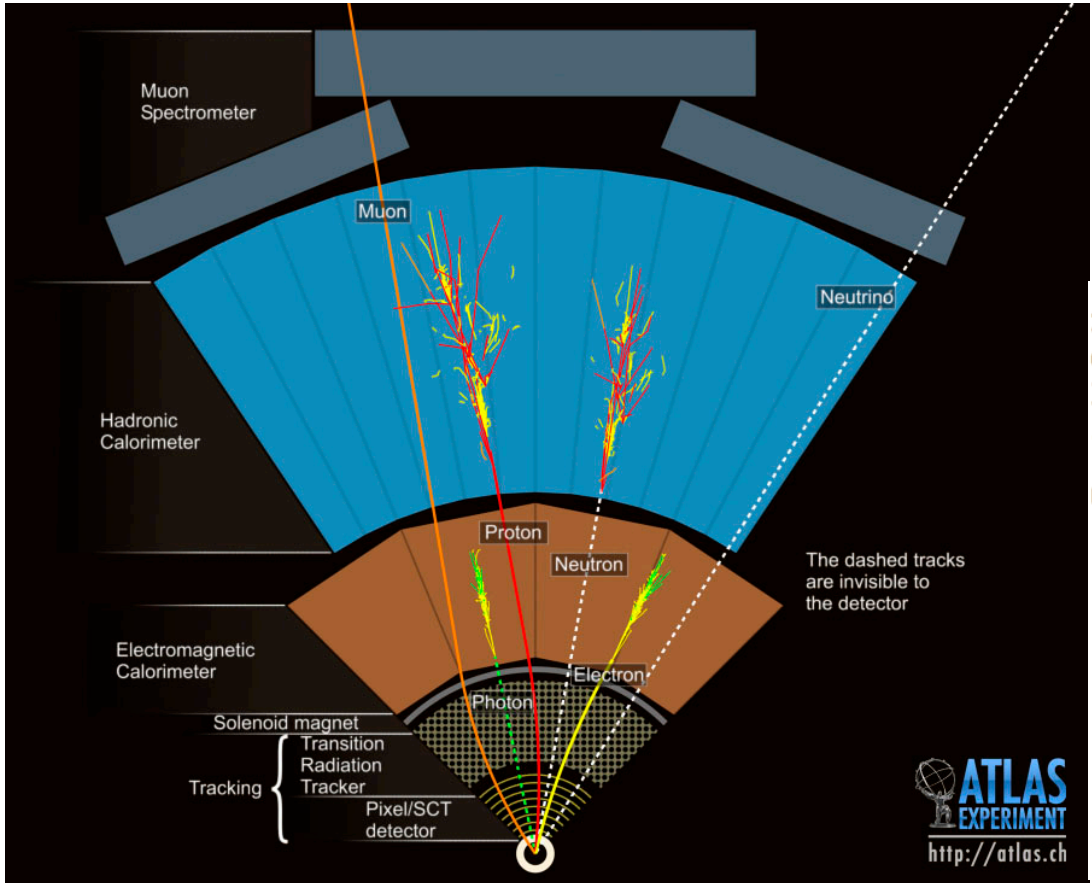
- Liquid **Ar**gon
- high granularity
- longitudinal segmentation

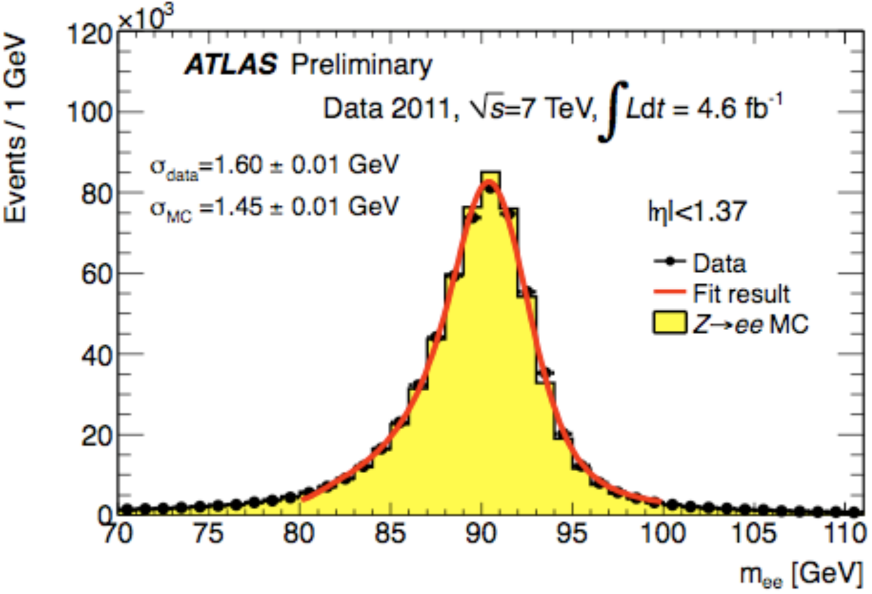
- **energy resolution:**

$10\%/\sqrt{E/\mathrm{GeV}} \oplus 0.7\%$

- **coverage:**

|η| < 2.5 (track)
|η| < 4.9 (cluster shape)

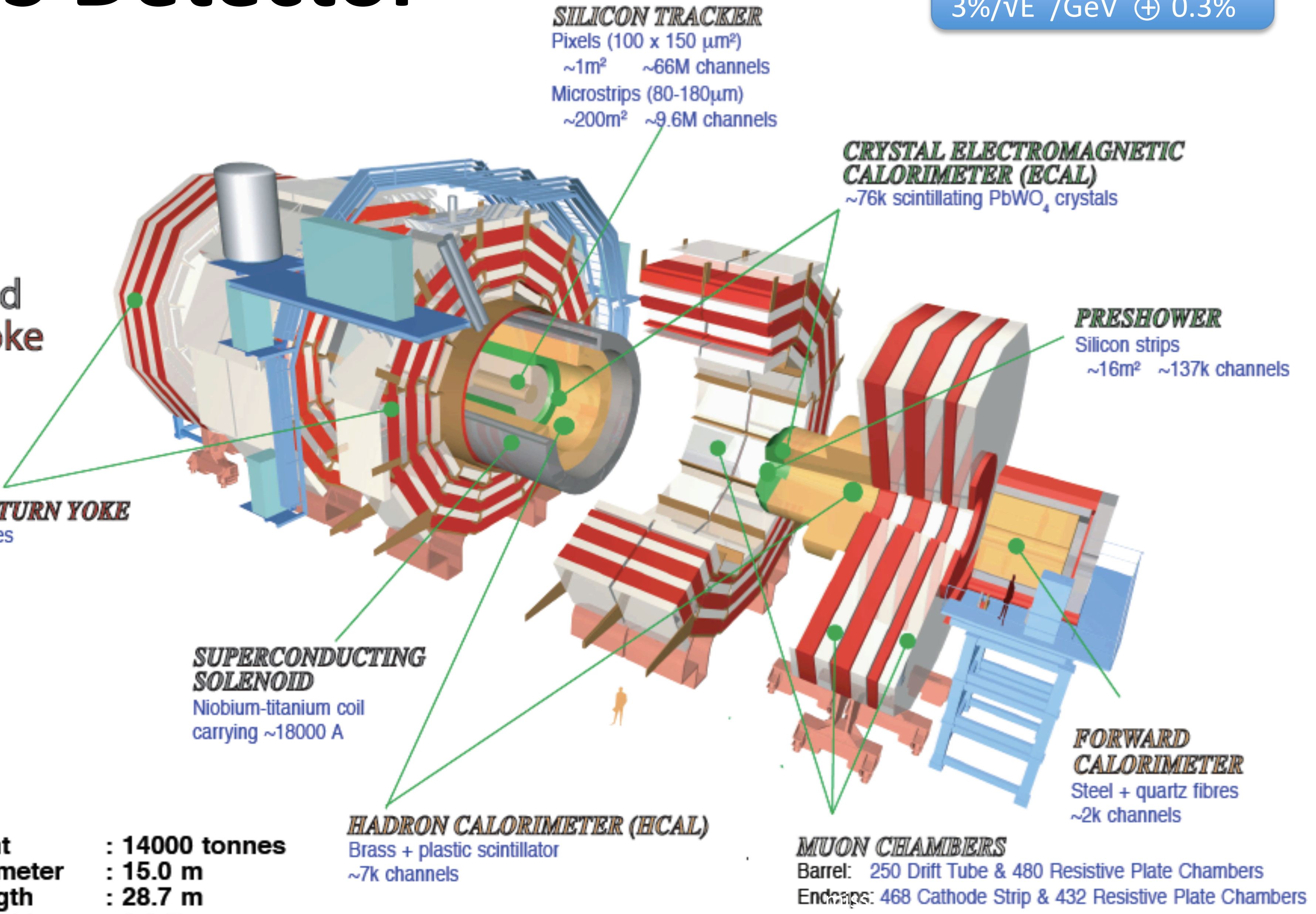




CMS Detector

- **energy resolution:** $3\%/\sqrt{E\ /GeV} \oplus 0.3\%$

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

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

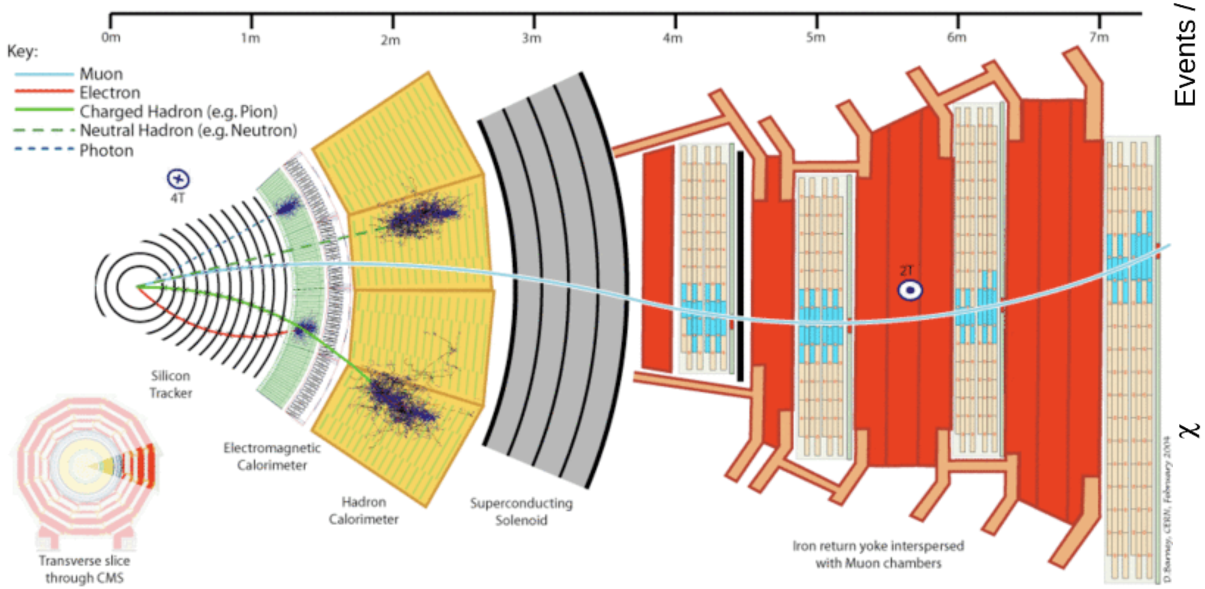
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

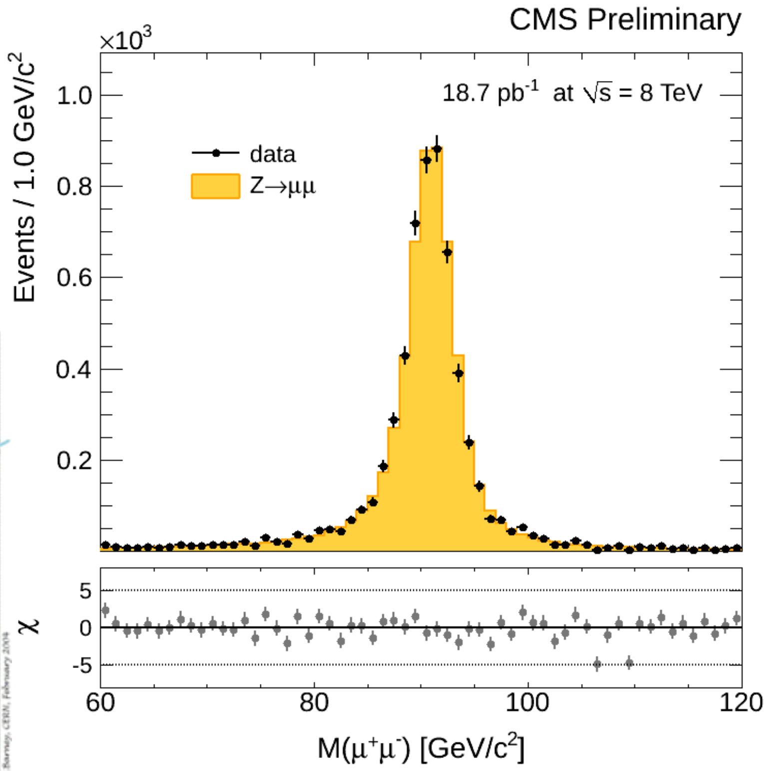
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

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

physics objects: muons

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





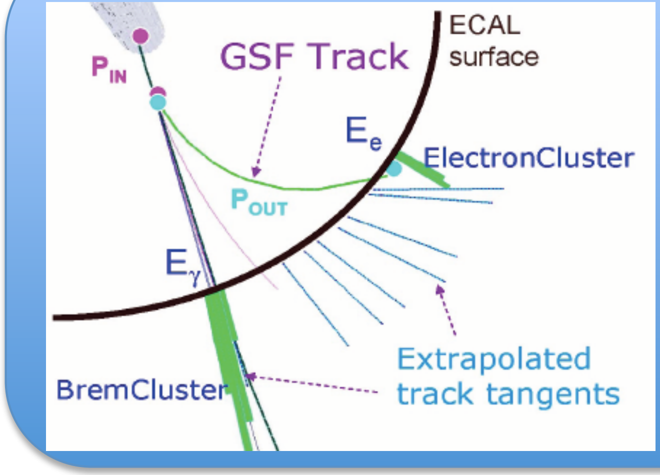
- **coverage:** |η| < 2.4, η = - ln [θ/2]
- **transverse momentum resolution**:

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

- 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}

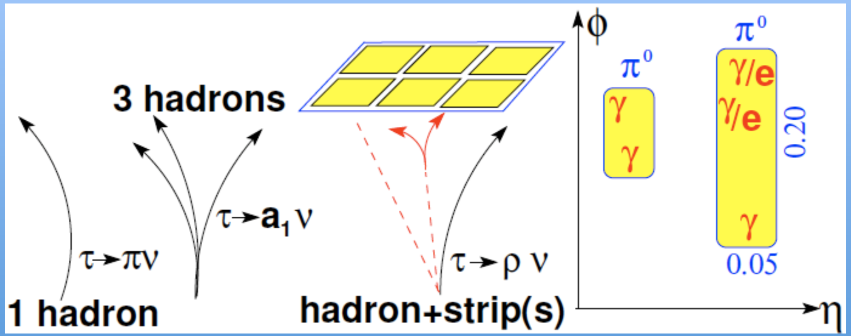
electron



- **Gauss Sum Function**
- **coverage:** |η| < 1.442 & 1.556 < |η| < 2.5
- **energy resolution:**

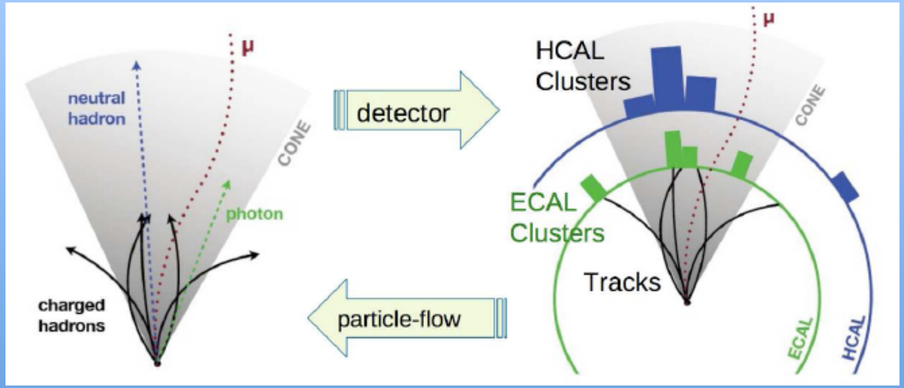
$3\%/\sqrt{E\ /GeV}$

τ lepton: hadronic decays

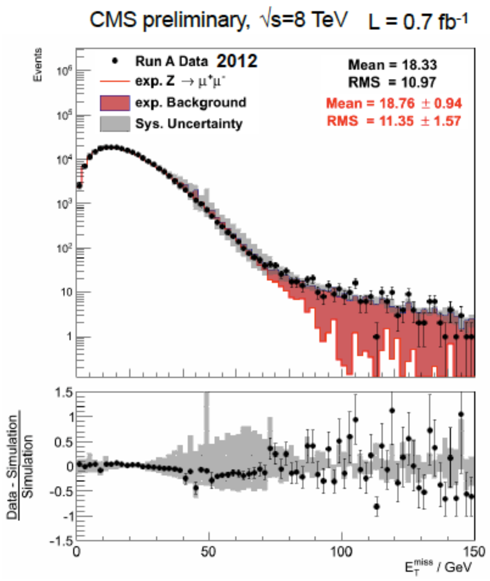


- **coverage:** |η| < 2.3
- **energy scale:** < 3 %

Particle Flow Jets in CMS:



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



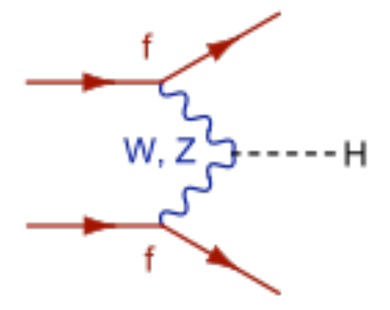
Missing Energy in Transverse plane

E_T^{miss}

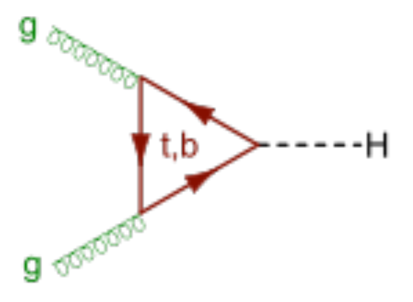
- **in CMS:** negative vector sum of all particle candidates reconstructed with the PF algorithm

Higgs: what do (we think) we know

Vector Boson fusion

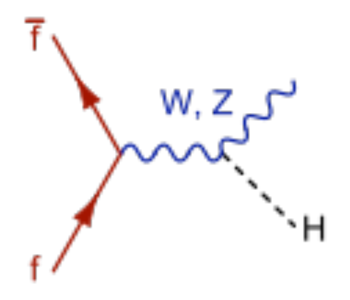


gluon-gluon fusion

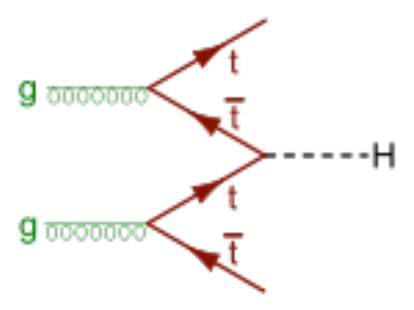


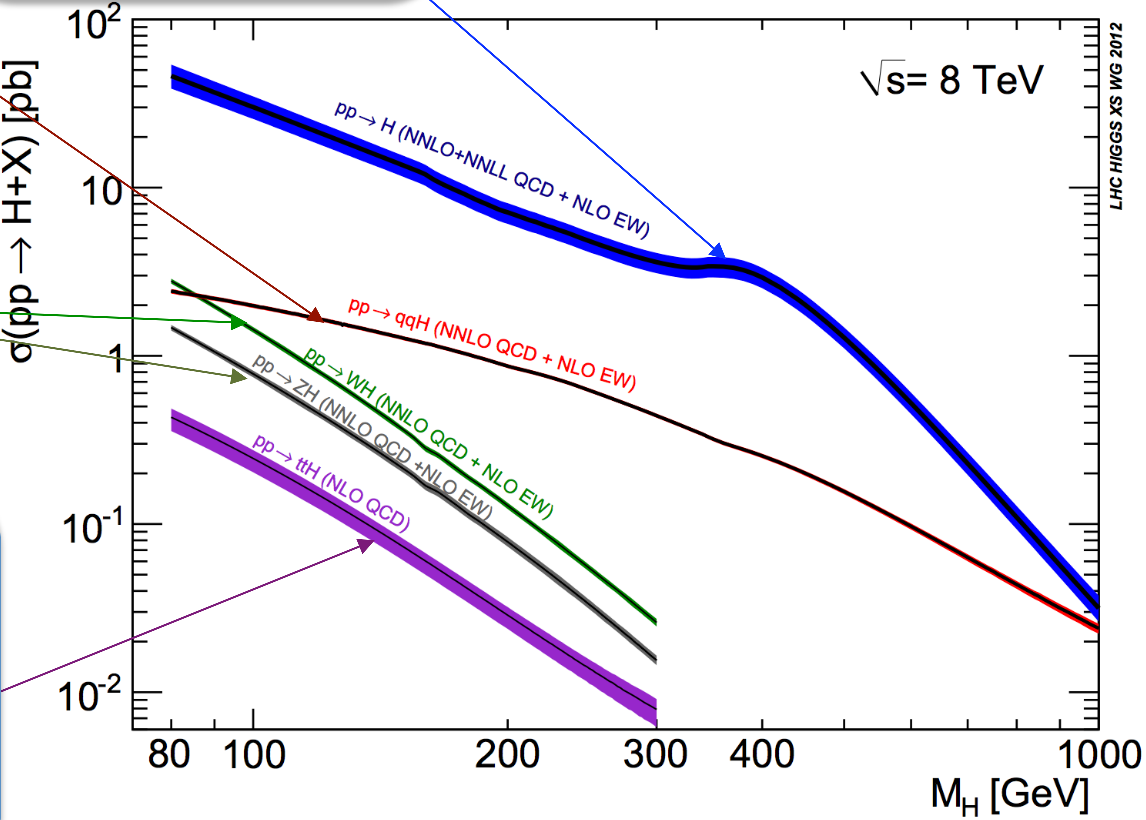
LHC Higgs Cross Section WG
YR1: Inclusive cross sections **arXiv:1101.0593**
YR2: Differential cross sections **arXiv:1201.3084**

W/Z assoc. prod.



top assoc. prod.

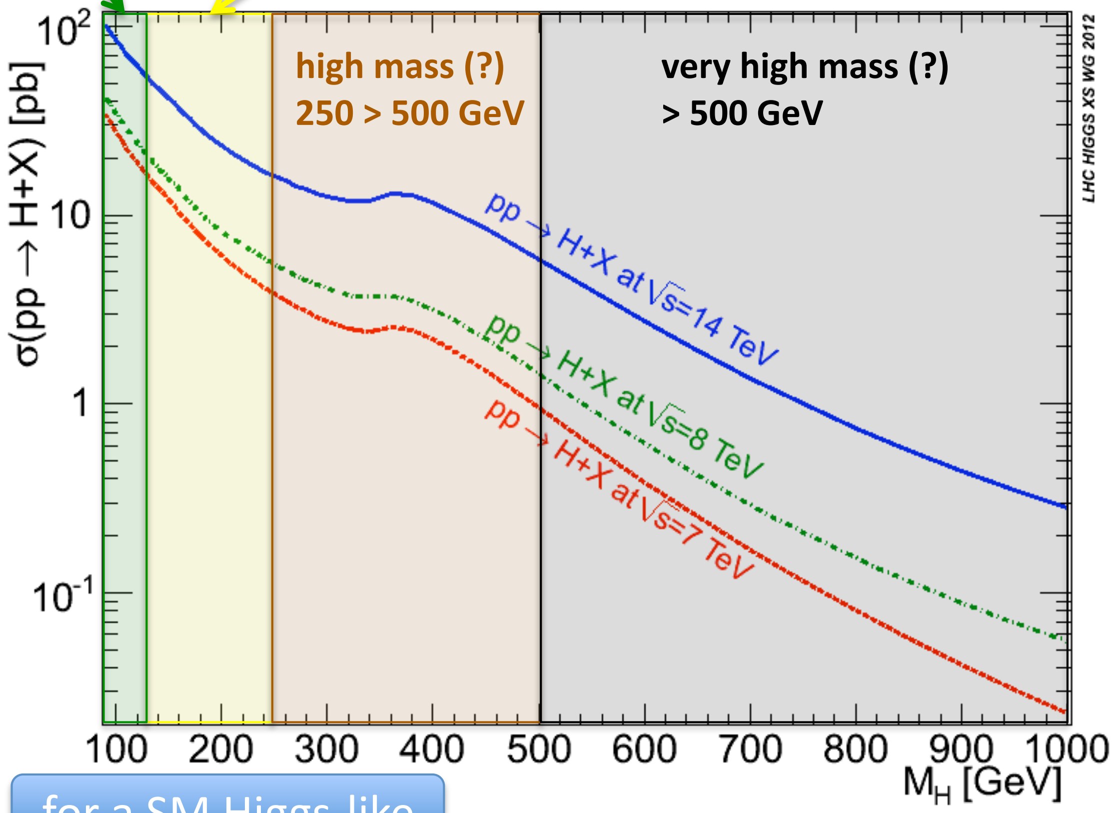




how shall we define high mass?

low mass
< 125 GeV

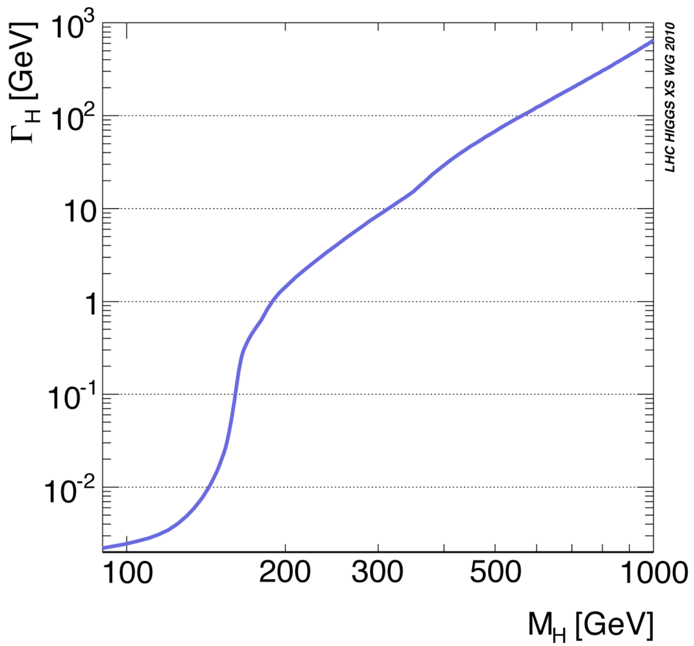
medium mass (?)
125 > 250 GeV

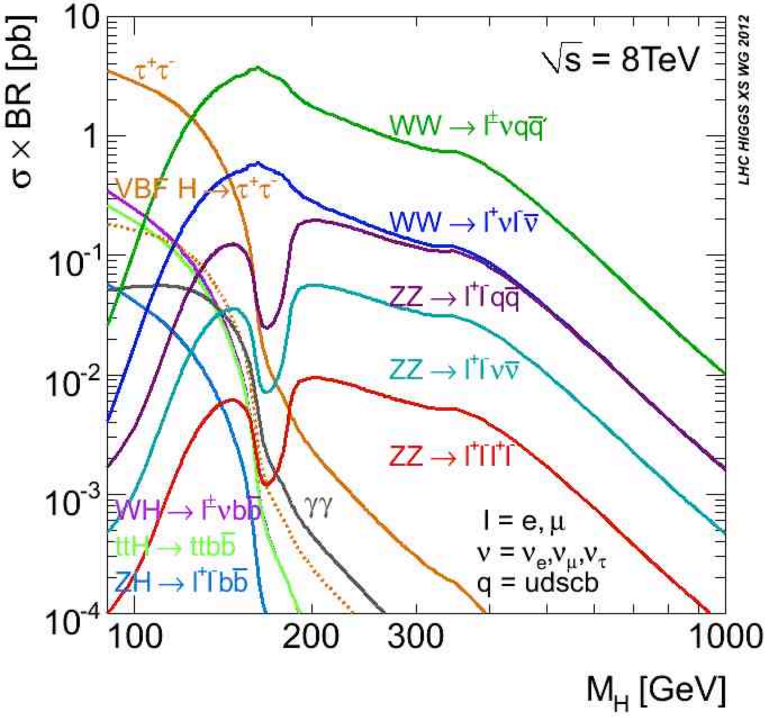


high mass (?)
250 > 500 GeV

very high mass (?)
> 500 GeV

for a SM Higgs-like





2HDM

- **TYPE I**: one Higgs doublet provides masses to all quarks (up- and down-type quarks (~SM)
- **TYPE II**: one Higgs doublet provides masses for up-type quarks and one for down-type quarks (~MSSM)
- **TYPE III & IV**: different doublets provide masses for down type quarks and charged lepton

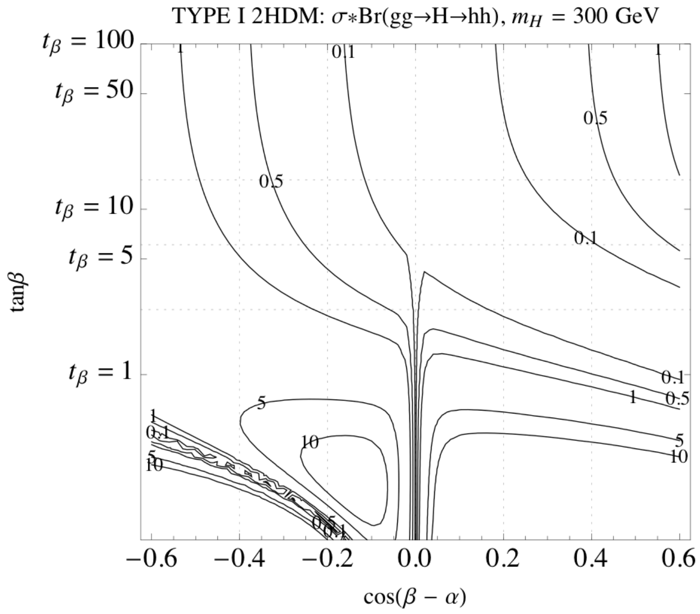
non-CP violating 2HDM Higgs sector has 6 free parameters:

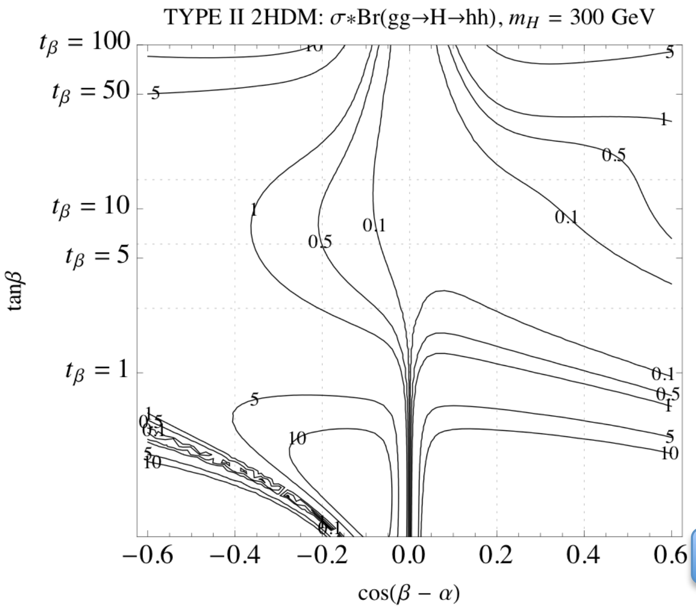
more in arXiv: 1106.0034

$M_{H^\pm}, M_{H^0}, M_{h^0}, m_{A^0}, tan\beta, \alpha$ - Higgs mixing angle

- couplings of neutral Higgs bosons to SM fermions and massive gauge bosons as a function of α and β

- σ*BR (H→hh) contours for TYPE I (left) and TYPE II (right) 2HDM
- α and tanβ: Heavy Higgs's couplings to SM fermions and massive gauge bosons





1	2HDM I	2HDM II
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
AVV	0	0
AQu	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$

more in arXiv:1207.4835

2HDM: H(hh) & A(Zh)

HIG-13-025

muons & electrons
- isolated
- $p_T > 10$ GeV and $|\eta| < 2.4$

taus
- dR > 0.1 relative to μ and e
- $p_T > 20$ GeV and $|\eta| < 2.3$

photons
- isolated
- $p_T > 20$ GeV and $|\eta| < 2.5$

jets
- PF, dR > 0.4 to μ, τ, γ and e
- $p_T > 20$ GeV and $|\eta| < 2.5$

event selection
- multileptons (≥ 3)
  - $m_{ll} > 12$ GeV
  - bin in number of τ_h
  - number of OSSF pairs
- photons (2)
  - 1 or 2 leptons
  - 1 or 2 hadronic taus
- search in bins of PF MET and number of jets

h(126) decays

h(126) decays

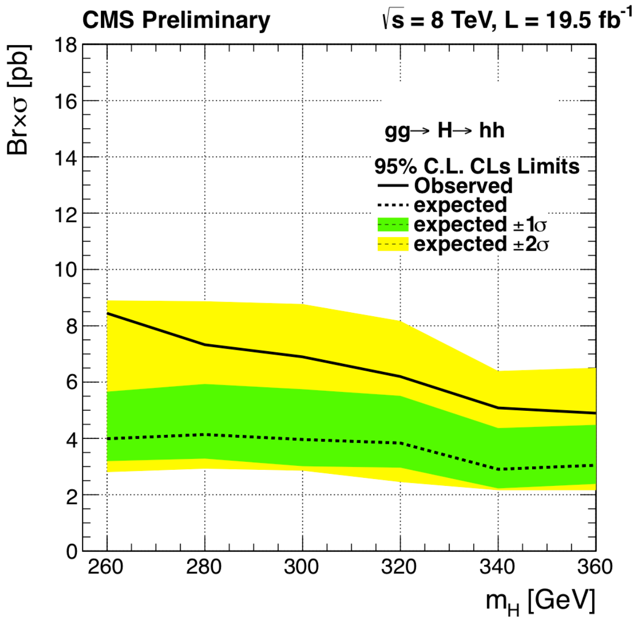
	WW*	ZZ*	τ τ	bb	γ γ
WW*	✓	✓	✓	X	✓
ZZ*	_	✓	✓	✓	✓
τ τ	_	_	✓	X	✓
bb	_	_	_	X	X

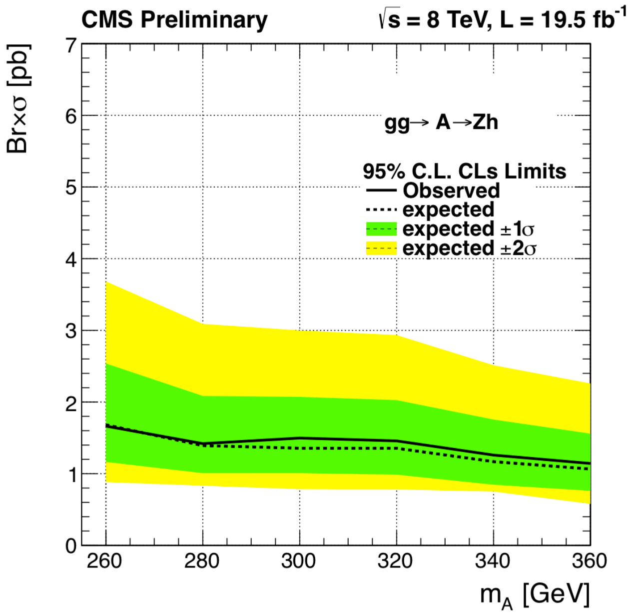
h(126) decays

Z^0 decays

	WW*	ZZ*	τ τ	γ γ
ll	✓	✓	✓	✓
qq	X	✓	X	X
ν ν	X	✓	X	X

between tt and signal events





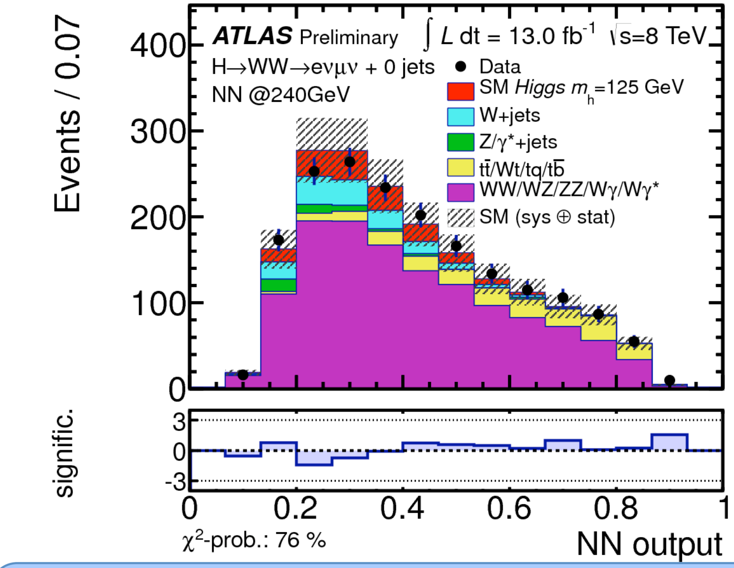
2HDM searches with $H \rightarrow WW \rightarrow e\nu\ \mu\nu$

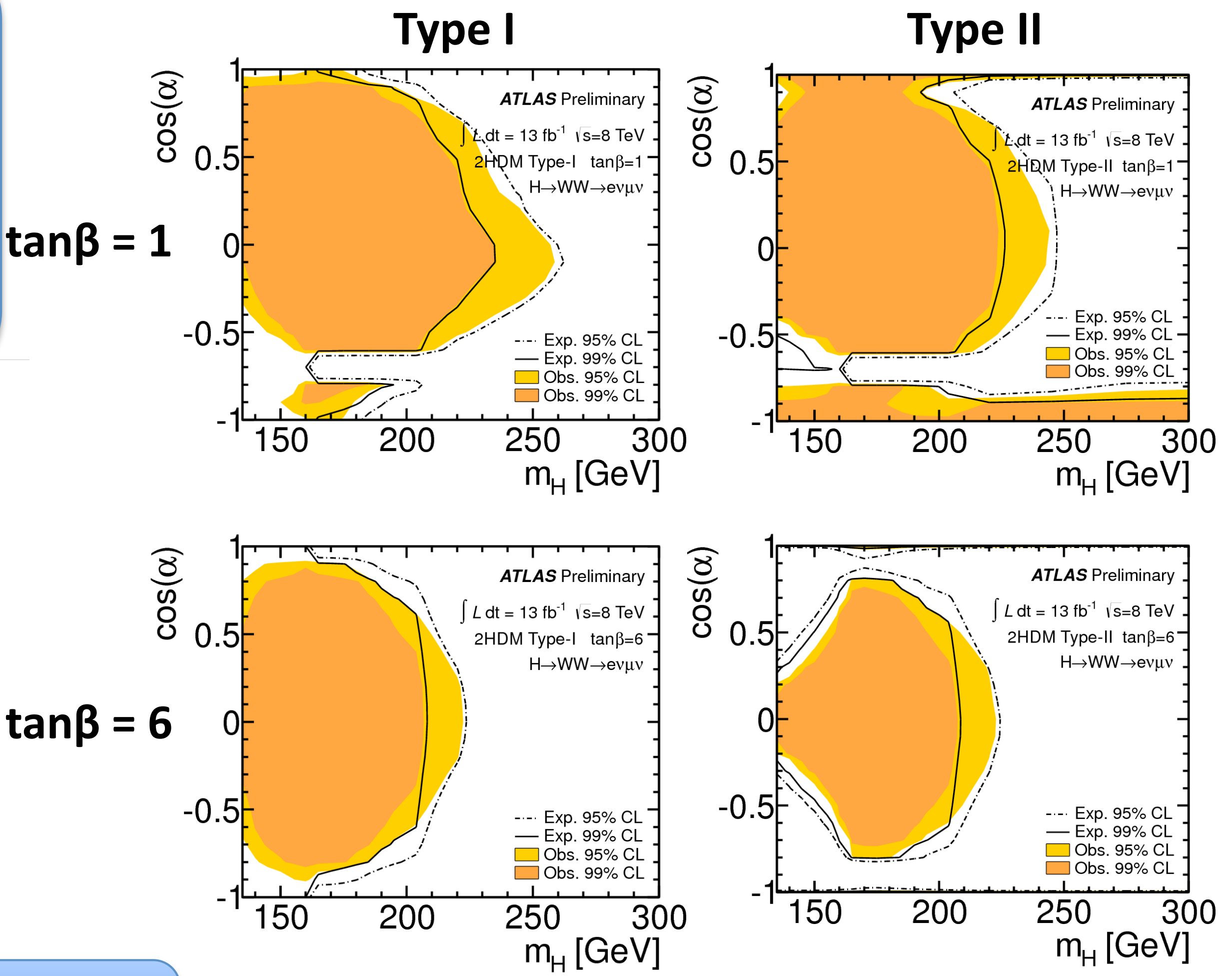
ATLAS-CONF-2013-027

muons & electrons
- isolated
- $p_T > 25\ (15)$ GeV and $|\eta| < 2.4\ (2.47)$

jets
- $p_T > 20$ GeV and $|\eta| < 2.5$
- $p_T > 30$ GeV and $2.5 < |\eta| < 4.5$

events:
- exactly 0 jets or 2 non b-tagged jets



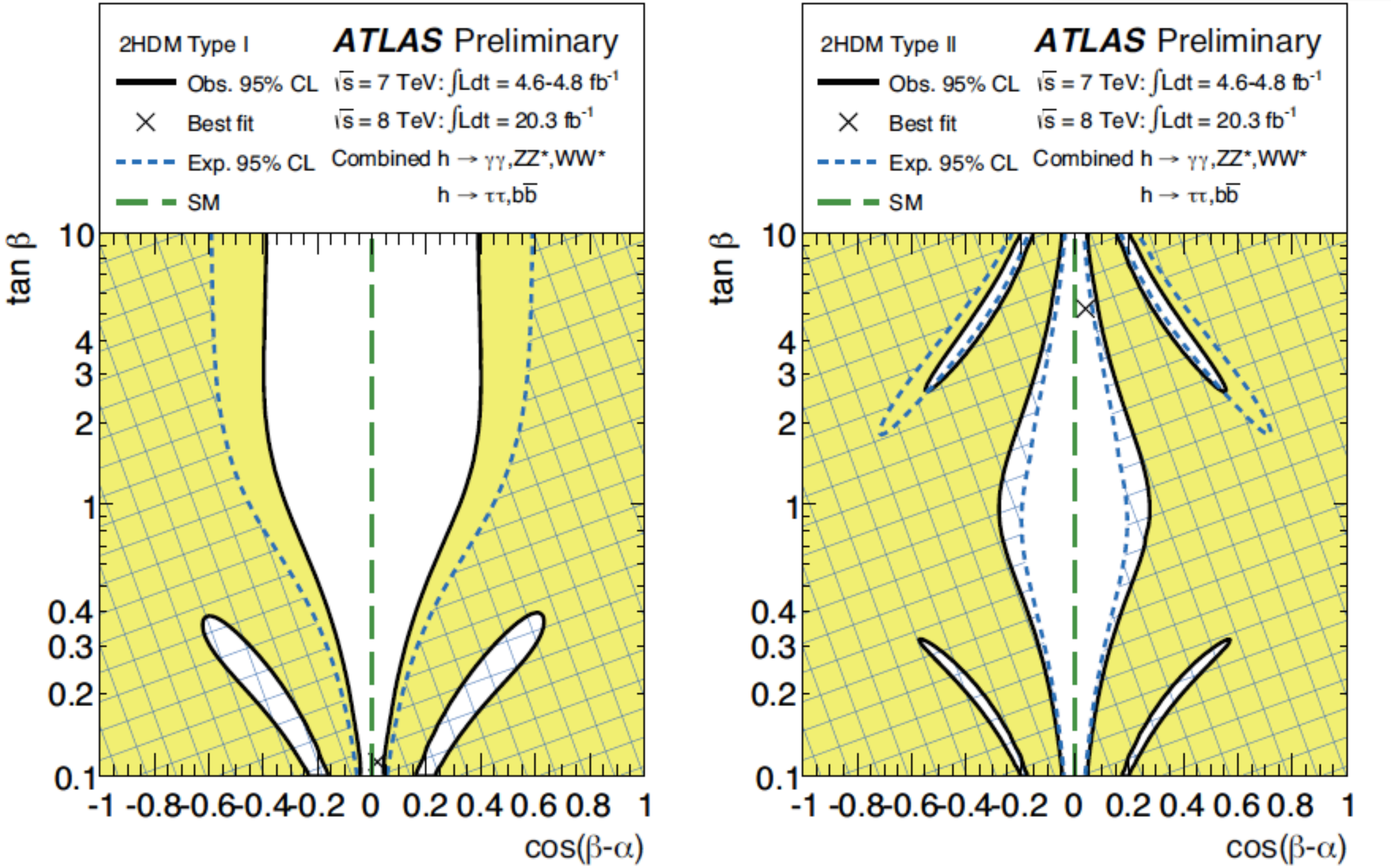


- signal hypothesis includes Higgs-like boson at 125 GeV as light scalar *h* of a 2HDM
- null hypothesis assumes no Higgs boson

- no additional Higgs boson (H) is found in the mass range of $135 < m_H < 300$ GeV

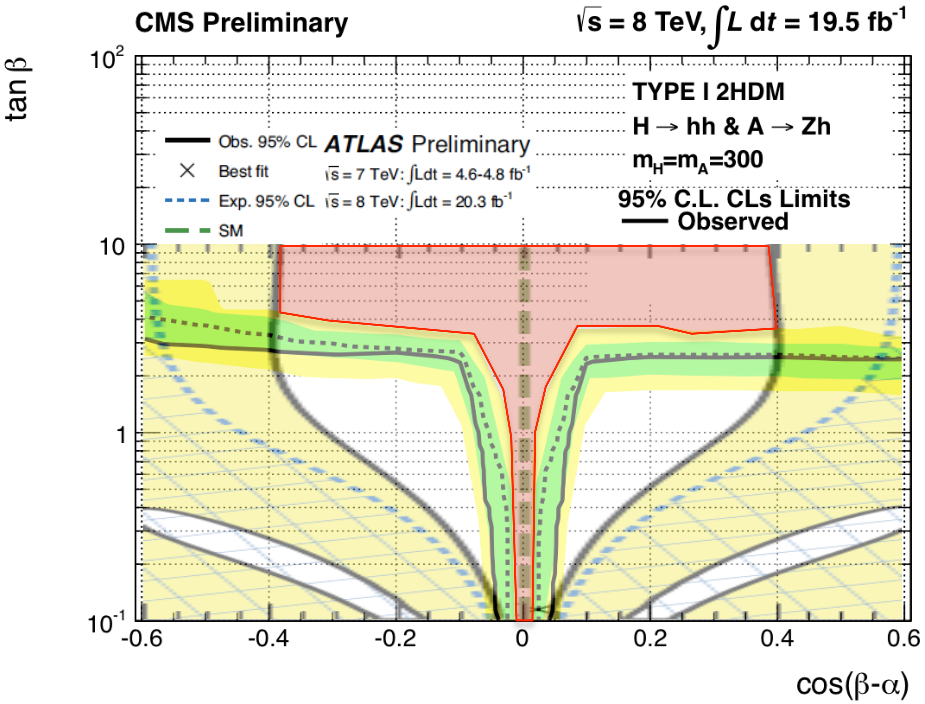
2HDM results combined

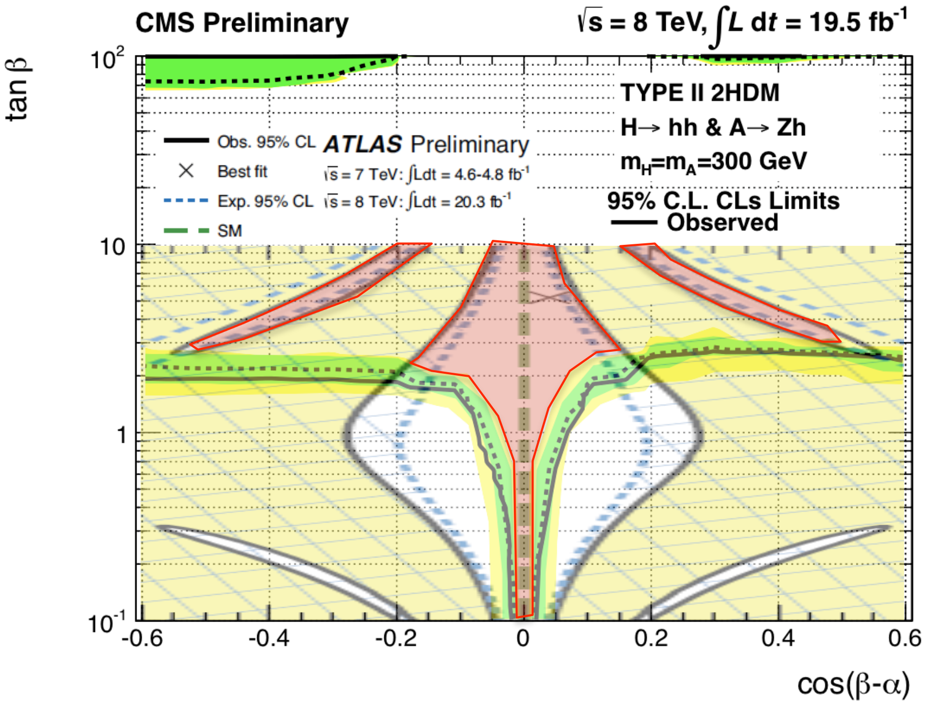
ATLAS-CONF-2014-010



2HDM results combined

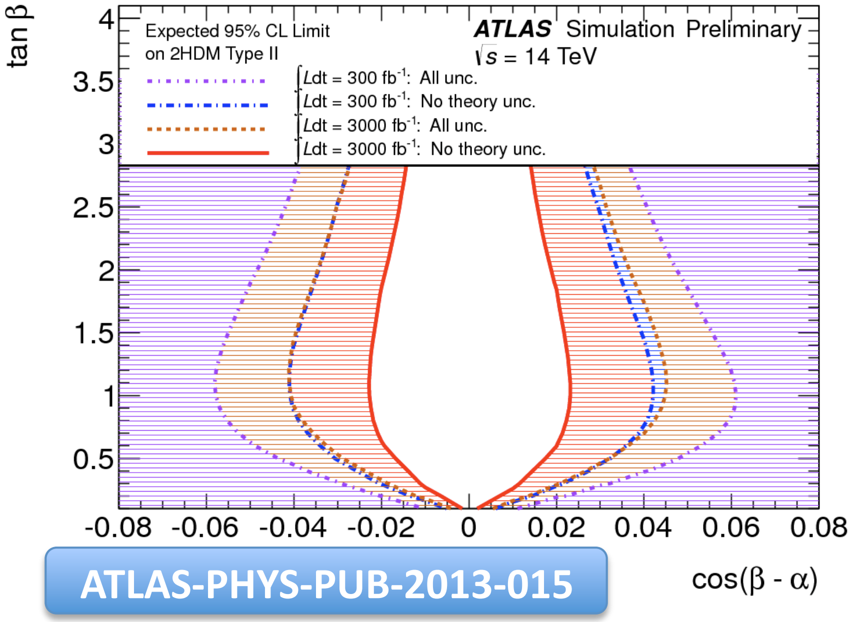
🟥 “allowed” (eye) combined regions from ATLAS and CMS



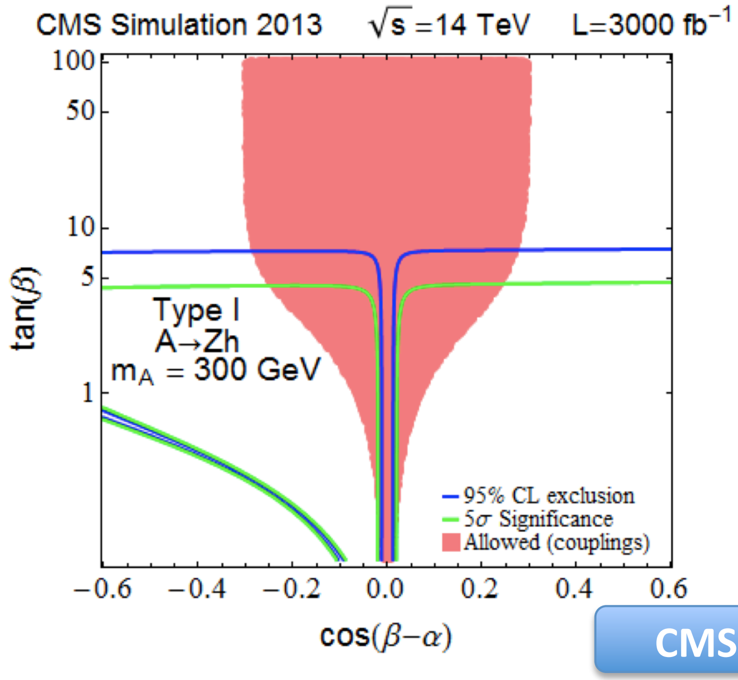


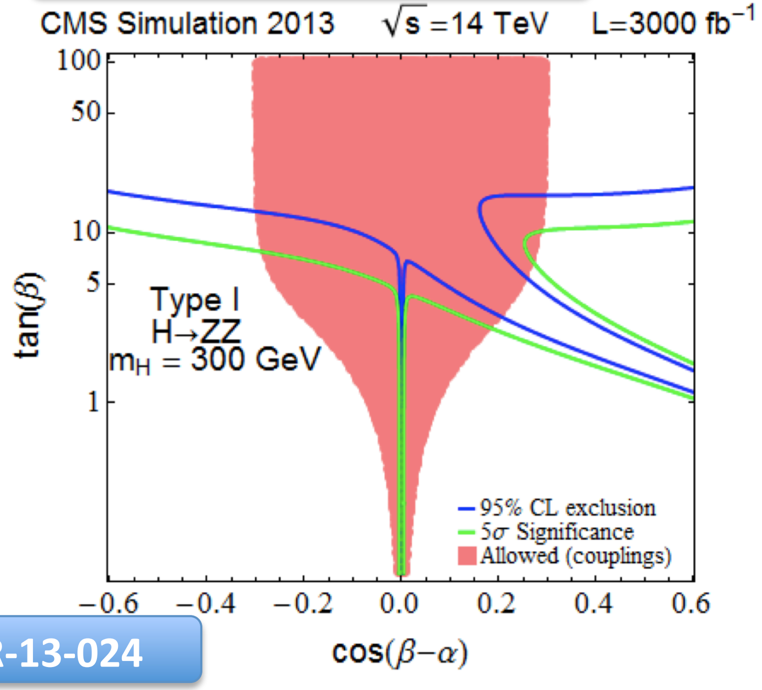
2HDM perspectives

- allowed phase space will shrink more and more, but if we do not find a signal we need more brilliant ideas to close it



ATLAS-PHYS-PUB-2013-015





CMS-PAS-FTR-13-024

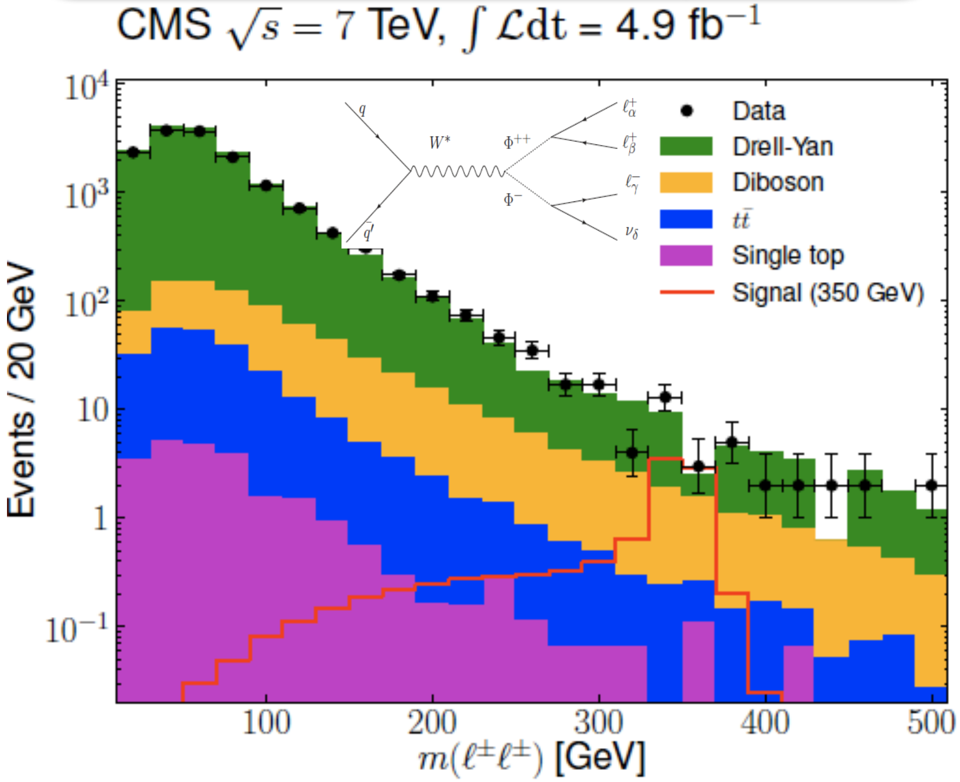
double charged Higgs

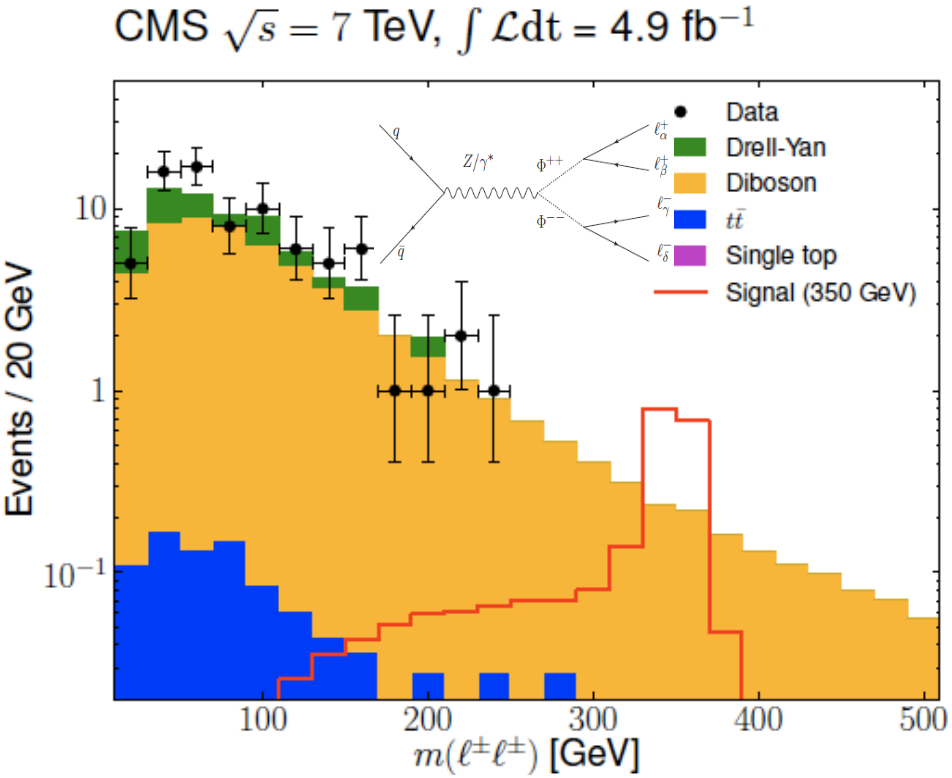
minimal type II seesaw model:

- 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
- production processes: $\Phi^{++}\Phi^{--}$ pair & $\Phi^{++}\Phi^{-}$ associated production

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 states)

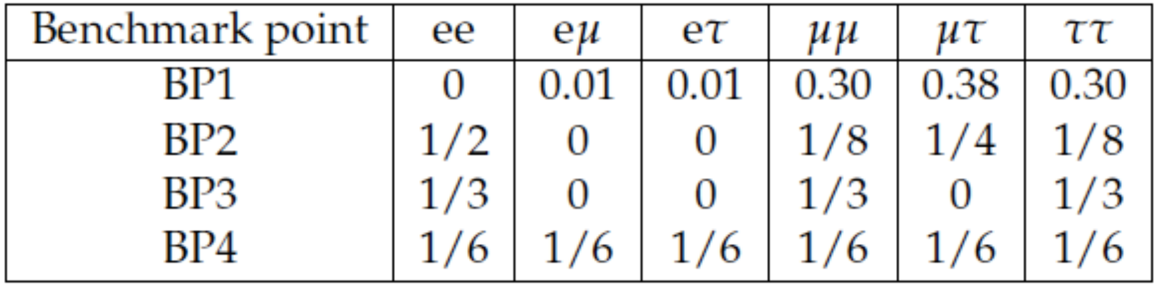




double charged Higgs

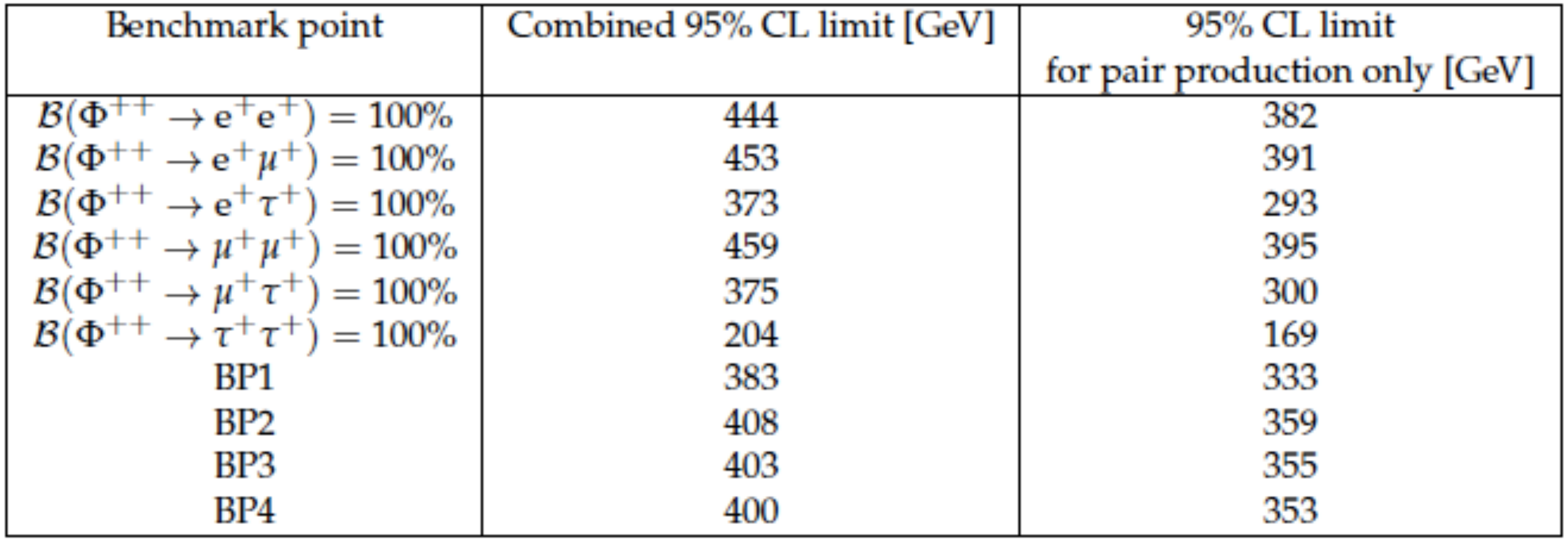
- BP1: a massless neutrino, normal mass hierarchies
- BP2: a massless neutrino, inverted mass hierarchies
- BP3: degenerate neutrino mass spectrum (0.2 eV)
- BP4: Φ^{++} with equal BR to each lepton generation.

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

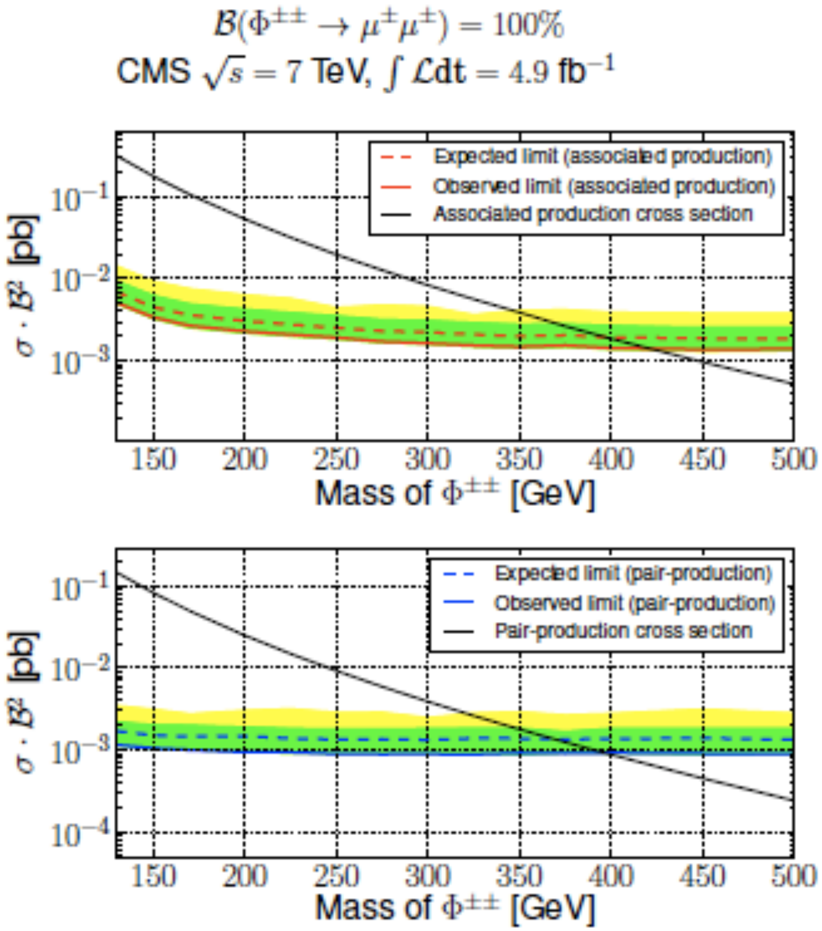
observed limits:

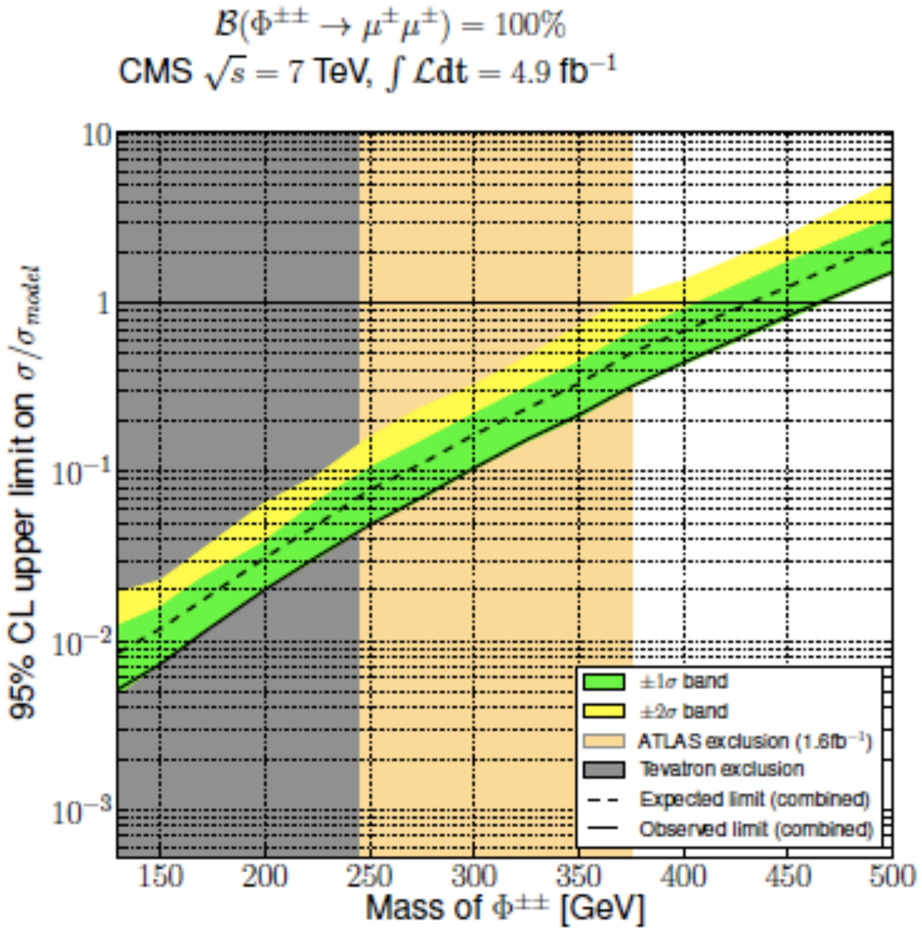


Benchmark point	Combined 95% CL limit [GeV]	95% CL limit for pair production only [GeV]
$\mathcal{B}(\Phi^{++} \to e^+e^+) = 100\%$	444	382
$\mathcal{B}(\Phi^{++} \to e^+\mu^+) = 100\%$	453	391
$\mathcal{B}(\Phi^{++} \to e^+\tau^+) = 100\%$	373	293
$\mathcal{B}(\Phi^{++} \to \mu^+\mu^+) = 100\%$	459	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

CMS

double charged Higgs





- **limits calculated also for**
  $\Phi^{\pm\pm} \to e^\pm e^\pm$, $\Phi^{\pm\pm} \to e^\pm\mu^\pm$,
  $\Phi^{\pm\pm} \to e^\pm\tau^\pm$, $\Phi^{\pm\pm} \to \mu^\pm\tau^\pm$, $\Phi^{\pm\pm} \to \tau^\pm\tau^\pm$

more details in Eur. Phys. J. C 72 (2012) 2189

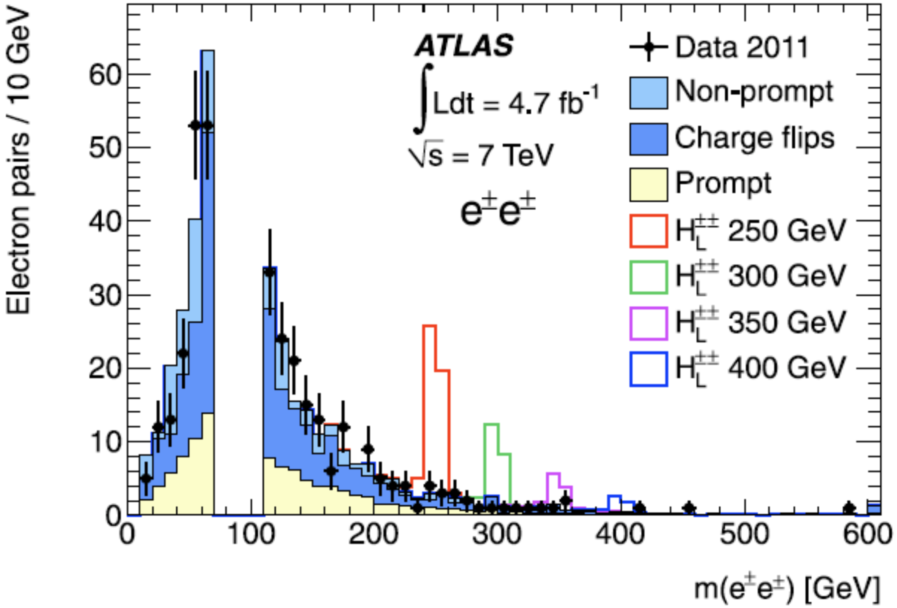
double charged Higgs

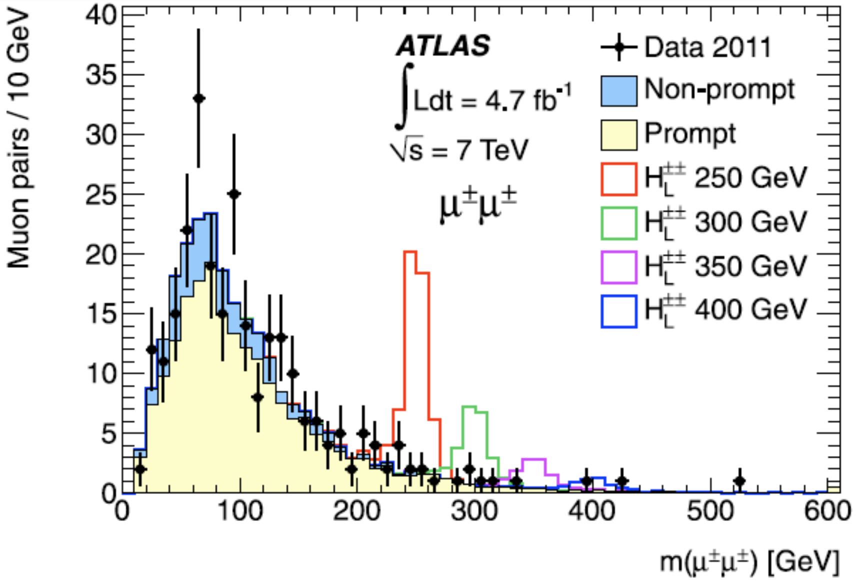
- **final states:** $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$

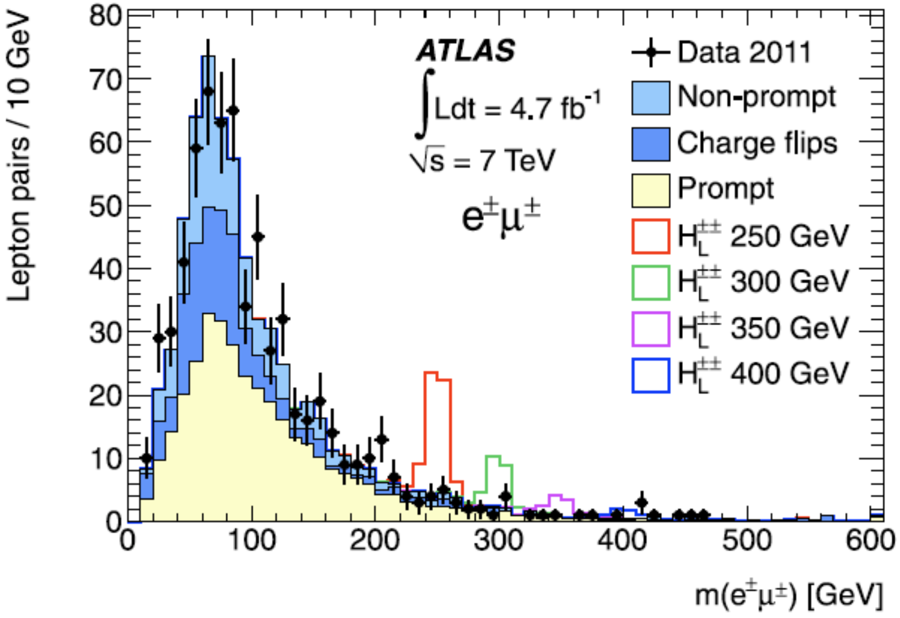
- only $H^{\pm\pm}$ prompt decays: $c\tau < 10\ \mu m$

- **event selection:**

- single lepton triggers with $p_T > 18$ (20 & 22) GeV for μ (e)
- leading p_T lepton with $p_T > 25$ GeV, while next-to-leading lepton with $p_T > 20$ GeV
- $m_{ll} > 15$ GeV and for $e^{\pm}e^{\pm}$ $70 < m_{ll} < 110$ GeV excluded due to charge misidentification



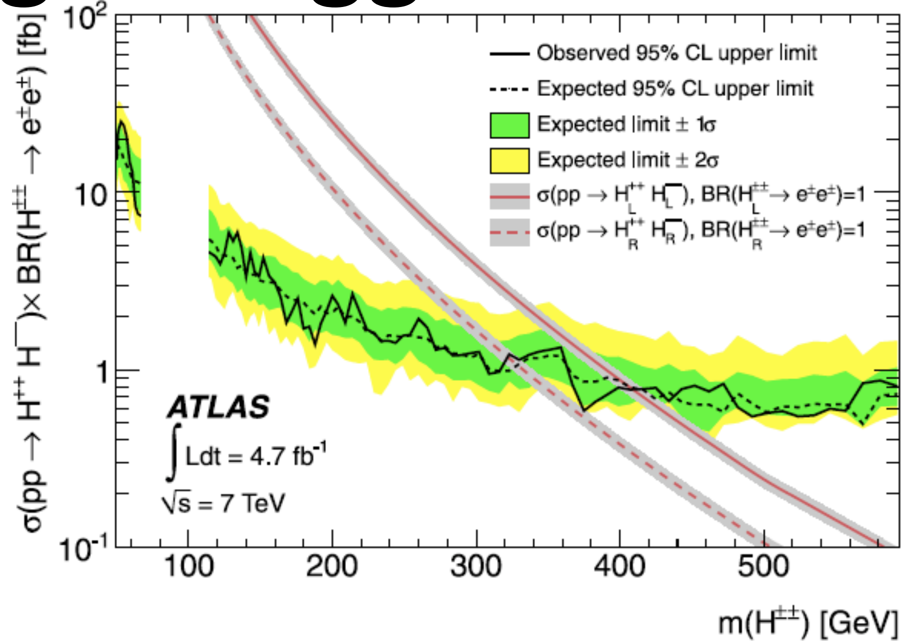


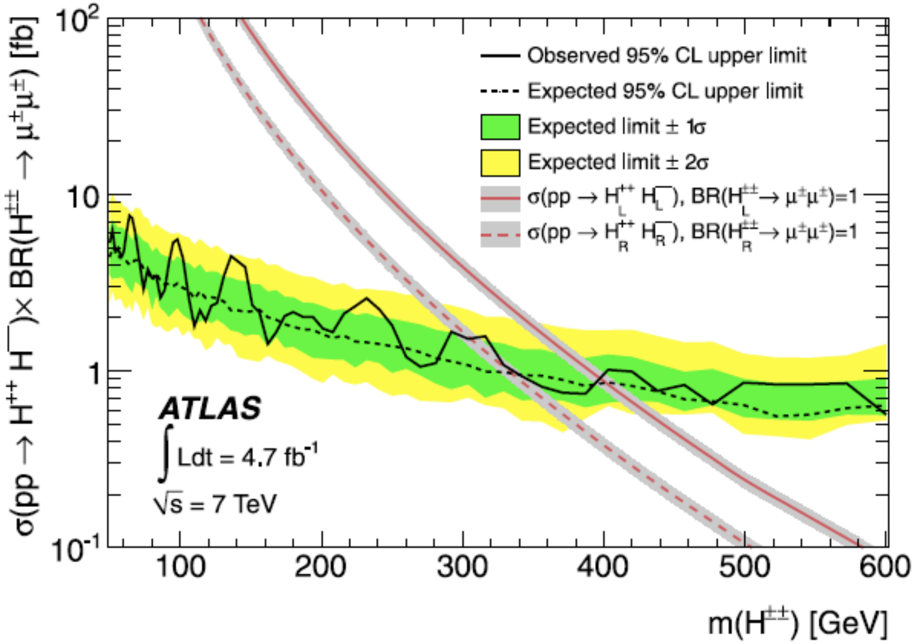


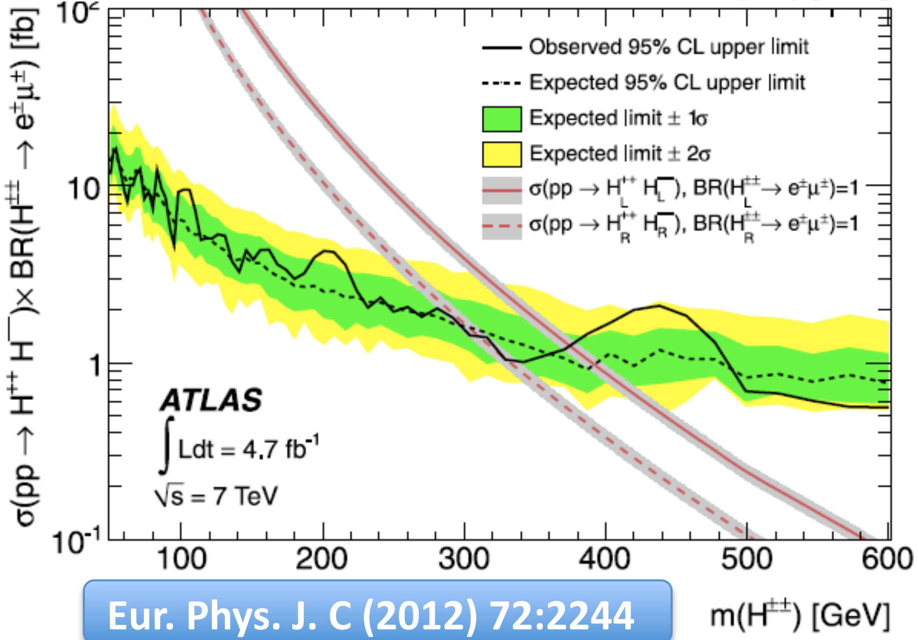
ATLAS

double charged Higgs

- couples to either left- or right-handed fermions
- in left-right asymmetric models the two cases are distinguished: $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$
- $\sigma(H_L^{++}H_L^{--})/\sigma(H_R^{++}H_R^{--}) \approx 2.5$ (due to different couplings to Z boson)







Eur. Phys. J. C (2012) 72:2244

SM & EWK singlet scalar

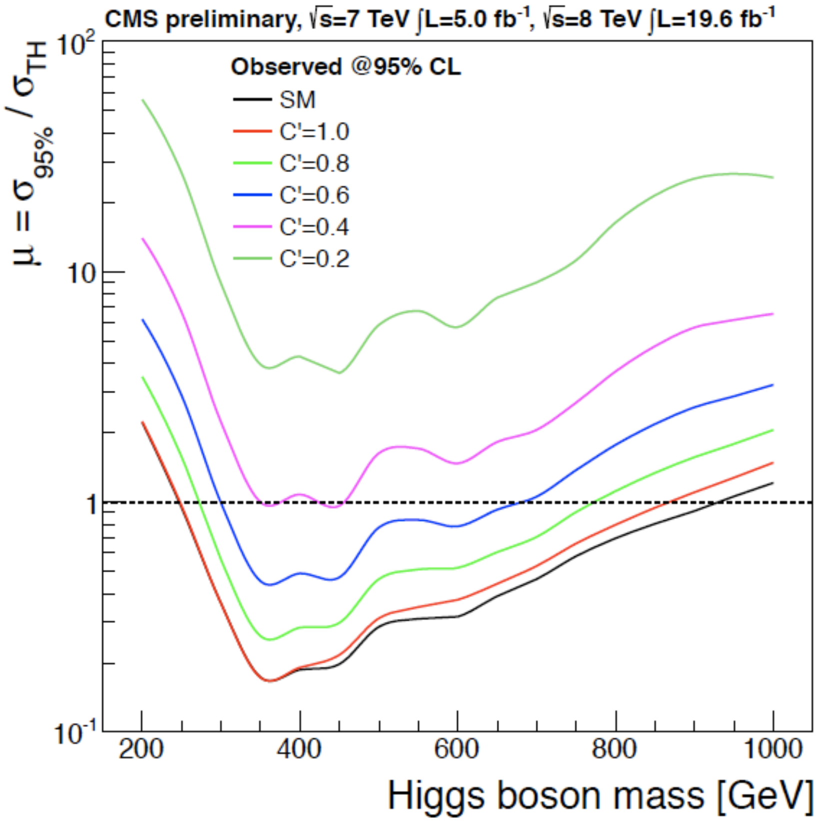
(at high mass with H→ZZ→2l2ν)

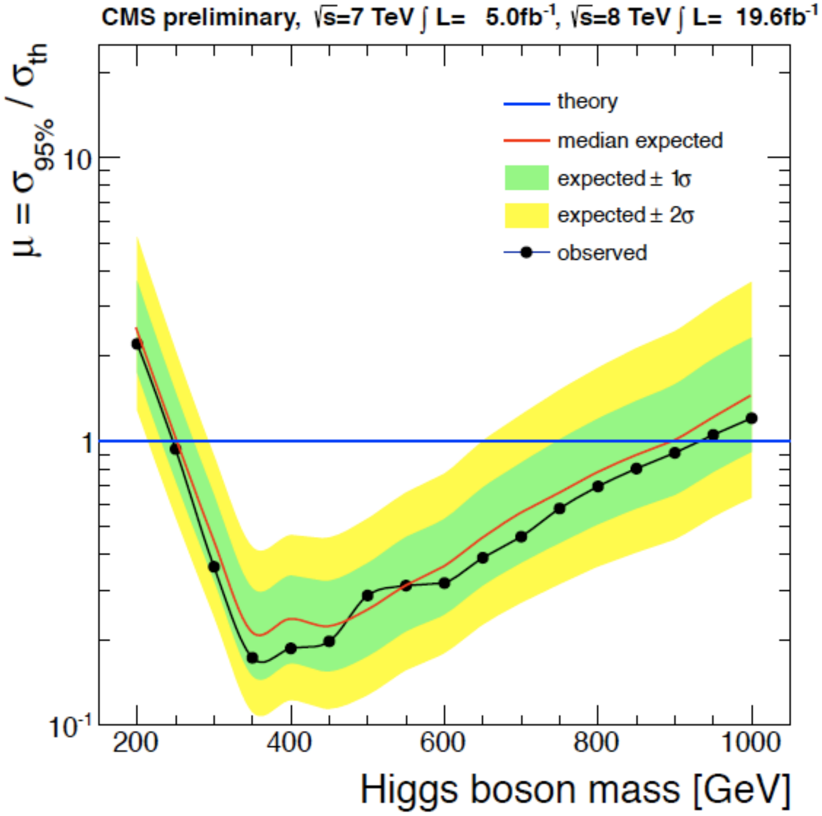
$C^2 + C'^2 = 1$ *unitarity condition*

$$\mu' = C'^2 \cdot (1 - BR_{\mathrm{new}})$$

$$\Gamma' = \Gamma_{\mathrm{SM}} \cdot \frac{C'^2}{1 - BR_{\mathrm{new}}}$$

- electroweak singlet scalar mixing with the h^0 (125 GeV)
- C (C') couplings scale factors of the low (high) mass relative to SM
- EWK singlet cross-section modified by a factor μ'
- width Γ'
- BR_{new}: branching ratio of EWK singlet to non-SM-like decay modes





CMS-PAS-HIG-13-014

ATLAS

SM & EWK singlet scalar

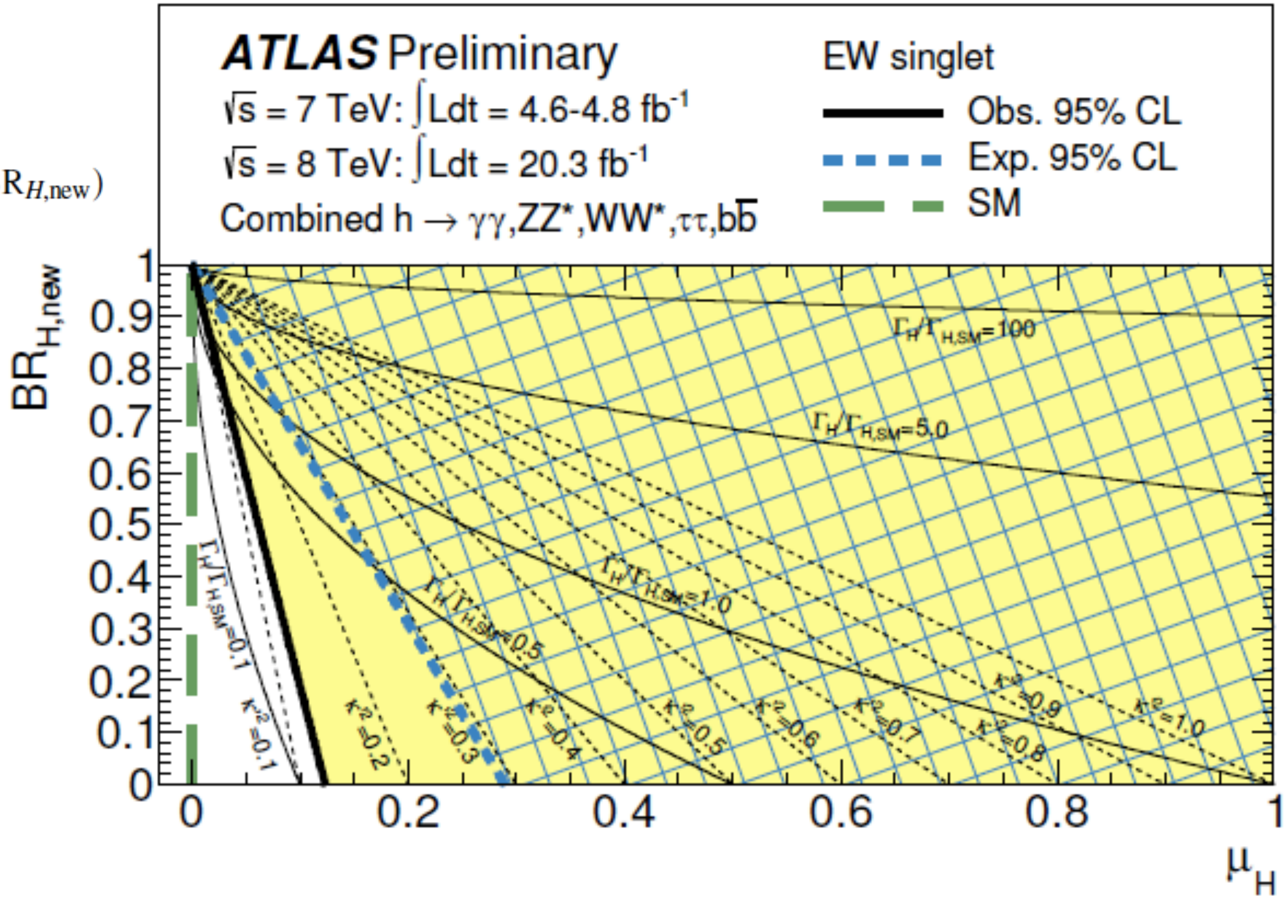
$$\mu_h = \frac{\sigma_h \times \mathrm{BR}_h}{(\sigma_h \times \mathrm{BR}_h)_{\mathrm{SM}}} = \kappa^2$$

$$\mu_H = \frac{\sigma_H \times \mathrm{BR}_H}{(\sigma_H \times \mathrm{BR}_H)_{\mathrm{SM}}} = \kappa'^2\,(1 - \mathrm{BR}_{H,\mathrm{new}})$$

$\kappa'^2 = 1 - \mu_h$ $\kappa' = C'$ *(from CMS)*

- heavy Higgs squared coupling as function of signal strength of the light Higgs boson

limit on κ'^2:
expected $\kappa'^2 < 0.29$
observed $\kappa'^2 < 0.12$



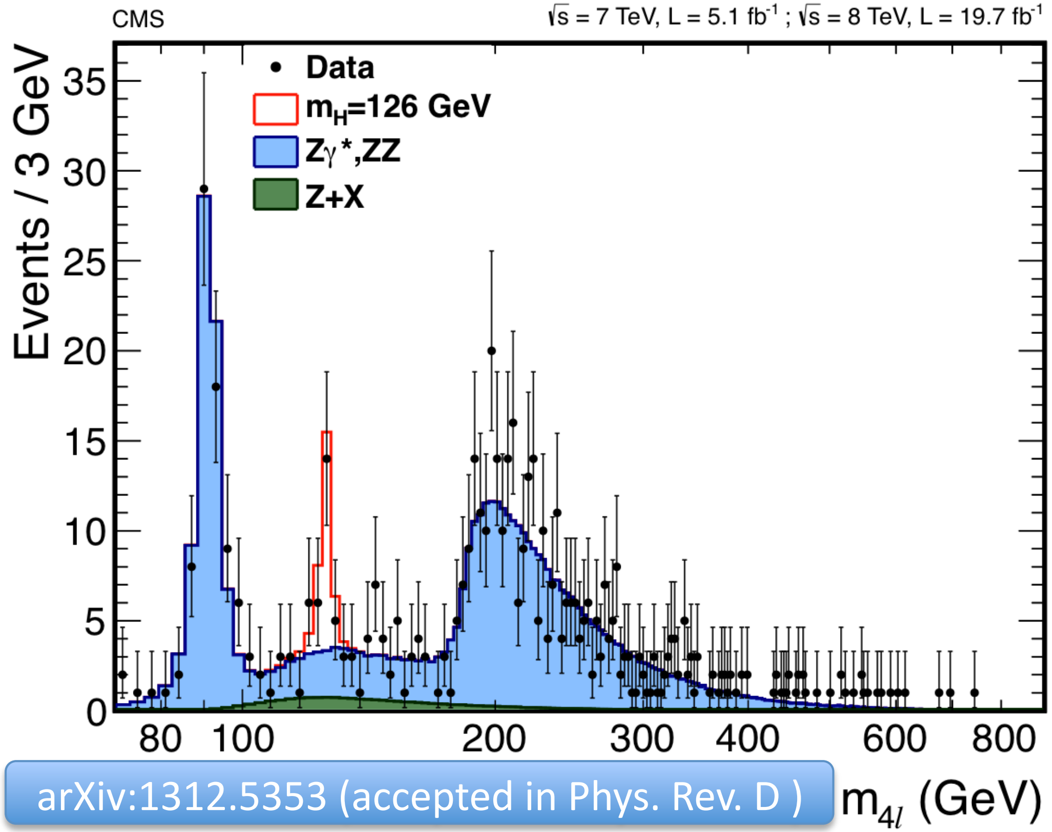
other searches at high mass in SM: $H \rightarrow ZZ \rightarrow 4\ell$

- Z - with mass between **40** and **120** GeV
- Z* - with mass between **12** and **120** GeV
- both Z bosons decay into 2 leptons and the following combinations are used: ee ee, ee μμ, μμμμ
- no τ leptons due to worse mass resolution

event selection:

- 4 isolated leptons coming from same primary vertex (Z decay):
  $p^{\mu}_{T} > 5$ GeV and $|\eta^{\mu}| < 2.4$
  $p^{e}_{T} > 7$ GeV and $|\eta^{e}| < 2.5$
- at least one lepton with $p_T >$ **20** GeV and one with $p_T >$ **10** GeV
- make use of di-jet (VBF), untagged category (gg fusion) and kinematics
- **clean signal** over small background contributions from ZZ, Z+jets (b) and tt

no 4-lepton event observed for invariant mass **above 800** GeV

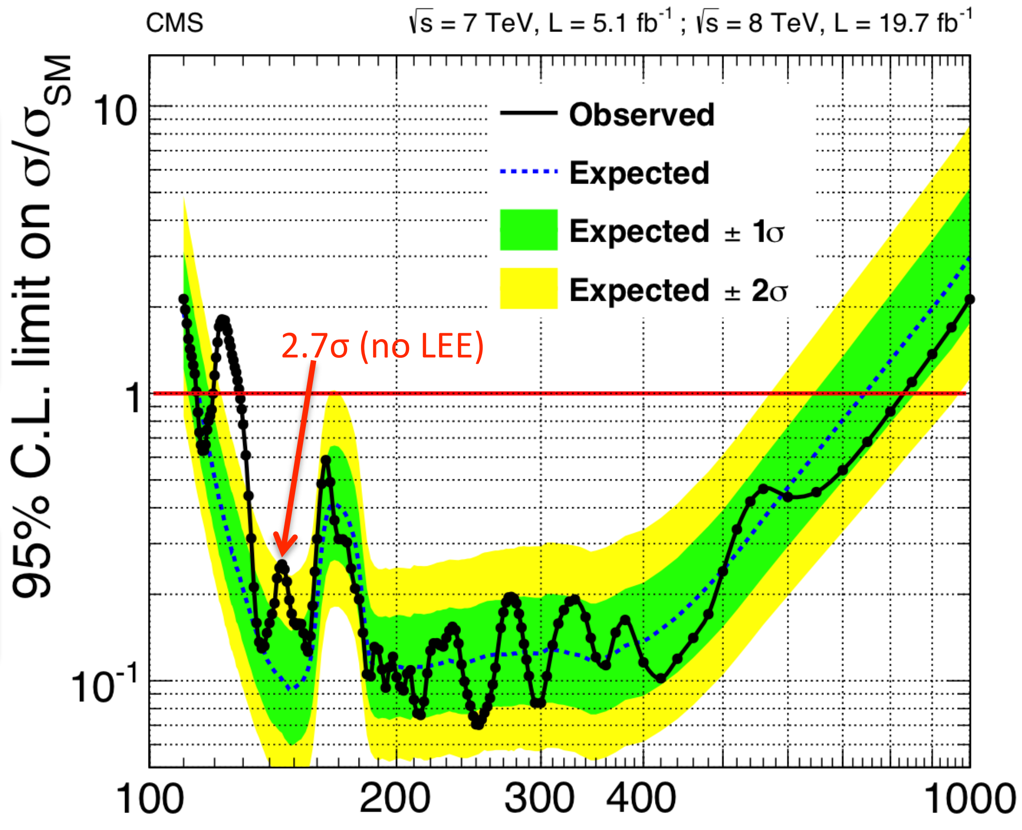


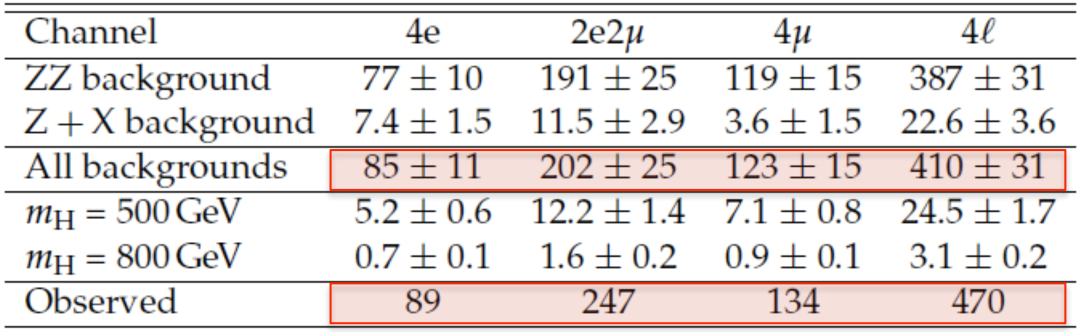
arXiv:1312.5353 (accepted in Phys. Rev. D)

high mass SM: $H \rightarrow ZZ \rightarrow 4\ell$

SM-like Higgs boson excluded in the four-lepton channels at a 95% CL in the mass ranges **114.5–119.0** GeV
and **129.5–832.0** GeV,
for an expected exclusion range **115–740** GeV.

hopefully once the “Higgs rash” is gone we go back to limits on σ x BR





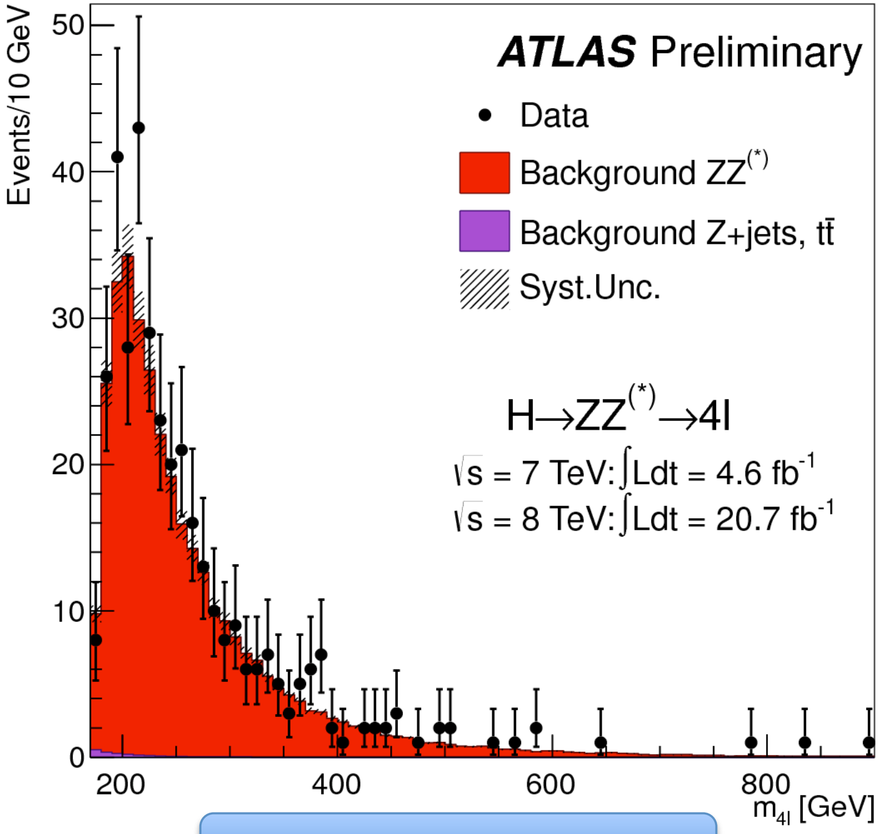
Channel	4e	$2e2\mu$	4μ	4ℓ
ZZ background	77 ± 10	191 ± 25	119 ± 15	387 ± 31
Z + X background	7.4 ± 1.5	11.5 ± 2.9	3.6 ± 1.5	22.6 ± 3.6
All backgrounds	85 ± 11	202 ± 25	123 ± 15	410 ± 31
$m_H = 500$ GeV	5.2 ± 0.6	12.2 ± 1.4	7.1 ± 0.8	24.5 ± 1.7
$m_H = 800$ GeV	0.7 ± 0.1	1.6 ± 0.2	0.9 ± 0.1	3.1 ± 0.2
Observed	89	247	134	470

high mass SM: $H \rightarrow ZZ \rightarrow 4\ell$

- Z - with mass between **50** and **106** GeV
- Z* - with mass between **12** and **115** GeV for $m_{4l} < 140$ GeV
  goes linearly to **50** and **115** GeV up to $m_{4l} < 190$ GeV
- both Z bosons decay into 2 leptons and the following combinations are used: ee ee, ee μμ, μμμμ
- no τ leptons due to worse mass resolution

event selection:

- 4 isolated leptons coming from same primary vertex (Z decay):
  $p^{\mu}_{T} > 6$ GeV and $|\eta^{\mu}| < 2.7$
  $p^{e}_{T} > 7$ GeV and $|\eta^{e}| < 2.47$
- at least one
  lepton with $p_T >$ **20** GeV,
  one with $p_T >$ **15** GeV
  and one with $p_T >$ **10** GeV
- make use of di-jet (VBF), additional leptons (W/ZH) and untagged category (gg fusion)



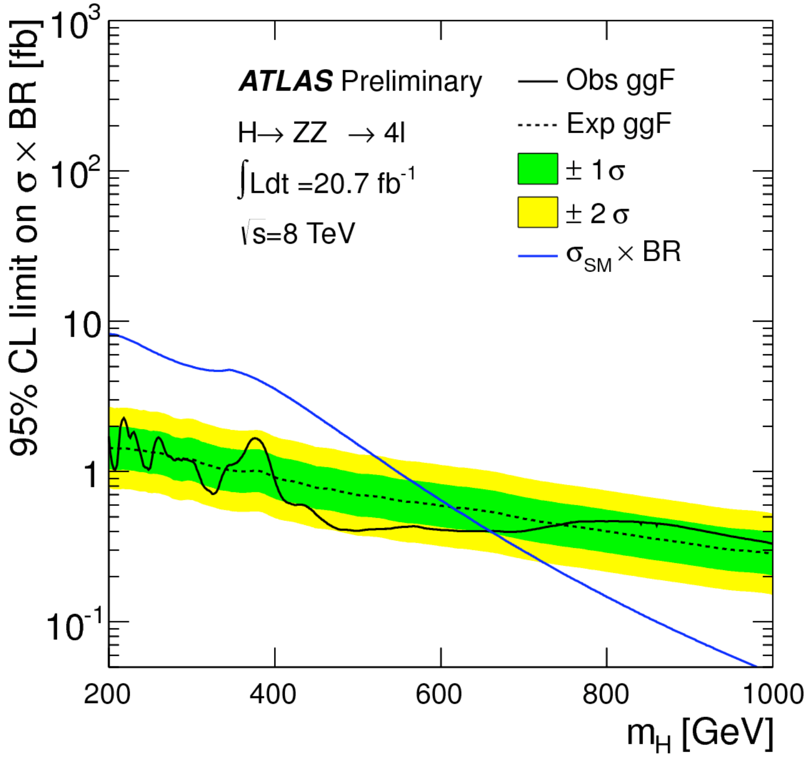
between 800 and 900 GeV, 2 events with 4-leptons are observed

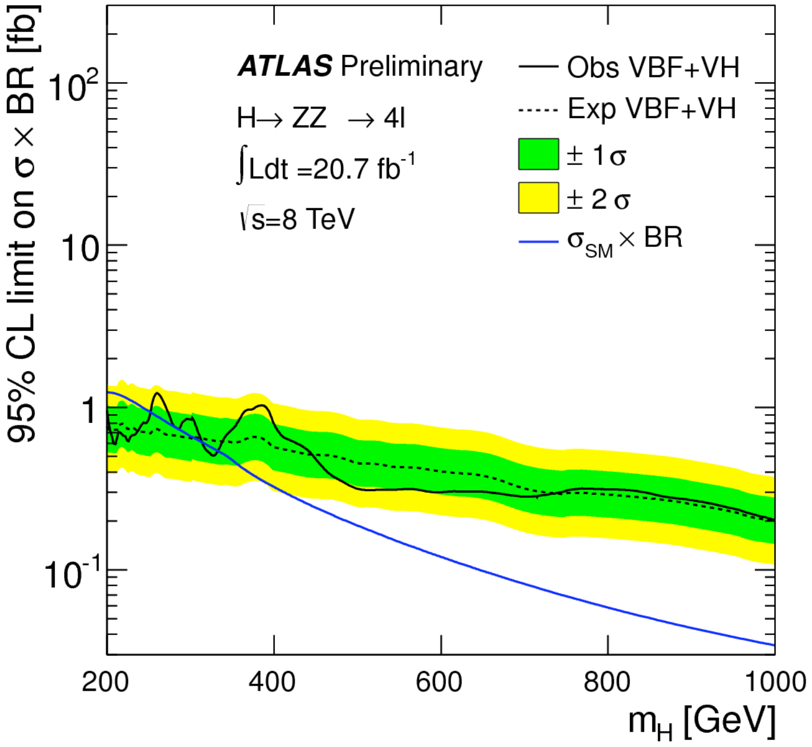
ATLAS-CONF-2013-013

high mass SM: H→ZZ→ 4ℓ

	4μ		2μ2e/2e2μ		4e	
	< 160 GeV low mass	≥ 160 GeV high mass	low mass	high mass	low mass	high mass
$\sqrt{s}$ = 8 TeV integrated luminosity 20.7 fb^{-1}						
$ZZ^{(*)}$	12.4 ± 0.6	92.6 ± 6.7	14.7 ± 0.9	144 ± 11	5.4 ± 0.5	55.9 ± 4.5
Z, $Zb\bar{b}$, and $t\bar{t}$	1.9 ± 0.6	0.5 ± 0.2	6.1 ± 1.5	1.5 ± 0.4	2.5 ± 0.6	0.6 ± 0.2
total background	14.3 ± 0.8	93.1 ± 6.7	20.8 ± 1.8	145 ± 11	8.0 ± 0.8	56.5 ± 4.5
data	27	93	28	169	13	55

2.1σ (no LEE)





high mass SM: H → WW

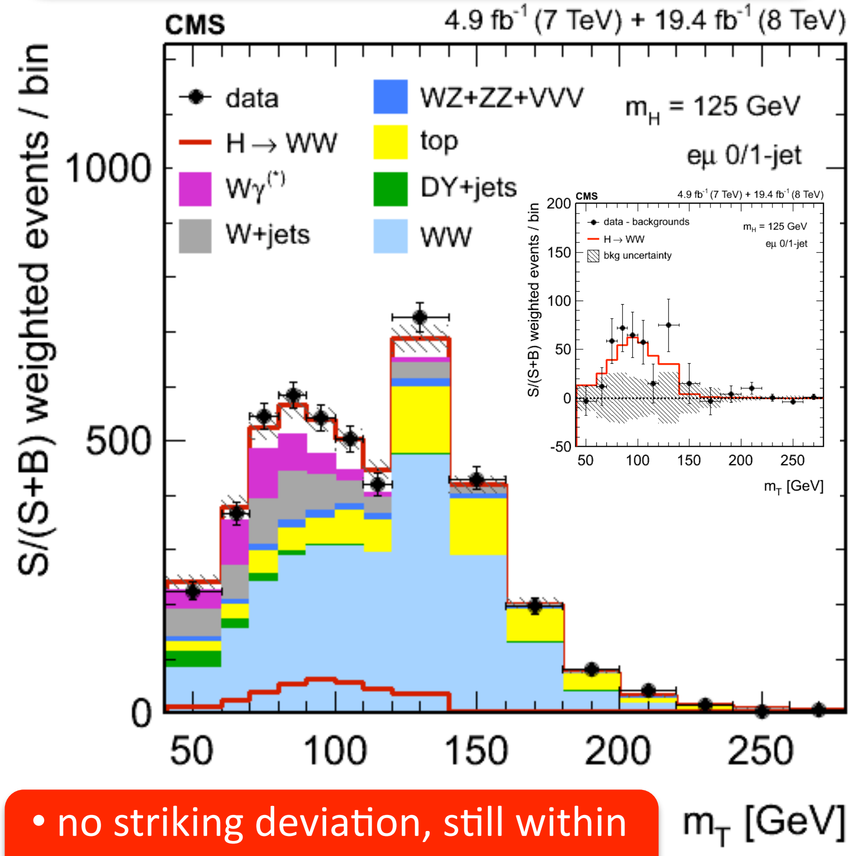
$$m_{\mathrm{T}}^2 = 2p_{\mathrm{T}}^{\ell\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\Delta\phi(\ell\ell,\vec{E}_{\mathrm{T}}^{\mathrm{miss}}))$$

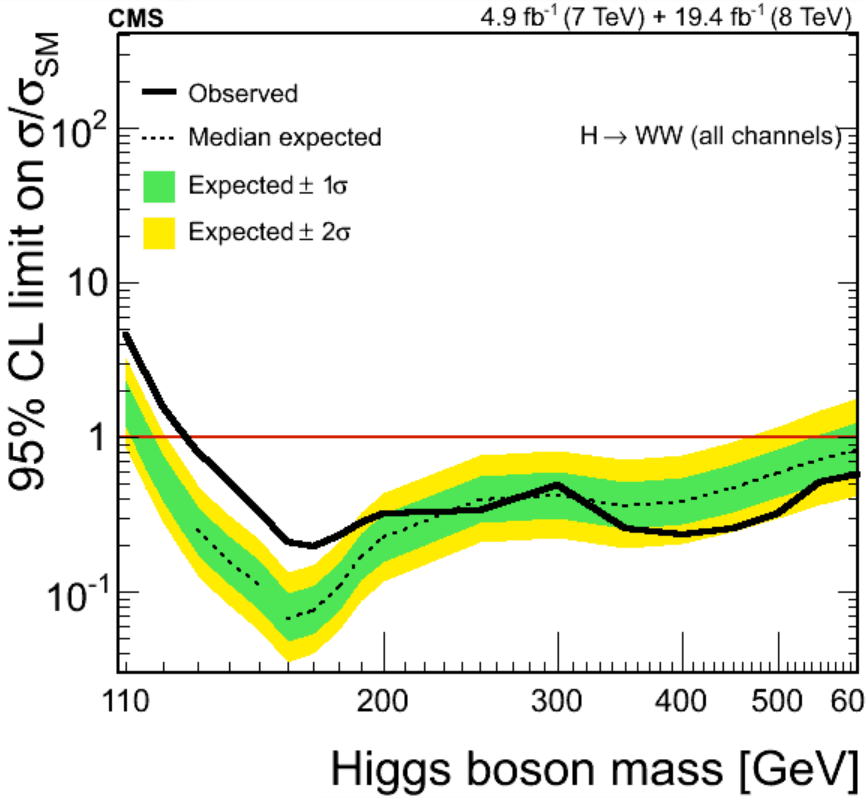
$p_{\mathrm{T}}^{\ell\ell}$ - dilepton transverse momentum

$\Delta\phi(\ell\ell,\vec{E}_{\mathrm{T}}^{\mathrm{miss}})$ - azimuthal angle between dilepton momentum and MET

event selection:

- 2 isolated opposite charged high pT leptons (e, μ) and missing energy from the neutrinos
- gain sensitivity splitting statistics in events with 0-, 1- and 2-jets categories
- cut'n count and shape analyses (2D)
- **signal not any longer clean:** background contributions from WW, W+jets, tt and Drell-Yan - use control regions





- no striking deviation, still within the errors

arXiv:1312.1129

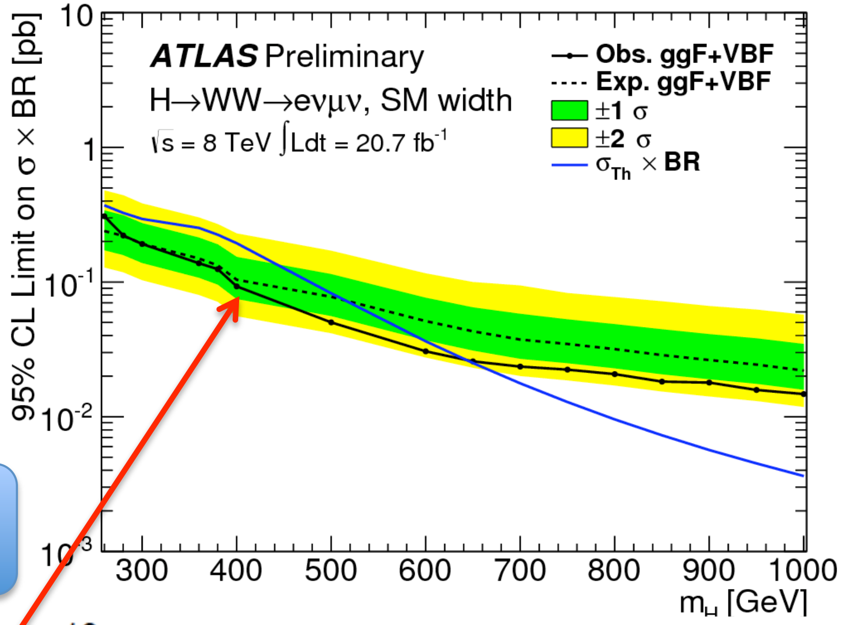
ATLAS

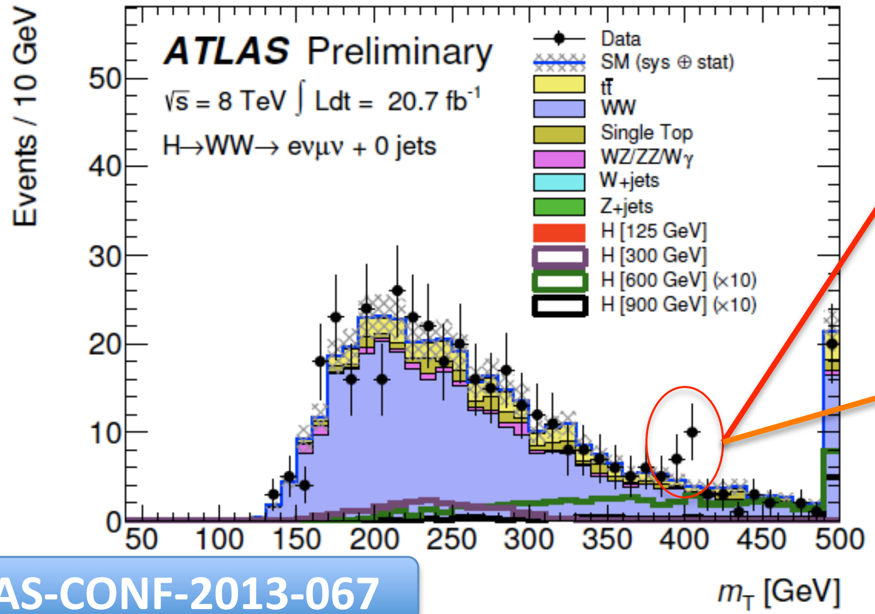
high mass SM: $H\rightarrow WW$

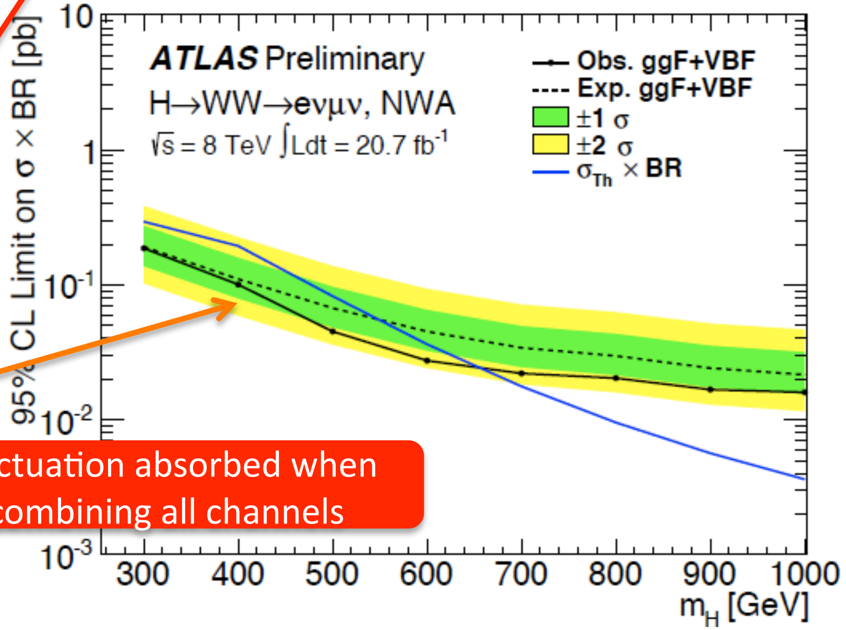
event selection:

- 2 isolated opposite charged high pT leptons (e, μ) and missing energy from the neutrinos
- gain sensitivity splitting statistics in events with 0,1- and 2-jets categories
- NWA - narrow line shape
- **background contributions from:** WW, W+jets, tt and Drell-Yan - use control regions

- mass range 260 GeV < m_H < 642 GeV excluded at 95% CL (SM cross sections are used for gluon-gluon fusion and VBF)







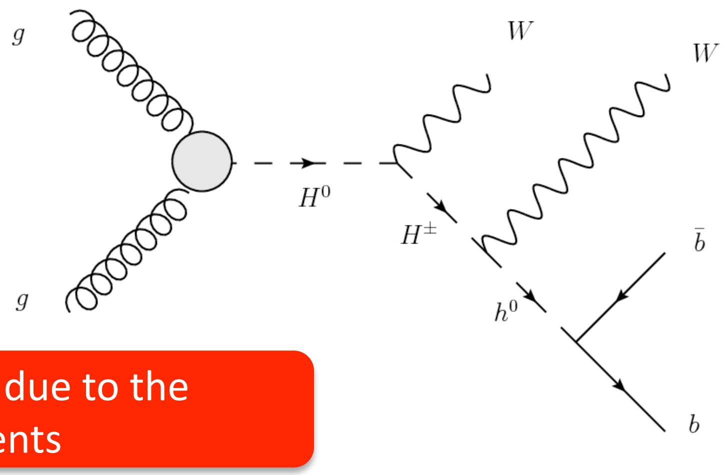
fluctuation absorbed when combining all channels

ATLAS-CONF-2013-067

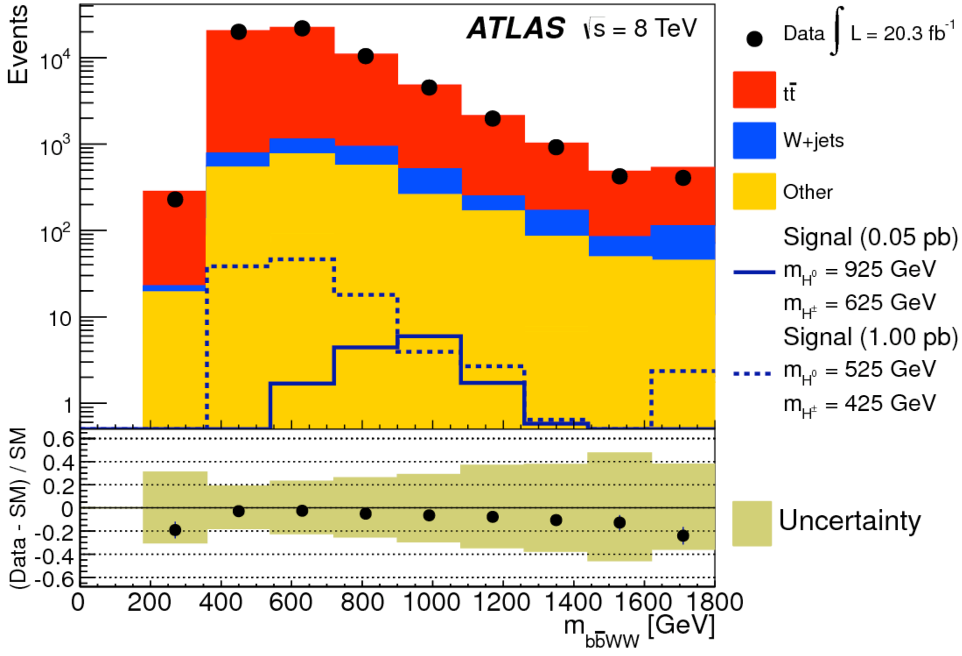
multi-Higgs cascade in WWbb

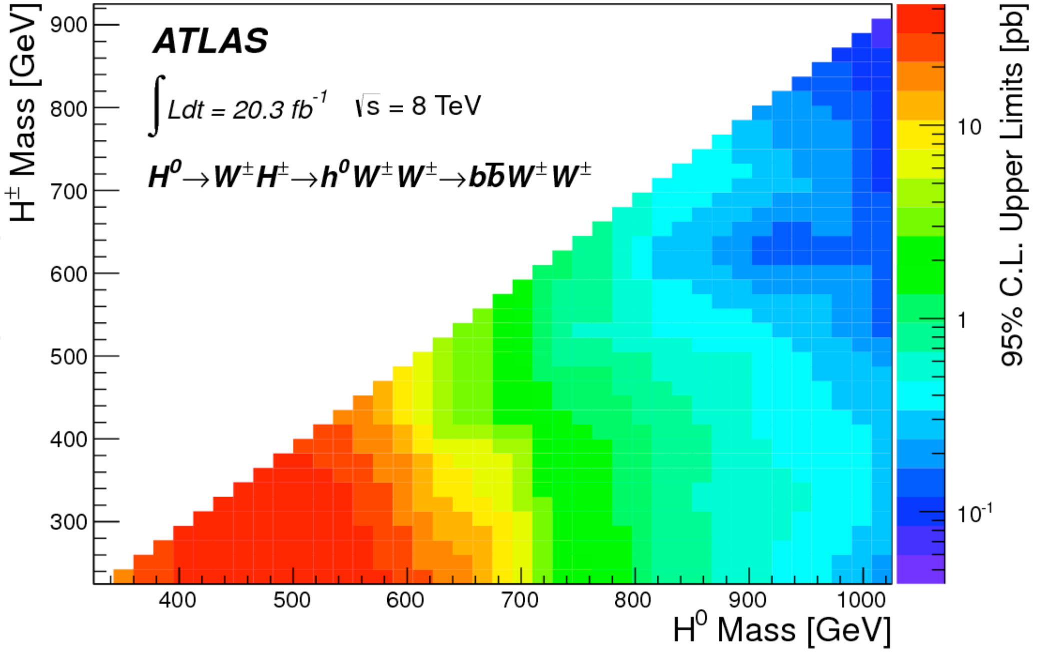
Phys. Rev. D 89, 032002 (2014)

event selection:
- one isolated high p_T lepton (e or μ) and missing energy from the neutrinos
- 4 (2 b-tagged) jets with $p_T > 25$ GeV and $|\eta|<2.5$
- **BDT** used to discriminate between Higgs cascade and main background tt
- **background contributions from:** tt, W+jets, Z+jets, fake leptons, single t

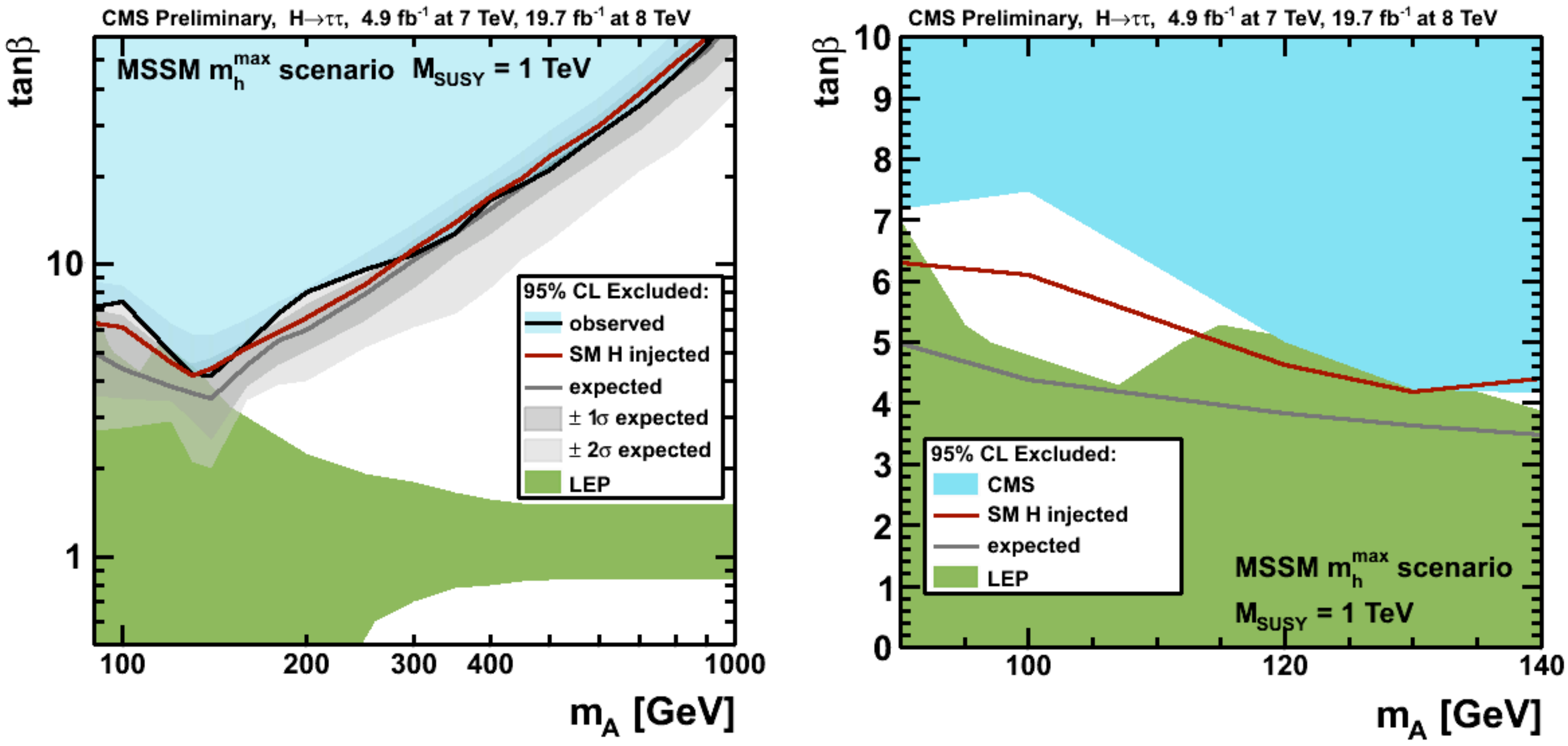


- limits are the weakest in low mass regions due to the poorer separation between tt and signal events





from last MSSM updates: ττ channel

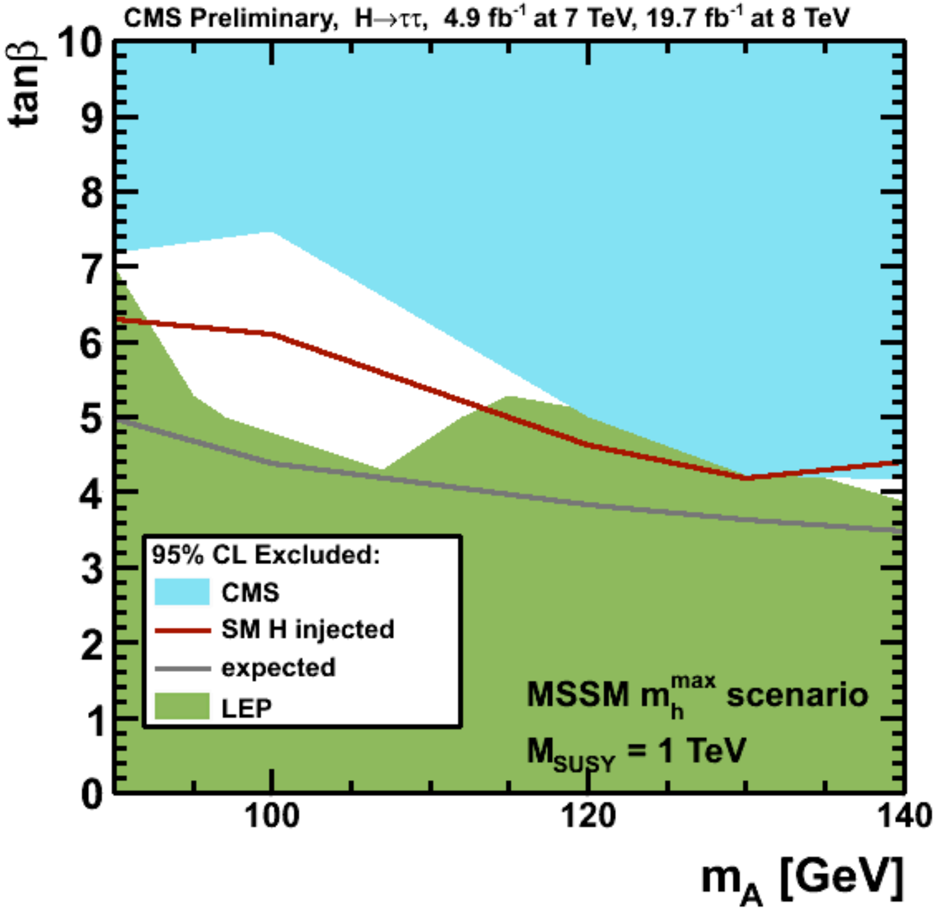


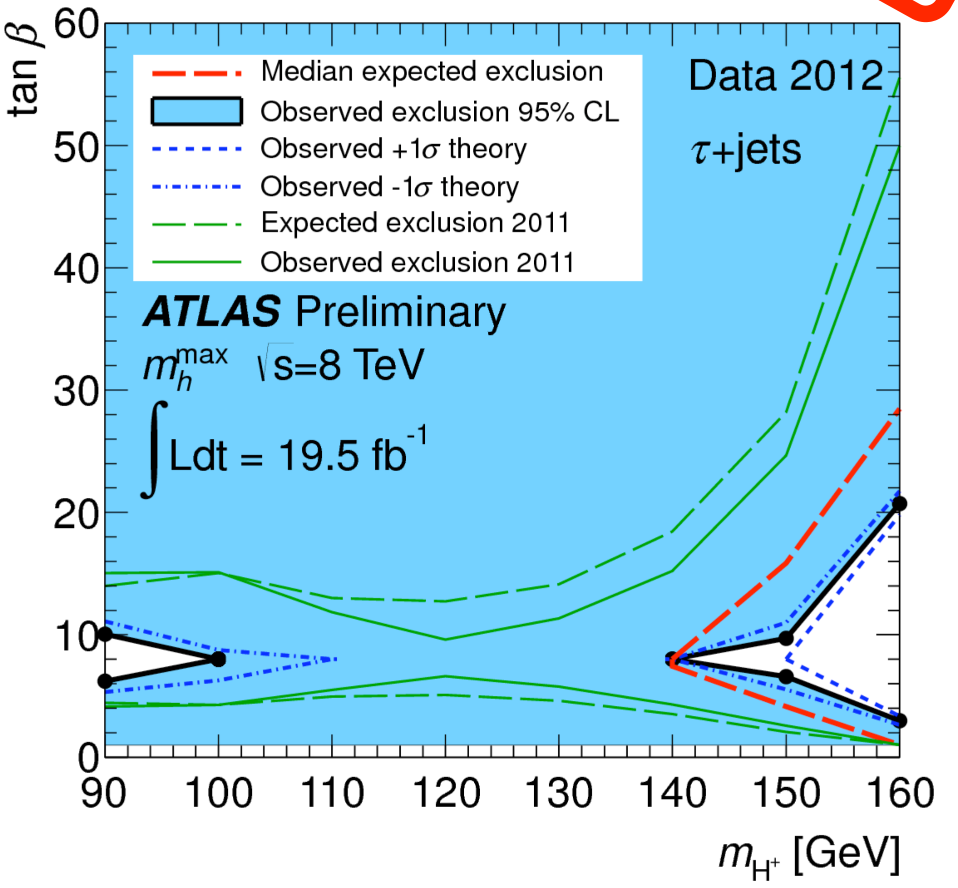
- tanβ vs. m_A window(s) are becoming smaller and smaller

CMS

so, what did we discover…

ATLAS





- is not A^0
- definitely not $H^{\pm}$
- for tanβ < 10, mass of H^0 larger than 130 GeV => this time the small h^0 wins

- in other words the “heavy” Higgs still waits to be discovered

is there still hope for MSSM?

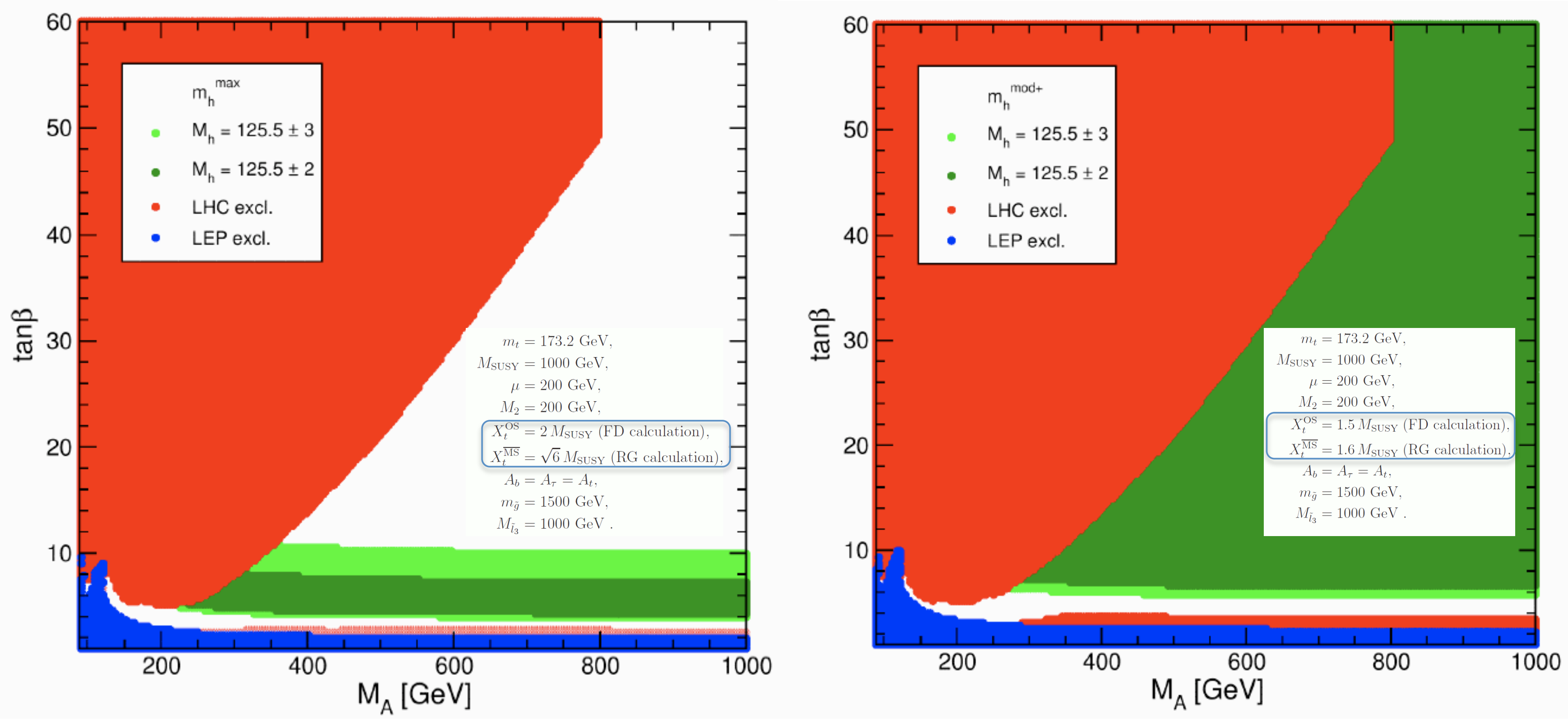
- let's open the window(s) again

a new scenario (arXiv:13027033):

- **m_h^{mod}**

- A/H decays to charginos/neutralinos are open here (arXiv:0709.1029)

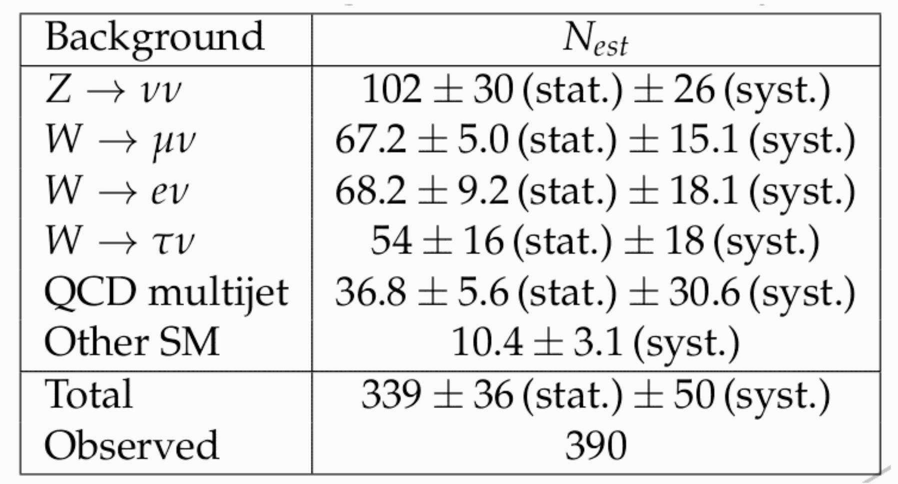
only green areas are allowed considering 125 GeV for h^0



VBF H invisible decays

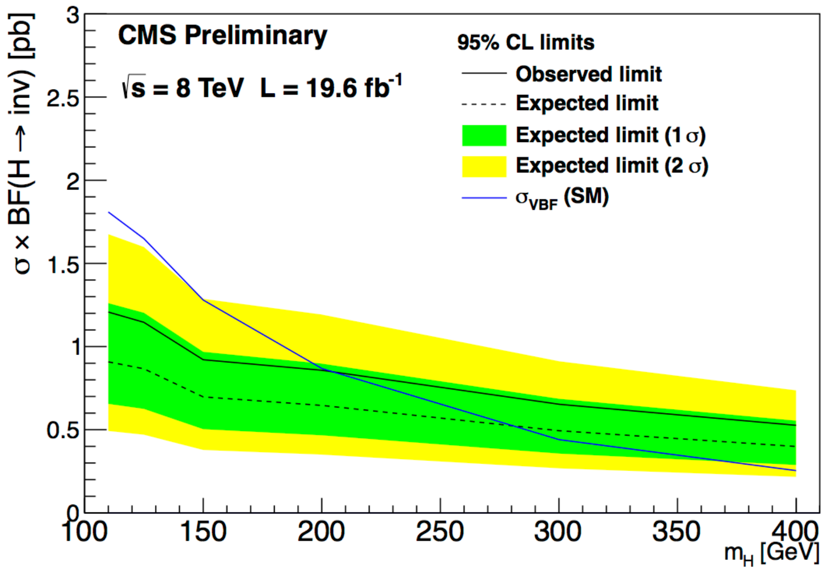
- events selection
- e and μ veto $p_T > 10$ GeV, $|\eta| < 2.1$
- 2 jets, $p_T > 50$ GeV, $|\eta| < 4.7$ and $\eta1 \cdot \eta2 < 0$
- $|\Delta\eta_{jj}| > 4.2$ and $M_{jj} > 1100$ GeV
- $E_T^{miss} > 130$ GeV
- central jet vet: $p_T > 30$ GeV, $\eta_{jet1} < \eta < \eta_{jet2}$
- $\Delta\varphi jj < 1.0$

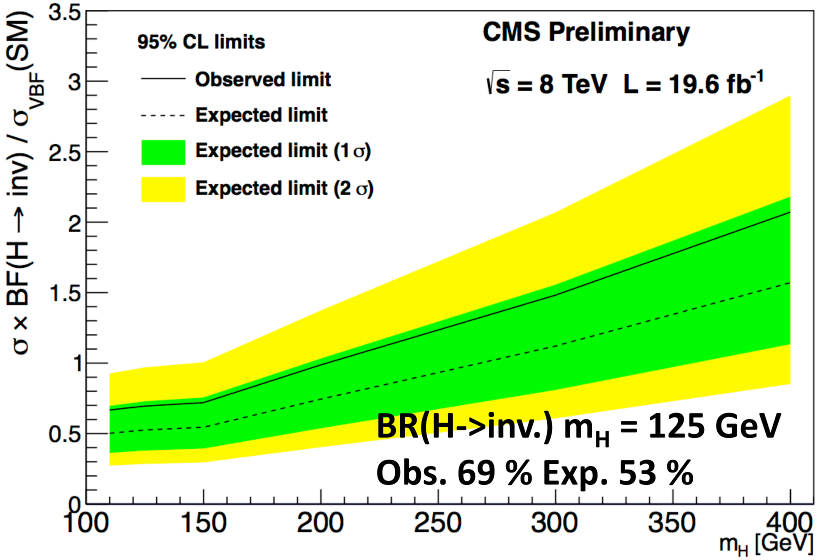
- background estimation



Background	N_{est}
$Z \to \nu\nu$	102 ± 30 (stat.) ± 26 (syst.)
$W \to \mu\nu$	67.2 ± 5.0 (stat.) ± 15.1 (syst.)
$W \to e\nu$	68.2 ± 9.2 (stat.) ± 18.1 (syst.)
$W \to \tau\nu$	54 ± 16 (stat.) ± 18 (syst.)
QCD multijet	36.8 ± 5.6 (stat.) ± 30.6 (syst.)
Other SM	10.4 ± 3.1 (syst.)
Total	339 ± 36 (stat.) ± 50 (syst.)
Observed	390

- more details in **HIG-13-013**



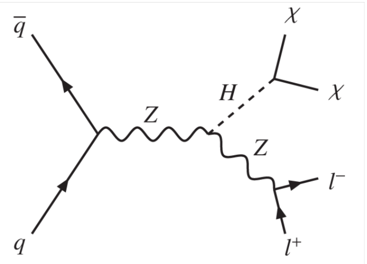


BR(H->inv.) m_H = 125 GeV

Obs. 69 % Exp. 53 %

ATLAS

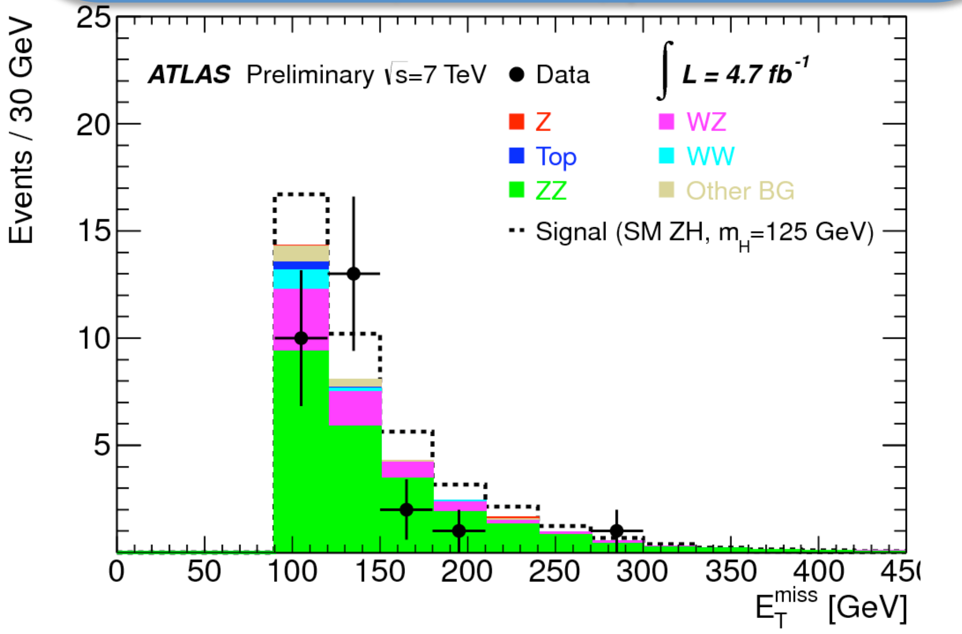
Z(ll)H invisible decays

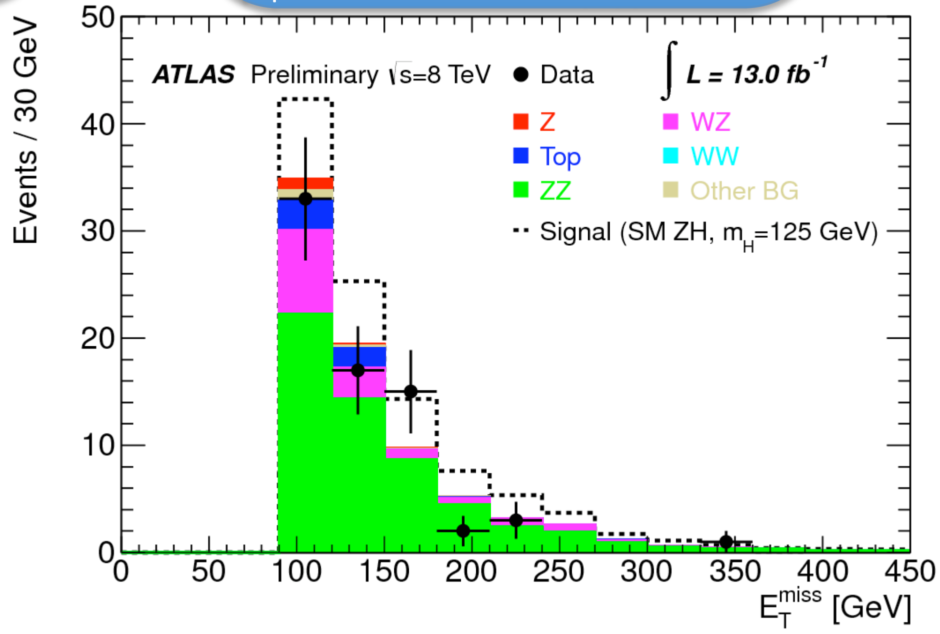


event selection:

- single and double leptons triggers
  - signal efficiency: 100% for $Z^0 \to e^+e^-$ and 95% for $Z^0 \to \mu^+\mu^-$
- lepton selection
  - two isolated opposite charge leptons with $p_T > 20$ GeV and $|\eta_e| < 2.47$ while $|\eta_\mu| < 2.4$
  - $76 < m_{ll} < 106$ GeV
  - veto on third lepton with $p_T > 7$ GeV

- topological cuts
  - $E_T^{miss} > 90$ GeV
  - $\Delta\phi\ (E_T^{miss}, p_T^{miss}) < 0.2$ rad
  - $\Delta\phi\ (Z_{ll}, E_T^{miss}) > 2.6$ rad
  - $\Delta\phi_{ll} < 1.7$ rad
  - $|E_T^{miss} - p_T^{ll}|/p_T^{ll} < 0.2$
  - no jet with $p_T > 20$ GeV and $|\eta| < 2.5$





Z(ll)H invisible decays

what is invisible?

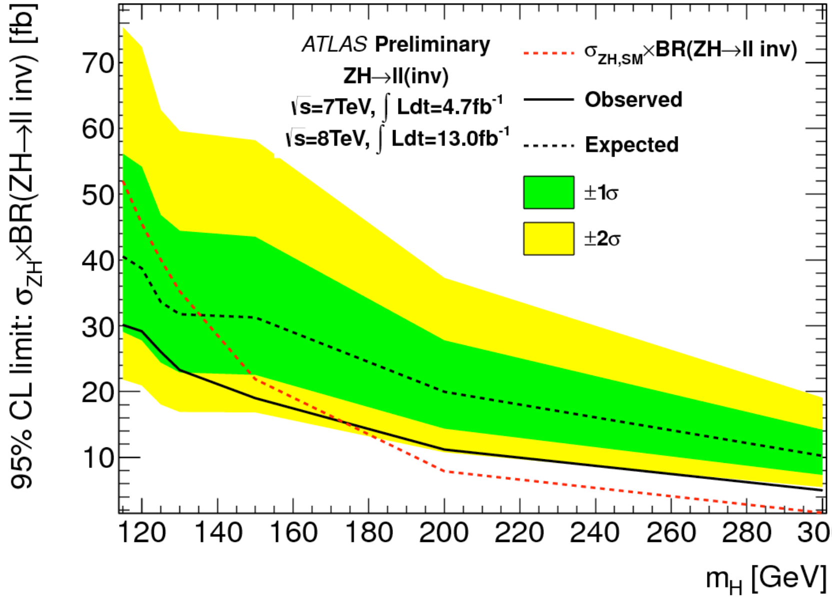
- SM: H->2Z->4ν (SM with BR ~0.1%)
- BSM: Higgs decays into a pair of LSPs

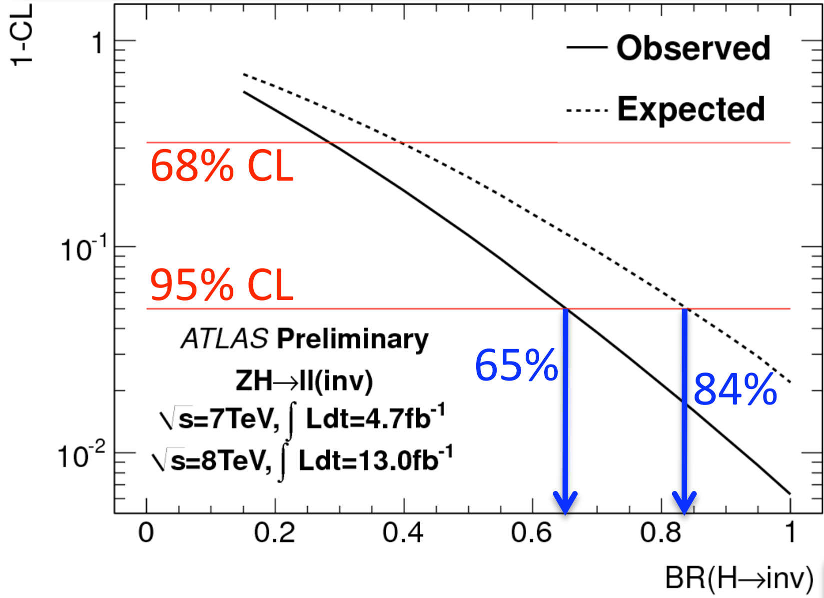
- Higgs decays/oscillates into graviscalars
- Higgs decays into dark matter particles

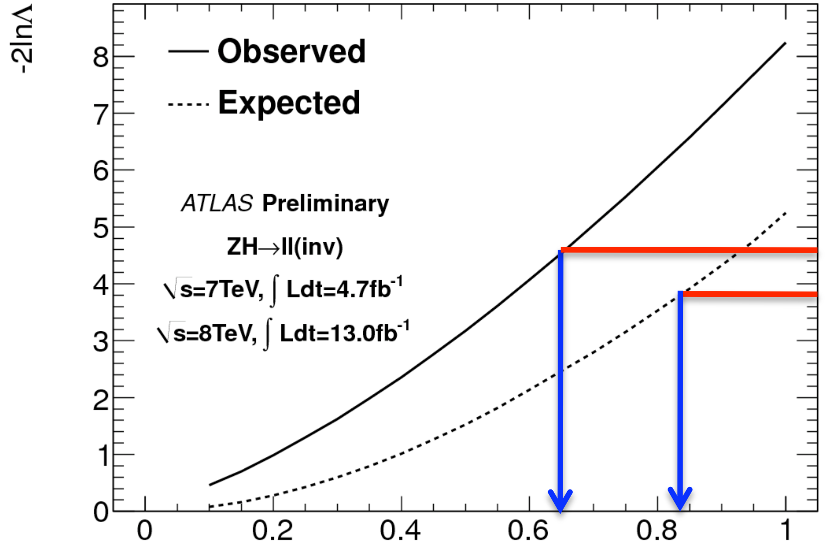
limits:

- on σ_{ZH} x BR(ZH-> ll inv.): no excess observed between 115 and 130 GeV
- on BR(H->inv.):

< 65% observed and < 84% expected



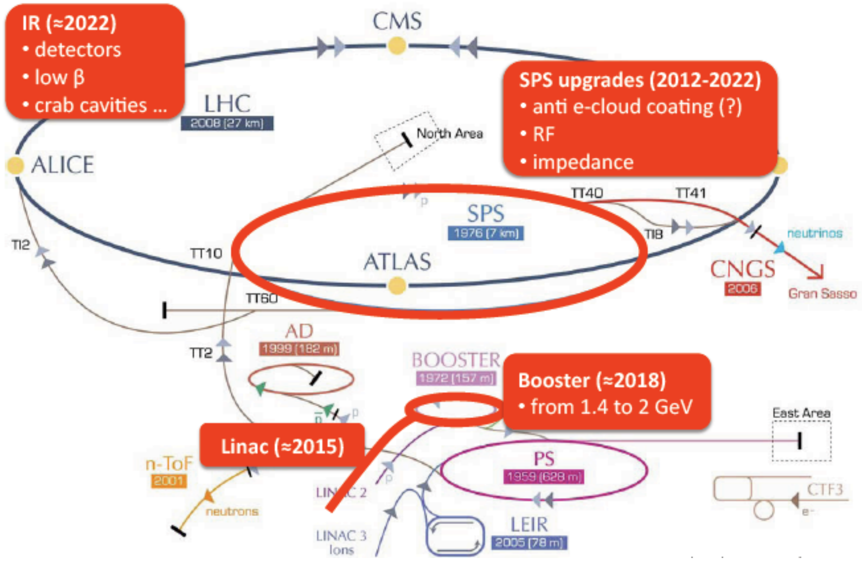




more details in **ATLAS-CONF-2013-011**

perspectives

HL-LHC

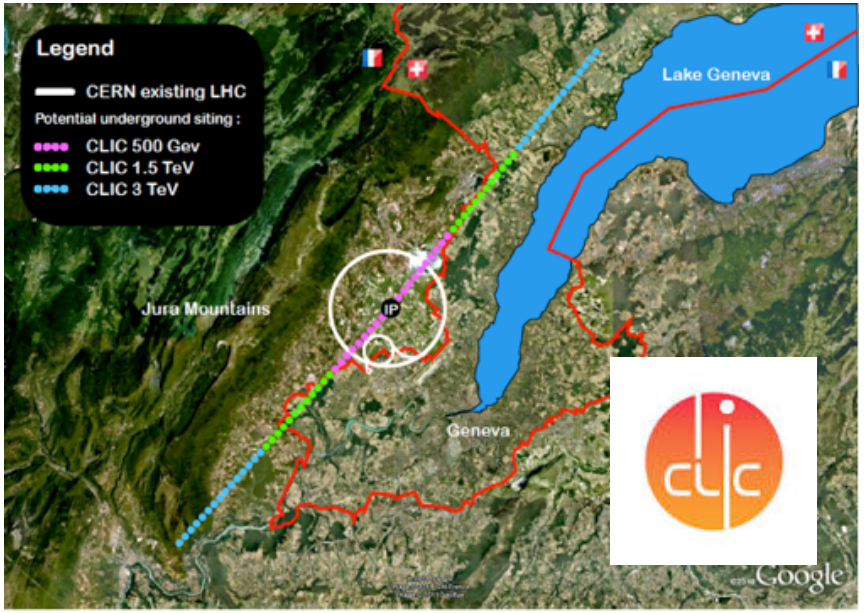


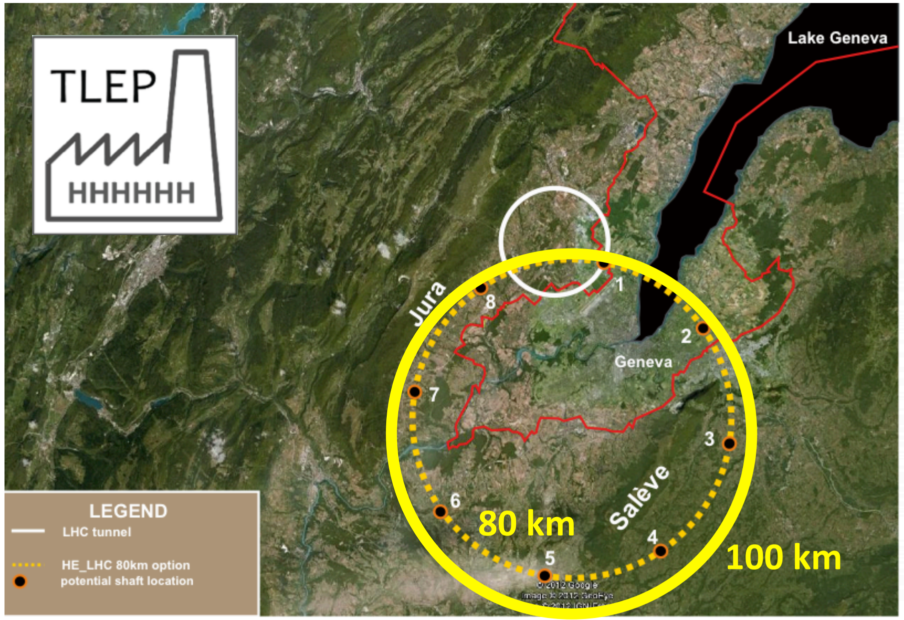
IR (≈2022)
- detectors
- low β
- crab cavities ...

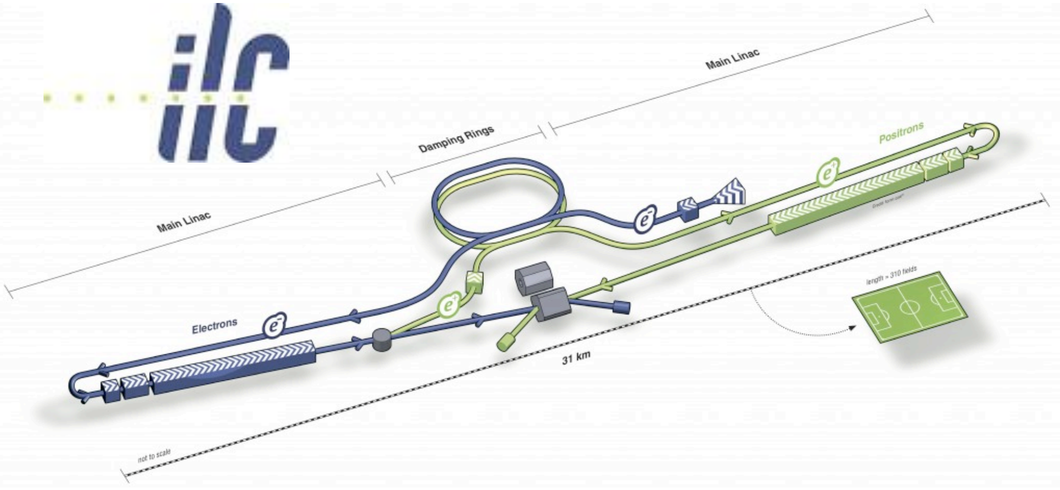
SPS upgrades (2012-2022)
- anti e-cloud coating (?)
- RF
- impedance

Booster (≈2018)
- from 1.4 to 2 GeV

Linac (≈2015)

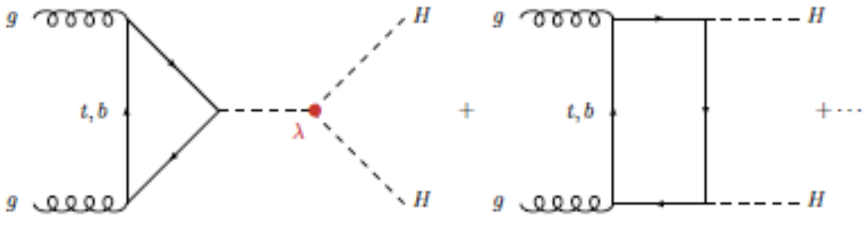






new measurements: Higgs self-coupling

$\sqrt{s}$ [TeV]	$\sigma^{\mathrm{NLO}}_{gg\to HH}$ [fb]
8	8.16
14	33.89



at 3 ab^{-1} : although additional checks are needed, a 3σ sensitivity is expected

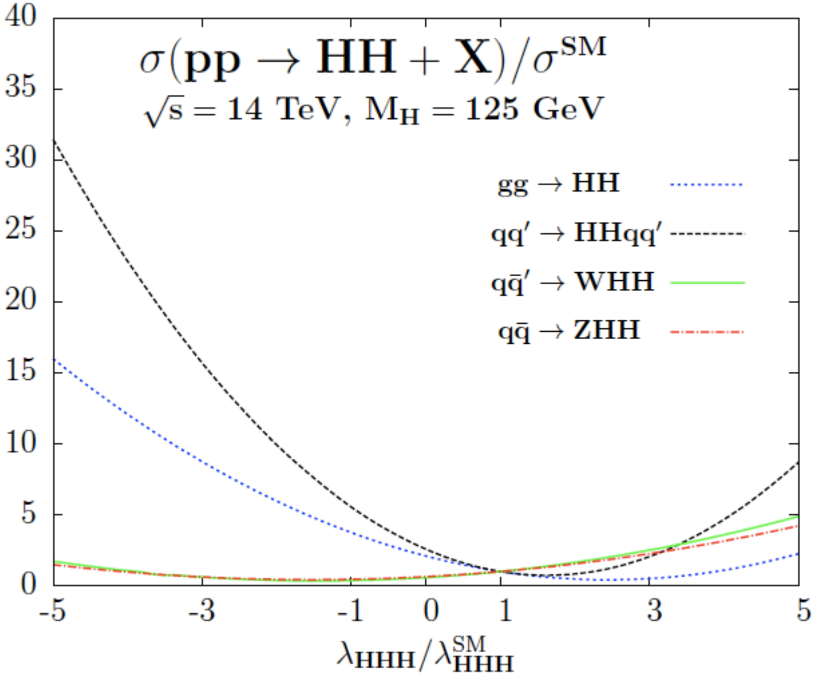
- bbγγ: clean, but low BR
- bbττ: clean, but worse mass resolution
- bbμμ: clean, but even lower BR
- bbW*W $^{(*)}$: very challenging

systematic uncertainties (theo.):

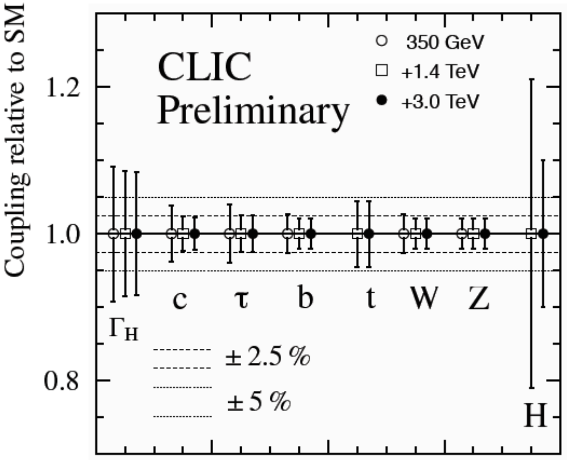
- QCD scale $^{+18}_{-15}$%
- PDF 7%
- EFT 10%

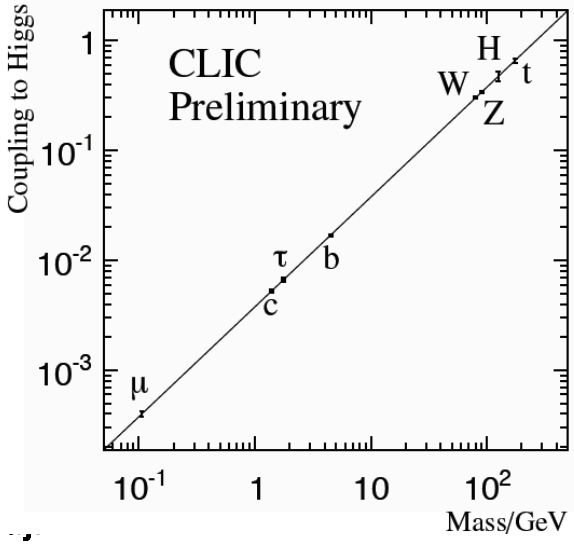
total: ≈ 30(40)%

- a factor 1/2 can be improved



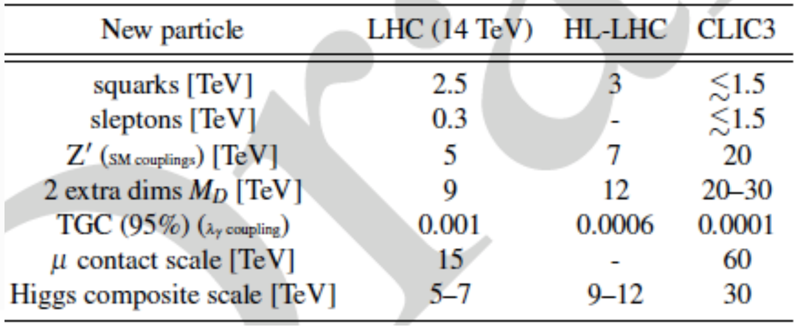
Linear Colliders



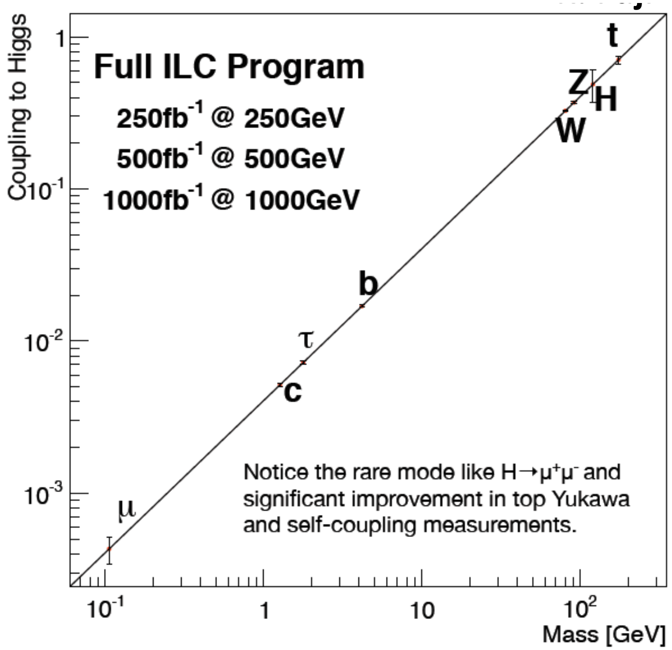


- LHC: √s = 14 TeV with 100 fb^{-1}
- HL-LHC: 1 ab^{-1}
- CLIC3: √s = 3 TeV with 2 ab^{-1}

http://arxiv.org/abs/1307.5288



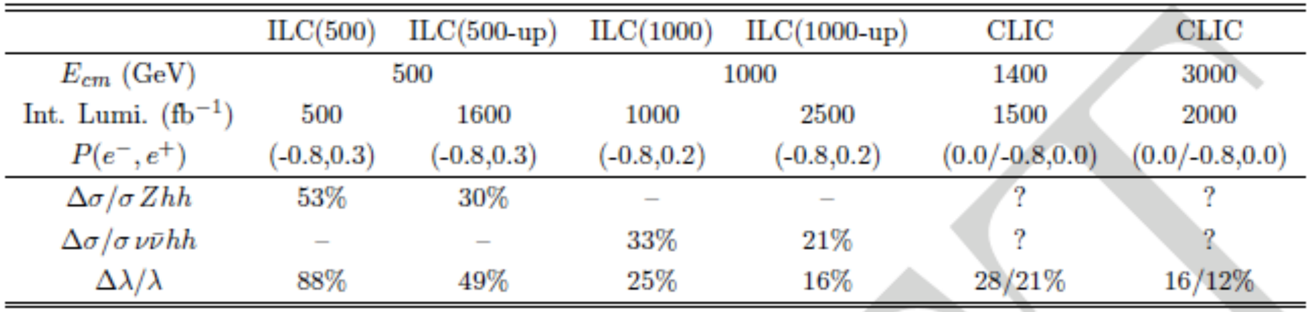
New particle	LHC (14 TeV)	HL-LHC	CLIC3
squarks [TeV]	2.5	3	$\lesssim 1.5$
sleptons [TeV]	0.3	-	$\lesssim 1.5$
Z' ($_{\text{SM couplings}}$) [TeV]	5	7	20
2 extra dims M_D [TeV]	9	12	20–30
TGC (95%) ($_{\lambda_\gamma \text{ coupling}}$)	0.001	0.0006	0.0001
μ contact scale [TeV]	15	-	60
Higgs composite scale [TeV]	5–7	9–12	30



Notice the rare mode like H→μ⁺μ⁻ and significant improvement in top Yukawa and self-coupling measurements.

- double Higgs cross-section production
- λ - Higgs self coupling parameter

http://indico.cern.ch/getFile.py/access?contribId=6&resId=0&materialId=0&confId=262870

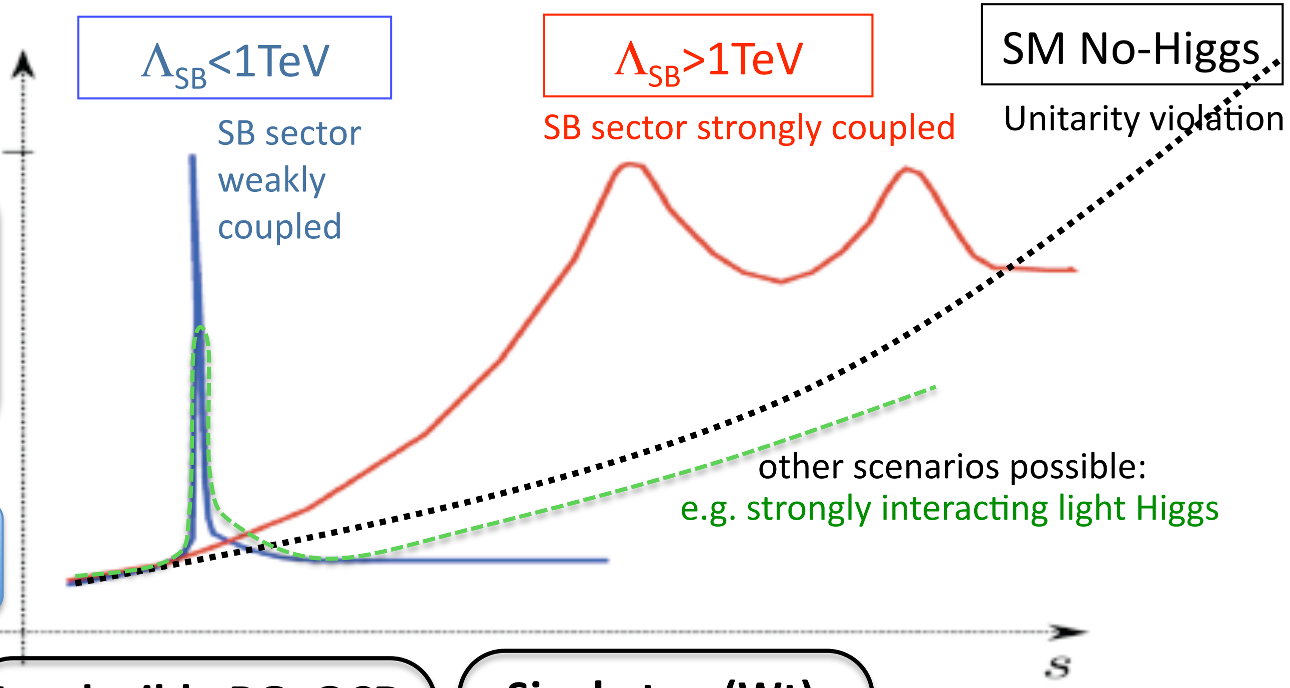


	ILC(500)	ILC(500-up)	ILC(1000)	ILC(1000-up)	CLIC	CLIC
E_{cm} (GeV)	500		1000		1400	3000
Int. Lumi. (fb^{-1})	500	1600	1000	2500	1500	2000
$P(e^-, e^+)$	(-0.8,0.3)	(-0.8,0.3)	(-0.8,0.2)	(-0.8,0.2)	(0.0/-0.8,0.0)	(0.0/-0.8,0.0)
$\Delta\sigma/\sigma\, Zhh$	53%	30%	–	–	?	?
$\Delta\sigma/\sigma\, \nu\bar{\nu}hh$	–	–	33%	21%	?	?
$\Delta\lambda/\lambda$	88%	49%	25%	16%	28/21%	16/12%

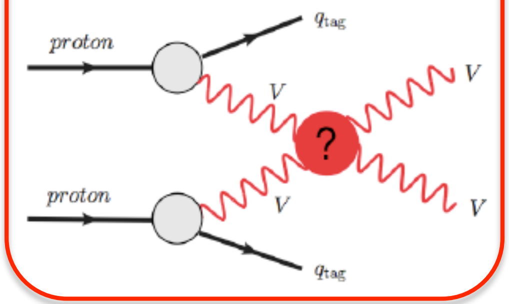
new measurements: VV scattering

- **σ(VV→VV) vs. M(VV)**
- test nature of Higgs boson
- find alternative EWSB mechanism

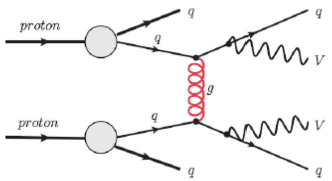
resonances in VBF spectrum



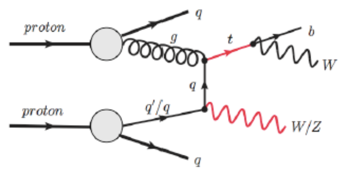
Signal: resonance



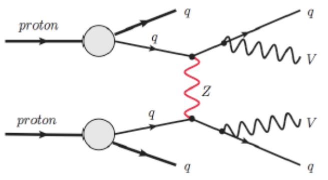
Irreducible BG: QCD



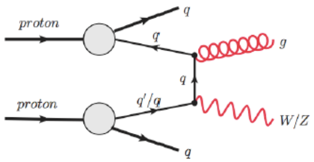
Single top (Wt)



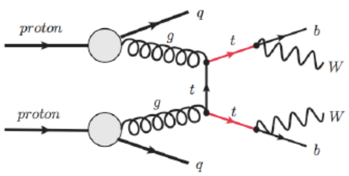
Irreducible BG: EWK



W/Z + jets



tt



many thanks A.Ballestrero and P. Giacomelli

summary

- we have seen results from the searches for 2HDM, double charged Higgs and other high mass searches in SM and MSSM
- what they have in **common**: so far we have only **limits**
- limits have plenty of one and two sigma “blubs” – but they do not appear consistently at the same mass(es)
- we need to show in our papers also the global p-values (not only the local ones)

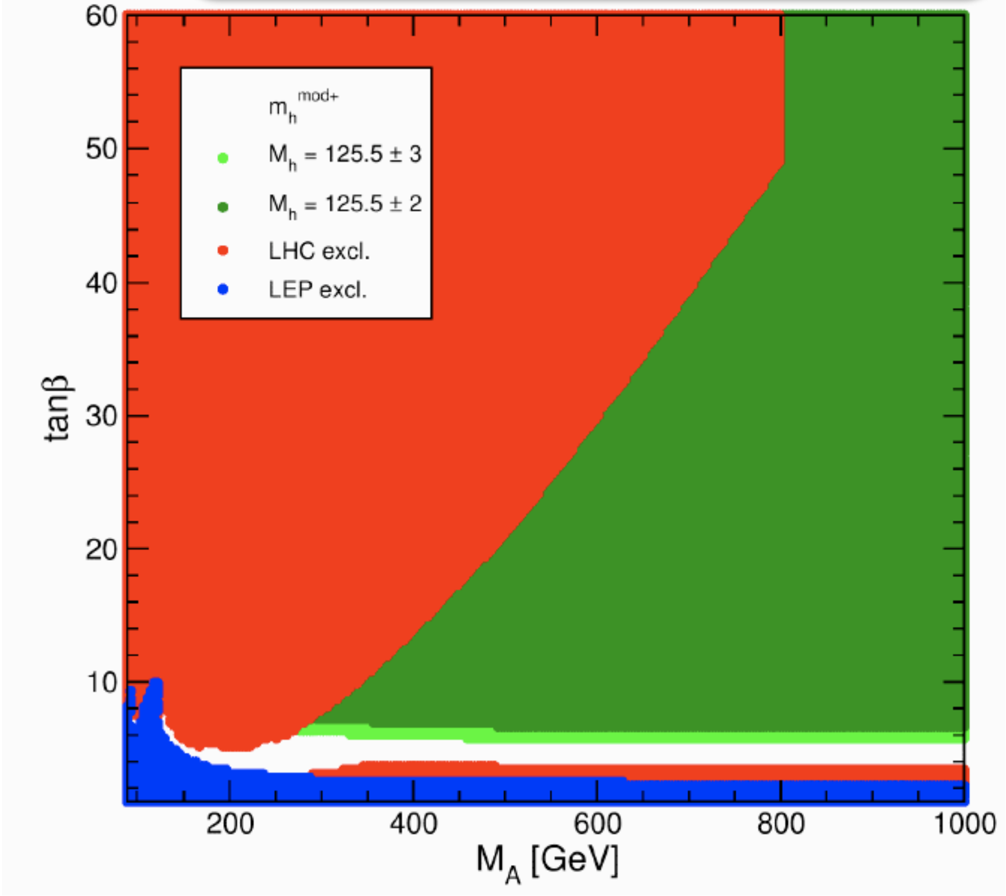
- we have two wonderful detectors and they still have a lot of potential to be exploited even after more than one year since LHC stopped delivering 8 TeV data
- still to come: graviton search in the “dihiggs” channel, 2HDM inverted mass hierarchy and the list can go on
- we are now more rich in ideas and analyses ready to be run for the next LHC data than we were in 2010

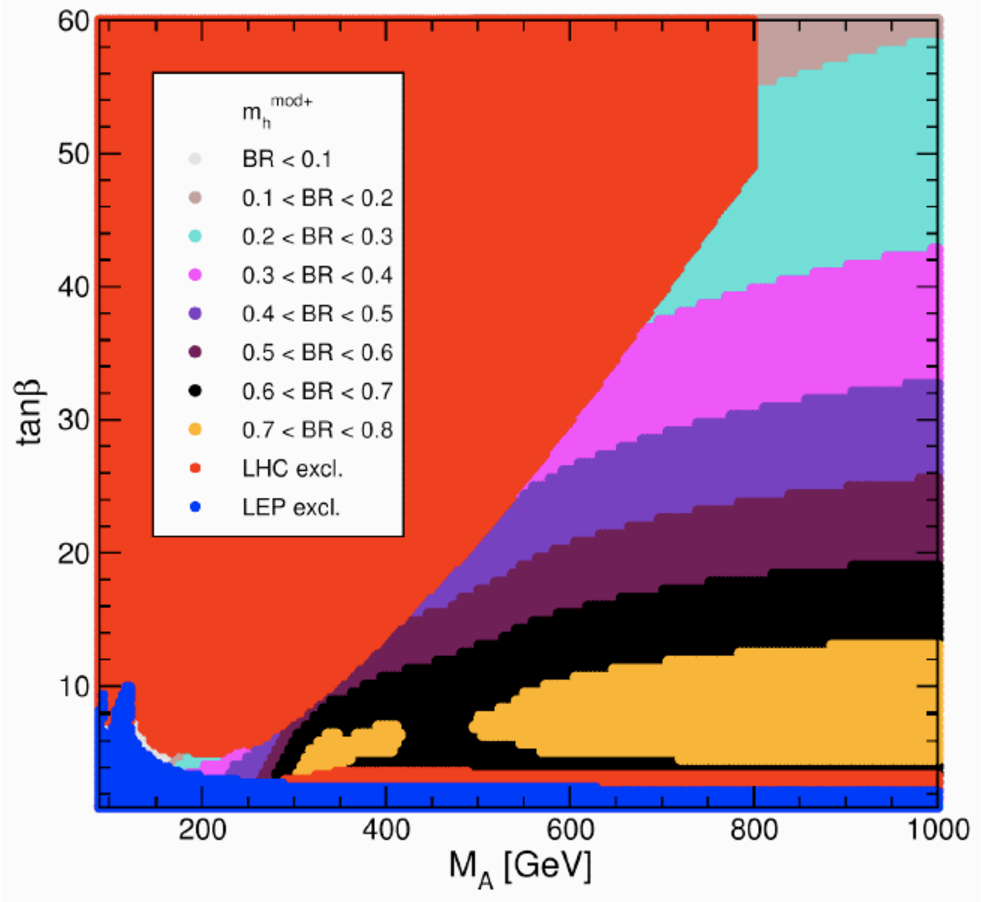
backup

is there still hope for MSSM?

a new scenario (arXiv:13027033):
- **m_h^{mod}**
- now we know also a correlation with the BR to charginos/neutralinos

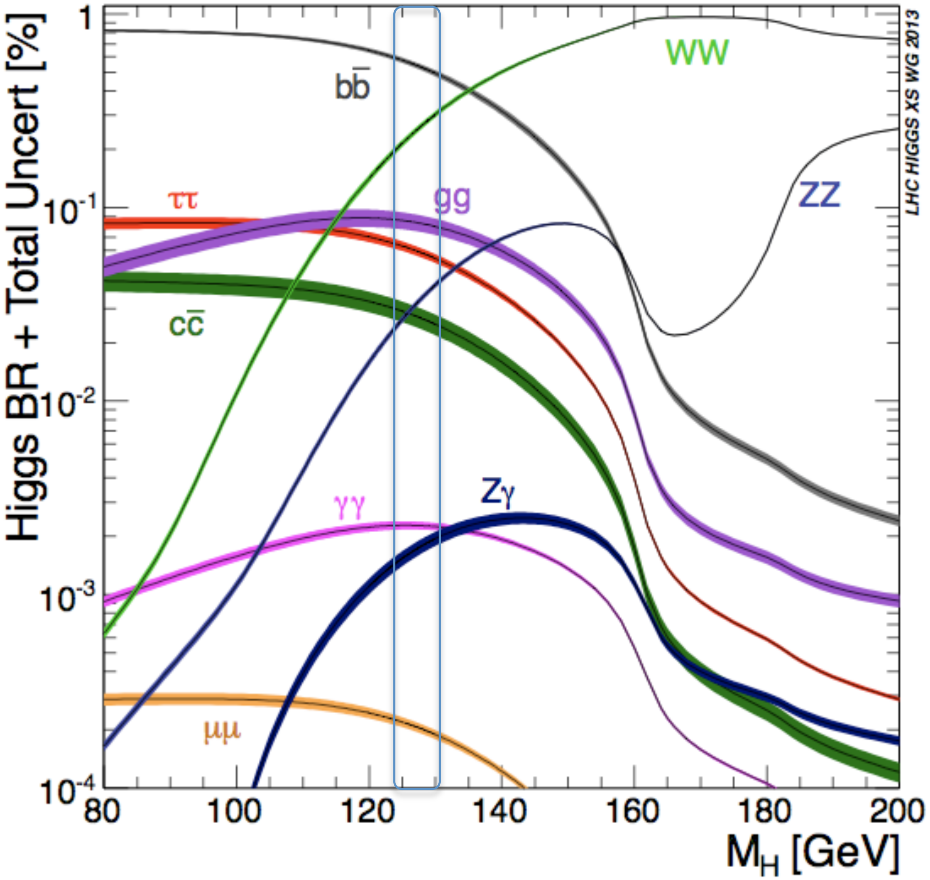
$$\begin{aligned}
m_t &= 173.2\ \text{GeV}, \\
M_{\text{SUSY}} &= 1000\ \text{GeV}, \\
\mu &= 200\ \text{GeV}, \\
M_2 &= 200\ \text{GeV}, \\
X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}}\ \text{(FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= 1.6\, M_{\text{SUSY}}\ \text{(RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500\ \text{GeV}, \\
M_{\tilde{l}_3} &= 1000\ \text{GeV}\ .
\end{aligned}$$

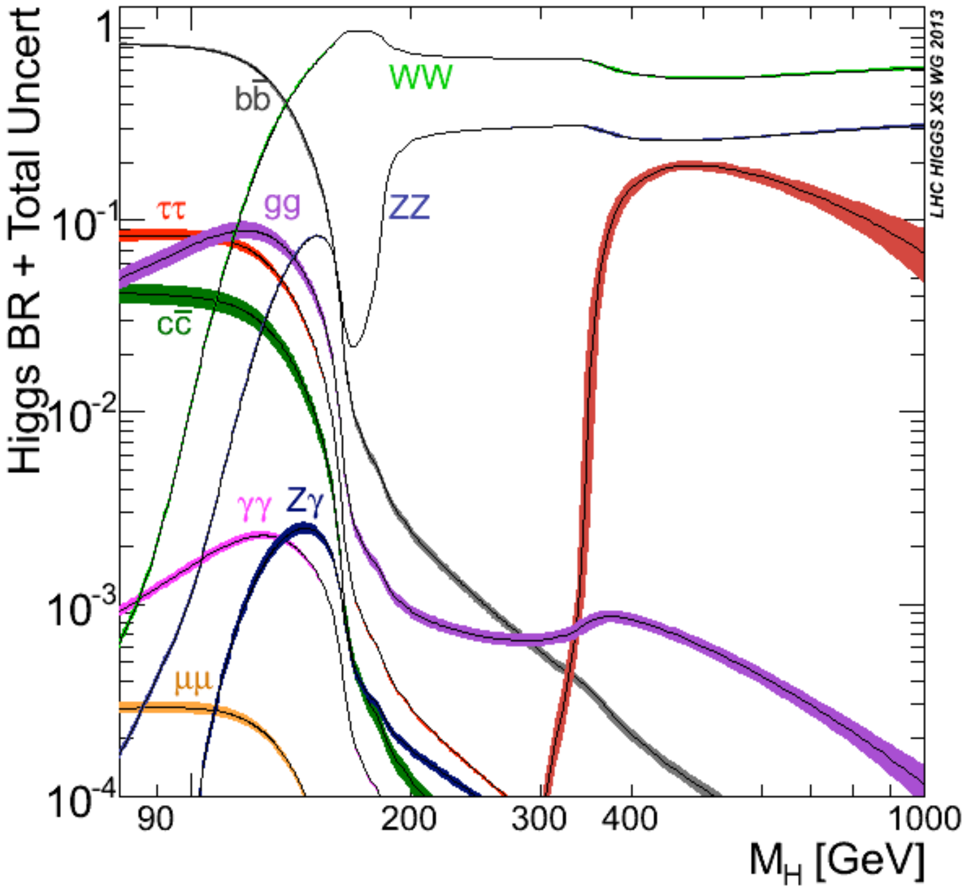




Higgs: what (else) do (we think) we know

LHC Higgs Cross Section WG
YR3: Properties **arXiv:1307.1347**





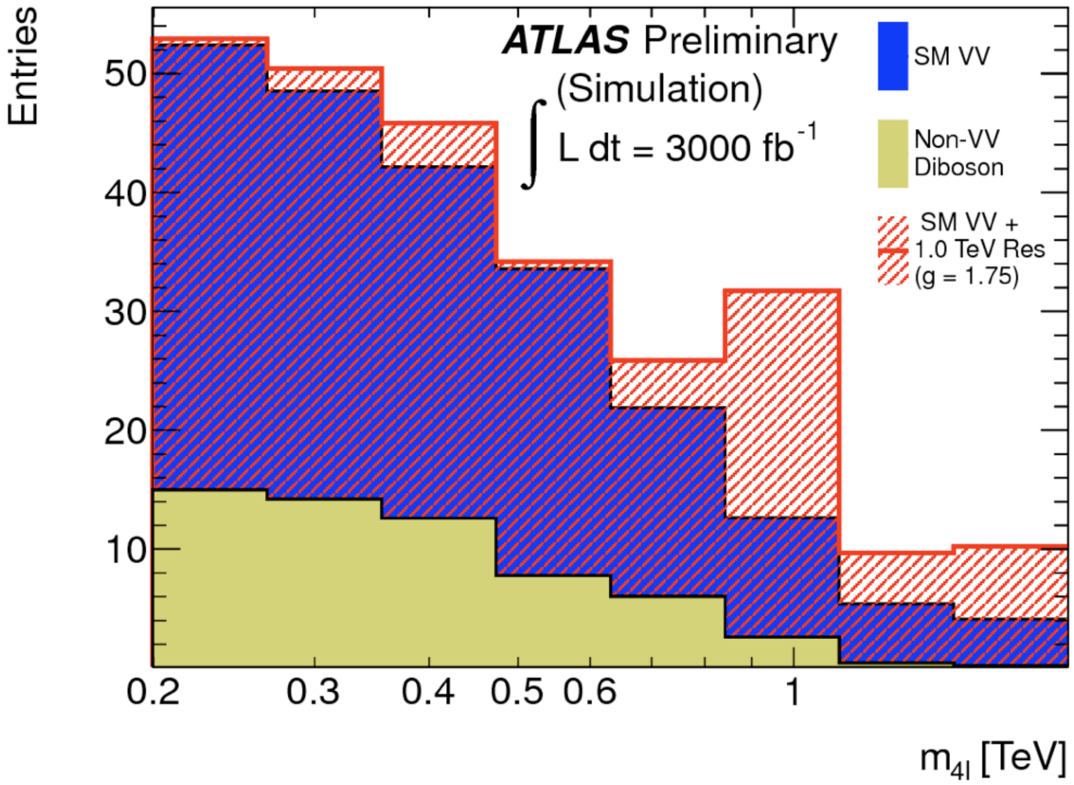
searches: ZZ resonance

pp→ZZ+2j→4ℓ+2j channel

- sensitive to anomalous ZZ resonances in VV scattering

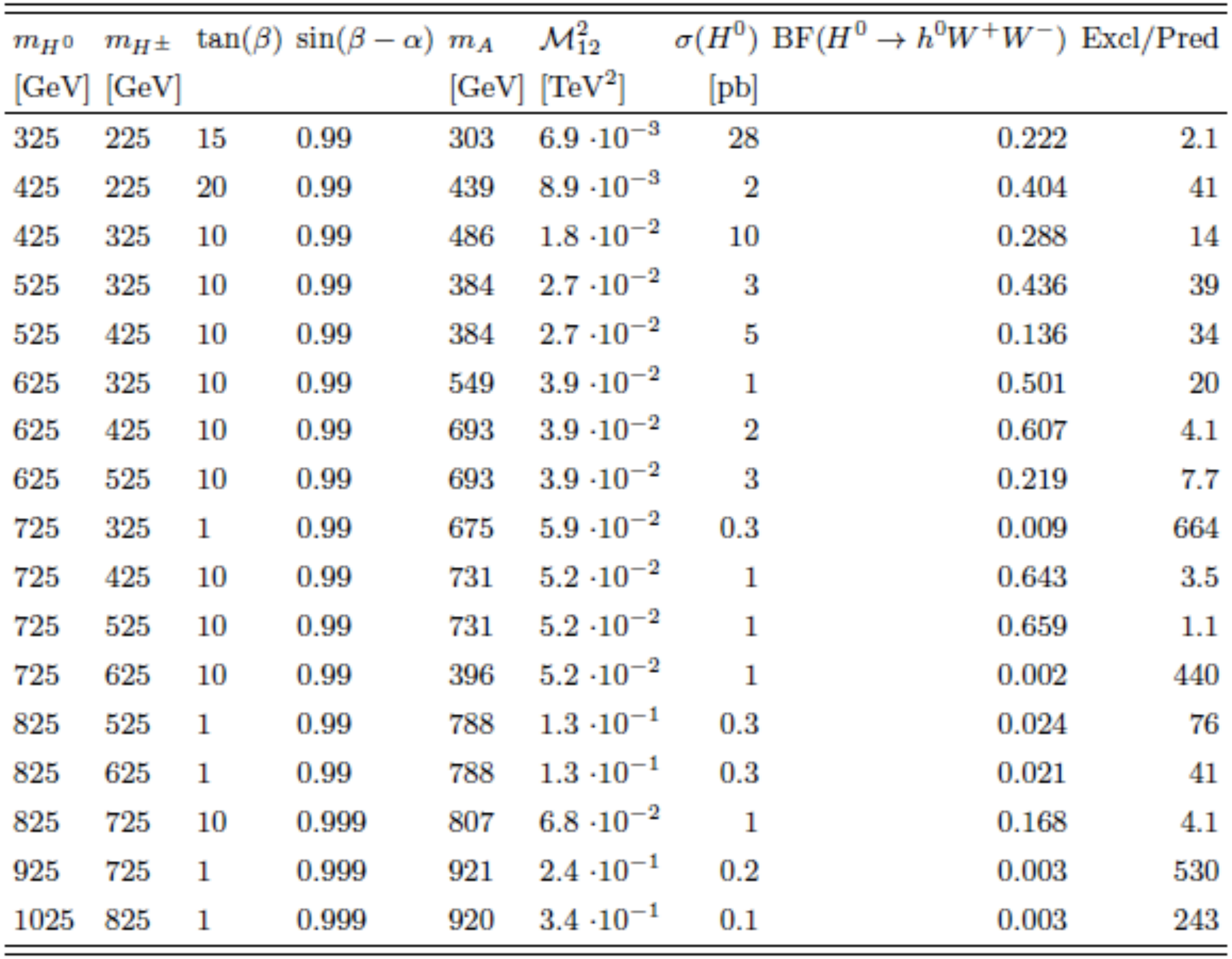
ATL-PHYS-PUB-2012-00

model	300 fb^{-1}	3000 fb^{-1}
$m_{\mathrm{resonance}} = 500$ GeV, $g = 1.0$	2.4σ	7.5σ
$m_{\mathrm{resonance}} = 1$ TeV, $g = 1.75$	1.7σ	5.5σ
$m_{\mathrm{resonance}} = 1$ TeV, $g = 2.5$	3.0σ	9.4σ



multi-Higgs cascade in WWbb

- type-II 2HDM parameter space choices -



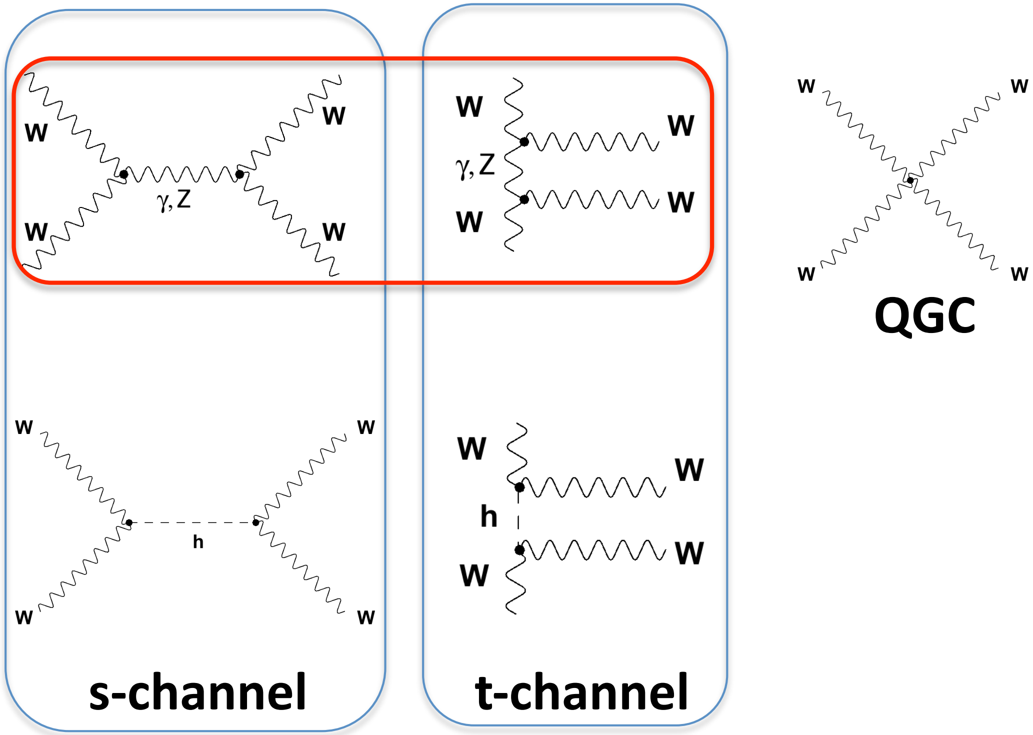
m_{H^0} [GeV]	$m_{H^\pm}$ [GeV]	$\tan(\beta)$	$\sin(\beta-\alpha)$	m_A [GeV]	$\mathcal{M}^2_{12}$ [TeV^2]	$\sigma(H^0)$ [pb]	$\mathrm{BF}(H^0 \to h^0 W^+ W^-)$	Excl/Pred
325	225	15	0.99	303	$6.9 \cdot 10^{-3}$	28	0.222	2.1
425	225	20	0.99	439	$8.9 \cdot 10^{-3}$	2	0.404	41
425	325	10	0.99	486	$1.8 \cdot 10^{-2}$	10	0.288	14
525	325	10	0.99	384	$2.7 \cdot 10^{-2}$	3	0.436	39
525	425	10	0.99	384	$2.7 \cdot 10^{-2}$	5	0.136	34
625	325	10	0.99	549	$3.9 \cdot 10^{-2}$	1	0.501	20
625	425	10	0.99	693	$3.9 \cdot 10^{-2}$	2	0.607	4.1
625	525	10	0.99	693	$3.9 \cdot 10^{-2}$	3	0.219	7.7
725	325	1	0.99	675	$5.9 \cdot 10^{-2}$	0.3	0.009	664
725	425	10	0.99	731	$5.2 \cdot 10^{-2}$	1	0.643	3.5
725	525	10	0.99	731	$5.2 \cdot 10^{-2}$	1	0.659	1.1
725	625	10	0.99	396	$5.2 \cdot 10^{-2}$	1	0.002	440
825	525	1	0.99	788	$1.3 \cdot 10^{-1}$	0.3	0.024	76
825	625	1	0.99	788	$1.3 \cdot 10^{-1}$	0.3	0.021	41
825	725	10	0.999	807	$6.8 \cdot 10^{-2}$	1	0.168	4.1
925	725	1	0.999	921	$2.4 \cdot 10^{-1}$	0.2	0.003	530
1025	825	1	0.999	920	$3.4 \cdot 10^{-1}$	0.1	0.003	243

sample points in the space of the parameters which
- satisfy potential stability, unitarity and perturbativity constraints
- give the smallest ratio of excluded to predicted cross section

new measurements: VV scatering

- VV scattering: EWSB smoking gun

$W^+_L W^-_L \rightarrow W^+_L W^-_L$ violates unitarity w/o SM Higgs boson, at √s ≥ 1.2 TeV



$$A\left(W_L^+W_L^- \rightarrow W_L^+W_L^-\right) \approx \frac{1}{v^2}\left(\boxed{-s-t} + \frac{s^2}{s-m_H^2} + \frac{t^2}{t-m_H^2}\right)$$

many thanks Sara Bolognesi

ATLAS

2HDM results combined

ATLAS-CONF-2014-010