Higgs physics in ATLAS and CMS
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Beyond the standard model

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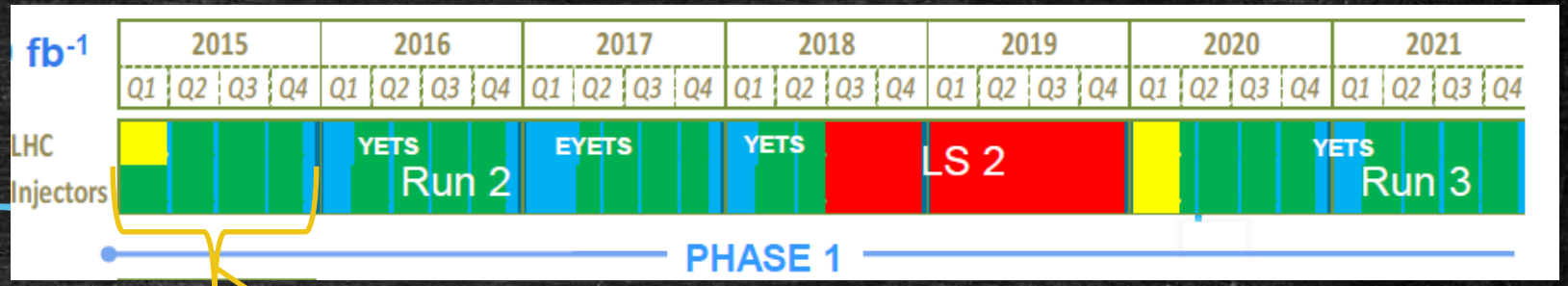
NExT meeting, 19 November 2014

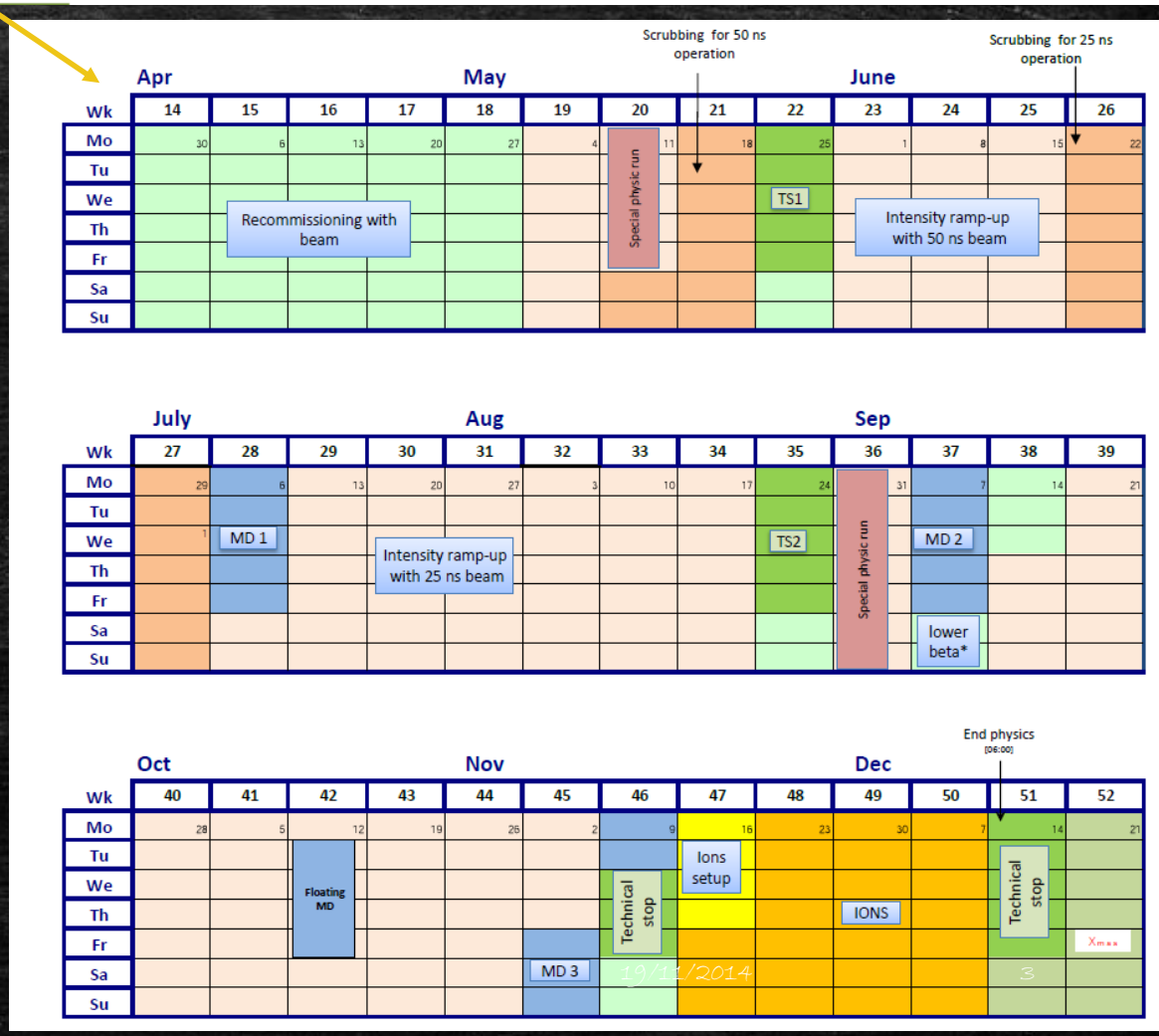
In this talk…

- The LHC, ATLAS and CMS in run 2
- Higgs mass measurement
- Higgs spin measurement
- BSM Higgs scenarios
- 2Higgs Doublet Models (2HDM), MSSM/NMSSM
- Additional Higgs bosons searches-examples
- Exotic Higgs searches

LHC schedule

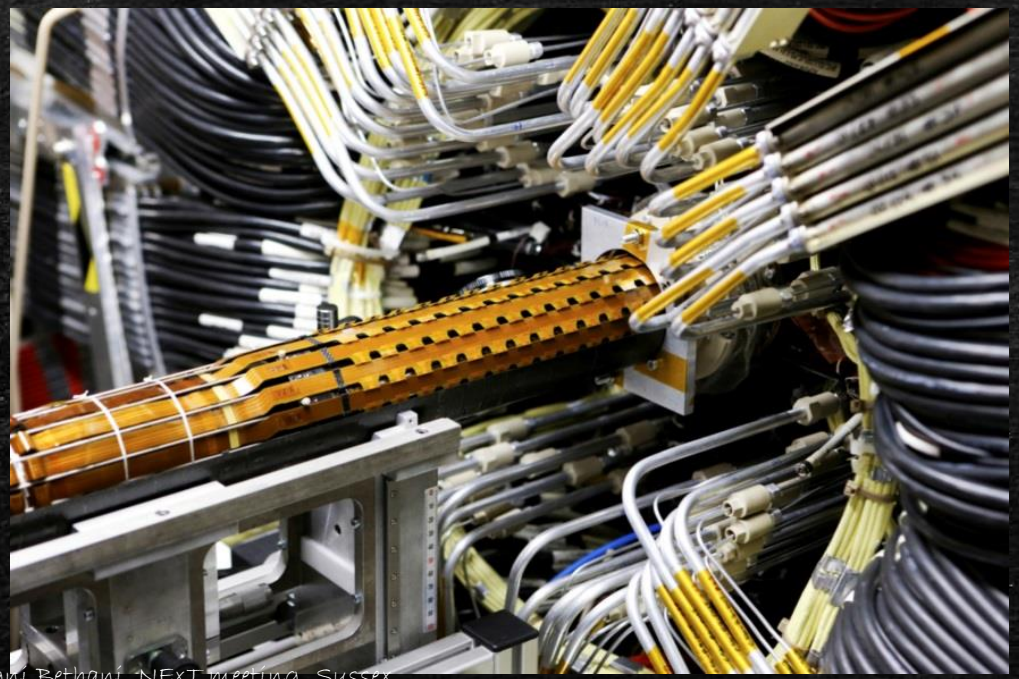


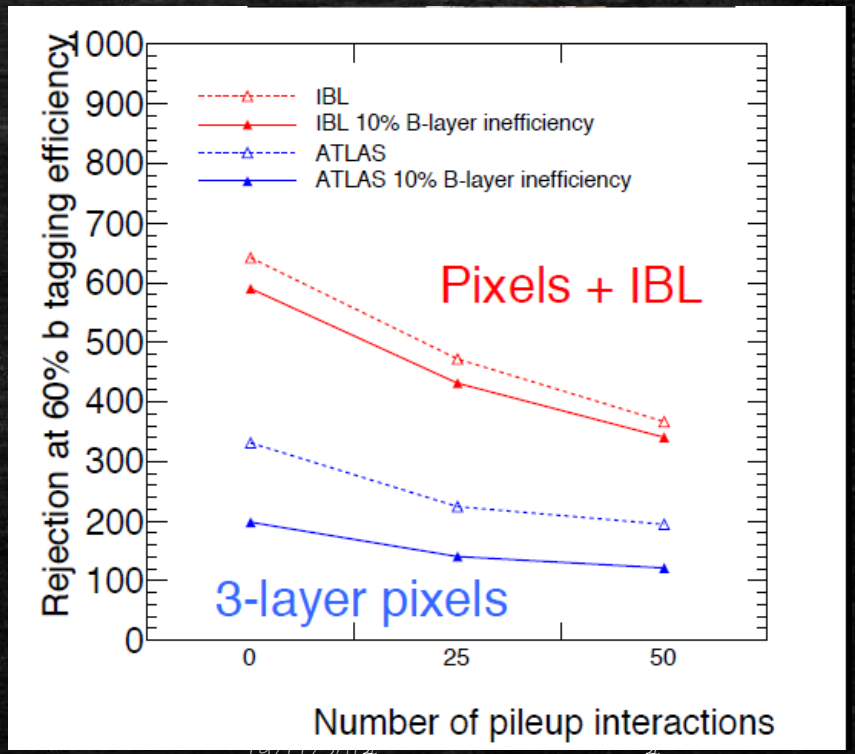
- Ready for run 2 (almost!)
  - Physics run starts next May
- What's new?
  - Energy 13 TeV
  - 25 ns bunch crossing (not straight away)
  - Expected ~100 fb^{-1} integrated luminosity at the end of Run2
  - ATLAS and CMS upgrades



Major ATLAS upgrades

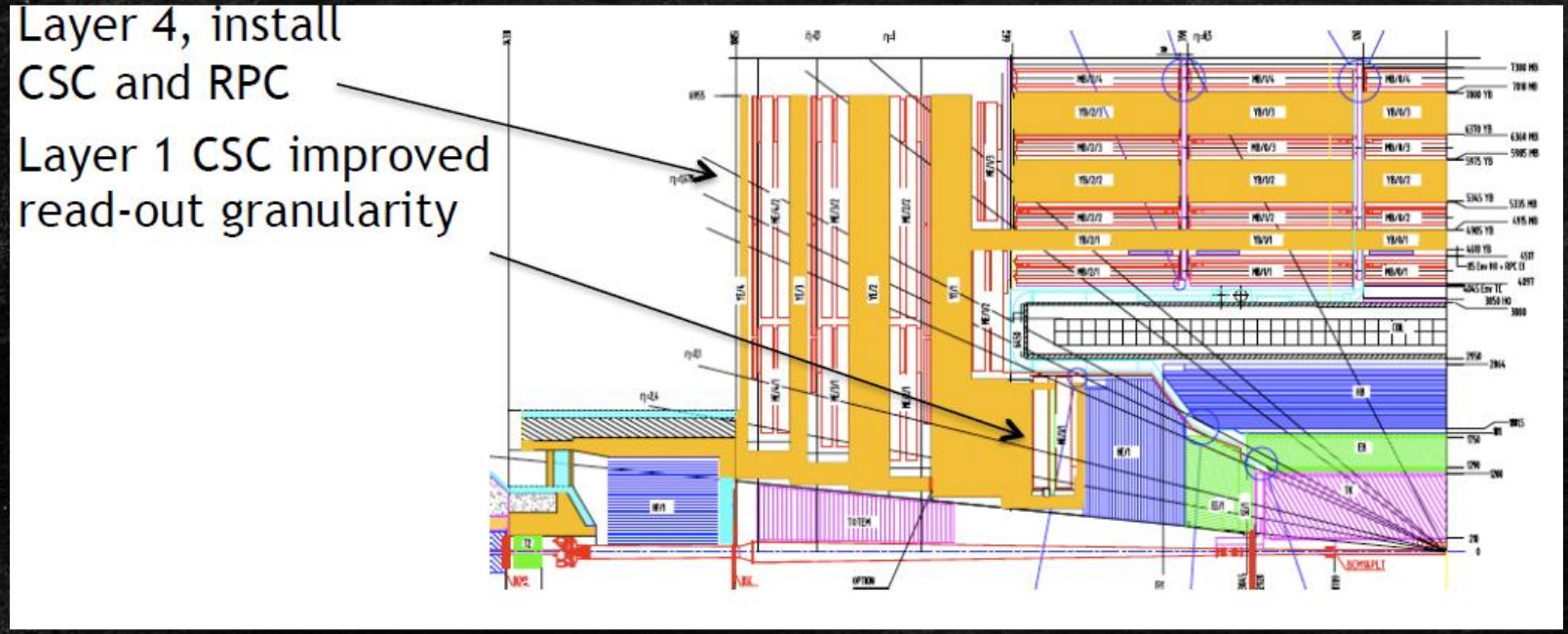
- Additional Insertable B-Layer (Pixels)
- New beam pipe
- Complete muon coverage

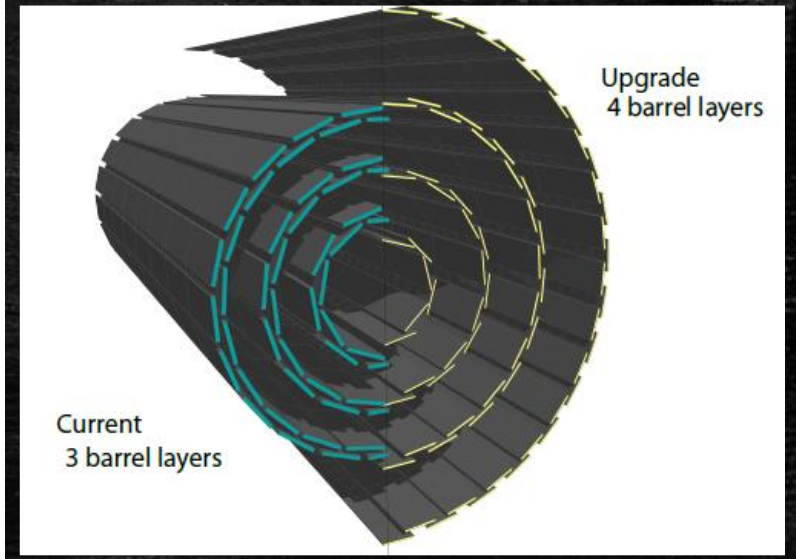




Major CMS upgrades

- Additional (4th) layer of pixels
- smaller radius beam pipe in LS1, and plan to install new pixels in extended 2016-2017 shutdown
- Hybrid Photodiodes (HPD) of HCAL are replaced with Silicon Photomultipliers (SiPM) in the barrel and endcap.
- Complete muon coverage



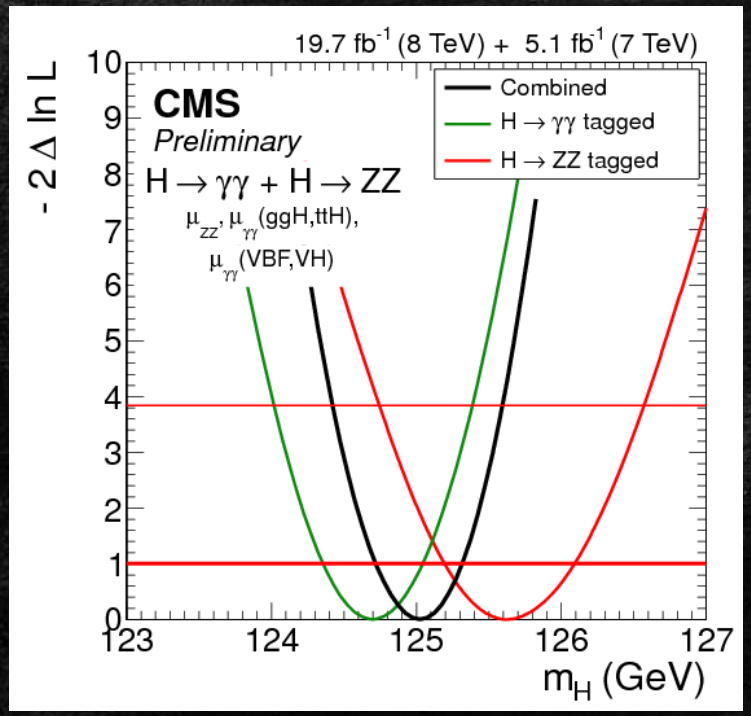


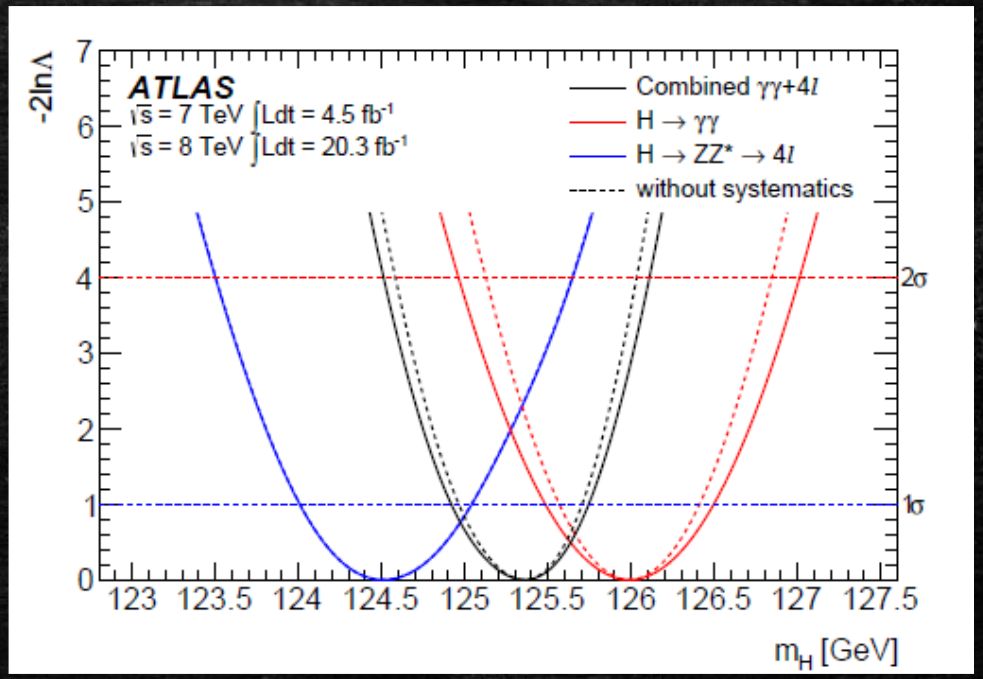
Higgs mass measurement

Both experiments use the H->γγ and H->ZZ channels.
25 fb^{-1} of data.
The precision is already in the order of %, dominated by statistical uncertainty!

$m_H = 125.03 - 0.27 + 0.26\ (stat)\ ^{+0.13}_{-0.15}\ (sys)$
$= 125.03\ ^{+0.29}_{-0.31}\ GeV$

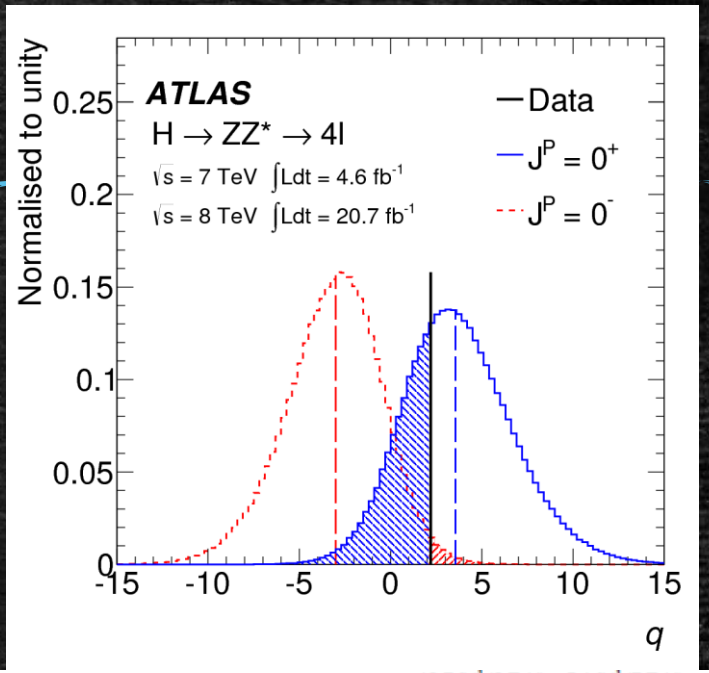
$m_H = 125.36 \pm 0.37(stat) \pm 0.18(sys)\ GeV$
$= 125.36 \pm 0.41\ GeV$

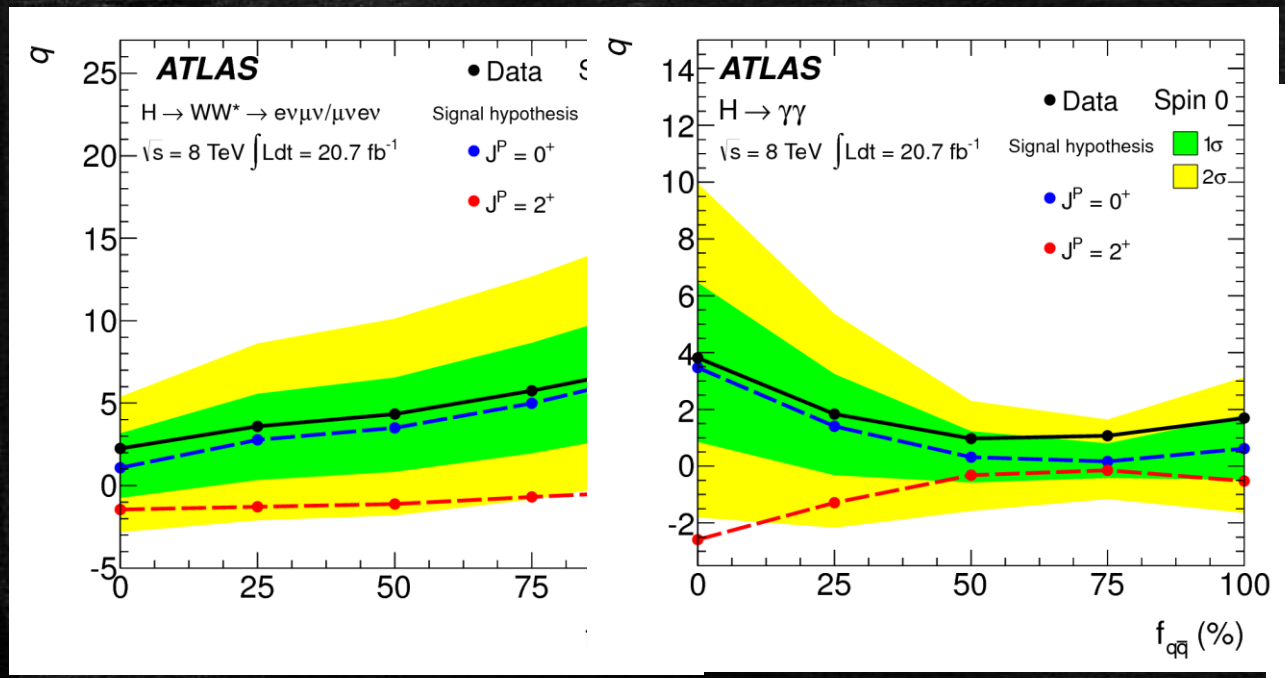


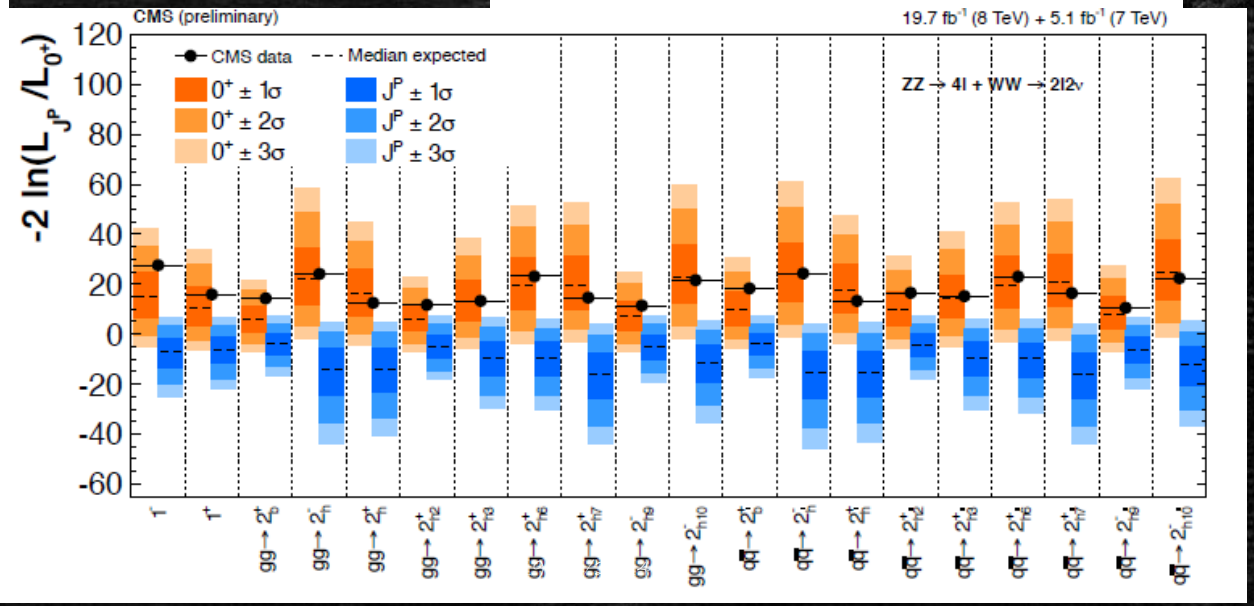


Higgs Spin measurements

- The spin and parity measurements are based on exclusion of an alternative J^P hypothesis.
  - The results are consistent with the SM.
- Exotic Higgs: J=1,J=2 excluded at >95% CL by both CMS and ATLAS

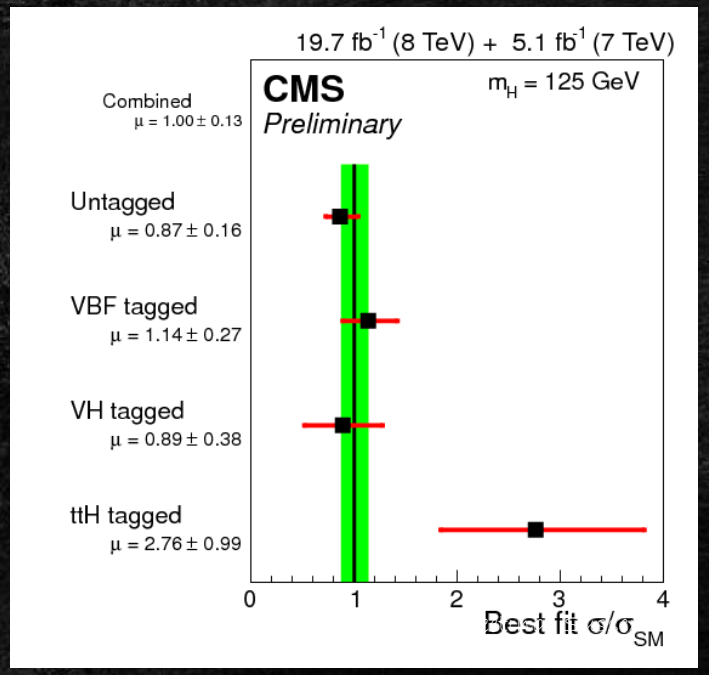


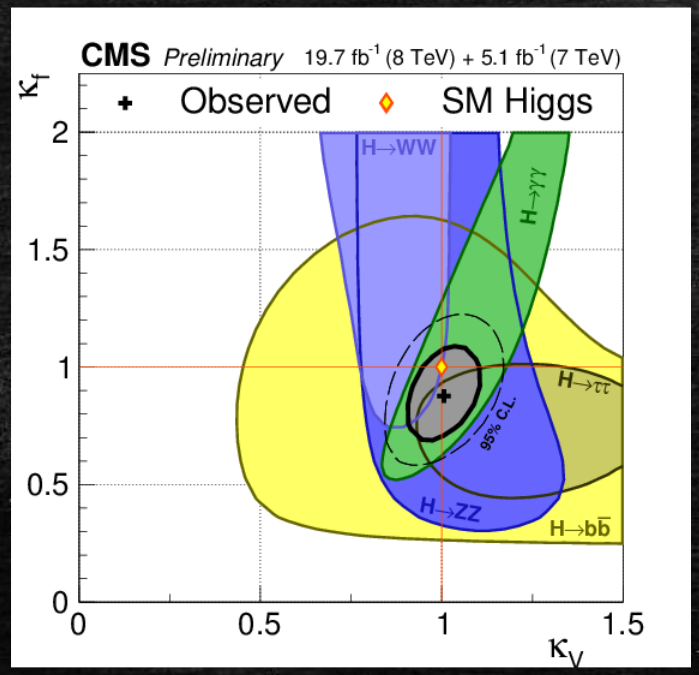


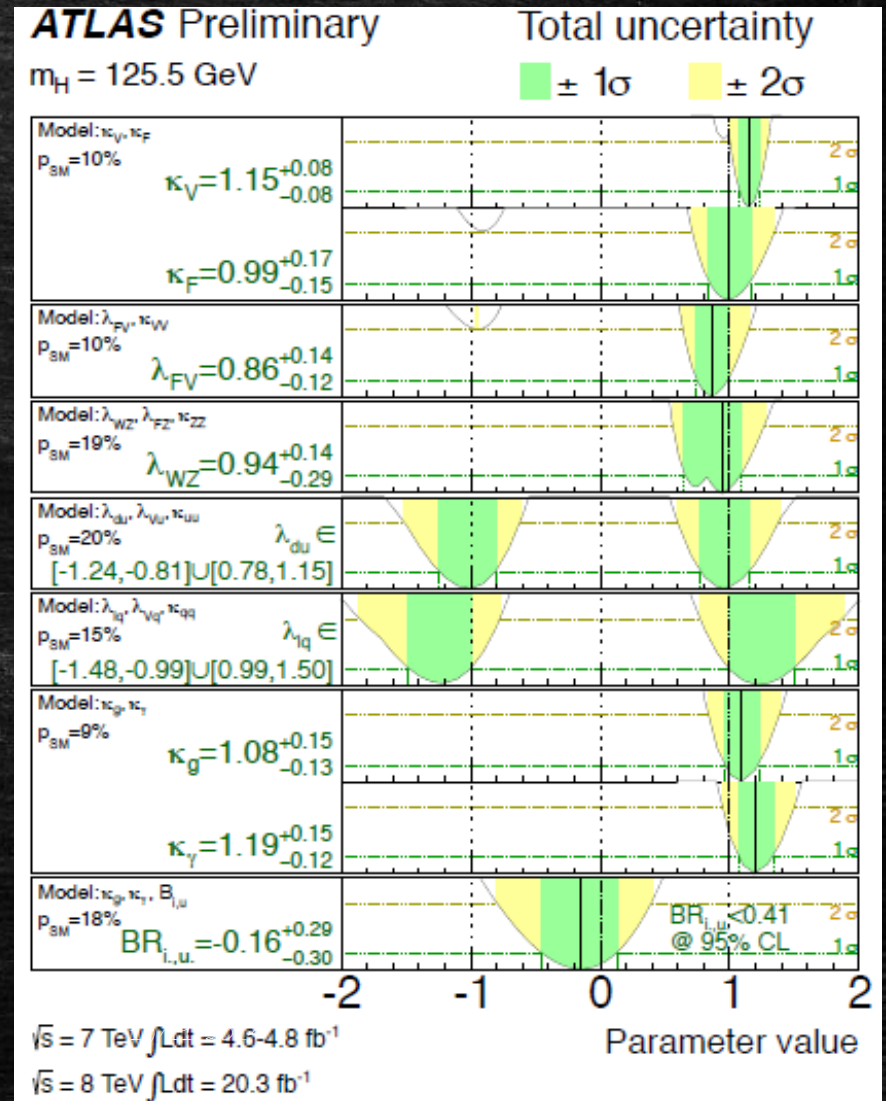


Higgs coupling measurements

- Coupling strengths g of the Higgs to other SM particles scale with the particle mass
  Fermions: $g_F = \sqrt{2}m_F/v$, Gauge bosons: $g_V = 2m^2_V/v$
- Results consistent with the SM
- CMS found an excess with 2σ significance in the ttH production







Higgs physics in Run2

- Precision measurements
- Searches for rare decays and processes
- Searches for new particles

Beyond the Standard Model Higgs

High mass 2HDM/MSSM

- H to yy
- H to WW to lvlv
- H to WW to lvqq
- H to ZZ to 4l
- H to ZZ to llvv
- H to ZZ to llqq
- H to ZZ to vvbb
- (b)tau tau (leplep, lephad, hadhad)
- (b)bb
- (b)mumu
- very high mass tautau

NMSSM

- a to mumu
- 2a to 4y (multiphoton)
- 2a to 4taus
- (bb)a to (bb)tautau to (bb)emu
- 2a to tautaumumu
- H+ to aW

LFV

- tau mu
- tau e
- e mu

Heavy Higgs decays

- Zh to lltautau (leplep, lephad, hadhad)
- Zh to (ll/vv)bb
- hh to yybb
- hh to 4b
- hh to bbtautau
- hh to yyVV to yy4j
- top pair
- Doubly charged Higgs

Other BSM

- mono photon
- mono Higgs
- Cascade decays H to H+W to hWW to bbWW

Charged Higgs

- taunu+jets
- taunu+lep
- tb
- cs
- AW
- Wh
- WZ to (lvqq, qqll)
- very high mass tb (allhad, lep+jets)
- H+ to Wgamma

Invisible Higgs decays

- Mono jet.
- ZH to (ll)inv
- VBF H to inv
- VH to (jj)inv
- Mono-W analysis substructure

Exotic Higgs

- Hidden valley pions
- Dark Z, H to ZdZ(d) to 4l

multi Higgs doublet models

- The Higgs sector is the last unknown piece of the SM of particle physics.
- the Higgs sector might consist of multi-Higgs doublet fields.
- multi-Higgs models are realised in various new physics models including supersymmetry.
- Supersymmetry is an appealing candidate for BSM physics: the introduction of a fermion-boson symmetry solves the electroweak hierarchy puzzle, offers a dark matter candidate and is consistent with grand unification
- Other models are little Higgs, twin Higgs, hidden valleys and others.

2 Higgs doublet models

- Extend SM Higgs sector by an additional electroweak doublet
  Five Higgs bosons:
  - two CP-even bosons h and H
  - one neutral CP-odd boson A
  - two charged bosons $H^{\pm}$
- Higgs sector described by six parameters
  - Four Higgs boson masses (m_h, m_H, m_A and $m_{H^{\pm}}$)
  - Ratio of the vacuum expectation values, $\tan\beta = v_1/v_2$
  - Mixing angle α of the two neutral, CP-even Higgs states

2 Higgs doublet models: Types

- Type 1
  Fermiophobic: all fermions couple to H1 all vector bosons to H2
- Type 2
  MSSM-like: down type fermions couple to H1 and up type fermions to H2
- Type 3
  Lepton specific: Higgs-quark couplings like type 1 and Higgs-lepton couplings like type 2
- Type 4
  Flipped model: Higgs-quark couplings like type 2 Higgs-lepton couplings like type 1

MSSM and NMSSM

MSSM	NMSSM
2 Higgs doublets [*]	2 Higgs doublets [*] + complex Higgs singlet
$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad S$
2 scalars: h, H	3 scalars: h_1, h_2, h_3
1 pseudo-scalar: A	2 pseudo-scalars: a_1, a_2
2 charged Higgs bosons: H^+, H^-	2 charged Higgs bosons: H^+, H^-

[*] TypeII 2HDM

- MSSM: Only two free parameters at tree-level to describe the system: $\tan\beta$, M_A
- The NMSSM adds a gauge singlet S and allows a relaxation of the electroweak fine tuning and the naturalness conditions.

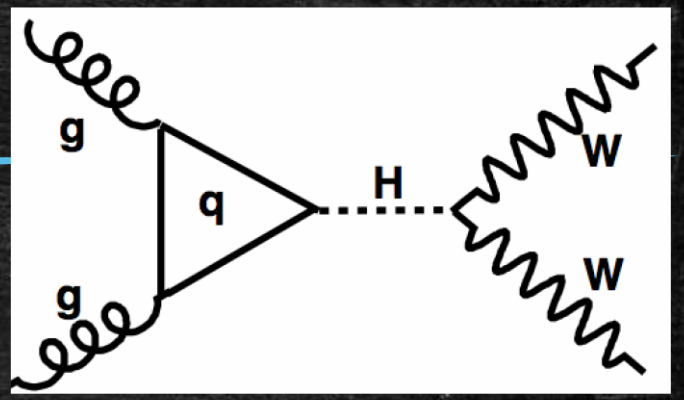
Neutral CP-even Higgs

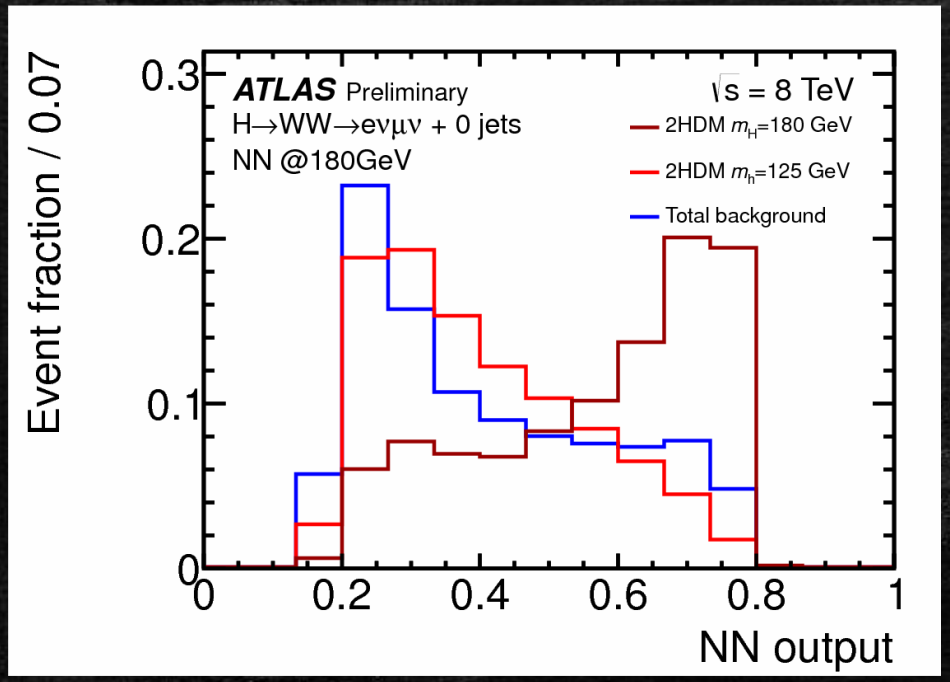
- Usual assumption is that the 125 GeV Higgs is the lightest cp-even higgs (h)
- Search for a heavier neutral CP-even partner (H) to the 125 GeV light Higgs (h)
- Very much like the SM higgs
- Searches in the same channels as the SM higgs
  - H->WW/ZZ
  - H->$\gamma\gamma$
- Searches in exotic signatures, such as invisible, H->hh, SUSY cascades etc.*

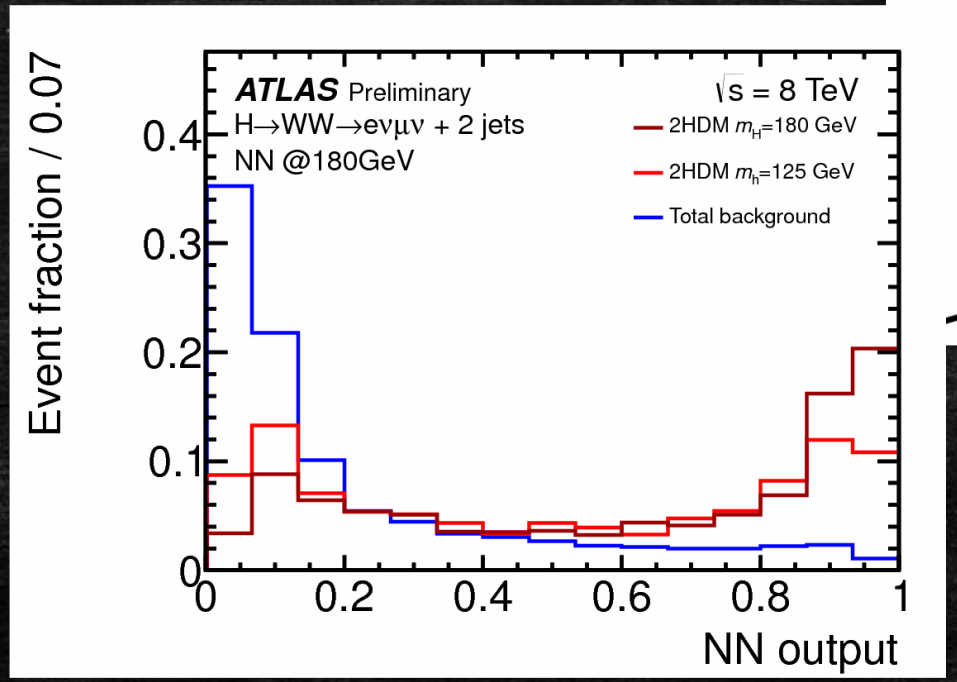
* Some discussed later in this talk

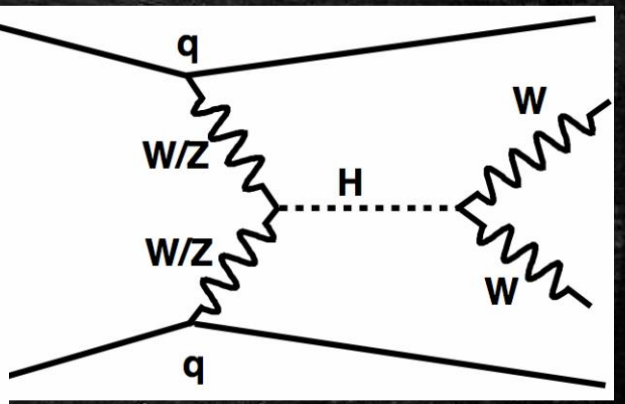
Heavy H->WW->eνμν, 2HDM

- Split into 0-jet (ggF) and 2-jet (VBF) channels
- Use neural network to separate signal from background



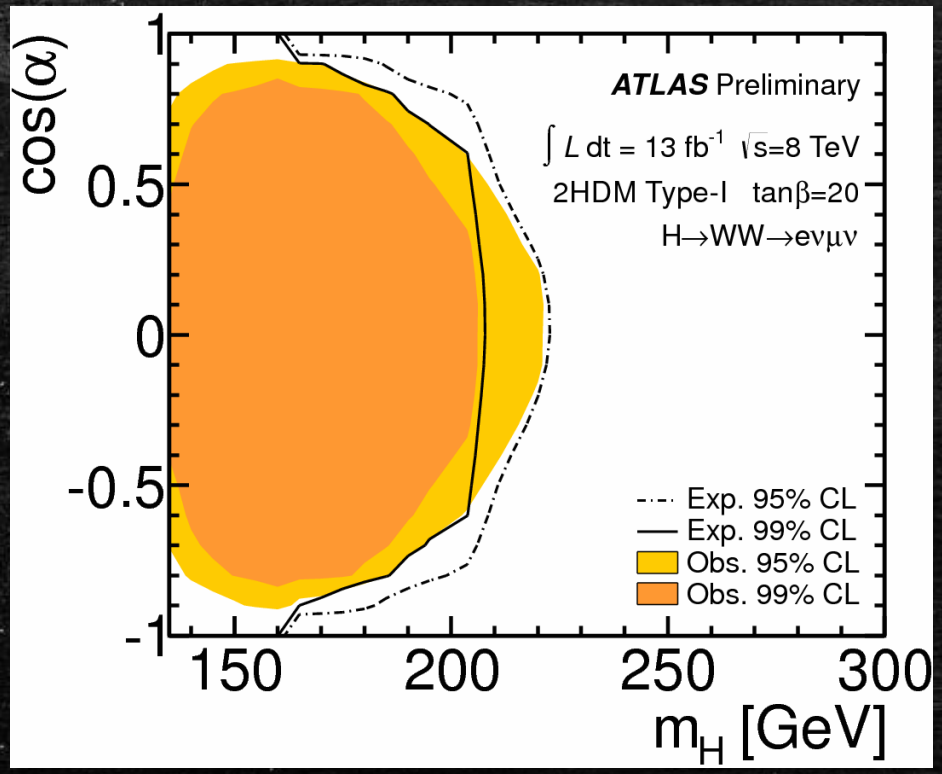


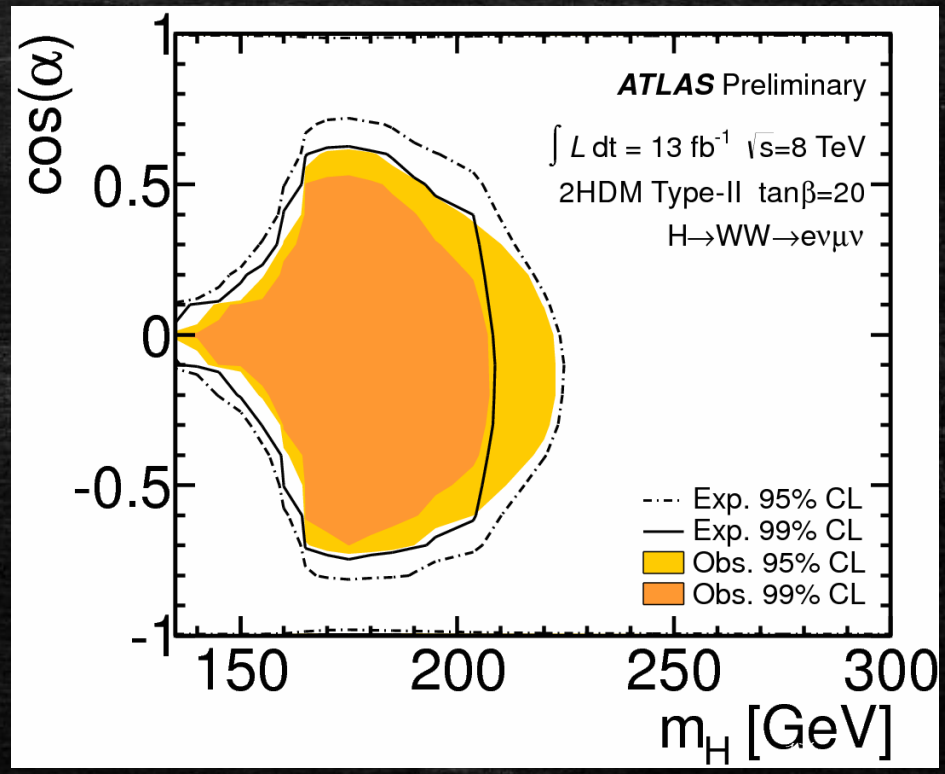




Heavy H->WW->eνμν, 2HDM

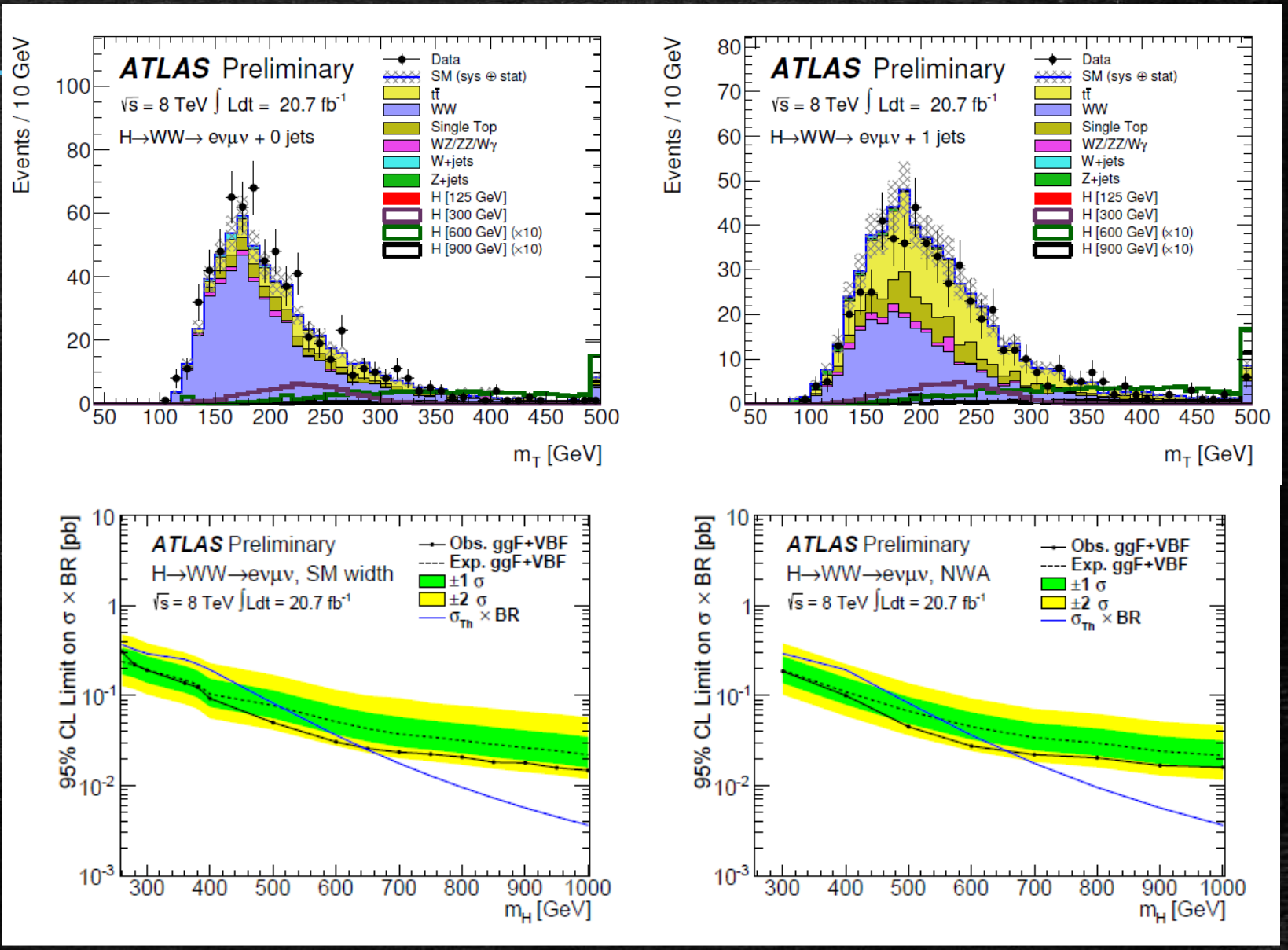
- No evidence for signal found in the mass range of [135, 300] GeV
- Limits set in cos(α) vs. mH plane for Type 1 and 2 2HDM





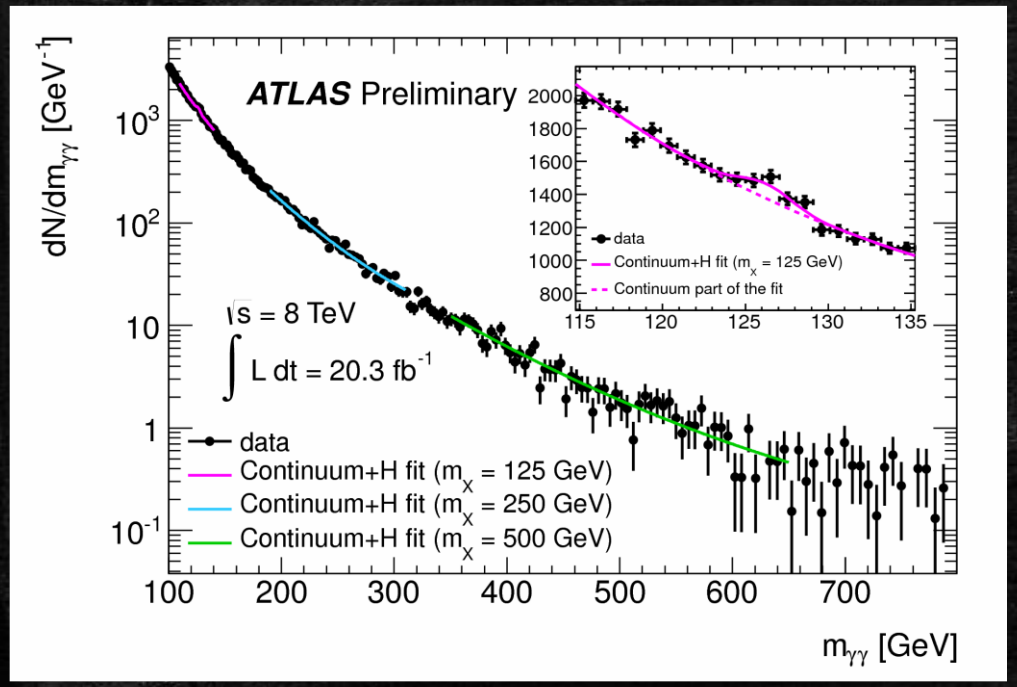
Heavy H->WW->eνμν

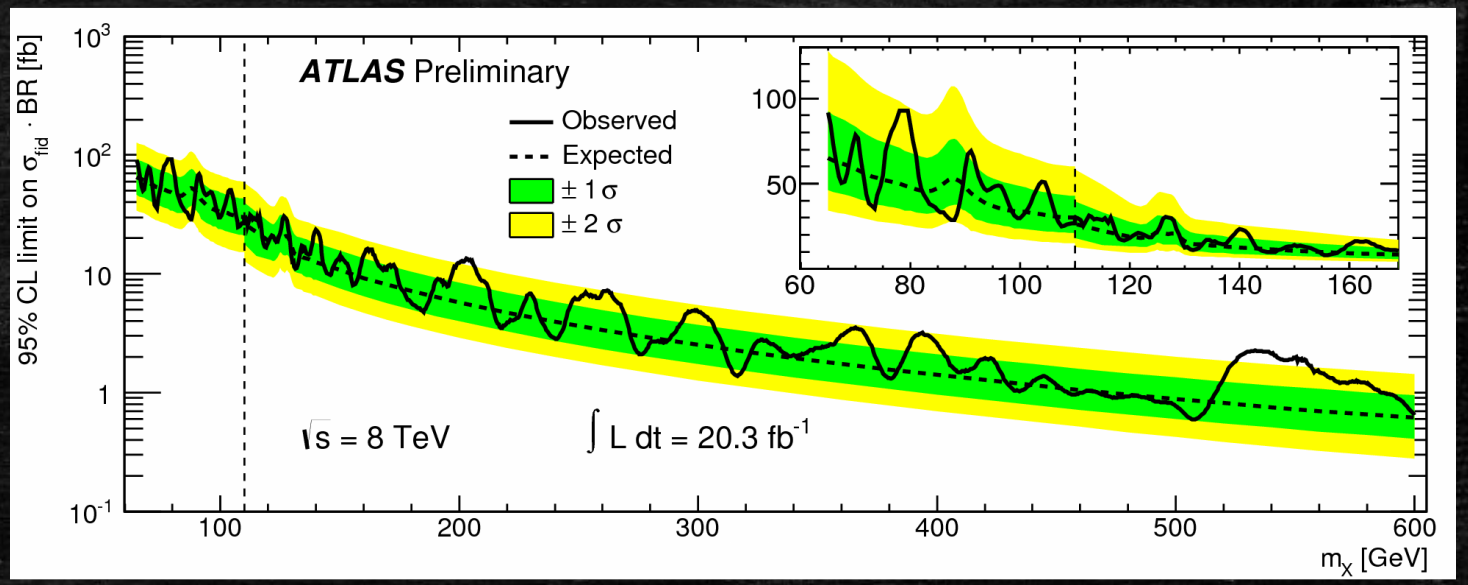
- Generic search for neutral scalar resonance in the mass range 300 GeV-1 TeV
- Cut based analysis, optimised in categories according to the number of jets in the event
- Final discriminating variable m_T



Heavy H->γγ

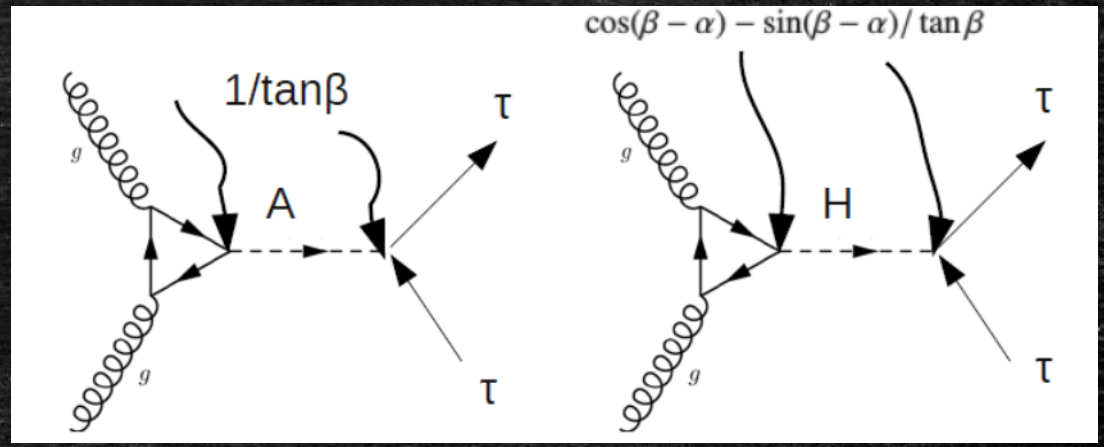
- Extension of the techniques developed for the discovery of h(125)→γγ to search for additional narrow resonances decaying into γγ in an extended mass range
- $M_{\gamma\gamma}$ spectrum fitted with analytical descriptions of signal and background distributions
- h(125) contribution is included in background





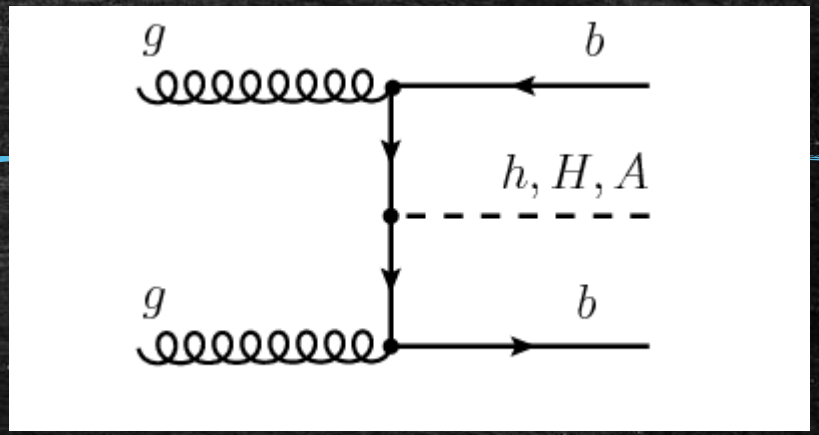
CP odd Higgs

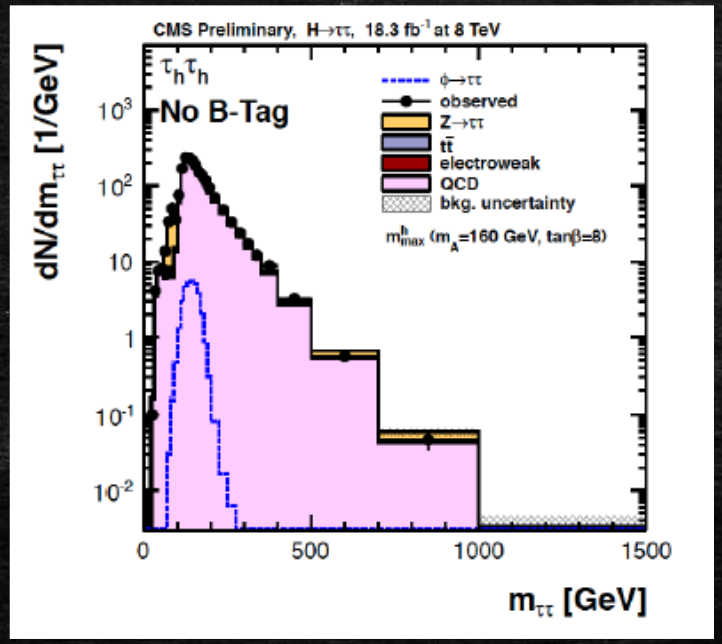
- At tree level, cp-odd pseudoscalar can decay to:
  - a pair of standard model fermions $f^{-} f$ ($b\bar{b}$,$\tau\tau$),
  - Zh, ZH
  - $W^{\pm}H^{\mp}$
  - or other BSM particles
- In type 1 and 2 2HDM the production and deay of the CP odd A depends only on tanβ.

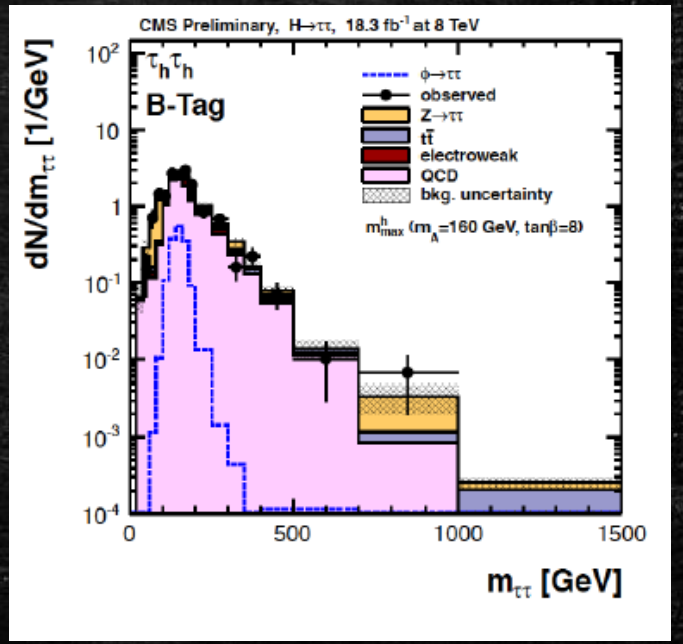


H/A->ττ

- Channels: different τ decays exploited
- Associated production with b quarks enhanced for larger values of tanβ
- Both experiments use b-tag and no btag categories

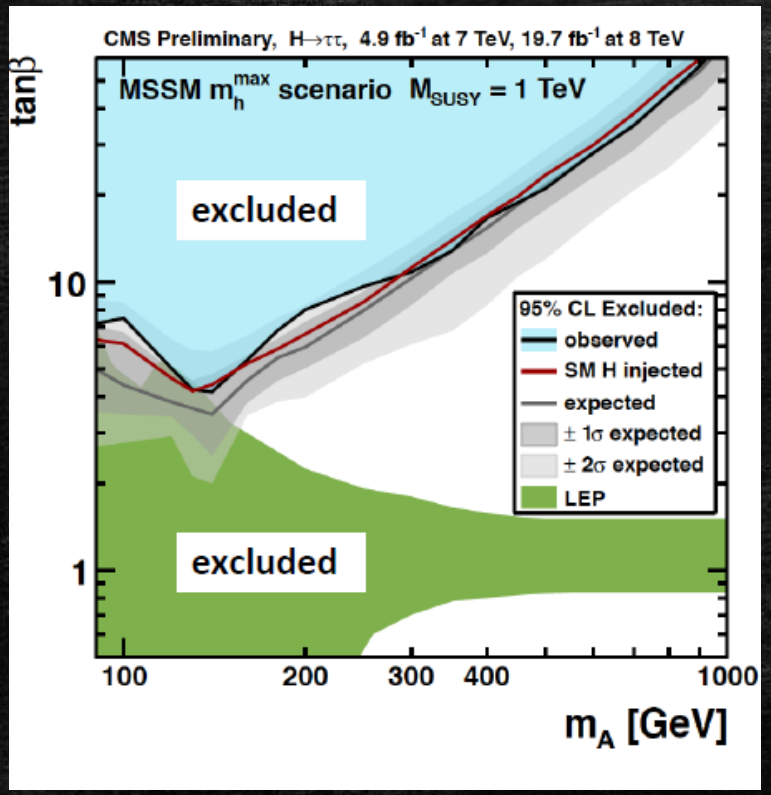


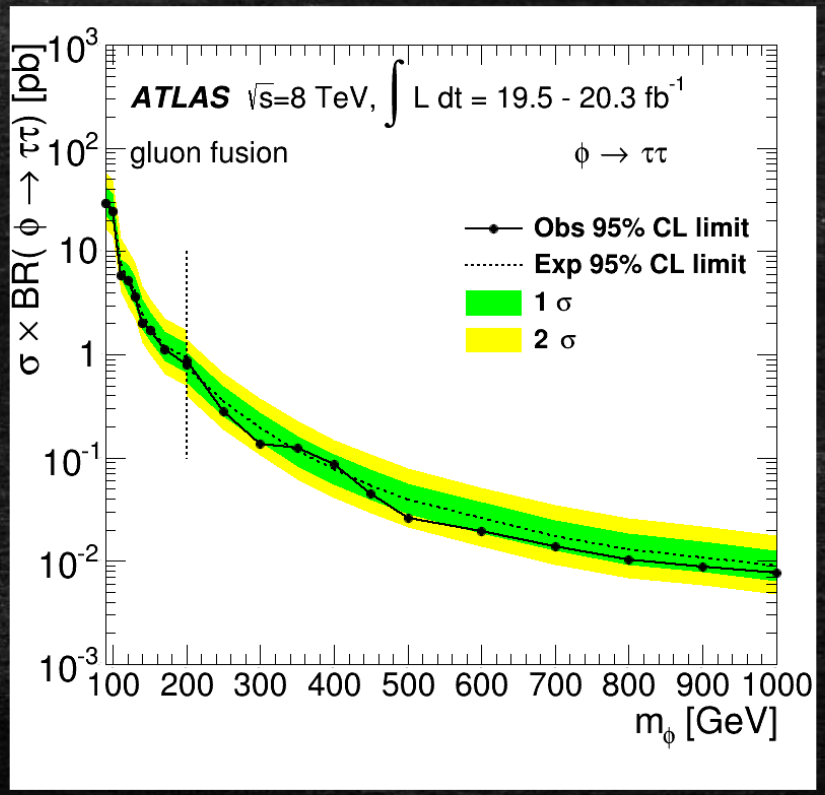


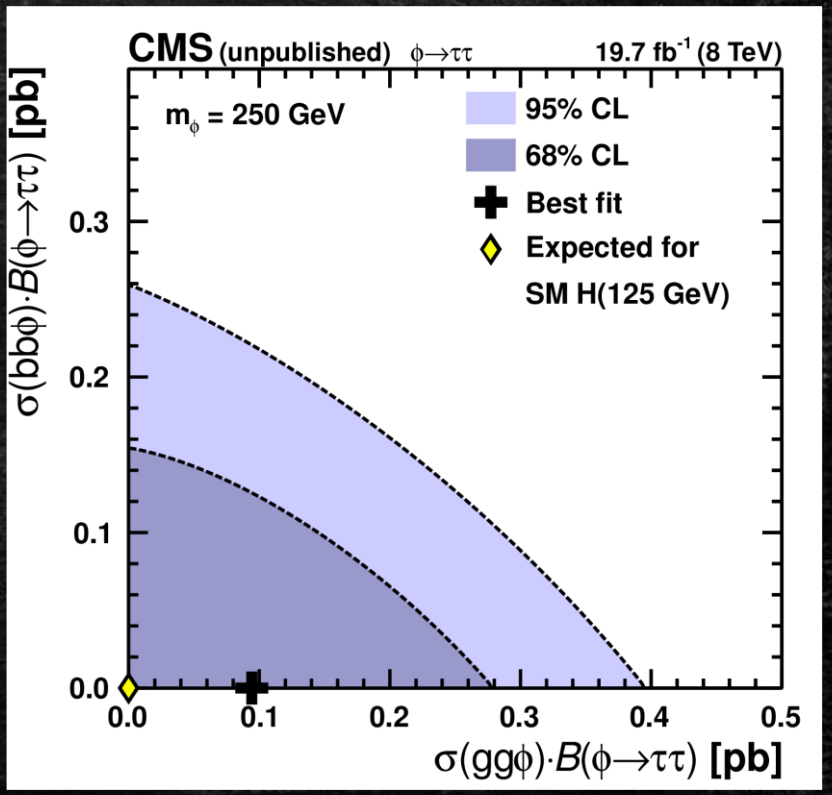


H/A->ττ

- Different ways of presenting the results
  - SUSY parameter space, model independent, wtr to production mechanisms

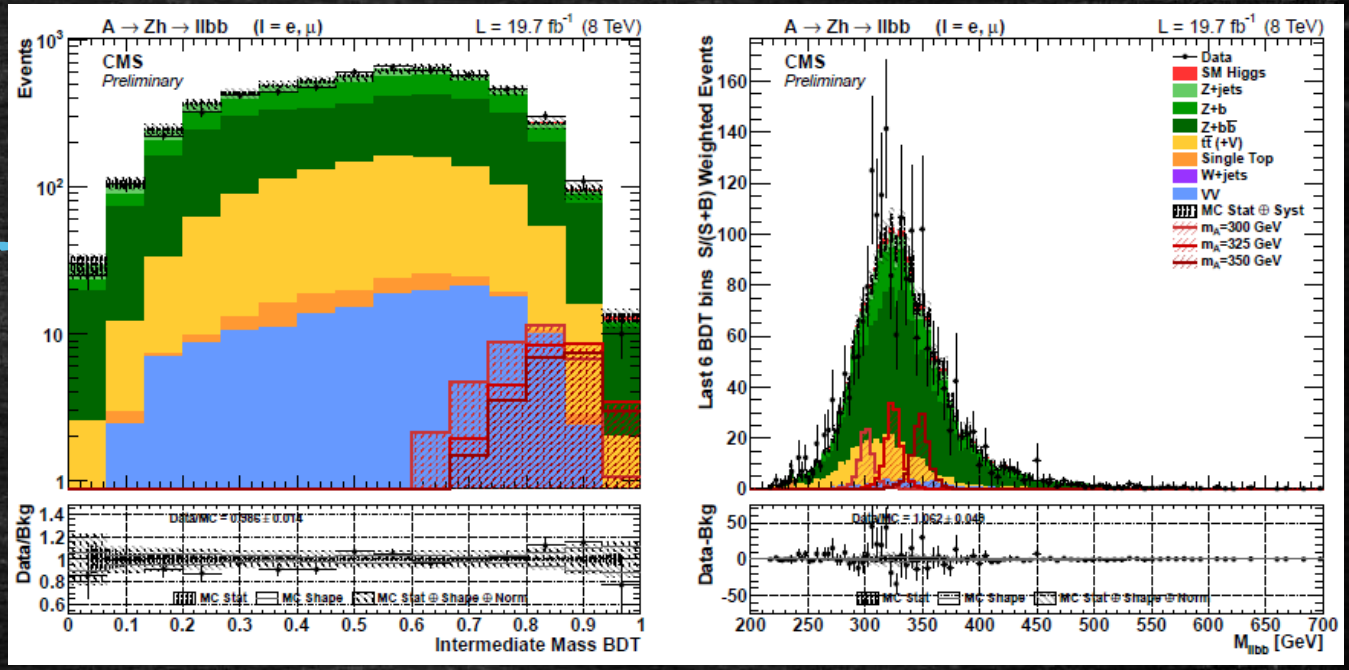


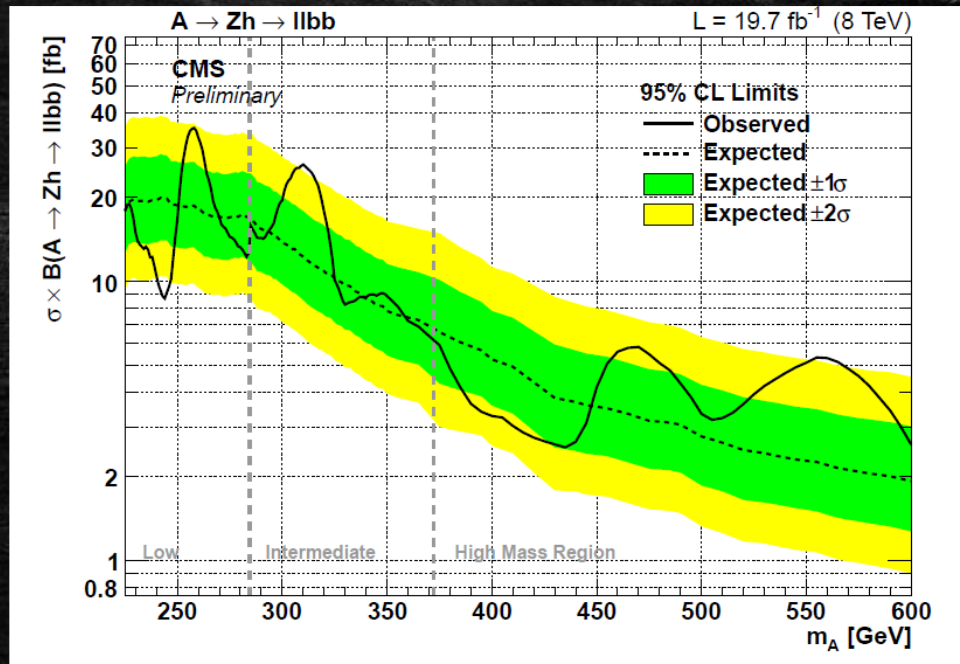




A->Zh->bbll

- heavy pseudoscalar Higgs A, decaying into a Z and an h boson
- Events with opposite sing same flavour leptons and two b tagged jets.
- The analysis strategy is to fully reconstruct the Z, h, and A bosons from the visible decay products
- a narrow peak in the m_{llbb} spectrum
- Backgrounds Z+b jets, ttbar with leptonic W decays
- Final selection using Boosted Decision Trees





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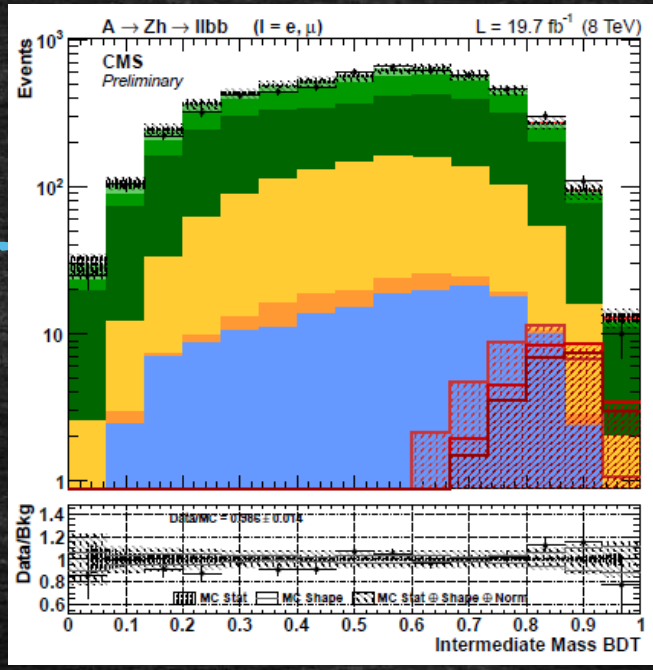
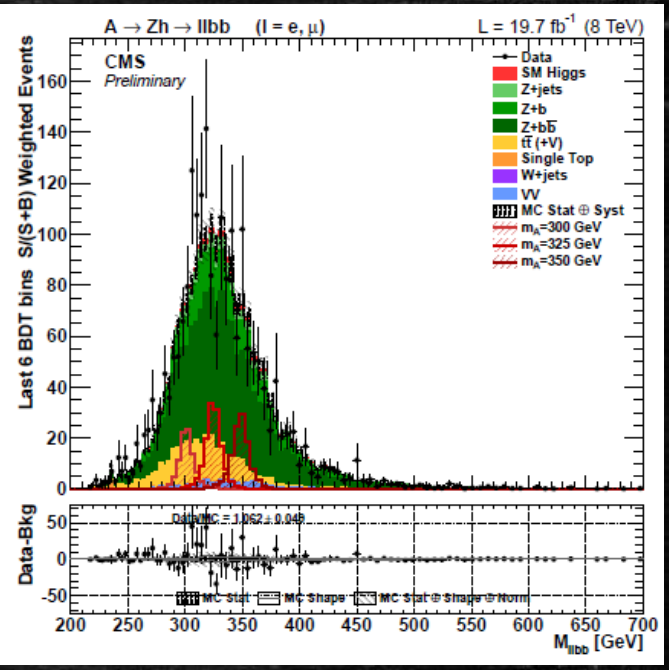
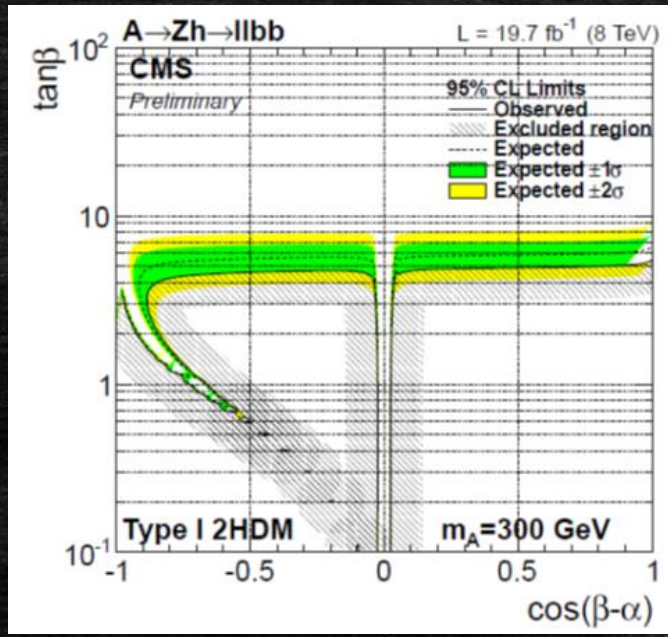
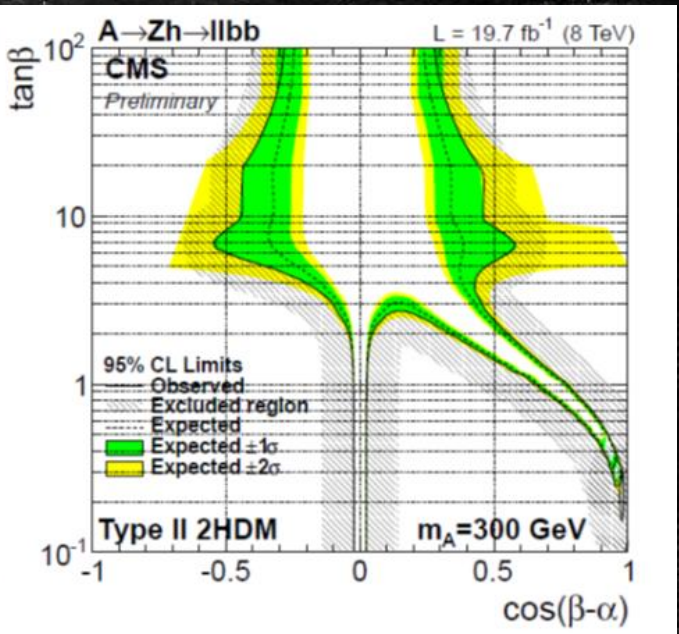


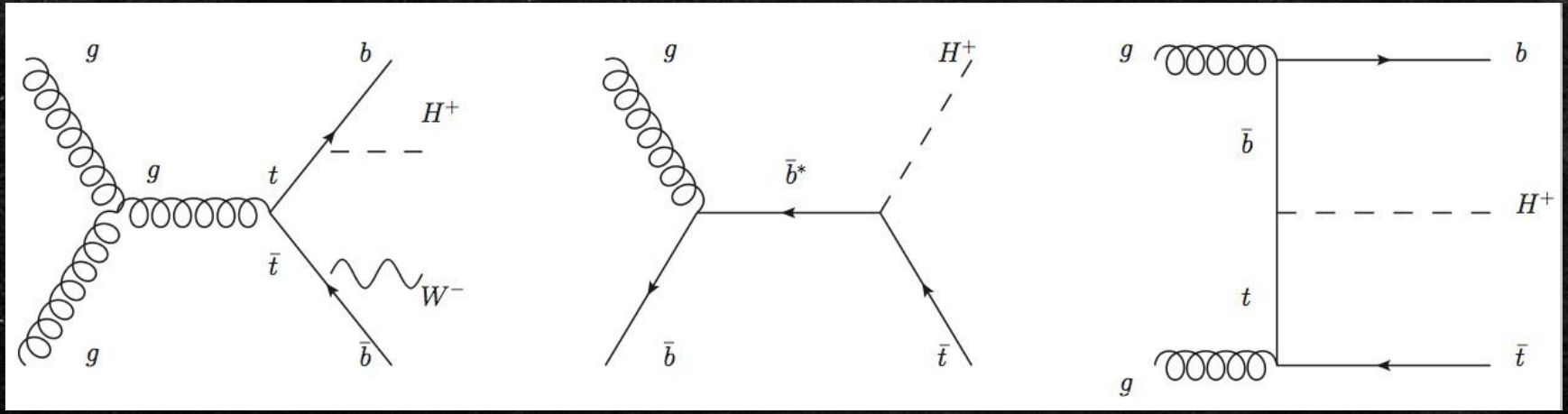






Charged Higgs

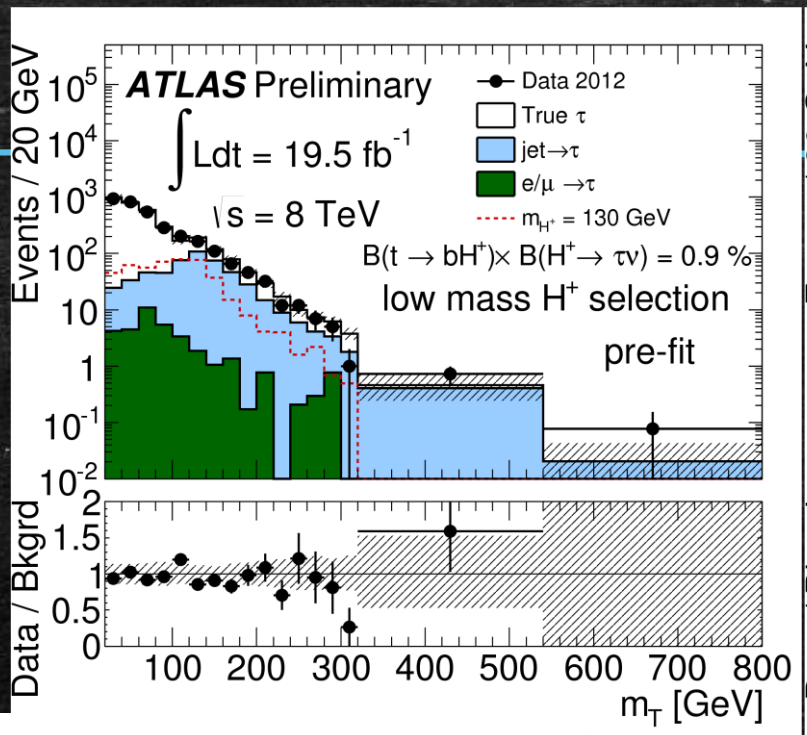
- Charged Higgs part of SM extensions
- Not so many final states explored yet
- New results on the way; More planned for Run 2
  - $H^+ \to \tau\nu$
  - $H^+ \to tb$
  - $H^+ \to Wh, WZ$
  - $H^+ \to cs/cb$ and more !

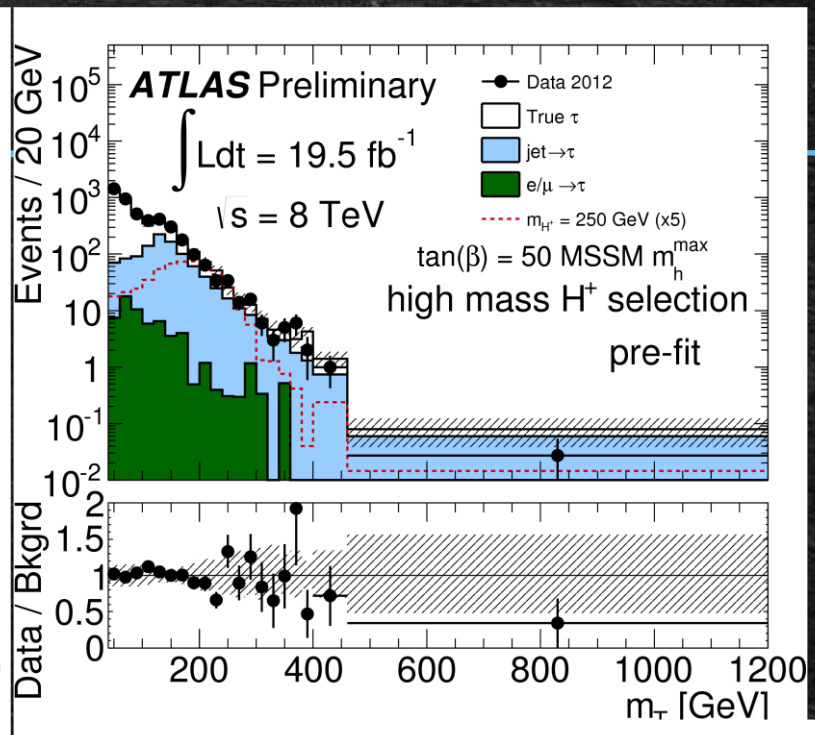


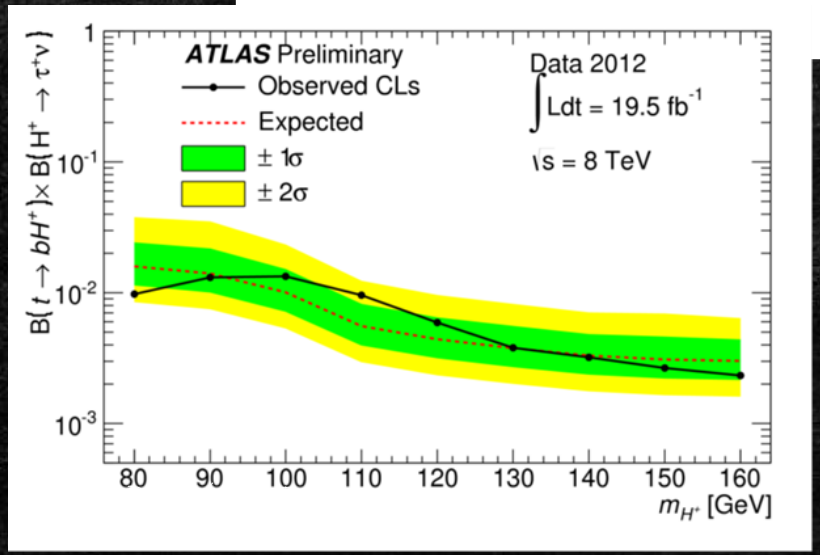
Charged Higgs ATLAS $H^+ \to \tau_h \nu$

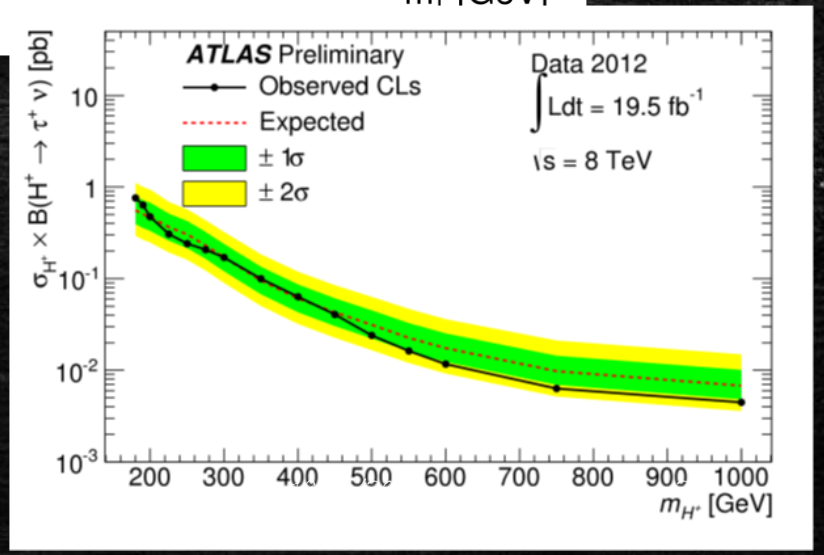
- Backgrounds
  - ttbar
  - single top
  - W+jets,Z+jets, WW,WZ,ZZ
  - QCD multijet
- Discriminating variable the reconstructed tau mass.
- $m_\tau = \sqrt{2 p_T^\tau E_T^{miss} \left(1 - cos\Delta\Phi_{\tau,miss}\right)}$
- background estimation using embedding method.* (details in the backup)
  - select events that are topologically similar to main background but contain μ instead of τ
  - remove μ track, simulate τ hadronic decay
  - merge original event and simulated $\tau\alpha$
  - reconstruct whole event

Charged Higgs ATLAS H-> $\tau_h \nu$







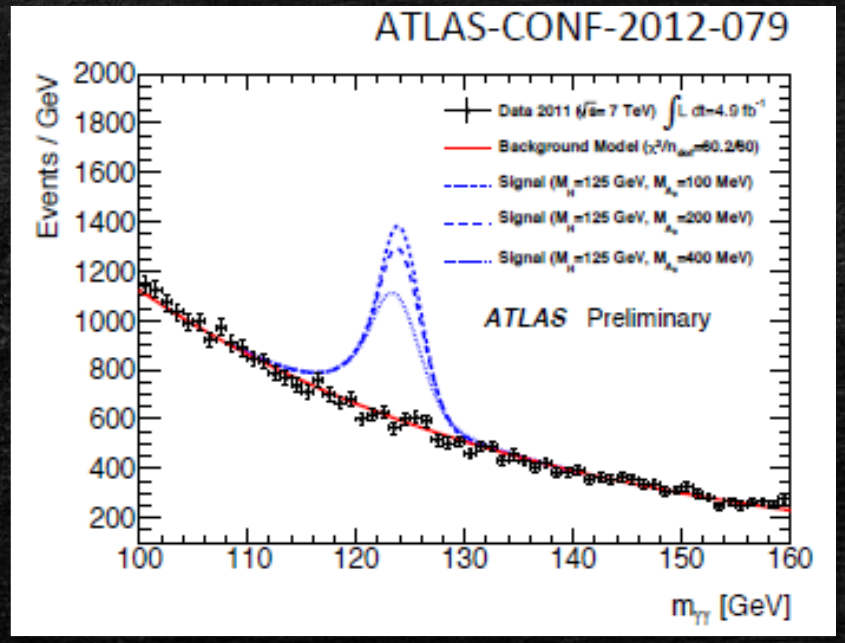


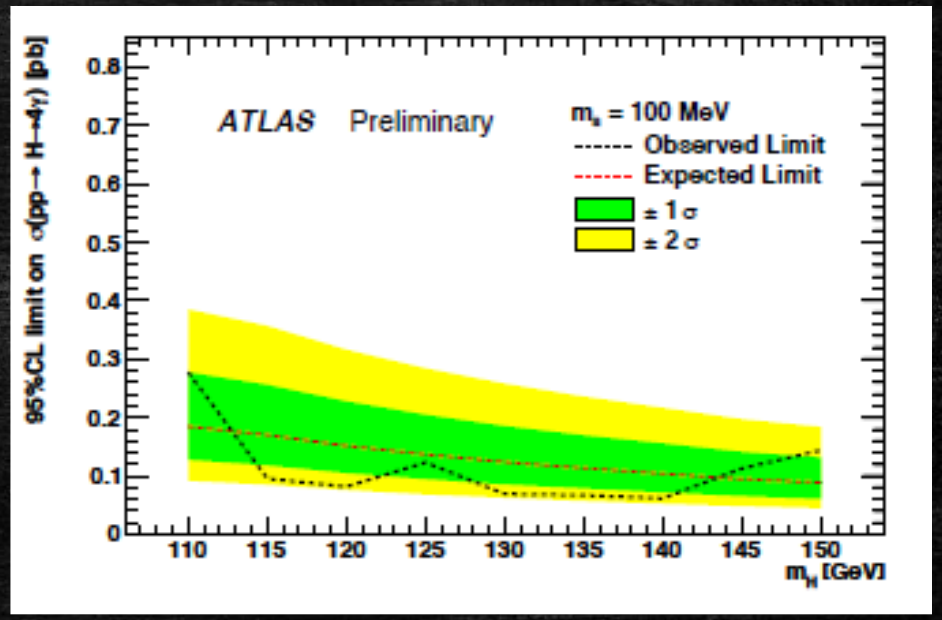
Light higgs (NMSSM)

- Light higgs boson h coupling to the H=125 GeV Higgs
  In the context of the NMSSM can be very light! (<10 GeV)
- Many final states and productions are being studied as we speak
  Many new results to come by the end of the year
  Many more are getting ready for Run2
- H->hh->2μ2τ
- t-> bH$^+$-> baW, a->2μ
- H->hh->2b2μ
- H->hh->4τ …

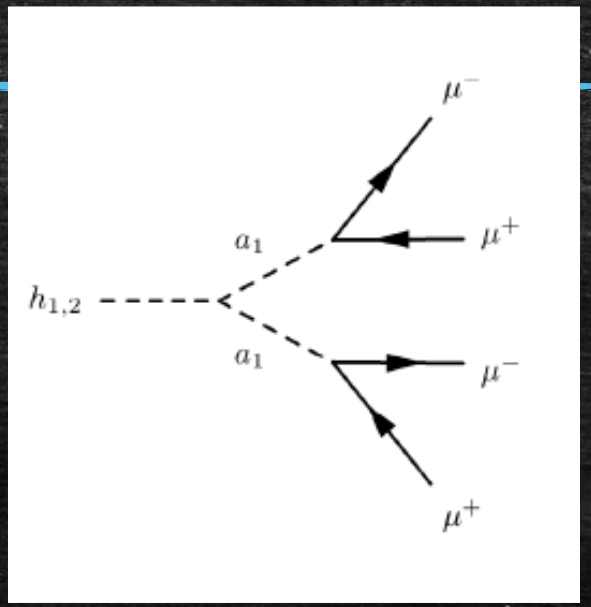
ATLAS h->aa->4γ

- 4 high energy photons
- background dominated by QCD diphotons
  - fitted to sidebands
- No excess observed

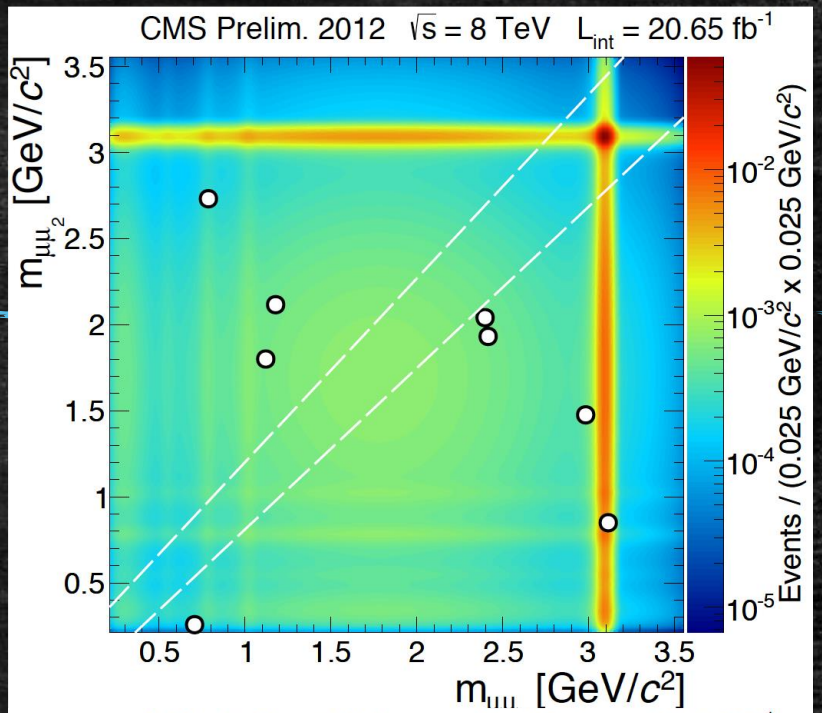


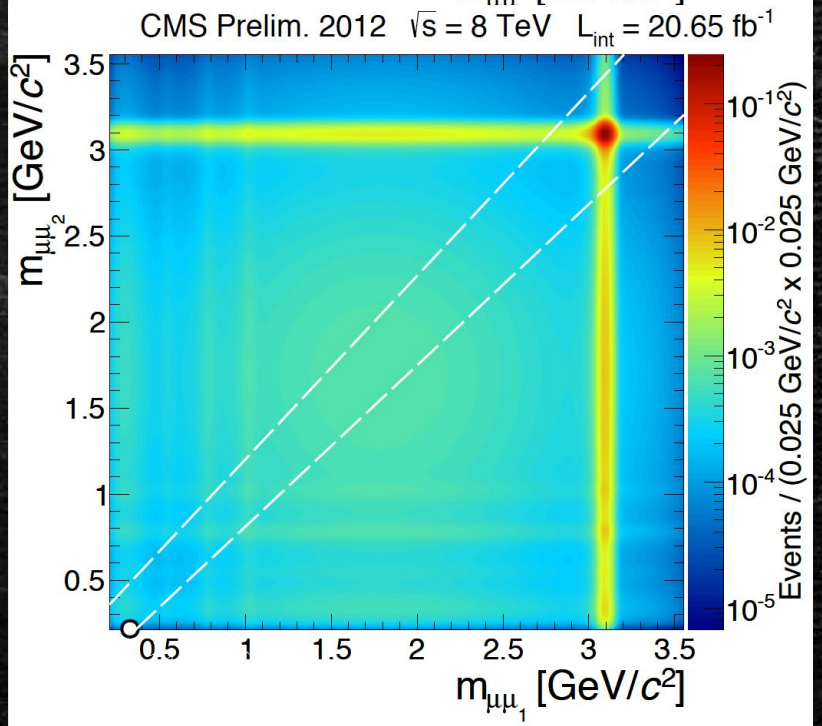


CMS h->aa->4μ



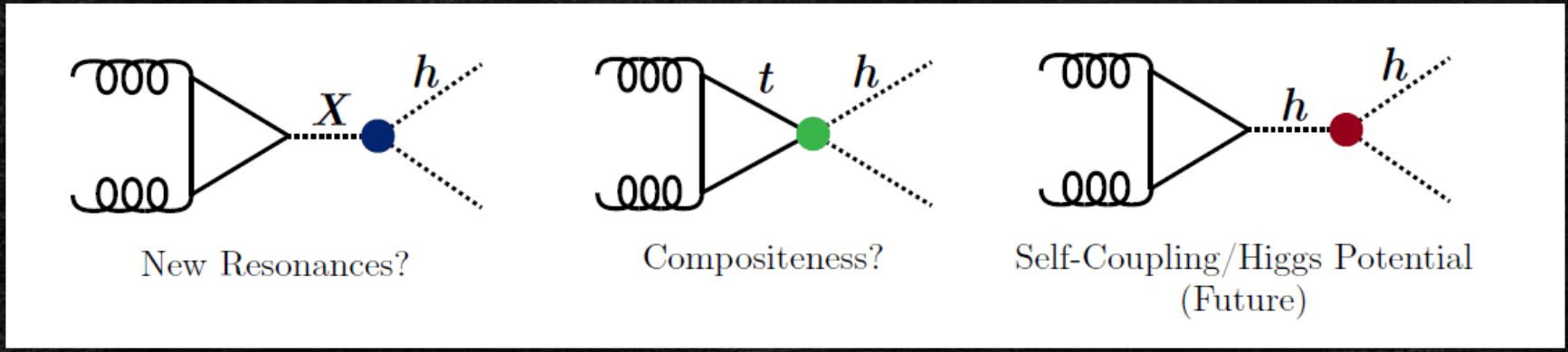
- 2 muon pairs with 0 charge and similar mass
- Backgrounds
  - bbbar decays to muons
  - di-J/Ψ direct production
- Sideband region of $m_{\mu\mu 1} \neq m_{\mu\mu 2}$
  - background prediction of 3.8 +/- 2.1
- 1 event observed in signal region compatible with background prediction





Double Higgs production

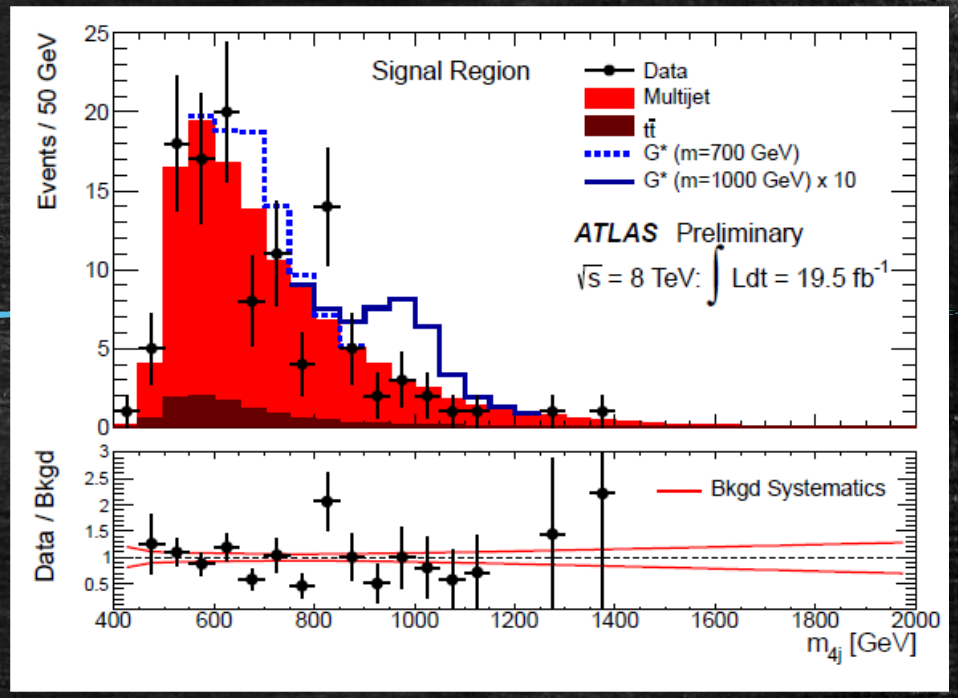
- TeV-scale resonances decaying to two Higgs bosons predicted by several models, including:
  - RS KK Graviton→hh
  - H→hh in 2HDM
  - Enhancement of non-resonant di-Higgs production
  - SM di-Higgs production at HL-LHC

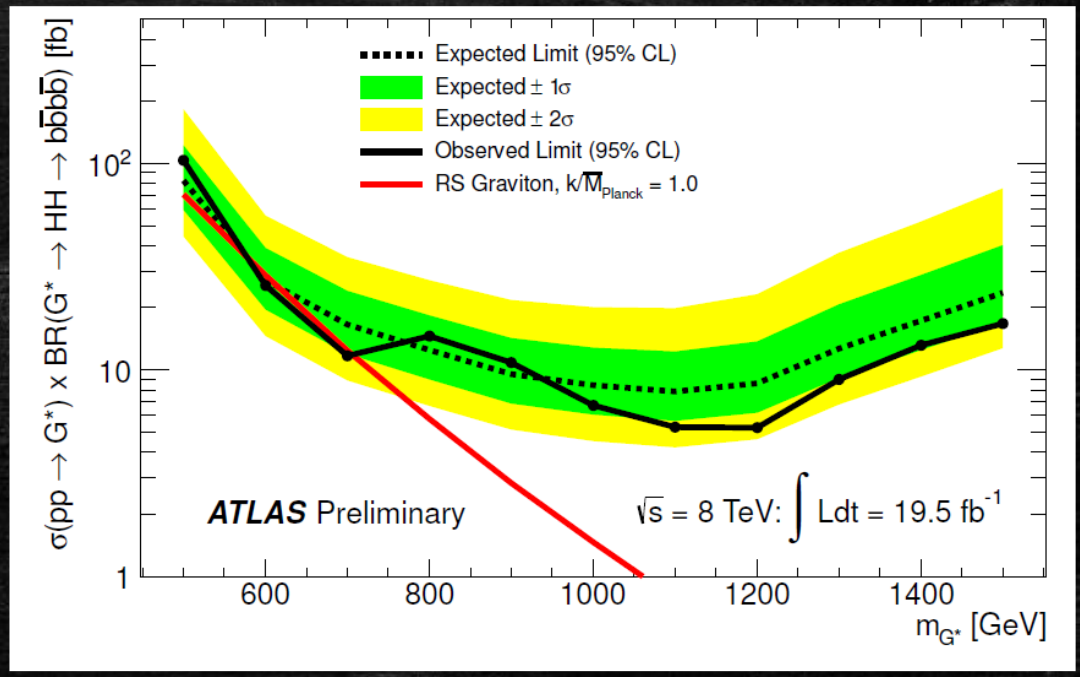


New Resonances? Compositeness? Self-Coupling/Higgs Potential (Future)

hh->bbbb

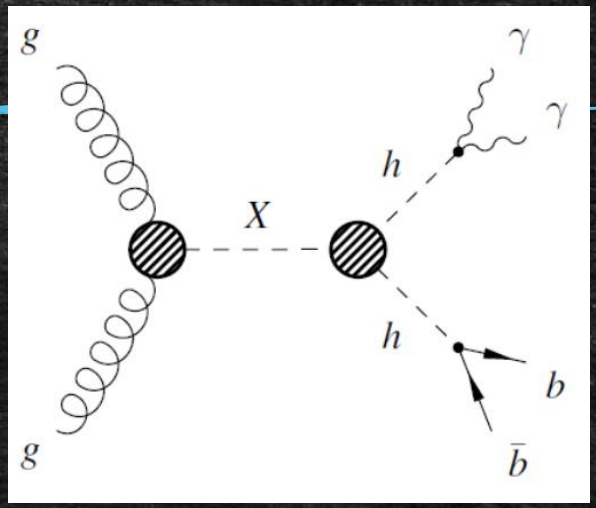
- Search for TeV-scale resonances decaying to a pair of Higgs bosons
- hh->bbbb, two back to back, high p_T, pairs of b-tagged jets.
- dijet mass must be compatible with 125GeV
- final discriminant, mass of the all four jets, m_{4j}

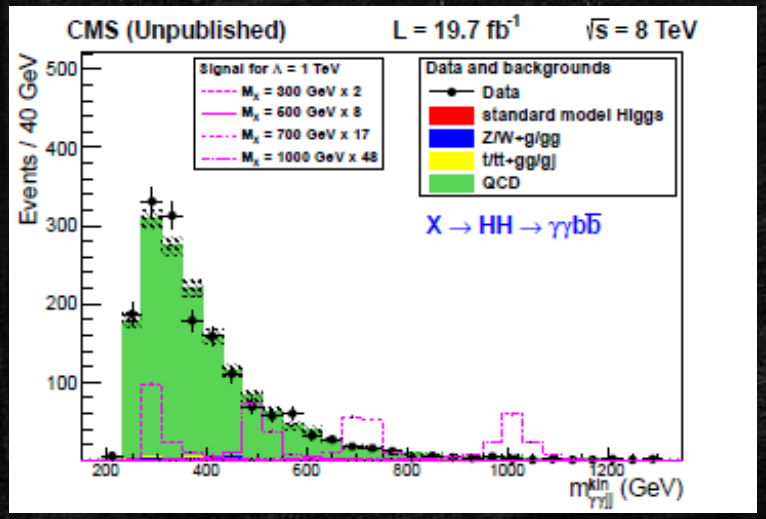


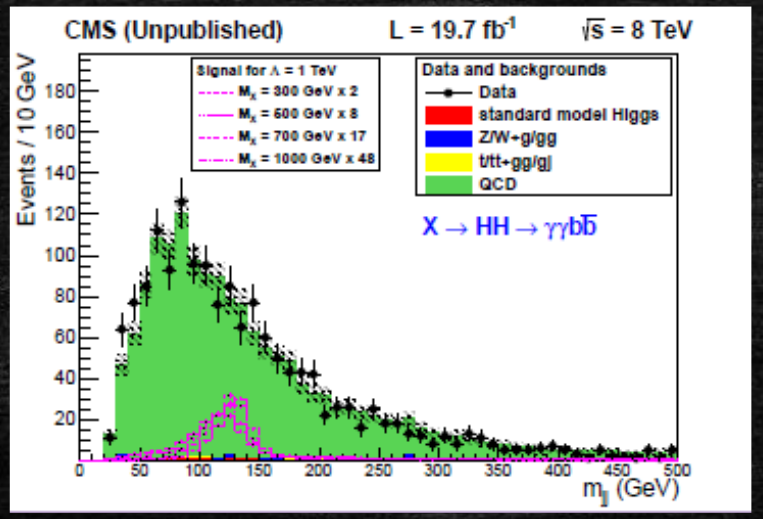


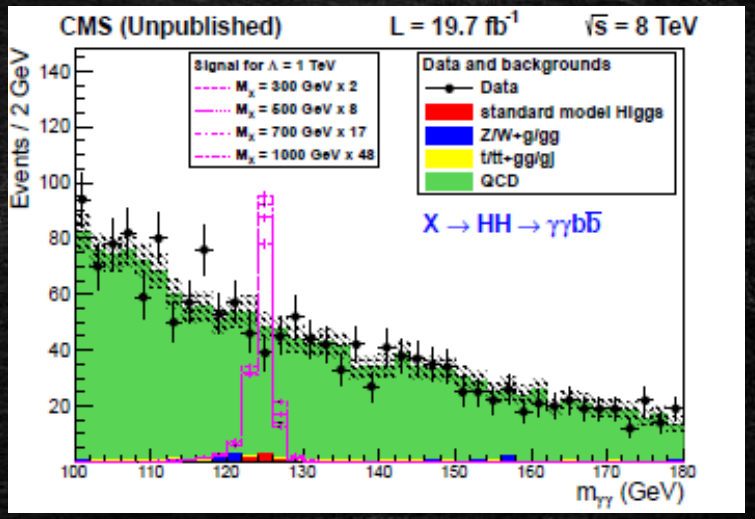
hh->bbγγ

- 2 photons
- At least one b-tagged jet
- Background: QCD γγ+jets









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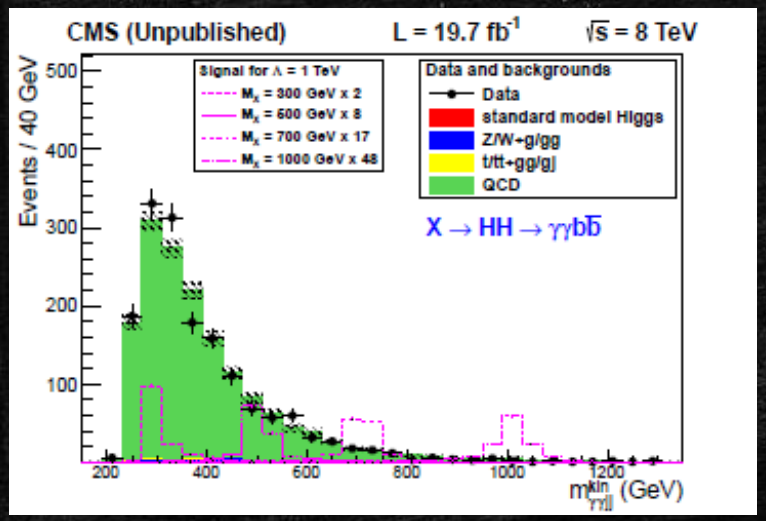
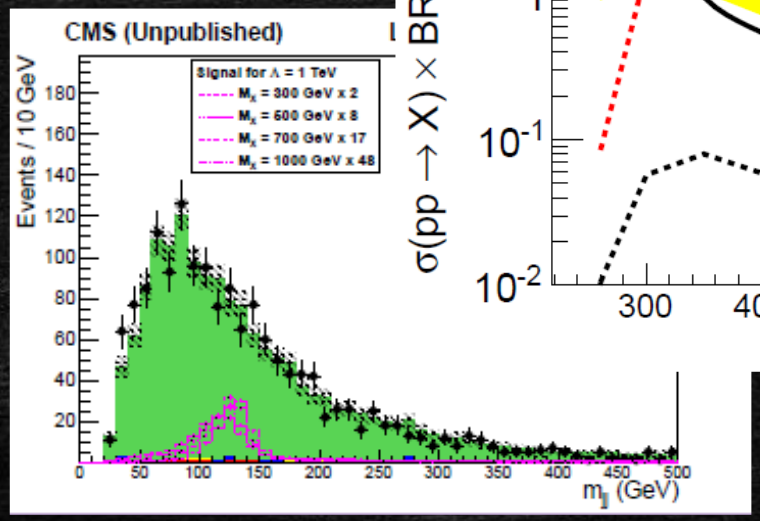
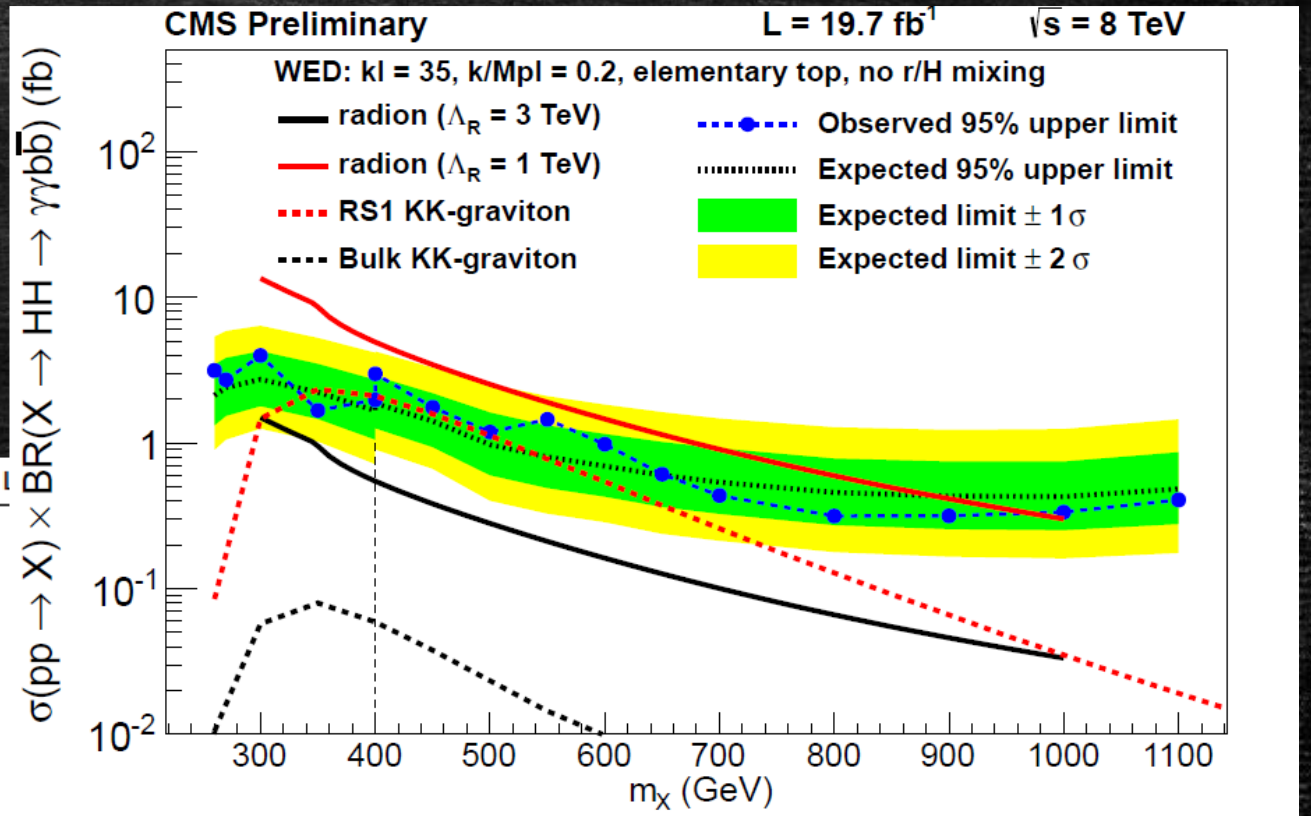
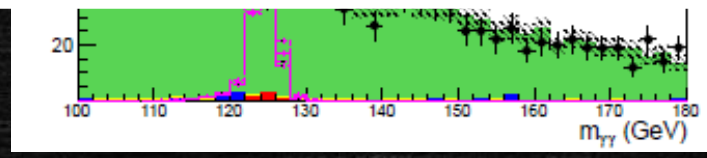




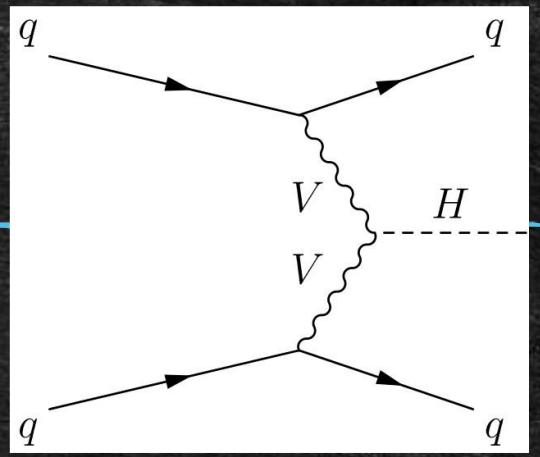




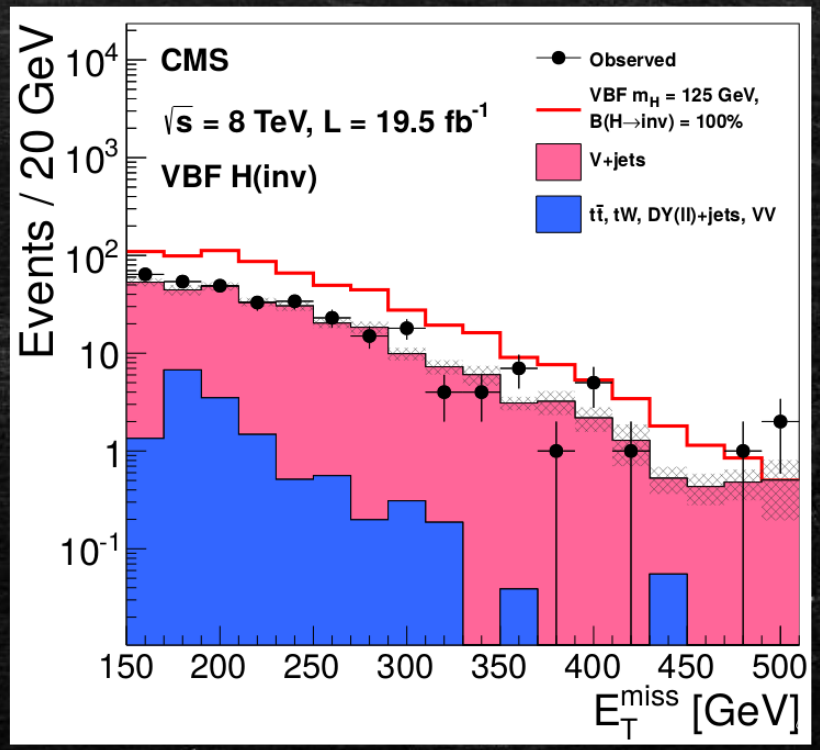
Higgs invisible

- Some extensions of the Standard Model allow a Higgs boson to decay to a pair of stable or long lived particles that cannot be observed
- Higgs decaying to a hidden/dark sector
  - Higgs portal (SM+singlet) dark matter scenario

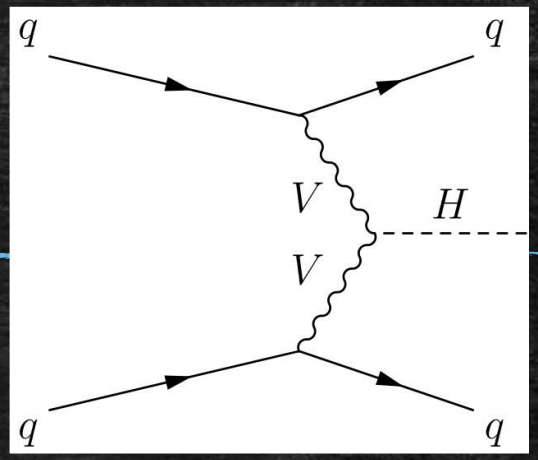
Higgs invisible VBF



- VBFH
  - 2 forward jets with big rapidity gap between them and high invariant mass.
  - A lot of missing transverse energy (MET)
- Backgrounds
  - $Z(\nu\nu)$ + jets
  - $W(l\nu)$ + jets, $DY(ll)$ + jets
    - lepton veto: no ℓ with $p > 10$ GeV/c
  - Single top, tt, diboson
  - QCD multijets
    - $\Delta\varphi(jj) < 1.0$ rad



Higgs invisible VBF



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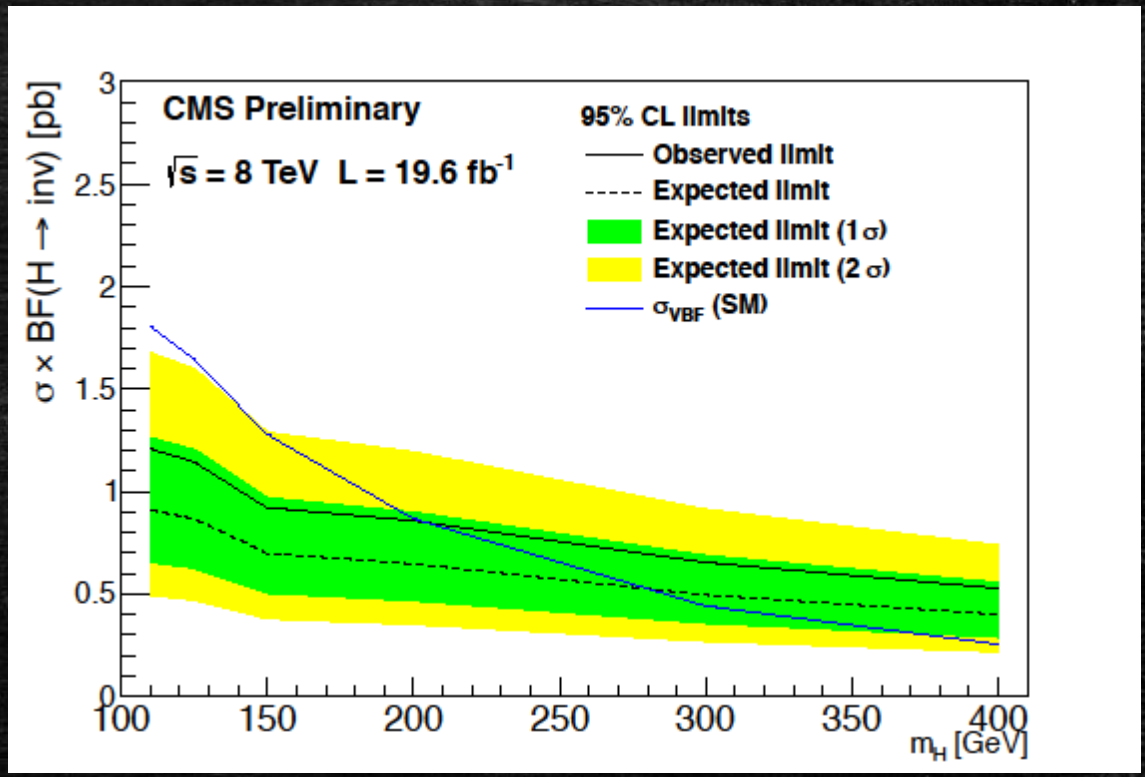
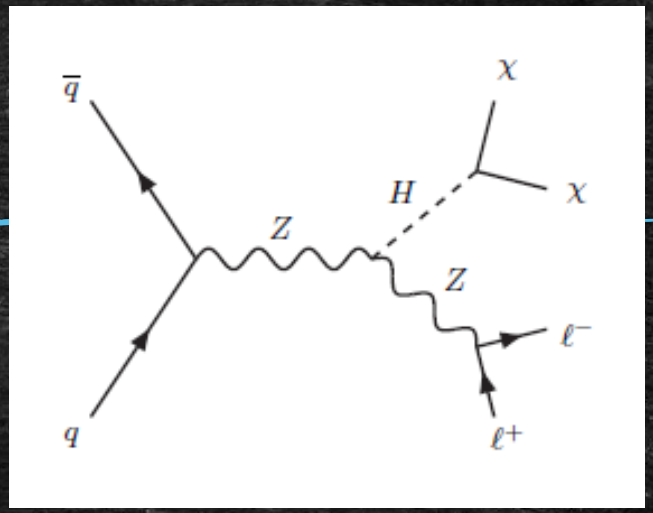


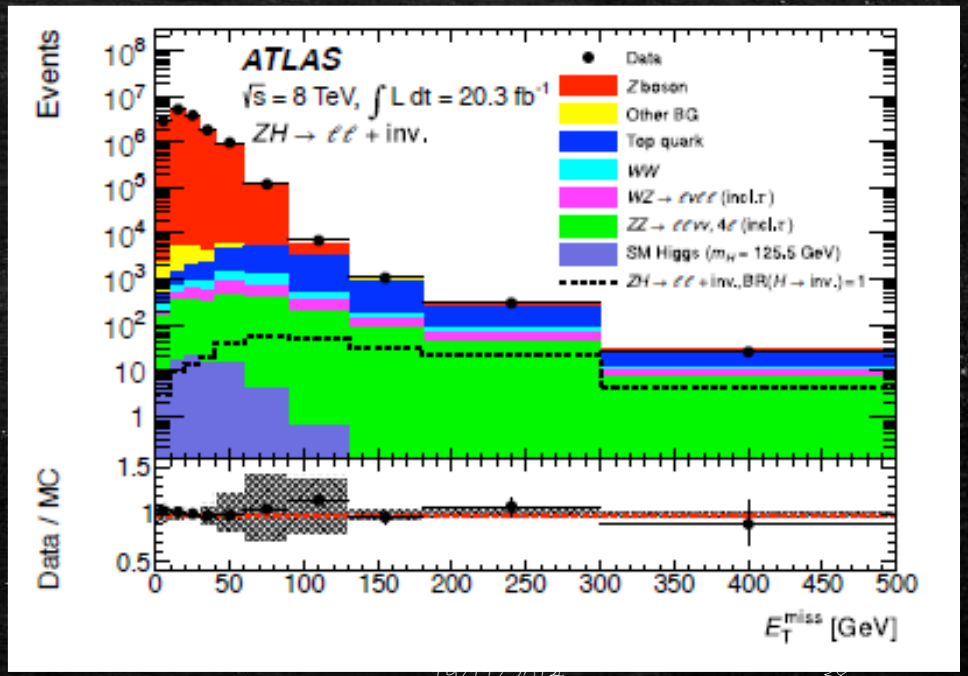
Higgs Invisible VH

- Pair of isolated leptons
- Dilepton mass near Z mass
- A lot of missing transverse energy

Backgrounds:

- Diboson WW/ZZ/WZ
- Z->μμ/ee
- Ttbar, Wt..





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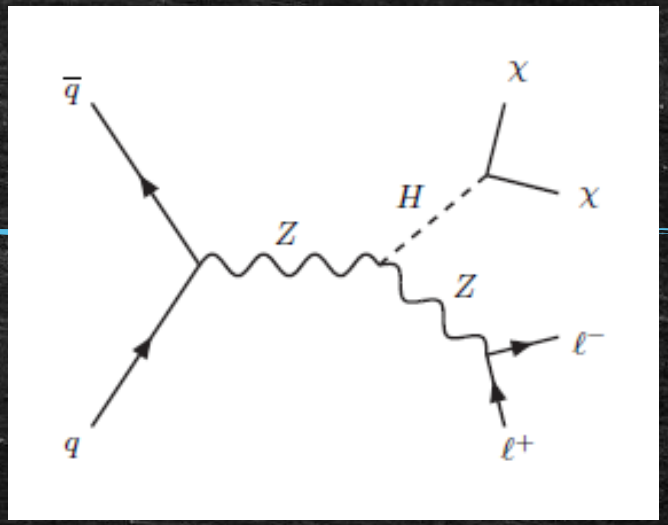
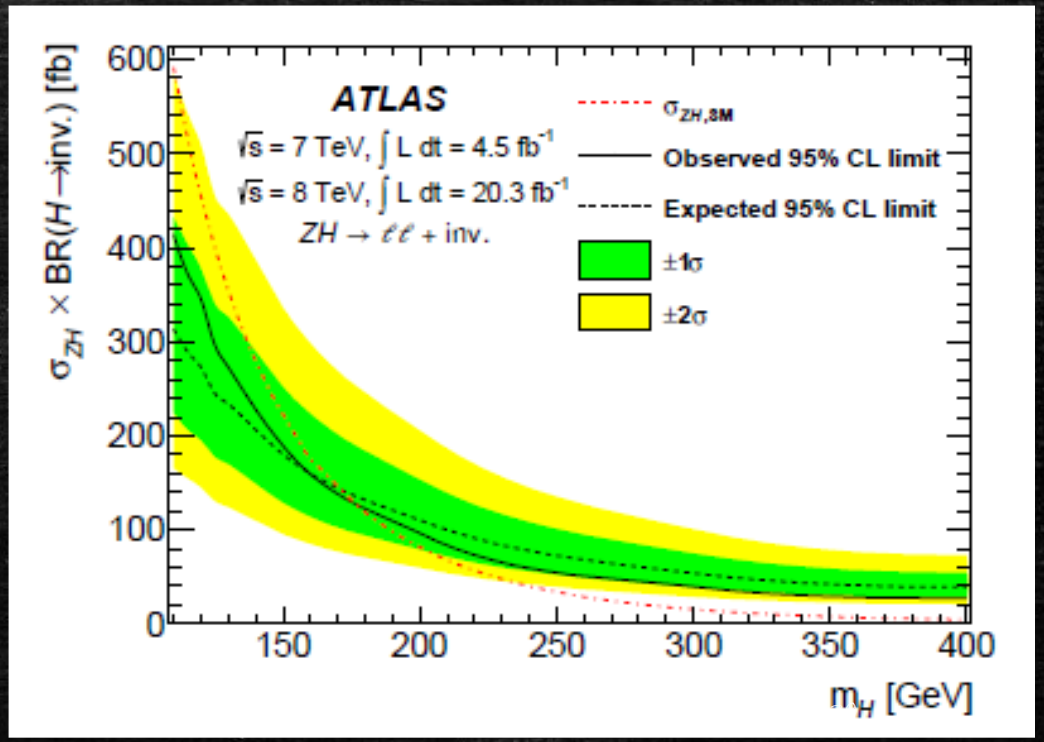
- Dilepton mass near Z mass
- A lot of missing transverse energy

Backgrounds:

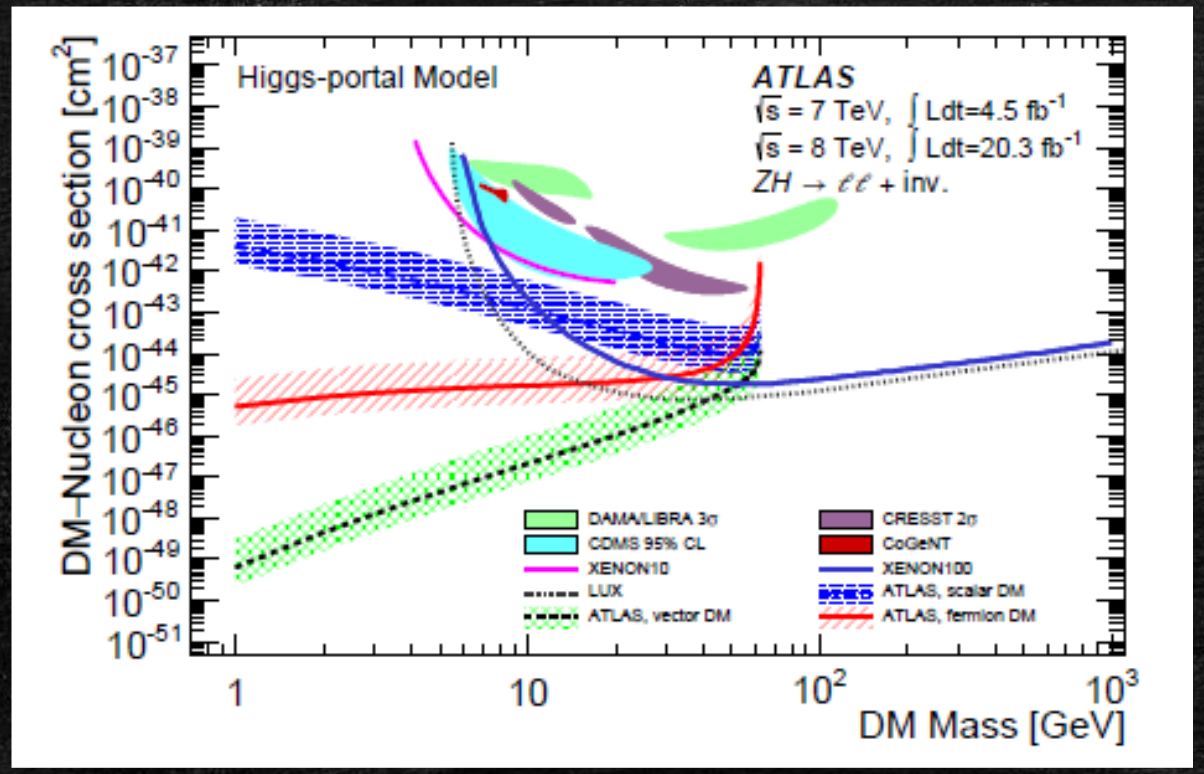
- Diboson WW/ZZ/WZ
- Z->μμ/ee
- ttbar, Wt..

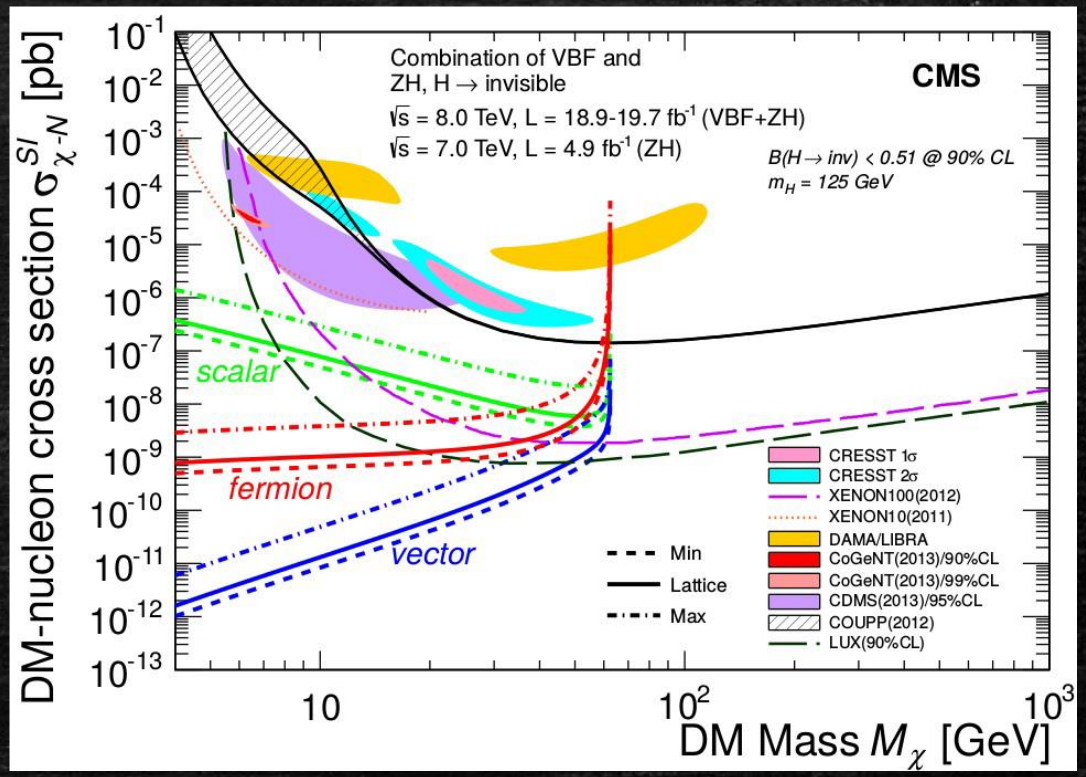




Higgs and dark matter

- The results of the H->Inv. Can be interpreted in the dark matter higgs portal scenario





Many more Higgs searches of interest

- SUSY cascade decays with higgs bosons
- Search for displaced signatures
- Doubly charged Higgs (part of multi higgs doublet models)
- Lepton flavour violating decays
  - $H^- \to \tau\mu$
- …

Looking forward to RUN 2

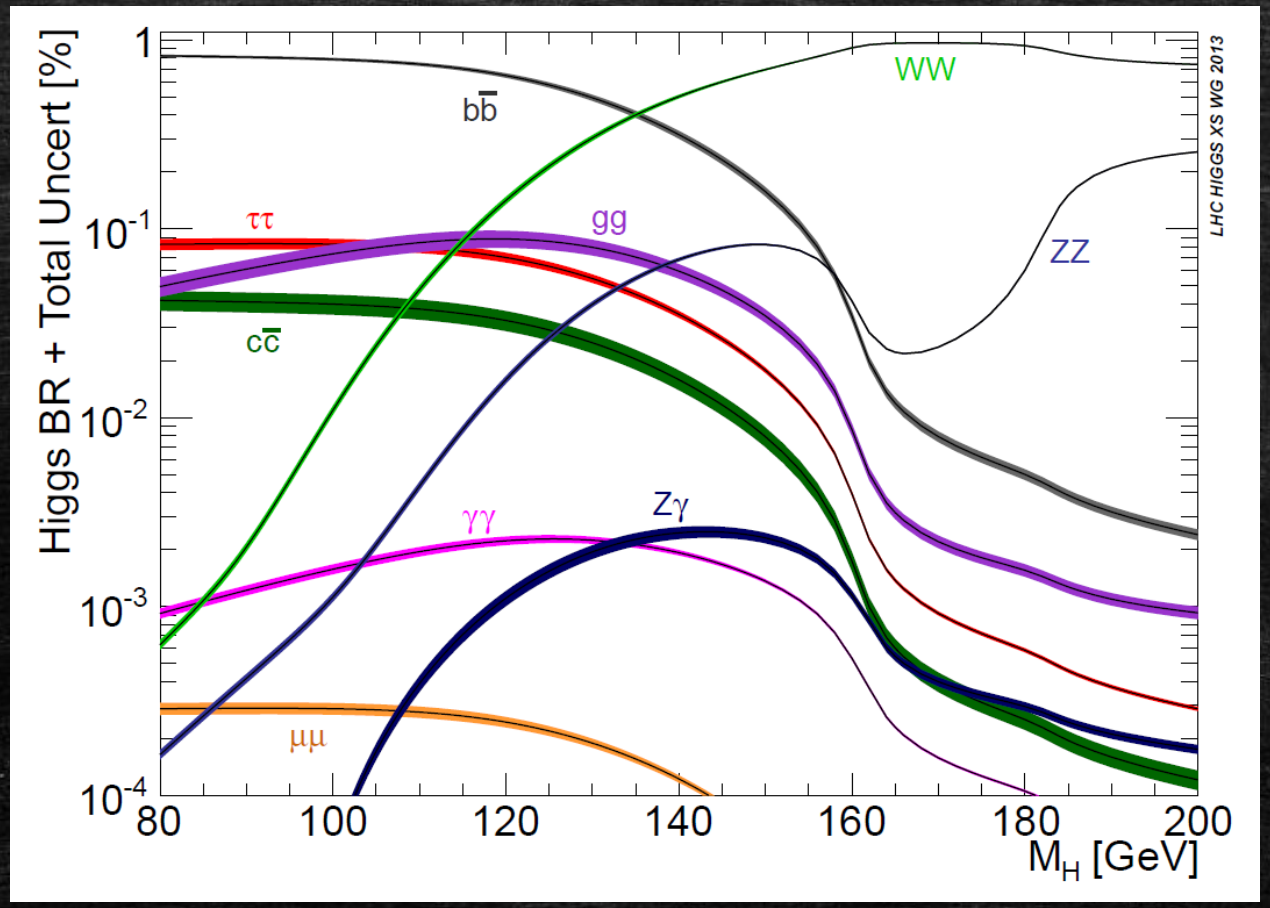
- ATLAS and CMS search for new physics in the Higgs sector
- Searches and measurements in parallel.
- The plan is to test all hypotheses. We have to look everywhere!
- Sophisticated analysis methods used in order to exploit every fb of data
- Aiming for discoveries and not limits! ;)

Looking forward to more energy and new data!

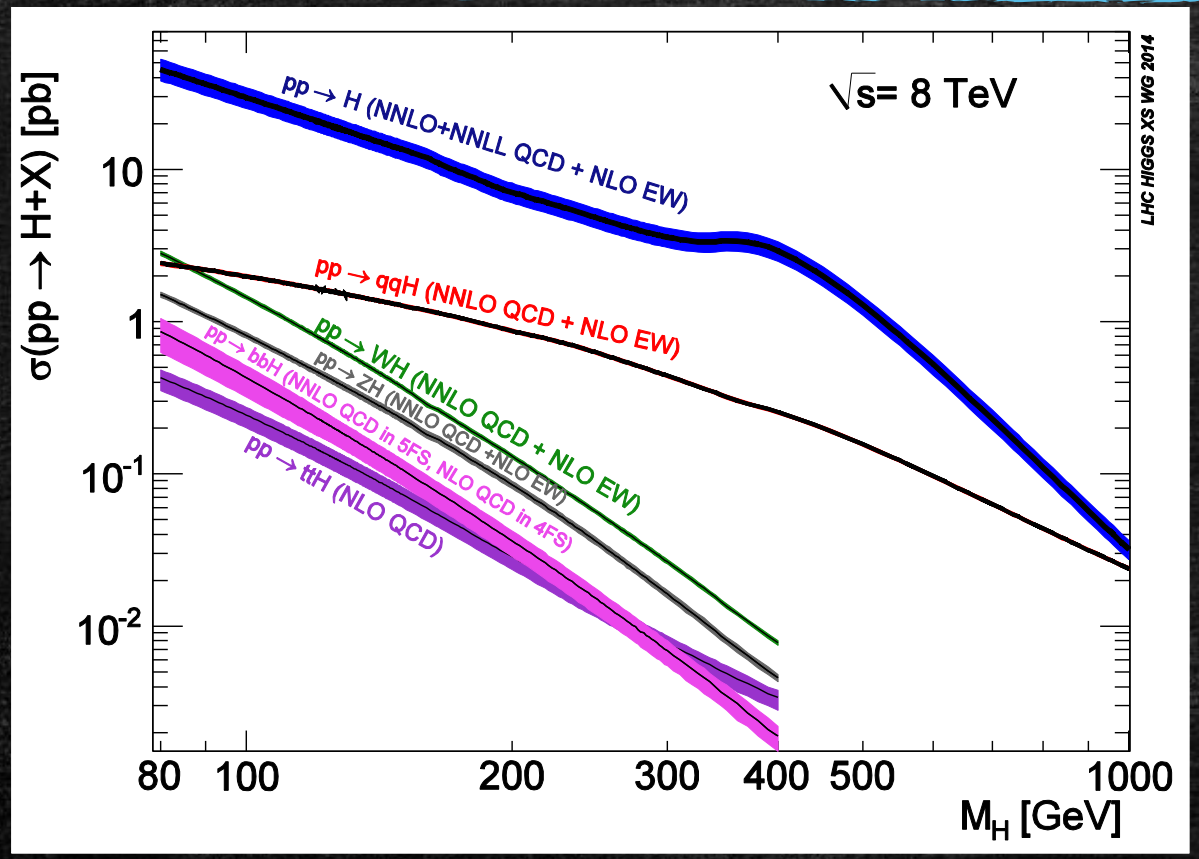
Thank you ☺

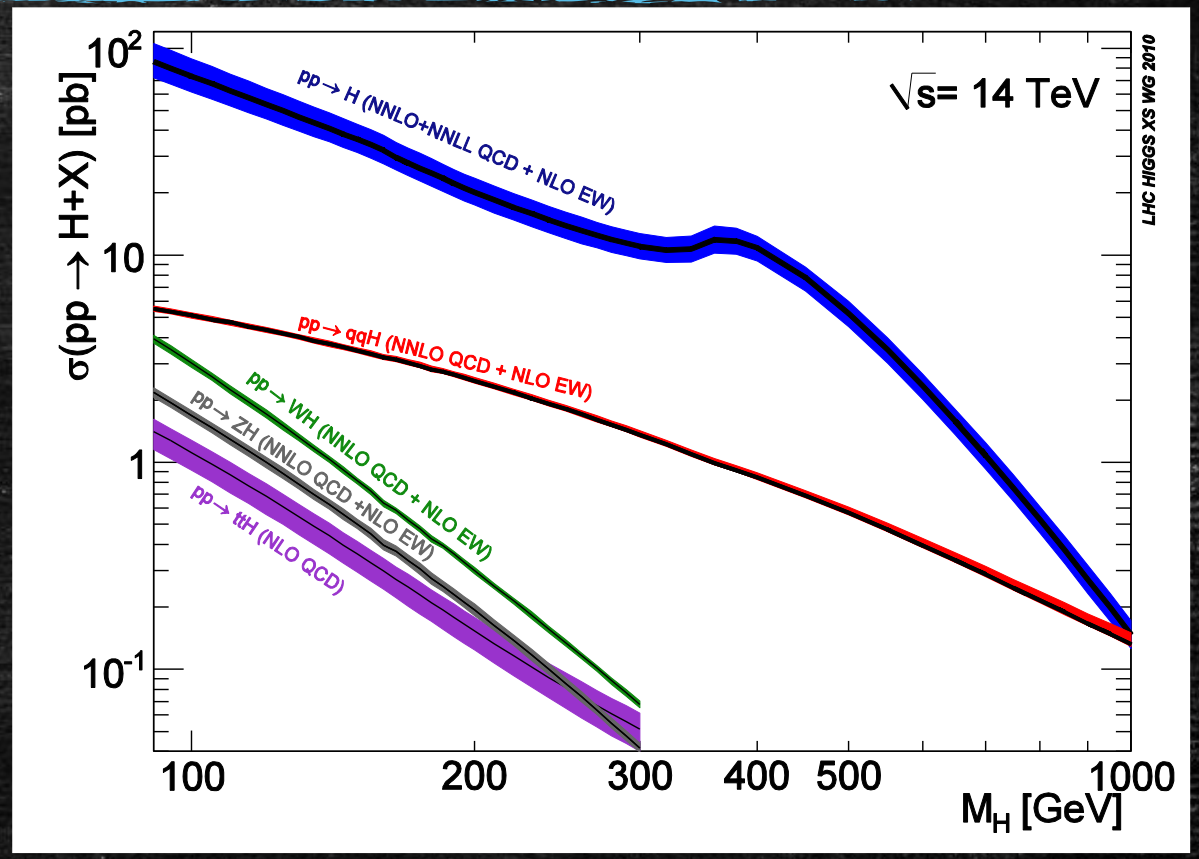
Back-up material

Higgs Branching fractions



Higgs production cross sections

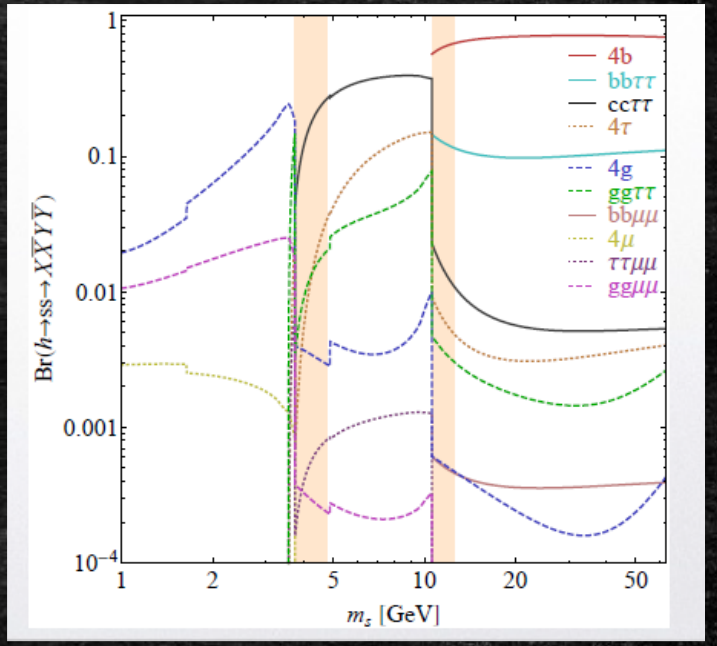




Higgs portal

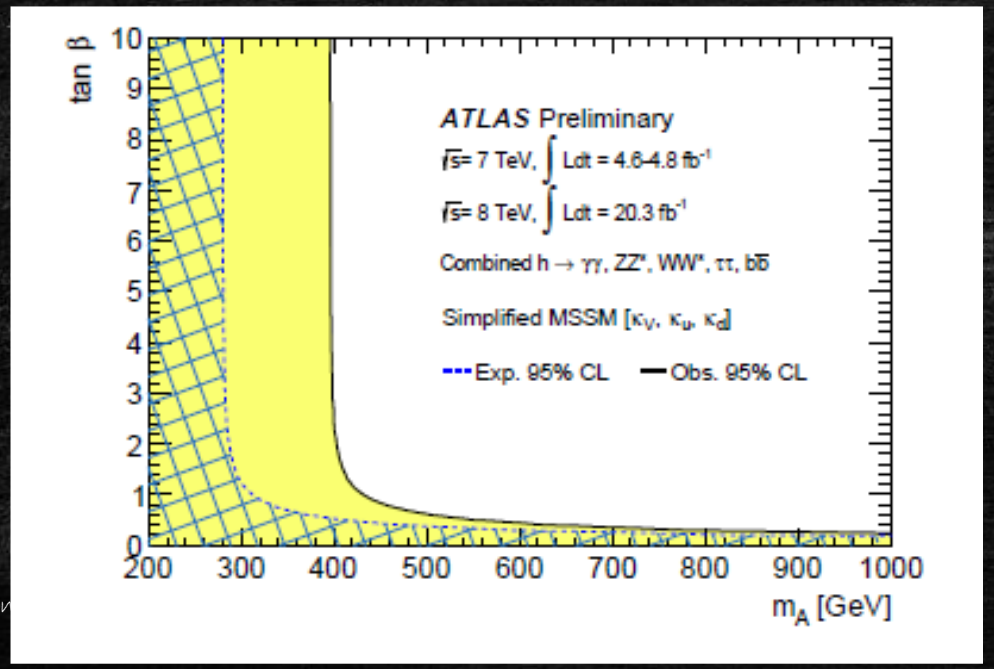
$$V(H,S) = -\mu^2 |H|^2 - \frac{1}{2}\mu'^2 S^2 + \lambda |H|^4 + \frac{1}{4}\kappa S^4 + \frac{1}{2}\zeta S^2 |H|^2.$$

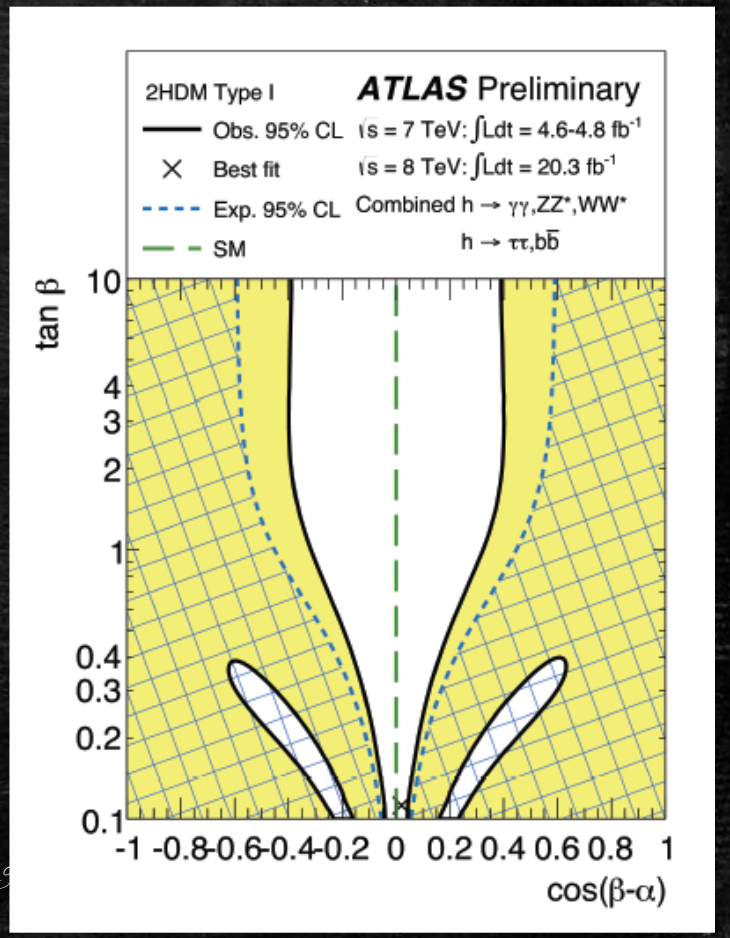
- if S is light enough the coupling ζ induces h->ss decay mode



SM Higgs measurements: conseaquenses

- Various scenarios tested
  - Asymmetric couplings to u/d type fermions
  - Asymmetric couplings to quarks/leptons
  - …
- Coupling measurements place constraints on BSM models.





Embedding method

- used to estimate background a events with true leptons in a data-driven way
- little dependence on theoretical and detector-related uncertainties
- main assumption: same amount of $W \rightarrow \mu\nu$ and $W \rightarrow \tau\nu$ events, same kinematics

➢ select events that are topologically similar to main background but contain μ instead of τ

➢ rescale μ momentum

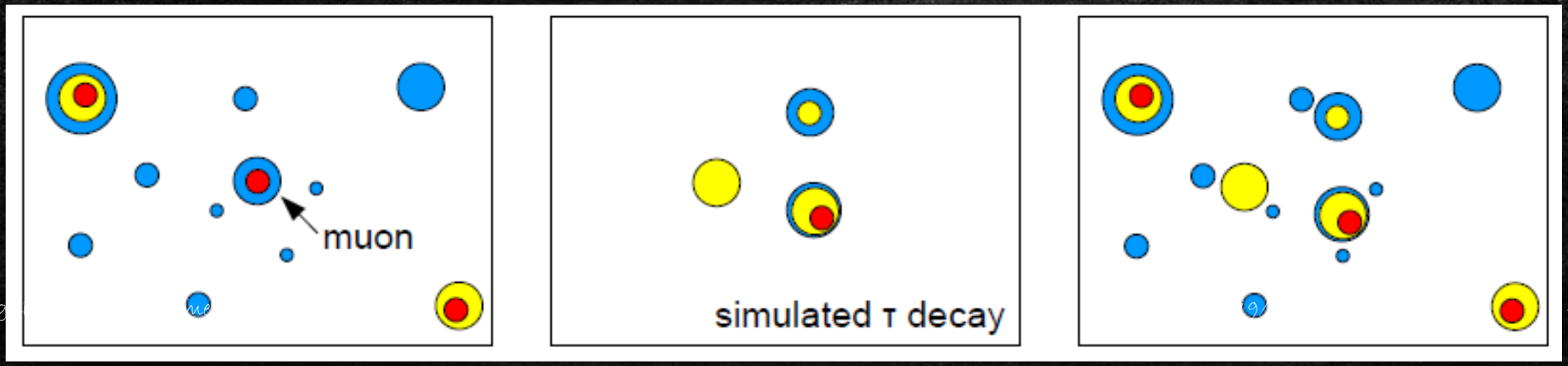
➢ remove μ track

➢ simulate μ, subtract calorimeter cells of this μ

➢ simulate $\tau \rightarrow$ had decay

➢ merge original event and simulated τ

➢ reconstruct whole event



2HDM coupling scale factors

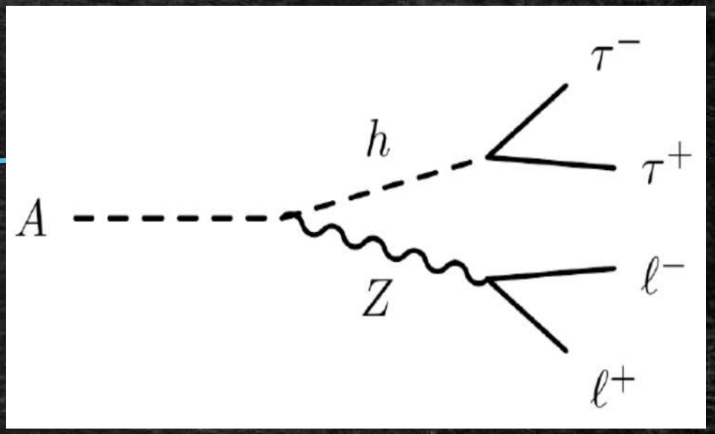
Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

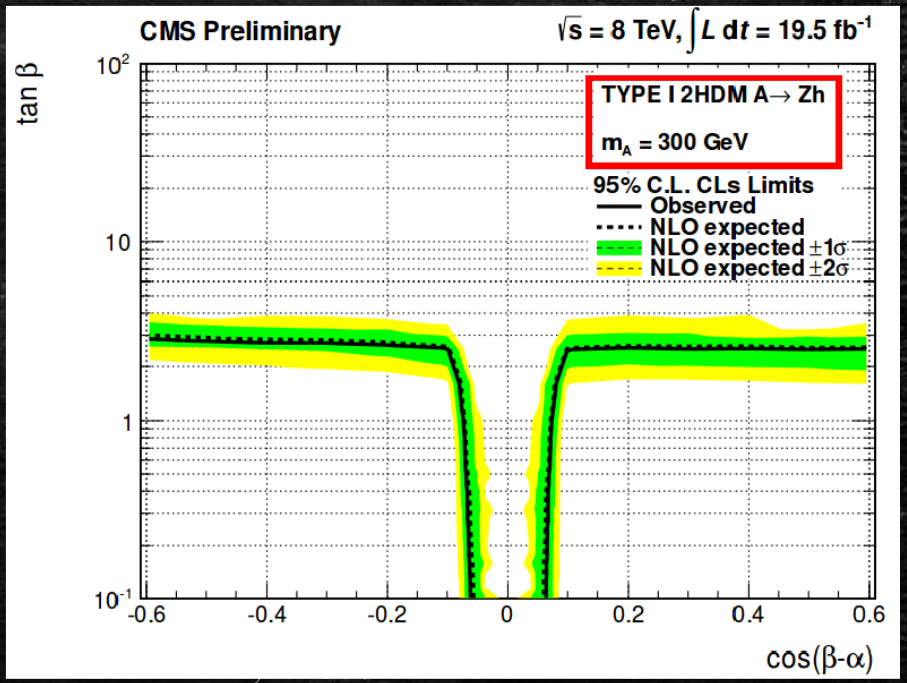
NMSSM couplings

	type-I	type-II
ξ_h^u	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$
ξ_h^d	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)-\cos(\beta-\alpha)\cdot\tan\beta$
ξ_h^l	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)-\cos(\beta-\alpha)\cdot\tan\beta$
ξ_H^u	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$
ξ_H^d	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)+\sin(\beta-\alpha)\cdot\tan\beta$
ξ_H^l	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)+\sin(\beta-\alpha)\cdot\tan\beta$
ξ_A^u	$1/\tan\beta$	$1/\tan\beta$
ξ_A^d	$-1/\tan\beta$	$\tan\beta$
ξ_A^l	$-1/\tan\beta$	$\tan\beta$

CP odd Higgs A->Zh multileptons

- Same flavour leptons with dilepton mass near Z
- Events classified according to the number of opposite sign-same flavour pairs
- CMS multilepton events:
  At least 3 leptons/max one τ->had.
- Backgrounds Z+jets, diboson production





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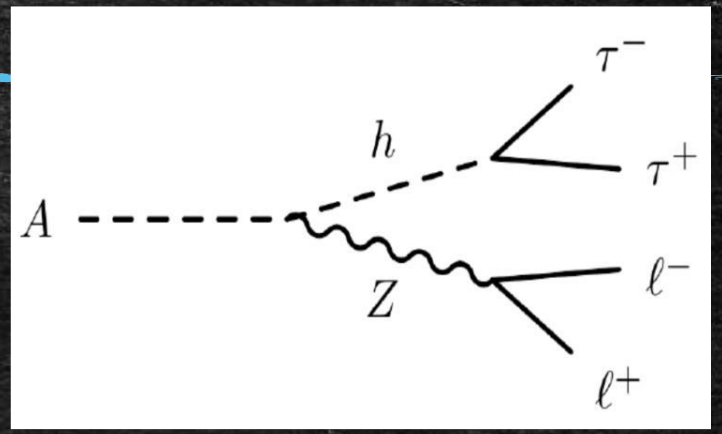
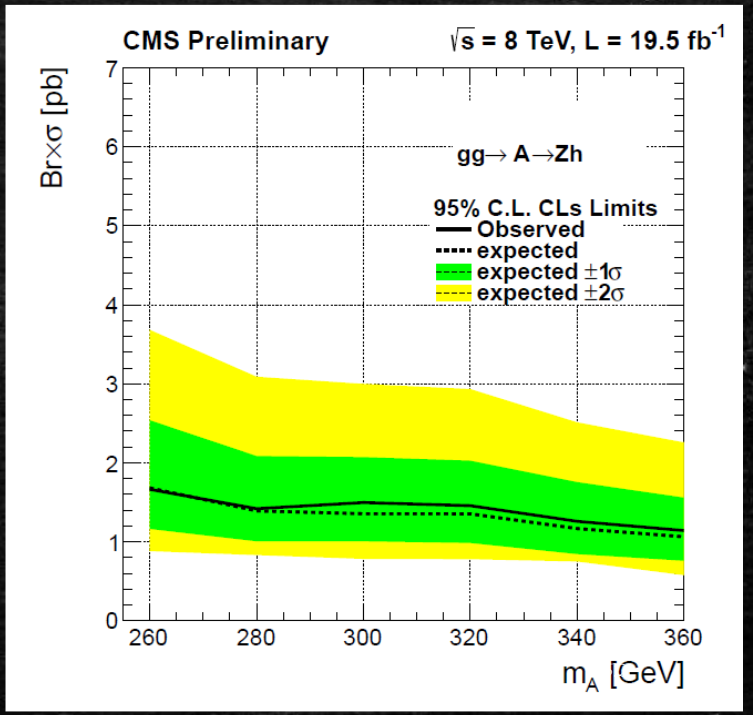


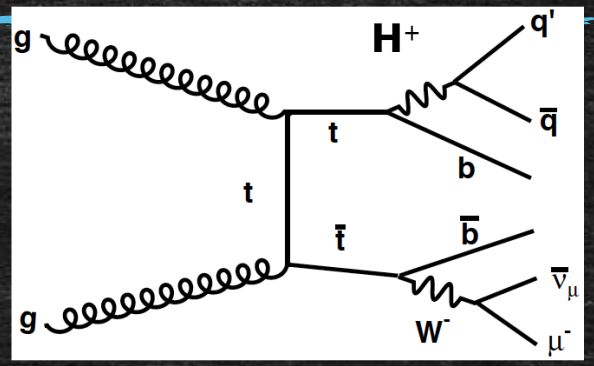


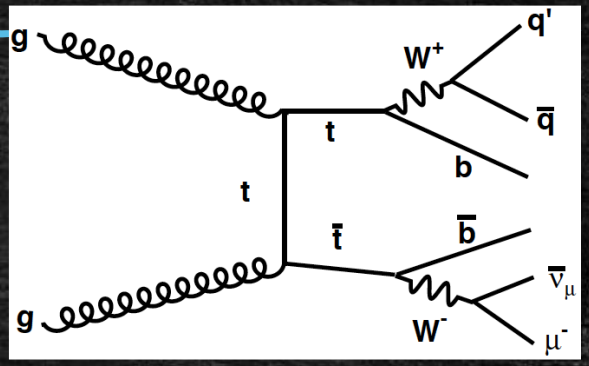
Charged Higgs CMS H->cb

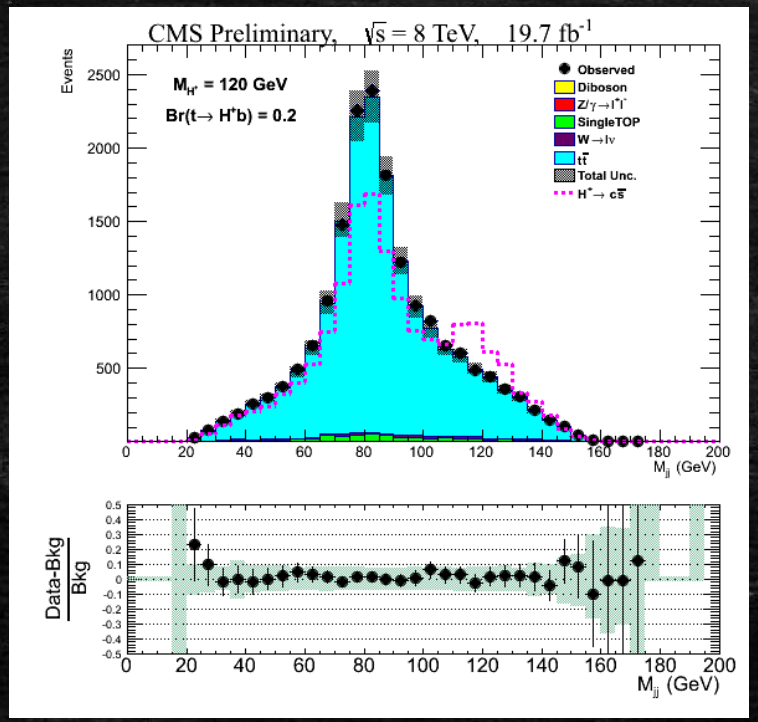
- 2 b tagged jets
- 2 additional jets
- Missing transverse energy
- Isolated lepton

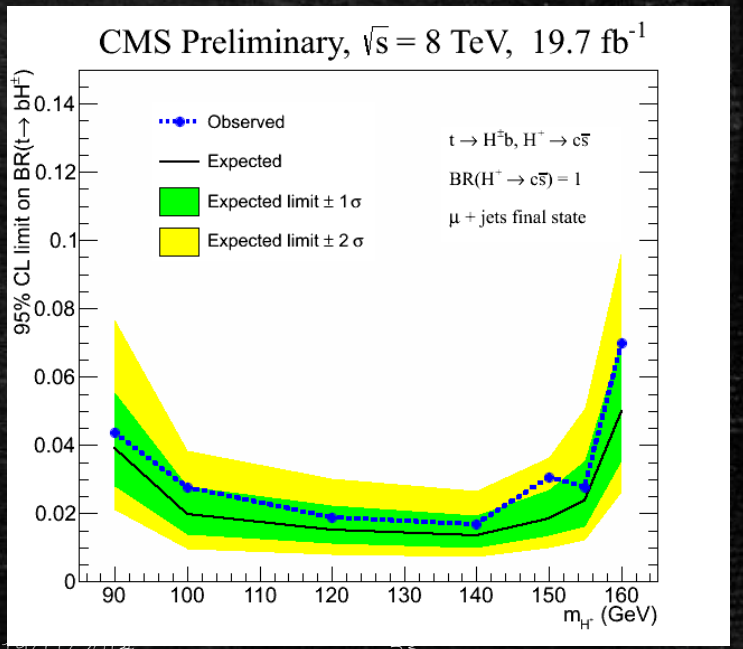
Main background SM ttbar

Looking at mass of jets without btag



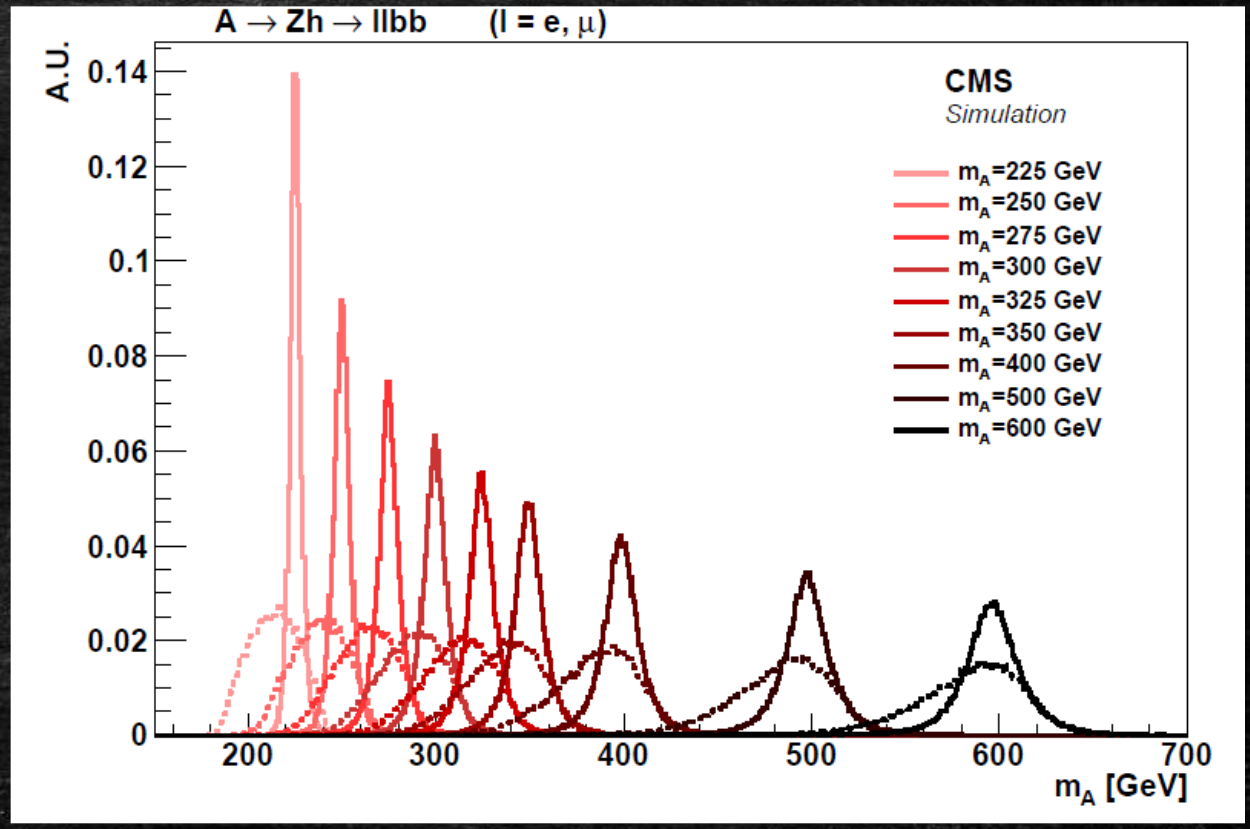




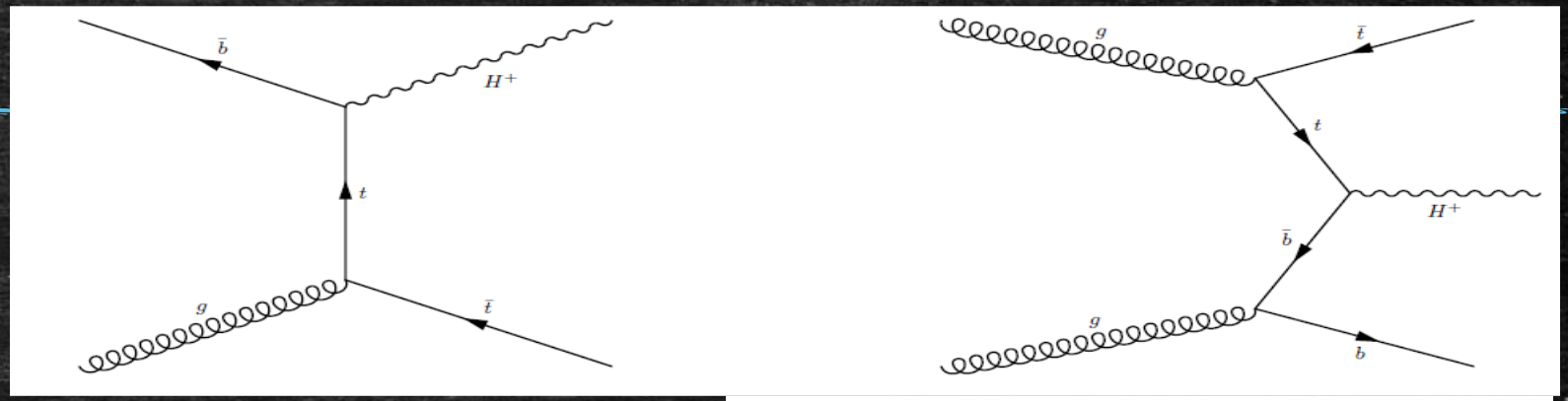


A->Zh->bbll

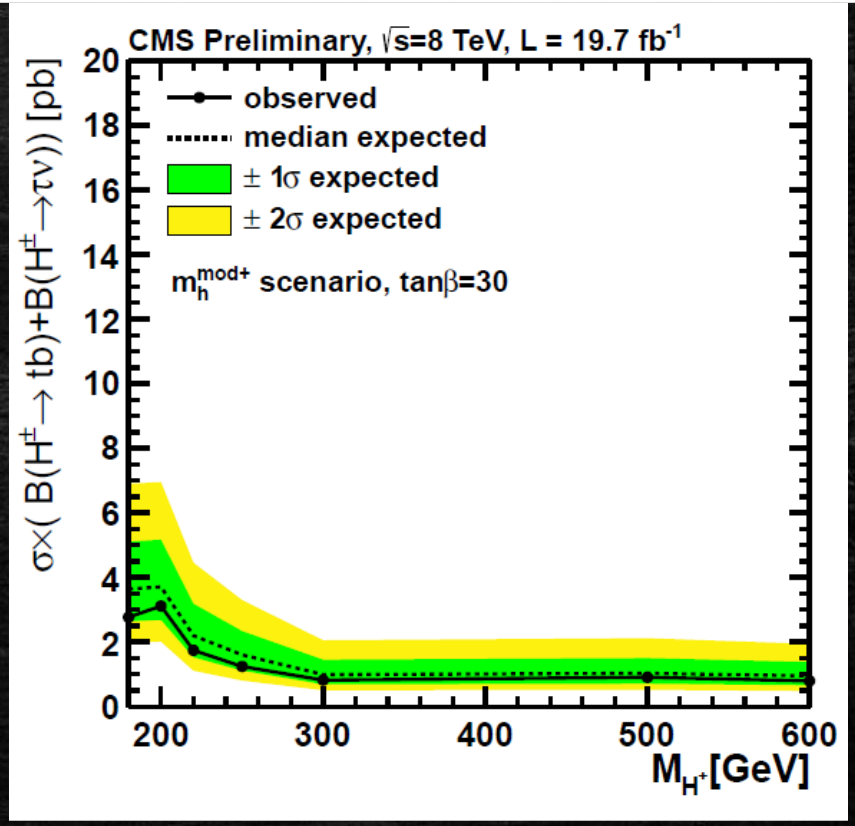
- the two b-jets originate from the decay of the scalar h boson.
- h mass has been measured with better precision than the one which can be obtained from the b-jet measurement resolution alone.
- The measured jets p_T, η, and φ are varied according to their resolution in a kinematic fit based on Lagrange multipliers to force the dijet invariant mass to be equal to m_h =125 GeV.
- The x^2 of the fit is used in the subsequent steps of the analysis as a discriminating variable in place of the dijet mass m_{bb}.



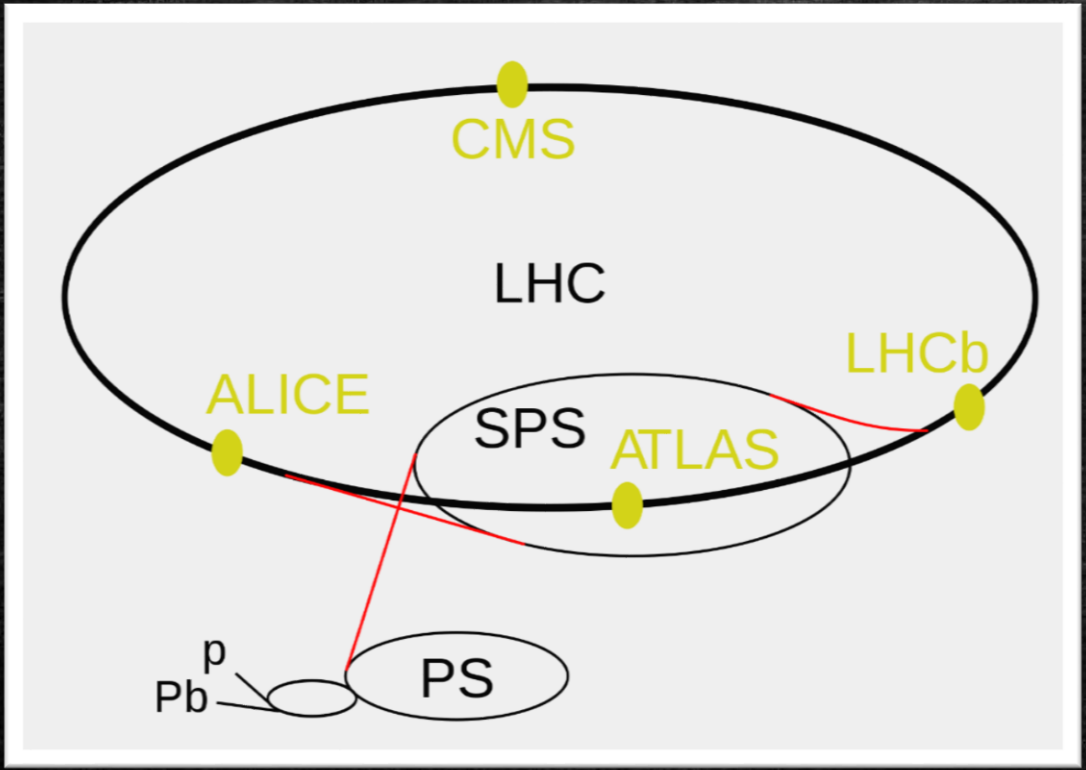
Heavy charged Higgs tbH^+ , $H^+ \to tb/\tau\nu$



- $m_{H+} > m_t$
- 2 final states:
  - $\tau_h\nu$
  - $ee, e\mu, \mu\mu$
- $\tau_h\mu$
  - isolated μ, a hadronic τ jet and at least one more jet, at least one b-tagged jet
  - DY, ttbar
- $ee, e\mu, \mu\mu$
  - isolated, oppositely charged leptons



LHC


CMS
LHC
LHCb
ALICE
SPS
ATLAS
p
Pb
PS


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

ATLAS and CMS