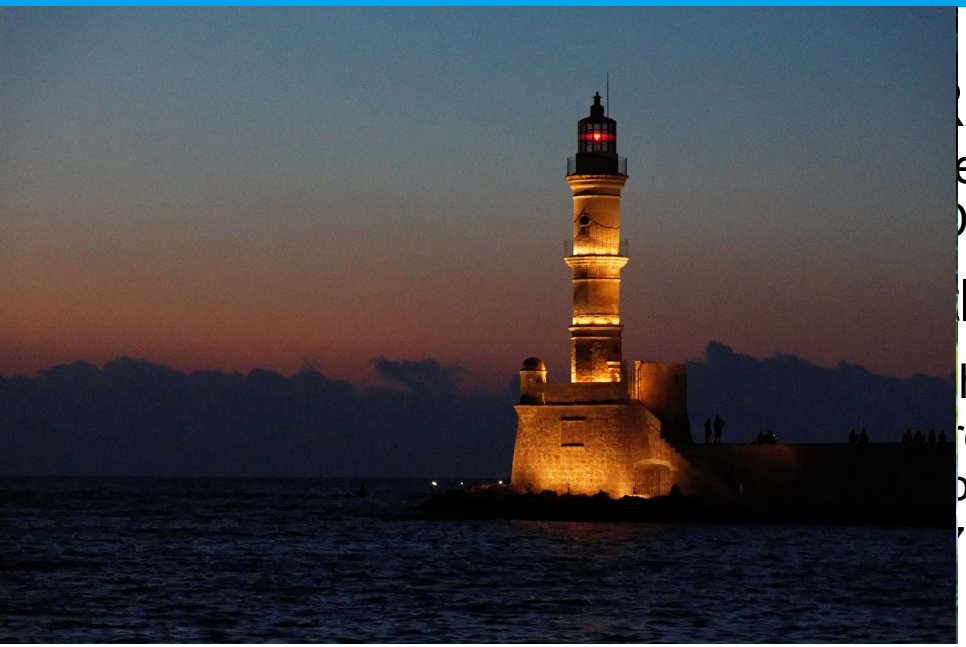
Beyond the Discovery: Higgs Results from CMS



ainer Mankel

eutsches Elektronen-Synchrotron
ESY)

for the CMS collaboration --
le style

h International Conference on New
rontiers in Physics (ICNFP 2015)
olymbari, Greece
August 2015

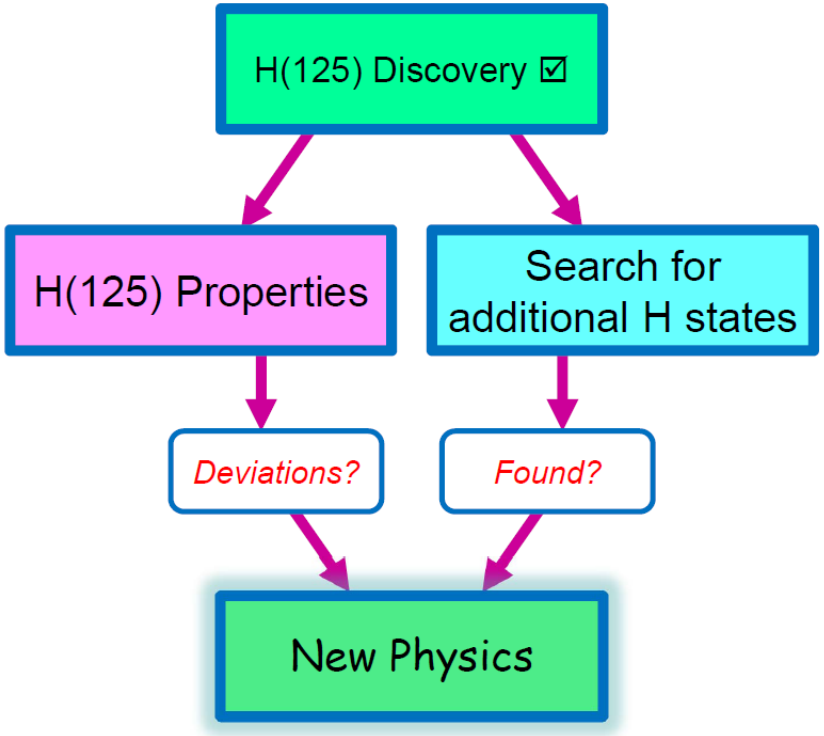
HELMHOLTZ ASSOCIATION

CMS

DESY

Higgs Road of Discovery

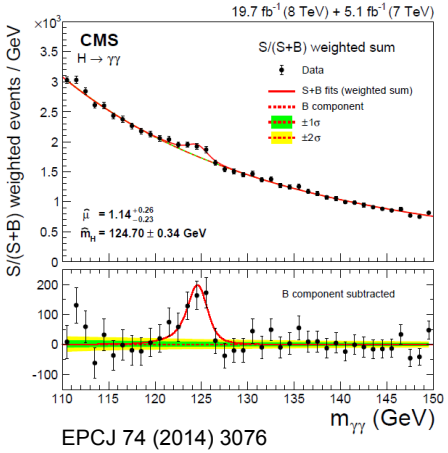
- After the discovery of a Higgs state at 125 GeV:
  - final word on Higgs sector according to LHC Run-I
- **Huge number of new results**
  - properties of the H(125) state
  - search for additional Higgs bosons beyond the Standard Model
- Only **selected highlights** can be shown in this presentation



Properties of the H(125)

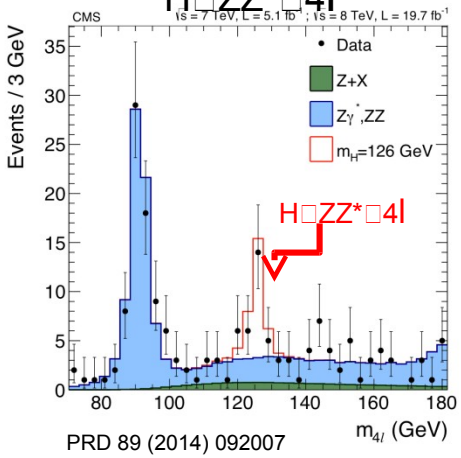
H(125) Properties

H□□□



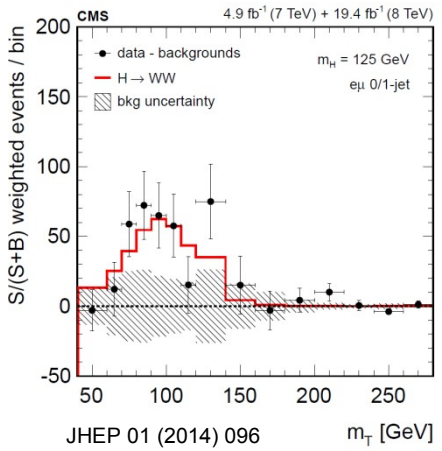
EPCJ 74 (2014) 3076

H□ZZ*□4l



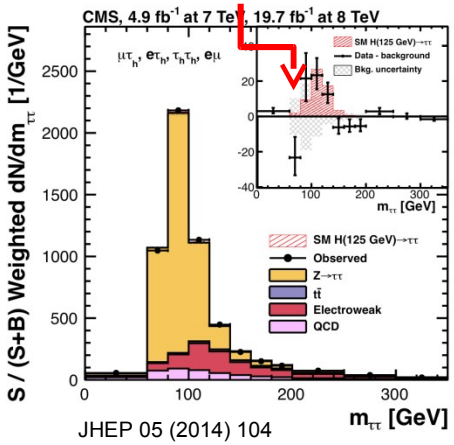
PRD 89 (2014) 092007

H□WW



JHEP 01 (2014) 096

H□□□



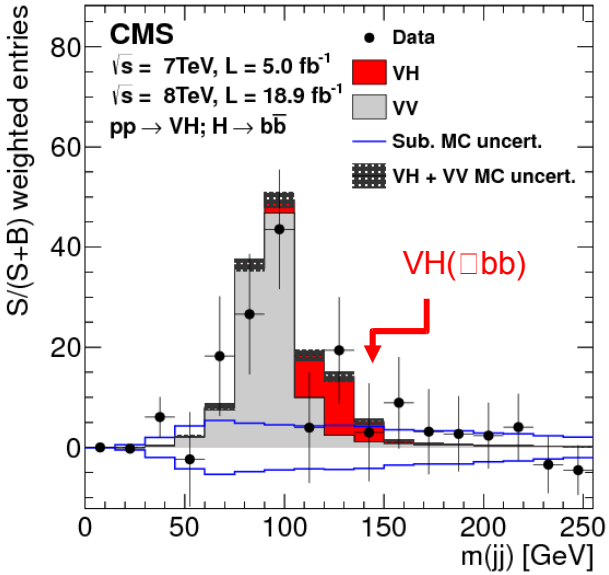
JHEP 05 (2014) 104

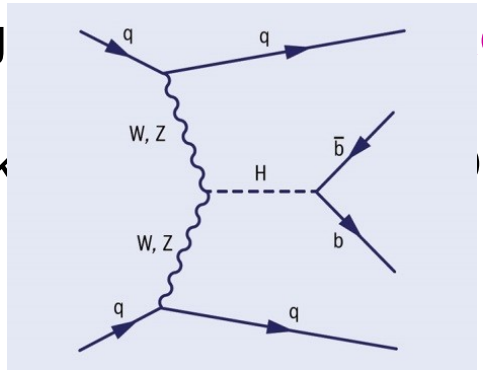
- H(125) firmly established in di-boson decay channels
- Mass measured to ~0.19 % precision (ATLAS+CMS, see presentation by P. Vanlaer)
  mH = 125.09 □ 0.24 GeV
- Spin-parity analysis: state consistent with JP=0+
- Fermionic decay modes more elusive
  - evidence for H□□□ at the level of 3.2 σ (3.7 σ expected)

Search for H□bb

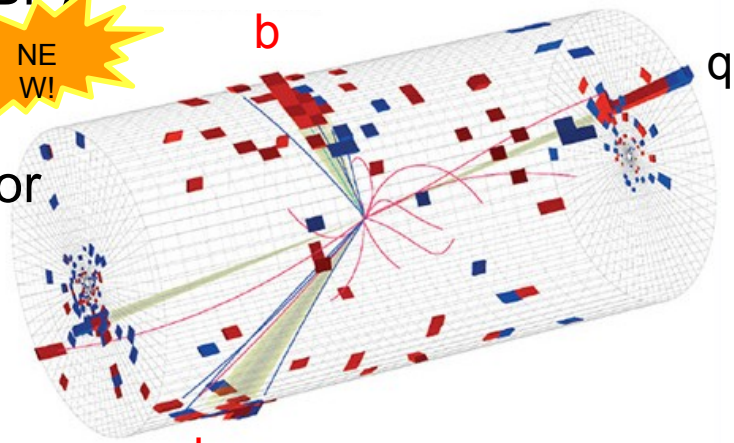
Phys. Rev. D 89 (2014) 012003, Nature Phys. 10 (2014) 557

- H□bb channel: largest BR, but also difficult background conditions
- First studies focused on production with associated vector boson (VH, V=W,Z)
  - improved signature (S/B)
  - excess of 2.1□ significance (3.8□ combined with H□□□)
  - signal strength □ / □SM =1.0 □ 0.5
- New: search in vector boson fusion (VBF)
  - first SM Hig… dr… state!
  - electroweak … color exchanged





NE W!

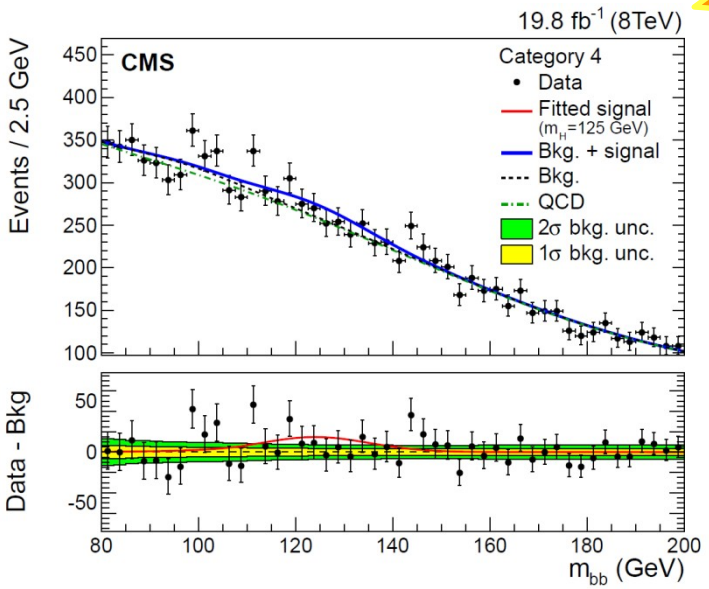


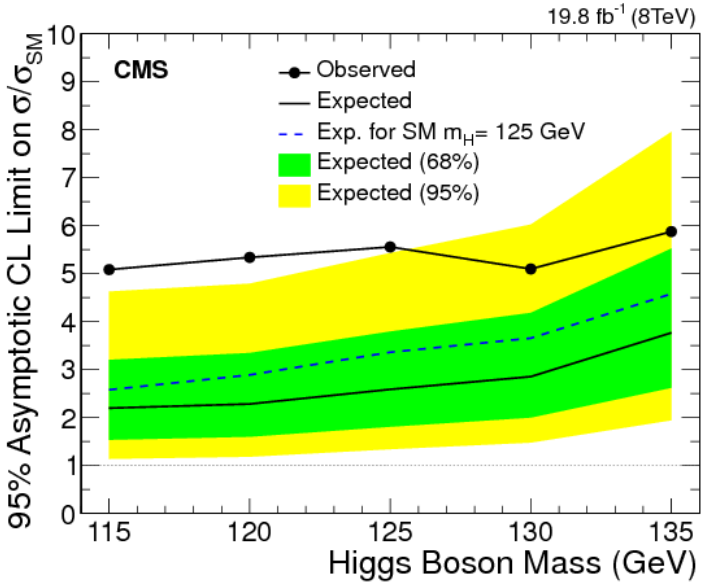
arXiv:1506.01010; Accepted by Phys. Rev. D

VBF H□bb

NEW!

arXiv:1506.01010; accepted by Phys. Rev. D

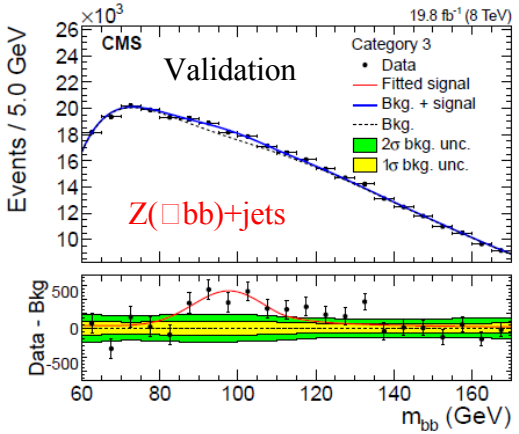




- BDT categorization. Validate with Z(□bb)+jets
- Signal significance of 2.2σ observed (0.8σ exp
- Combination VBF+VH+ttH: □ / □SM =1.03 □ 0.44
  - significance of 2.6σ observed (2.7σ expected)

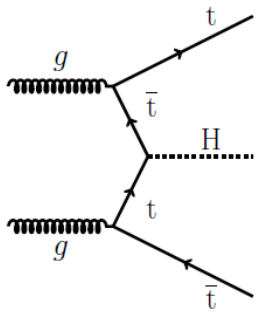
➔ Convincing hint for H(125) coupling to b quarks

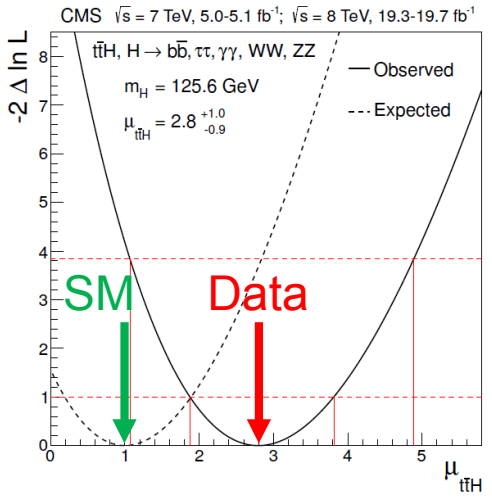
  - follow up in Run-II with 13 TeV data



Top-Higgs Coupling

JHEP 09 (2014) 087

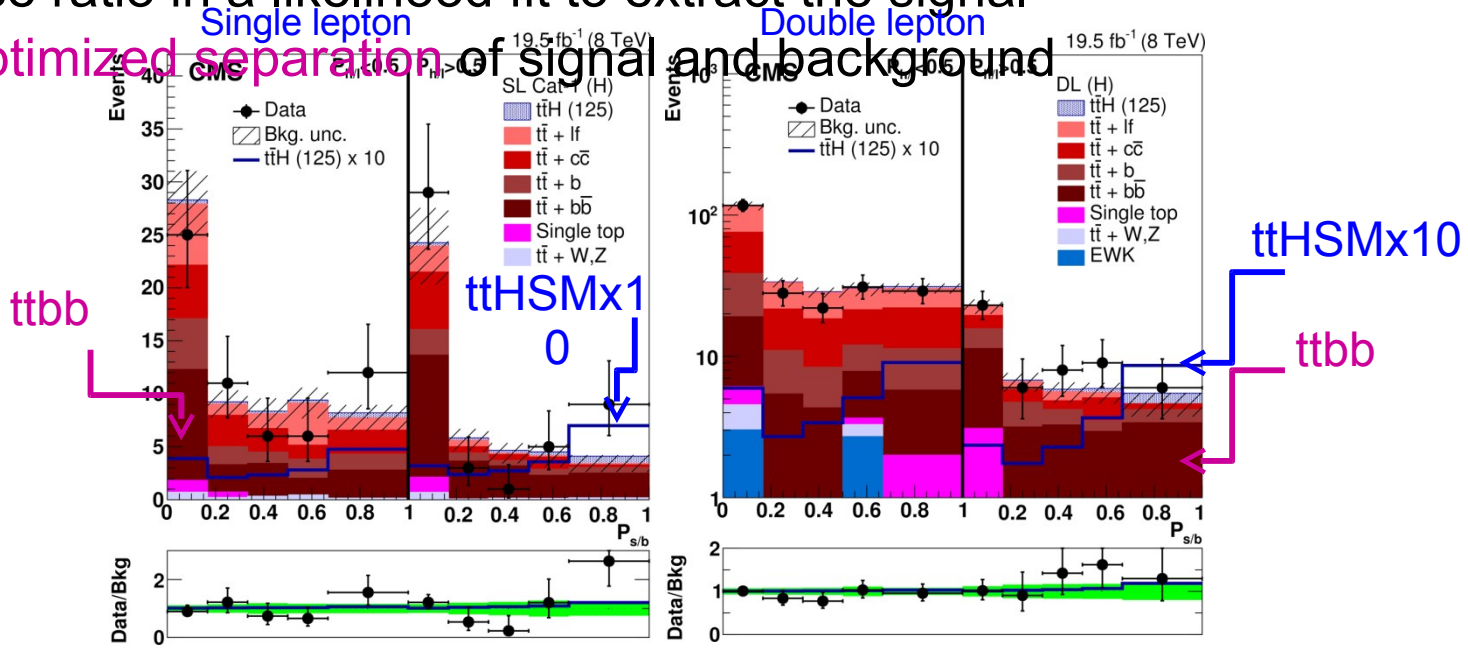




ttH Matrix-Element Method

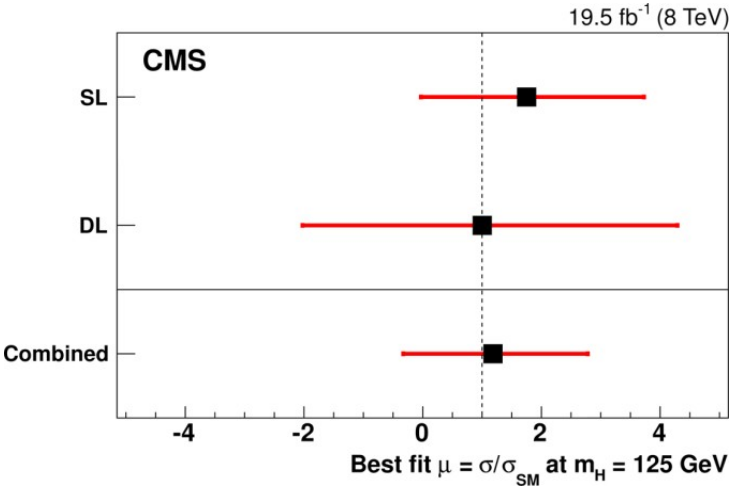
Eur. Phys. J. C 75 (2014) 251

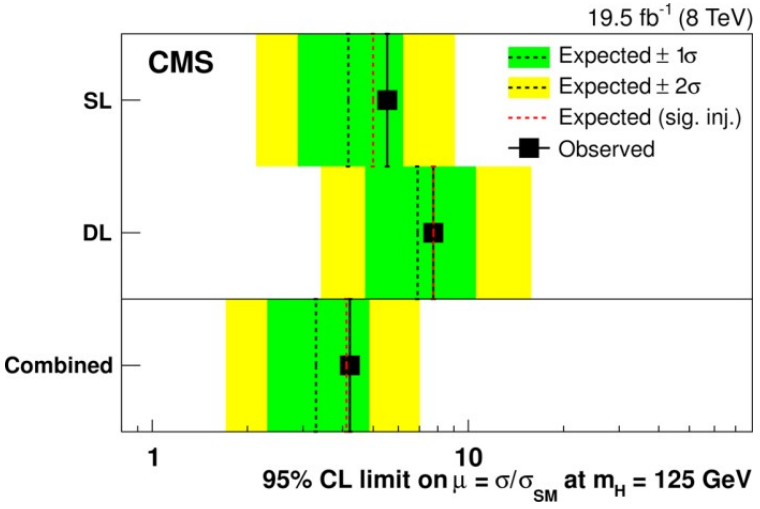
- Matrix elements of signal and most prominent background process (ttbb) known
- To each event, assign probability density value under signal or background hypotheses
  - use ratio in a likelihood fit to extract the signal
  - ➔ optimized separation of signal and background



ttH ME Method (cont'd)

Eur. Phys. J. C 75 (2014) 251



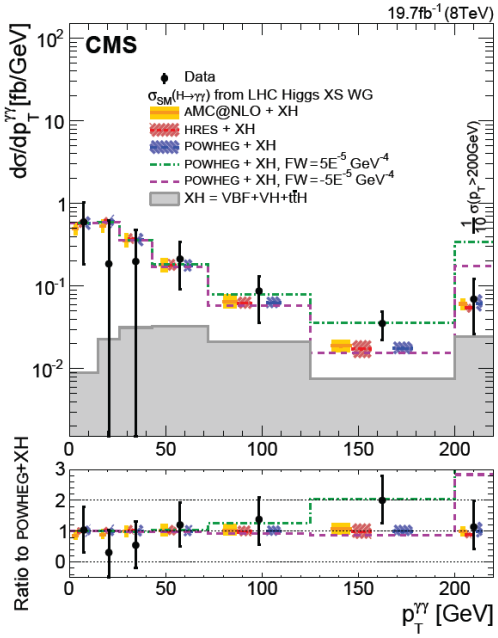


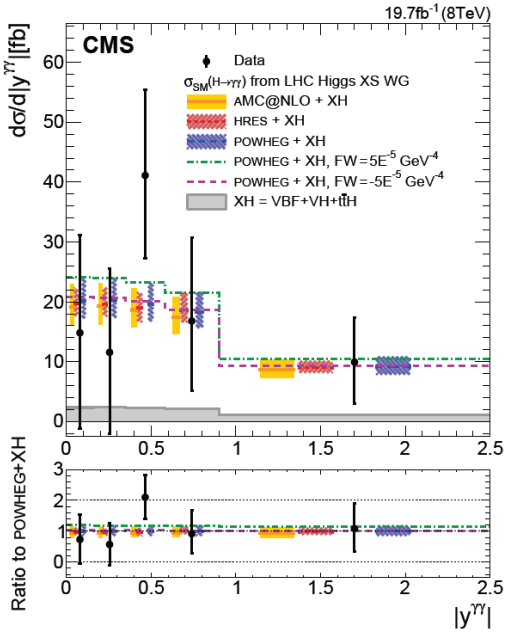
Differential Cross Sections (H□□□)

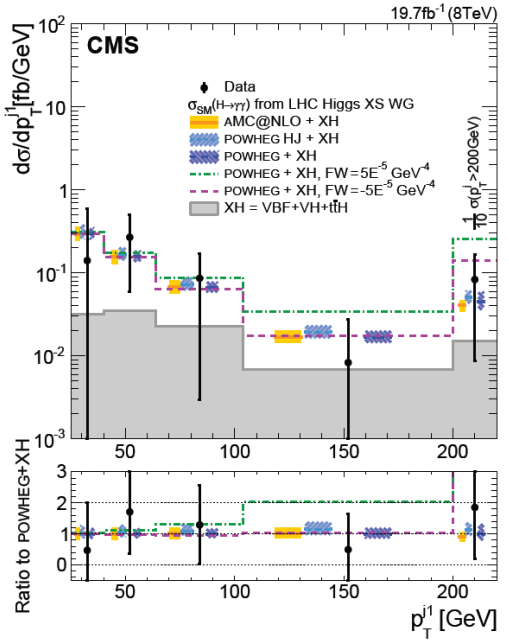
HIG-14-016, to be submitted to arXiv and EPJ C

NE W!

- Direct test of perturbative QCD calculations in the Higgs sector
- pT□□ and pTj1 distributions: sensitive to HO corrections in perturbative QCD





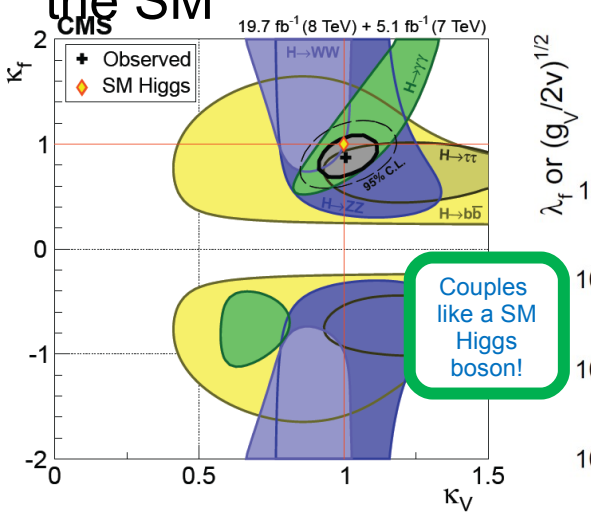


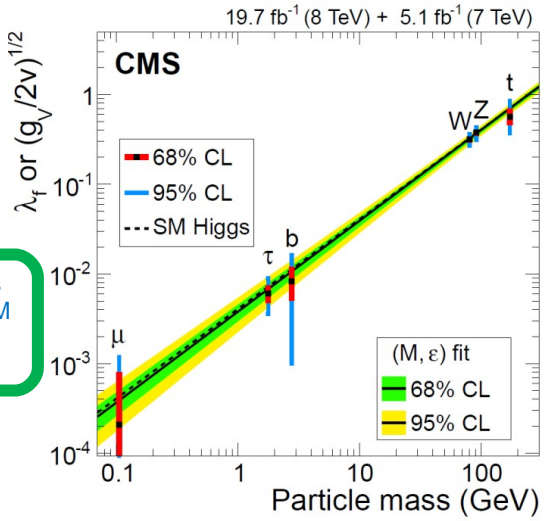
➔ All distributions agree with QCD predictions within errors

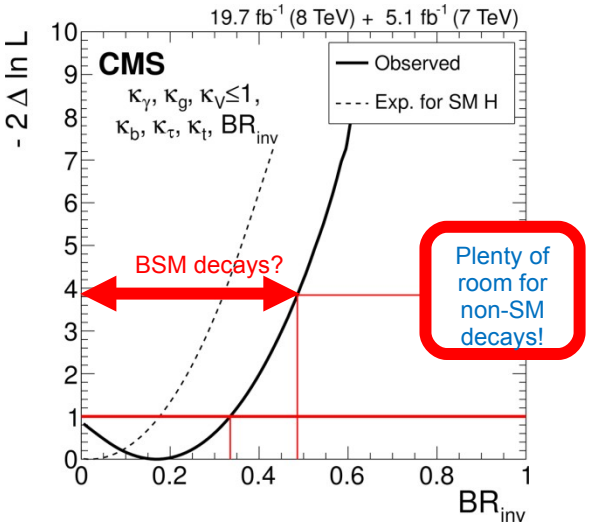
Higgs Couplings

Eur. Phys. J. C 75 (2015) 212

- At the level of current precision, the H(125) couples as expected in the SM







- Is the H(125) state the standard model Higgs boson, or only standard-model-like?

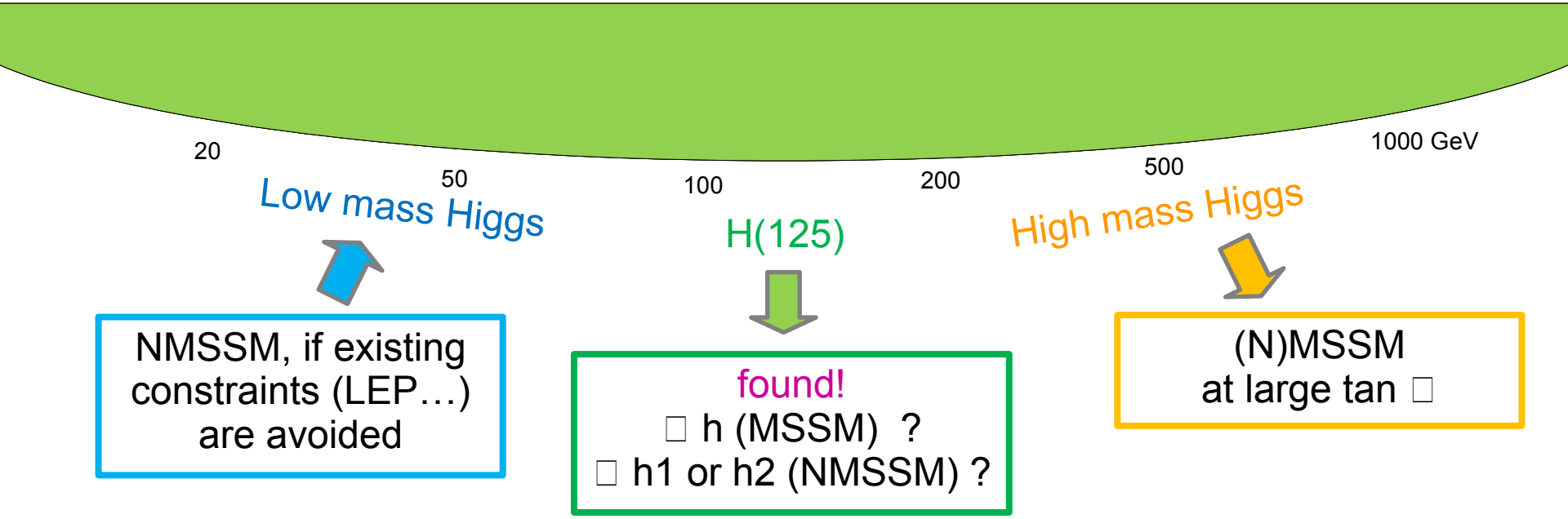
➔ Observed boson could well be only the first member of an extended Higgs sector

- would indicate New Physics
- Needs to be clarified by direct search for additional Higgs bosons

Higgs Beyond the Standard Model

Additional Higgs Bosons According to SUSY

Model	Structure	CP-even	CP-odd	Charged	
MSSM	2 doublets	h, H	A	H□	(h, H, A) □ □
NMSSM	2 doublets+1 singlet	h1, h2, h3	a1, a2	h□	

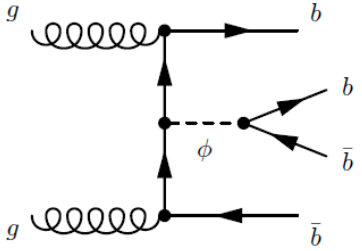


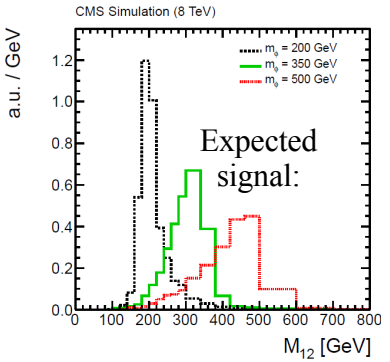
MSSM H□bb Search

NE W!

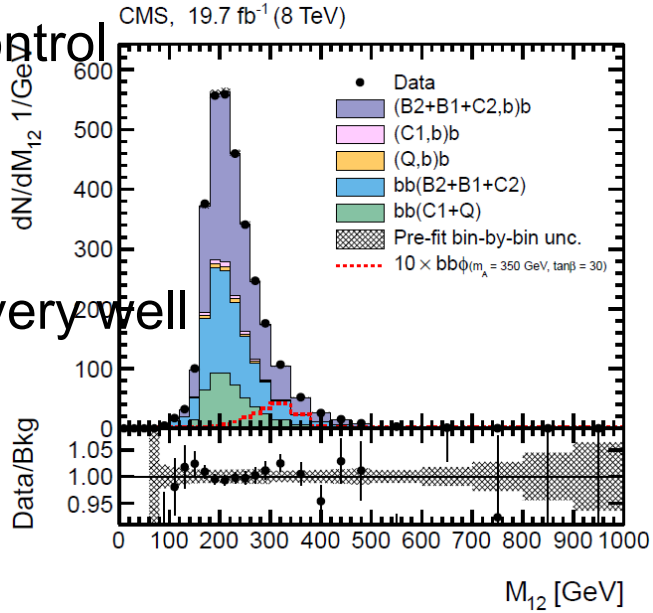
arxiv:1506.08329. Submitted to JHEP

- Search for degenerate H and A in higher mass region
  - large BR(□bb)
- Main challenge: huge background rate from QCD multijet production





- b-associated production: cross section enhanced by ~2 tan2□, better background control
  - require at least three b-tagged jets
  - → dedicated trigger



- → Background-only hypothesis describes data very well
  - → no signal observed

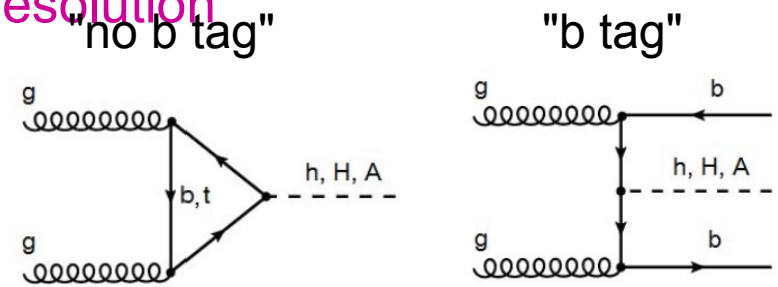
- → CMS analysis is unique at the LHC
- → Best sensitivity in this channel to date

MSSM H□ □ □

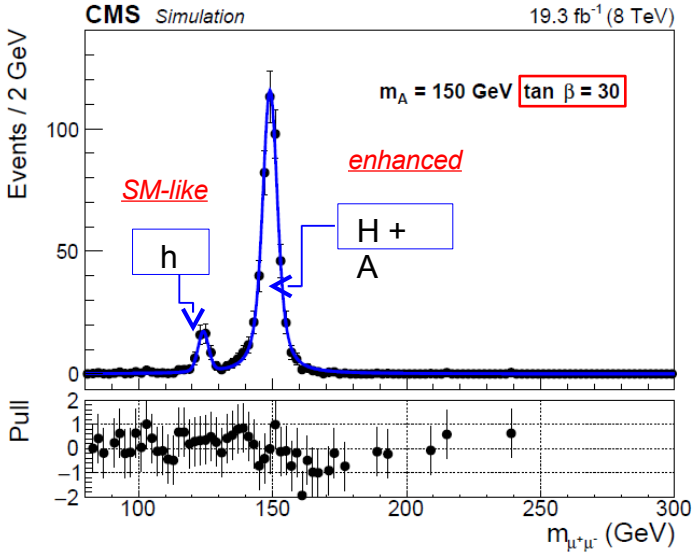
NE W!

arXiv:1508.01437. Submitted to PLB

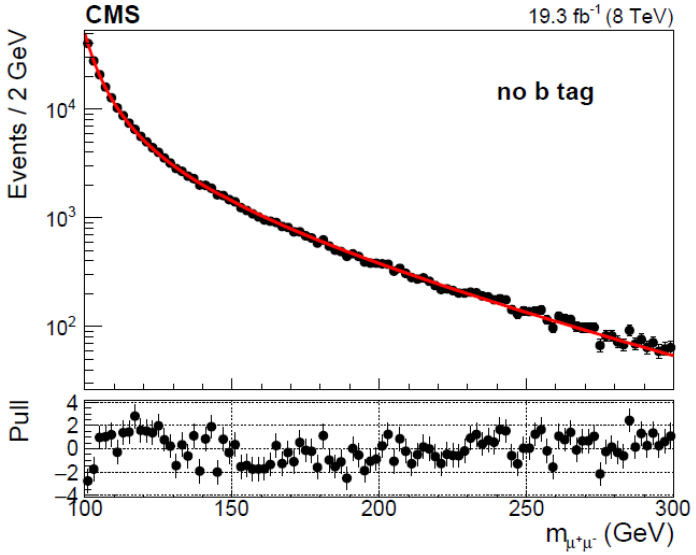
- Low expected BR, but excellent mass resolution (□m~1.2 GeV at m=125 GeV)
  - ➔ good control of background
  - largest background Drell-Yan produ
- Parametric signal + background model



Signal model:



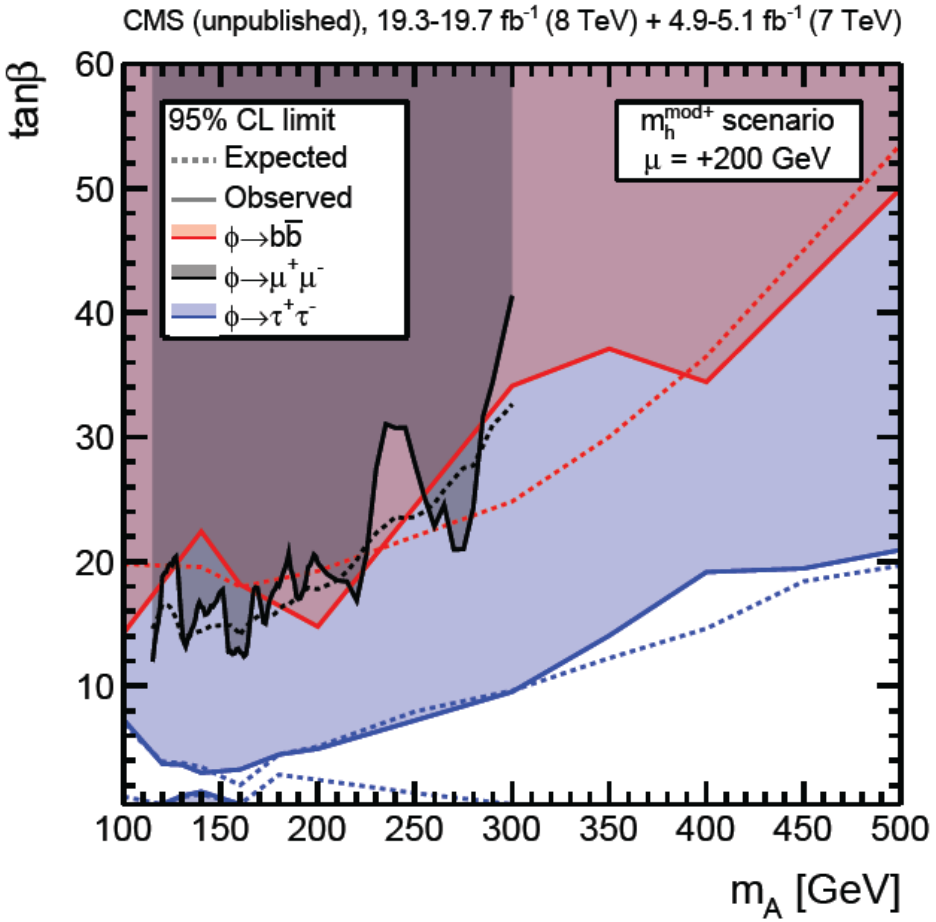
Data:



MSSM Interpretation

arXiv:1508.01437, arxiv:1506.08329, HIG-14-029

- Interpretation in mhmod scenario [1], upper limits for MSSM parameter tan □
- Published H□□□ results [JHEP 10 (2014) 160] updated, with improved □had identification
- Different mass resolutions clearly visible (best for □□, worst for □□)
- Most stringent direct limits from □□ mode. bb and □□ ~comparable to each other.
- Large mA and tan□ still possible



http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-14-017/

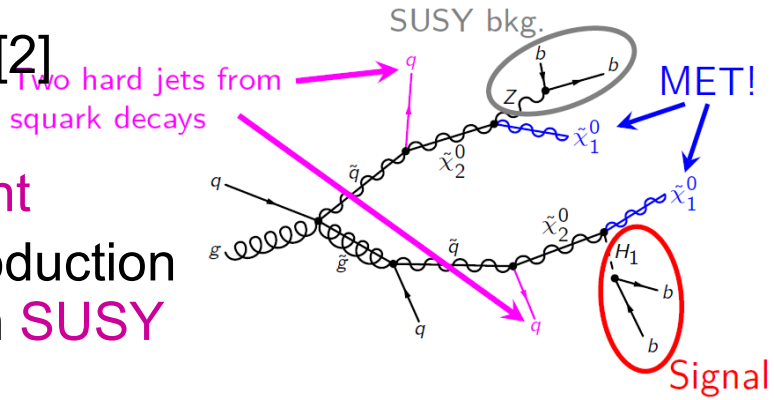
[1] M. Carena et al., Eur.Phys.J. C73, 2552 (2013)

Light NMSSM Higgs Search

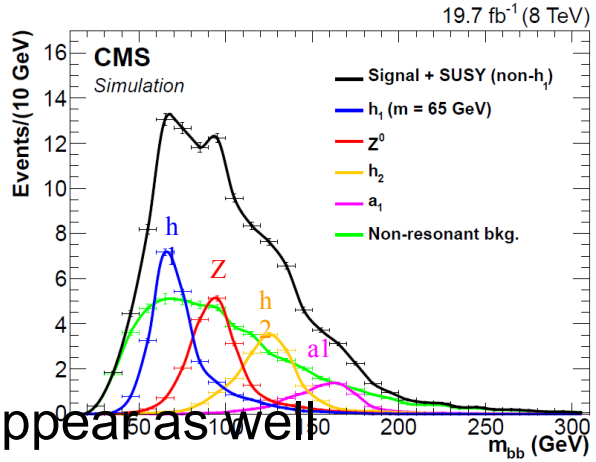
NEW!

HIG-14-030

- Light Higgs (<100 GeV) with "standard" couplings excluded by LEP
- In NMSSM: “P4” benchmark scenario [2]
  - associate h2 □ H(125), SM-like
  - light h1 with large singlet component
  - ➔ suppressed in "standard" Higgs production channels, but copious production in SUSY cascades



□ *Discover BSM Higgs and SUSY simultaneously?*

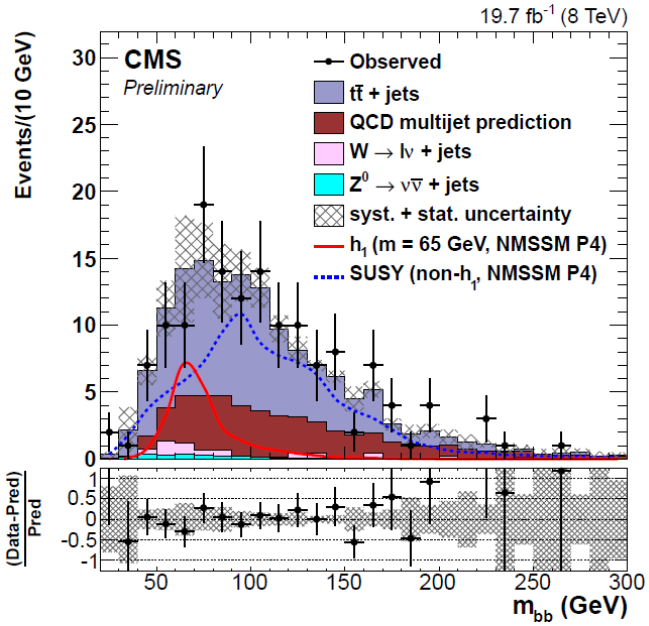


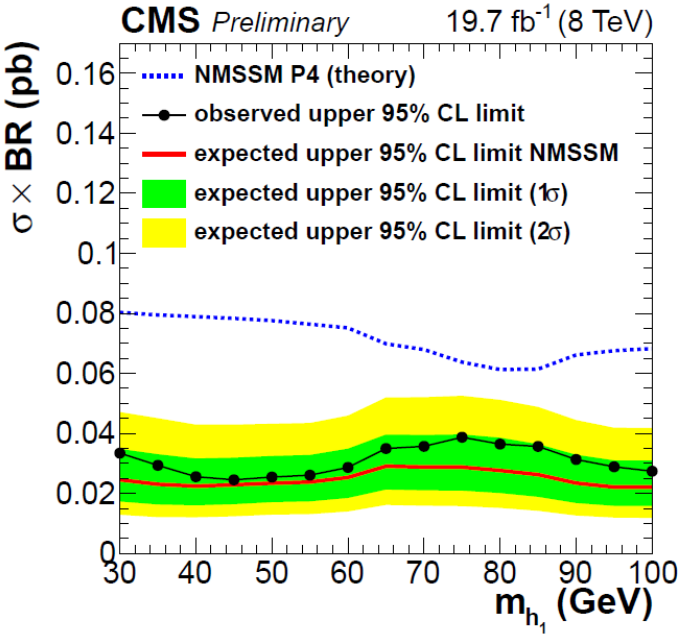
- For the first time explored at the LHC
  - other resonances (Z, h2, a1) should appear as well
  - □ complex signal model

[2] G. Weiglein, O. Stål, *JHEP* **01**, 071 (2012)

Results

HIG-14-030





NE
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Summary

- Beyond the Higgs boson discovery, a large number of new CMS results have been obtained, constituting the "final word" from LHC Run-I

- Properties of the H(125) state determined to remarkable precision
  - methodology enhanced in many places; will fully bear fruit with future data

- At the current measurement accuracy, the state is compatible with the SM Higgs boson
  - any mild deviations are covered by the uncertainties

- Search for New Physics looking for additional Higgs states
  - stringent limits for MSSM parameters obtained (three direct search channels), large values of mass and tan β still allowed
  - still wide open Higgs parameter space in NMSSM
  - also other models tested

Outlook

Run-II just started, exciting program ahead…

… stay tuned!

- Backup Slides

Links to Information

- CMS Collaboration, "Search for the standard model Higgs boson produced through vector boson fusion and decaying to b bbar", arXiv:1506.01010, accepted by Phys. Rev.D

- CMS Collaboration, "Search for a standard model Higgs boson produced in association with a top-quark pair and decaying to bottom quarks using a matrix element method", Eur. Phys. J. C 75 (2014) 251.

- CMS Collaboration, "Measurement of differential cross sections for Higgs boson production in the diphoton decay channel in pp collisions at sqrt(s) = 8 TeV", HIG-14-016, to be submitted to arXiv and EPJ C.

- CMS Collaboration, "Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV", Eur.Phys.J. C75(2015) 212. http://arxiv.org/abs/arXiv:1412.8662

Links to Information (cont'd)

- CMS Collaboration, "Search for neutral MSSM Higgs bosons decaying into a pair of bottom quarks", CMS-HIG-14-017, CERN-PH-EP-2015-133, arXiv:1506.08329 [hep-ex], submitted to JHEP. http://arxiv.org/abs/arXiv:1506.08329

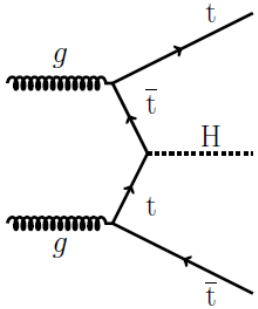
- CMS Collaboration, "Search for neutral MSSM Higgs bosons decaying to μ+μ− in pp collisions at $\sqrt{s}$= 7 and 8 TeV", arXiv:1508.01437, submitted to Phys. Lett. B

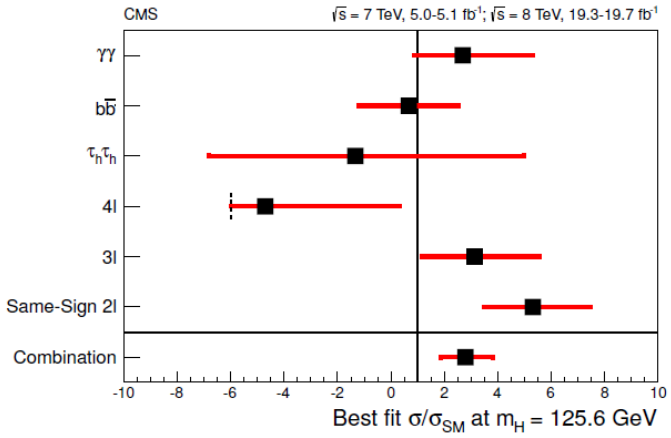
- CMS Collaboration, "Search for additional neutral Higgs bosons decaying to a pair of tau leptons in pp collisions at $\sqrt{s}$= 7 and 8 TeV", CMS-HIG-14-029, http://cds.cern.ch/record/2041463?ln=en

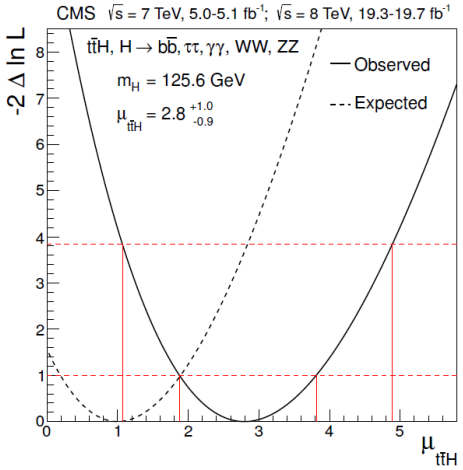
- CMS Collaboration, "Search for a light NMSSM Higgs boson produced in supersymmetric cascades and decaying into a b-quark pair", CMS-HIG-14-030. http://cdsweb.cern.ch/record/2002557?ln=en

Top-Higgs Coupling

JHEP 09 (2014) 087

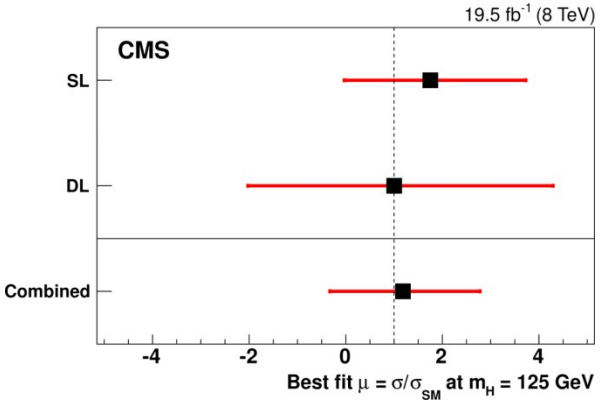


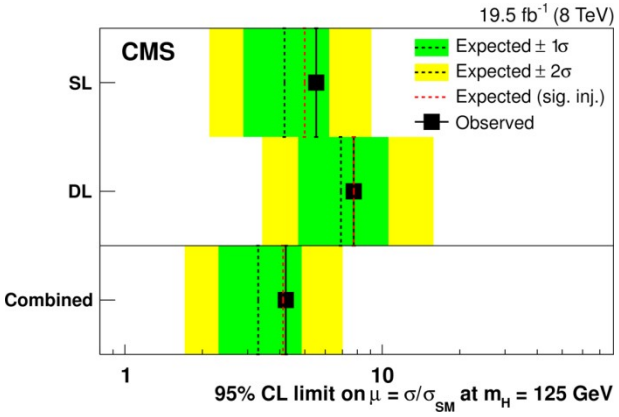


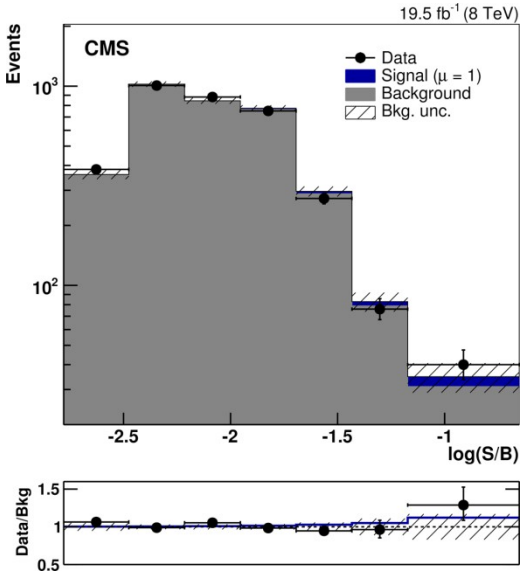


ttH ME Method (cont'd)

Eur. Phys. J. C 75 (2014) 251



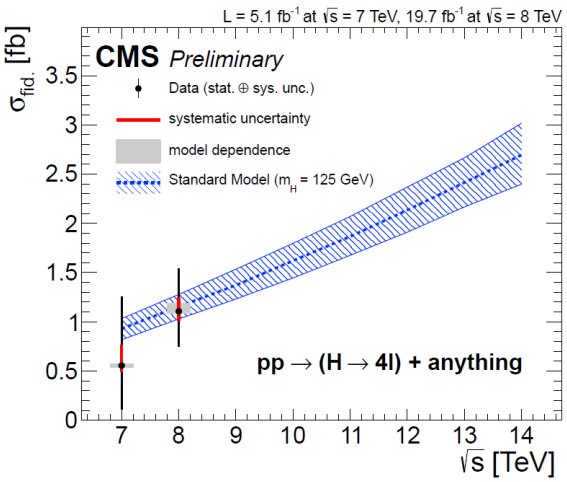


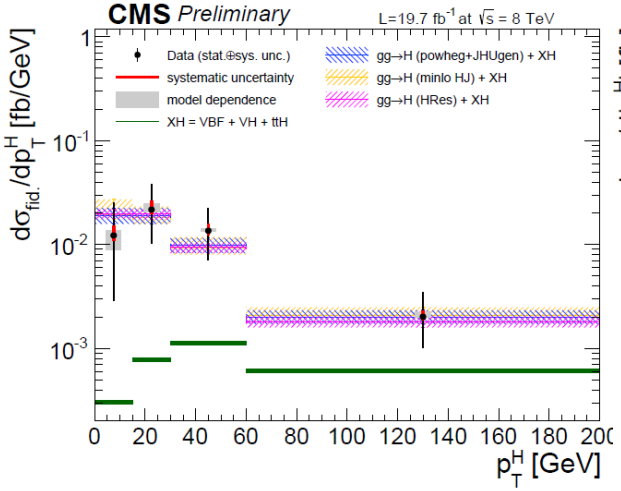


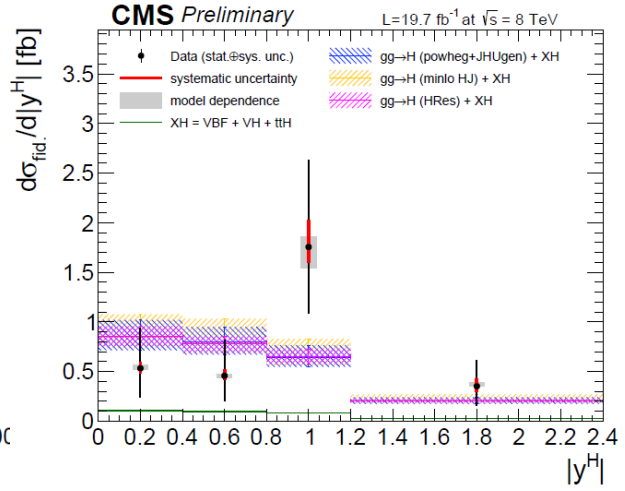
Fiducial Cross Sections (H□4l)

HIG-14-028, to be submitted to arXiv and JHEP

NE
W!







- Definition of fiducial phase space volume

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
leading lepton p_T	$p_T > 20$ GeV
next-to-leading lepton p_T	$p_T > 10$ GeV
additional electrons (muons) p_T	$p_T > 7(5)$ GeV
pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5(2.4)$
p_T sum of all stable particles within $\Delta R < 0.4$ from lepton	less than $0.4 \cdot p_T$
Event topology	
existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
inv. mass of the Z_1 candidate	$40\,\text{GeV} < m(Z_1) < 120\,\text{GeV}$
inv. mass of the Z_2 candidate	$12\,\text{GeV} < m(Z_2) < 120\,\text{GeV}$
distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$ for any $i \neq j$
inv. mass of any opposite sign lepton pair	$m(\ell^+\ell'^-) > 4\,\text{GeV}$
inv. mass of the selected four leptons	$105\,\text{GeV} < m_{4\ell} < 140\,\text{GeV}$
the selected four leptons must originate from the $H \to 4\ell$ decay	

□ → ττ

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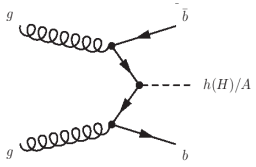
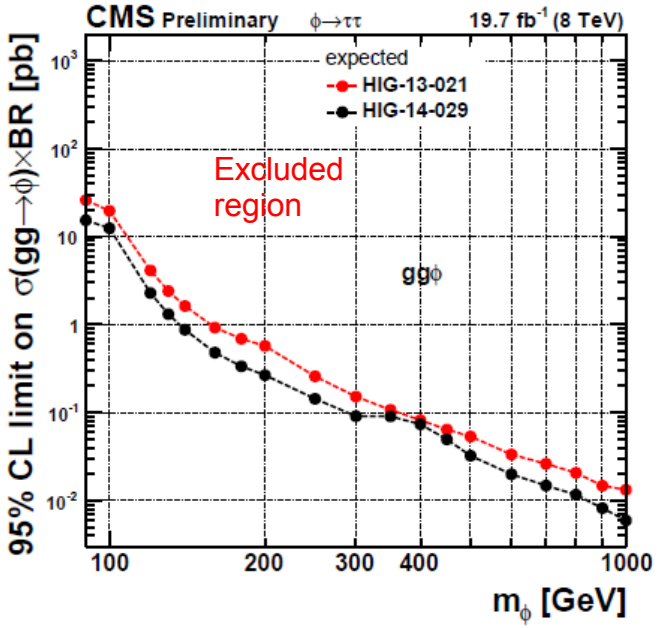
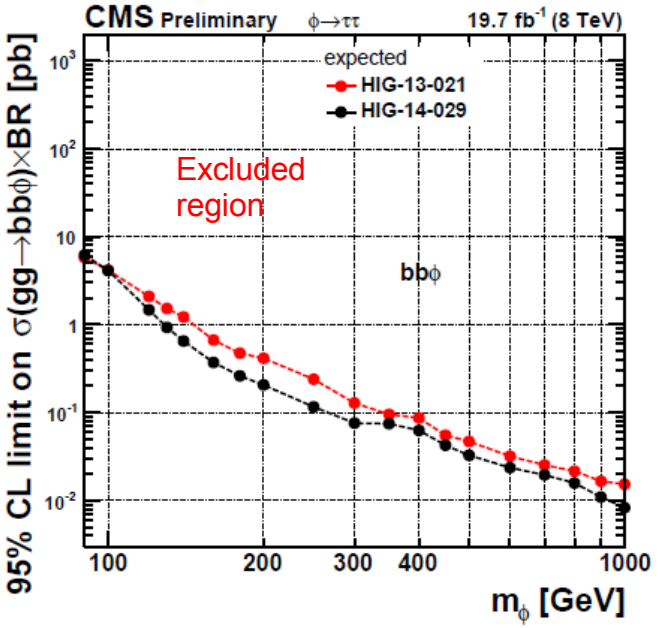
NEW!

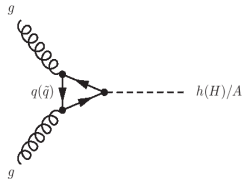
- Good compromise between relatively large BR and manageable backgrounds
- Mass of □ pair is reconstructed from visible □ decay products and missing ET
  - maximum likelihood technique
- Con







EP 10



□ □ □□: MSSM Interpretation

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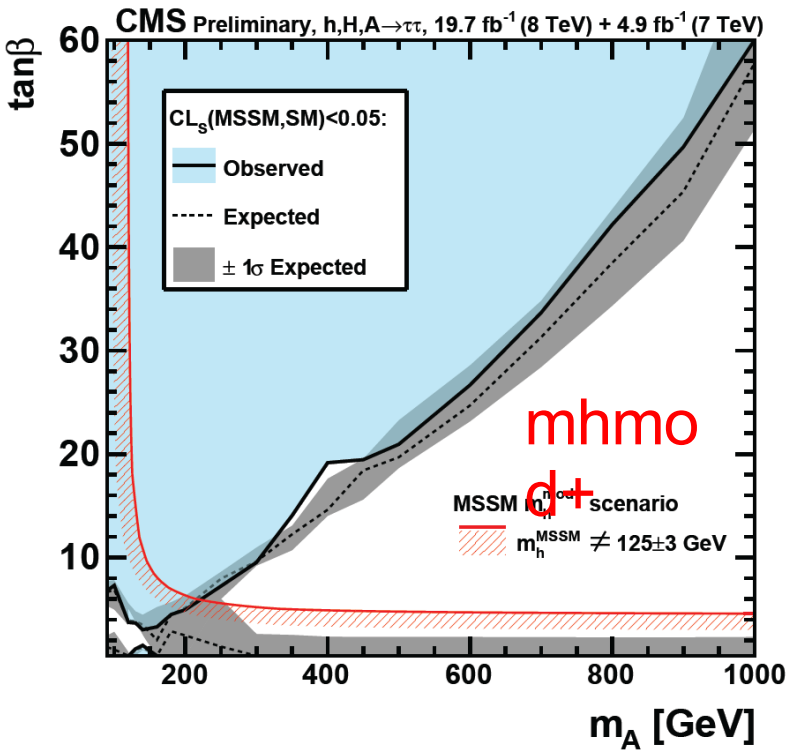
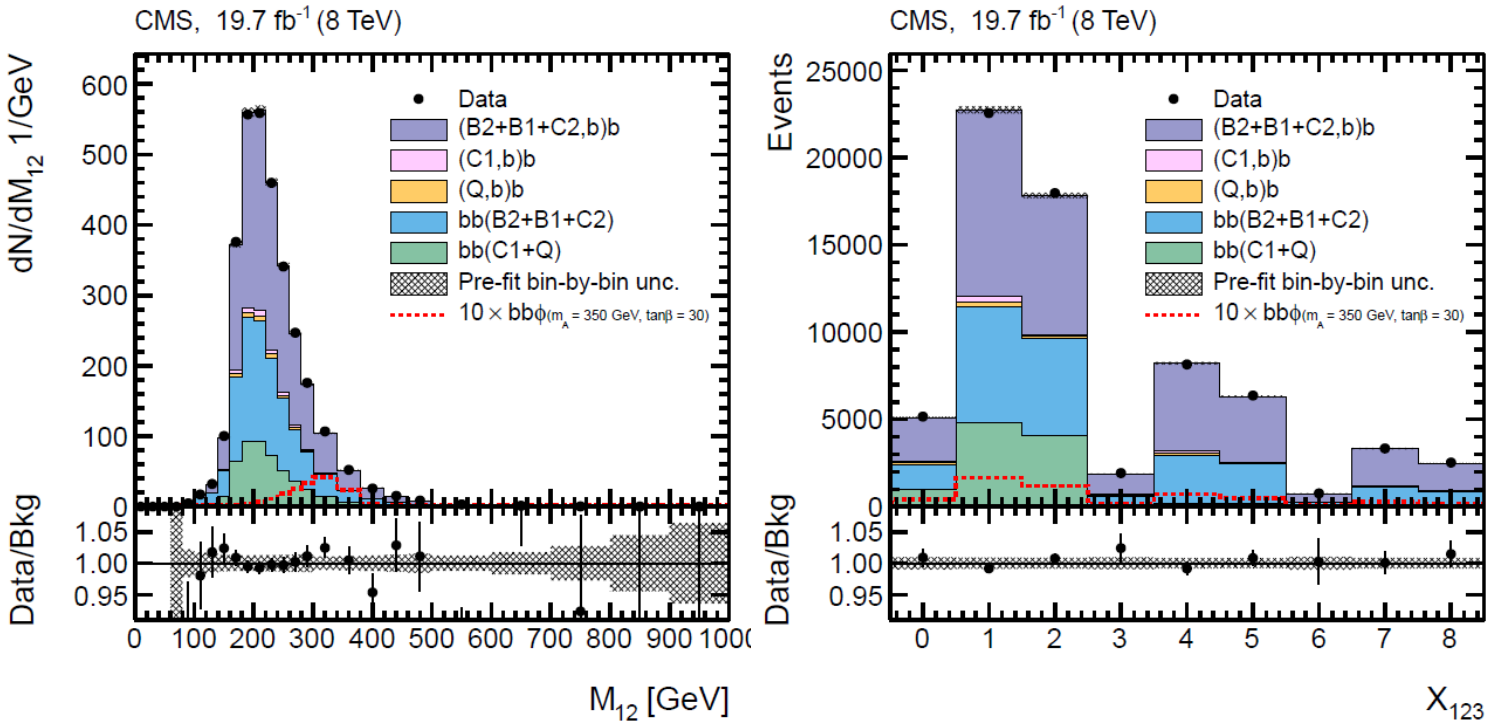


- Very low tan □ upper limits (tan □ < 5 for mA<250 GeV !)
- Interpretation in mhmod scenario [1]: better suited for known mass of H(125), than mhmax scenario
- Low values of tan □ indirectly excluded, since mh incompatible with H(125)

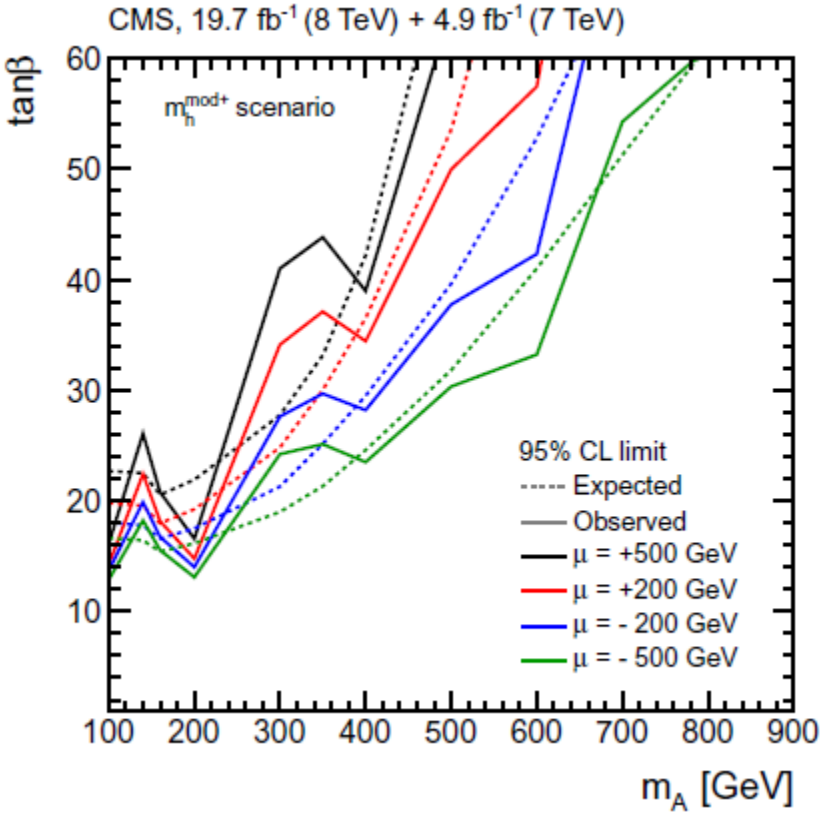
[1] M. Carena et al., Eur.Phys.J. C73, 2552 (2013)

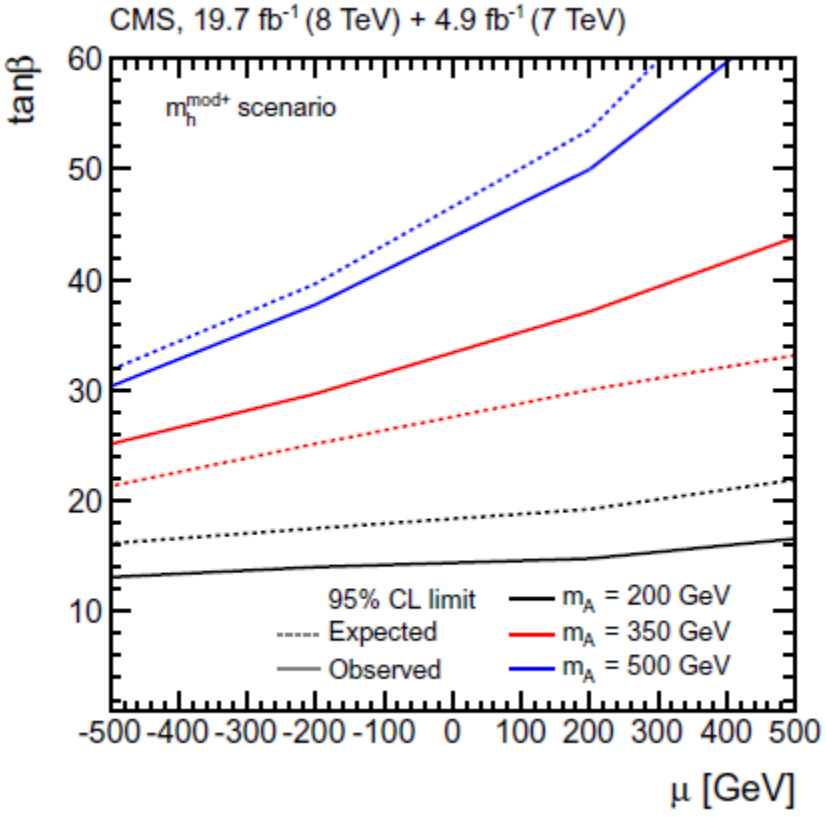
Hbb MSSM: Fit Results



- Background-only hypothesis describes data very well, □2 / Ndof = 205.2 / 208
  - no signal observed

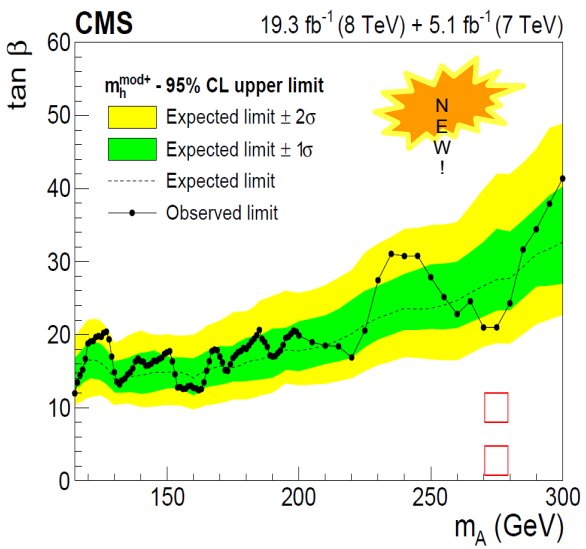
Hbb MSSM: μ Dependence



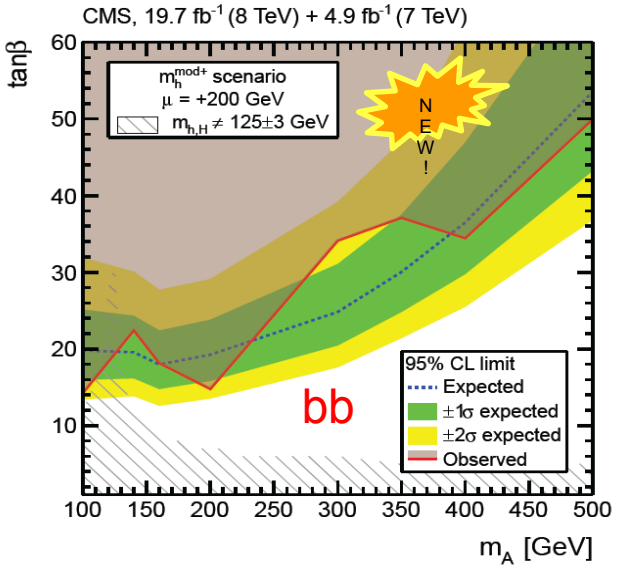


MSSM Interpretation

arXiv:1508.01437



arxiv:1506.08329



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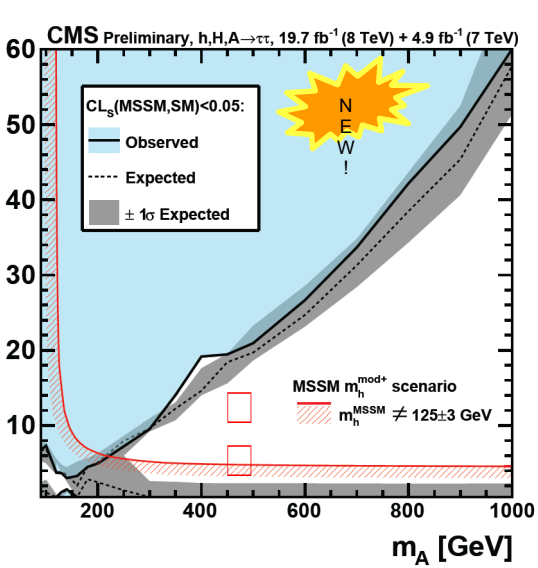
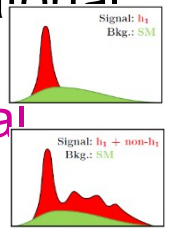


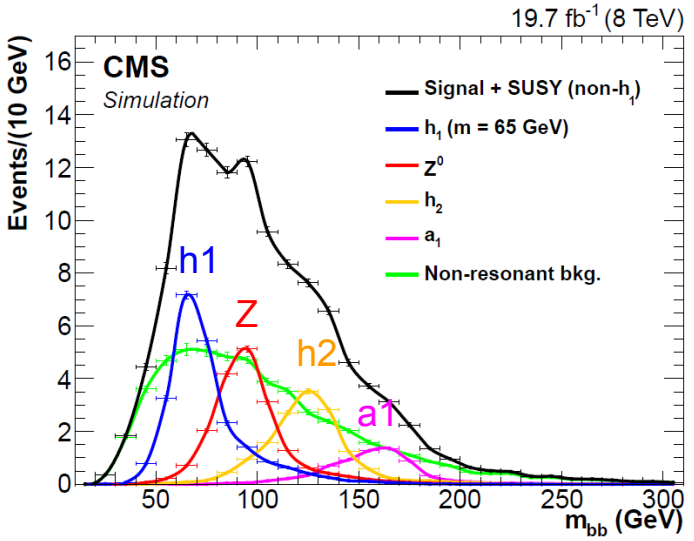
[1] M. Carena et al., Eur.Phys.J. C73, 2552 (2013)

- Interpretation in mhmod scenario [1], upper limits for MSSM parameter tan □
- Published H□□□ results [JHEP 10 (2014) 160] updated, improved □had identification
- Different mass resolutions clearly visible (best for □□, worst for □□)
- Most stringent direct limits from □□ mode. bb and □□ ~comparable to each other.
- Low values of tan□ excluded, since mh incompatible with Higgs □ indirectly. Results from CMS

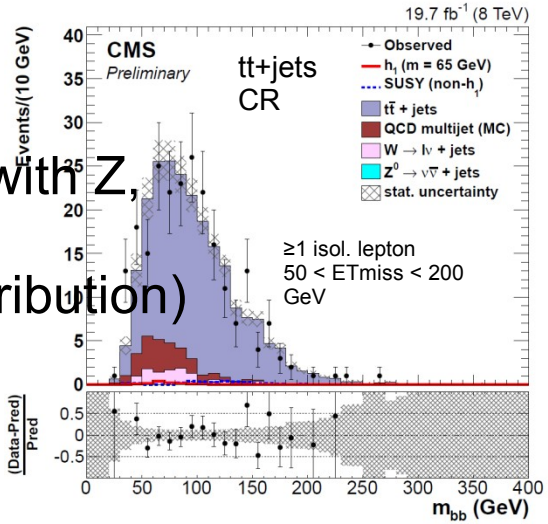
NMSSM Hbb: Signal & Background

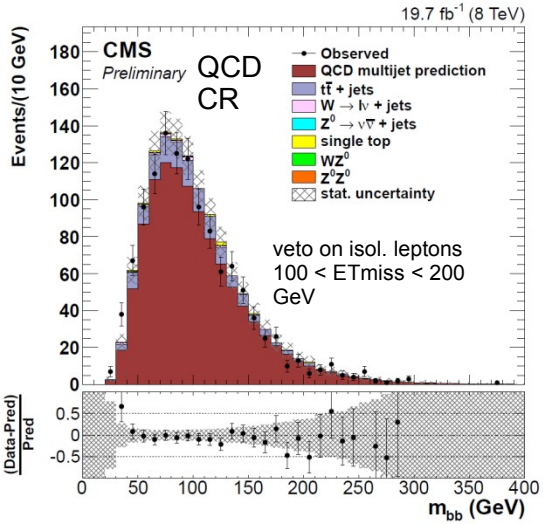
- Besides the h1, other resonances (Z, h2, a1) would be produced in the SUSY cascade, as well as combinatorial background ⇒ complex signal model





- Two search strategies:
  - single peak over SM background
  - full SUSY spectrum (with Z, h2, a1+nonresonant contribution)





- Dominant backgrounds:
  - tt + jets
    - normalization ML fit, shape MC