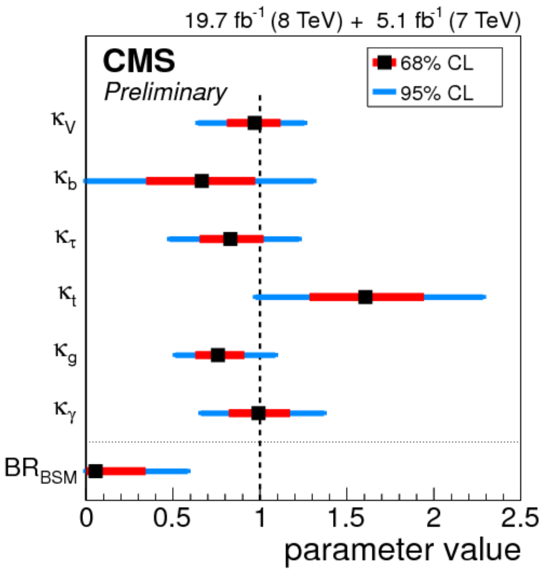
BSM Higgs searches at LHC

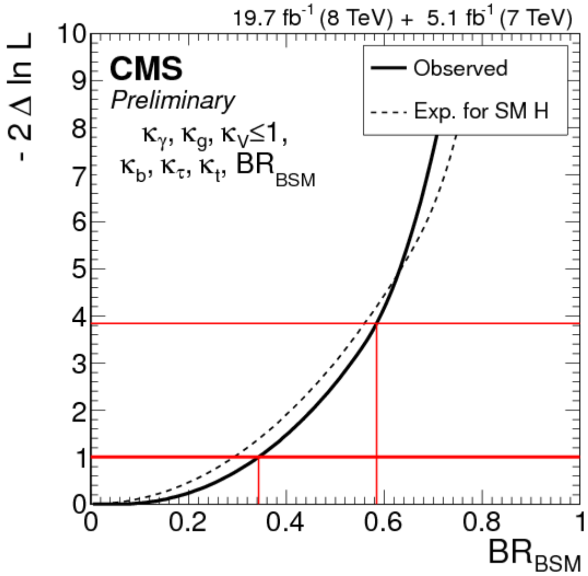
A. Nikitenko, Imperial College, London

Higgs Workshop in DESY, October 2014

BSM Physics with Higgs bosons

- **additional Higgs bosons**
- **non SM decays of h(125)**





BR_{BSM} < 0.58 at 95% CL (CMS)

- **precise measurements for h(125)**

will be discussed

- this year new results on direct searches for
  - $H \to \tau\tau$
  - $H \to h(125)h(125) \to \gamma\gamma bb$
  - $H^{+} \to \tau\nu$
  - $h(125) \to DM$
  - $h(125) \to \mu\tau$ (LFV)
  - $h \to \gamma\gamma$, m_h=[60-1000] GeV
- "model independent" σxBR limits and interpretations in MSSM and 2HDM
- prospects for 2015/2016

Higgs bosons in MSSM

- Unconstrained MSSM is the most "economic" version of SUSY (104 free parameters); 22 parameters in pMSSM
- It requires two Higgs superfields
  - P. Fayet (1975, 1976)
- Their scalar components, H1 and H2 give separately masses for up and down type of fermions
- 5 Higgs particles: CP even h and H, CP odd A, and $H^{+/-}$

Superfield	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Particle content
$\hat{Q}$	3	2	$\frac{1}{3}$	(u_L, d_L), $(\tilde{u}_L, \tilde{d}_L)$
$\hat{U}^c$	$\overline{3}$	1	$-\frac{4}{3}$	$\overline{u}_R$, $\tilde{u}^*_R$
$\hat{D}^c$	$\overline{3}$	1	$\frac{2}{3}$	$\overline{d}_R$, $\tilde{d}^*_R$
$\hat{L}$	1	2	-1	(ν_L, e_L), $(\tilde{\nu}_L, \tilde{e}_L)$
$\hat{E}^c$	1	1	2	$\overline{e}_R$, $\tilde{e}^*_R$
$\hat{H}_1$	1	2	-1	H_1, $\tilde{H}_1$
$\hat{H}_2$	1	2	1	H_2, $\tilde{H}_2$

The superfields of the fermions and Higgs bosons in the MSSM

At tree level Higgs sector of MSSM is determined by only two parameters:

M_A and $\tan(\beta)$

$$1 < \tan(\beta) = v_2/v_1 = (v \sin(\beta)) / (v \cos(\beta)) < 60$$

where v_1 and v_2 are vacuum expectation values (vev) of the neutral components of two Higgs doublets.

$$v_1^2 + v_2^2 = v^2 = 2M_Z^2 / (g_2^2 + g_1^2) = (246\ \mathrm{GeV})^2$$

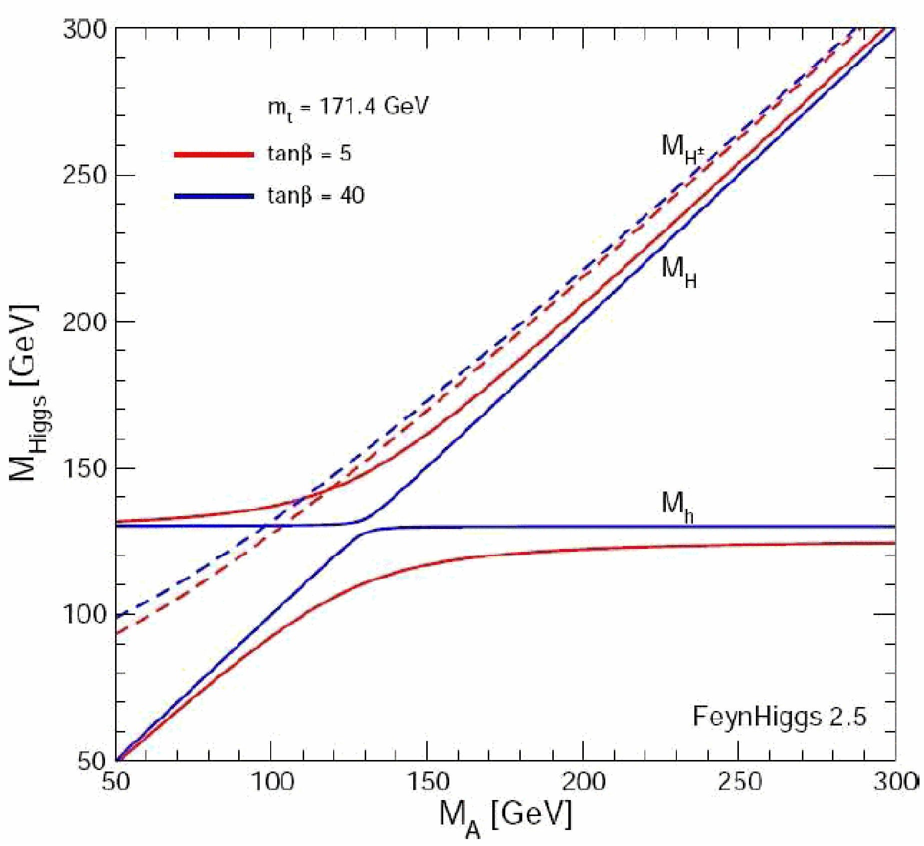
Higgs masses at tree level

$$m_{H,h}^2 = \frac{1}{2}\left[(m_A^2 + m_Z^2) \pm \left((m_A^2 + m_Z^2)^2 - 4 m_Z^2 m_A^2 (\cos^2 2\beta)\right)^{1/2} \right]$$

$$m_{H+}^2 = m_A^2 + m_W^2$$

$$m_h < m_Z$$

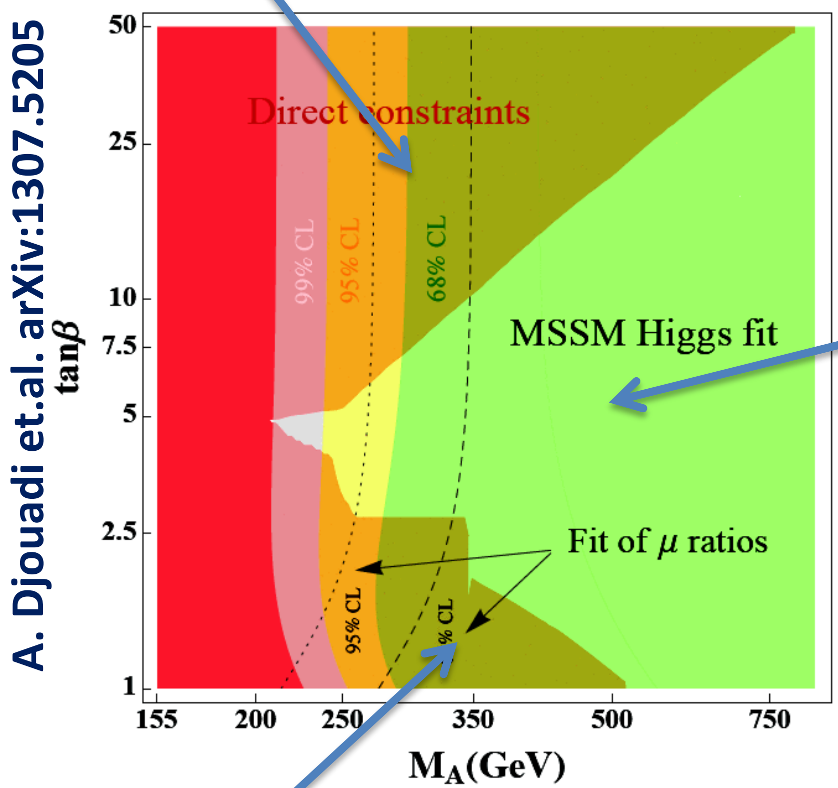
Masses of MSSM Higgs bosons



- **Five Higgs bosons in MSSM:**
  - **two CP-even h, H; one CP-odd A, two charged $H^{+/-}$**
  - ***what is discovered as state of 125 GeV, h or H ?***

Landscape of BSM Higgs channels in MSSM

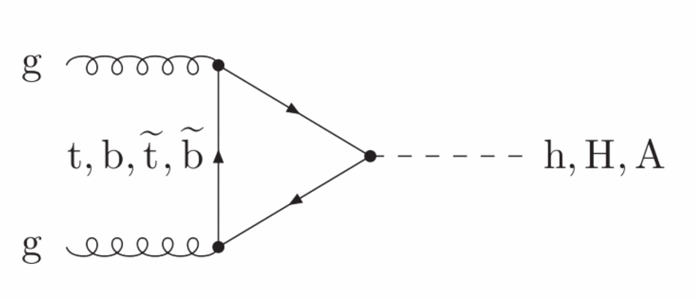
- ***High tanβ***: $\phi\to\tau\tau$, $\phi\to\mu\mu$; $H^+\to\tau\nu$, tb

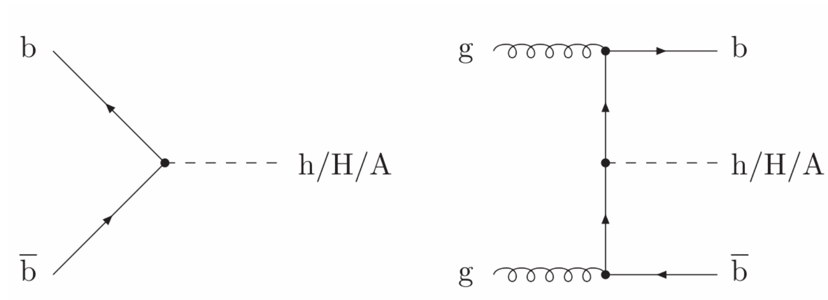


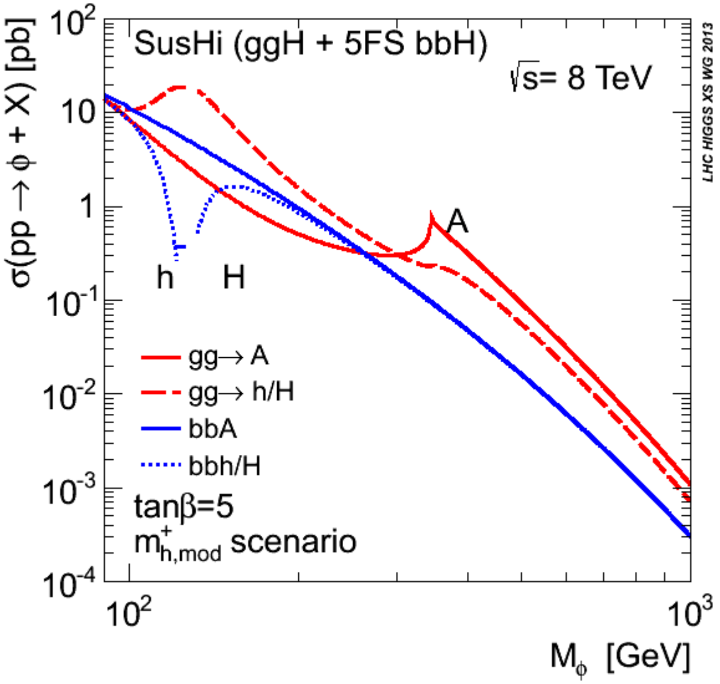
- ***Intermediate tanβ:***
  - $H/A\to\chi_i^0\chi_j^0$, $\chi_i^+\chi_j^-$
  - $H^+\to\chi_i^+\chi_j^0$

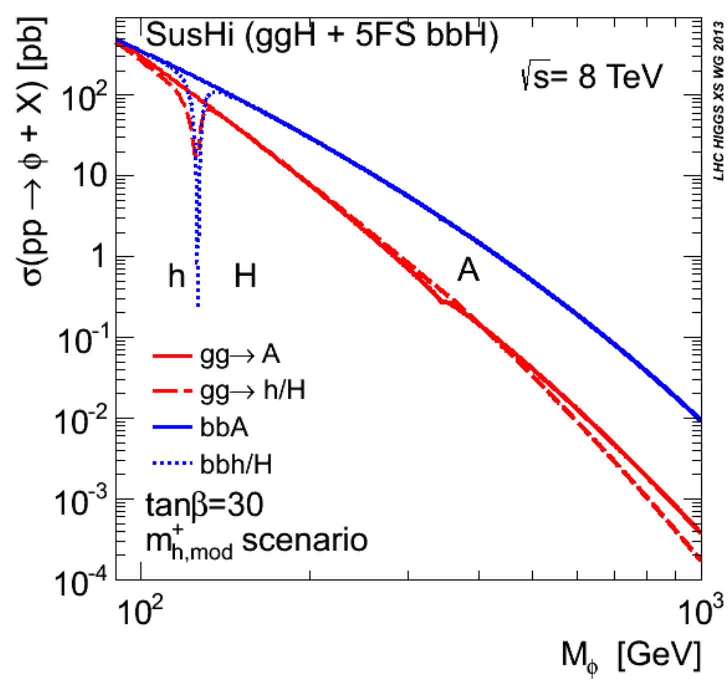
- ***Low tanβ:*** $A\to Zh$; $H\to hh$, tt; $H^+\to cs$, cb, $\tau\nu$, tb, Wh

MSSM neutral $\phi\text{->}\tau\tau$



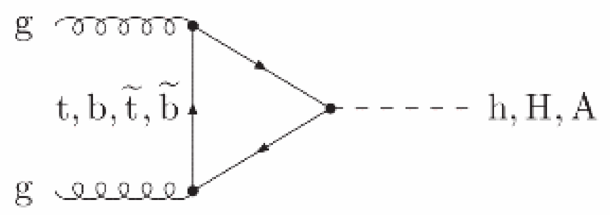


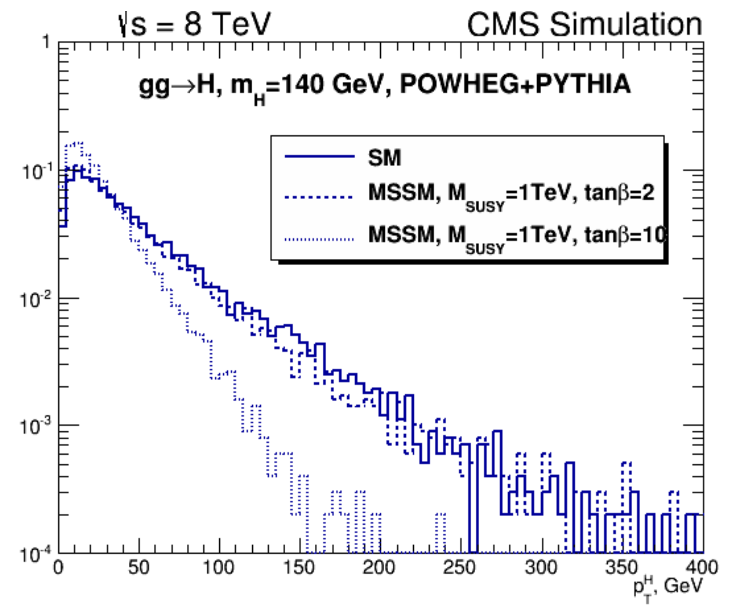




- **split events into b-tag and no-b-tag categories**
- **consider $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_h\tau_h$, $\tau_e\tau_\mu$, $\tau_\mu\tau_\mu$ final states**

gg->H in SM and MSSM





At high tanβ b-loop dominates and Higgs p_T is changing
This effect is discussed in:

1. *Spira et al. hep-ph/0604156*
2. *J. Alwall, Q Li, F. Maltoni arXiv:1110.1728*
3. *E.Bagnaschi, G. Degrassi, P. Slavich, A.Vicini. arXiv:1111.2854*

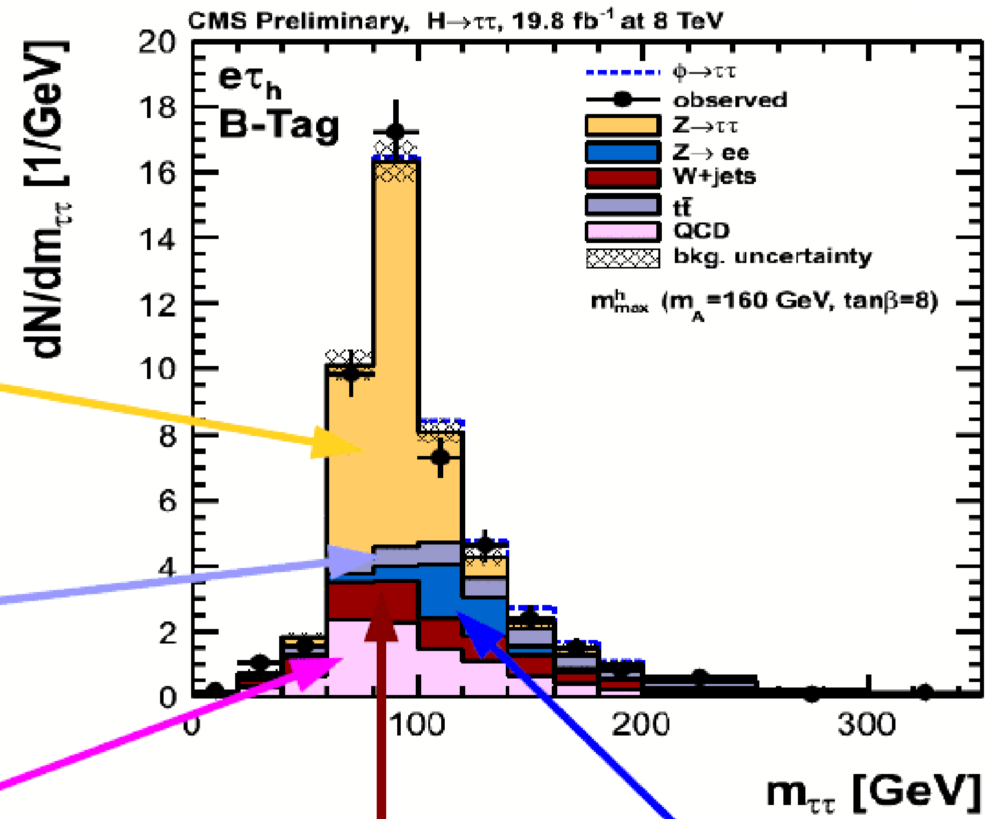
CMS analysis is designed in a such way that signal acceptance is model independent:

does not depends on assumption of what is in the loop

Background estimation in $\Phi \to \tau\tau$

$Z/\gamma^* \to \tau\tau$:
- Embedding: in $Z \to \mu\mu$, replace μ by sim. τ decay
- Normalized from $Z \to \mu\mu$ events

ttbar:
- From simulation
- Normalization from sideband

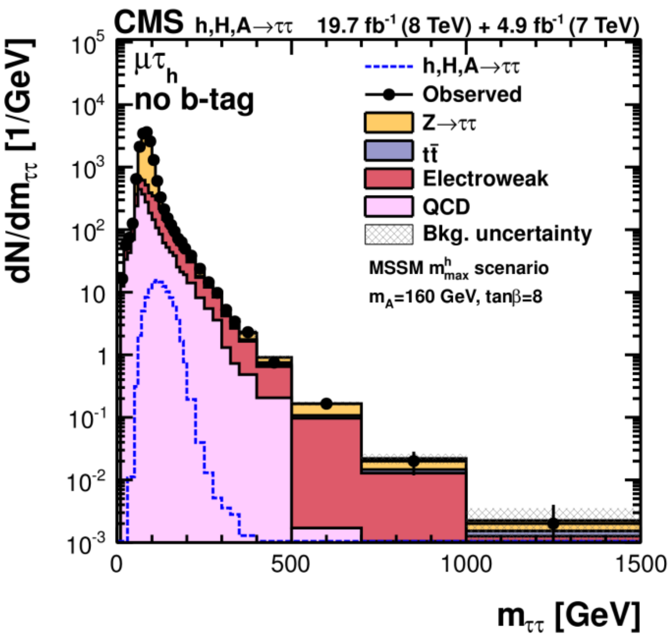


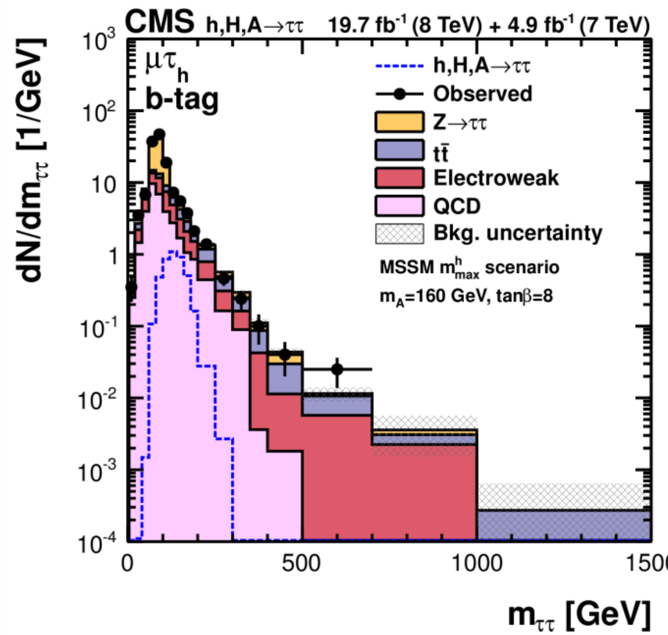
QCD:
- Normalization & shape taken from SS/OS or fakerate

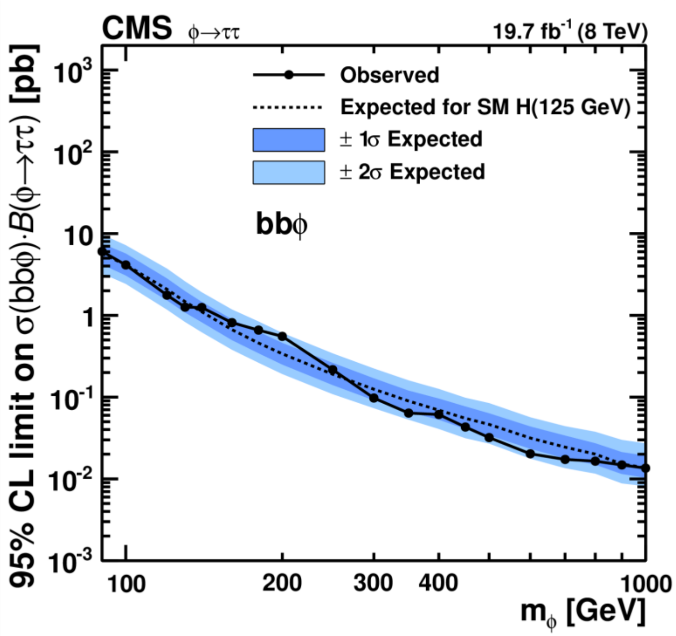
Di-boson/W+jets:
- From simulation or data
- Normalization from sideband

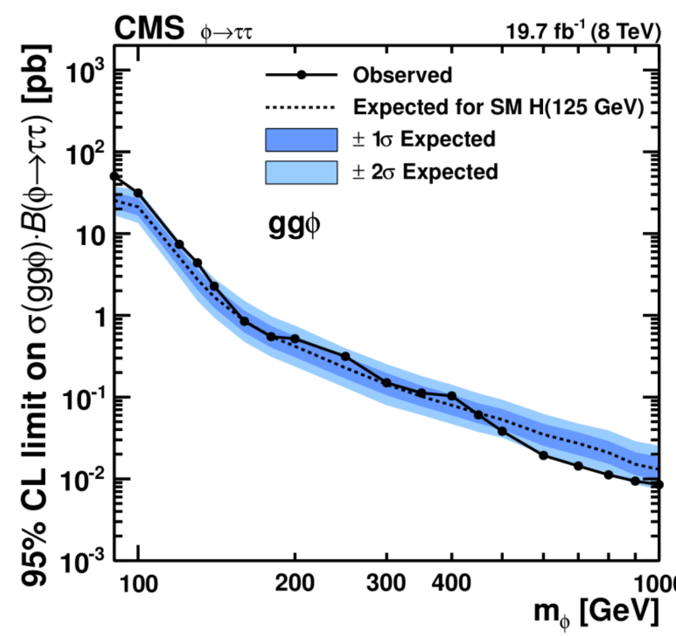
$Z/\gamma^* \to ee$ ($\mu\mu$):
- From simulation or data
- Corrected for jet $\to \tau$, $e/\mu \to \tau$ fakerate

ϕ->ττ : “model independent” limits



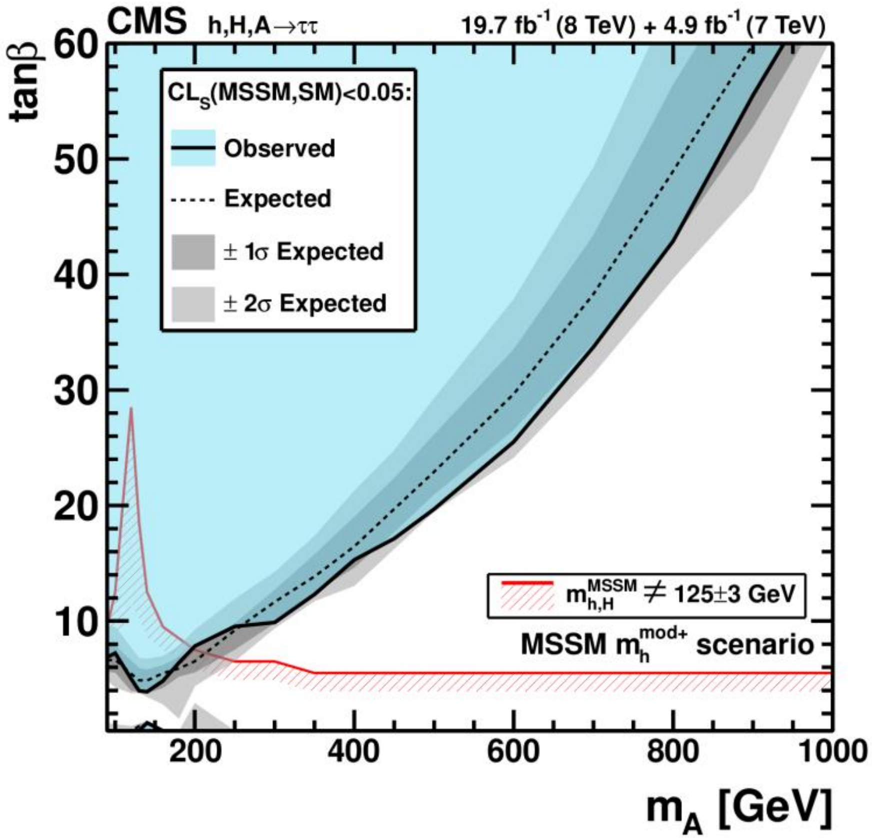


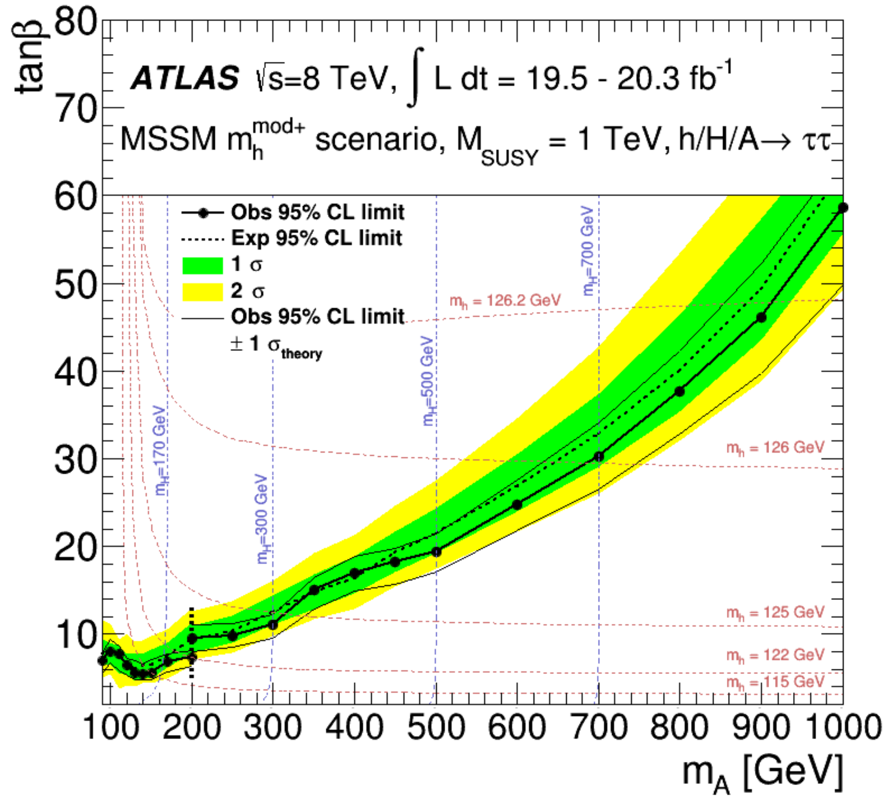




ϕ->ττ : limits in MSSM benchmark scenarios

- m_h^{mod+} scenario from M.Carena at al. arXiv:1302.7033



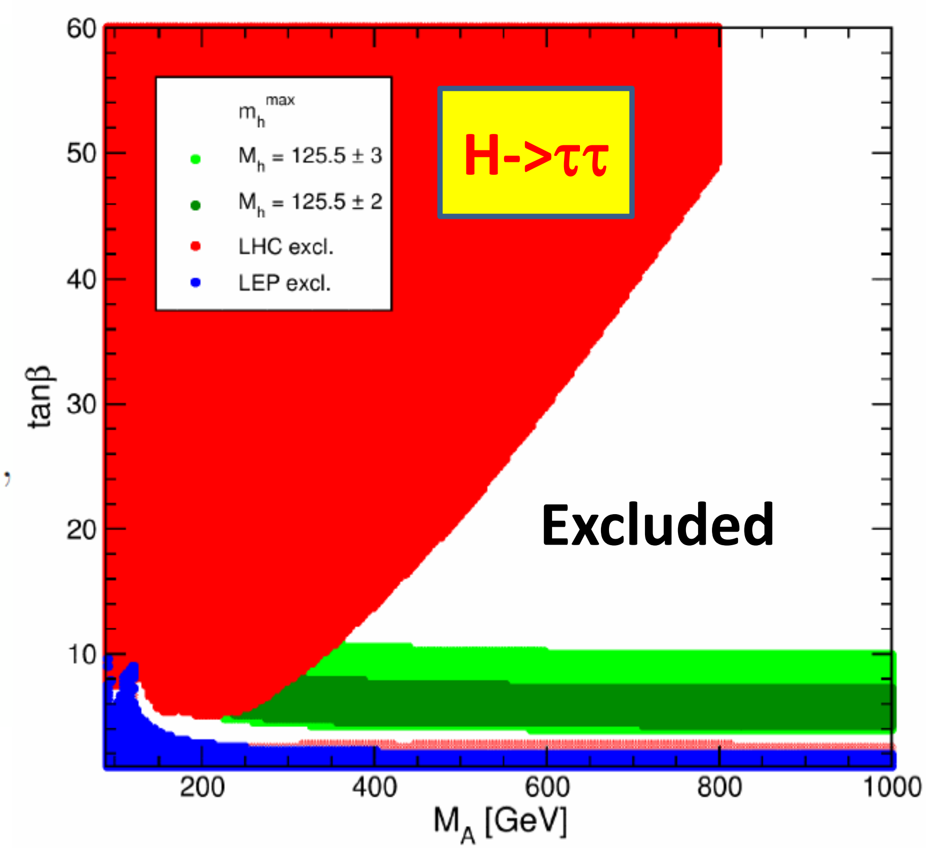


A few words on interpretation in the “benchmark” scenarios

MSSM benchmark scenarios (I)
(from M. Carena et al arXiv:13027033)

- m_h^{max} updated scenario:
  - green strip is allowed region of M_A-tanβ

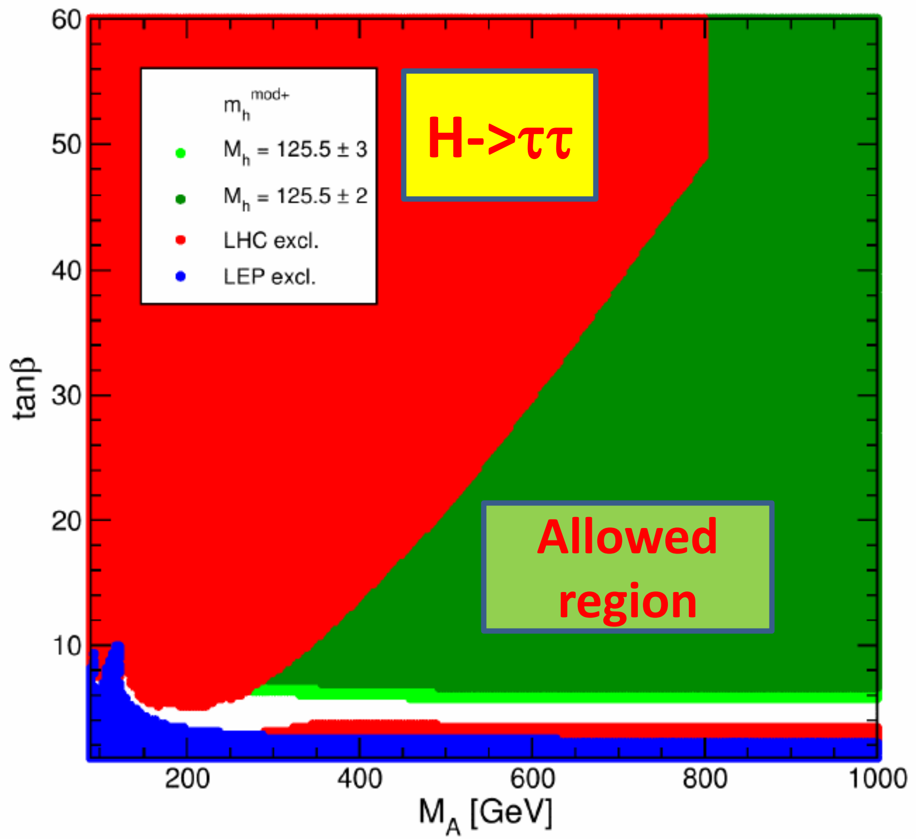
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 2\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= \sqrt{6}\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV}\ .
\end{aligned}
$$



MSSM benchmark scenarios (II)
(from M. Carena et al arXiv:13027033)

- m_h^{mod} scenario:
  - green area is allowed region of M_A-$\tan\beta$

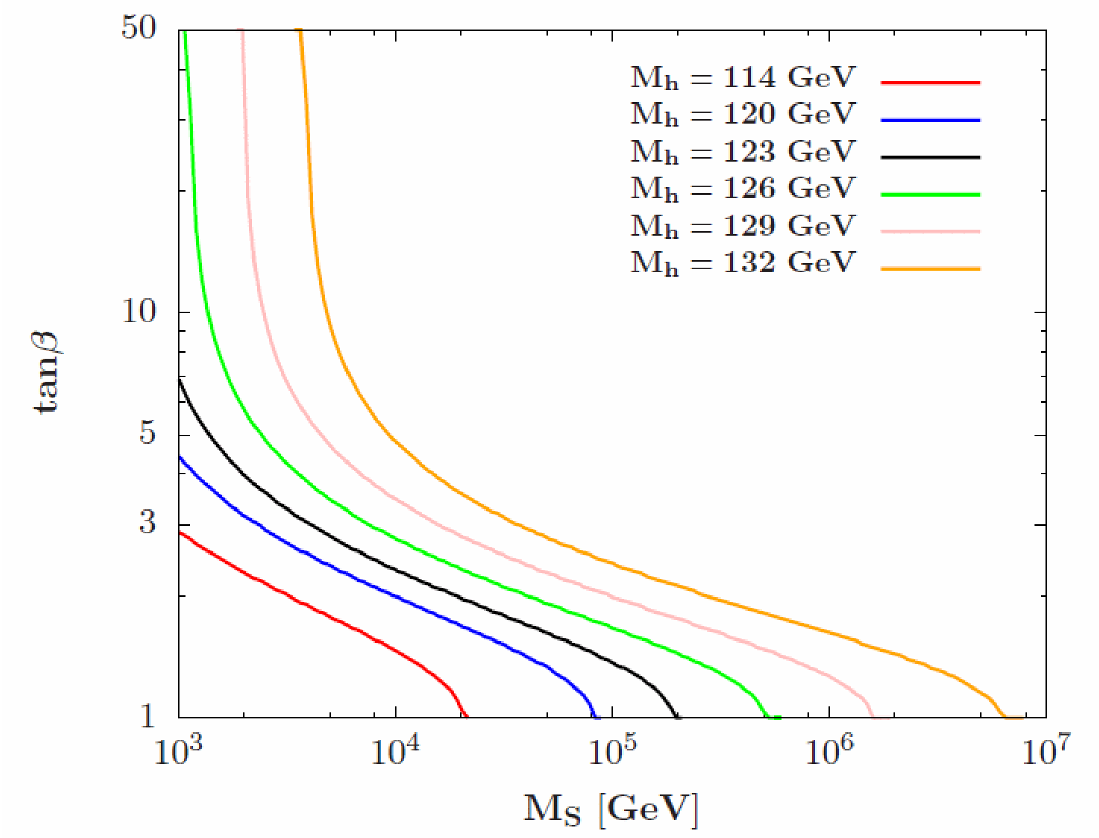
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= 1.6\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau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



Is low tanβ region excluded ?

(A. Djouadi at el., arXiv:1304.1787)

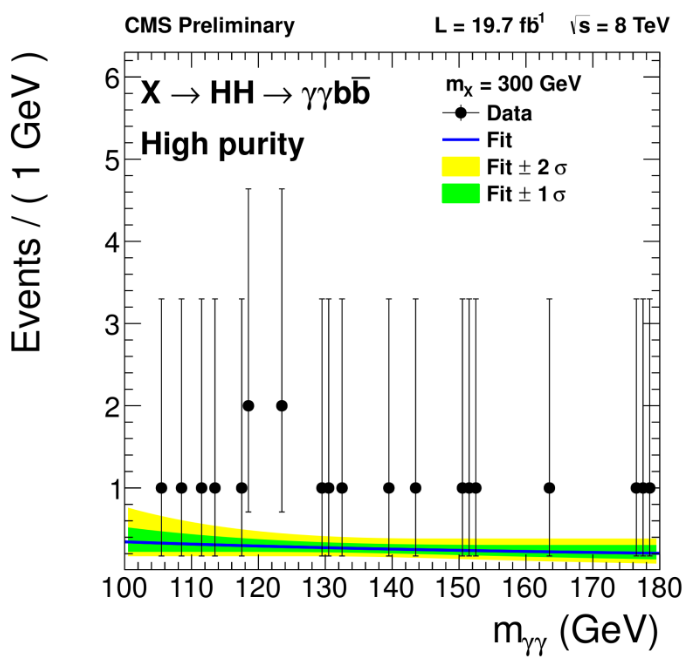
- Low tanβ region is not excluded for large M_S

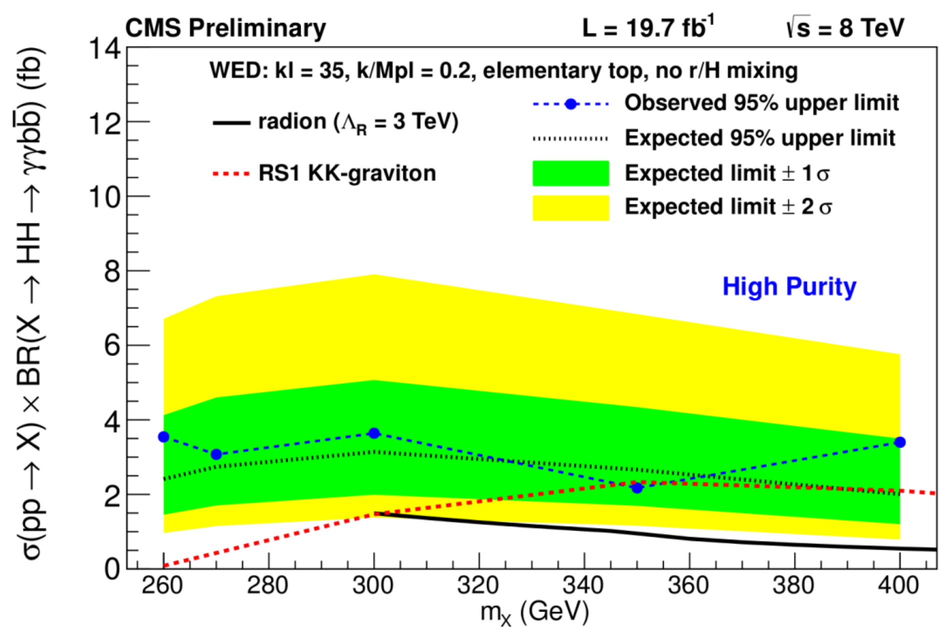


with m_t uncertainty 3 GeV (from tt~ cross-section) $\Delta^{th}m_h$ is ~ 6 GeV

low tanβ mode :$H \to hh \to \gamma\gamma bb$

- **Search strategy:**
  - looking for signal in $m_{\gamma\gamma}$ distribution for $\gamma\gamma bb$ events selected within m_{bb} and $m_{\gamma\gamma bb}$ mass windows
- In hMSSM (A. Djouadi et.al. arXiv:1307.5205):
  - $\sigma(gg \to H) x BR(H \to hh \to \gamma\gamma bb)$=2.9 fb for m_A=300 GeV, tanβ=2
    - close to observed limit !

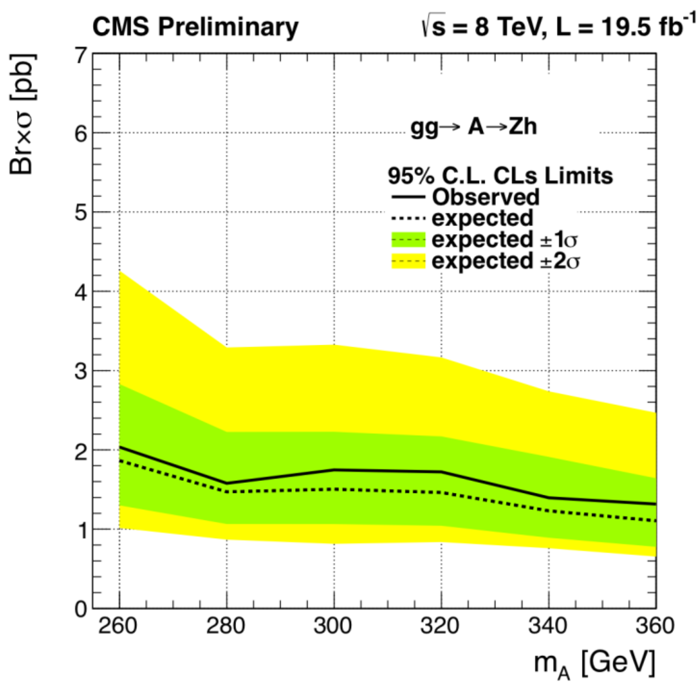


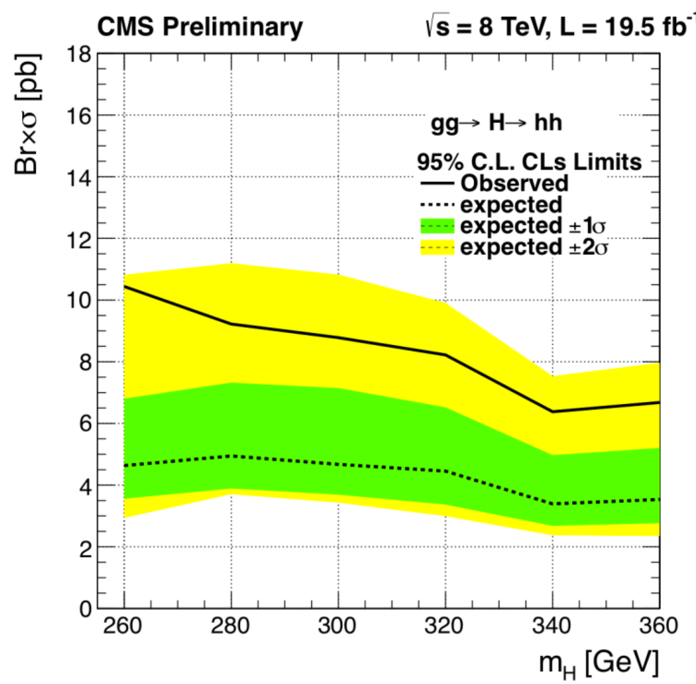


Theorists are invited to make the model interpretation

low tanβ modes: H->hh and A->Zh with multi-lepton and di-photon final states

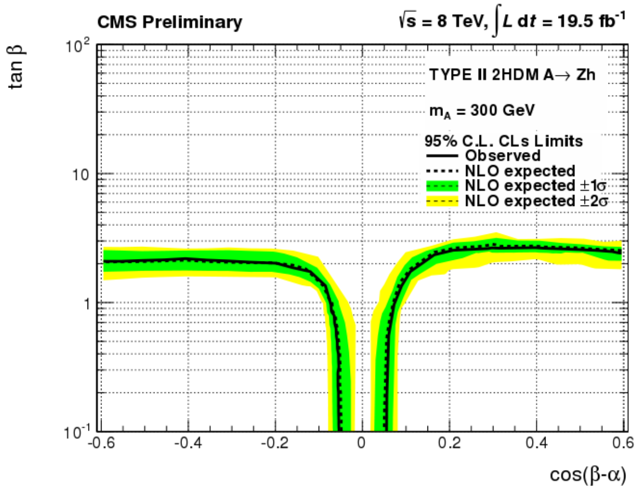
- **Limits on σxBr for gg->H->hh (gg->A->Zh) are given assuming SM BRs for h and no contribution from gg->A->Zh (gg->H->hh)**
- In hMSSM (A. Djouadi et.al. arXiv:1307.5205):
  - σ(gg->A)BR(A->Zh)=1.7 pb for m_A=300 GeV, tanβ=2.0 - close to observed limit !
  - σ(gg->H)BR(H->hh)=3.9 pb for m_A=300 GeV, tanβ=1.0 – lower than observed limit

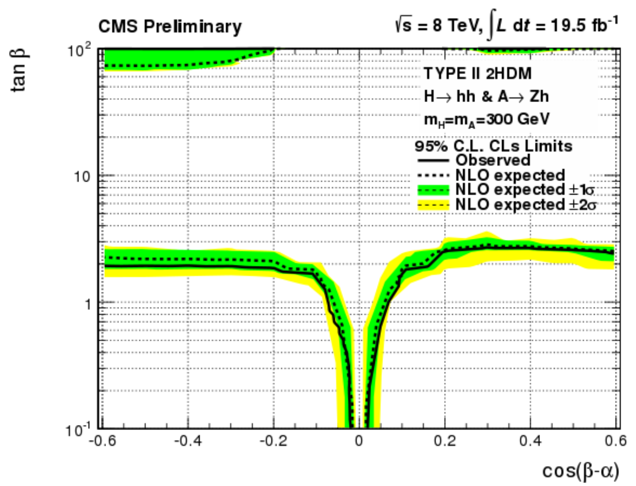




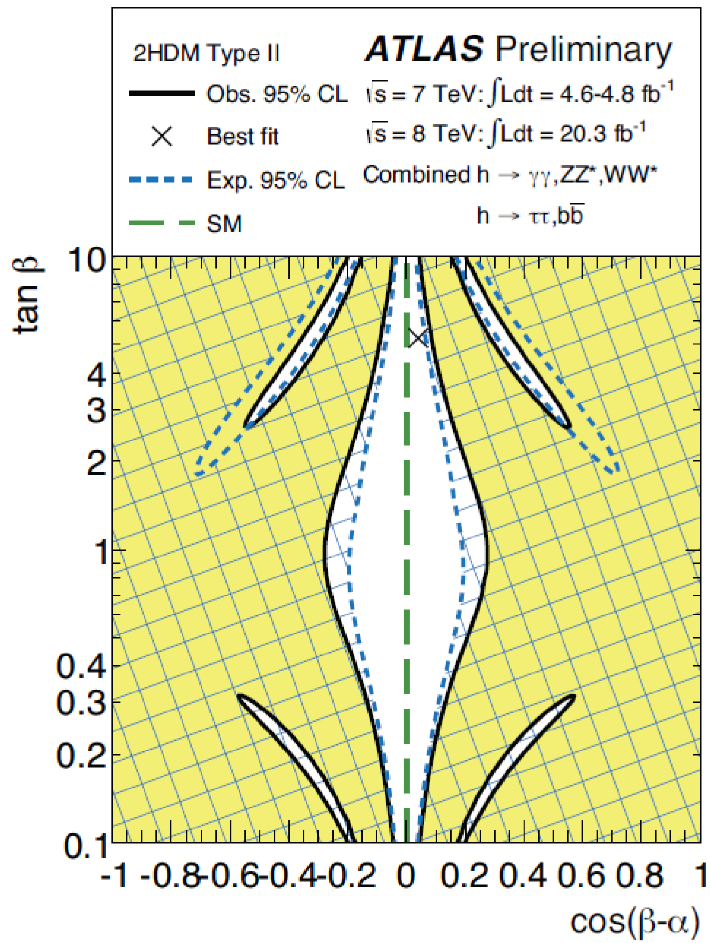
interpretation in 2HDM from direct search

H->hh & A->Zh ->ℓ's, $\gamma\gamma$



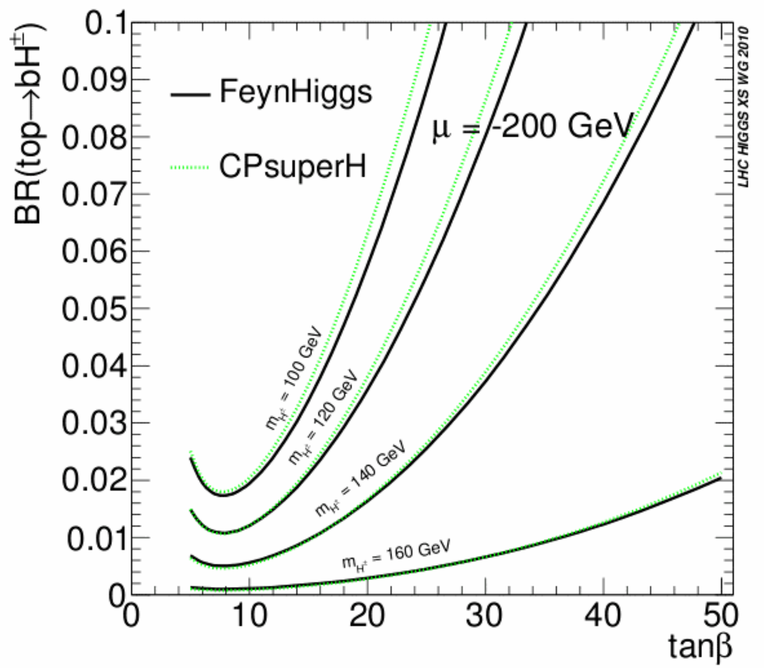


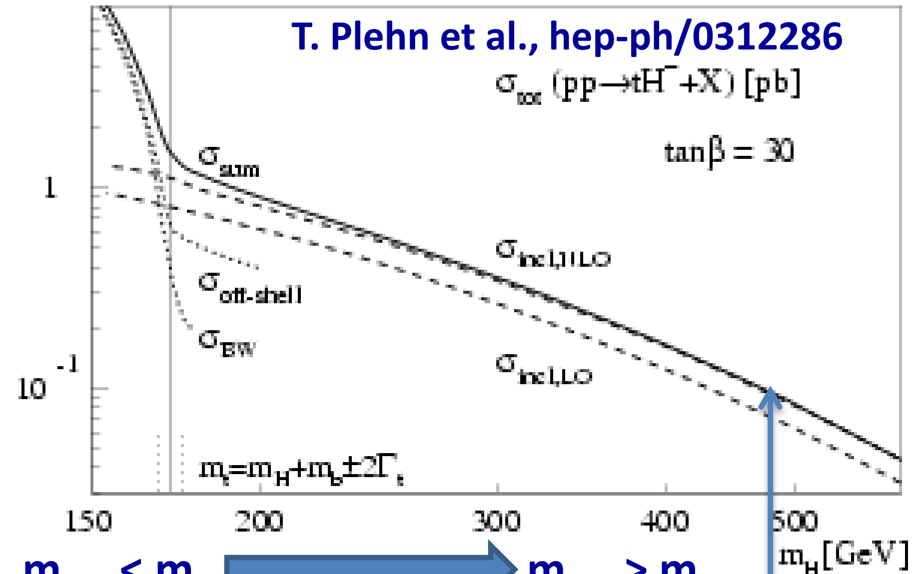
- and from ATLAS measurement of h(125) ATLAS-CONF-2014-010



Searches for $H^+ \to \tau\nu$ ($t \to bH^+$, $gb \to tH^+$)

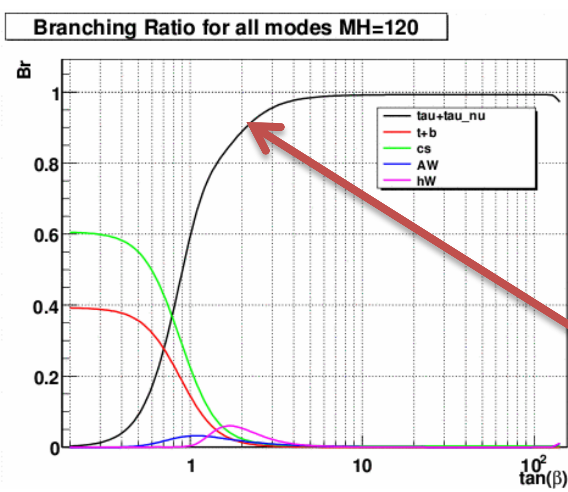
$$g_{H^+\bar{t}b} \quad \propto \quad m_b \tan\beta(1+\gamma_5) + m_t \cot\beta(1-\gamma_5)$$





$m_{H+} < m_t$ → $m_{H+} > m_t$

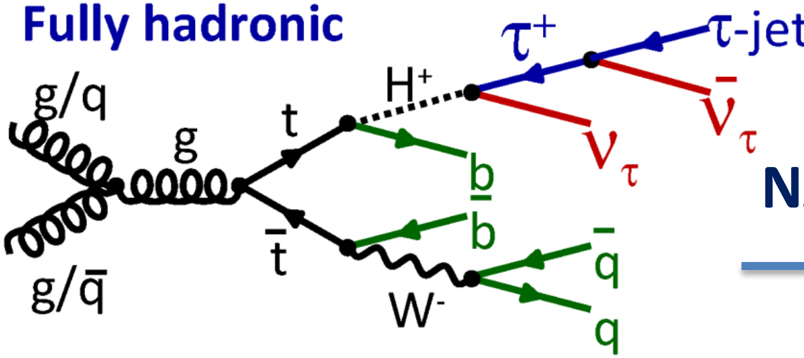
pp->tbH$^+$ is in MC@NLO (T.Plehn et al)
recipie for $m_{H+} \sim m_t$: add tt and tbH$^+$
4FS and 5FS NLO calculations exist



- ***Study decay mode $H^+ \to \tau\nu$***

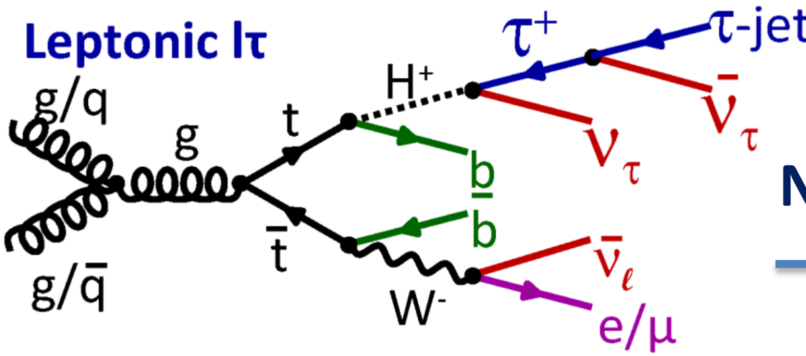
$H^{+}\to\tau\nu$. Topologies considered:

Fully hadronic



$N_{tt}^{SUSY} > N_{tt}^{SM}$

Leptonic lτ



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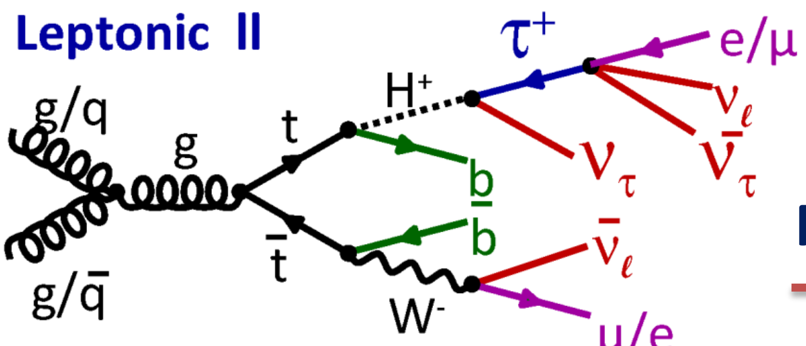
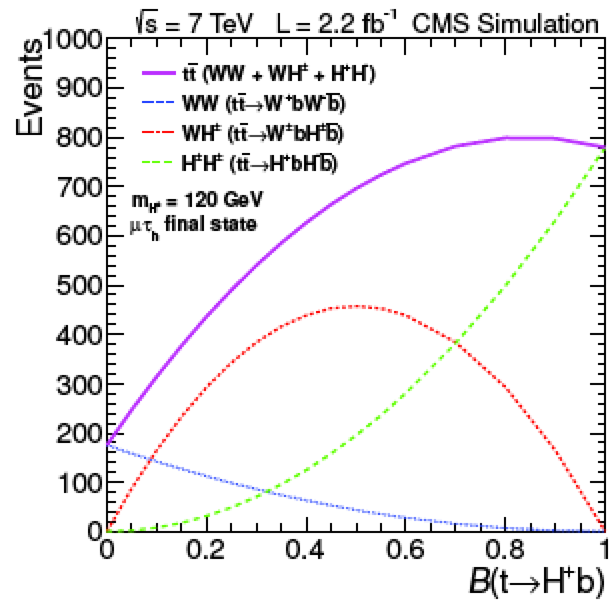
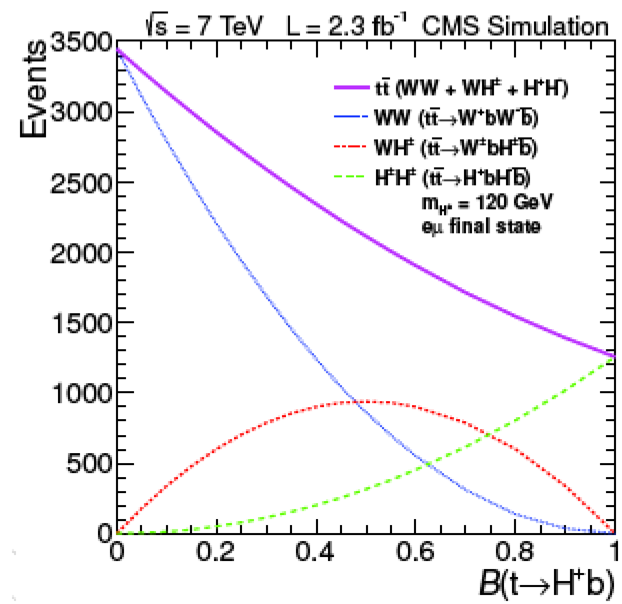
Leptonic ll



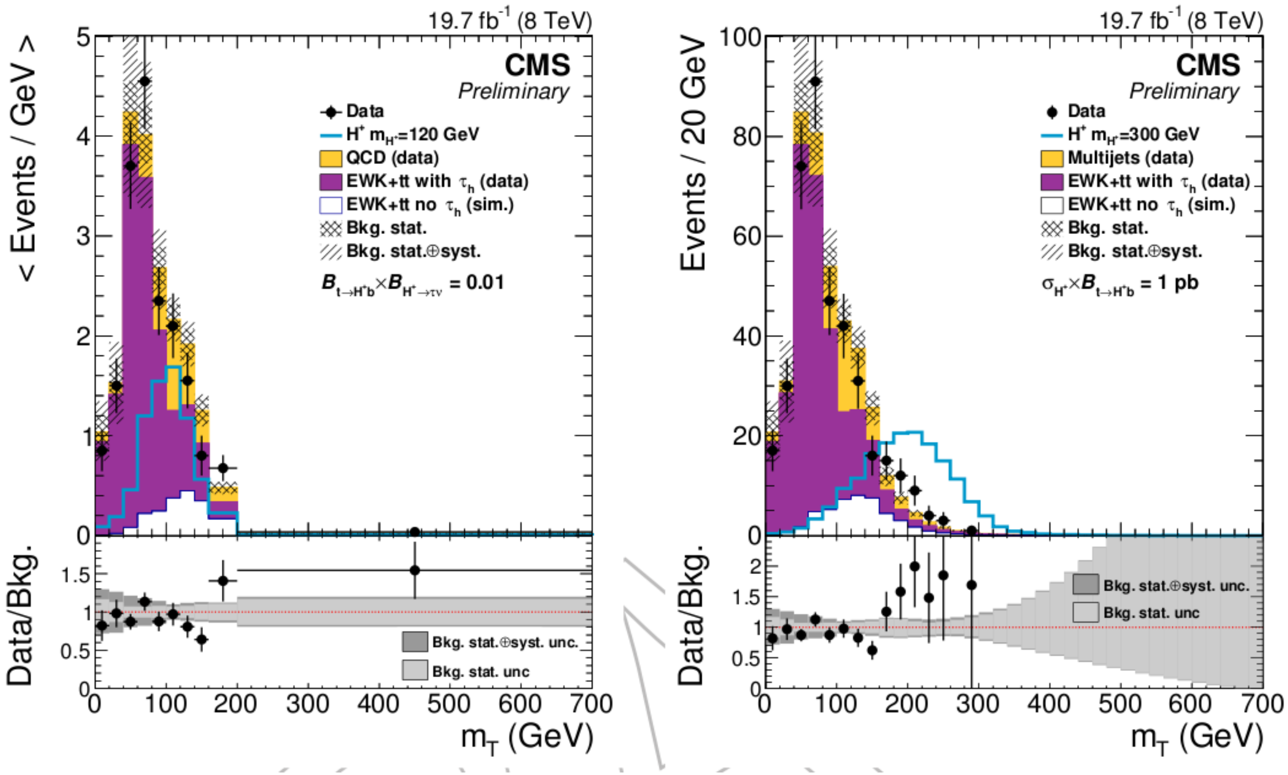
$N_{tt}^{SUSY} < N_{tt}^{SM}$



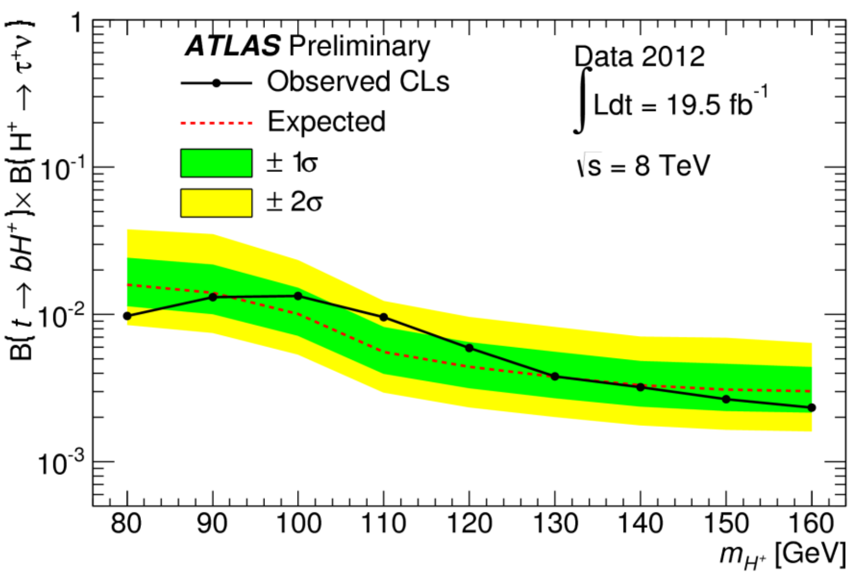


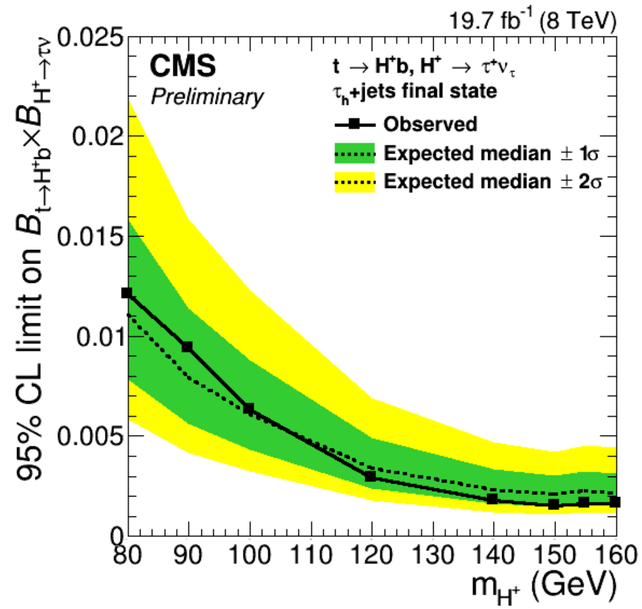
τ_h+jets is the most sensitive topology

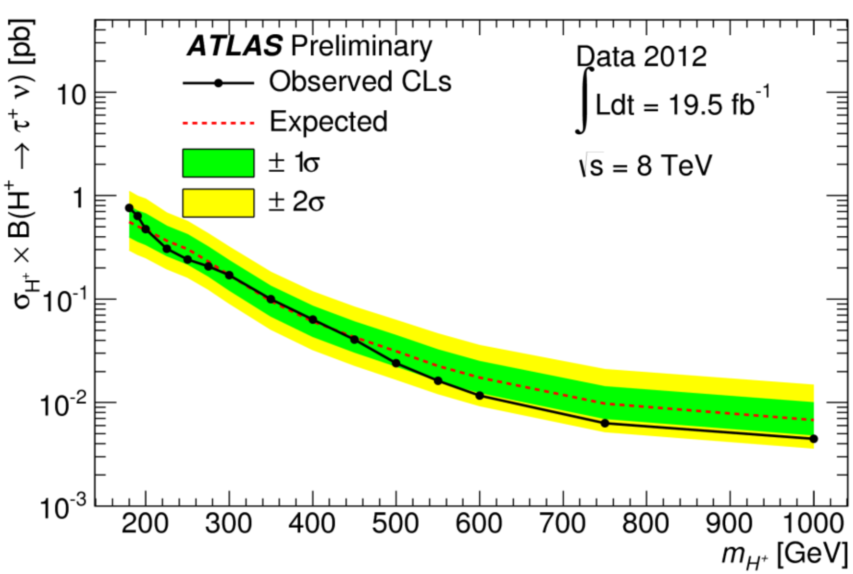
- $\tau_h + E_T^{miss}$ (35,70) trigger at HLT; seeded by L1 E_T^{miss} > 40 GeV
- at least 3 jets p_T > 30 GeV, $|\eta|<2.4$, at least one b-tagged jet
- one τ_h with p_T > 41 GeV, $|\eta|<2.1$, $R_\tau = p_T^{\pi}/p_T^{\tau h} > 0.7$
- Lepton veto
- E_T^{miss} > 60 GeV, cuts on $\Delta\phi(\tau_h, E_T^{miss})$, $\Delta\phi(\text{jet}, E_T^{miss})$
- W+tt~ with real τ's from embedding, multijet bkg from data

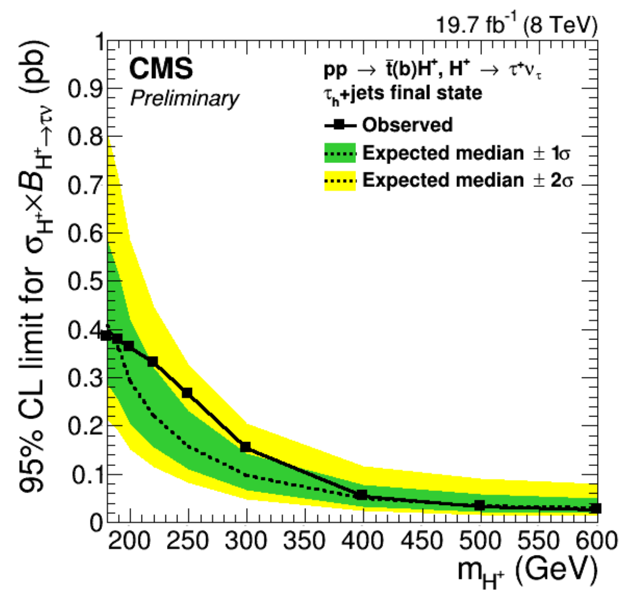


H+->τν: "model independent" limits



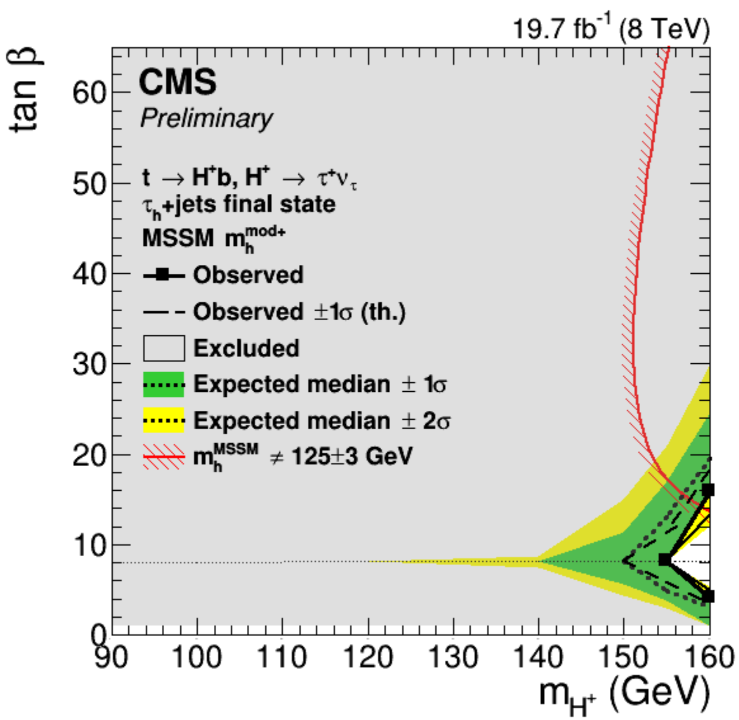


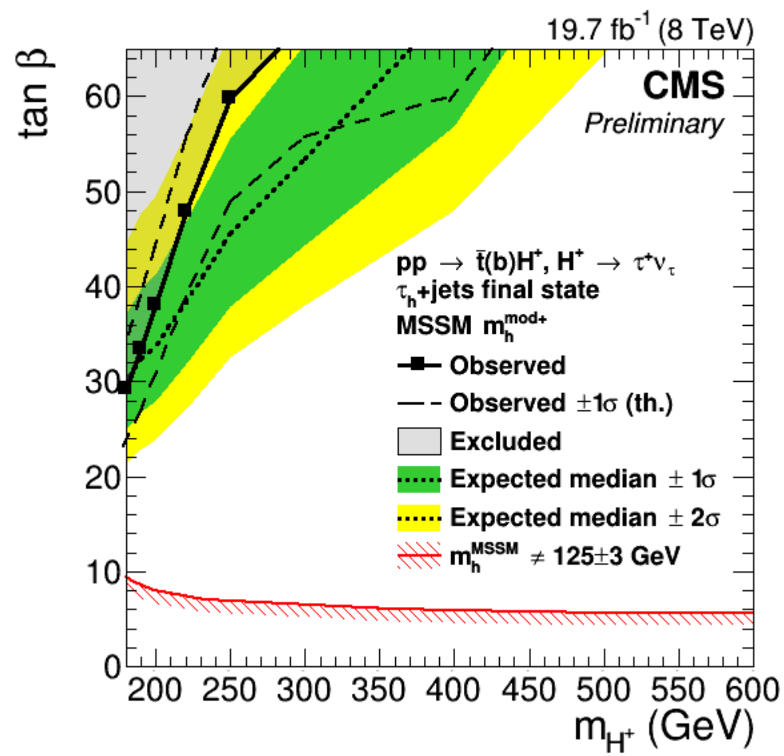




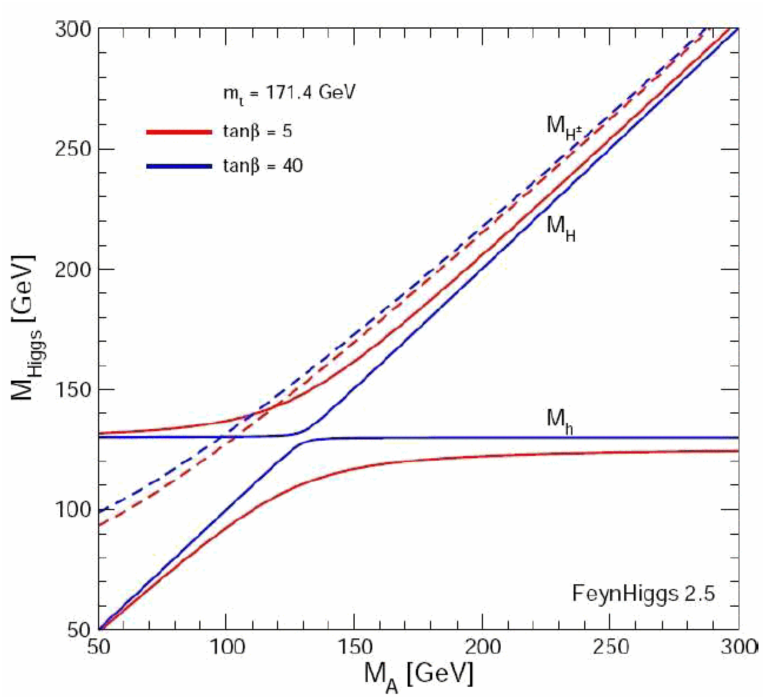
$H^+ \to \tau\nu$: limits in MSSM benchmark scenarios

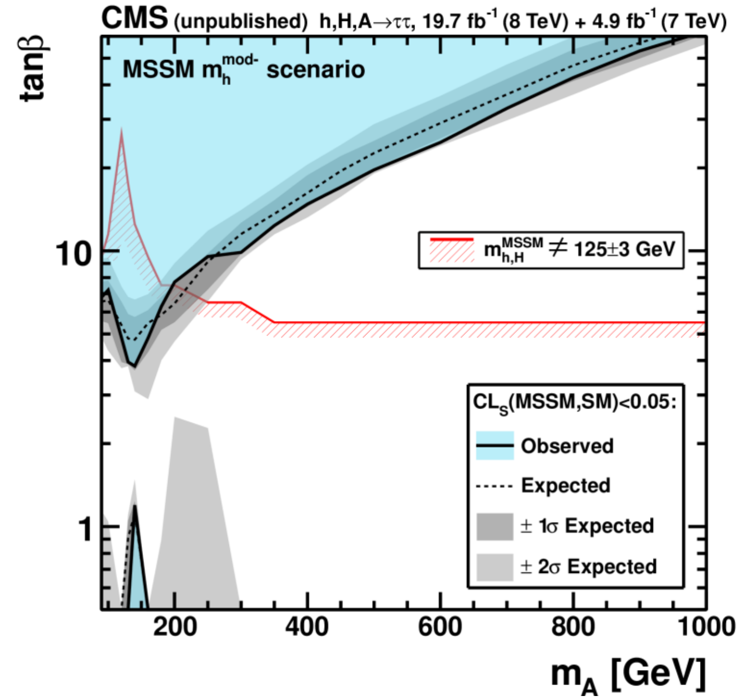
- m_h^{mod+} scenario from M.Carena at al. arXiv:1302.7033

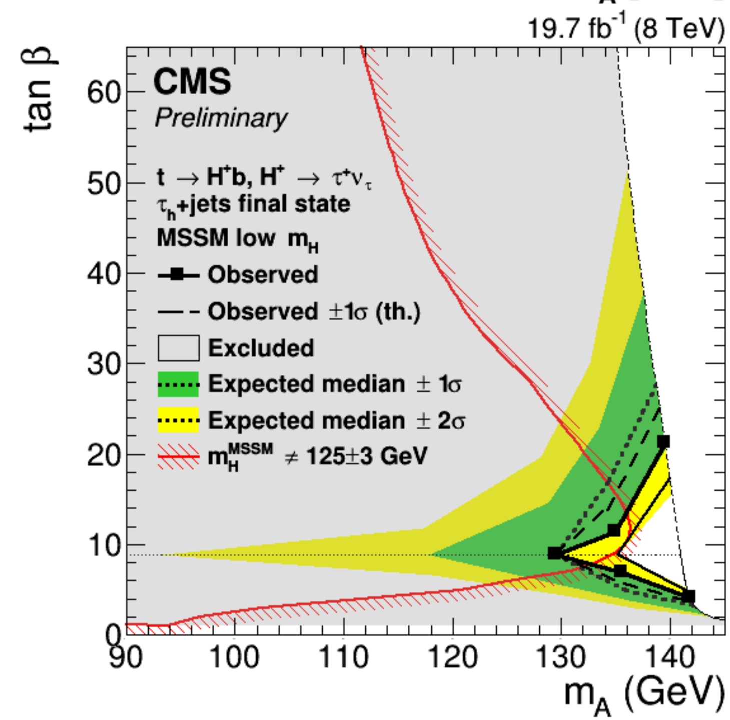




What Higgs boson is discovered in MSSM, h or H ?





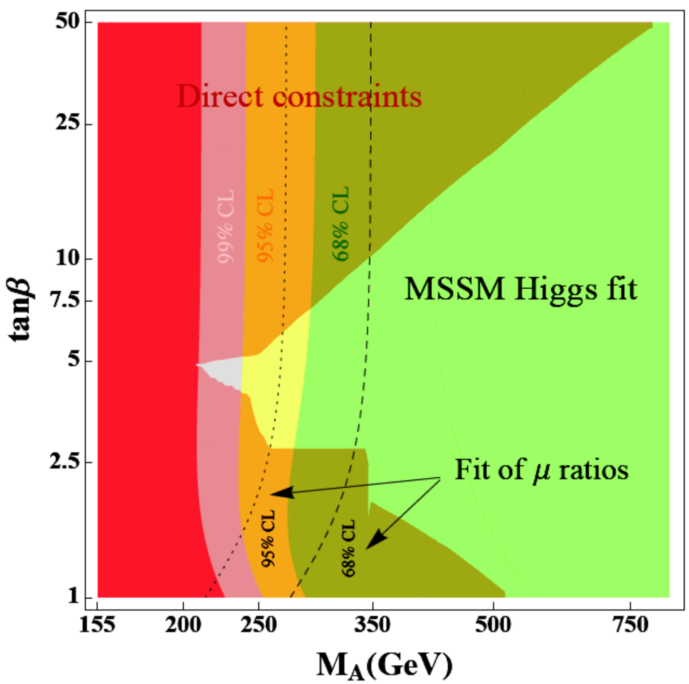


It is the little Higgs boson, h !

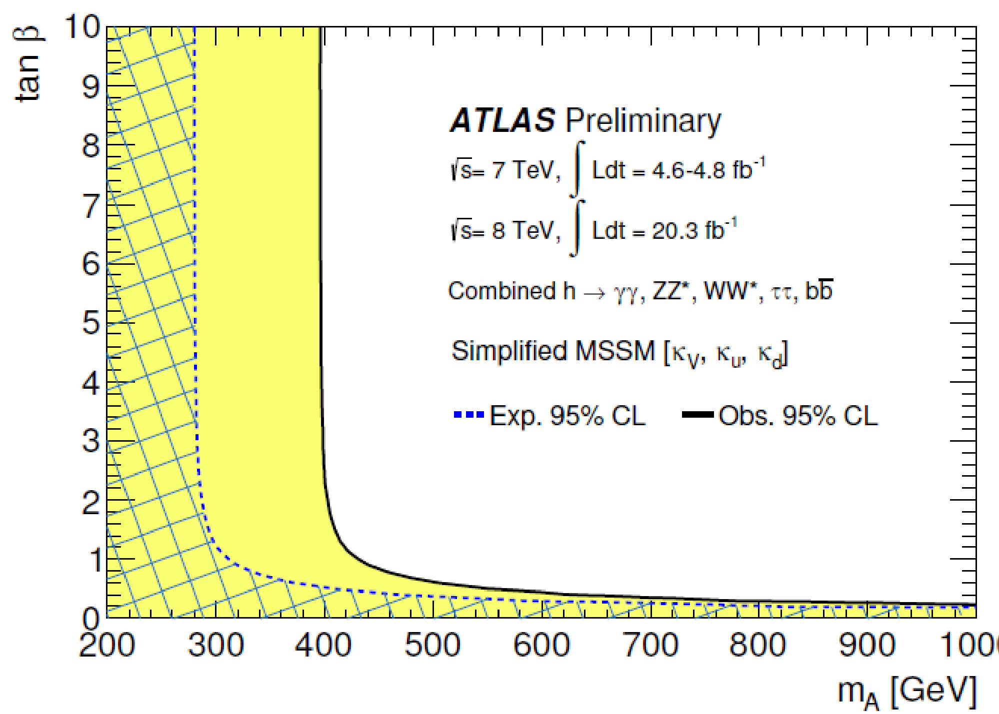
Interpretation of h measurements in hMSSM (A. Djouadi et.al. arXiv:1307.5205)

- Plots below are valid under conditions
  - small Δ_b (SUSY QCD) corrections – decoupling regime
  - heavy stops – no stop (and sbottom) in the gg->h loop
  - no charginos, staus in h->$\gamma\gamma$
  - no invisible decays

A. Djouadi et.al. arXiv:1307.5205



ATLAS-CONF-2014-010

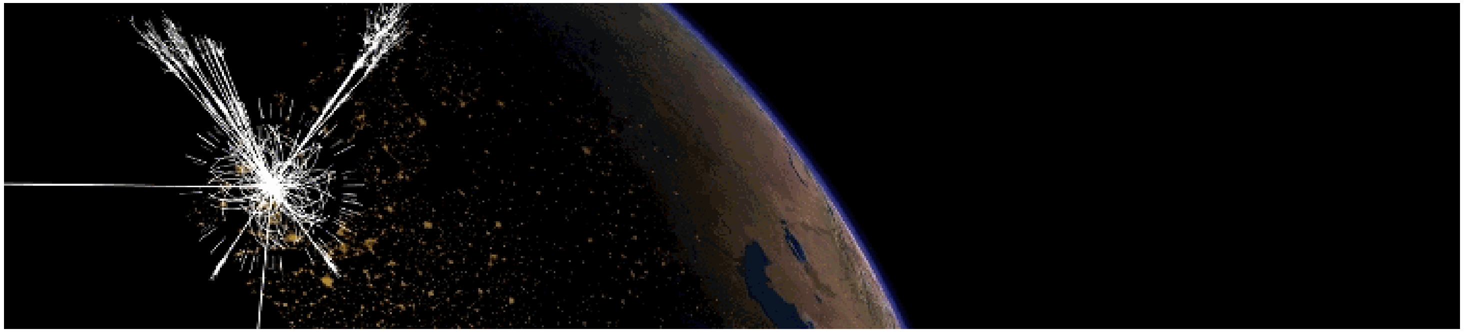


$$\mathcal{L}_h = c_V\, g_{hWW}\, h\, W^+_\mu W^{-\mu} + c_V\, g_{hZZ}\, h\, Z^0_\mu Z^{0\mu} - c_t\, y_t\, h\bar{t}_L t_R - c_t\, y_c\, h\bar{c}_L c_R - c_b\, y_b\, h\bar{b}_L b_R - c_b\, y_\tau\, h\bar{\tau}_L \tau_R + \text{h.c.}$$

$$c_V^0 = \sin(\beta-\alpha)\,,\quad c_t^0 = \frac{\cos\alpha}{\sin\beta}\,,\quad c_b^0 = -\frac{\sin\alpha}{\cos\beta}$$

Non-SM h decays:

searches for h→invisible with VBF h, Zh (Z->ℓℓ,bb)



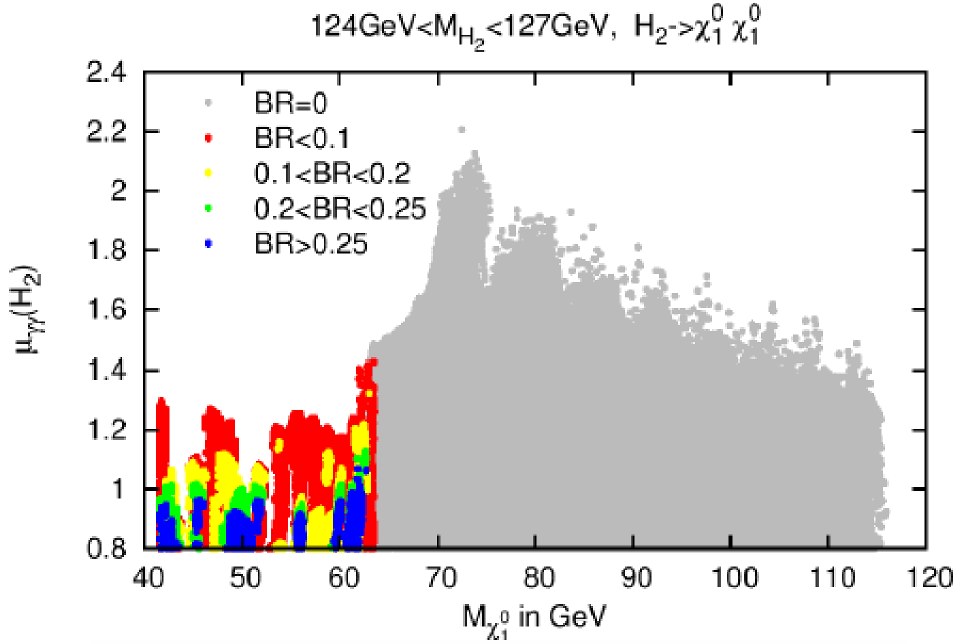
Detection of Dark Matter

H->invisible BR in (N)MSSM

- **NMSSM H_2 (125)>$\chi^0\chi^0$**

  S. King et al., arXiv:1211.5074

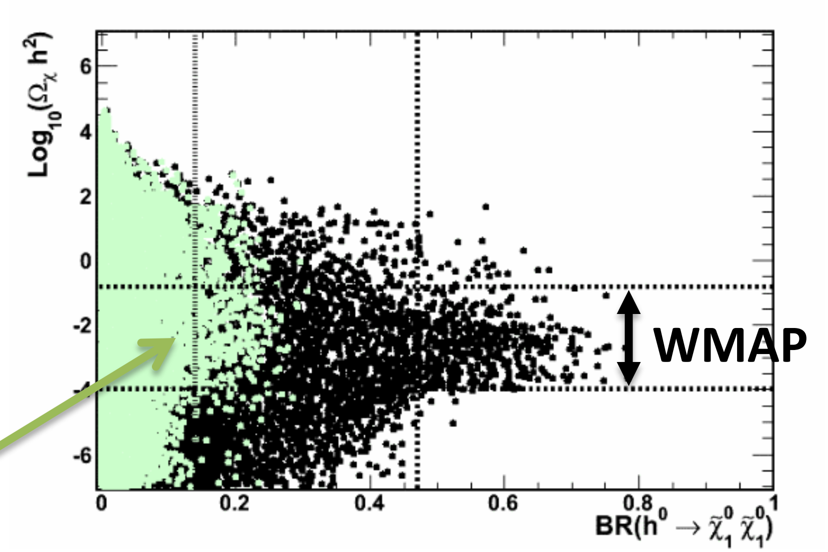
  BR ~ 10-20 %



- **pMSSM h->$\chi^0\chi^0$**

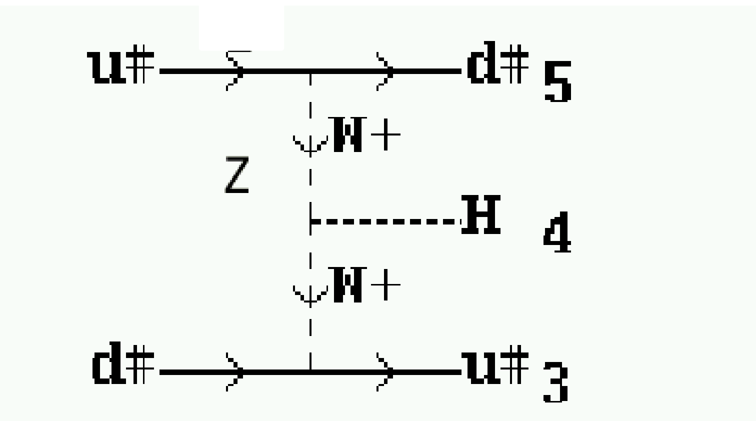
  A. Arbey et al., arXiv:1211.4004

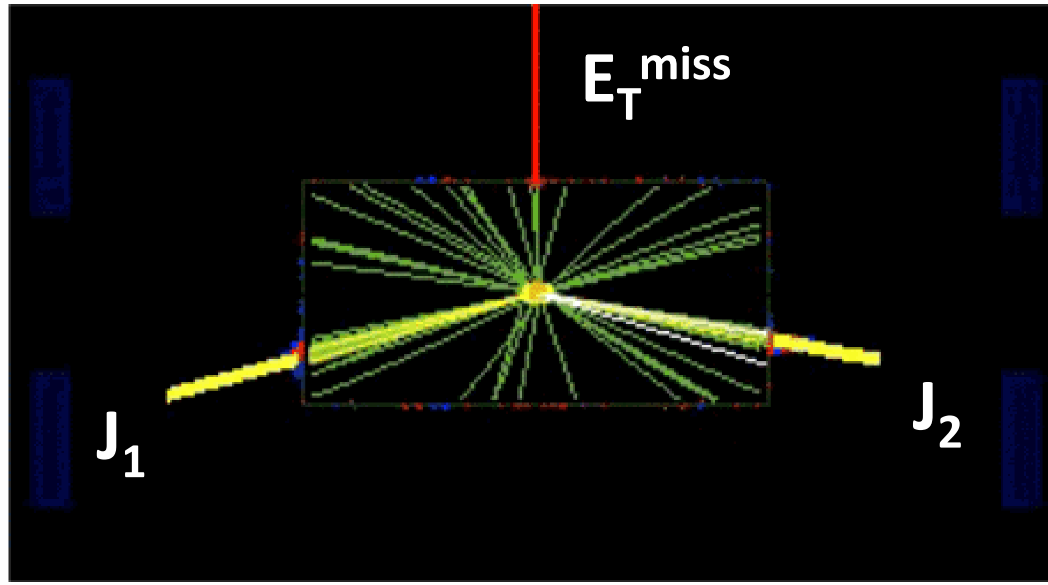
  BR < 25 %



Compatible with LHC Higgs data (green color)

most sensitive mode qq’→qq’h (VBF h)



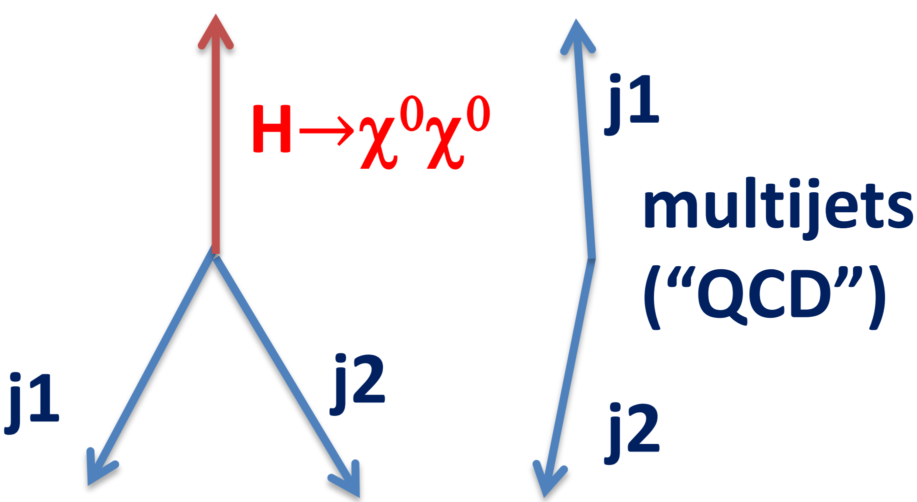


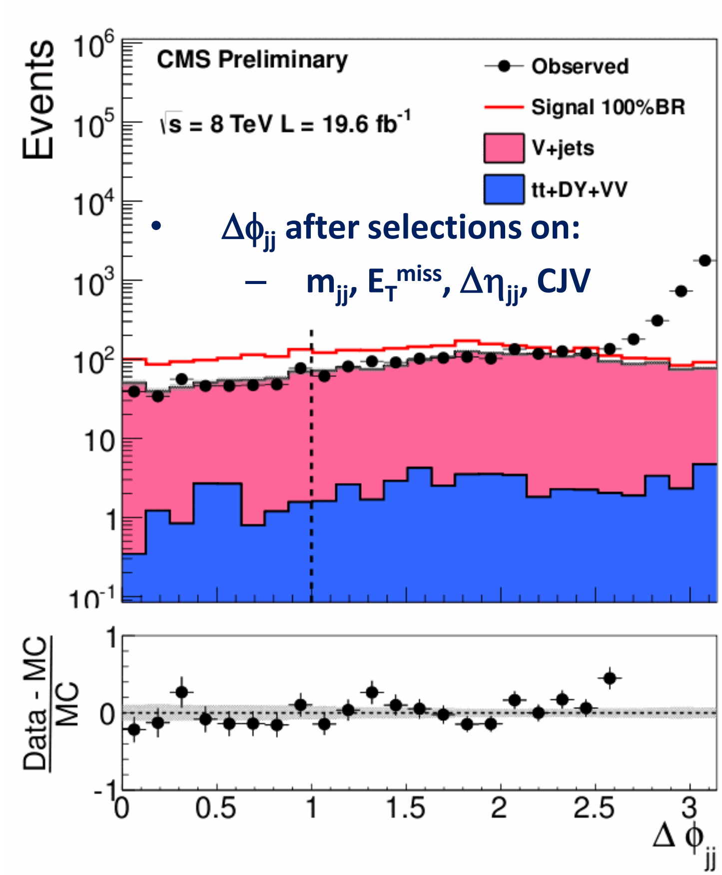
Event 191202:51:82701983

VBF $h \rightarrow$invisible: offline signal selections and topology

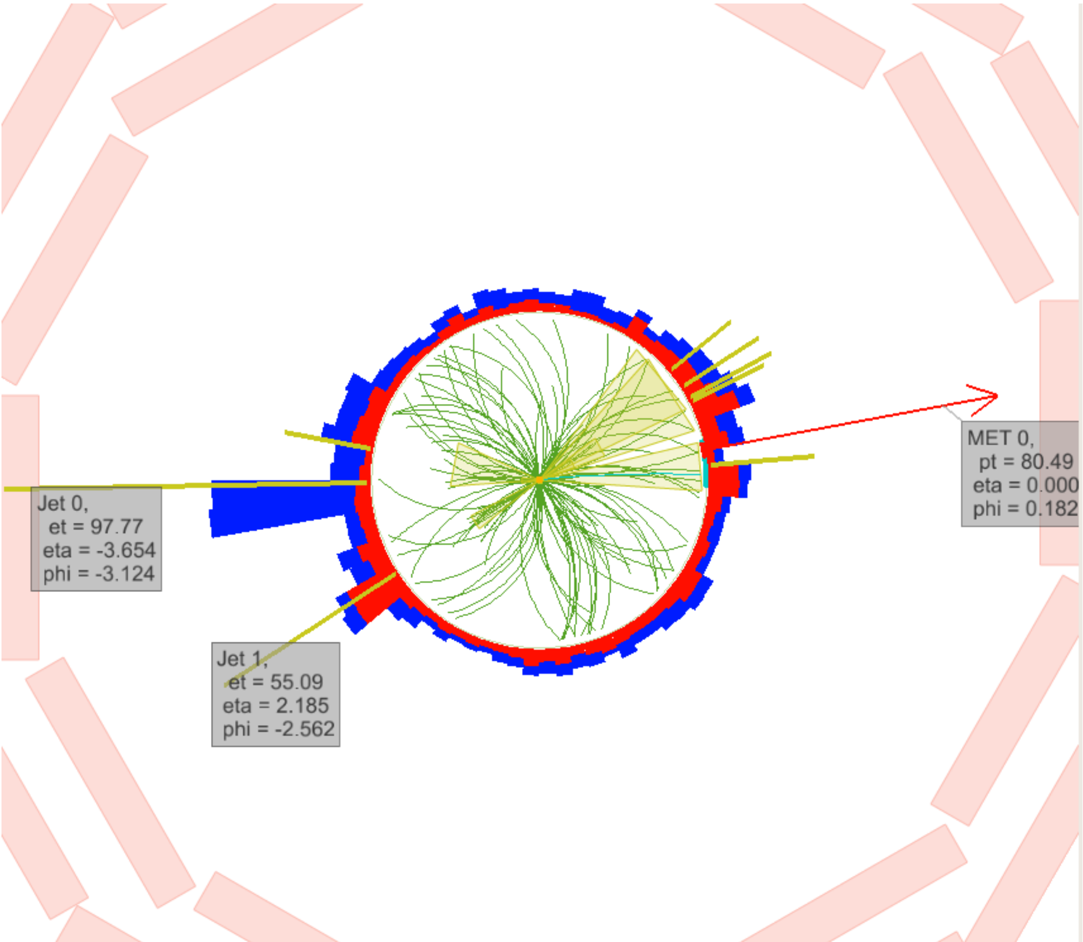
- two jets p_T>50 GeV, $|\eta|$<4.7
- m_{jj} > 1100 GeV
- $\Delta\eta_{jj}$ > 4.2
- E_T^{miss} > 130 GeV
- $\Delta\phi_{jj}$ < 1.0
- Central Jet Veto (CJV)

Signal: small $\Delta\phi_{jj}$
QCD: large $\Delta\phi_{jj}$



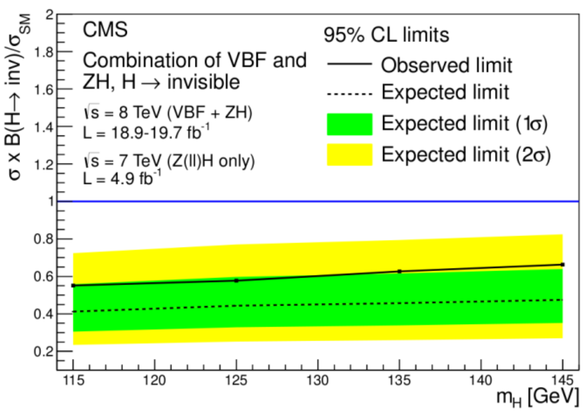


Signal region, with CJV (x,y view)



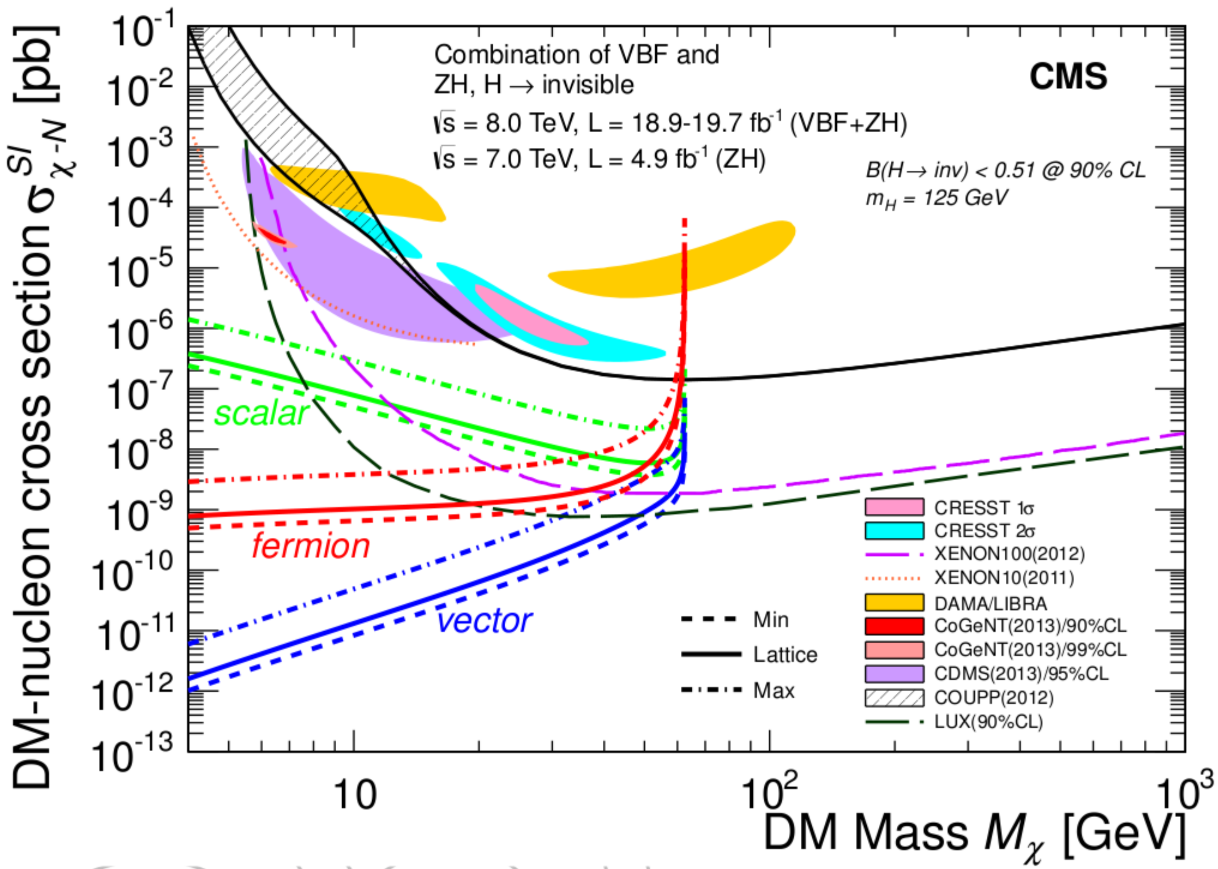
	▽pT	eta	phi
0	97.8	-3.654	-3.124
1	55.1	2.185	-2.562
2	27.0	-0.200	0.084
3	24.8	2.286	0.502
4	23.4	-2.044	2.958
5	23.0	0.359	0.575
6	21.6	-2.901	0.472
7	20.4	1.349	0.691

Interpretation of H->invisible direct search in Higgs-portal Dark Matter model
(as in A. Djouadi et.al arXiv:1112.3299, arXiv:1205.3169)



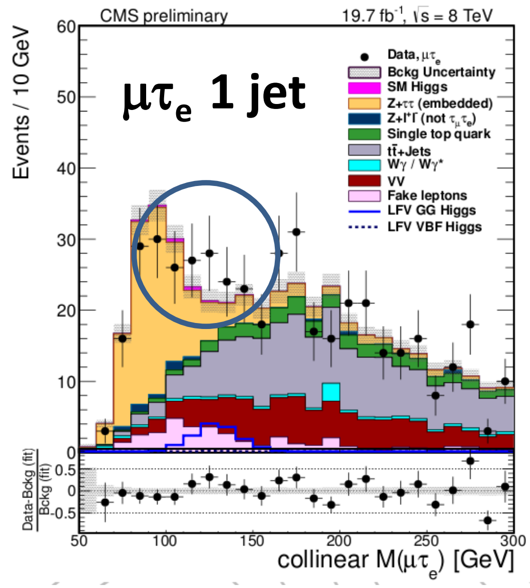
BR($h_{125\ GeV} \rightarrow$inv) < 0.58 at 95 % CL (expected < 0.44)

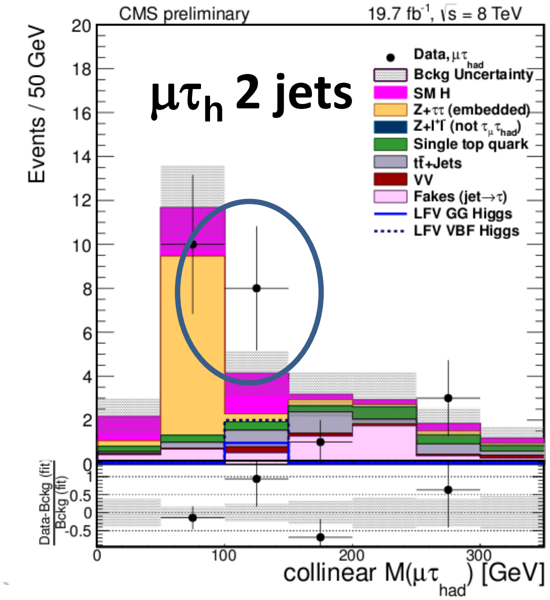
with VBF+ZH



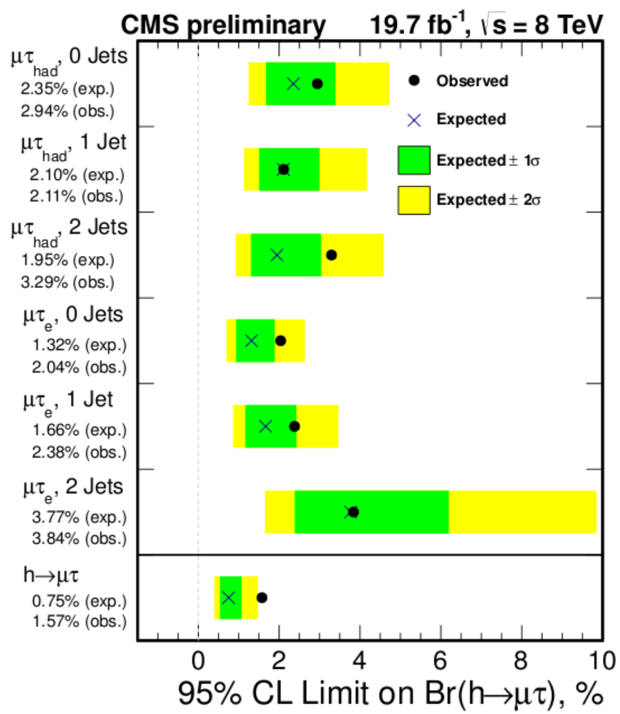
Non-SM h decays:
LFV with $h \to \mu\tau$

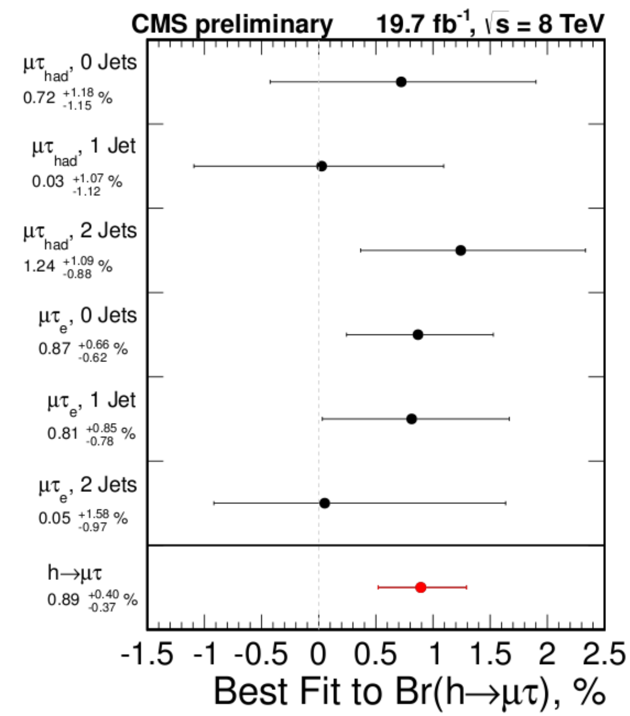
- Events are subdivided on 0, 1, 2 jet categories
- $\mu\tau_e$, $\mu\tau_h$ topologies
- m_h is reconstructed in collinear approximation





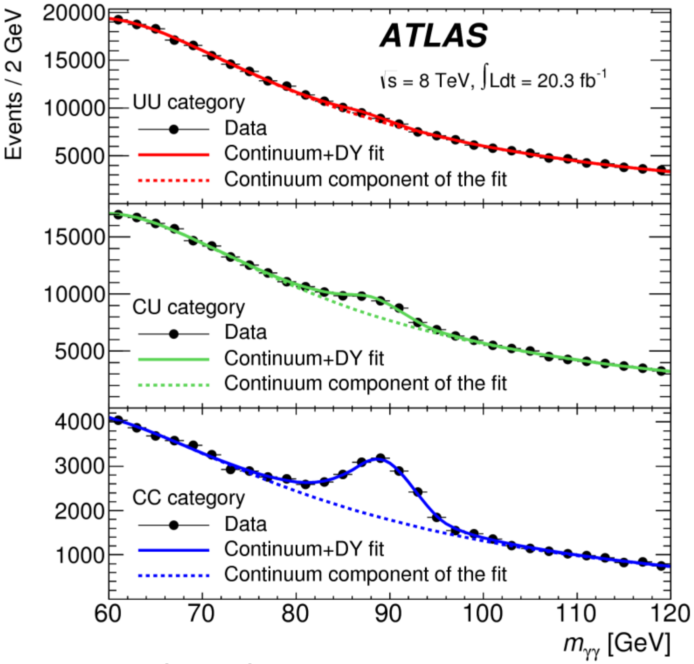
- **Upper limit:**
  - BR < 1.57 %
- ~ 2.5 σ access



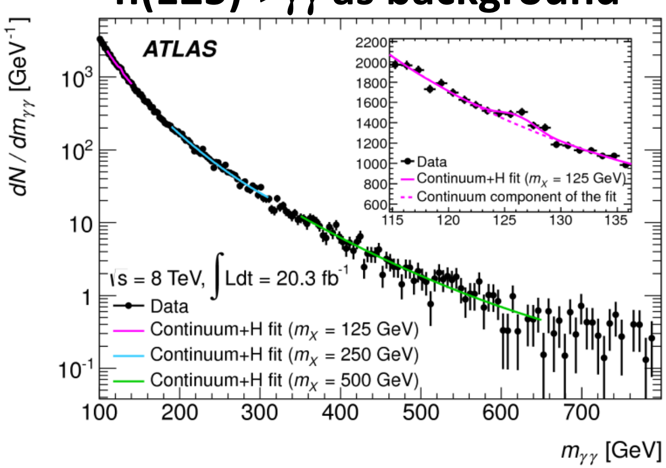


Search for scalar di-photon resonances, m_X=[65-600] GeV

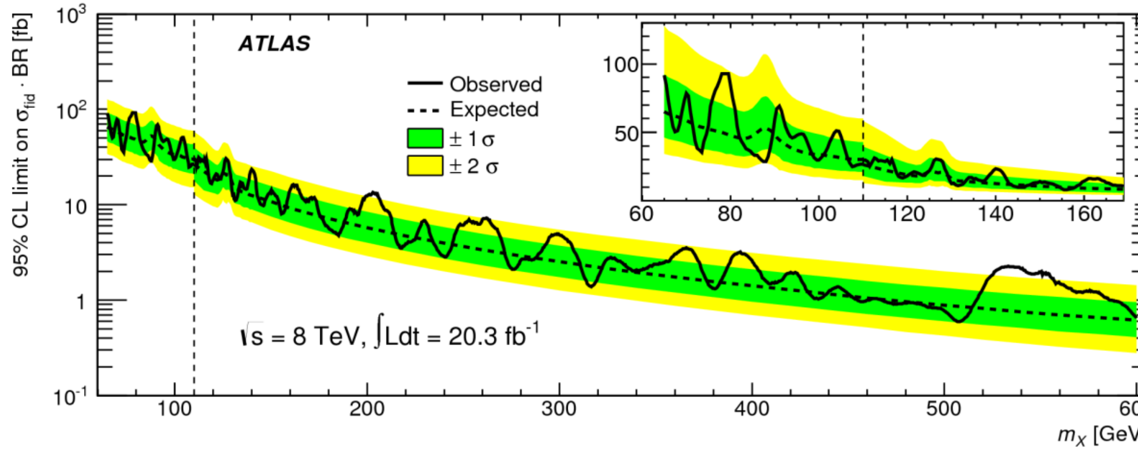
Z->ee as background



h(125)->γγ as background



Result: limit on σ x BR in fiducial volume



Is it sensitive to Higgs Singlet Extension of the SM ?

From talk of Tania Robens at SUSY 2014

What about the "inverse" scenario, ie. $m_H = 125.7$ GeV

mainly ruled out by LEP and/ or χ^2 fit from HiggsSignals
however, *still* large number produced due to large $\sigma_{gg \to h}$

m_h[GeV]	$\lvert\sin\alpha\rvert_{\text{min, exp}}$	$\lvert\sin\alpha\rvert_{\text{min, }2\sigma}$	$(\tan\beta)_{\max}$	$\#gg \sim$
110	0.82	0.89	9.2	10^5
100	0.86	−−	10.1	10^5
90	0.91	−−	11.2	10^5
80	0.98	−−	12.6	10^4
70	0.99	−−	14.4	10^4
60	0.98	$\gtrsim$ 0.99	16.8	10^4

σ x BR = $(1-\sin^2\alpha)\sigma_{SM}$ x BR_{SM} < 12.2 fb at 100 GeV

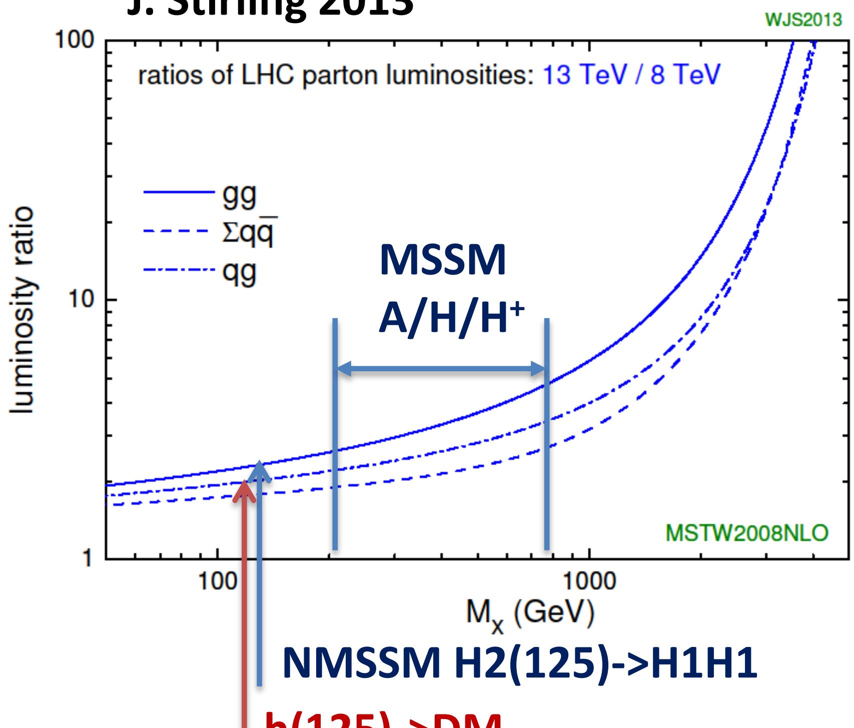
Prospects for 2015-2016

- **No immediate discovery for Higgs-Exotics channels with first 5-10 fb^{-1} in 2015 is expected so far:**

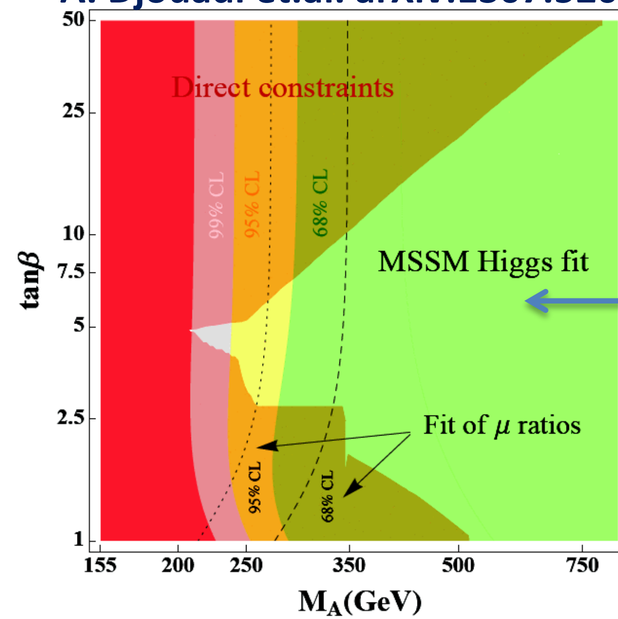
  rare processes, need luminosity

  – with ~ 5-10 fb^{-1} at 13 TeV expect to reach 8 TeV/20 fb^{-1} sensitivity of current 8 TeV analyses and start to explore a new territory

J. Stirling 2013



A. Djouadi et.al. arXiv:1307.5205



Conclusions

- Very reach physics program for BSM Higgs boson searches at LHC
- We expect to have a second discovery in the Higgs sector during LHC or HL-LHC operation

THE END

$t\bar{t} \to bWbH^+$, $H^+ \to cs$, $m_{H+} < m_t$

- **Search strategy:**
  - trigger with muon from $t \to Wb \to \mu\nu b$ decay
  - search for bump in di-jet mass distribution for jets from 2nd top decay
  - kinematic fit with top mass constraint