Searches for light BSM higgs bosons at the LHC

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RAL

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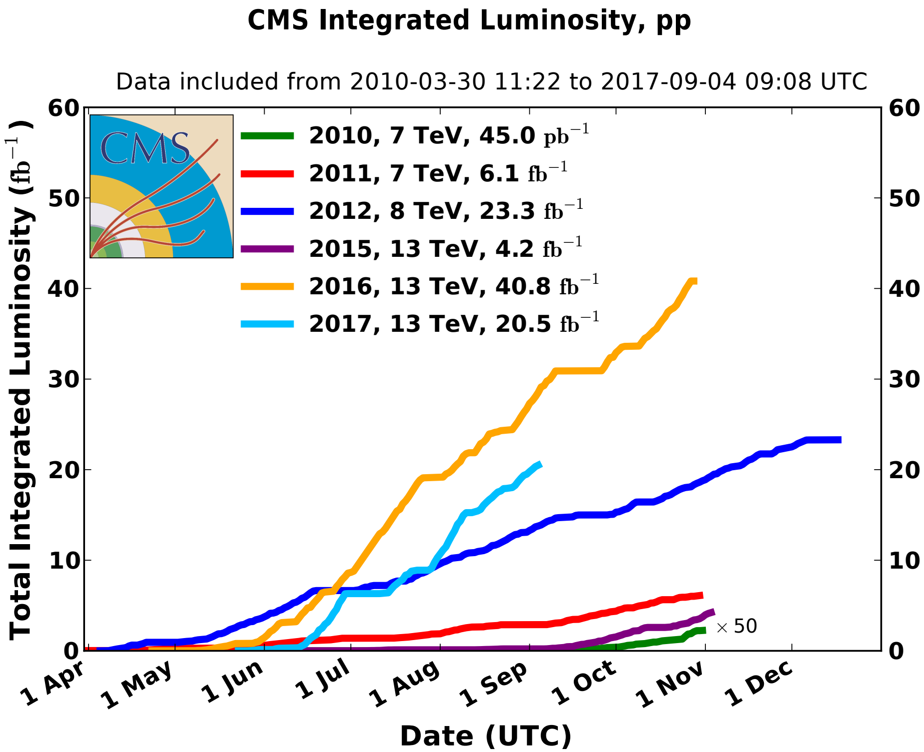
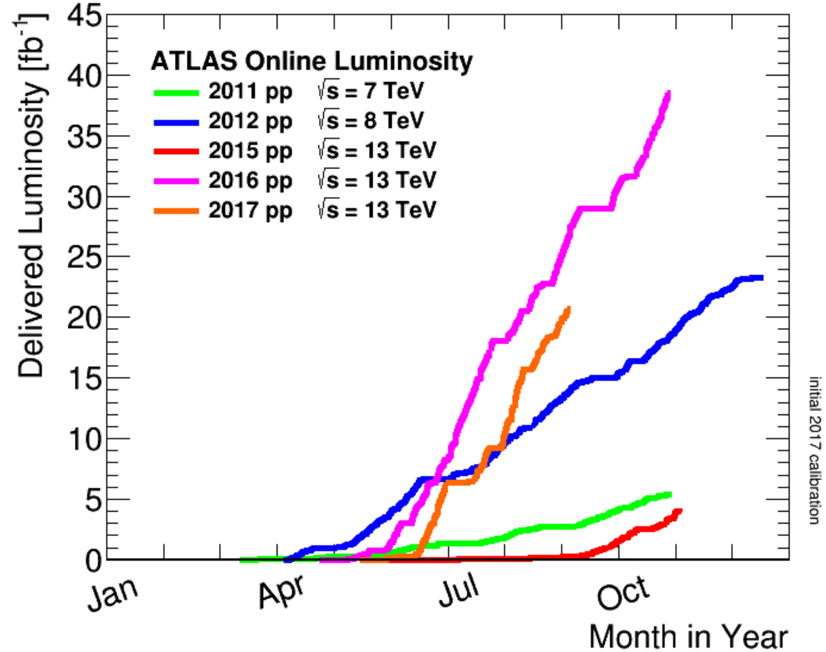
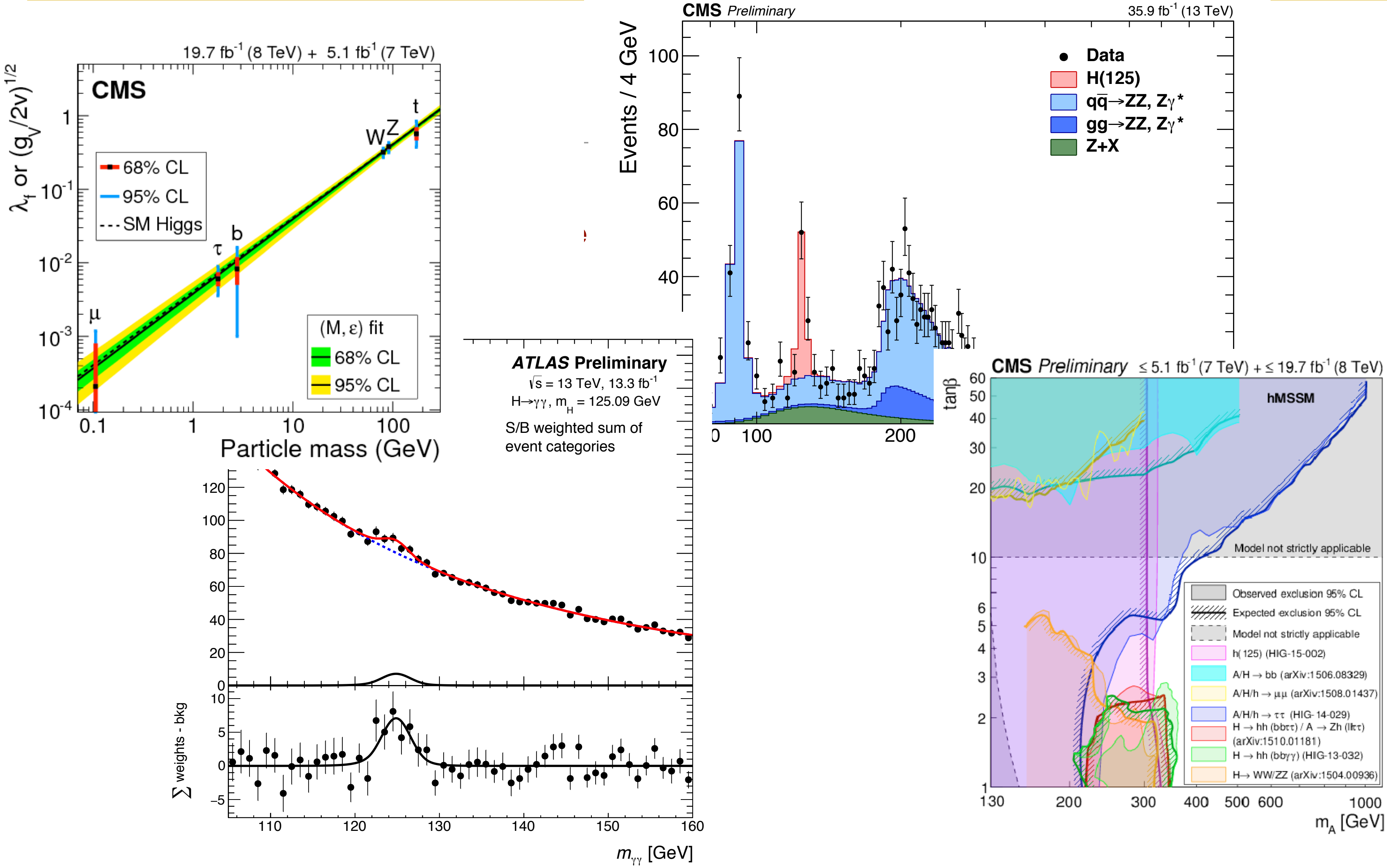
LHC Integrated Luminosities





Analyses discussed here mainly use 8 TeV data. 13 TeV to come.

Observed Higgs



Where do we stand with 125 boson

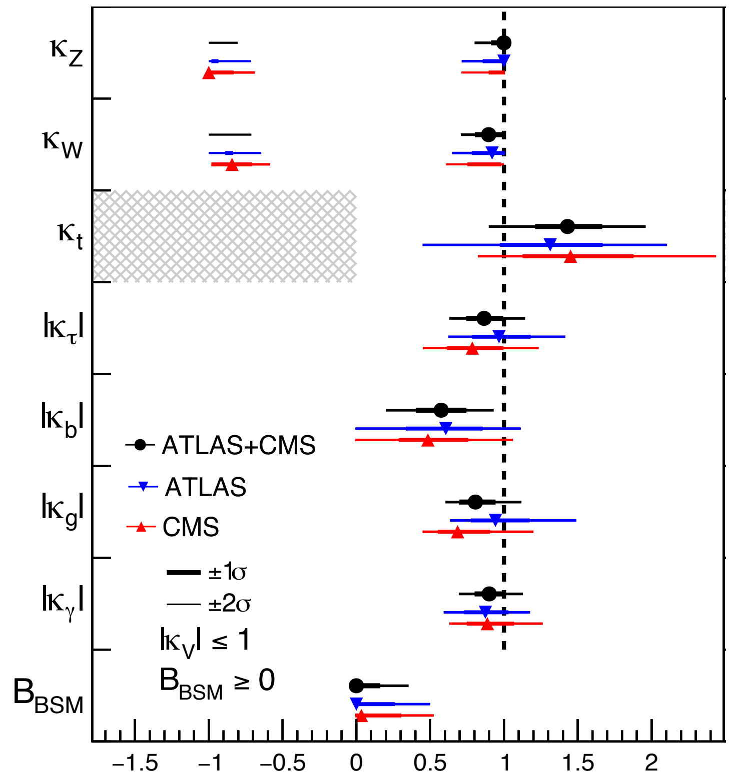
JHEP 08 (2016) 045

Best fit set of κ ($\kappa_j^2 = \sigma_j/\sigma_j^{SM}$) where BR to BSM decays (B_{BSM}) is allowed to be non-zero.

Combination of ATLAS and CMS data at 7 and 8 TeV

B_{BSM} = 0.34 at 95% CL

Room for new physics to exist



Higgs sector in BSM models

- Have found 1 Higgs so look for more
- SUSY models include extended Higgs sectors.
  - In the MSSM all extra Higgses are heavier than the SM-like H.
  - Heavier Higgses have decay patterns covered by searches used for discovery of existing Higgs.
- Beyond simplest SUSY model (MSSM) Higgs sectors can be expanded.
- Higgses lighter than the discovered Higgs can exist within such models

MSSM → NMSSM

MSSM: two higgs doublets

$$\hat{H}_d = \begin{pmatrix} \hat{H}_d^0 \\ \hat{H}_d^- \end{pmatrix}, \quad \hat{H}_u = \begin{pmatrix} \hat{H}_u^+ \\ \hat{H}_u^0 \end{pmatrix}$$

H_d couples to down type quarks and leptons

H_u couples to up type quarks

5 physical Higgs states h, H, A, $H^{+/-}$

M_A, $\tan\beta$ describe parameter space

NMSSM: two Higgs doublets and new Higgs singlet superfield S

- New scalar and pseudoscaler Higgs bosons & new higgsino
- Solves μ-problem

MSSM → NMSSM

MSSM superpotential

$$\mathcal{W}_{\text{MSSM}} = \mu \hat{H}_u \hat{H}_d + \mathcal{W}_{\text{Yukawa}}$$

The μ problem

μ is parameter with dimensions of mass and no a priori link to EWK scale

Natural values 0 or M_{Planck}. Require at EWK/SUSY scale.

NMSSM Introduce additional Singlet superfield to superpotential

$$\mathcal{W}_{\text{NMSSM}} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + \mathcal{W}_{\text{Yukawa}}$$

Effective μ term generated by dynamical symmetry breaking

S develops a non-zero vacuum expectation value

$$\lambda S H_u H_d \longrightarrow \lambda \langle S \rangle H_u H_d = \mu_{\text{eff}} H_u H_d$$

$$\mu = \lambda \langle S \rangle$$

λ dimensionless - scale invariant

NMSSM Higgs Sector

Higgs sector now has 7 particles

$h_{1,2,3}$ 3 neutral scalars. SM-like Higgs can be $h_{1,2}$

$a_{1,2}$ 2 pseudoscalars

$h^{+/-}$ Charged Higgses

λ	couplings to other Higgs [if $\lambda = 0$, new states decouple]
κ	contributes mass to new Higgs
A_λ, A_κ	associated soft SuSy-breaking parameters
$\langle S \rangle$, $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$	vacuum-expectation-values

Higgs sector now described by 6 parameters as opposed to 2 (M_A, $\tan\beta$) in MSSM

Lightest scalar and pseudoscalar can have large singlet component and hence evade exclusion limits from earlier searches (e.g. LEP)

nMSSM

$$W_{\mathrm{NMSSM}} \supset \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

Z_3 symmetry

$$W_{\mathrm{nMSSM}} \supset \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \xi_F \widehat{S}$$

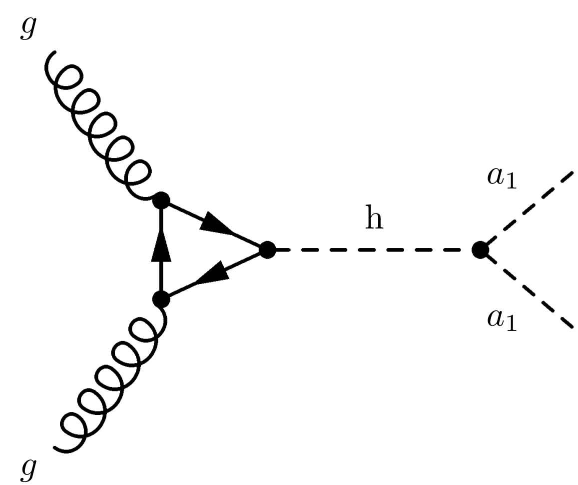
Discrete R-symmetry

- No mass term for singlino.
- LSP has large singlino component hence naturally light.
- Relic abundance fixed by annihilation through a_1
- Different phenomenology.

$H_{125} \rightarrow a_1 a_1$ decays

- Lightest Higgs does not have to be observed Higgs
- $H \rightarrow hh$ (scalar or pseudoscaler) possible in many models
  - In general pseudoscaler more potential hence label a_1 in slides.
- Possible a_1 decay modes and BR depend on mass

  - $H \rightarrow a_1 a_1 \rightarrow bbbb$
  - $H \rightarrow a_1 a_1 \rightarrow bb\tau\tau$
  - $H \rightarrow a_1 a_1 \rightarrow \tau\tau\tau\tau$
  - $H \rightarrow a_1 a_1 \rightarrow bb\mu\mu$
  - $H \rightarrow a_1 a_1 \rightarrow \tau\tau\mu\mu$
  - $H \rightarrow a_1 a_1 \rightarrow \mu\mu\mu\mu$



Note analyses only rely on masses and kinematics not type of higgs

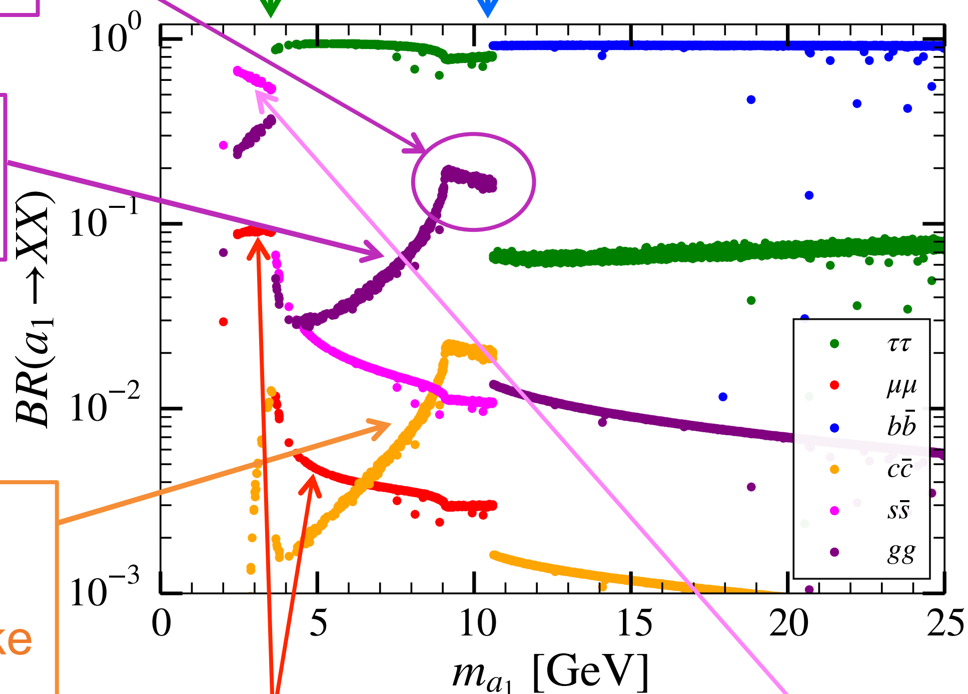
Branching Ratios for a_1 - NMSSM

b quark pole mass
≠ B meson mass

$\tau\tau$ threshold

bb threshold = 2 B meson mass

$a_1 \rightarrow gg$ dominated
by b quark loop



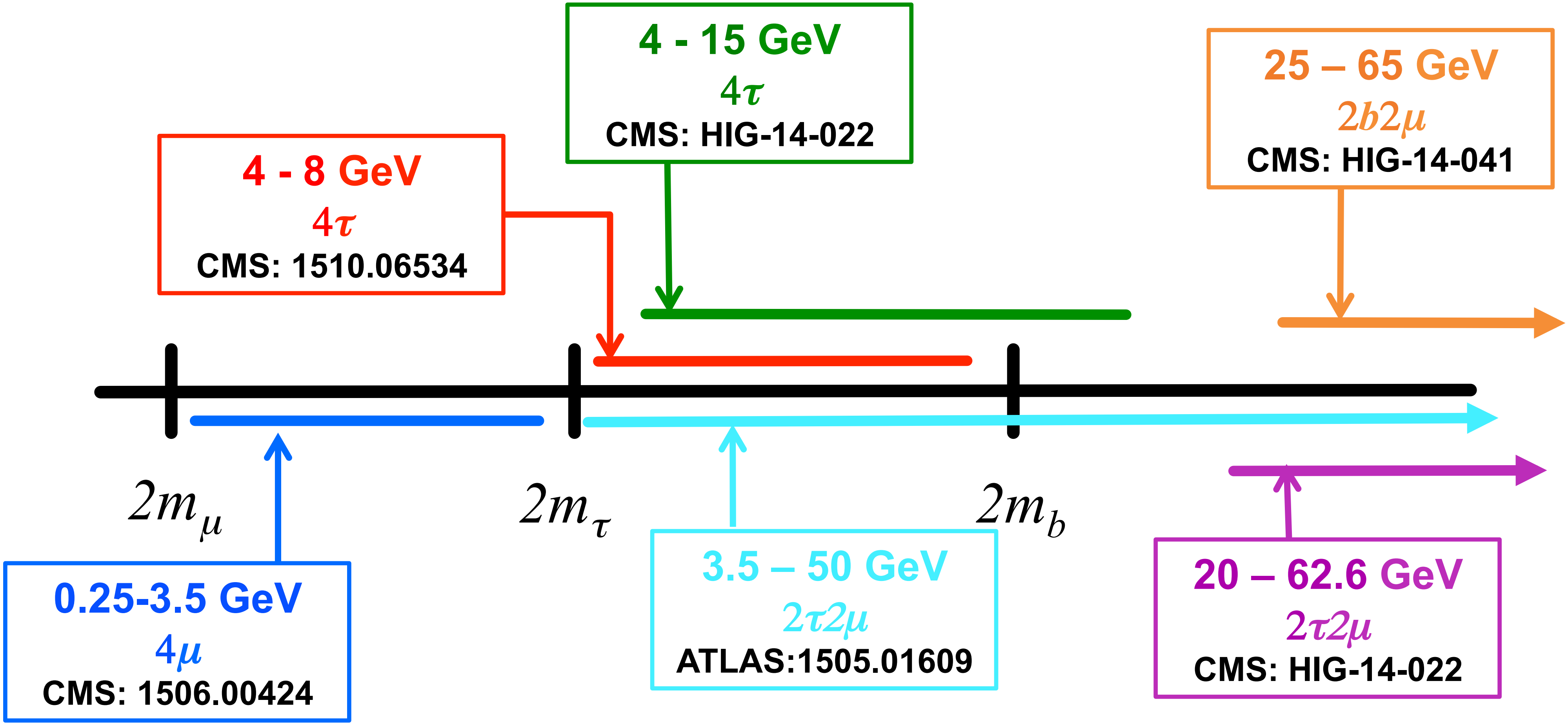
Plot produced using NMSSMTools

$a_1 \rightarrow gg^* \rightarrow gcc$ dominant mode. Hence behaves like gg mode

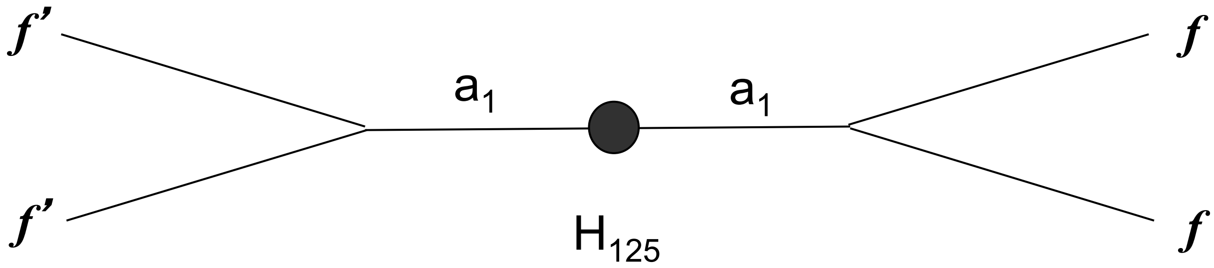
$\mu\mu$ final state

ss dominant below $\tau\tau$ threshold
favoured over $\mu\mu$ by colour factor

Mass ranges for analyses ($H \to a_1 a_1$ only)



Analysis Characteristics

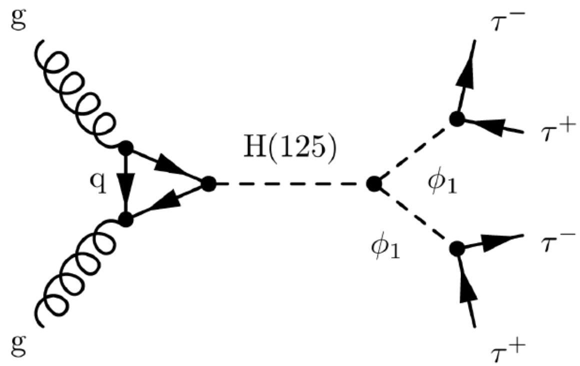


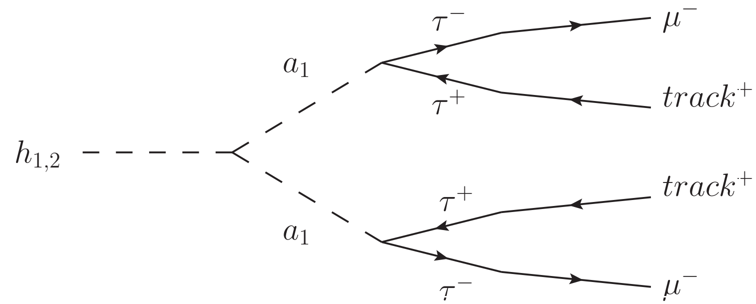
$$\Delta R \sim \frac{2m_a}{p_T^a} \sim \frac{4m_a}{m_H}$$

For large mass differences between H and a_1 decay products can be very boosted

m_a < 10 GeV	m_a ~ 10 – 15 GeV	m_a > 20 GeV
Boosted Techniques	Intermediate region a challenge	Standard techniques

CMS Four tau analyses



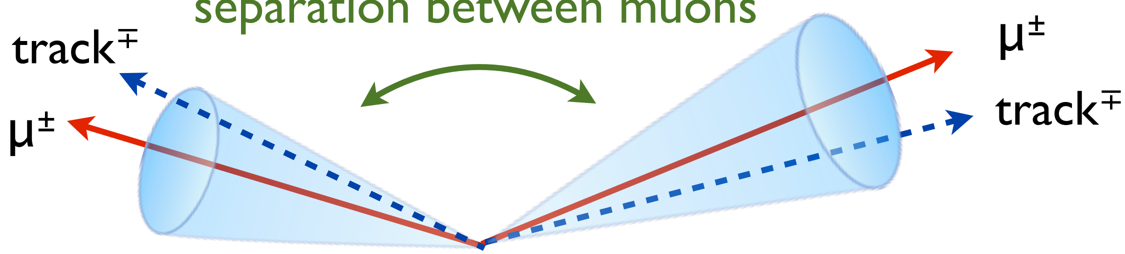


$m_h >> m_{a1} \rightarrow a_1$ boosted, tau pair highly collimated

Look for 1 track close to mu (opposite-charge)

$h_{1,2}$ has low $p_T \rightarrow$ large separation between muons

Same-charge muons to remove BGs

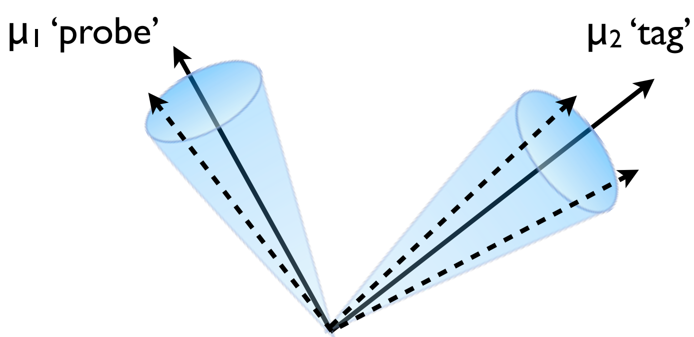


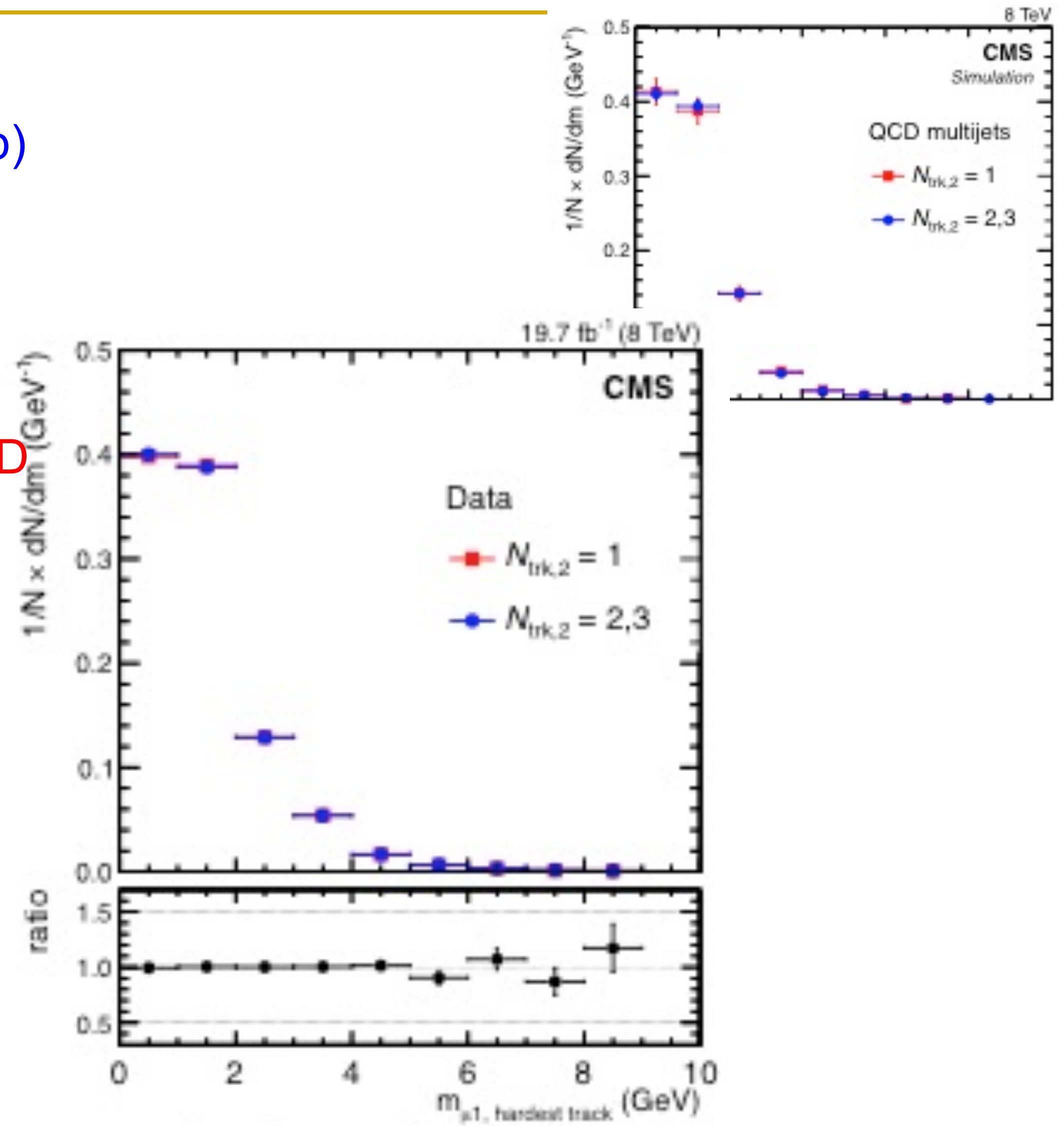
Enabling this analysis required a trigger modification to allow non-isolated muons

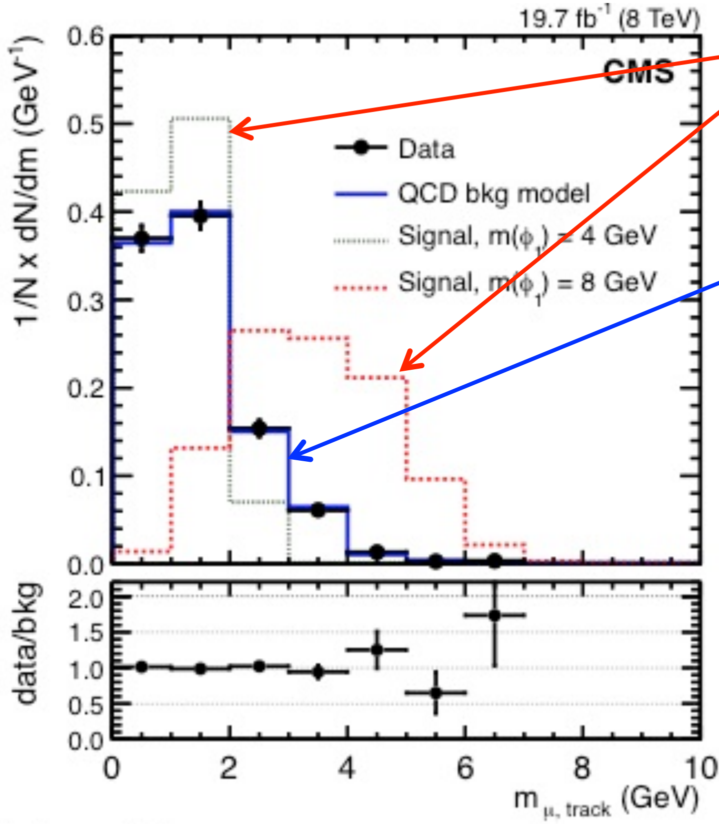
Background estimation 4τ channel

Dominant background is QCD (mostly bb)

- Tag as QCD by allowing more tracks around "tag" muon (μ_2).
- Use mass μ_1 + track to determine QCD mass distribution
- Assumes 2 masses uncorrelated

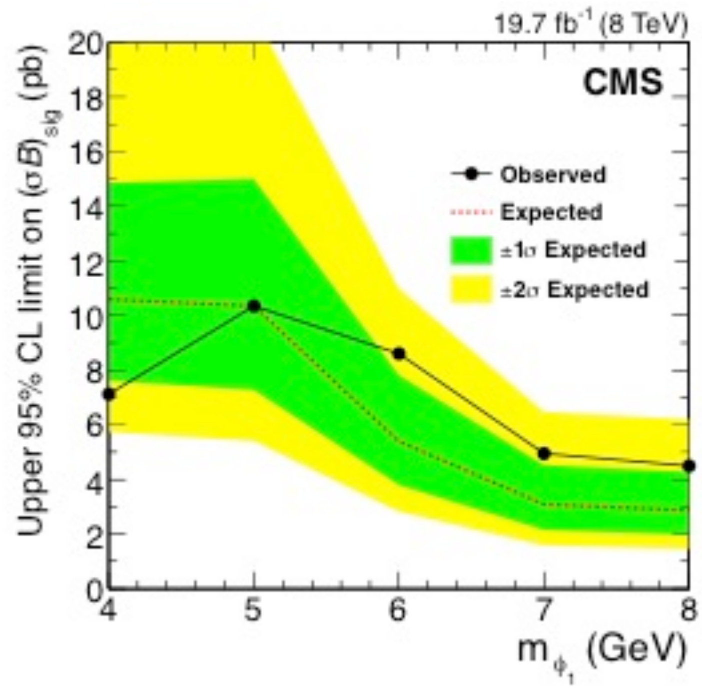






Signal mass (μ + trk) function of mass

Background determined from data



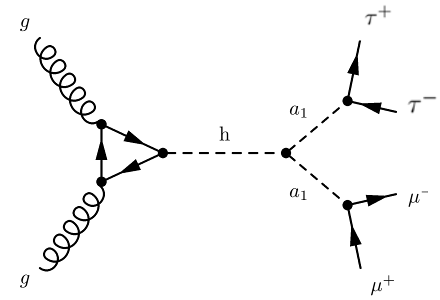
No evidence of a signal.

Dataset 19.7 fb^{-1} 8 TeV CMS

CMS 2μ 2τ analysis

Combinations

$\mu\mu\tau_e\tau_e$, $\mu\mu\tau_e\tau_\mu$, $\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$, $\mu\mu\tau_h\tau_h$



Use μμ for good mass resolution & hence background rejection.

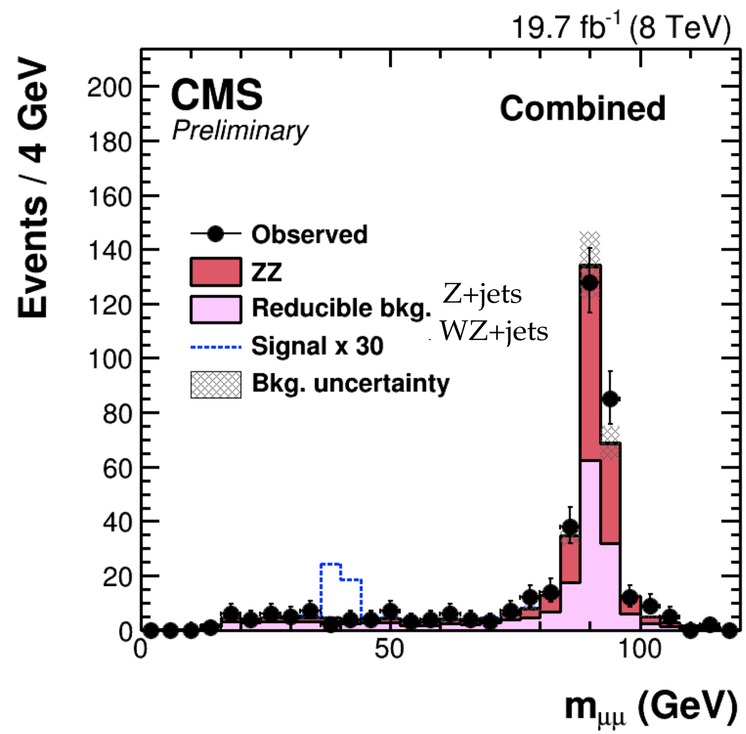
Mass range 20 – 62.5 GeV ($M_H/2$)

Above 20 GeV little boost.

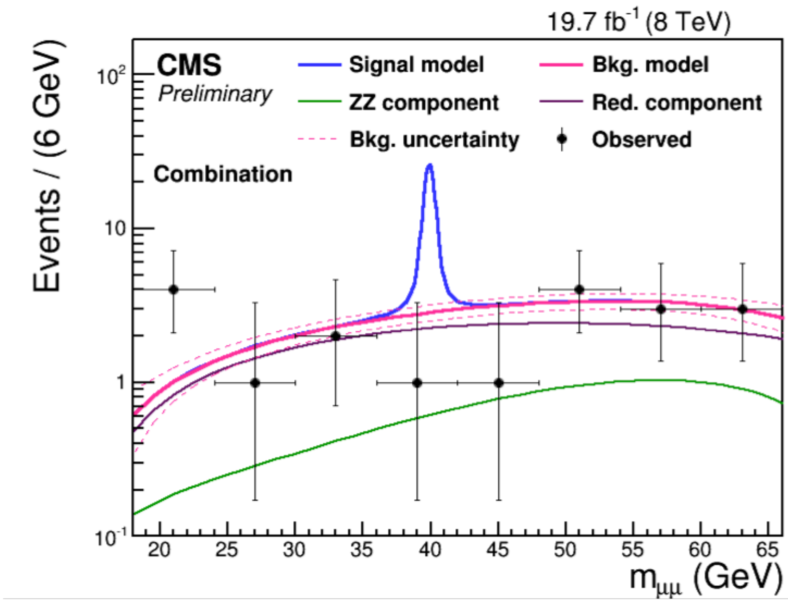
→ All separated by at least ΔR = 0.4

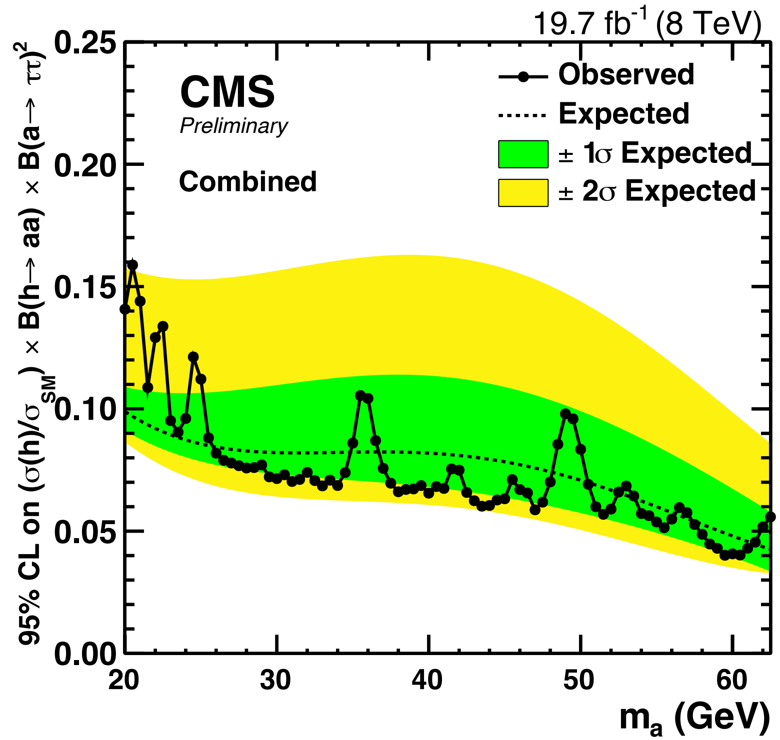
→ Use standard hadronic tau reco

Use b-tag veto to remove top bg.



CMS 2μ 2τ analysis



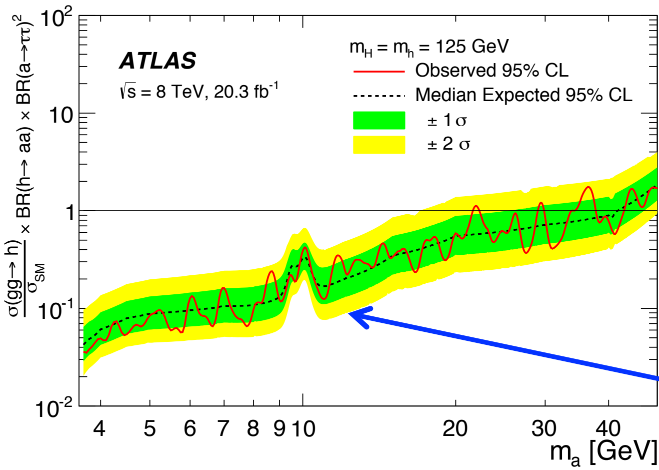


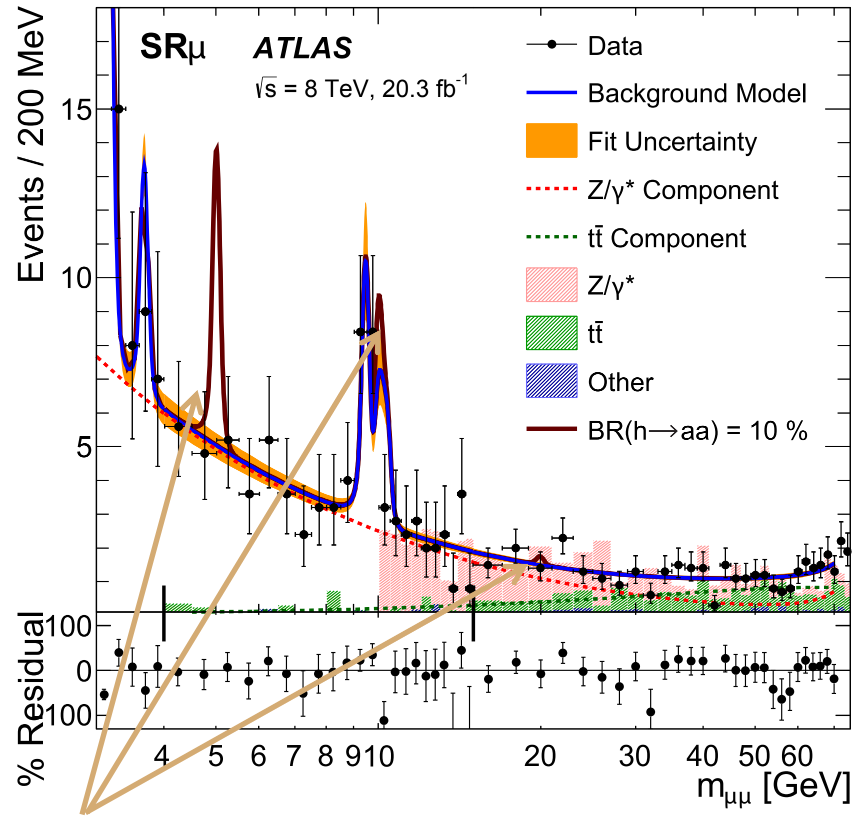
ATLAS μμττ

Search range 3.5 – 50 GeV.
Optimized for < 10 GeV.

a → μμ trades trigger efficiency
and signal/background for cross section.

One τ → e or μ other τ → 1-3 trks.
Use to select events only. Overcomes
issue of boost at low m_a.





Signal examples

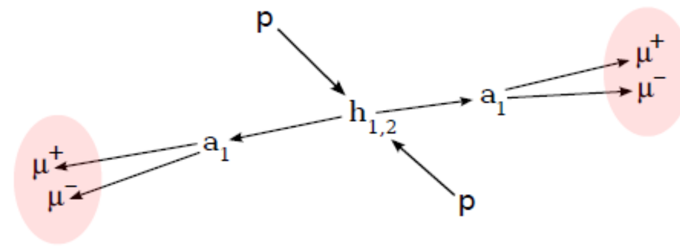
$+\ \tau \rightarrow \mu$

Resonant background $J/\psi, \psi', \Upsilon_{1S}, \Upsilon_{2S}, \Upsilon_{3S}, Z$

~ 3 GeV ~10 GeV

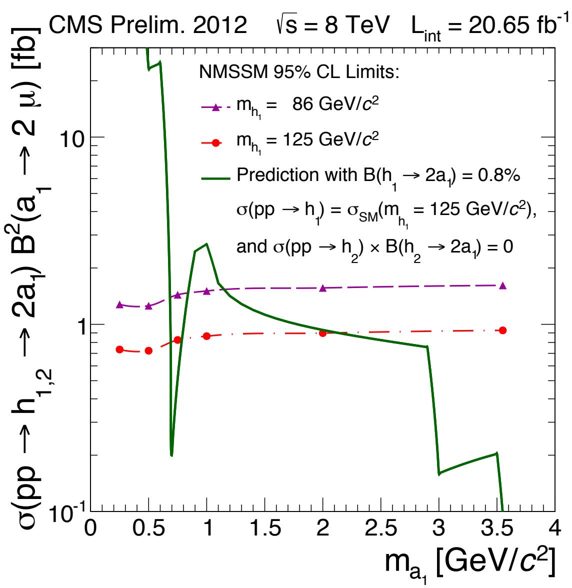
CMS $H_{125} \rightarrow a_1 a_1 \rightarrow 4\mu$

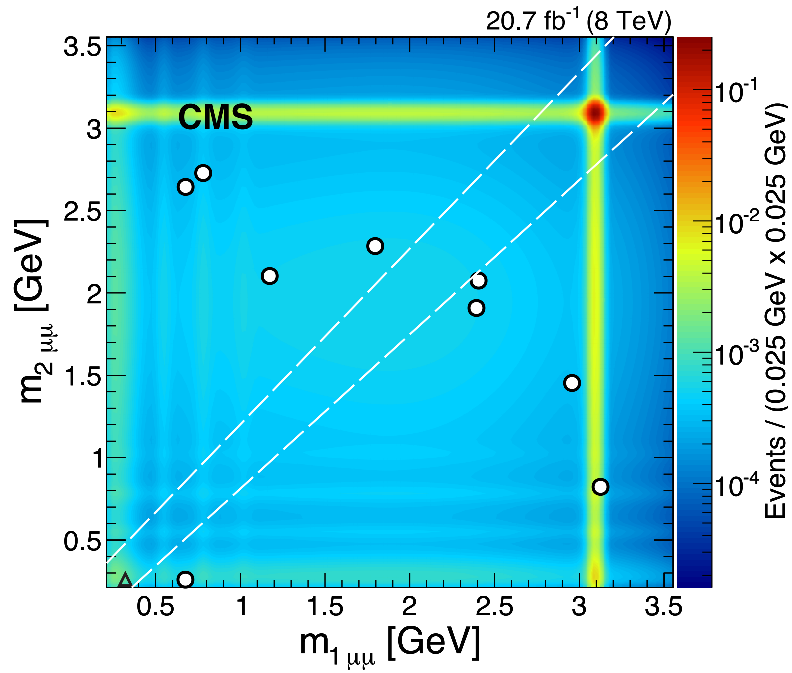
BR to μ large for $2m_\mu < m_{a_1} < 2m_\tau$



μ are very boosted. Isolation criteria take this into account

For 8 TeV dataset 1 event observed
2.7 expected





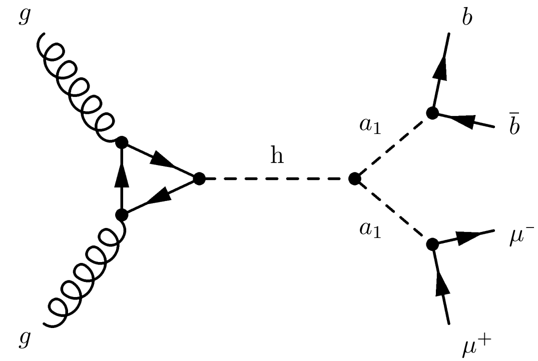
CMS H→a_1a_1→ 2b2μ

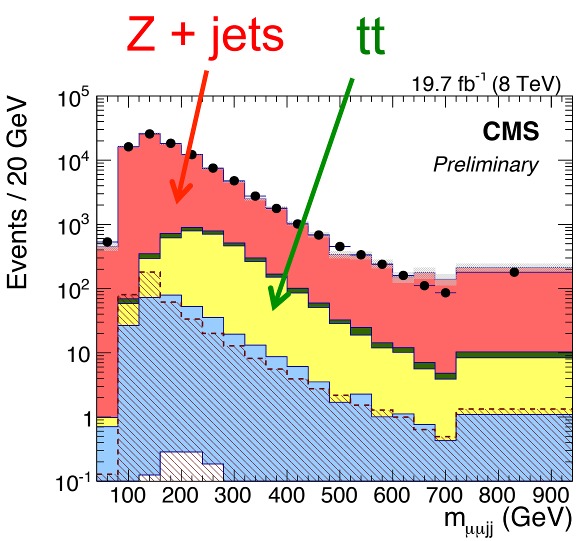
Above $2m_b$ threshold bb dominant.

2μ used to suppress bg. (4b alone v. large bg)

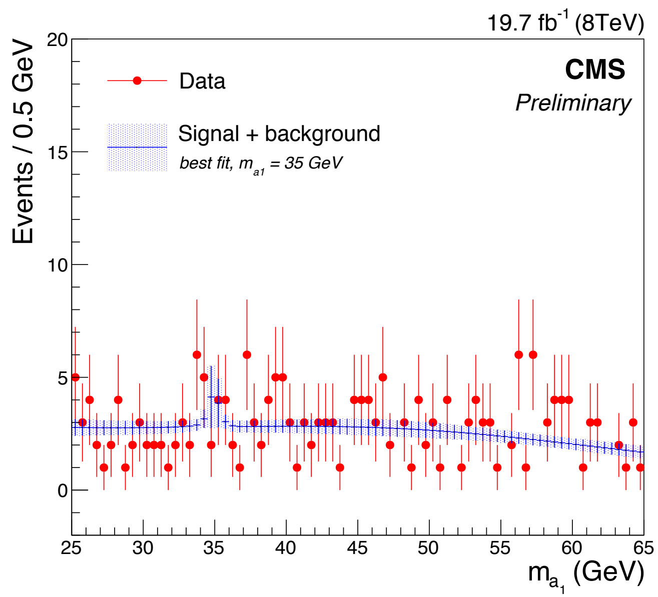
Mass range 25-65 GeV (no boost issues)

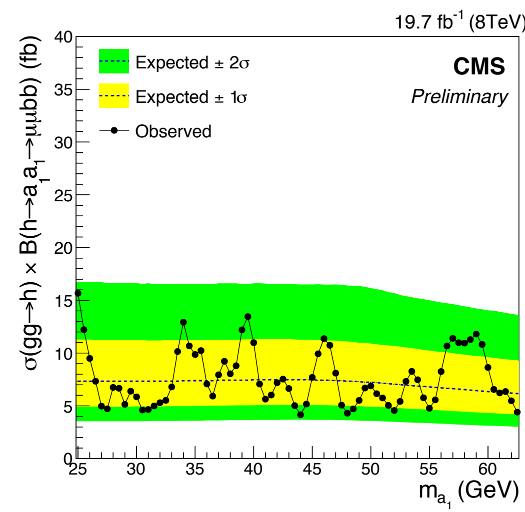
Use 4 body mass constraint $|m_{\mu\mu bb} - 125| < 25\,\mathrm{GeV}$





m(μμjj)





What is full picture?

- Number of searches for light higgses covering range ~ 0.3 – 60 GeV.
- Bring all of this information together to see how models space constrained for generic 2HDM, NMSSM and nMSSM.
- Paper **JHEP 1702 (2017)** Robin Aggleton (Rutherford & Bristol U. & Southampton U.) , Daniele Barducci (Annecy, LAPTH) , Nils-Erik Bomark (Adger U. Coll., Kristiansand) , Stefano Moretti (Rutherford & Southampton U.) , Claire Shepherd-Themistocleous (Rutherford)

Methodology

- Scan over model parameter spaces to determine total cross section for production and decay chain
- Applying existing experimental constraints
- Compare results of searches to parameter space allowed before the search.

Scans over parameter spaces

A variety of public tools used

- NMSSMTools
  - Provides mass spectra, couplings BR.
  - Will compare particular point in parameter space to previously existing experimental limits using Lilith database.
  - Dark matter relic abundance from micrOMEGA.
- 2HDMC (Two Higgs Doublet model calculator)
  - Higgs masses, couplings, BR
- HiggsBounds & HiggsSignals
  - Given input from above will impose experimental constraints

Experimental constraints

Constraints implemented through NMSSMTools, HiggsBounds and HiggsSignals

- Higgs signal measurements from LHC, LEP, Tevatron
  - Measurements on 125 GeV SM-like Higs
  - Limits from other searches.
- Flavour constraints LHC, Belle, BaBar (MultiNest, SuperIso)
- g-2 (muon anomalous magnetic moment) ($\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$)
- Dark Matter relic density abundance. (micrOMEGAs)

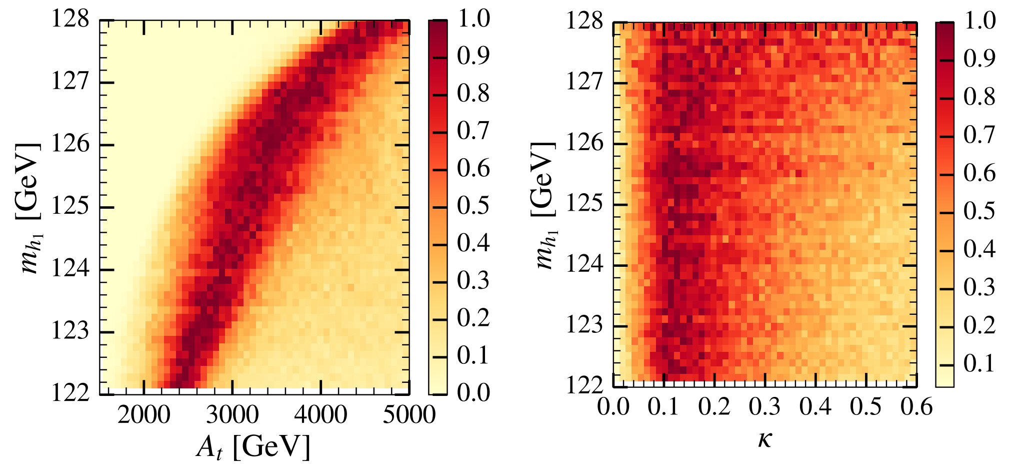
Relaxed set of constraints: $\Delta a_\mu > 0$, $\Omega_{DM} h^2 < 0.131$ and R(D), R(D*) constraints ignored

Parameter Scan Method

Each scan point is defined by choosing a random value for each model parameter within constrained ranges.

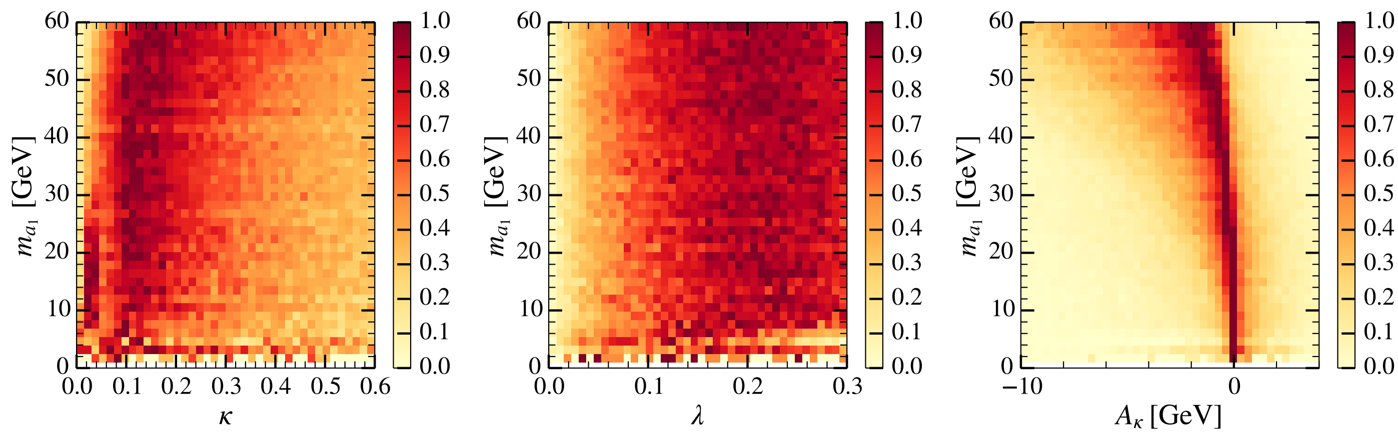
Dependence of observables of interest on model parameter varies considerably.

Example results impose constraints

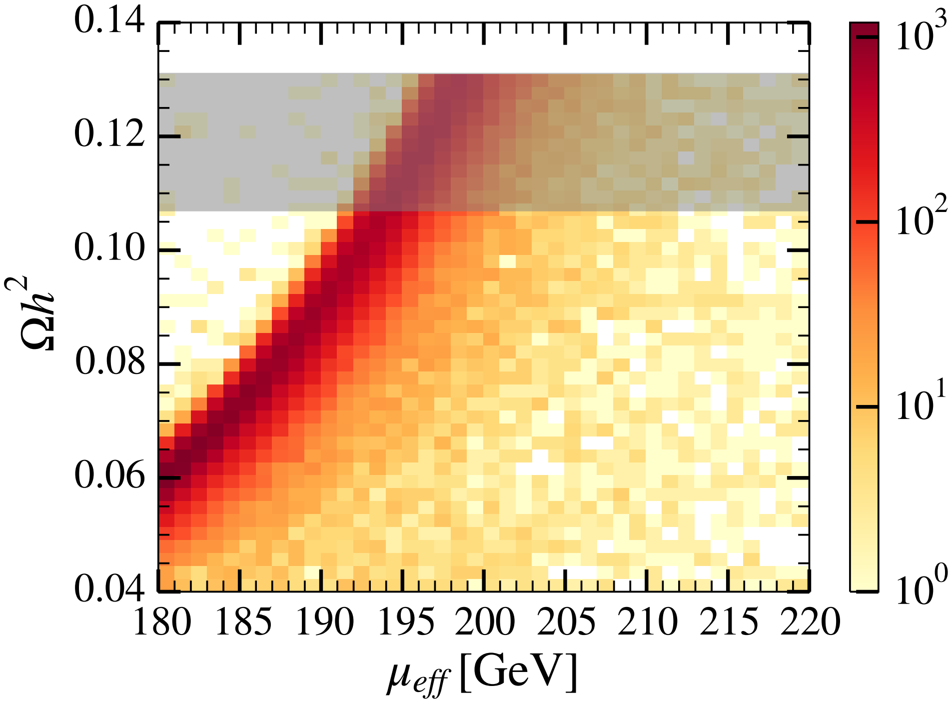


Examples of $m(h_1)$ dependence on NMSSM params (A_t, κ)

Examples of $m(a_1)$ dependence on NMSSM params



DM relic abundance wrt effective mu parameter



Scan Parameter Ranges - NMSSM

Parameter	Range
λ	0–0.3
κ	0–0.6
$\tan\beta$	10–30
μ_{eff}	180–220 GeV
A_λ	100–4000 GeV
A_κ	-10–4 GeV
A_t	1500–5000 GeV
A_b	500–2500 GeV

Parameter	Range
M_1	150 GeV
M_2	300 GeV
M_3	250–2500 GeV
$M_{U_1} = M_{U_2} = M_{U_3}$	500–2500 GeV
$M_{D_1} = M_{D_2} = M_{D_3}$	500–2500 GeV
$M_{Q_1} = M_{Q_2} = M_{Q_3}$	800–2500 GeV
$M_{E_{1/2/3}} = M_{L_{1/2/3}}$	1000 GeV
$A_{e/\mu/\tau}$	2500 GeV

NMSSM

parameters

at SUSY scale

Parameter	Extended range	Reduced range
m_0 (GeV)	200–2000	200–2000
$m_{1/2}$ (GeV)	100–2000	100–1000
A_0 (GeV)	−5000–5000	−3000–3000
μ_{eff} (GeV)	50–1000	100–200
$\tan\beta$	1–30	1–6
λ	0.01–0.7	0.4–0.7
κ	0.01–0.7	0.01–0.7
A_λ (GeV)	200–2000	200–1000
M_p (GeV)	3–140	3–140

GUT inspired NMSSM

scalar masses, trilinear couplings and gaugino masses common values at GUT scale

parameters at EWK scale

Scan Parameter Ranges 2HDM

$h = h_{125}$	
Parameter	Range
m_h	124–128 GeV
m_H	128–1000 GeV
m_A	3.5–40 GeV
$m_{H^\pm}$	128–1000 GeV
$\tan\beta$	0.5–50
m_{12}^2	10–10^5 GeV^2
$\lvert\sin(\beta-\alpha)\rvert$	0.9–1

$H = h_{125}$	
Parameter	Range
m_h	3.5–124 GeV
m_H	124–128 GeV
m_A	3.5–40 GeV
$m_{H^\pm}$	128–1000 GeV
$\tan\beta$	0.5–50
m_{12}^2	10–10^5 GeV^2
$\lvert\cos(\beta-\alpha)\rvert$	0.9–1

2HDM parameter ranges for h = h_{125} and H = h_{125}

TYPE I all SM fermions couple to 1 doublet

TYPE II down type quarks and leptons up type quarks to other doublet

Scan Parameter Ranges - nMSSM

JHEP01 (2016) 050 study of nMSSM with LHC run 1 constraints

One region compatible with light a_1 mass $m(a_1) \sim 2m(\chi_1^0)$

Sub-regions

1A small m_0 and $M_{1/2}$ both below 1 TeV

1B small $M_{1/2}$ large m_0

In these region the SM-like Higgs is the h_2

Region 1A	
Parameter	Range
$\tan\beta$	6.6–10
λ	0.33–0.53
μ	240–400 GeV
m_0	0–1080 GeV
$M_{1/2}$	630–1200 GeV
A_0	−1700–50 GeV
A_λ	1400–6000 GeV
ξ_F	10–100 GeV^2
ξ_S	-6×10^4–2×10^4 GeV^3

Region 1B	
Parameter	Range
$\tan\beta$	6–8
λ	0.49–0.52
μ	350–430 GeV
m_0	4040–4800 GeV
$M_{1/2}$	280–440 GeV
A_0	6700–7900 GeV
A_λ	7000–7900 GeV
ξ_F	-1.5×10^4—1.4×10^4 GeV^2
ξ_S	-1.9×10^7—1.6×10^7 GeV^3

Experimental Limit Relationships

Where measurements made in the same mass range but using different final states one can relate the limits through branching ratio relations

In all models considered all leptons and down-type quarks couple to the same doublet i.e. no tanβ dependence.

$$\frac{BR(a_1 \to \tau\tau)}{BR(a_1 \to \mu\mu)} = \frac{m_\tau^2 \beta(m_\tau, m_{a_1})}{m_\mu^2 \beta(m_\mu, m_{a_1})}$$

$$\beta(m_X, m_{a_1}) = \sqrt{1 - \left(\frac{2m_X}{m_{a_1}}\right)^2}$$

$$\frac{BR(a_1 \to \tau\tau)}{BR(a_1 \to b\bar{b})} = \frac{m_\tau^2 \beta(m_\tau, m_{a_1})}{3\bar{m}_b^2 \beta(\bar{m}_b, m_{a_1}) \times (1 + \Delta_{q\bar{q}} + \Delta_a^2)}$$

$$\Delta_{q\bar{q}} = 5.67\frac{\bar{\alpha}_s}{\pi} + (35.64 - 1.35N_f)\left(\frac{\bar{\alpha}_s}{\pi}\right)^2$$

$$\Delta_a^2 = \left(\frac{\bar{\alpha}_s}{\pi}\right)^2 \left(3.83 - \ln\frac{m_{a_1}^2}{m_t^2} + \frac{1}{6}\ln^2\frac{\bar{m}_q^2}{m_{a_1}^2}\right)$$

Radiative corrections

Cross Section

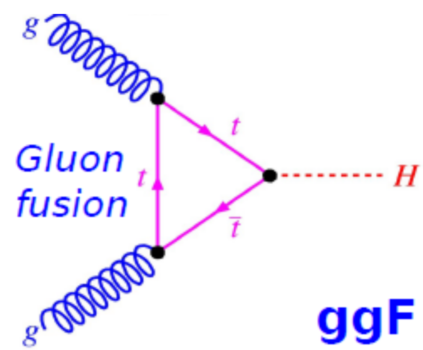
Total cross section for decay chain

$$\sigma \times BR(gg \to h \to 2a_1 \to 2X2Y) =$$
$$\sigma_{\rm SM}^{8\,\rm TeV}(ggh) \cdot g_{ggh}^2 \cdot BR(h \to 2a_1) \cdot BR(a_1 \to 2X) \cdot BR(a_1 \to 2Y) \cdot f$$

Reduced ggh coupling (1 in SM)

SM gluon fusion production cross-section

h_{125} can be either h_1 or h_2.

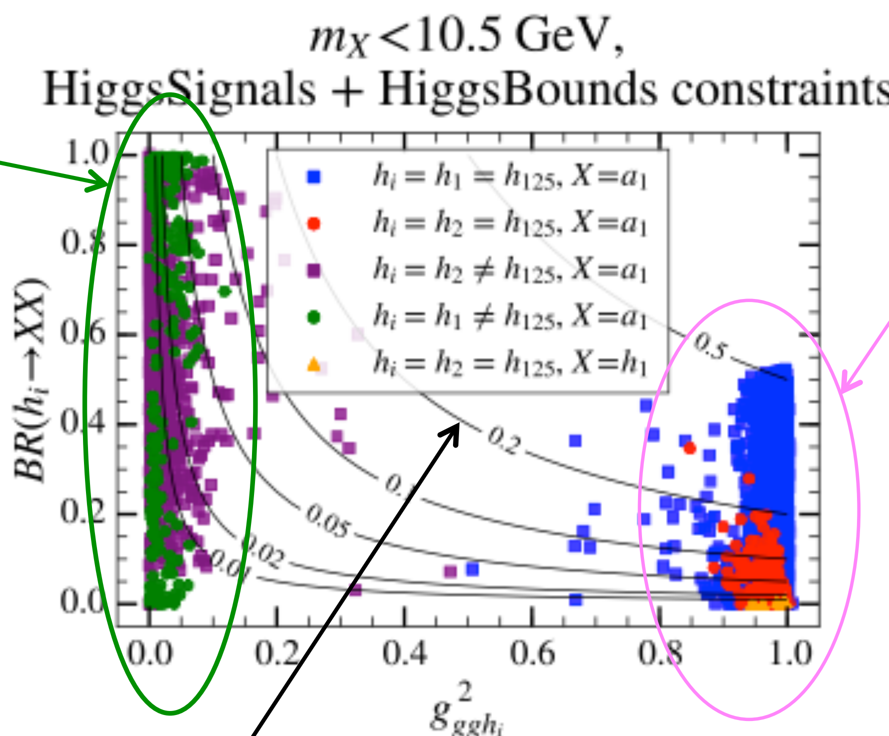


Scan results for h→XX BR

H → $a_1 a_1$

Heavier Higgs is NOT SM-like Higgs

Not observed so g_{ggh} small, but BR can be large



Contours constant g^2_{ggh}BR

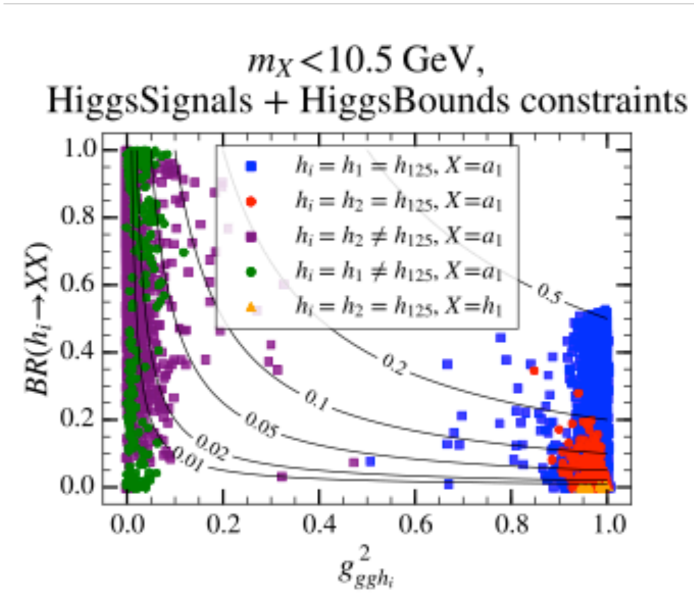
$h_{125} \to a_1 a_1$

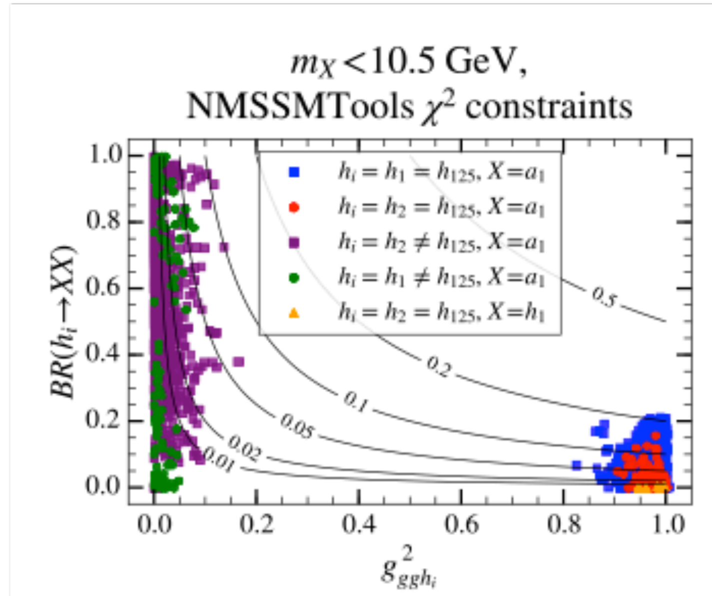
Heavier h is SM-like Higgs

Largest potential σBR

h_{125} can be either h_1 or h_2.

Comparison of constraint codes





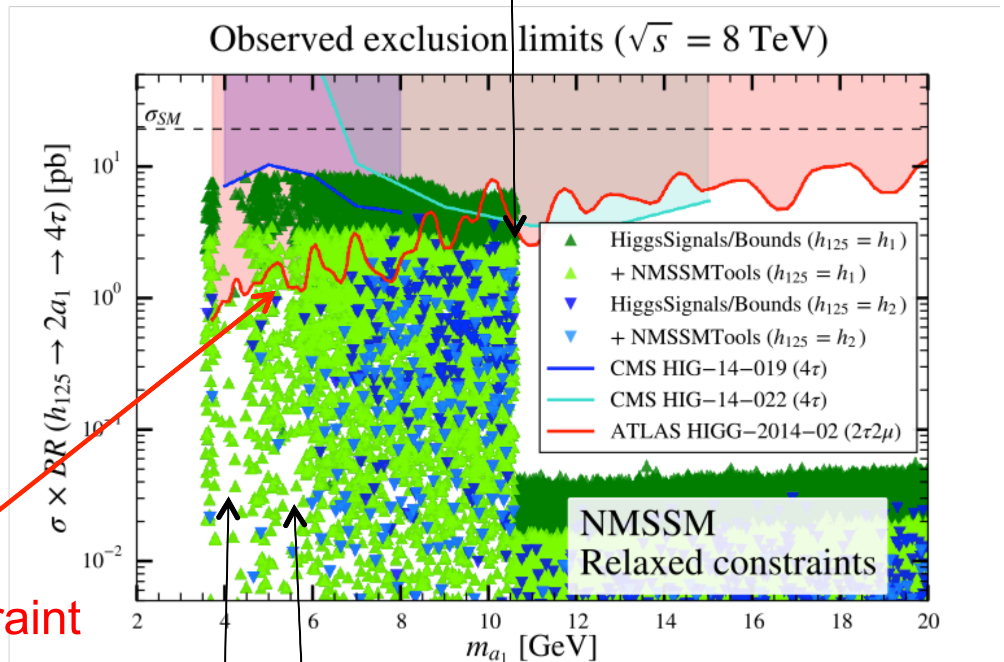
Difference between constraints from HiggsSignals + HiggsBounds and NMSSMTools.

Different methodologies for applying constraints (and some differences in exp. limits used)

H+H uses global χ^2 NMSSM χ^2 per channel

NMSSM

bb threshold



All results scaled to 4τ final state

ATLAS 2τ2μ significant constraint

Relaxed constraints used.

$\Delta a_\mu > 0$

$\Omega_{DM} h^2 < 0.131$

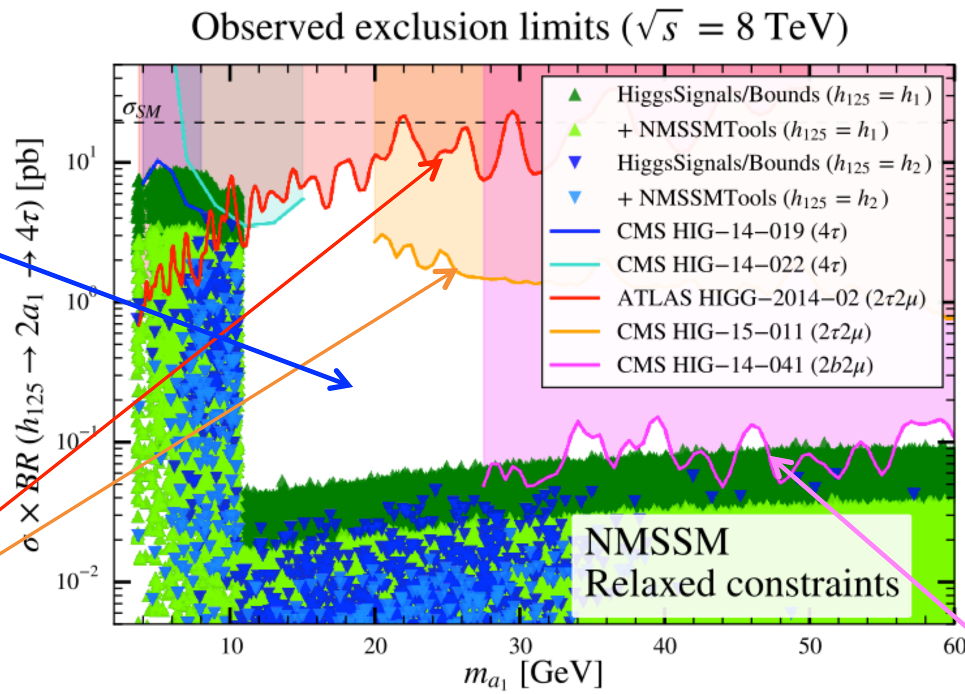
no R(D), R(D*)

Flavour constraints ($B \rightarrow X_s \mu\mu$ & $B_{s/d} \rightarrow \mu\mu$) exclude these regions

$h_{125} = h_1$ (green) larger cross sections than $h_{125} = h_2$ (blue)

Beyond bb threshold experimental results are not sensitive to allowed parameter space.

NMSSM

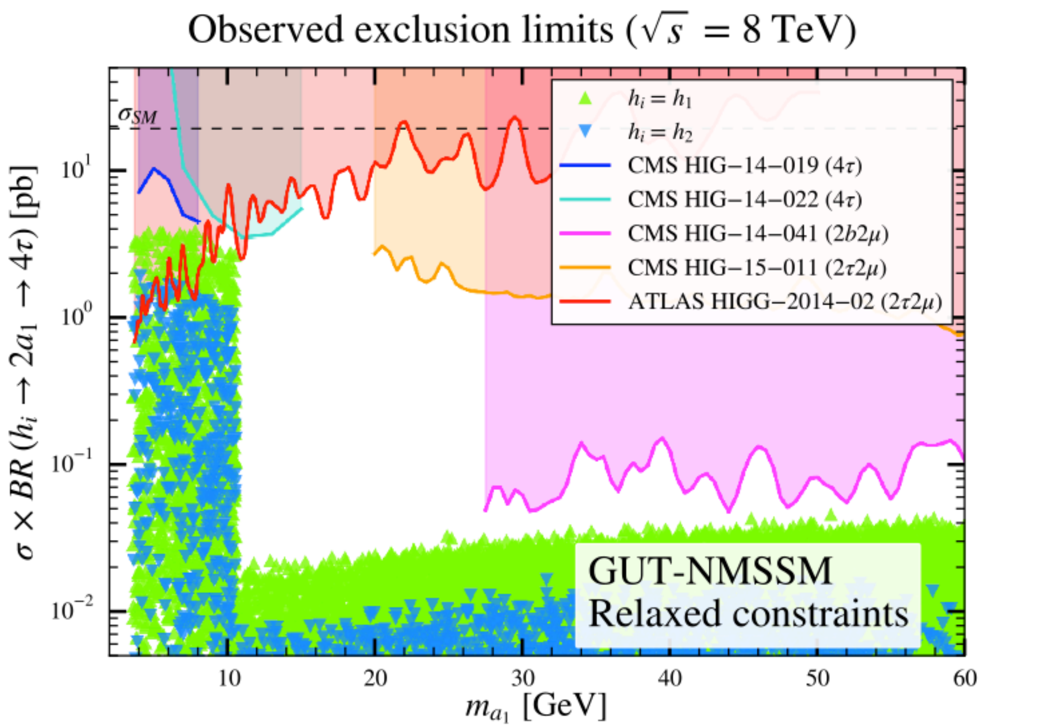


Current experimental results not sensitive enough

Different optimizations in ATLAS and CMS $2\tau2\mu$ searches give very different sensitivities at higher masses

$2b2\mu$ CMS analysis impact at higher masses

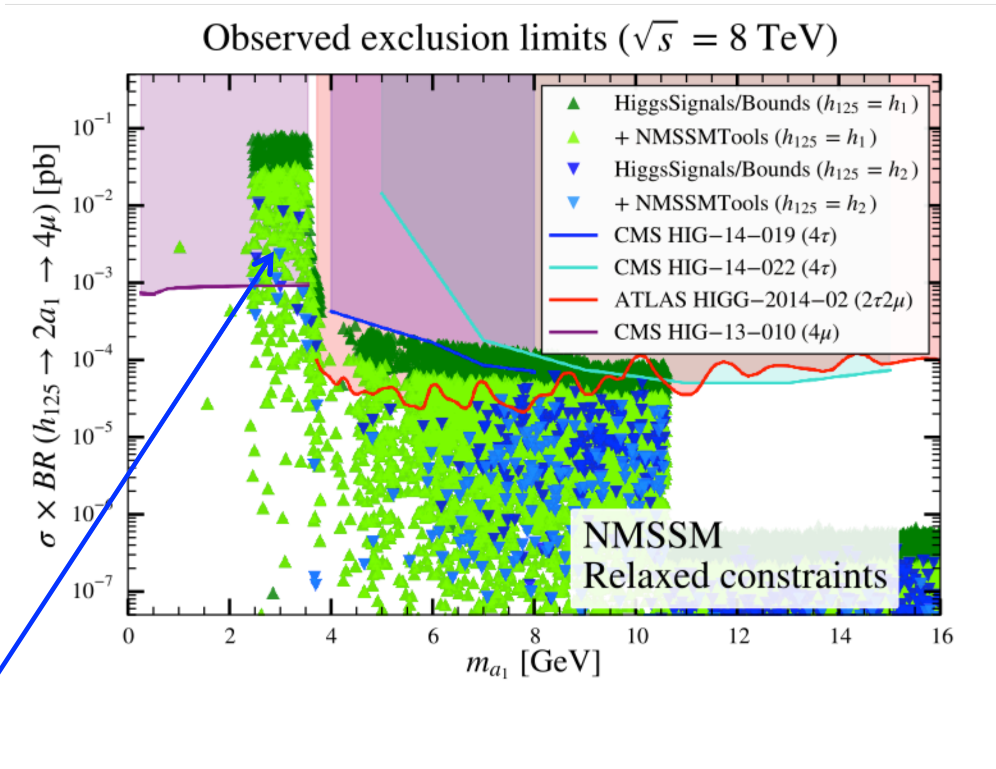
GUT-NMSSM



GUT constrained NMSSM similar to previous plots.

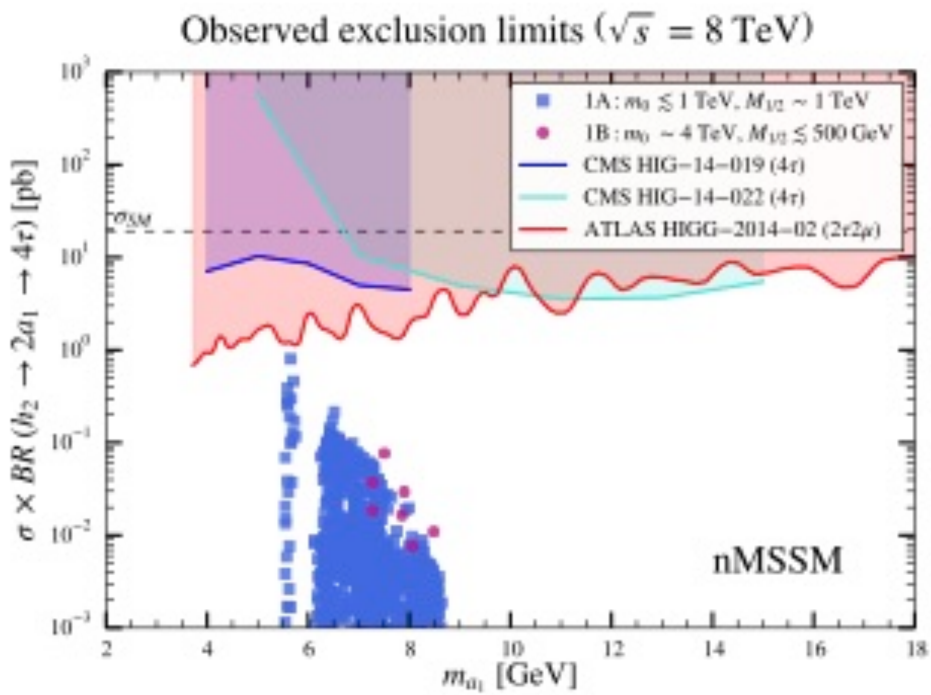
NMSSM – low masses 4μ results

All results scaled to 4μ final state



Significant model parameter exclusion

nMSSM



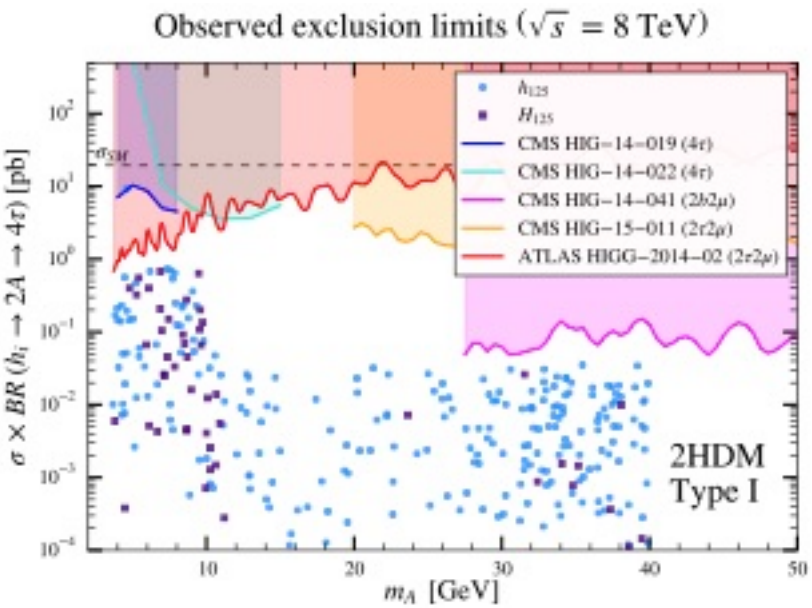
Very constrained mass range allowed

DM constraint. Lightest neutralino mass constrained to ~ 5 GeV
relic abundance fixed via annihilation through pseudoscalar a_1
$m(a_1) \sim 2m(\chi_1^0)$

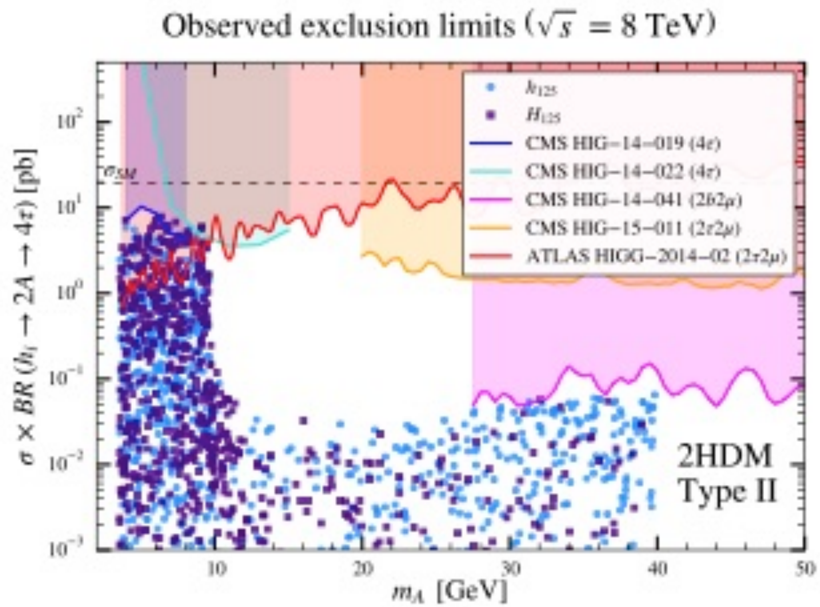
$a_1 \to \chi_1^0 \chi_1^0$ dominant decay channel

2HDM

TYPE I



TYPE II

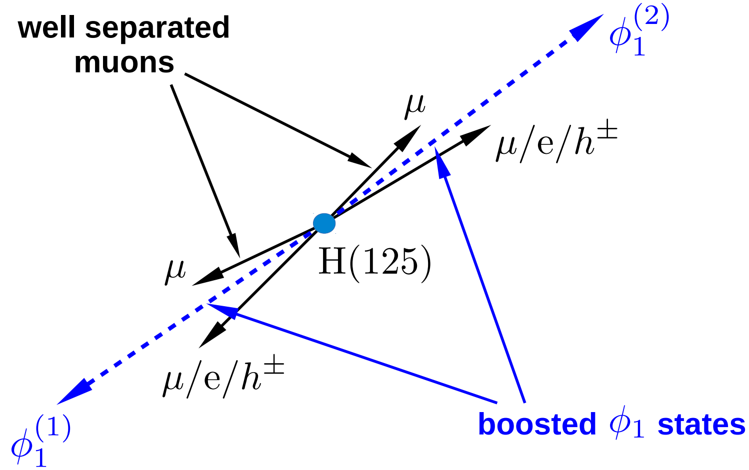


Type II 2HDM similar cross sections to NMSSM.

Conclusion

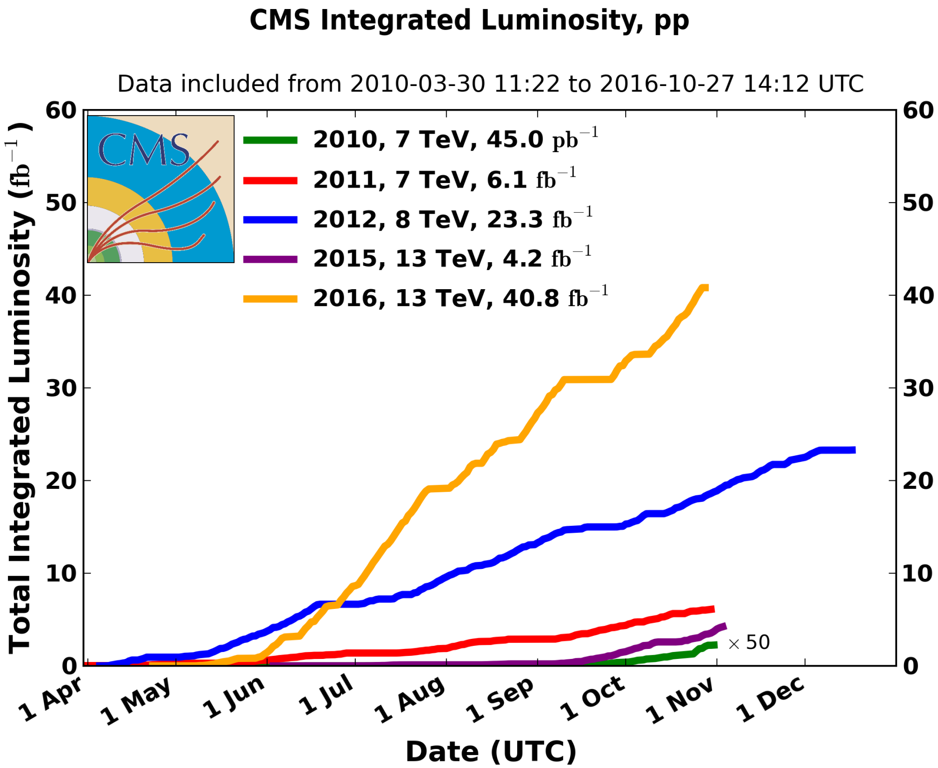
- LHC experiments performed a number of searches for light higgses
- Analyses often specialized for boosted light higgs
- Lack of evidence for such a particle in placing constraints on models beyond the MSSM with enlarged Higgs sectors
- Results for large 13 TeV data samples hopefully available soon.

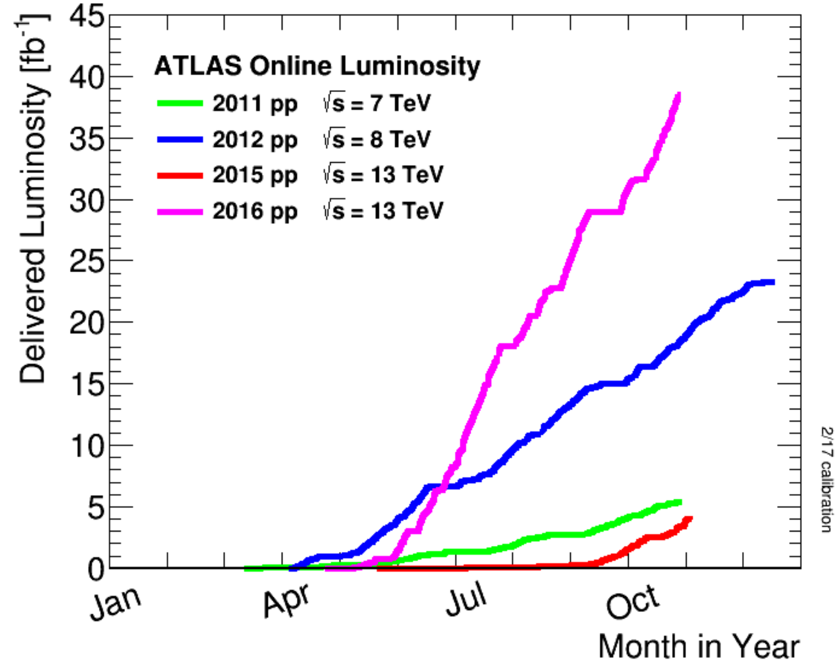
Summary


well separated
muons
μ
$\mu/\mathrm{e}/h^{\pm}$
$\phi_1^{(2)}$
H(125)
μ
$\mu/\mathrm{e}/h^{\pm}$
$\phi_1^{(1)}$
boosted ϕ_1 states

2HDM

LHC available data





Analyses discussed here mainly use 8 TeV data. Lots more to come.