Searches for BSM physics at LHC

A. Nikitenko,

NRC Kurchatov Institute (KKTEF), Moscow, Russia,

JINR, Dubna, Russia,

also Imperial College, London, UK

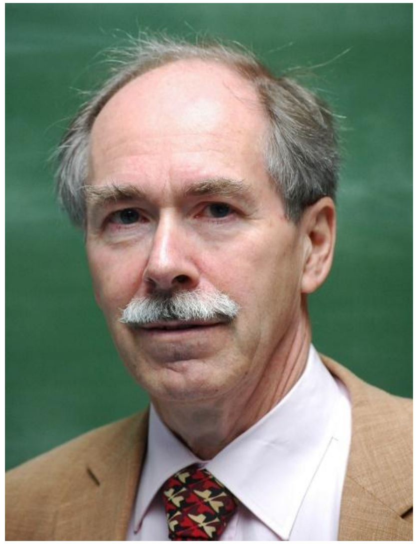
devoted to memory of V. Rubakov

V. Rubakov said at one of RDMS CMS Collaboration conference in Alushta (2011):
«Physics is in confusion…» meaning (I guess) no SUSY discovered at LHC

Gerard 't Hooft

Institute for Theoretical Physics
Utrecht University
the Netherlands

Presented at the Symposium to celebrate
Carlo Rubbia's 90th birthday,
October 18, 2024.

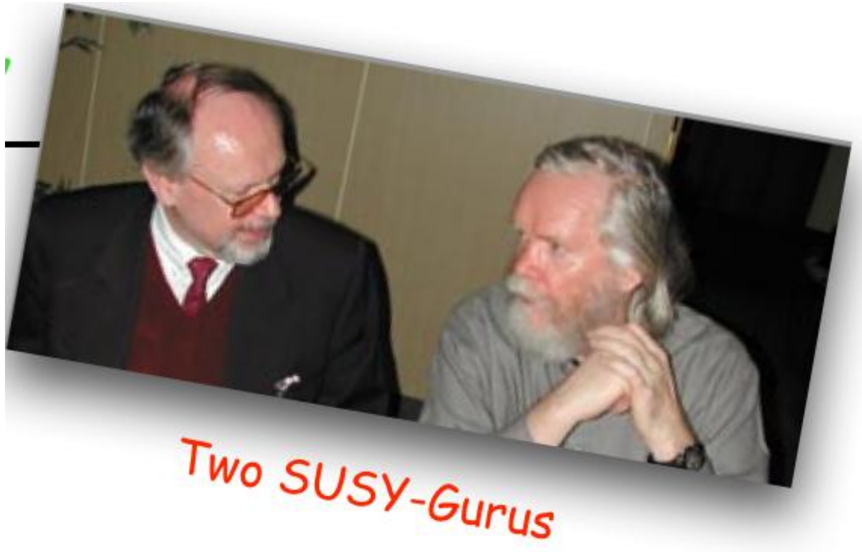


I wish theoreticians could say:

Experimentalists should not worry, we'll make a theory that explains what you are finding

In 2012 SUSY people were happy to say:

h_{125} is the first discovered SUSY particle

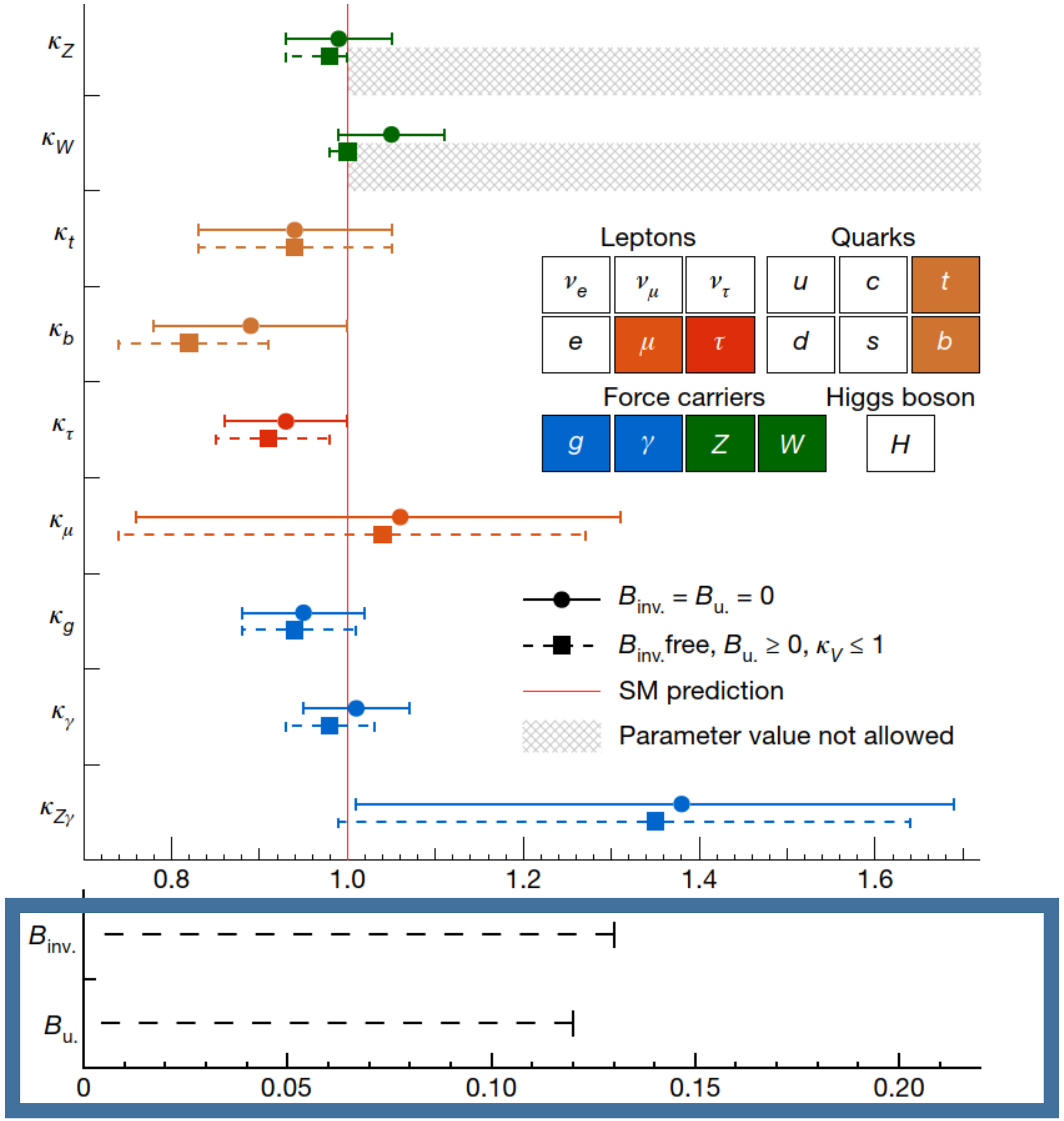


A lot of SUSY (and BSM) analyses in Higgs sector are still going on these days in ATLAS and CMS

BSM physics with Higgs bosons

- find an additional Higgs bosons
- find non SM decays of h(125)
- precise measurement of h(125) using “SM channels”

Summary of coupling strength modifiers for h_{125}



B_i – probability to decay to invisible mode (h_{125} →DM DM)
B_u – probability to decay to yet undetected BSM modes
h_{125}→ $\mu\tau$, hh,… + unknown/undetectable

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\kappa_H^2}{1-(\mathrm{BR}_{\mathrm{undet.}}+\mathrm{BR}_{\mathrm{inv.}})}$$

Room for New Physics with non SM decays of h_{125}:

B_u < 0.12 (expected 0.21)
B_{inv} < 0.13 (expected 0.08)
at 95 % CL

[Nature 607, 52-59, (2022)]

Additional Higgs bosons

in MSSM

$h, H, A, H^{\pm}$ ($m_h < m_H$)

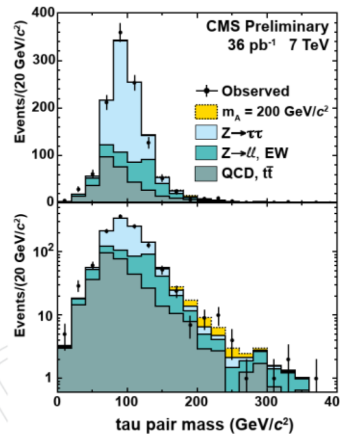
most probably h (not H) is discovered h_{125}

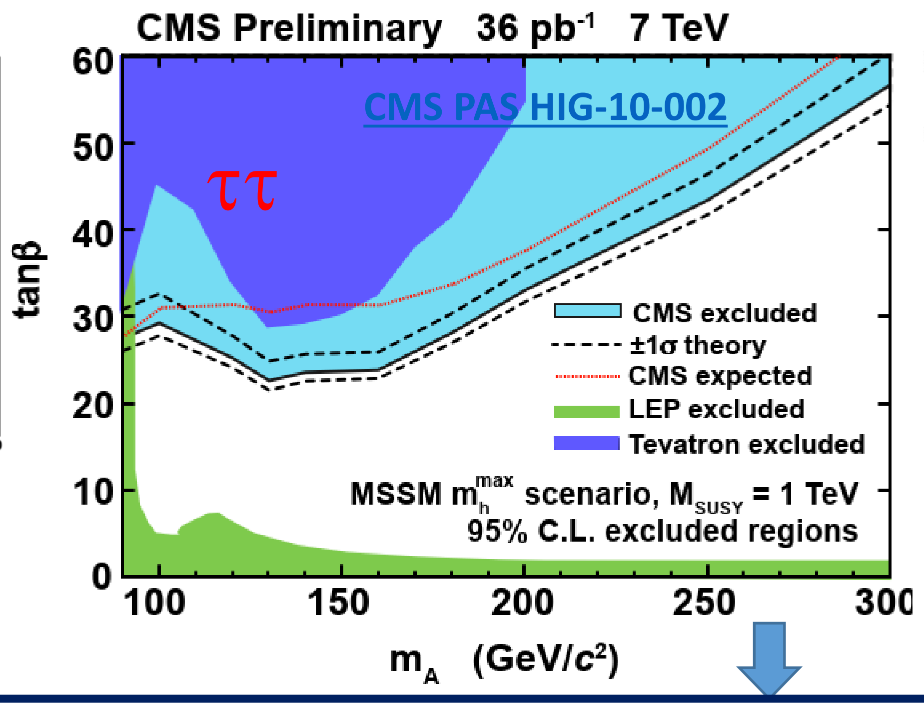
At tree level Higgs sector of MSSM is determined by only two parameters:

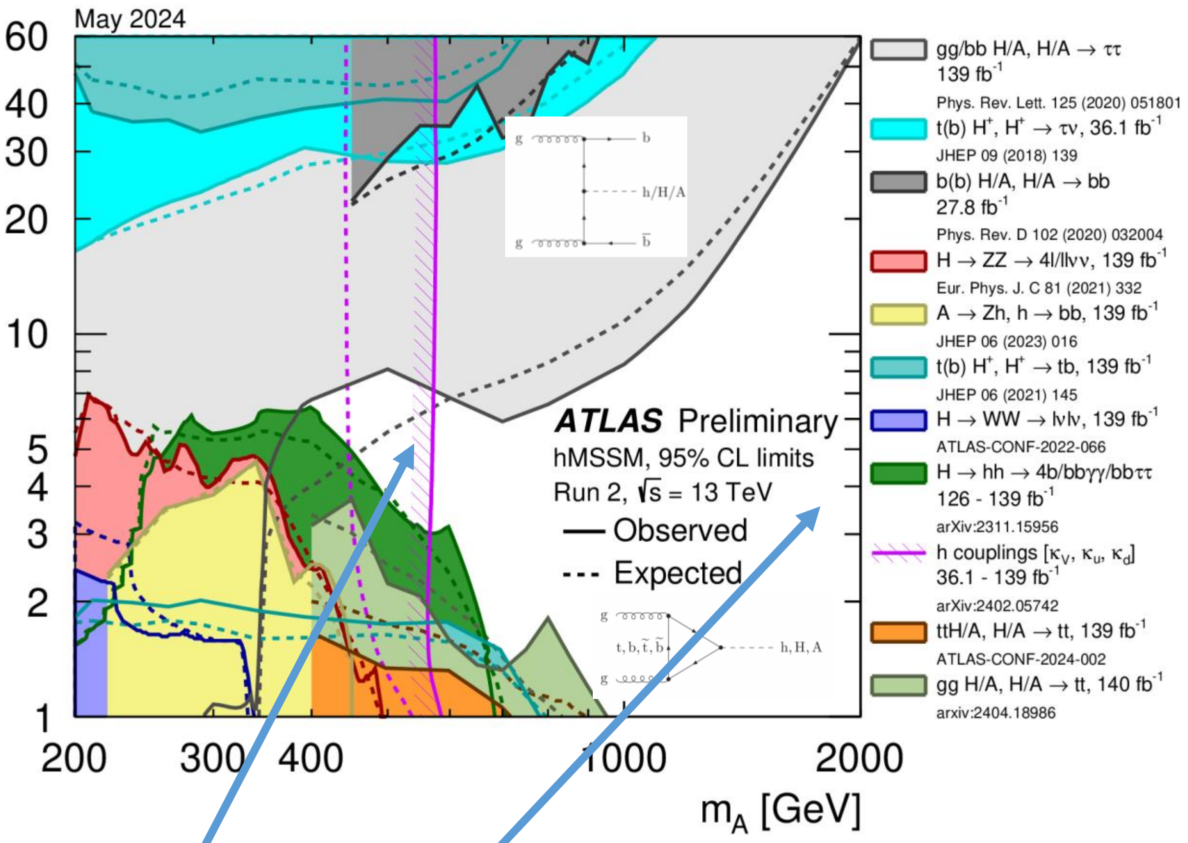
M_A and $\tan(\beta)$

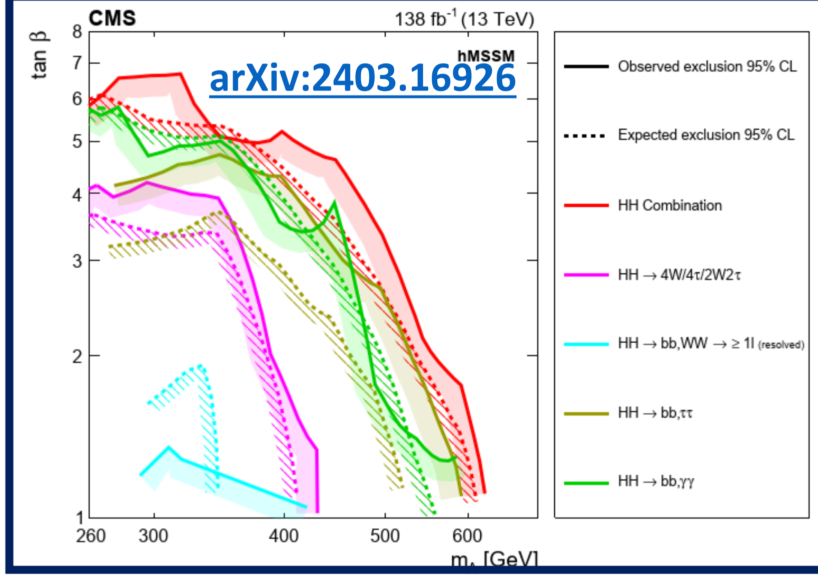
$1 < \tan(\beta) = v_2/v_1 = (v \sin(\beta)) / (v \cos(\beta)) < 60$

From 2010 to 2024 in MSSM Higgs searches









No interference with non resonant hh was taken into account in a signal model

H/A->χχ still to be done
(even in hMSSM:arXiv:2311.04033)

from h_{125} measurements and assuming $h==h_{125}$

Additional Higgs bosons
in 2HDM
$h, H, A, H^{\pm}$ ($m_h < m_H$), h or H is discovered

Free parameters of 2HDM:

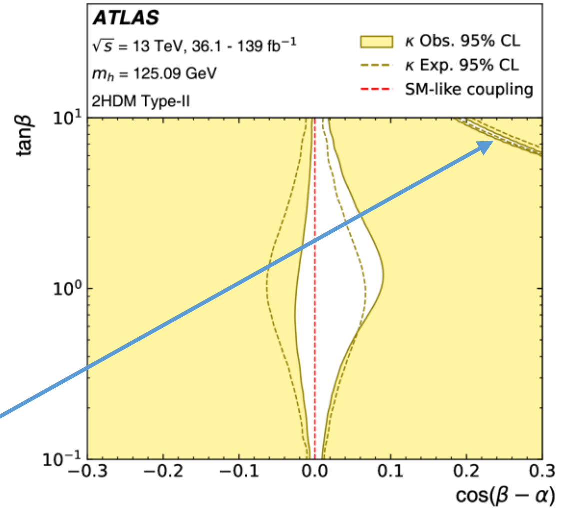
m_h, m_H, m_A, m_{H+}, α, $\tan\beta$, m_{12} (soft Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$) breaking parameter)

m_{12} != 0 to have a new mass scale. This allows the model to have a decoupling limit. When m_{12} goes to infinity we recover the SM m_{12} is often taken as in MSSM: $m_A^2 = m_{12}^2/(\sin\beta\cos\beta) - \lambda_5 v^2$ with $\lambda_5 = 0$ as in MSSM

arXiv:2402.05742

	Type I and Type II	Type I		Type II	
Higgs	C_V	C_U	C_D	C_U	C_D
h	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
H	$\cos(\beta-\alpha)$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
A	0	$\cot\beta$	$-\cot\beta$	$\cot\beta$	$\tan\beta$

$c_{\beta-\alpha}$	$s_{\beta-\alpha}$
HW^+W^-	hW^+W^-
HZZ	hZZ
ZAh	ZAH
$W^{\pm}H^{\mp}h$	$W^{\pm}H^{\mp}H$



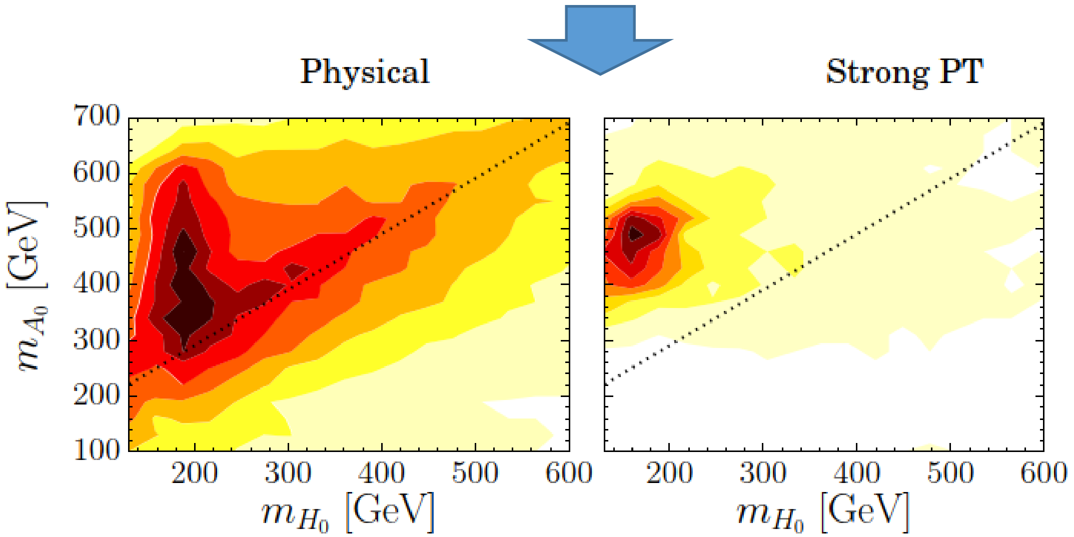
wrong sign Yukawa coupling ($C_D \approx -1$, $C_V = C_U \approx 1$) scenario, $\sin(\beta+\alpha) \approx 1$, can be excluded or confirmed with $h \to \gamma\gamma$ at HL-LHC, 3 ab^{-1}

Anaysis which does not make a sence in MSSM but does in 2HDM: **A(H)→ZH(A), h=h_{125}**

- **contrary to MSSM**
  - **A-boson can have a small mass**
  - **m_A !≈ m_H at large masses**
- **A→ZH decay ($m_A > m_H$) is the signature of a strongly first order electroweak phase transition (EWPT) in 2HDMs, as needed for Electroweak Baryogenesis** G. C. Dorsch, S. Huber, K. Mimasu and J. M. No, arXiv:1405.5537

See also:

Strong First Order Electroweak Phase Transition in the CP-Conserving 2HDM Revisited, M. Meuhlleitner at al, arXiv:1612.04086



2HDM Type I

Promising fast sim. result for llbb final state, m_A=400 GeV m_H=180 GeV. σ=5 at L=40fb^{-1} at 14 TeV LHC

Electroweak baryogenesis

Sakharov Conditions: [A.D. Sakharov, ZhETF Pis'ma 5 (1967) 32 (JETP Letters 5 (1967) 24)]

- B number violation (sphaleron processes).
- C- and CP-violation.
- Out-of-equilibrium

The EW phase transition must be a first order

create bubbles in early Universe with <Φ>‡0 and get system jumping from false to truth vev minimim

$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

M. Quiros, Helv. Phys. Acta 67 (1994) 451.

G.D. Moore, Phys. Rev. D 59 (1999) 014503.

In SM m_H should be less than 125 GeV in order to get barion asymmetry in universe due to EWPT of the first order.

Possible appearance of the baryon asymmetry of the universe in an electroweak theory

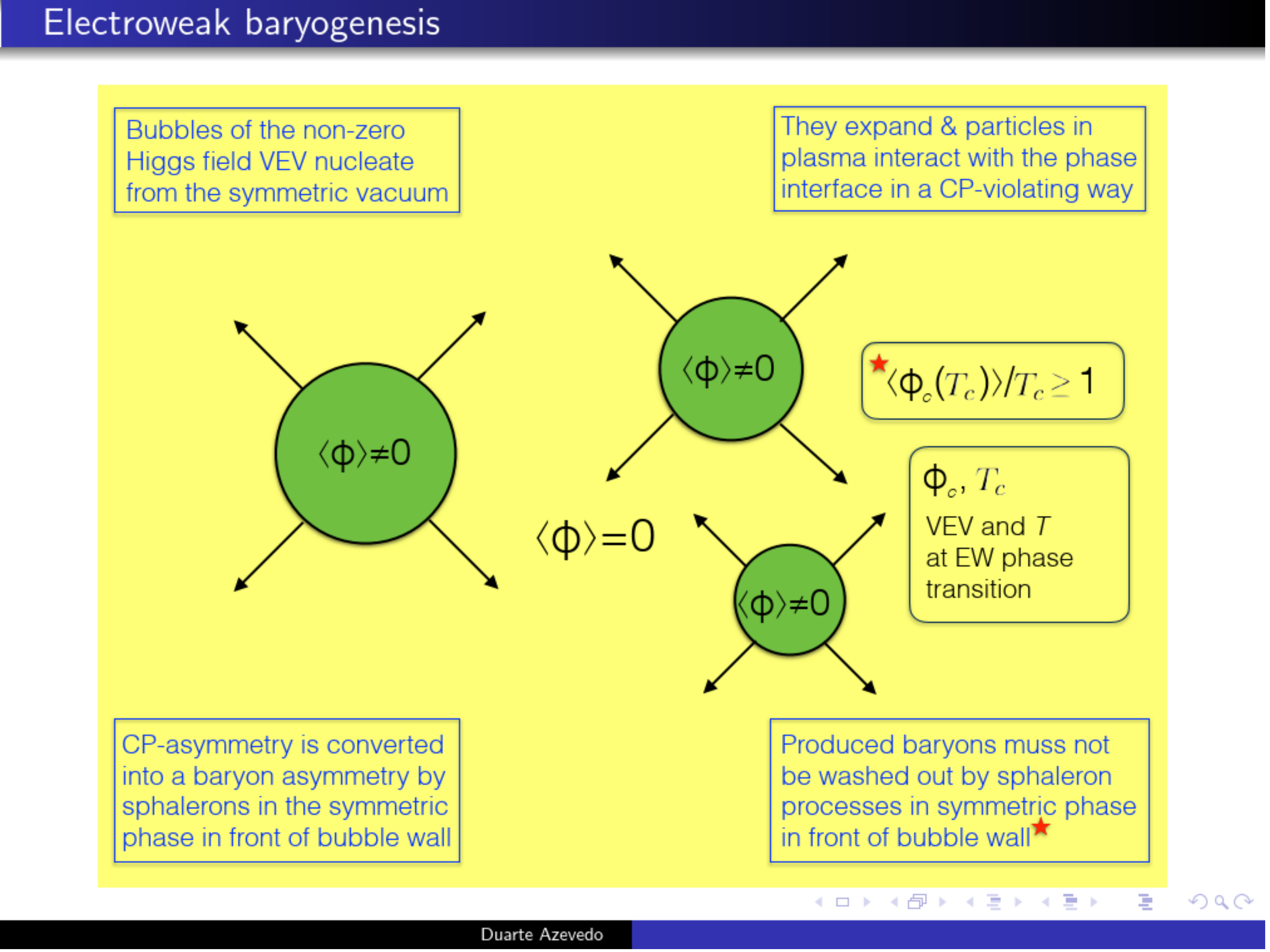
M. E. Shaposhnikov

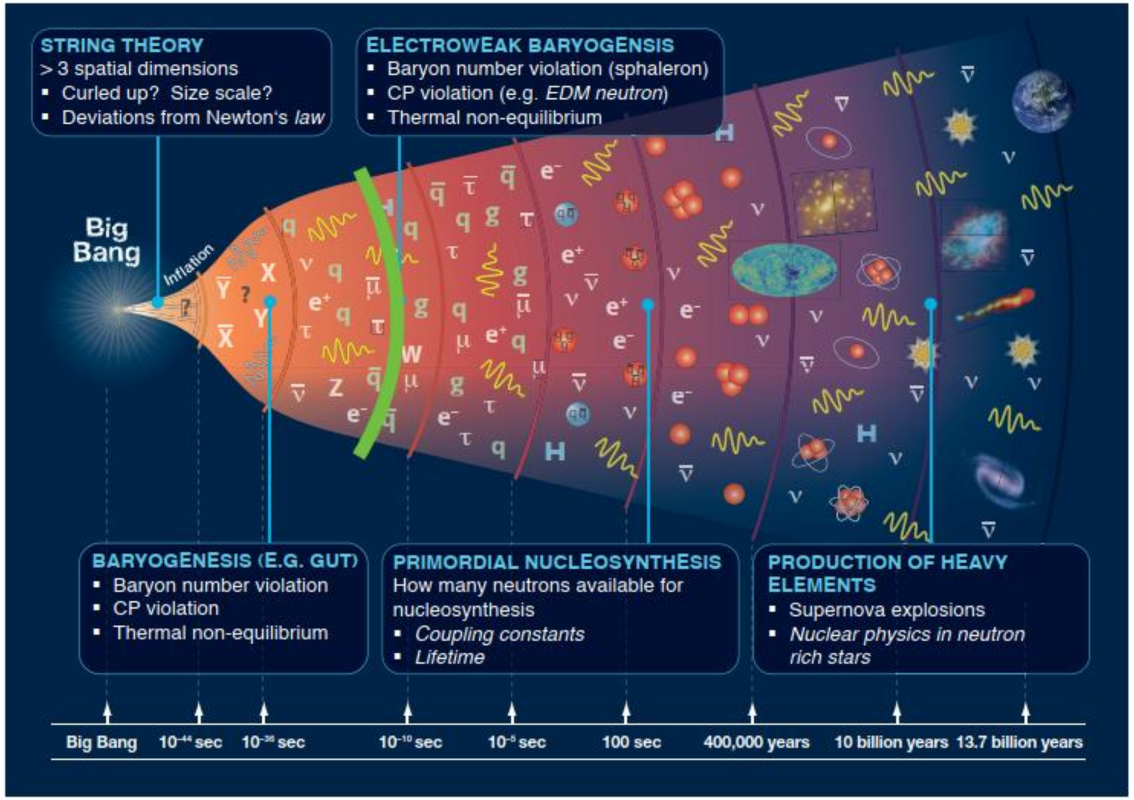
Institute of Nuclear Research, Academy of Sciences of the USSR

(Submitted 2 September 1986)

Pis'ma Zh. Eksp. Teor. Fiz. **44**, No. 8, 364–366 (25 October 1986)

A new mechanism is proposed for the generation of the baryon asymmetry of the universe in an electroweak theory. This mechanism involves an anomalous nonconservation of baryon number at high temperatures. A cosmological limitation on the mass of a Higgs boson is derived: 10 GeV $\lesssim m_H \lesssim$ 60 GeV. The sign of the baryon asymmetry is determined by the sign of the CP breaking in the decays of K^0 mesons.



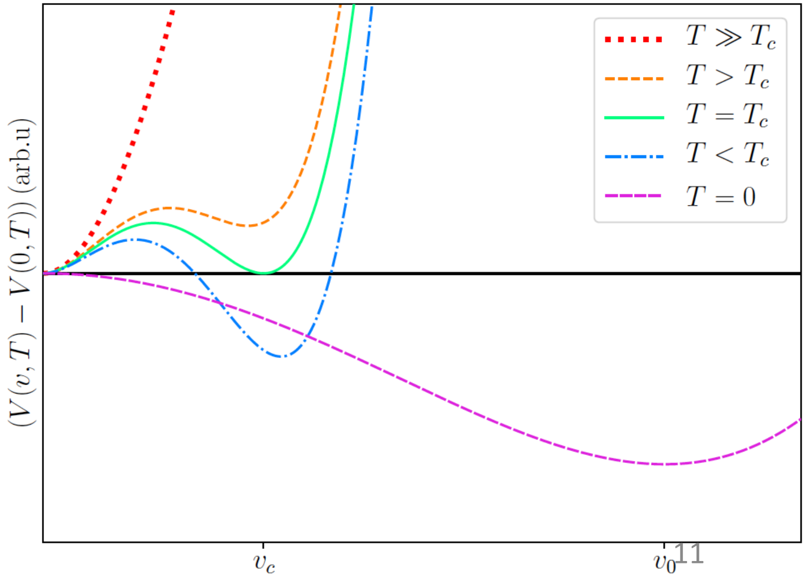


Condition for EWPT to be of strong first-order:

$$\xi_c \equiv \frac{v_c}{T_c} \gtrsim 1\,, \tag{14}$$

where $v_c \equiv \sqrt{\omega_1^2 + \omega_2^2}|_{T_c}$ is the Higgs VEV at the critical temperature T_c, which is defined when the would-be true vacuum and false vacuum are degenerate.

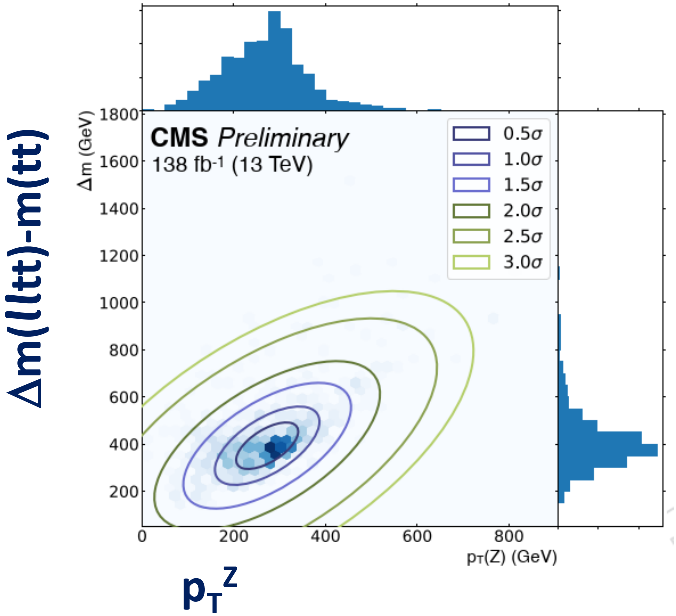
In the SM, we would need $m_H \approx 70$ GeV for $\xi_c \geq 1$ [Kajantie et. al; Jansen]

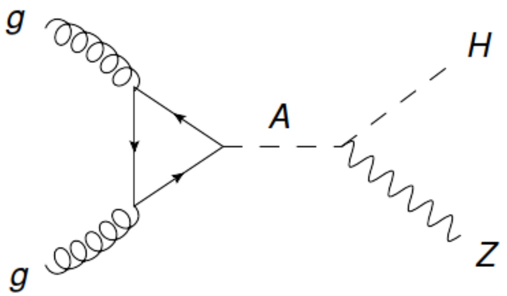


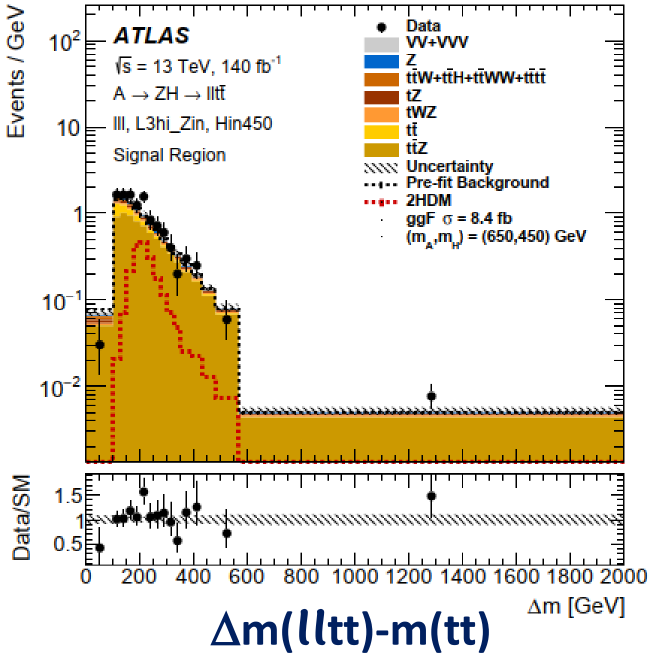
A→ZH→ℓ⁺ℓ⁻ tt analyses and interpretation

fully hadronic tt
CMS-PAS-B2G-23-006

semileptonic tt→ℓνbjjb
ATLAS:arXiv:2311.04033





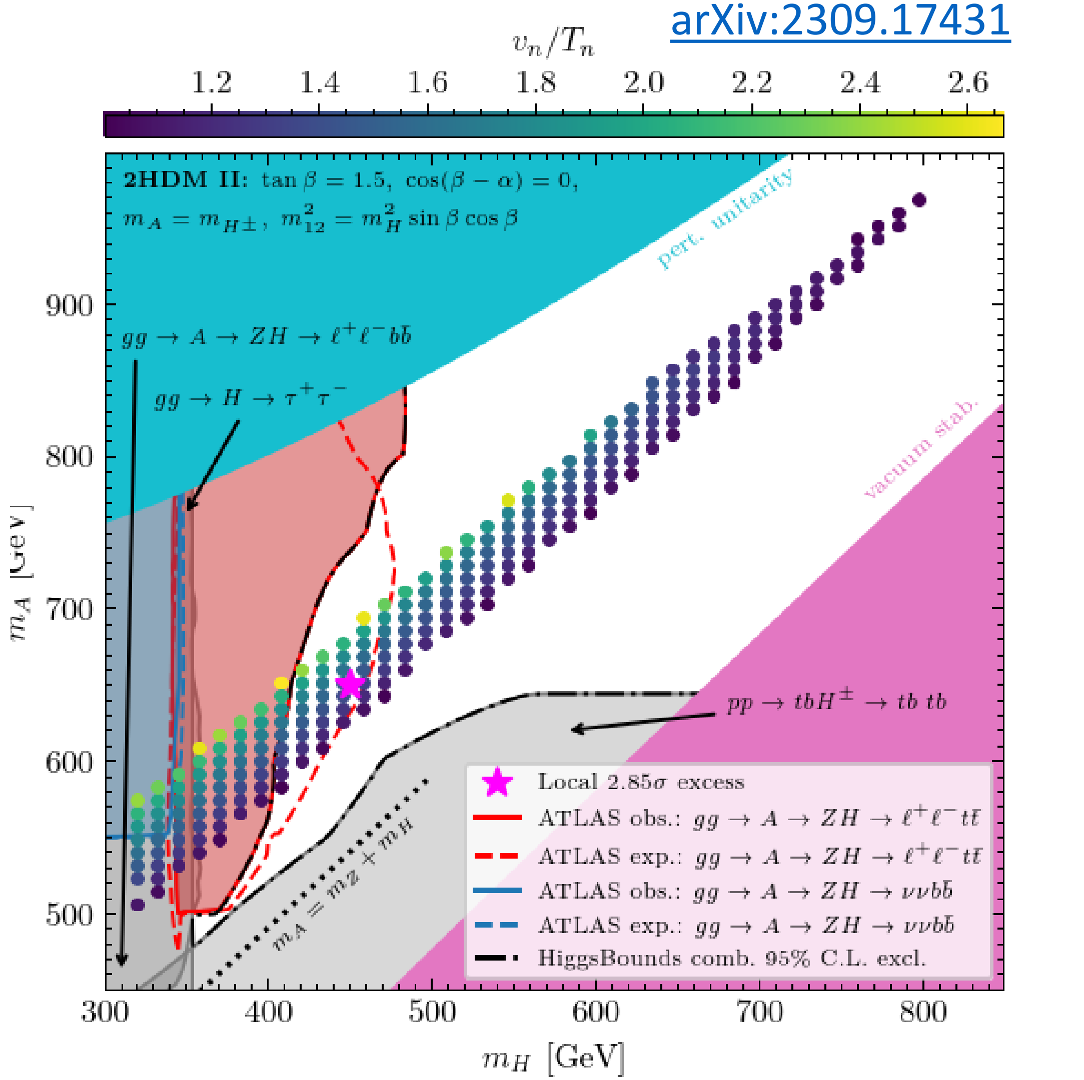


The largest excess over the SM background prediction, amounting to a local significance of 2.85 σ, is observed in the ℓ+ℓ−tt channel, for the signal hypothesis corresponding to (m_A, m_H) = (650, 450) GeV.

First shot of the smoking gun: probing the electroweak phase transition in the 2HDM with novel searches for $A \to ZH$ in $\ell^+\ell^- t\bar{t}$ and $\nu\nu b\bar{b}$ final states

Thomas Biekötter[1*], Sven Heinemeyer[2†], Jose Miguel No[2,3‡], Kateryna Radchenko[4§], María Olalla Olea Romacho[5¶] and Georg Weiglein[4,6‖]

arXiv:2309.17431



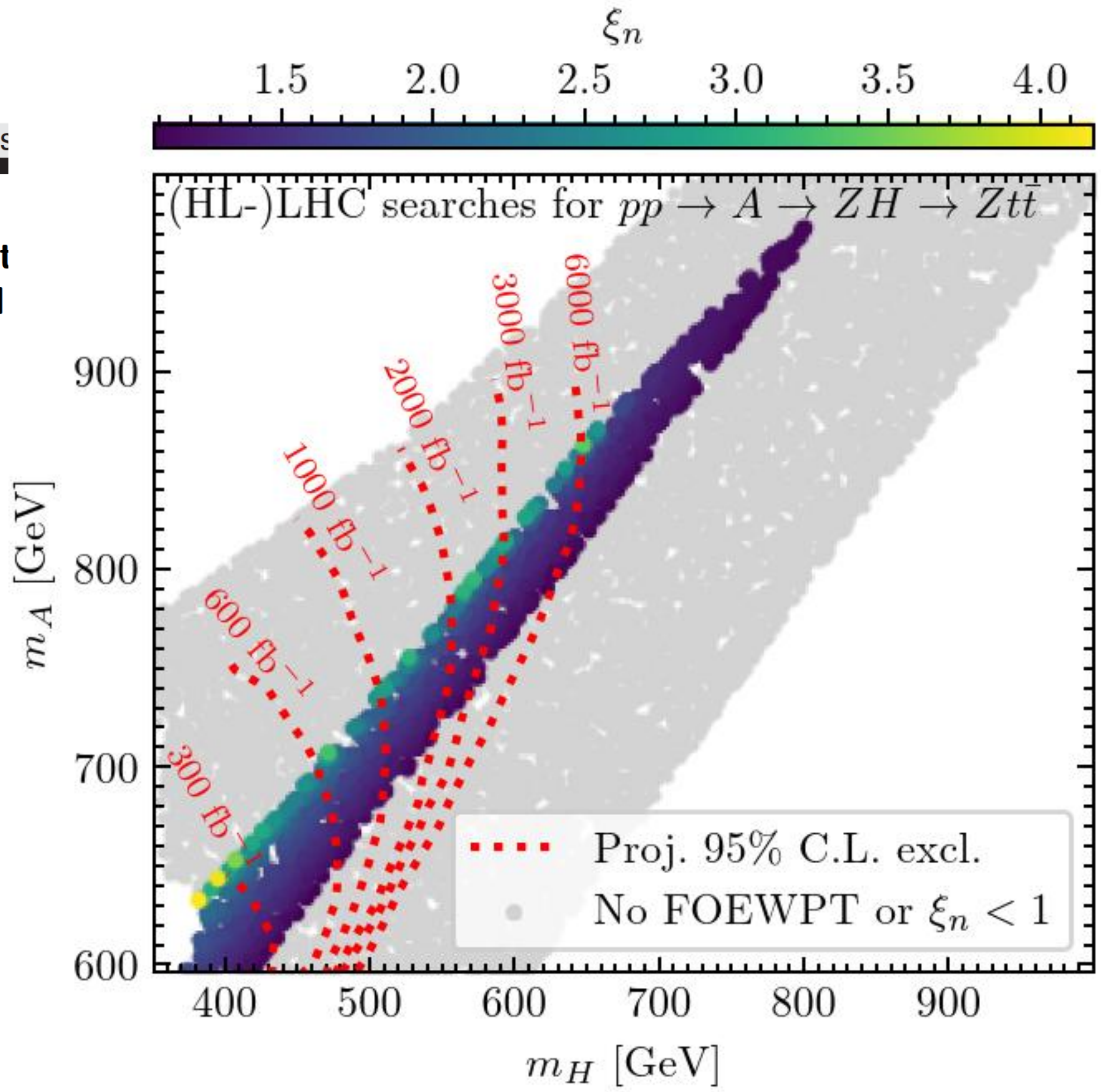
Prospects for A→ZH→l^+l^- tt at HL-LHC

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

The trap in the early Universe: impact on the interplay between gravitational waves and LHC physics in the 2HDM

Thomas Biekötter,[a] Sven Heinemeyer,[b] José Miguel No,[b,c] María Olalla Olea-Romacho[a] and Georg Weiglein[a,d]

JCAP 03(2023) 031

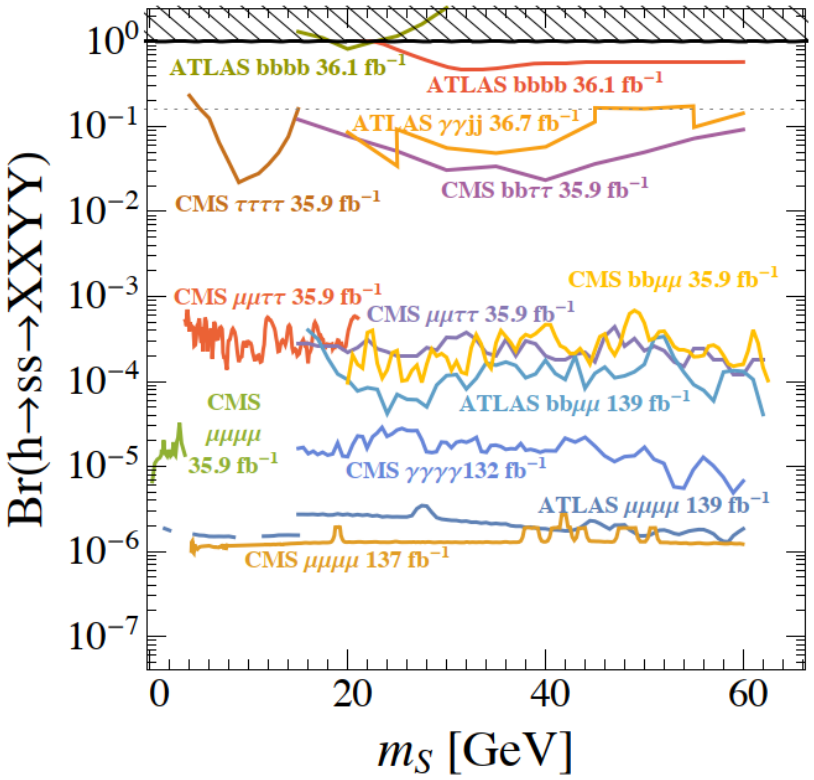


Searches for the light scalars from h_{125} decay

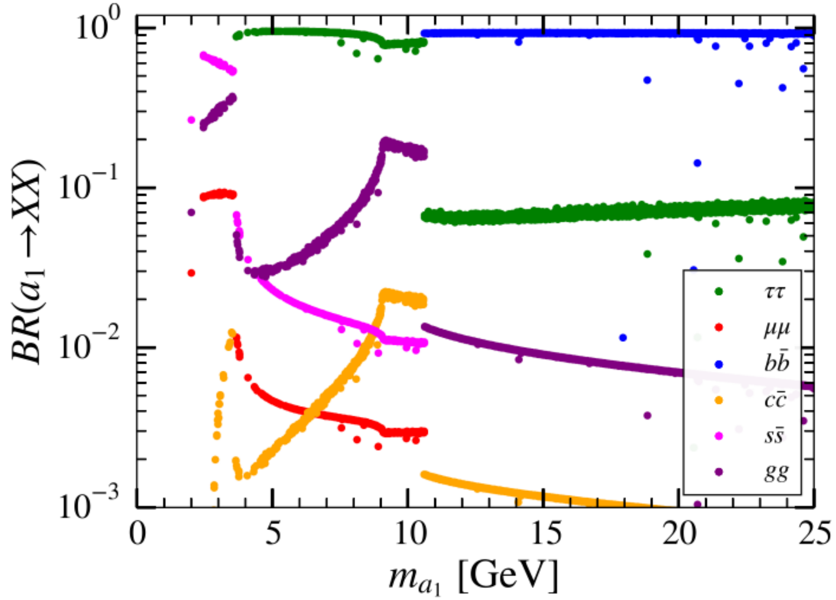
CMS and ATLAS searches for $h_{125} \to ss \to xxyy$ on one plot

M. Carena et al arXIv:2203.08206

see also M. Cepeda at el arXiv:2111.12751

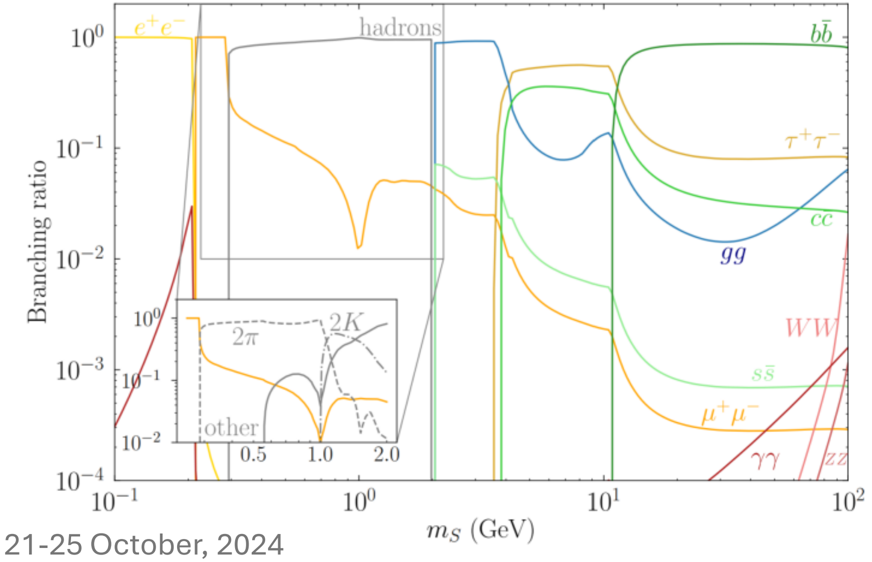


R. Aggleton at al, arXiv:1609.06089 Br's in NMSSM



M. Carena et al arXIv:2203.08206

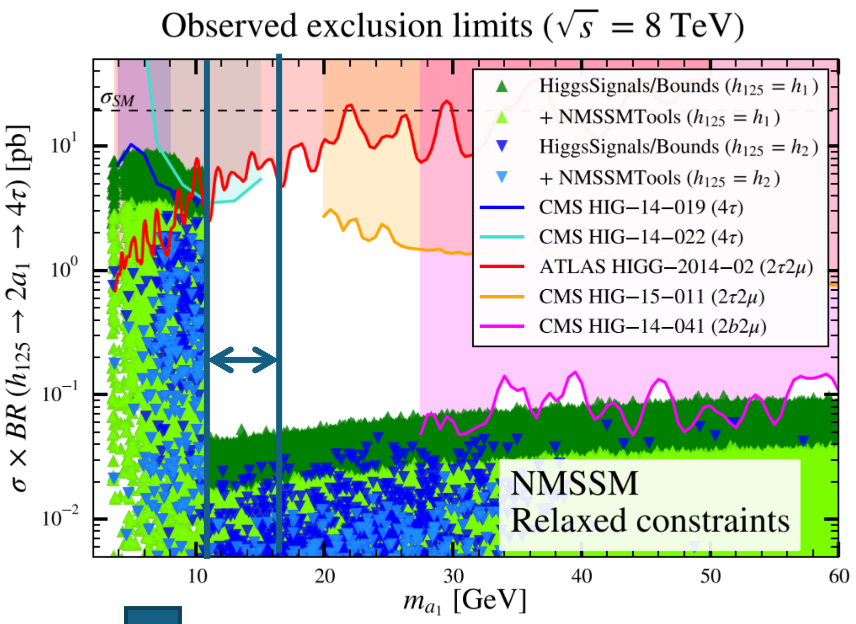
Br's in h125+singlet model



- **Recent ATLAS analyses of 2024**
  - **$h_{125} \to aa \to 4\gamma$**
  - **$h_{125} \to Za \to ll\gamma\gamma$**

Searches for h_{125} decay to aa(hh) vs models (I)

R. Aggleton at al, arXiv:1609.06089



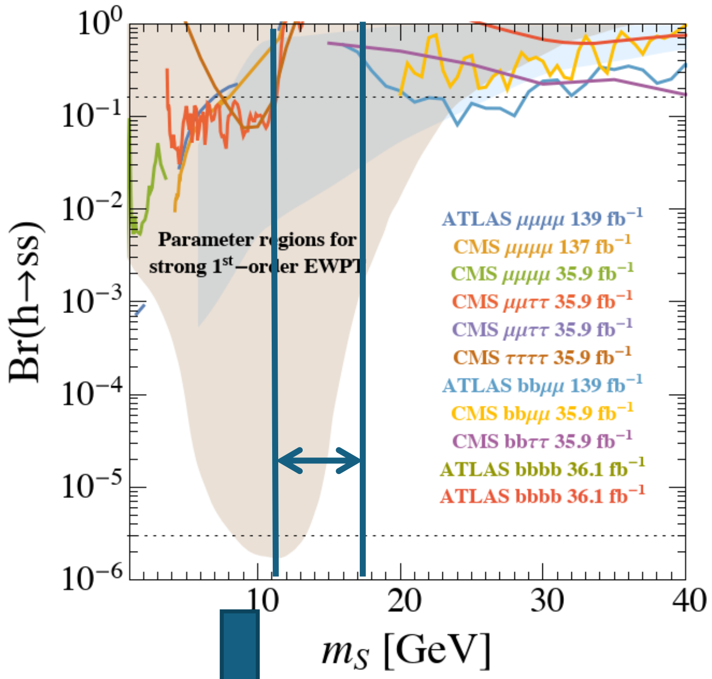
already sensitive to NMSSM

this plot need to be updated for

13 TeV (Run II) analyses. CMS:

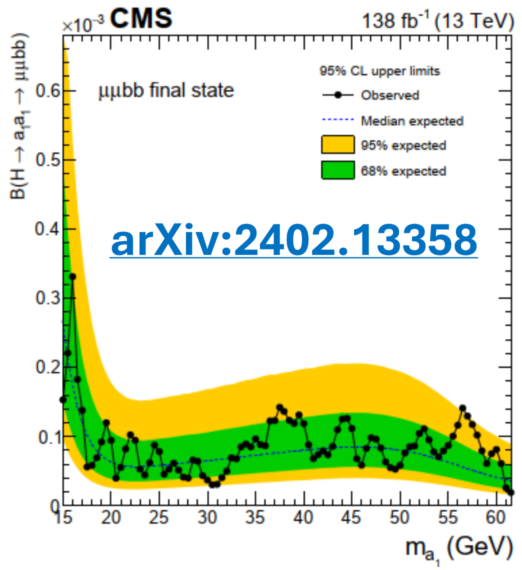
- μμbb: arXiv:2402.13358 – m_a range is 20-60 GeV
- ττbb: arXIv:2402.13358 – m_a range is 15-60 GeV
- μμττ: arXiv:2005.08694 – m_a range is 3.6-21 GeV
- ττττ : arXiv:1907.07235 – m_a range is 4.0-15 GeV
- μμμμ: arXiv:1812.00380 – m_a range is 0.25-8.5 GeV
- bbbb: arXiv:2403.10341 – m_a range is 15-60 GeV

M. Carena et al arXiv:2203.08206



h125+singlet model

Already sensitive to parameter regions for strong 1st order EWPT

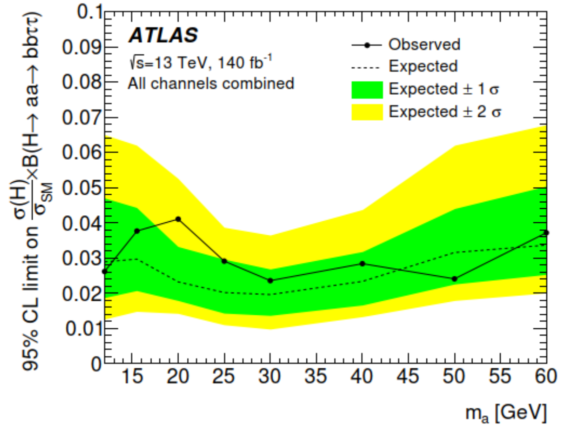


arXiv:2402.13358

mass range, m_a≈10-15 GeV was not accessible. μμ(ττ)bb could do it using a «fat jet», with two b-quarks inside.

arXiv:2407.01335

ATLAS, DeXTer method



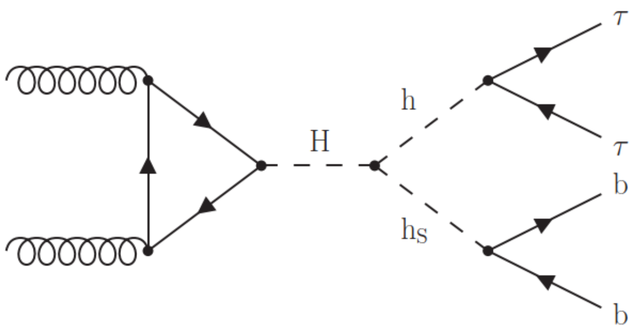
searches for $H(A) \rightarrow h_{125}h(a)_S$ decays

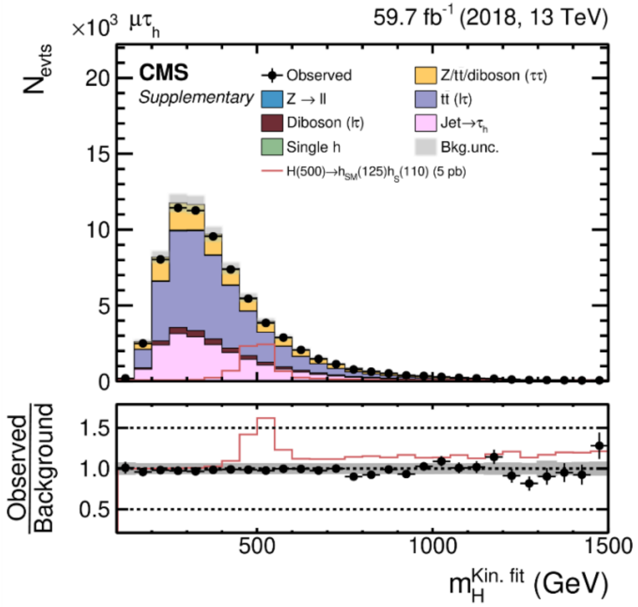
search for $H(A) \rightarrow h_{125} h(a)_S \rightarrow \tau\tau bb$ decay

- **240 < $m_{H(A)}$ < 3000 GeV, 60 < m_{hS} < 2800 GeV**

[arXiv:2106.10361](https://arxiv.org/abs/2106.10361)

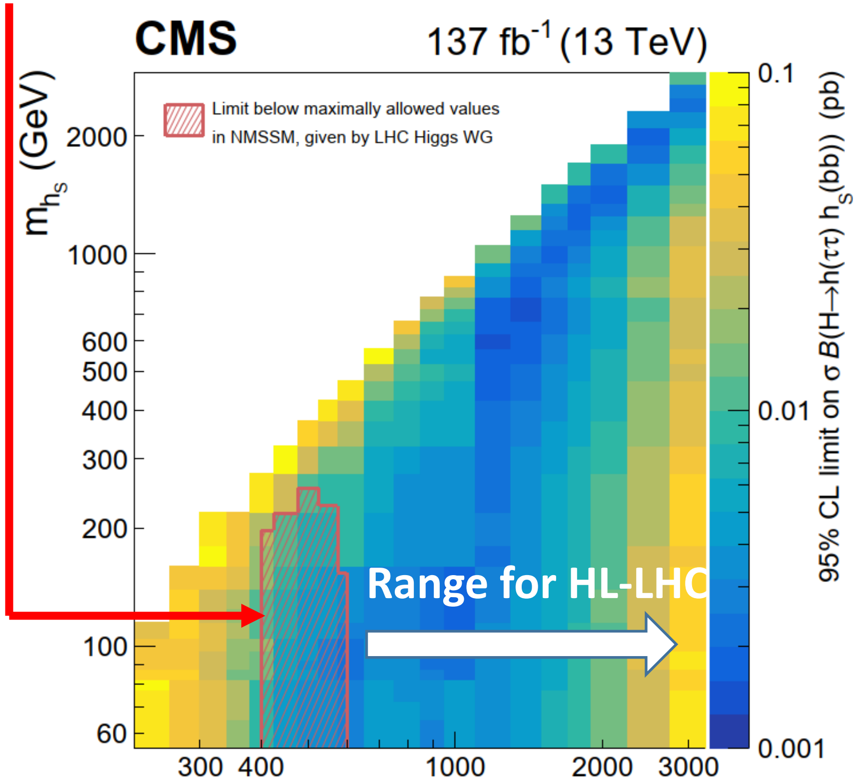
already sensitive to NMSSM





$\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$ plus at least two jets (at least one b-tagged) final states are used

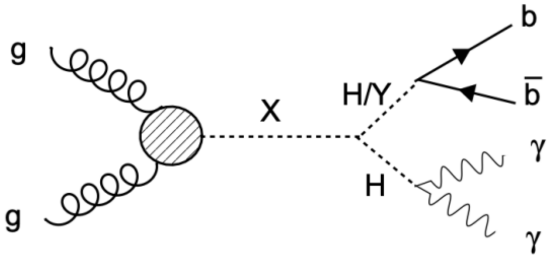
- Multi-class NN used, 4x background classes + 1 signal class
- Output is 5 scores, yi, that sum to 1
- Allocate events to categories based on largest y_i
- In each category fit maximum y_i as discriminating variable



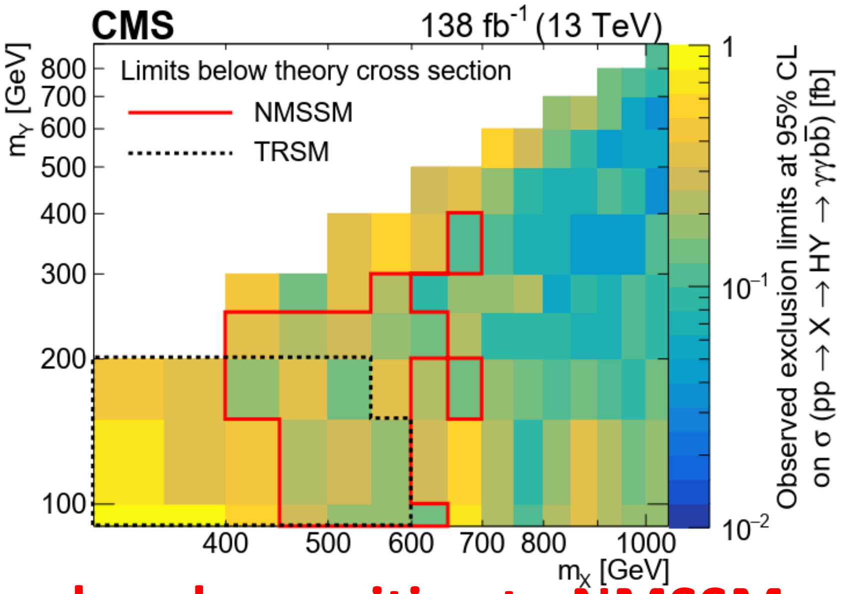
for m_H<400 GeV B physics kills most of the benchmark points (Ulrich Ellwanger, private communication)

search for H(A)→h_{125}h(a)$_S$→γγbb

arXiv:2310.01643



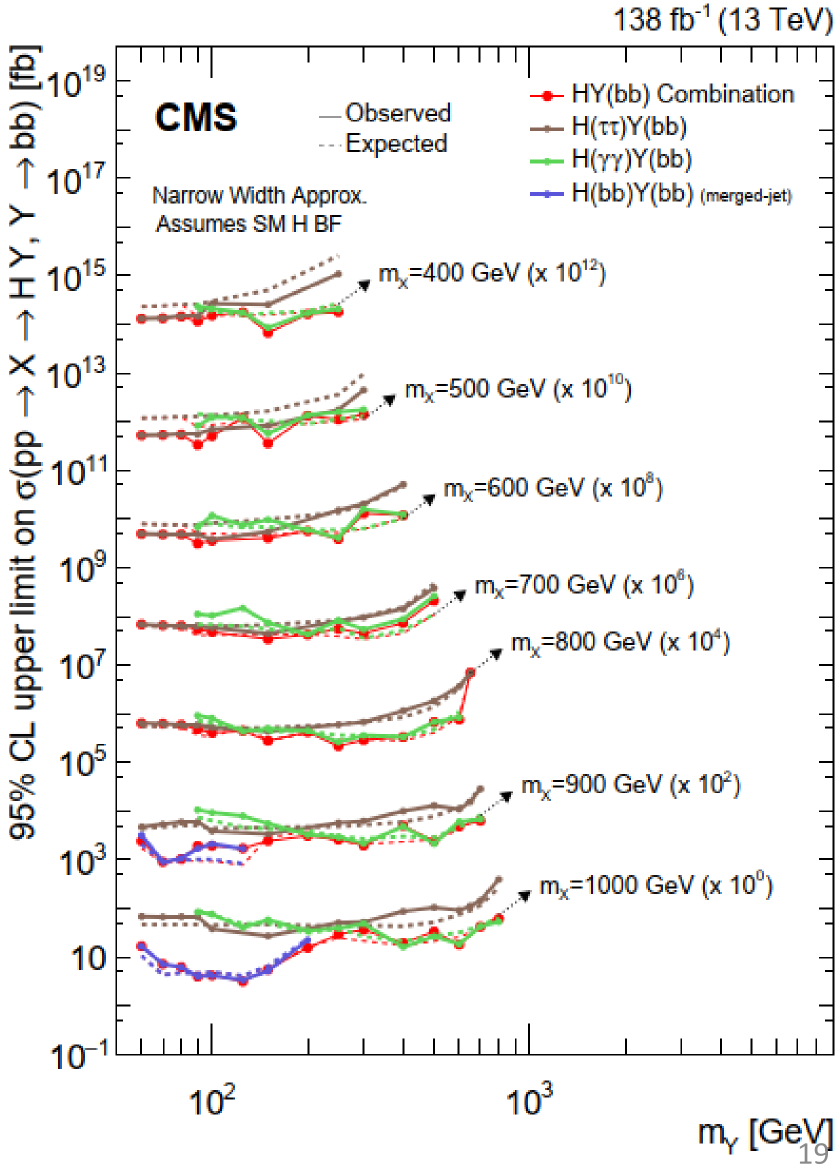
- Largest excess for m_Y=90 GeV, m_X = 650 GeV
  - Local (global) significance of 3.8 (2.8)σ @ m_Y=90 GeV



already sensitive to NMSSM

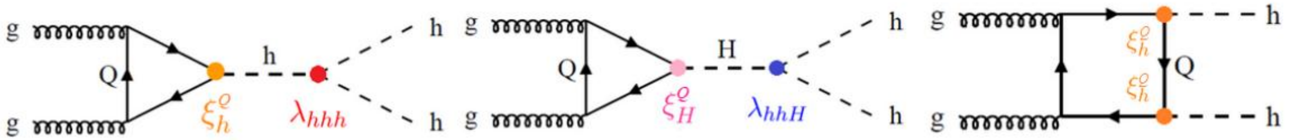
Combination assuming SM BR

h_{125}→γγ, ττ, bb arXIv:2403.16926

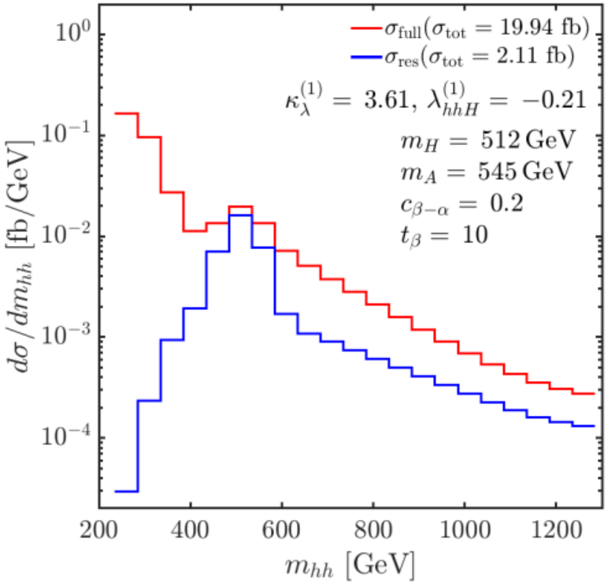


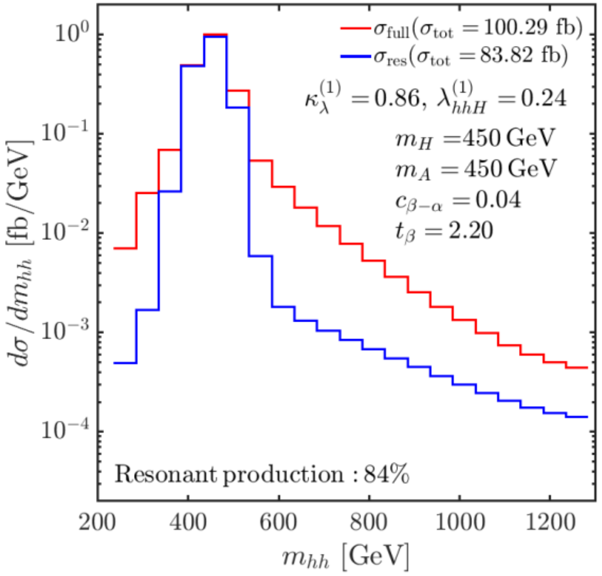
Do not show H→$h_{125}h_{125}$ CMS and ATLAS results since signal model taken in the analyses does not take into account interference with non resonant hh production

- **Importance of taking into account non-resonance production**
  - **S. Heinemeier at al. arXiv:2403.14776**
  - **T. Robens at al. arXiv:2409.06651**

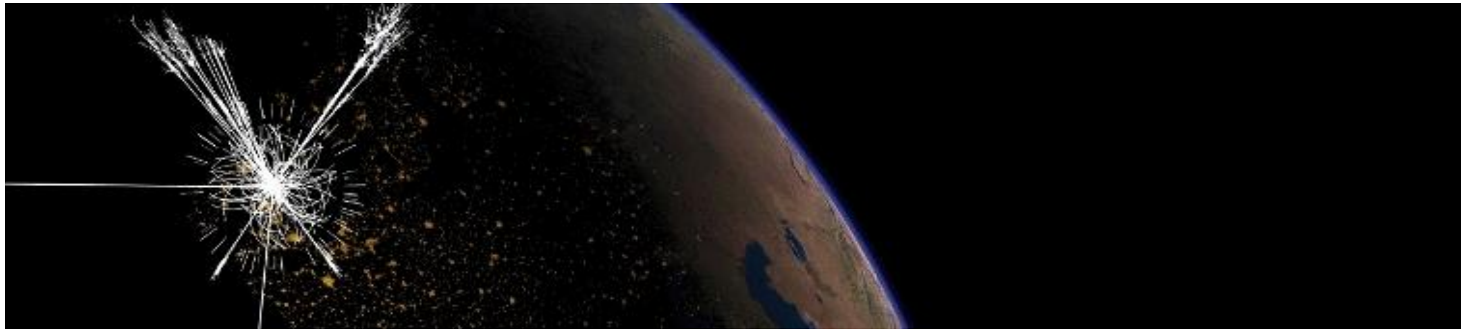


Two BP in 2HDM Type I were claimed to be excluded using resonance model only and neglecting non-resonance contributions





Search for Dark Matter in non-SM h(125) decays: $h_{125} \rightarrow invisible$



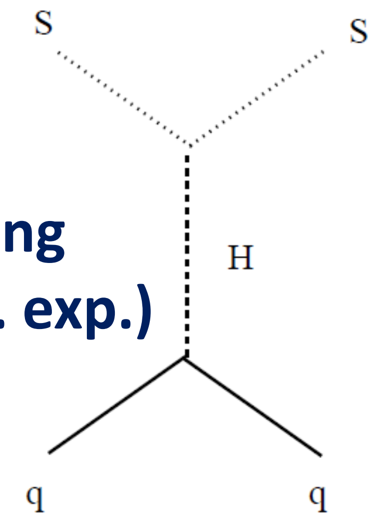
Connection between
LHC H->inv. and direct DM searches”

$$\sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_S+m_N)^2},$$

$$\sigma^{SI}_{V-N} = \frac{\lambda^2_{hVV}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_V+m_N)^2},$$

$$\sigma^{SI}_{f-N} = \frac{\lambda^2_{hff}}{4\pi\Lambda^2 m_h^4}\frac{m_N^4 M_f^2 f_N^2}{(M_f+m_N)^2},$$

DM-nucleon scattering (by XENON, LUX,… exp.)



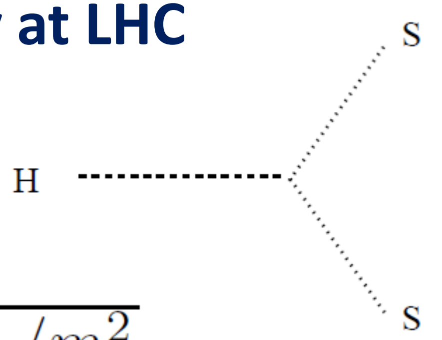
where f_N – Higgs-nucleon coupling

$$\Gamma^{inv}_{h\to SS} = \frac{\lambda^2_{hSS} v^2 \beta_S}{64\pi m_h},$$

$$\Gamma^{inv}_{h\to VV} = \frac{\lambda^2_{hVV} v^2 m_h^3 \beta_V}{256\pi M_V^4}\left(1-4\frac{M_V^2}{m_h^2}+12\frac{M_V^4}{m_h^4}\right)$$

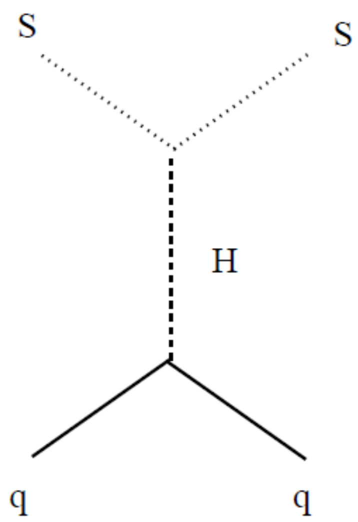
$$\Gamma^{inv}_{h\to \chi\chi} = \frac{\lambda^2_{hff} v^2 m_h \beta_f^3}{32\pi\Lambda^2}, \quad \text{where } \beta_X = \sqrt{1-4M_X^2/m_h^2}$$

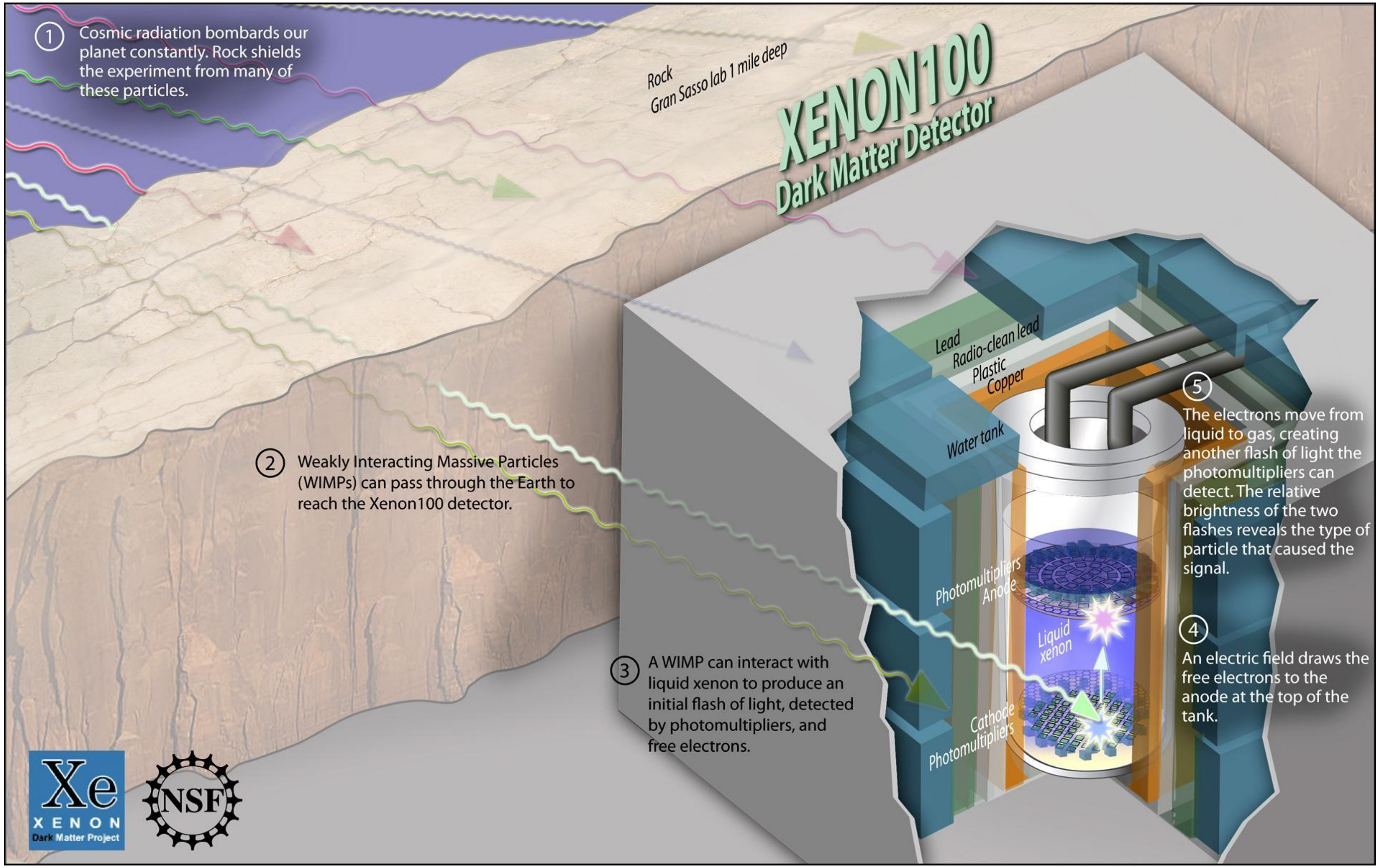
H->invisible decay at LHC



A. Djouadi et. al. arXiv:1112.3299

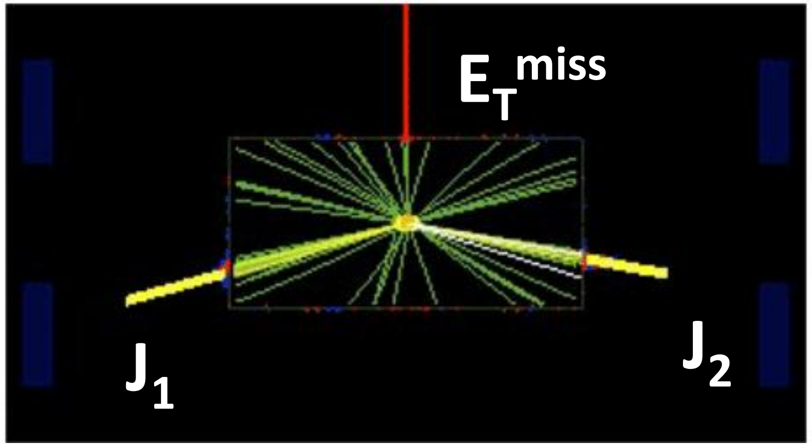
DM (WIMP) detection on Earth with XENON experiment



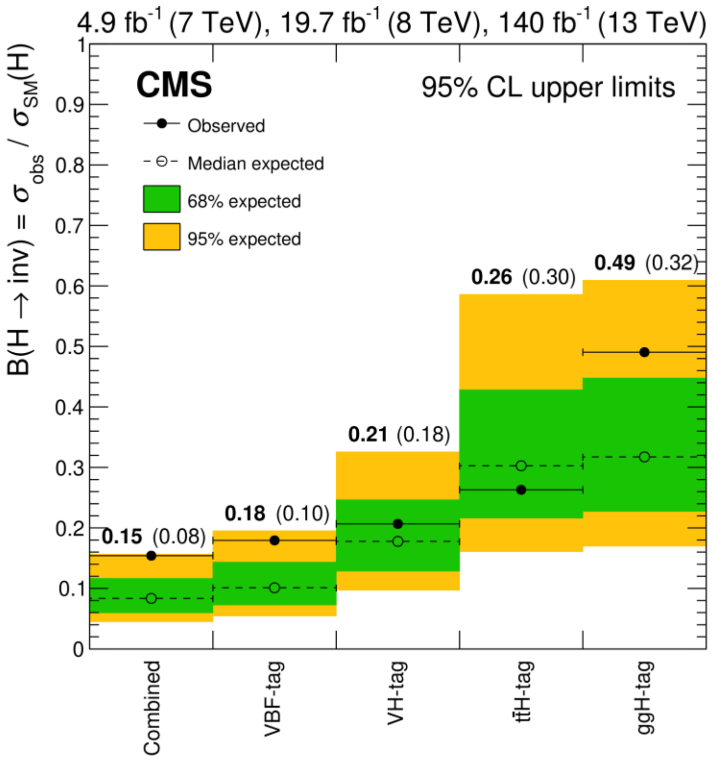


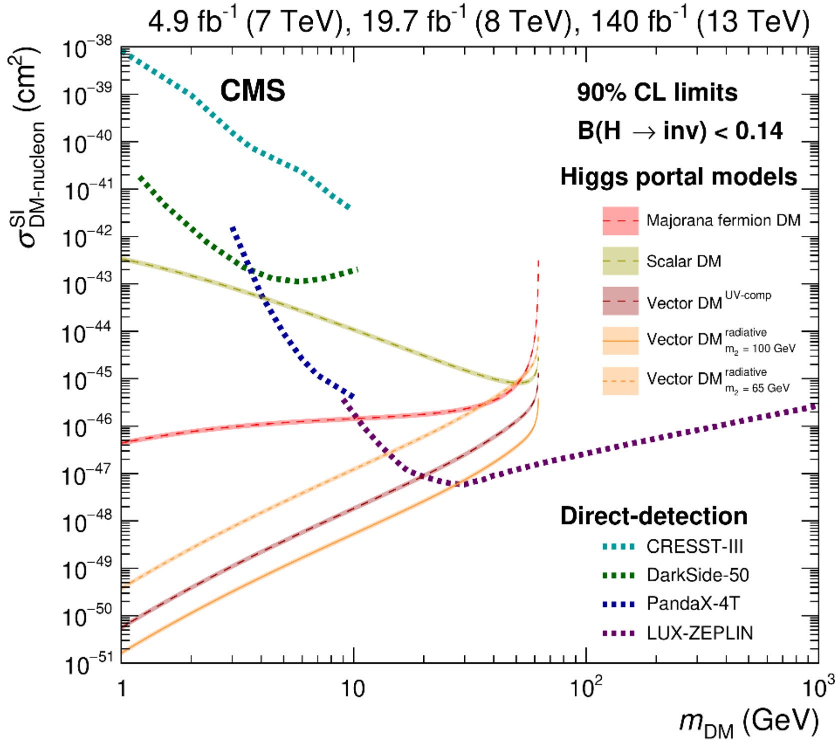
Start data taking in 2007 at Gran Sasso in Italy. Current XENON100 – 165 L xenon. Plan for 1000 L

most sensitive mode
qq'→qq'h (VBF h)



Eur. Phys. J. C 83 (2023) 933





Expect to reach ≈ 4 % at HL-LHC with 3 ab^{-1} (FTR-19-001)

How it is compared with MSSM and NMSSM predictions

- **seems not interesting for pMSSM with new limits from LZ experiment**

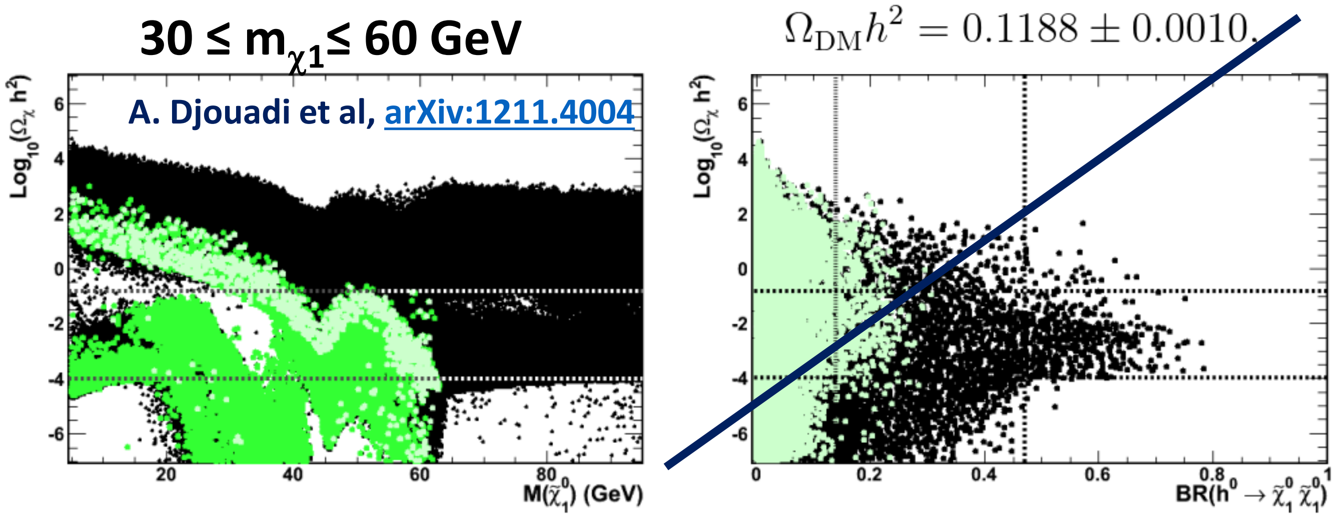


Figure 4: The neutralino relic density $\log_{10}(\Omega_\chi h^2)$ as a function of $M_{\chi_1^0}$ (left) and $BR(h \to \chi_1^0 \chi_1^0)$ (right) for the accepted set of pMSSM points (black dots), those with $BR(h \to \chi_1^0 \chi_1^0) \geq 15\%$ (green dots) and those compatible at 90% C.L. with the Higgs data (light green dots). The horizontal lines show the constraint imposed on $\Omega_\chi h^2$ and the vertical lines on the panel on the right the 68% and 95% C.L. constraints on the Higgs invisible decay branching fraction obtained by [26].

latest update in R. Godbole at al. arXiv:2402.07991 , BR(h→$\chi_1 \chi_1$) < 0.1 %

- **interesting in NMSSM**

U. Ellwanger et al, arXiv:2403.16884

Scenarios with light neutralino 1

	BP1
M_{H3}	3966
M_{A1}	21
LSP	singl.
$M_{\rm LSP}$	9.0
NLSP	wino$^\pm$
$M_{\rm NLSP}$	115
Slepton	$\tilde{\nu}_\tau$
$M_{\rm Slepton}$	140

BR h→invisible can reach ≈10-15 % due to destructive interferences among processes mediated by the CP-even scalars.

Cyril Hugonie, private communication

limits on the anomalous electromagnetic moments of the τ lepton (Rep. Prog. Phys. 87 (2024) 107801)

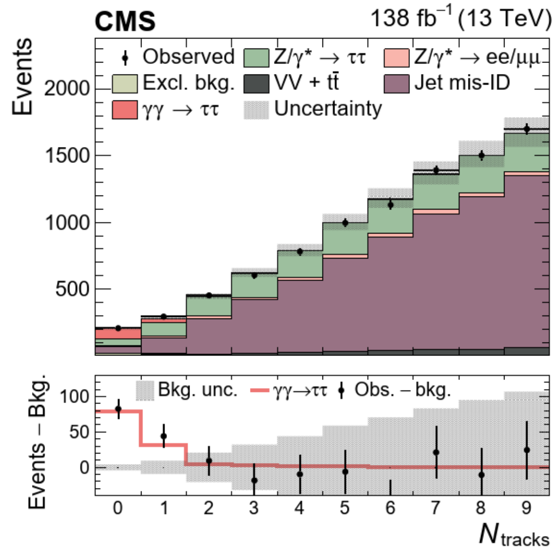
photon-lepton coupling, $ie\Gamma^\mu$

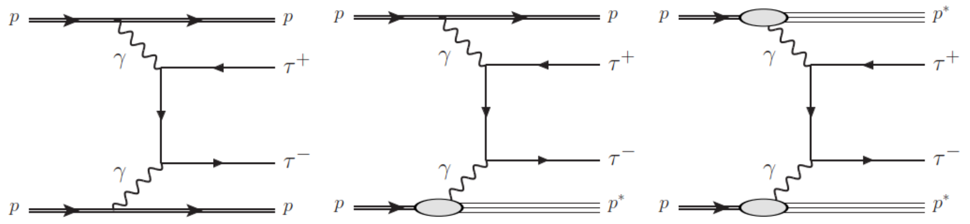
$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{\sigma^{\mu\nu} q_\nu}{2m}\left[iF_2(q^2) + F_3(q^2)\gamma_5\right]$$

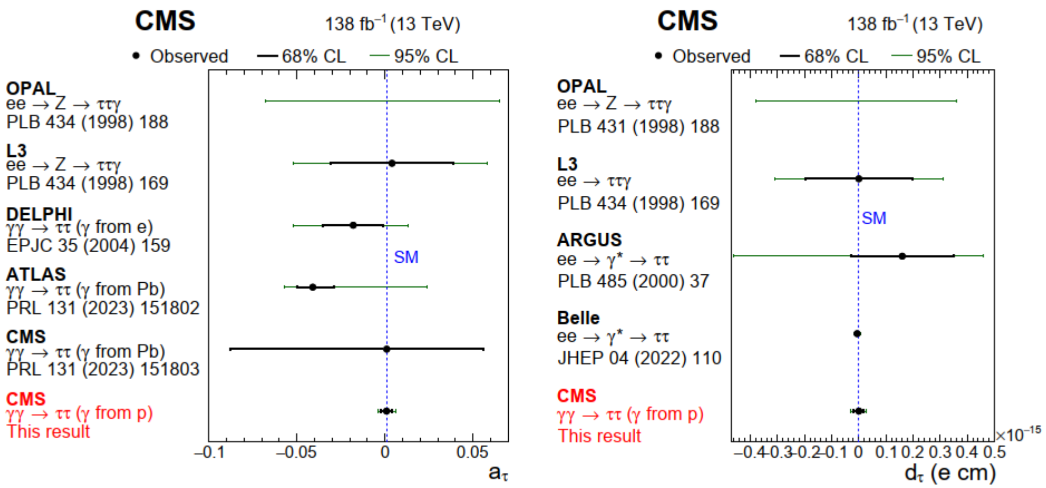
$$F_2(0) = a_\ell \equiv (g_\ell - 2)/2 \text{ and } F_3(0) = -2md_\ell/e,$$

the gyromagnetic ratio g_ℓ is a constant term that relates the magnetic moment of the lepton to its spin, and d_ℓ is the lepton anomalous electric dipole moment.

$a_\tau = 1.17721 \pm 0.00005 \times 10^{-3}$
in the SM (arXiv:hep-ph/0701260)
$d_\tau = -7.3 \times 10{-}38$ e cm in SM (arXiv:2003.08195)







qq→Z*→A+h/H→4τ (CMS-PAS-SUS-23-007)

- **motivated by the Type III 2HDM at large tanβ as an explanation of the muon g_μ-2 anomaly (arXiv:2104.10175)**

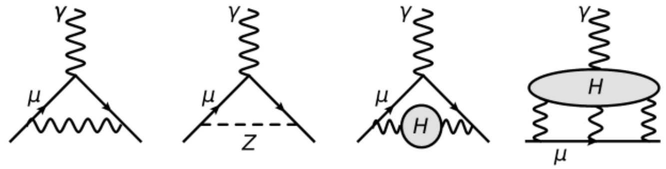
Four possible Z_2 charge assignments that forbid tree-level Higgs-mediated FCNC effects in the 2HDM

	Φ_1	Φ_2	t_R	b_R	τ_R	t_L, b_L, ν_L, e_L
Type I	+	−	−	−	−	+
Type II	+	−	−	+	+	+
Type X (lepton specific)	+	−	−	−	+	+
Type Y (flipped)	+	−	−	+	−	+

Couplings of Higgs particles to quarks and leptons

	u-type	d-type	leptons	ξ_A^u	ξ_A^d
type I	Φ_2	Φ_2	Φ_2	$\cot\beta$	$-\cot\beta$
type II	Φ_2	Φ_1	Φ_1	$\cot\beta$	$\tan\beta$
type III (lepton-specific)	Φ_2	Φ_2	Φ_1	$\cot\beta$	$-\cot\beta$
type IV (flipped)	Φ_2	Φ_1	Φ_2	$\cot\beta$	$\tan\beta$

SM contribution to magnetic momentum of muon



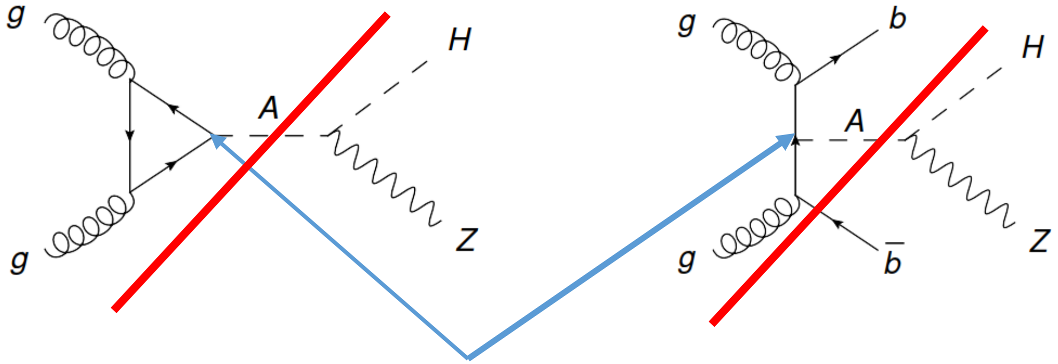
$$\Delta a_\mu^{\rm obs} = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59) \times 10^{-11}$$

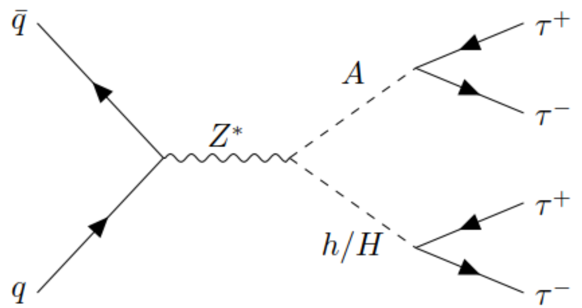
4.2 σ deviation from SM,
in 2HDM φ^0, A, H± contribute to loop

$$h_{\rm SM} = s_{\beta-\alpha} h + c_{\beta-\alpha} H.$$

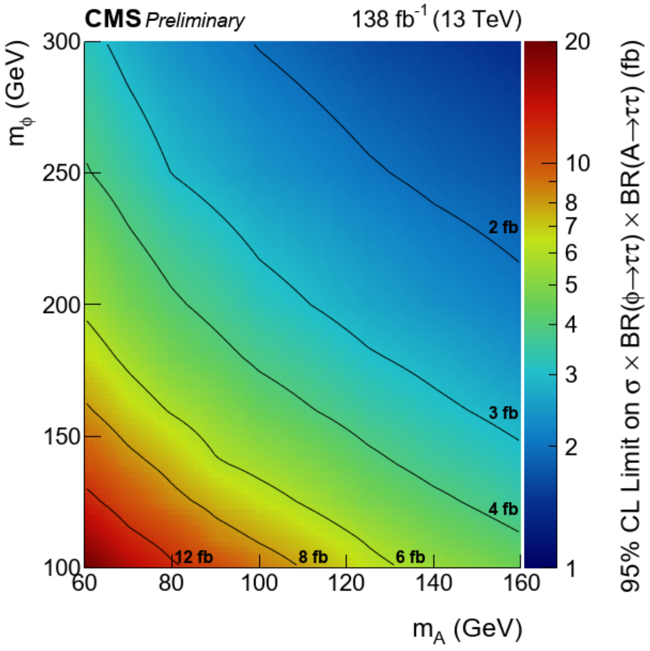
normal scenario (NS)	inverted scenario (IS)
$h_{\rm SM} = h, \quad \varphi^0 = H$	$h_{\rm SM} = H, \quad \varphi^0 = h$
$y_f^{h_{\rm SM}} = 1, \quad s_{\beta-\alpha} = 1$	$y_f^{h_{\rm SM}} = 1, \quad c_{\beta-\alpha} = 1$
$y_t^A = -y_t^{\varphi^0} = \frac{1}{t_\beta}, \quad y_\ell^A = y_\ell^{\varphi^0} = t_\beta$	$y_t^A = y_t^{\varphi^0} = \frac{1}{t_\beta}, \quad y_\ell^A = -y_\ell^{\varphi^0} = t_\beta$

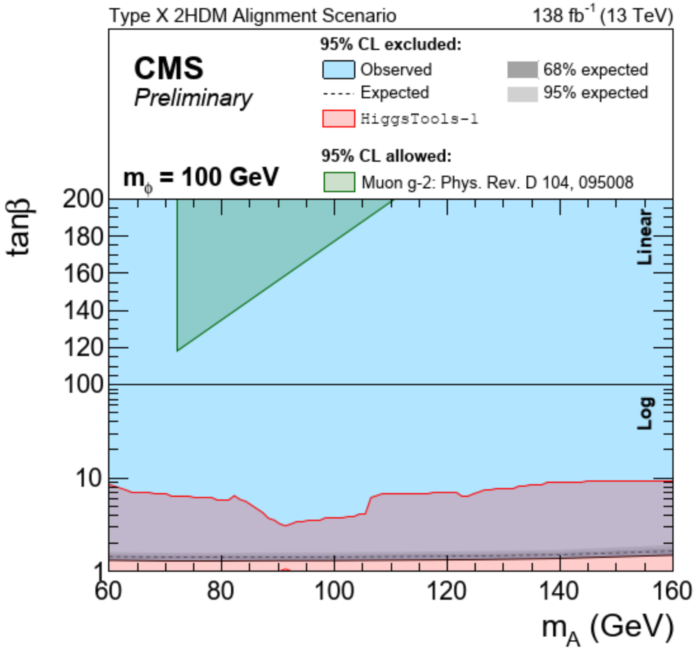
In Type III 2HDM couplings of A to up and down quarks are suppressed by 1/tanβ and couplings of A and φ^0 to leptons are enlarged by tanβ

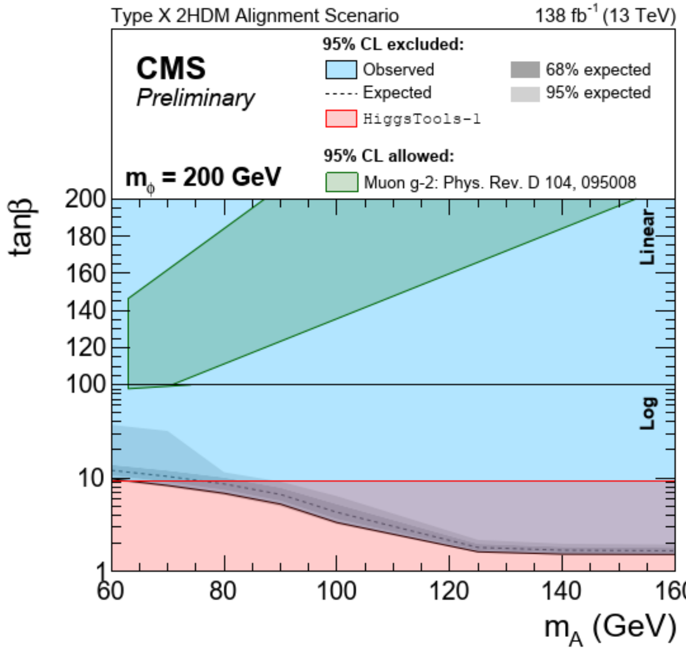




$\xi^t_A = -\xi^b_A = 1/\tan\beta$ $\xi_{AZ\varphi} \approx 1$, $\xi^\tau_A = \xi^\tau_\varphi = \tan\beta$







- **search excludes the allowed region for the g_μ-2 anomaly with a Type III 2HDM**
- **a complete exclusion of the type III 2HDM for many of the mass points scanned.**

Searches for processes with Lepton Number Violation

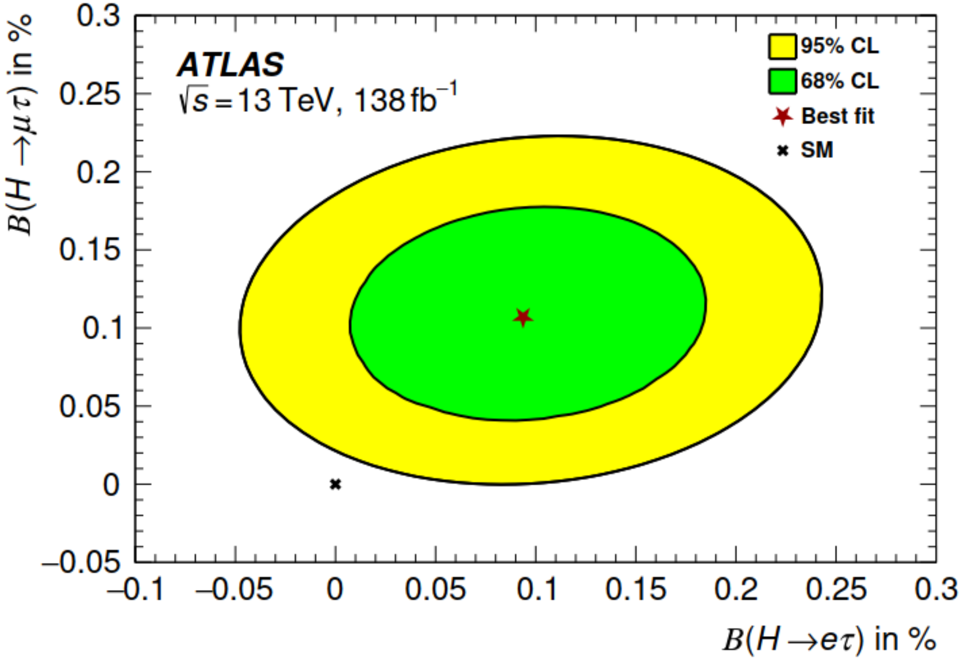
FCNC forbidden in SM imposing Z2 symmetry

Sheldon L. Glashow and Steven Weinberg Phys. Rev. D **15**, 1958

FCNC in Higgs sector: h125→μτ, eτ

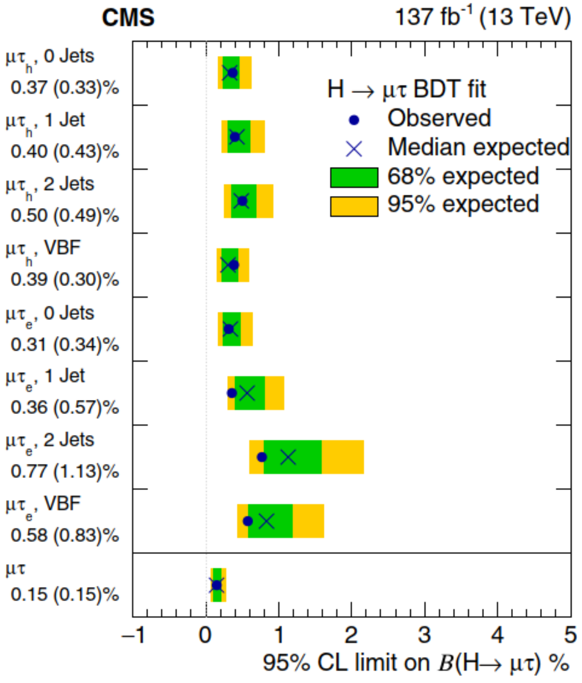
ATLAS
[JHEP07(2023)166]

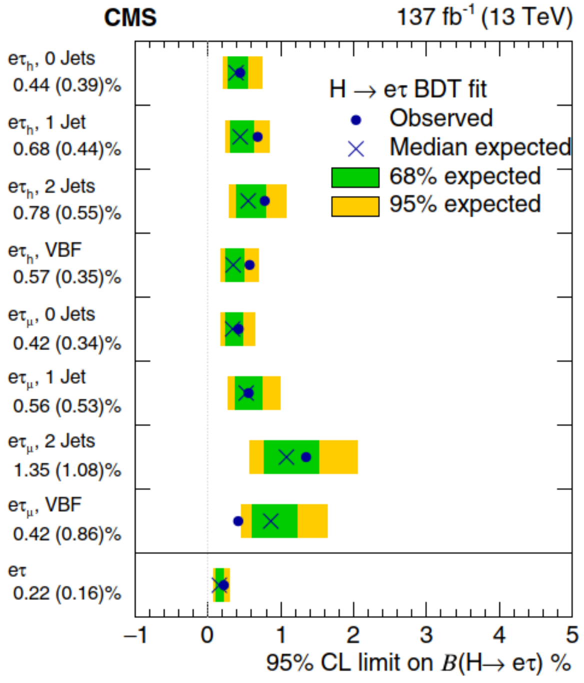
B(H → μτ) −B(H → eτ) measured is (0.25 ±0.10)%, compatible with zero within 2.5σ



CMS
[PHYSICAL REVIEW D 104, 032013 (2021)]

	Observed (expected) upper limits (%)	Best fit branching fractions (%)
$H \to \mu\tau$	<0.15 (0.15)	0.00 ± 0.07
$H \to e\tau$	<0.22 (0.16)	0.08 ± 0.08



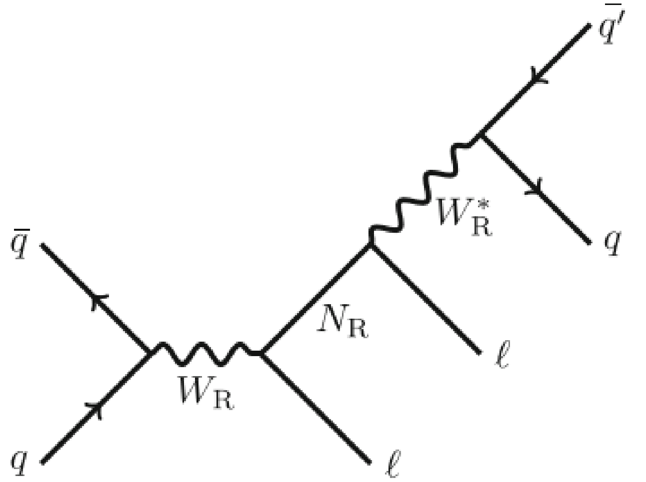


Mijorana neutrino.
searches for N_R and W_R in L-R SM

Pati, Salam '74
Mohapatra, Pati '74
Mohapatra, Senjanović '75
Senjanović '79

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \leftrightarrow \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

Left-Right Symmetry



Automatically implies massive neutrinos

$$m_\nu \overline{\nu_L} \nu_R$$

See-saw Mechanism

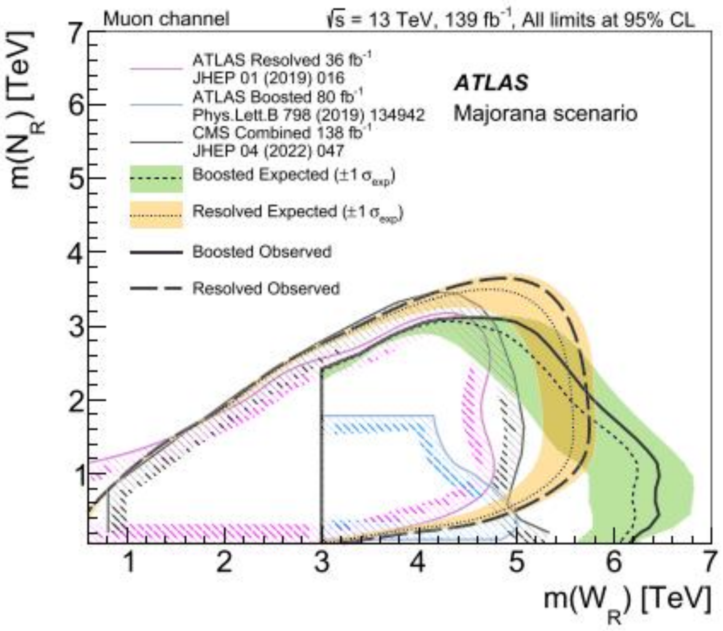
$$M_\nu = -M_D^T \frac{1}{M_N} M_D$$

$$M_D \propto \langle \Phi \rangle = v = \text{scale of } W_L$$
$$M_N \propto \langle \Delta_R \rangle = v_R = \text{scale of } W_R$$

$$m_\nu \propto \frac{M^2_{W_L}}{M_{W_R}}$$

Minkoswski '77
Mohapatra, Senjanović '79
Yanagida '79
Glashow '79
Gell-man et al. '79

Eur. Phys. J. C 83 (2023) 1164



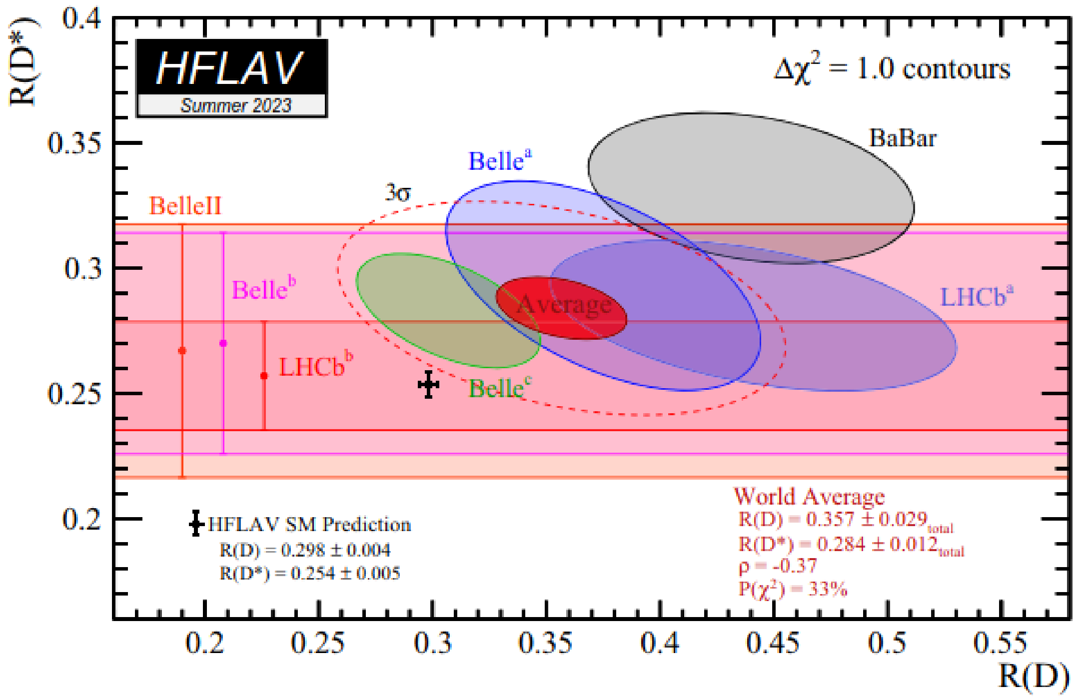
Lepton Number Violation in B-decays (LHCb)

[Eur. Phys. J. Spec. Top. 233, 225–240 (2024)]

Decay mode	Data analysed	Limit at 90% CL
$B^0 \to K^{*0}\mu^\pm e^\mp$	9 fb^{-1}	9.9×10^{-9}
$B_s \to \phi\mu^\pm e^\mp$	9 fb^{-1}	15.9×10^{-9}
$B^+ \to K^+\mu^- e^+$	3 fb^{-1}	7.0×10^{-9}
$B^+ \to K^+\mu^+ e^-$	3 fb^{-1}	6.4×10^{-9}
$B^+ \to K^+\mu^-\tau^+$	9 fb^{-1}	3.9×10^{-5}
$B_s \to \mu^\pm\tau^\mp$	3 fb^{-1}	3.9×10^{-5}
$B^0 \to \mu^\pm\tau^\mp$	3 fb^{-1}	1.2×10^{-5}
$B_s \to \mu^\pm e^\mp$	3 fb^{-1}	5.4×10^{-9}
$B^0 \to \mu^\pm e^\mp$	3 fb^{-1}	1.0×10^{-9}
$\tau \to 3\mu$	3 fb^{-1}	4.6×10^{-8}

Testing lepton universality ratios

Eur. Phys. J. Spec. Top. 233, 225–240 (2024)



$$\mathcal{R}(D^*) \equiv \mathcal{B}\left(\overline{B} \to D^*\tau^-\overline{\nu}_\tau\right)/\mathcal{B}\left(\overline{B} \to D^*\ell^-\overline{\nu}_\ell\right)$$

$$\mathcal{R}(D) \equiv \mathcal{B}\left(\overline{B} \to D\tau^-\overline{\nu}_\tau\right)/\mathcal{B}\left(\overline{B} \to D\ell^-\overline{\nu}_\ell\right)$$

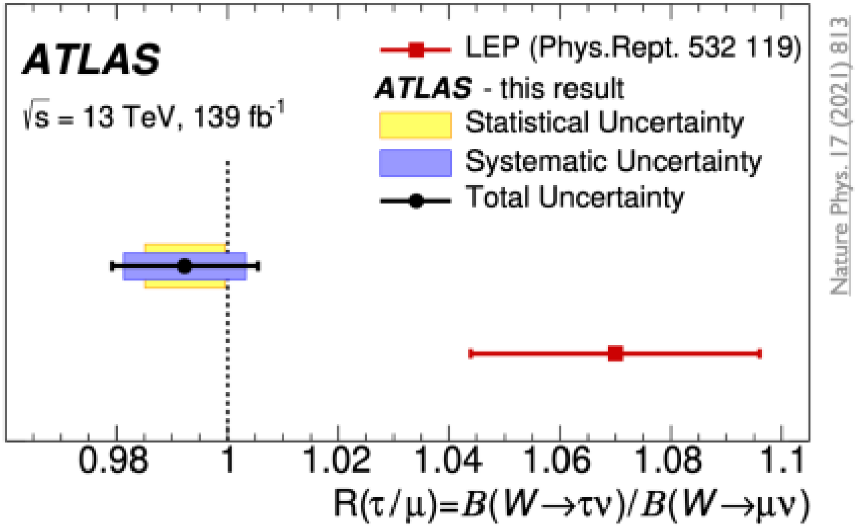
The combined average is 3.3σ tension with the Standard Mode

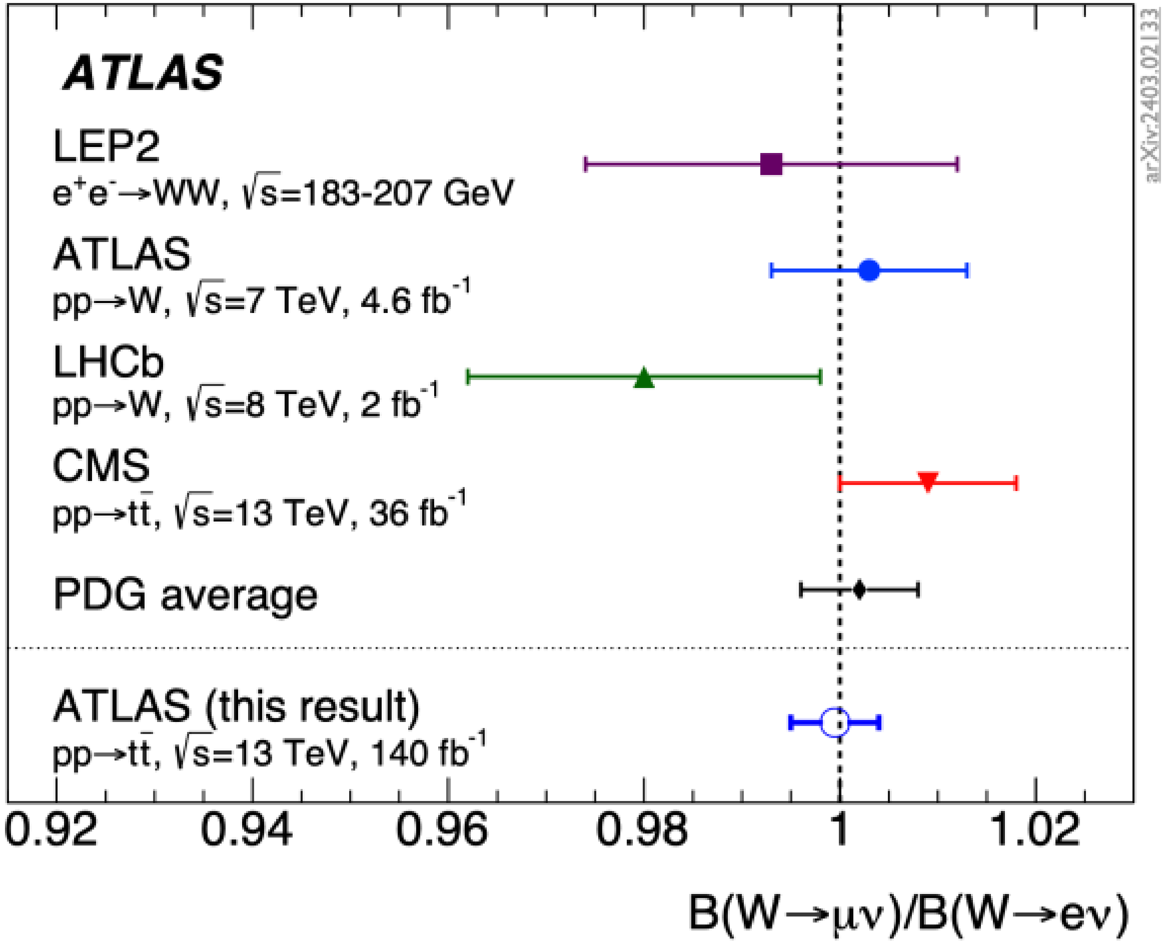
Lepton Universality in W decays

Recent result from ATLAS: W decays to electrons and muons from top-pair events

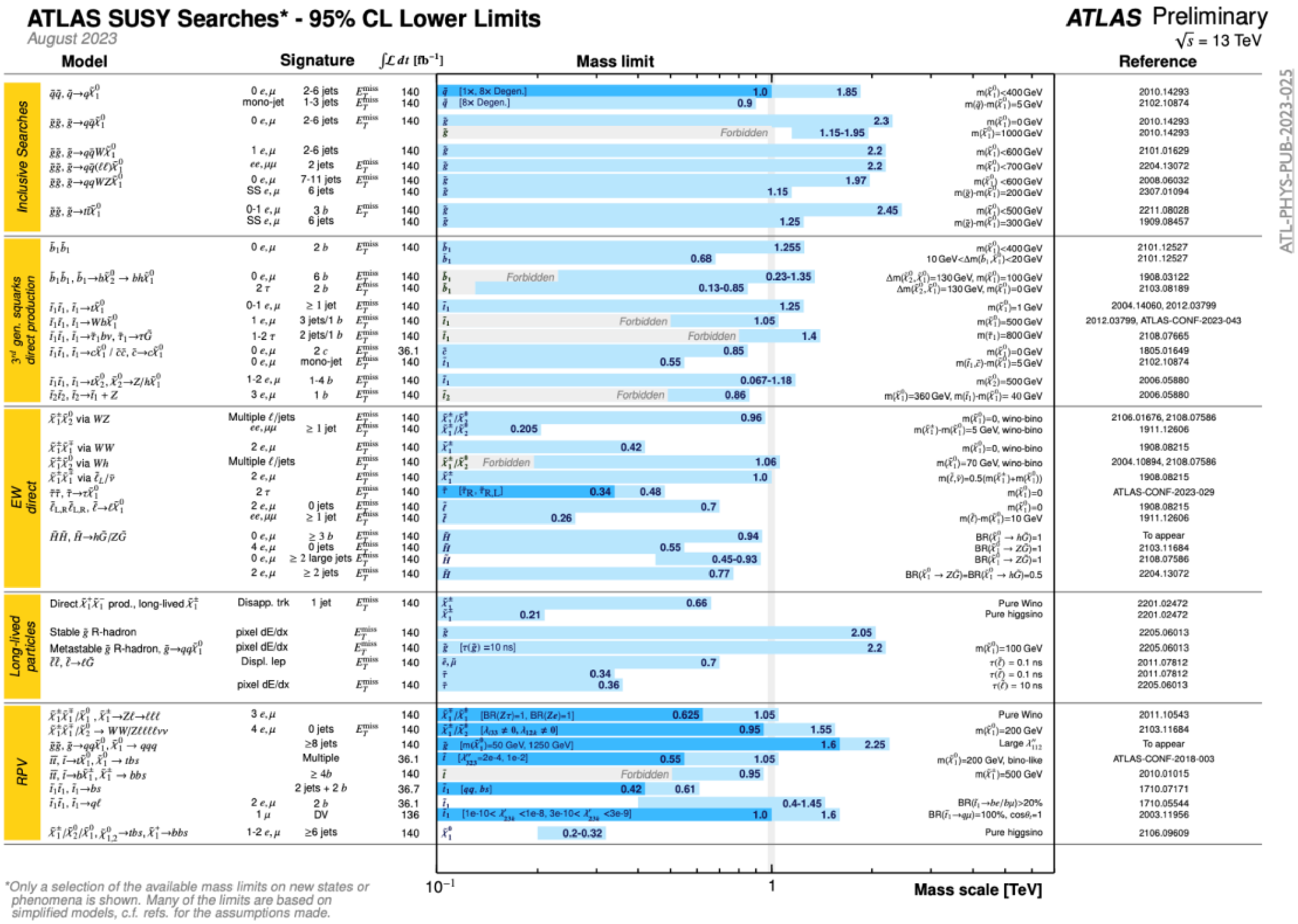
- **2x improvement on single-experiment precision**

Nature Phys. 17 (2021) 813





Searches for SUSY particles

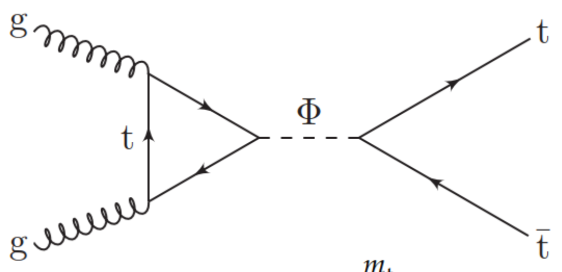


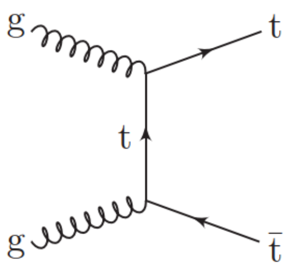
Excitements at the end:

some event excesses observed in CMS in searches for BSM Higgs bosons

Search for A/H→tt in CMS (CMS PAS HIG-22-013)

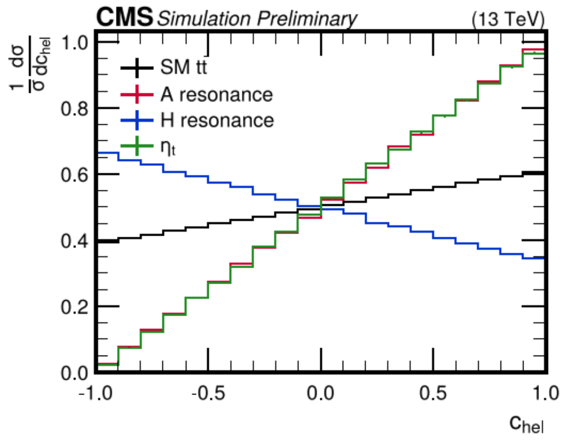
- **toponium (arXiv:2104.01927) or pseudoscalar Higgs boson observation at ≈2m_t mass near threshold ?**





$$\mathcal{L}_{\mathrm{Yukawa,A}} = i g_{\mathrm{At\bar{t}}} \frac{m_t}{v} \bar{t}\gamma_5 t A,$$

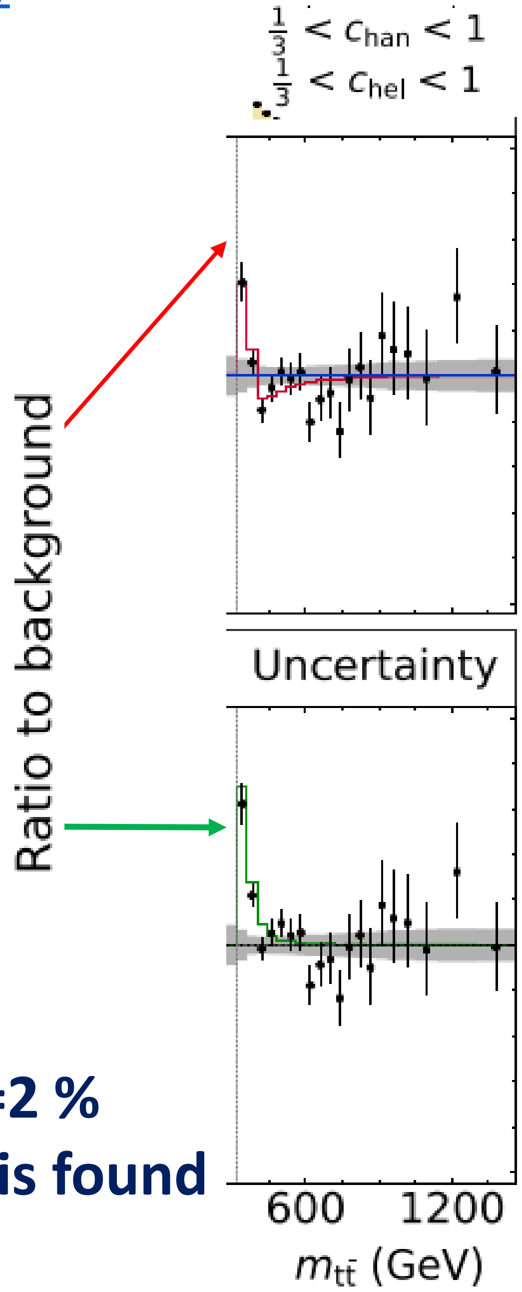
$$\mathcal{L}_{\mathrm{Yukawa,H}} = -g_{\mathrm{Ht\bar{t}}} \frac{m_t}{v} \bar{t} t H,$$



Postfit (BG + A/H) — A(365, 2%), $g_A = 0.75 \pm 0.03$ — H(365, 2%), $g_H = 0.0 \pm 0.27$ — Uncertainty

Postfit (BG + η_t) — η_t, $\mu(\eta_t) = 1.11 \pm 0.12$ — Uncertainty

. The η_t mass and width are set to 343 and 7 GeV, respectively.



for η_t only fit $\sigma(\eta_t)$= 7.1 pb (11 % error) agrees with σ_{th}=6.43 pb

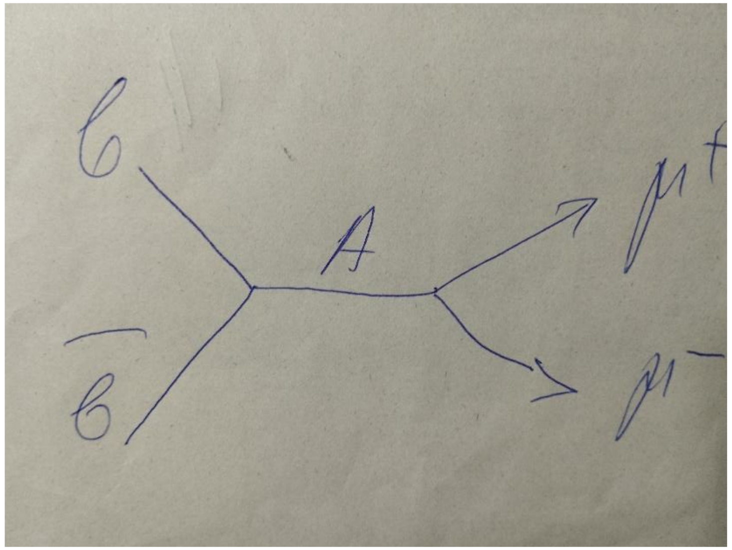
for single Φ only fit the best significance (> 5) for A with m_A=365 GeV, Γ_A=2 %

for single Φ only fit with η_t included as bkg. with floating $\sigma(\eta_t)$ no excess is found

Search for dimuon resonance with mass of ≈28 GeV in $\mu^+\mu^-$ + b-jet events using CMS Run I and Run II data

Motivation of $\mu^+\mu^-$+b analysis

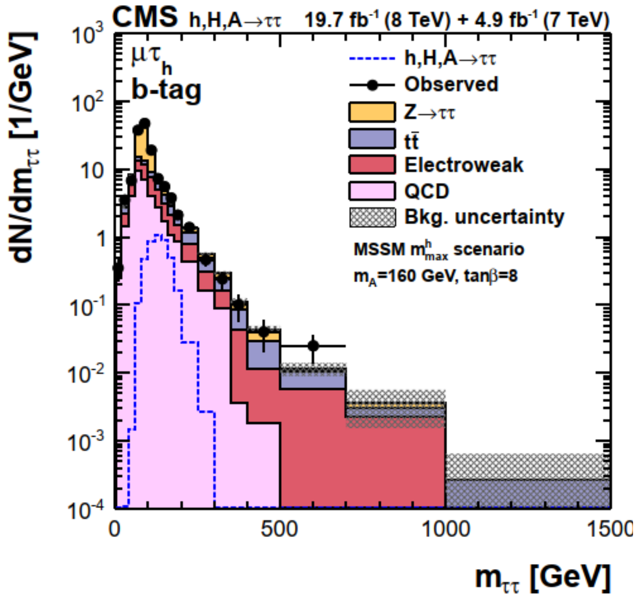
- **M.M. Almarashi and S. Moretti,**
  "Low mass Higgs signals at the LHC in NMSSM" ,
  [Eur. Phys. J. C71 (2011) 1618]
- **J. Bernon, J. F. Gunion, Y. Jiang, and S. Kraml,**
  "Light Higgs bosons in two-Higgs-doublet models",
  [Phys. Rev. D 91 (2015) 075019]



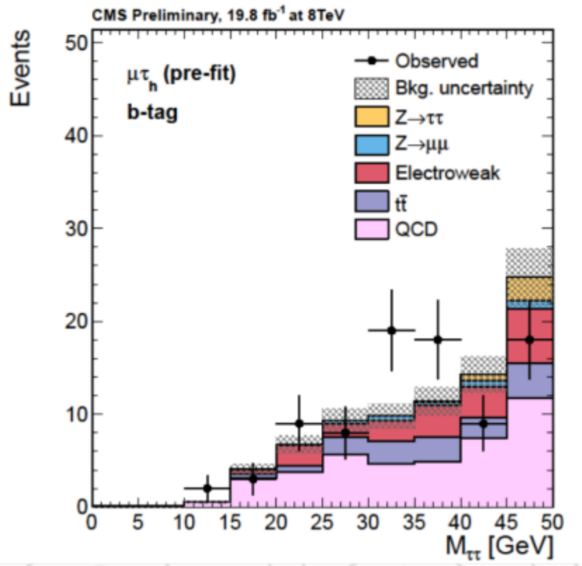
Selections

- $p_T^{\mu_1} > 25\,\text{GeV},\ |\eta_{\mu_1}| < 2.1;$
- $p_T^{\mu_2} > 5\,\text{GeV},\ |\eta_{\mu_2}| < 2.4;$
- $p_T^{\text{b jet}} > 20\,\text{GeV and } |\eta| < 2.4;$
- $p_T^{\text{miss}} < 40\,\text{GeV}.$

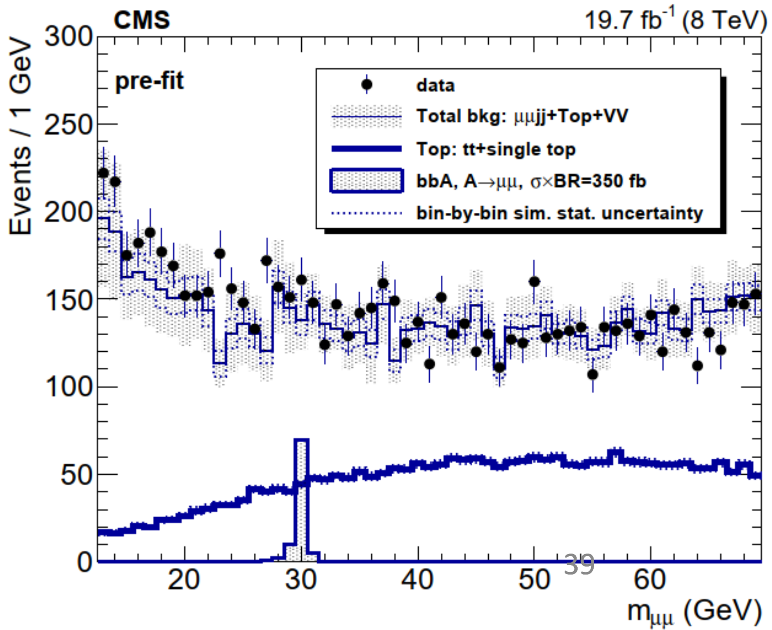
JHEP 10 (2014) 160



zoom at low mass

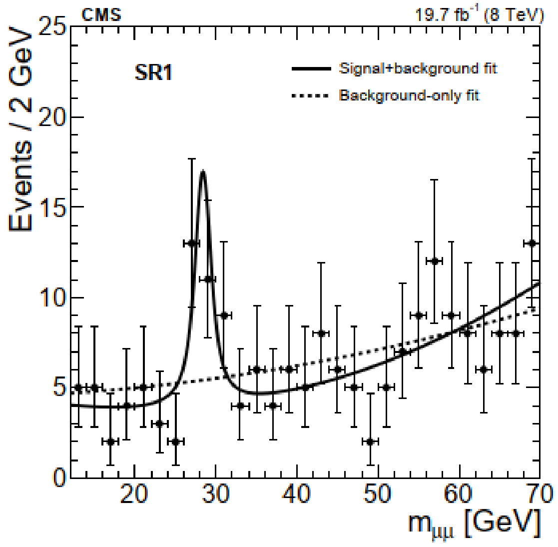


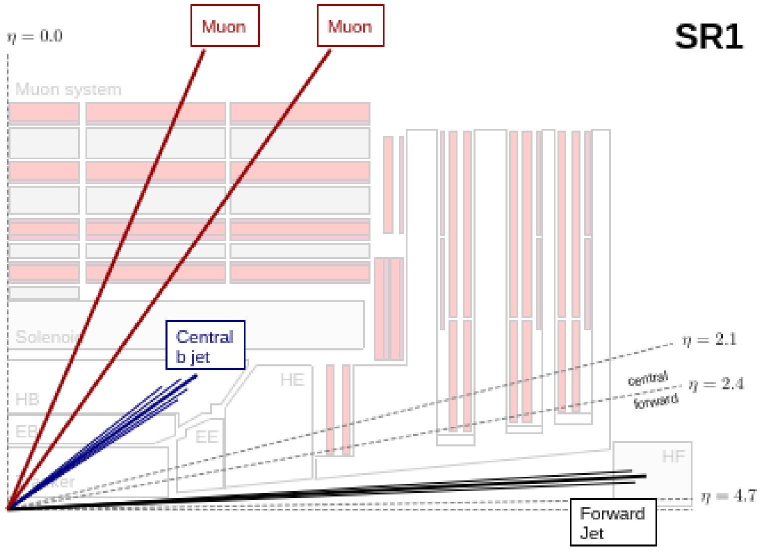
JHEP 11 (2017) 010

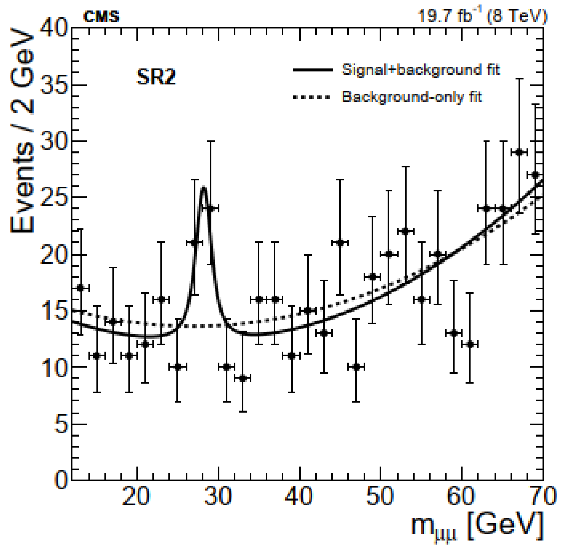


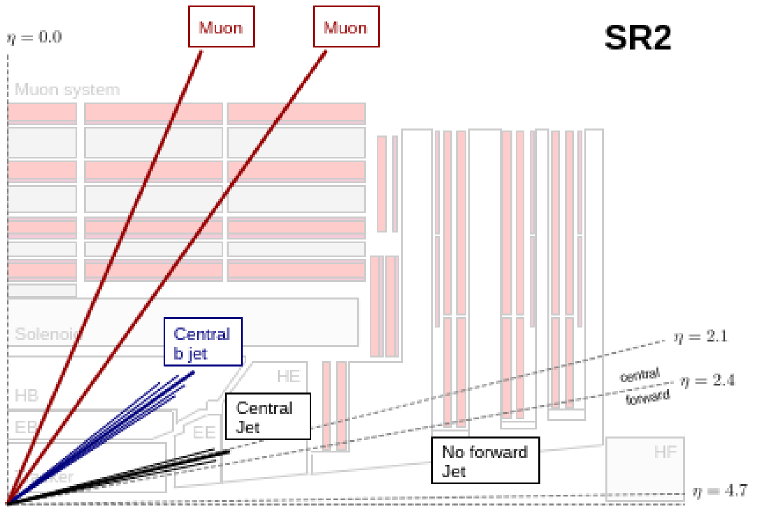
Observation of event excess at 8 TeV in 2014

- **due to good luck:** selection $p_T^{\mu 1,2}$>25 GeV instead of 25,10 GeV was applied due to typo in code for Search Region 1 (SR1)
- once bump was observed in SR1 Higgs PAG conveners wanted to be convinced by finding the same bump in different event category (SR2). **It was done.**

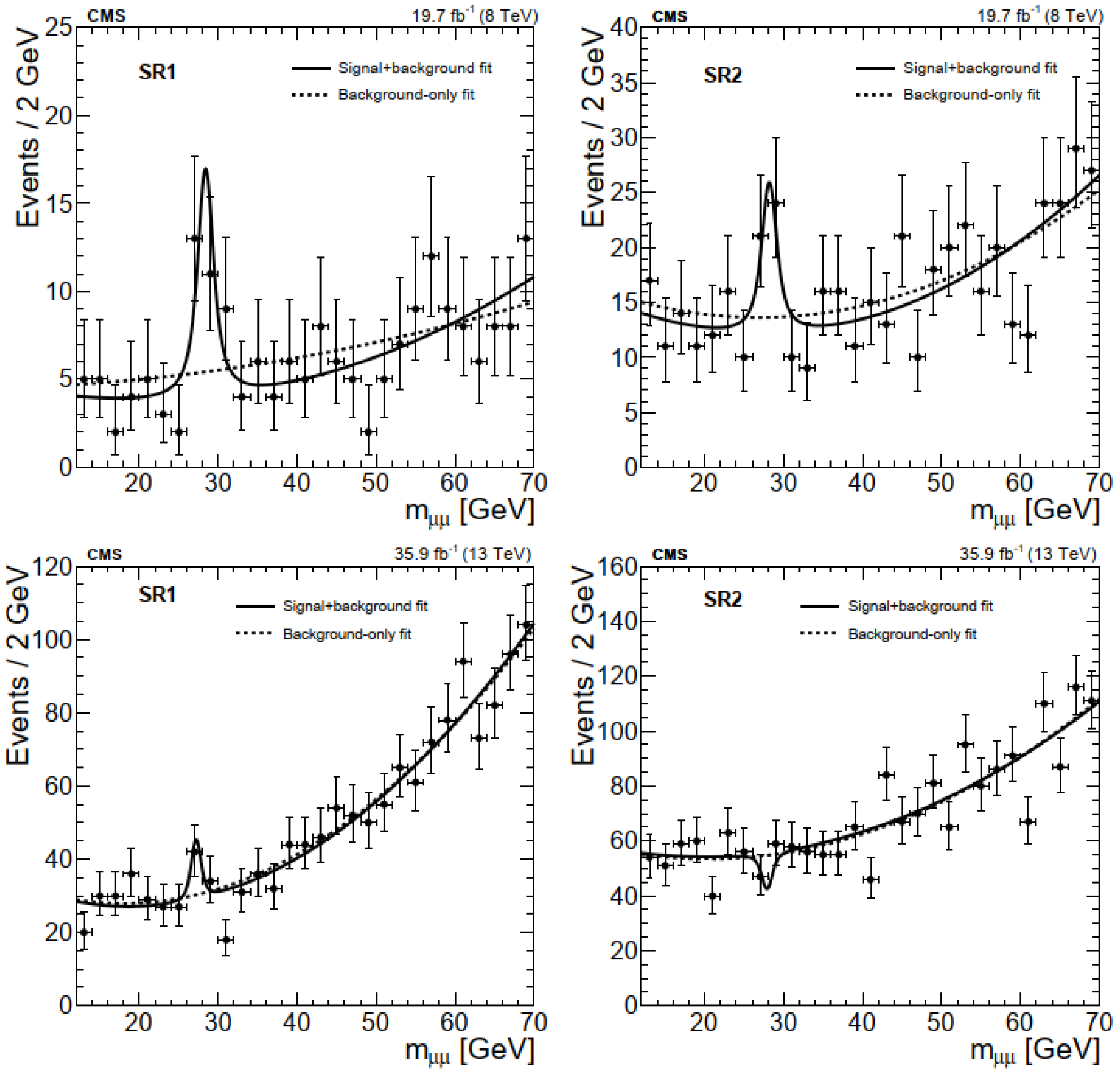








Once paper of 8 TeV analysis was ready to be out in 2016 we were requested to add 13 TeV 2016 data with the same selection. We published analysis (JHEP 11 (2018) 161) 2 years later in 2018.



Event category	SR1 Additional forward jet	SR2 Additional central jet
Muons	OS, $p_T > 25$ GeV, $\|\eta\| < 2.1$	
$m_{\mu\mu}$	$m_{\mu\mu} > 12$ GeV	
b-tagged jet	$p_T > 30$ GeV, $\|\eta\| \leq 2.4$	
Additional jet	$p_T > 30$ GeV, $2.4 < \|\eta\| < 4.7$	$p_T > 30$ GeV, $\|\eta\| \leq 2.4$
Jet veto	No other jets $p_T > 30$ GeV, $\|\eta\| \leq 2.4$	No jets $p_T > 30$ GeV, $2.4 < \|\eta\| < 4.7$
p_T^{miss}	—	<40 GeV
$\Delta\phi(\mu\mu, jj)$	—	>2.5 rad

Event category	SR1 Additional forward jet	SR2 Additional central jet
m_X (GeV)	28.4± 0.6	28.2± 0.7
$\Gamma_{\mu\mu}$ (GeV)	1.9±1.3	1.9±1.1

$\sqrt{s}$ (TeV)	8		13	
Event category	SR1	SR2	SR1	SR2
Local significance (s.d.)	4.2	2.9	2.0	1.4 deficit
m_X (GeV)	28.3± 0.4		27.2±0.6	
$\Gamma_{\mu\mu}$ (GeV)	1.8±0.8		0.7±1.0	
N_S	22.0 ± 7.6	22.8 ± 9.5	14.5 ± 9.3	-14.9 ± 10.1

M. Mangano: no observation at 13 TeV might be explained by the increase of tt background by a factor of 3.3

Analysis is on the way with full Run II data and re-optimized muon sélections using 13 TeV 2016 data. Stay tuned.

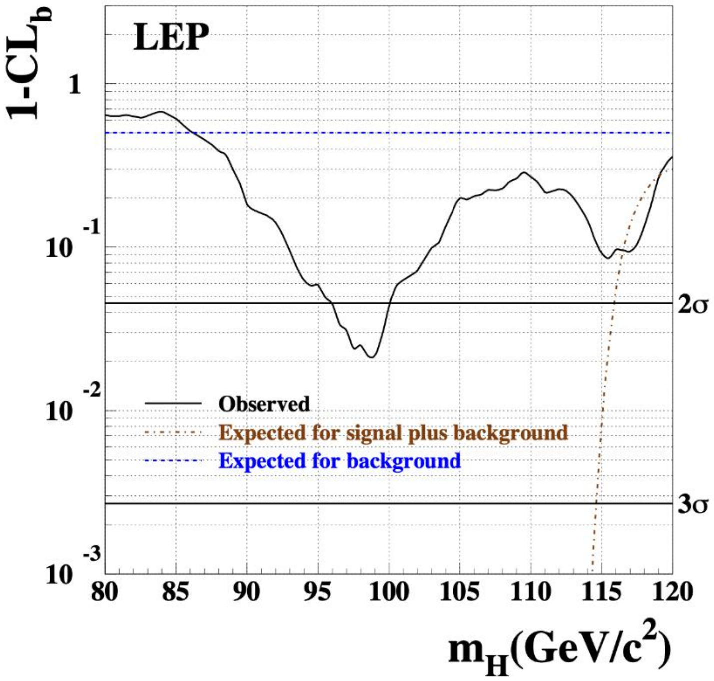
Conclusions

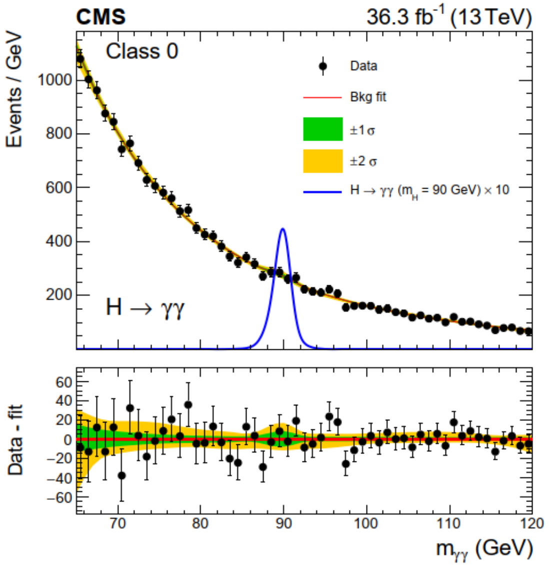
- very reach program for BSM physics at LHC and HL-LHC
- we hope for BSM discovery with Run II+III data and at HL-LHC

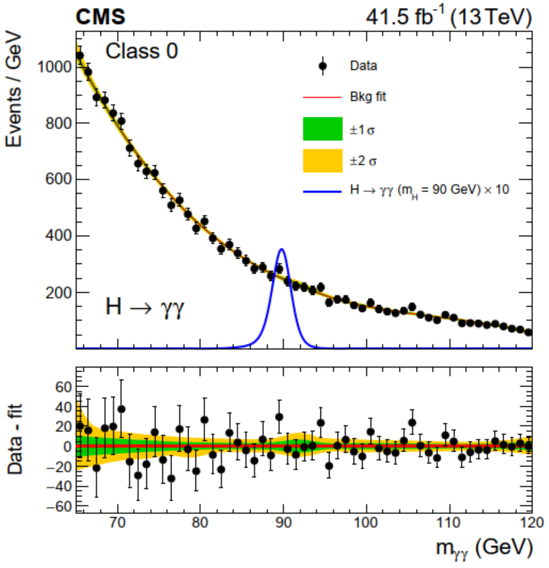
THE END

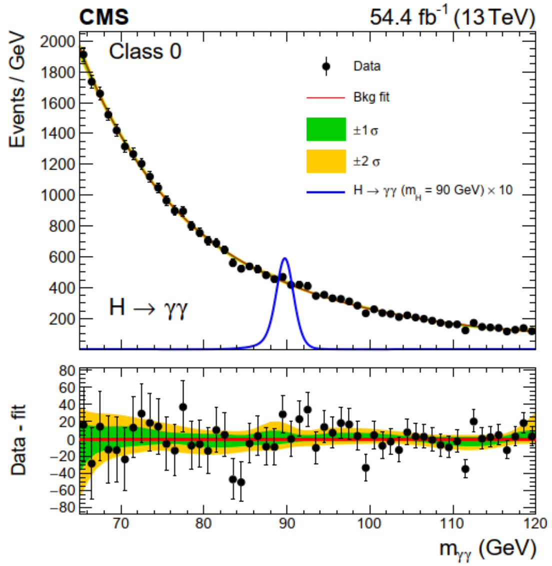
h95 GeV

[Phys. Lett. B 565 (2003) 61–75](#)

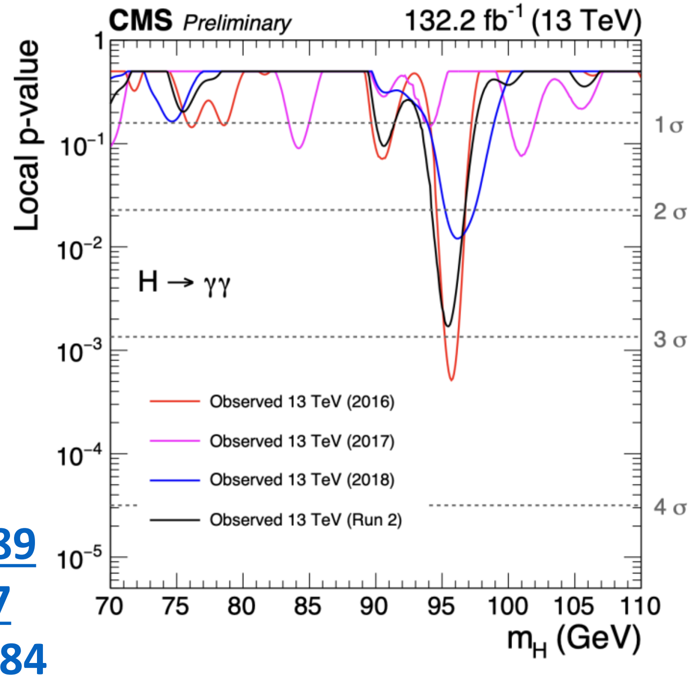




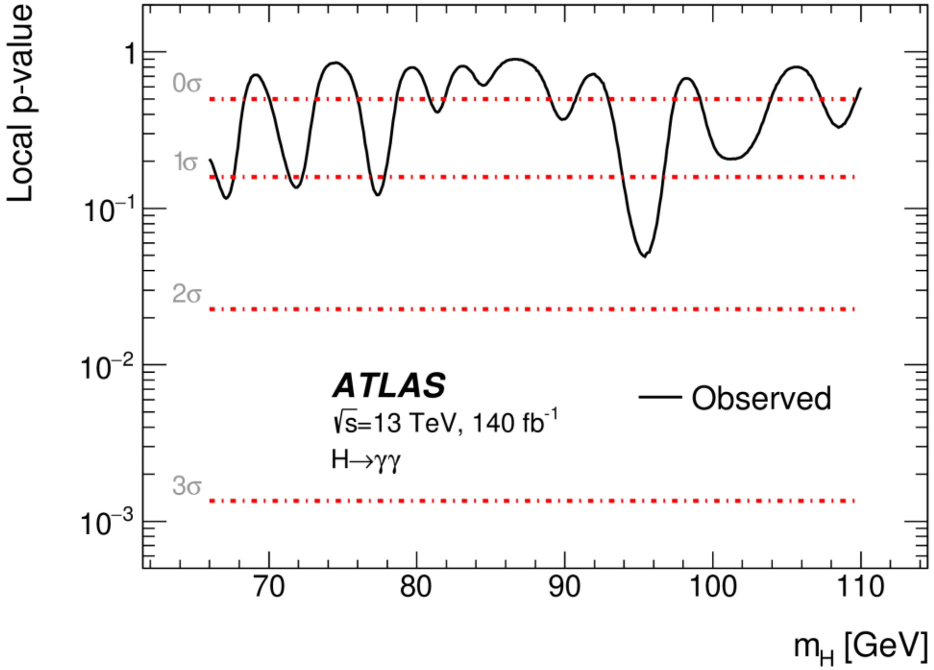




[arXiv:2405.18149](#)



[arXiv:2407.07546](#)



CMS: event classification according to di-photon BDT score (Class 0, 1, 2) + VBF in 2017, 2018
Class 0 has a largest sensitivity

can be explained in S2HDM, [arXiv:2306.03889](#)
can be explained in 2HDM, [JHEP11(2023)017](#)
can be explained in NMSSM, [arXiv:2403.16884](#)

Two Higgs Doublet Model (I)

Consider two complex EW doublets

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} \qquad \langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

- For the correct gauge bosons mass $v_1^2 + v_2^2 = v^2 \approx (246)^2$ GeV^2

Higgs potential

$$\mathcal{V} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\}. \quad (1)$$

parameters λ_6,λ_7=0 as result of Z_2 symmetry imposed to avoid FCNC (Φ_1->Φ_1, Φ_2->-Φ_2)

Soft Z_2 symmetry breaking: m_{12} != 0

m_{12} != 0 to have a new mass scale. This allows the model to have a decoupling limit.
when m_{12} goes to infinity we recover the SM

Two Higgs Doublet Model (II)

Yukawa interaction with fermions

$$-\mathscr{L}_{\rm Yuk} = \mathcal{Y}_b^1 \bar{b}_R \Phi_1^{i\,*} Q_L^i + \mathcal{Y}_b^2 \bar{b}_R \Phi_2^{i\,*} Q_L^i + \mathcal{Y}_\tau^1 \bar{\tau}_R \Phi_1^{i\,*} L_L^i + \mathcal{Y}_\tau^2 \bar{\tau}_R \Phi_2^{i\,*} L_L^i + \epsilon_{ij} \left[\mathcal{Y}_t^1 \bar{t}_R Q_L^i \Phi_1^j + \mathcal{Y}_t^2 \bar{t}_R Q_L^i \Phi_2^j \right] + \text{h.c.}$$

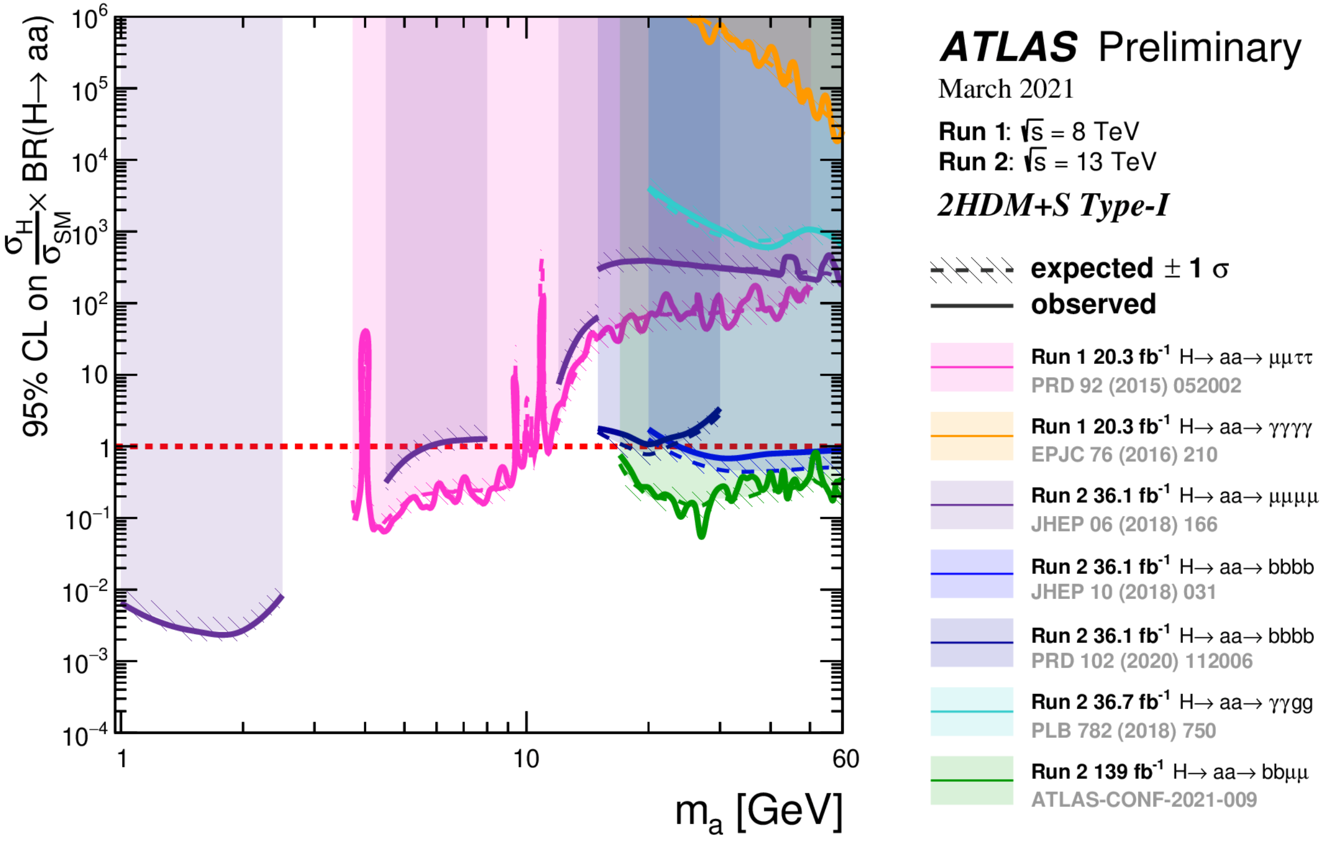
Four possible Z_2 charge assignments that forbid tree-level Higgs-mediated FCNC effects in the 2HDM

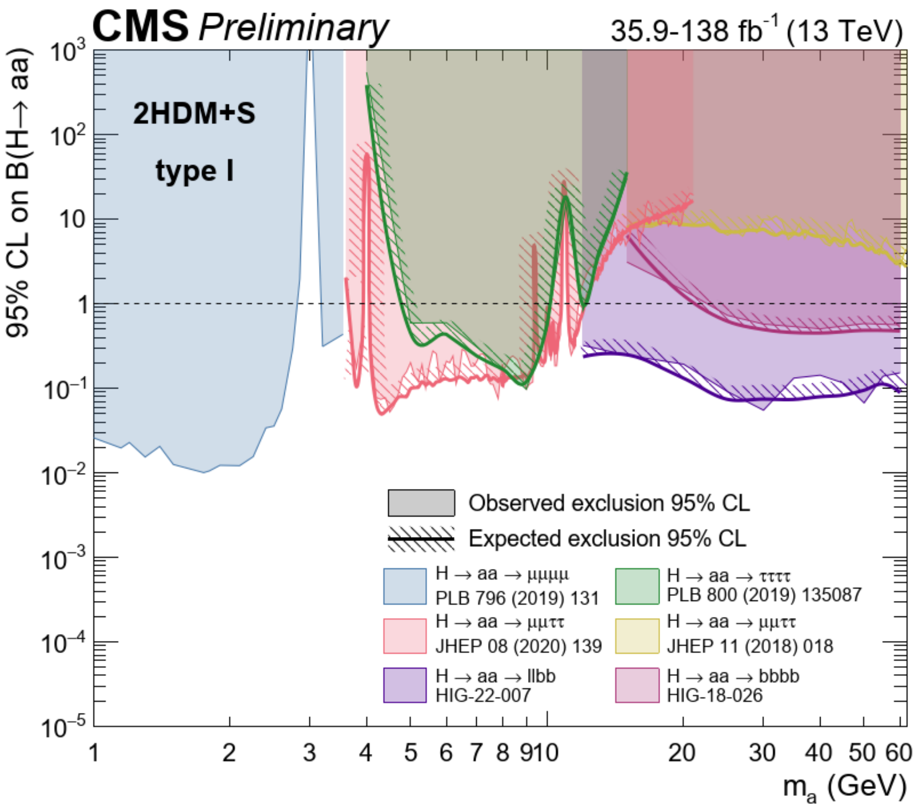
	Φ_1	Φ_2	t_R	b_R	τ_R	t_L, b_L, ν_L, e_L
Type I	$+$	$-$	$-$	$-$	$-$	$+$
Type II	$+$	$-$	$-$	$+$	$+$	$+$
Type X (lepton specific)	$+$	$-$	$-$	$-$	$+$	$+$
Type Y (flipped)	$+$	$-$	$-$	$+$	$-$	$+$

	u-type	d-type	leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

same as in MSSM (← Type II)

Searches for h_{125} decay to aa(hh) vs models (II)





Regions 3-5, 9-11 GeV are covered with calculations taking into account effect of mixing of pseudoscalar and η_c, η_b states ($h \to \eta_b \eta_c \to aa$, $\eta_b a \to aa$, ...). U. Haisch et al. arXiv:1802.02156