BSM Higgs in ATLAS and CMS 12 years later

at LHC Day in Split, 2022

A. Nikitenko,

Kurchatov Institute(ITEP), Moscow, Russia

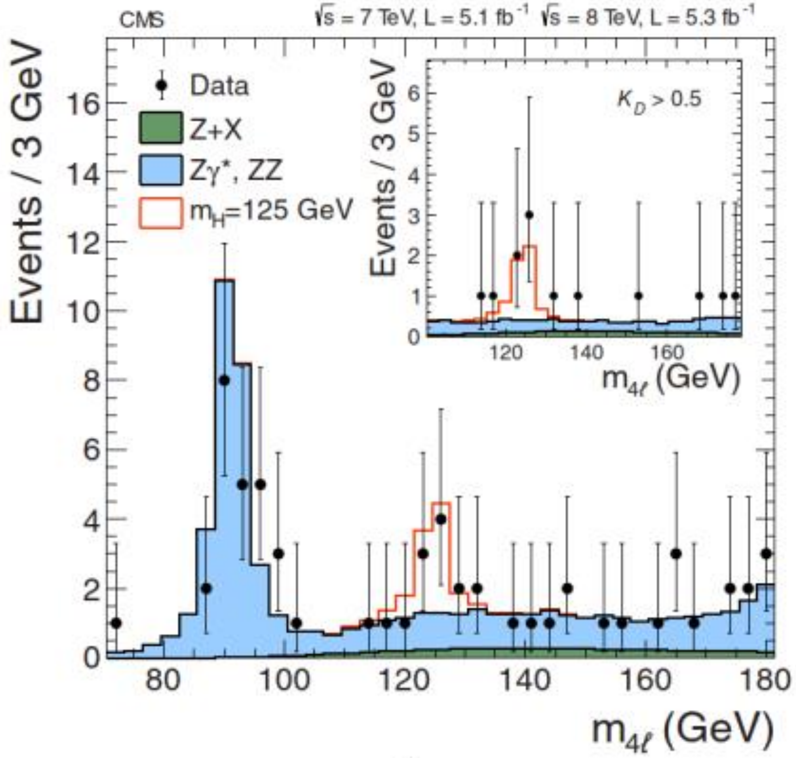
also Imperial College, London, UK

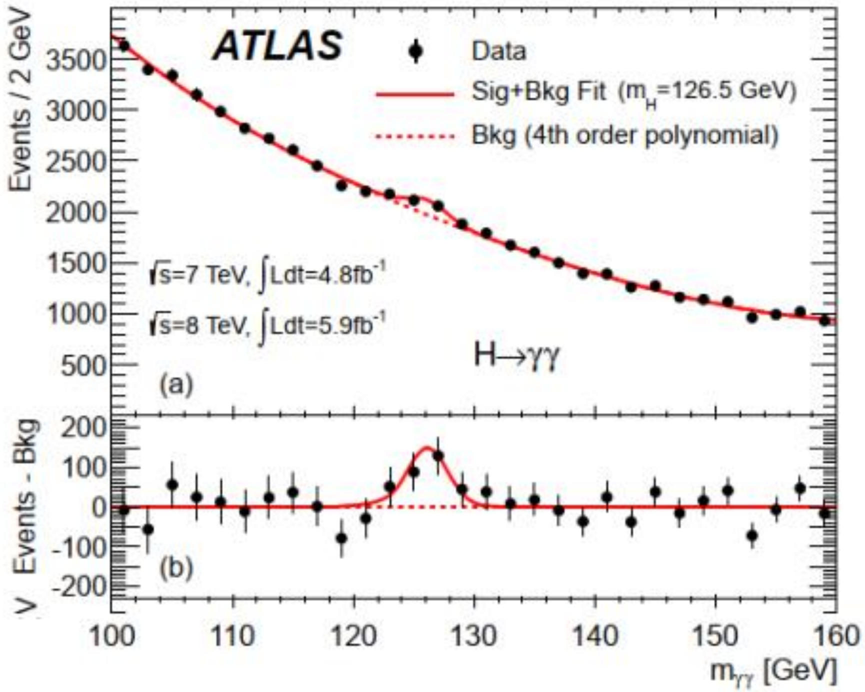
In 2012 SUSY people were happy to say:

h_{125} is the first discovered SUSY particle

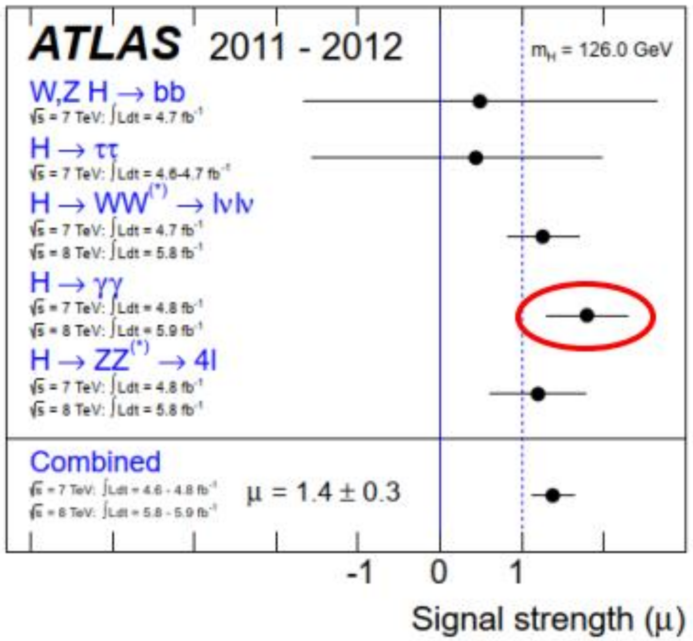
A lot of SUSY (and BSM) analyses in Higgs sector are still going on these days in ATLAS and CMS

Discovery papers, 2012

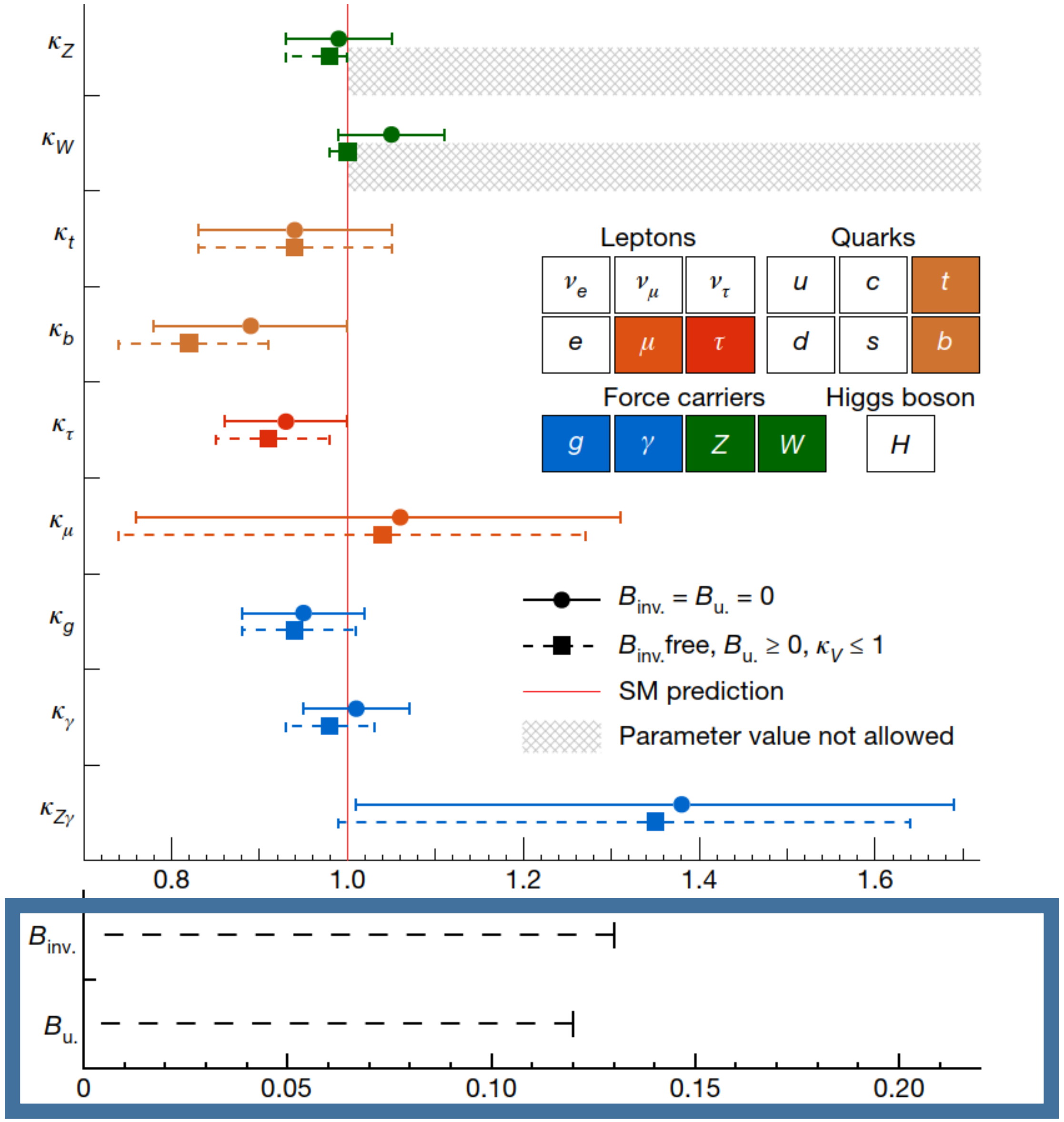




Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.8	3.2
$\tau\tau$ + bb	2.4	0.5
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0



Summary of coupling strength modifiers for h_{125}



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

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

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)

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”**

Additional Higgs bosons

in MSSM

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

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

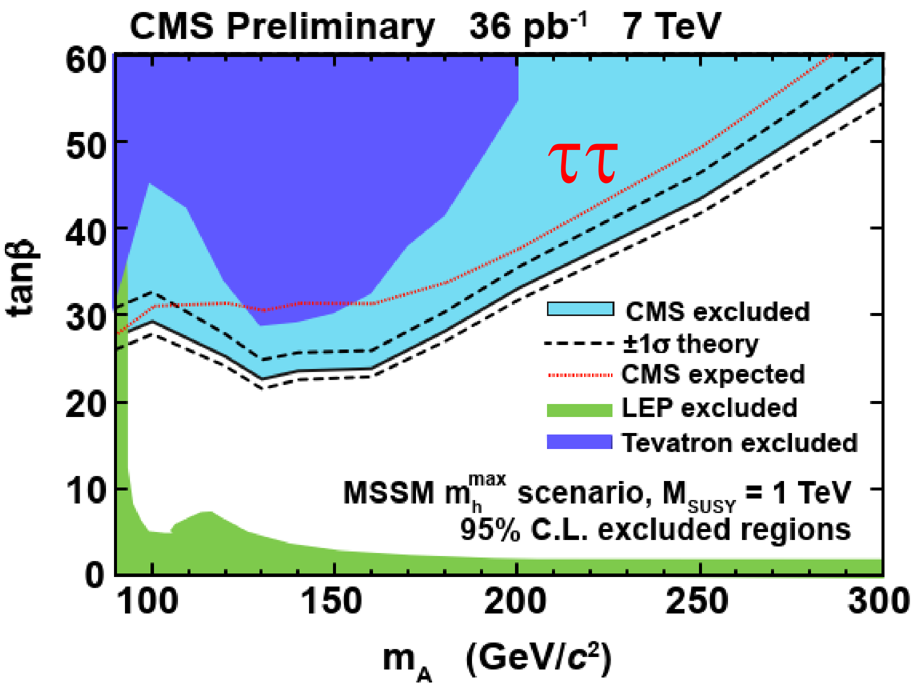
At tree level Higgs sector of MSSM is determined by only two parameters:

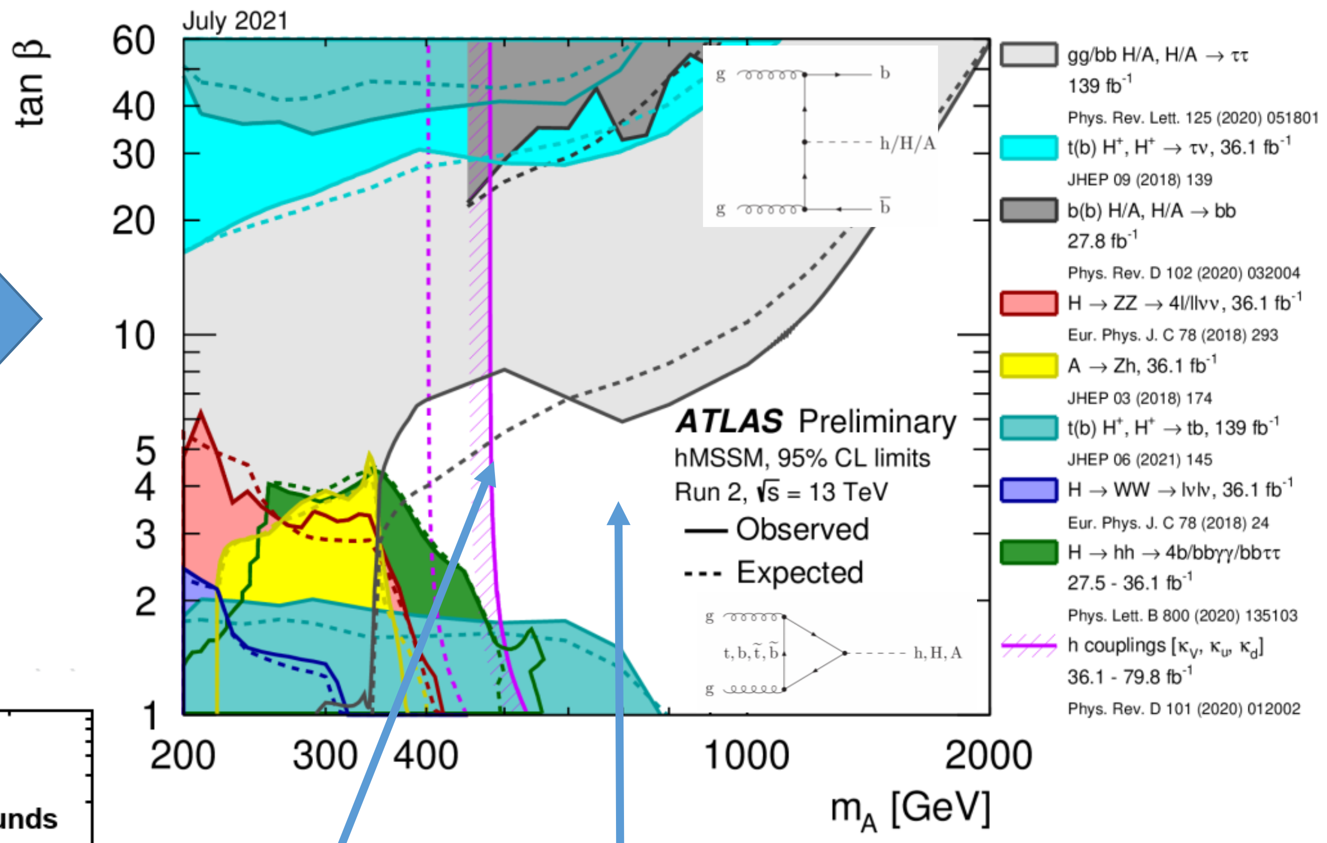
M_A and $\tan(\beta)$

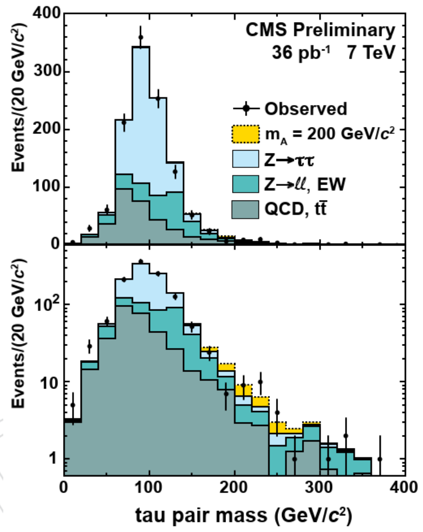
$1 < \tan(\beta) = v_2/v_1 = (v \sin(\beta)) / (v \cos(\beta)) < 60$

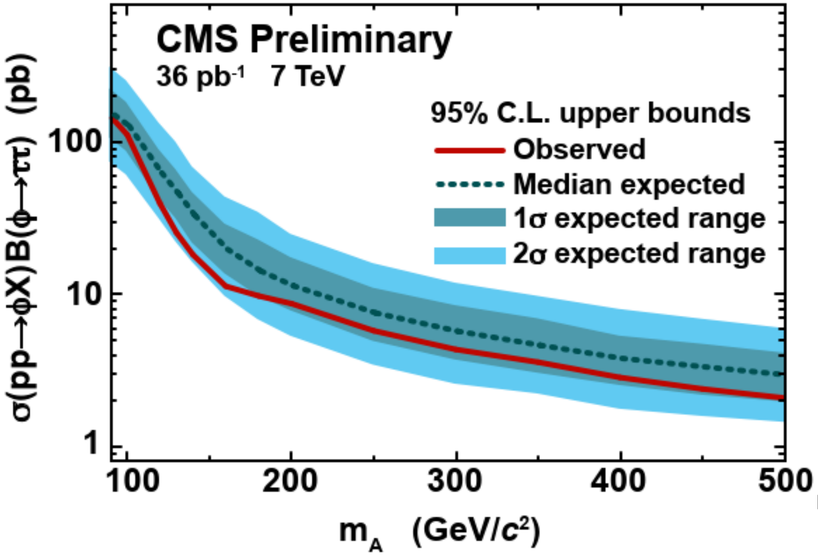
From 2010 to 2022 in MSSM neutral Higgs searches

CMS PAS HIG-10-002









H/A->χχ still to be done

from h125 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:

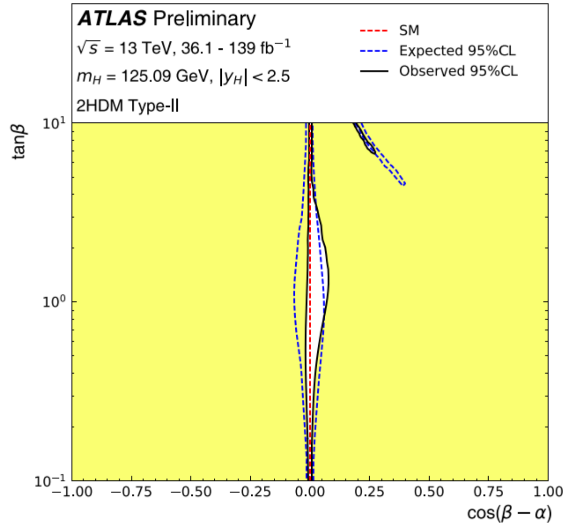
m_h, m_H, m_A, m_{H+}, α, tanβ, m_{12} (soft Z_2 symmetry (Φ_1->Φ_1, Φ_2->-Φ_2) breaking parameter)

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**

	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
$W^{\pm}H^{\mp}h$	$W^{\pm}H^{\mp}H$

ATLAS-CONF-2021-053

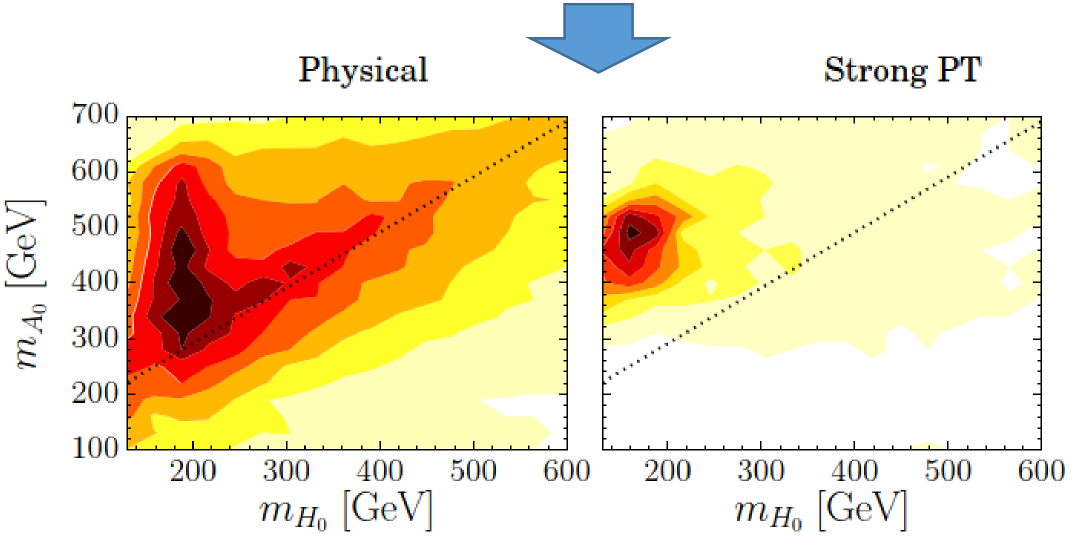


Anaysis which does not make a sence in MSSM but does in 2HDM: **A(H)→ZH(A), h=h_{125}**

- **contrary to MSSM**
  - **A-boson can have a small mass**
  - **m_A !≈ m_H at large masses**
- **A→ZH decay 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 more recent:

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 or CPT violation.

The EW phase transition must be a first order

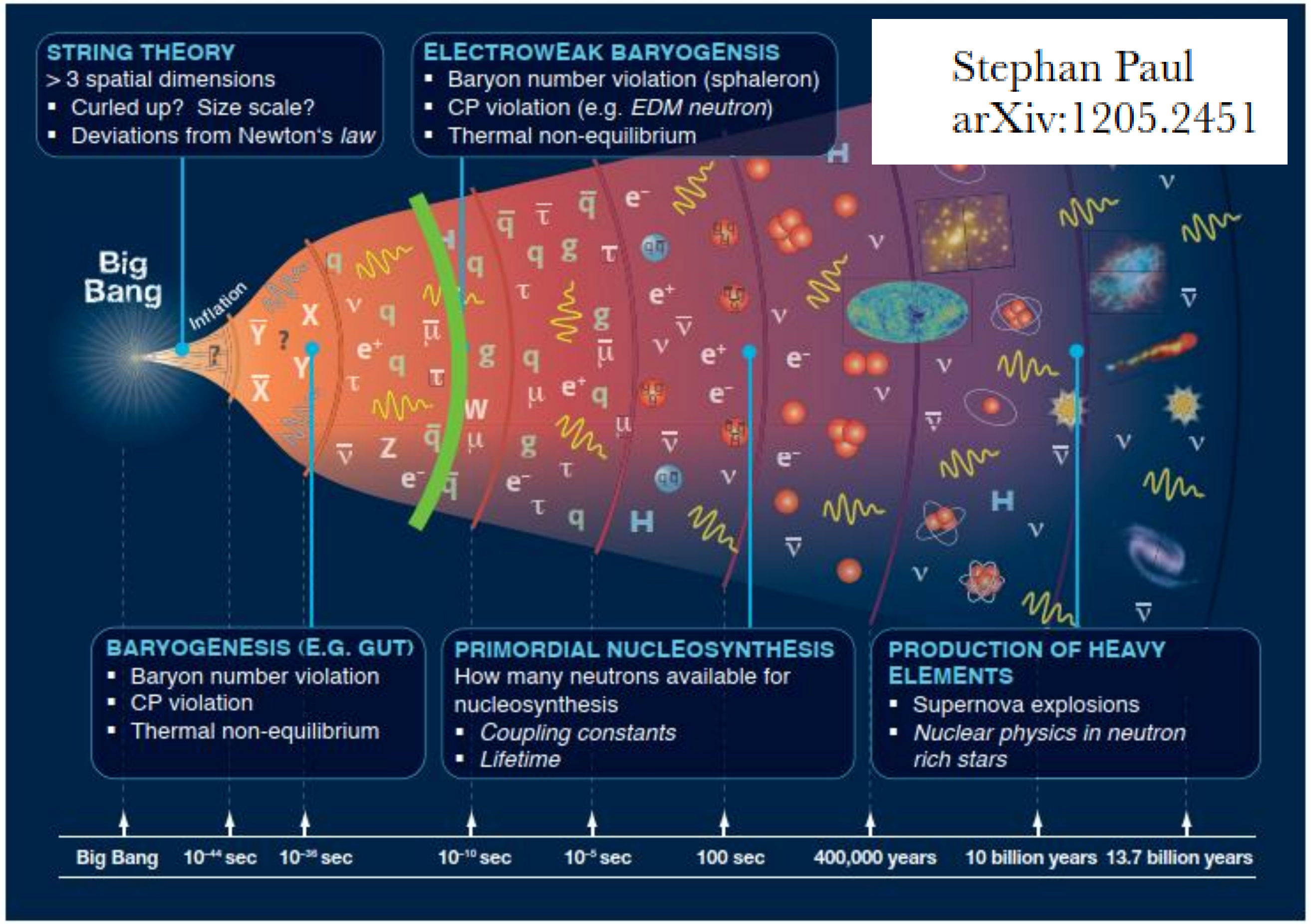
$$\xi_c \equiv \frac{\langle \Phi_c \rangle}{T_c} \geq 1$$

→

M. E. Shaposhnikov,
Journal of Experimental
and Theoretical Physics Letters,
Vol. 44, 1986, pp. 465-468

A. I. Bochkarev and M. E. Shaposhnikov,
Modern Physics Letters A,
Vol. 2, No. 6, 1987, pp. 417-427.

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



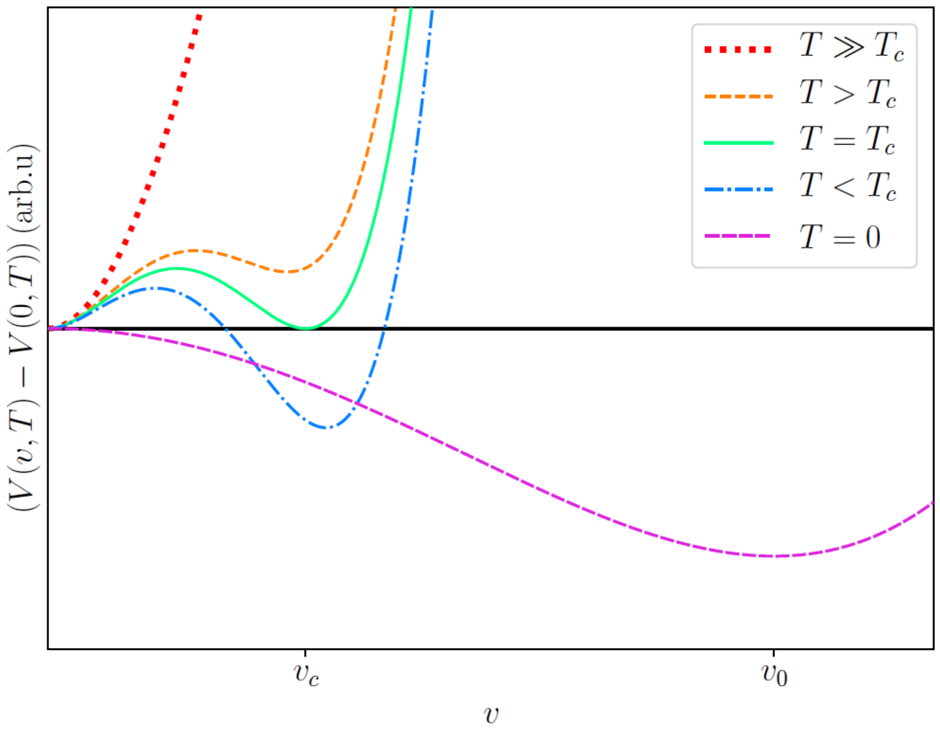


Figure 4.1.: The electroweak potential V at different temperatures as a function of the expectation value v of the Higgs field at fixed temperatures.

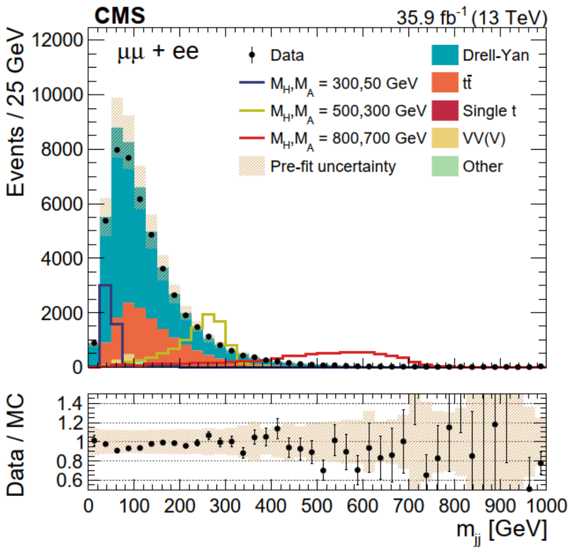
Philip Basler's PhD thesis, KIT

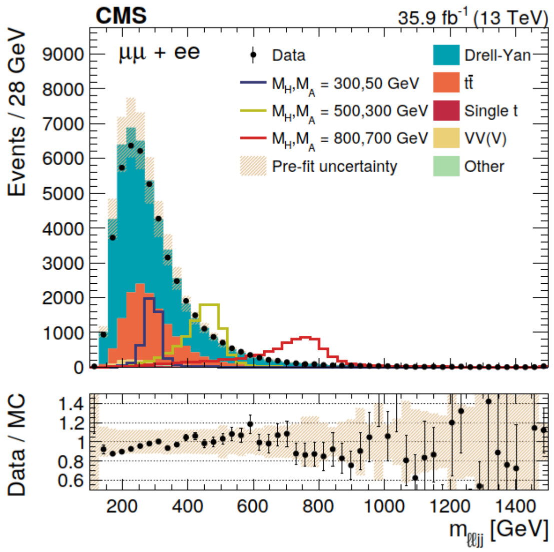
Condition for EWPT to be of strong first-order:

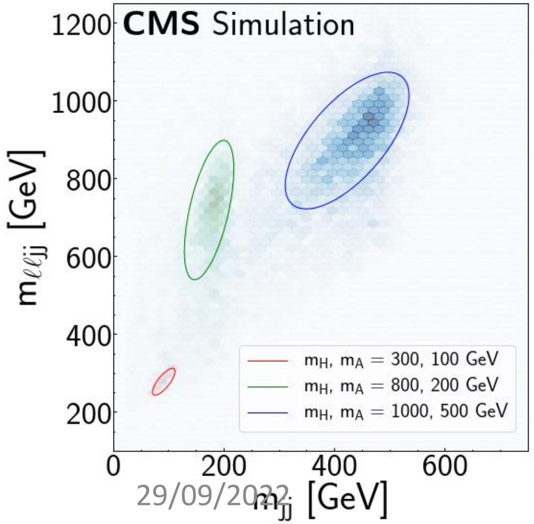
$$\xi_c \equiv \frac{v_c}{T_c} \gtrsim 1\,, \qquad (14)$$

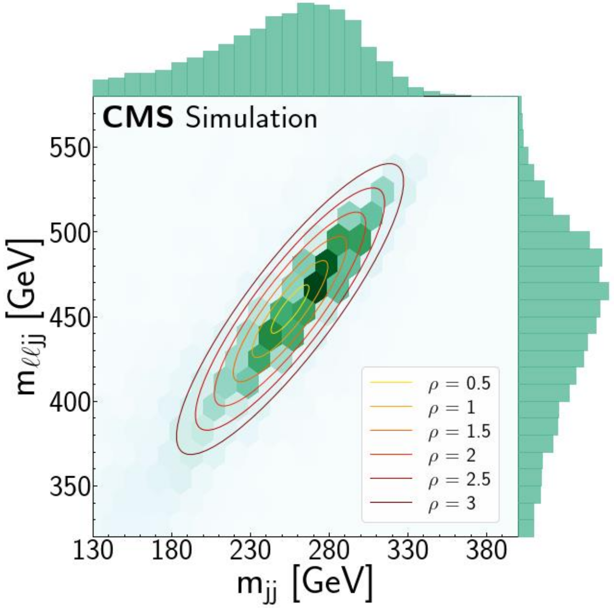
where $v_c \equiv \sqrt{\omega_1^2 + \omega_2^2}|_{T_c}$ is the Higgs VEV at the critical temperature T_c, which is defined when the would-be true vacuum and false vacuum are degenerate.

Analysis of 2D $m_{jj} - m_{\ell\ell jj}$ distributions using $\ell\ell$+two b-tag jet events, $70<m_{\ell\ell}<110$ GeV



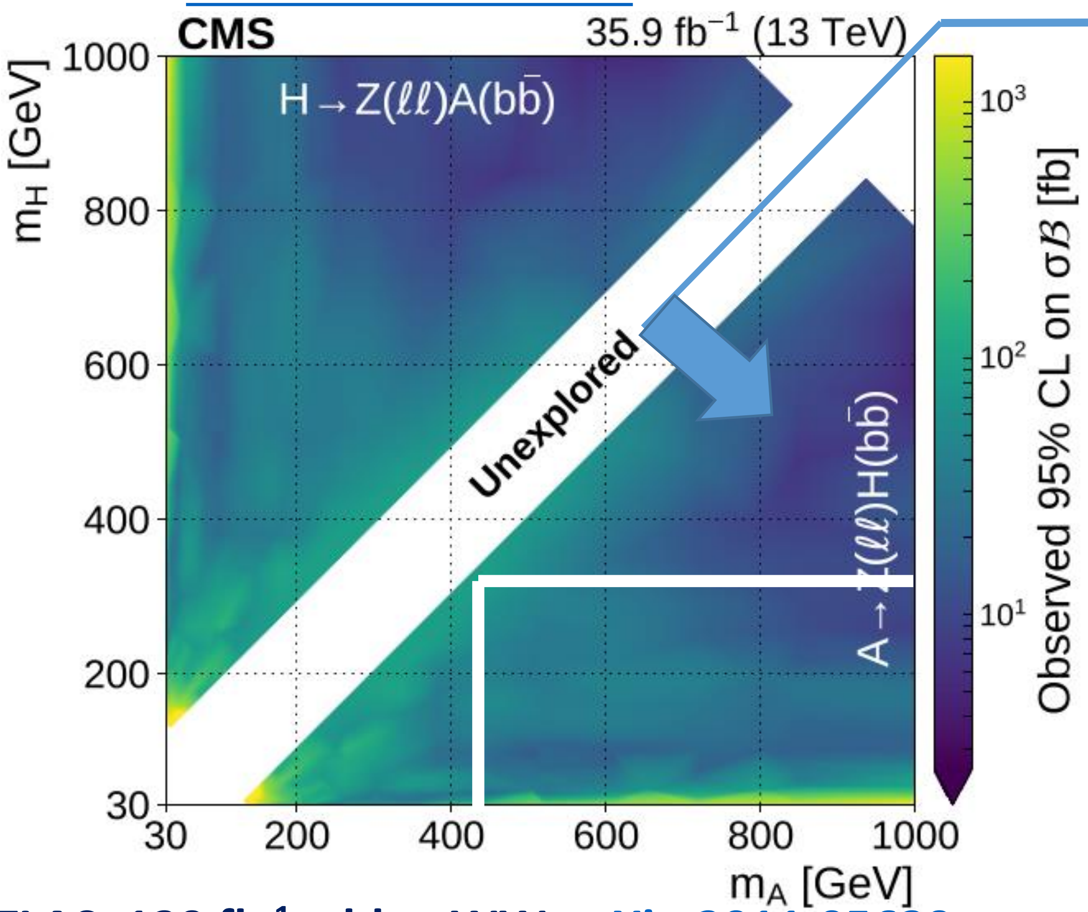






CMS result on A→ZH →$\ell^+\ell^-$bb analysis

arXIv:1911.03781



ATLAS, 139 fb^{-1}, $\ell\ell$bb, $\ell\ell$WW, arXiv:2011.05639

on going CMS analysis: A→ZH→$\ell\ell$tt

Additional Higgs bosons

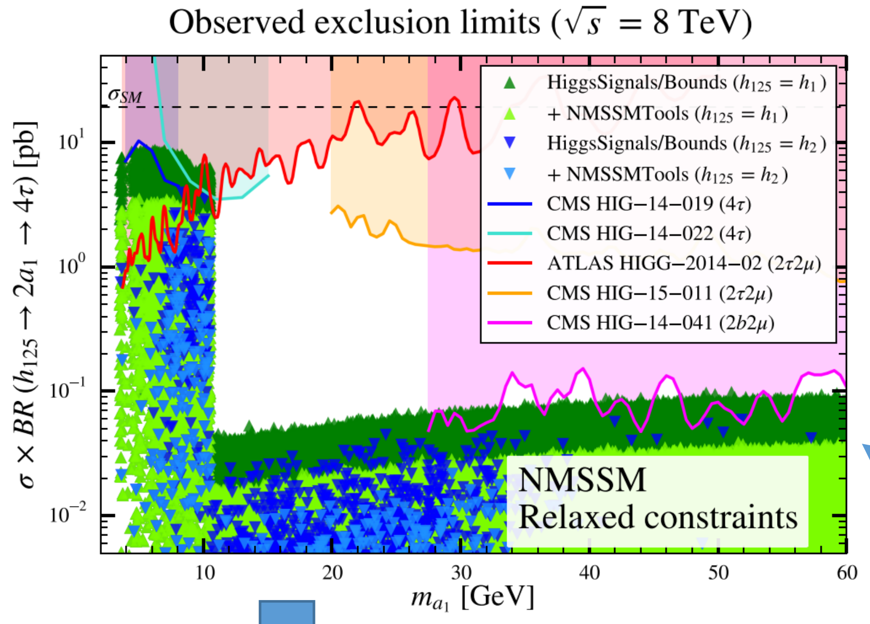
in NMSSM, 2HDM+S

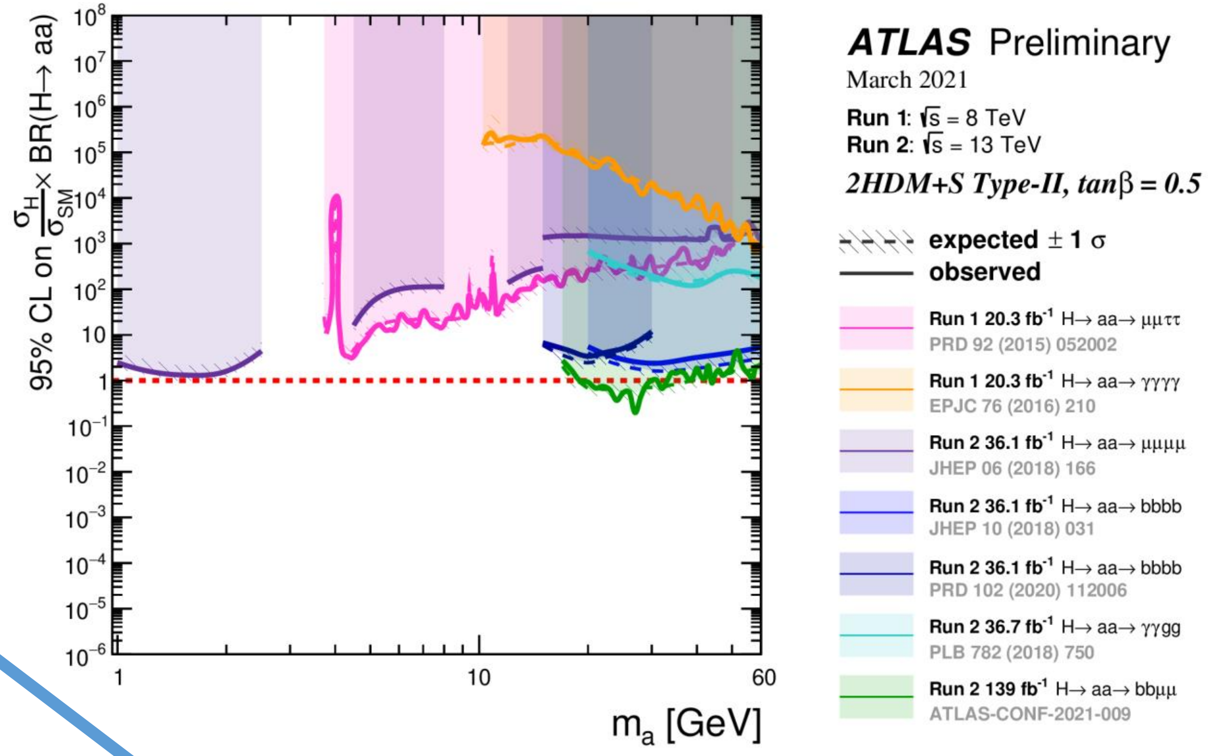
h_1, h_2, h_3, a_1, a_2, $h^{\pm}$; $m_{h1}<m_{h2}<m_{h3}$, $m_{a1}<m_{a2}$

h_1 or h_2 is discovered h_{125}

Searches for light scalars from h_{125} decay to aa(hh)

R. Aggleton at al, arXiv:1609.06089



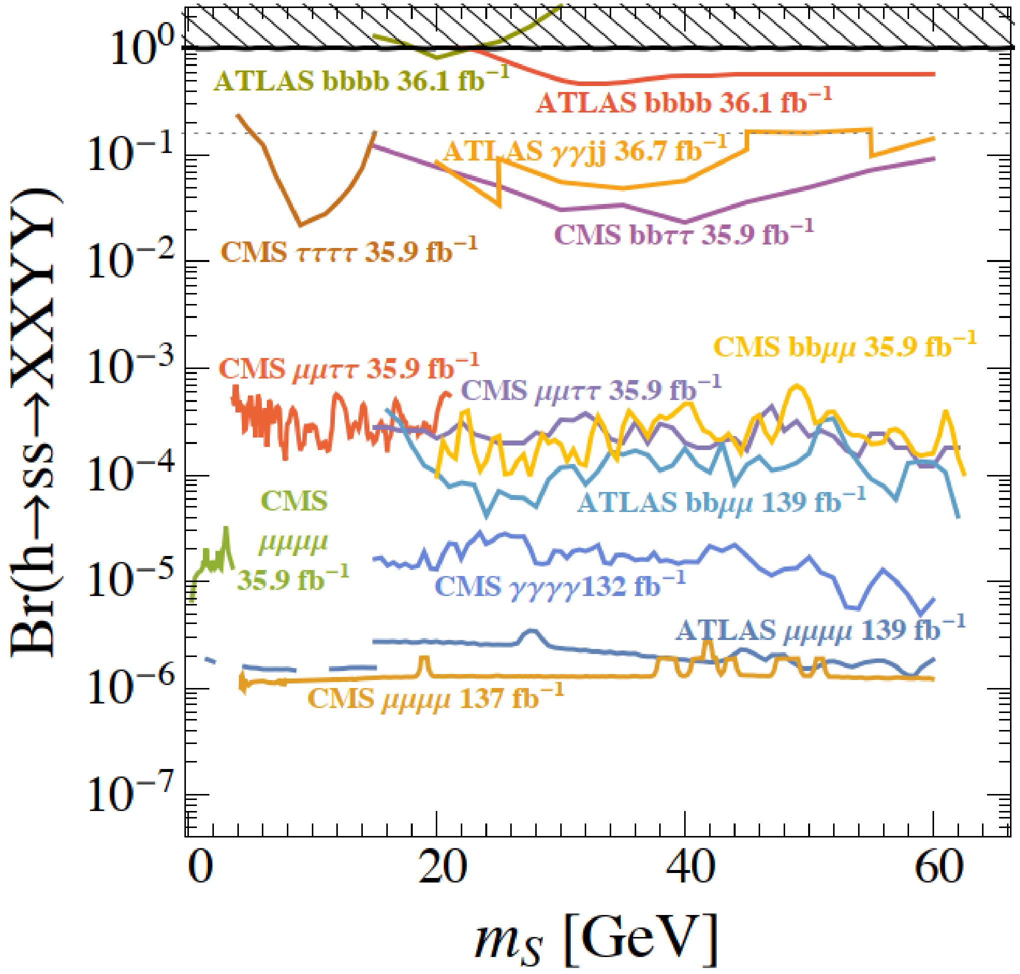


- **this plot need to be updated for 13 TeV (Run II) CMS analyses**
  - μμbb: arXiv:1812.06359 – m_a range is 20-60 GeV
  - ττbb: arXiv:1805.10191 – m_a range is 15-60 GeV
  - μμττ: arXiv:2005.08694 – m_a range is 3.6-21 GeV
  - ττττ : arXiv:1907.07235 – m_a range is 4.0-15 GeV
  - μμμμ: arXiv:1812.00380 – m_a range is 0.25-8.5 GeV

already sensitive to NMSSM

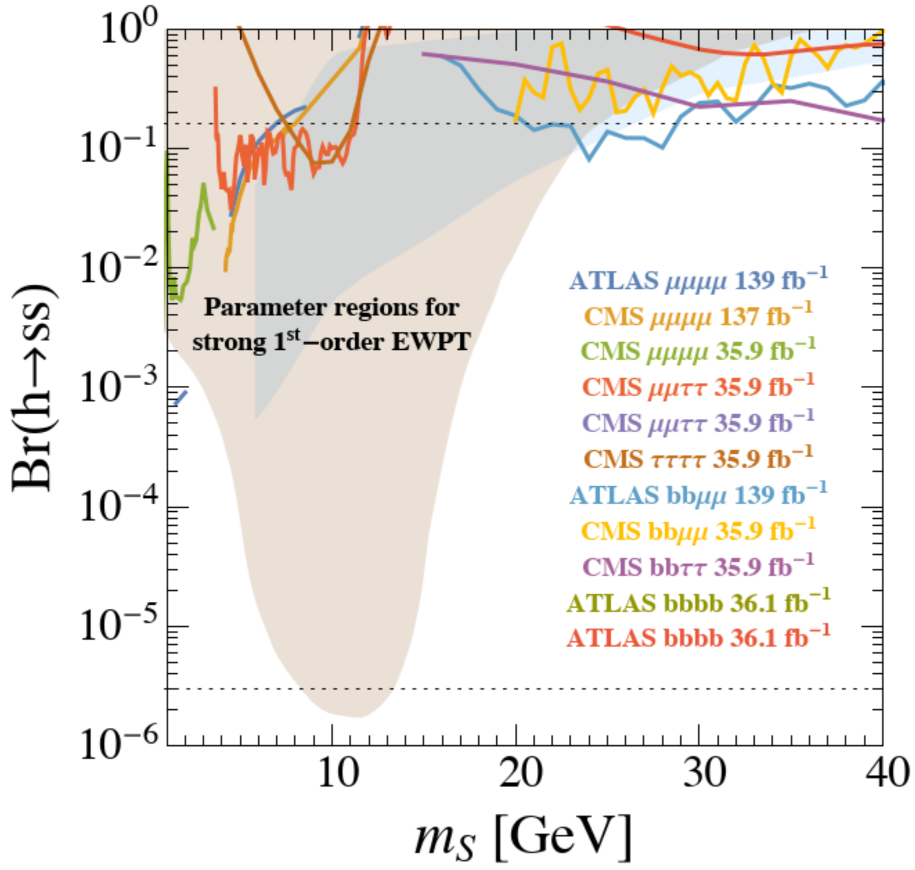
Latest CMS and ATLAS searches for $h_{125} \rightarrow ss \rightarrow xxyy$ on one plot

From "Probing the Electroweak Phase Transition with Exotic Higgs Decays"
[M. Carena et al arXIv:2203.08206]()



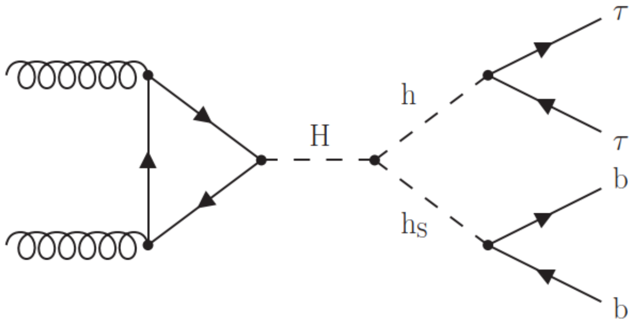
[Interpretation in h125+singlet model]()

Already sensitive to parameter regions for strong 1st order EWPT



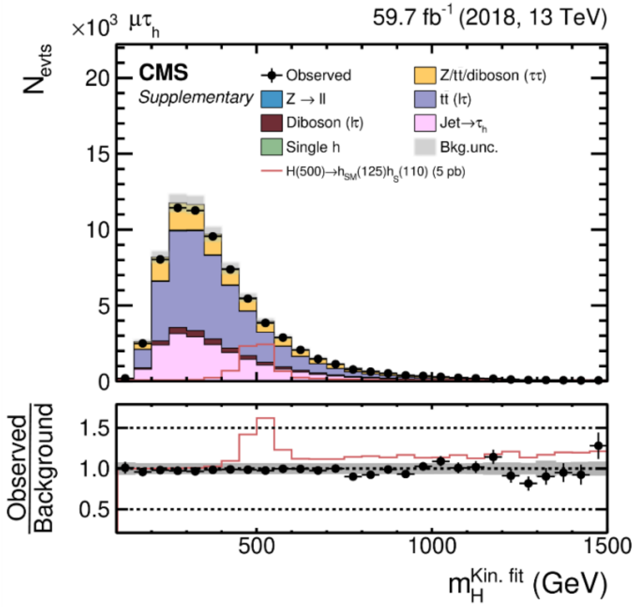
NMSSM: search for $H(A) \rightarrow h_{125} h(a)_S \rightarrow \tau\tau bb$ decay

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



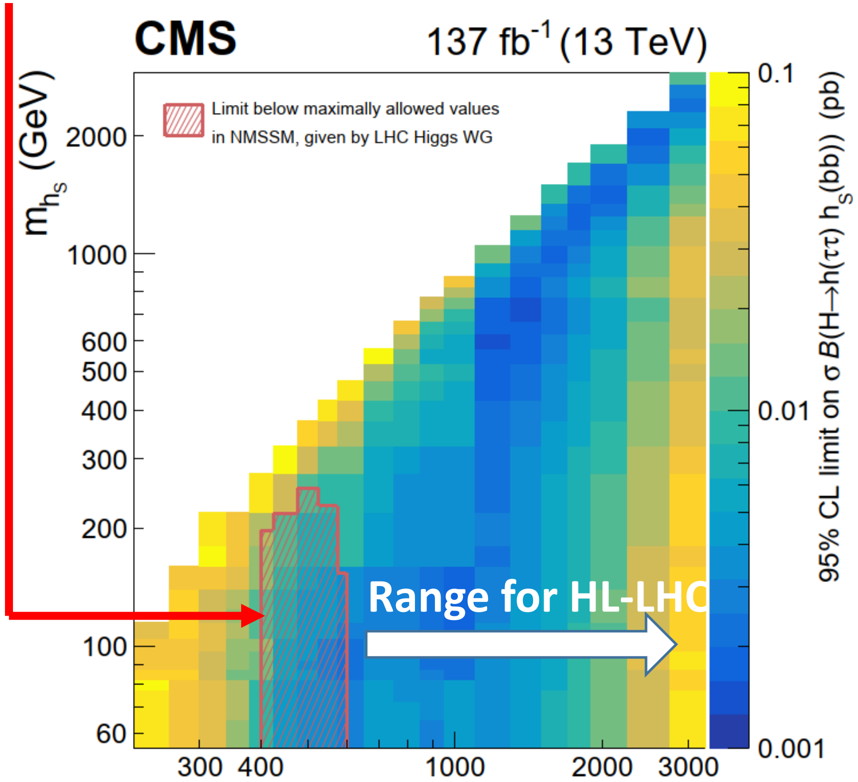
arXiv:2106.10361

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

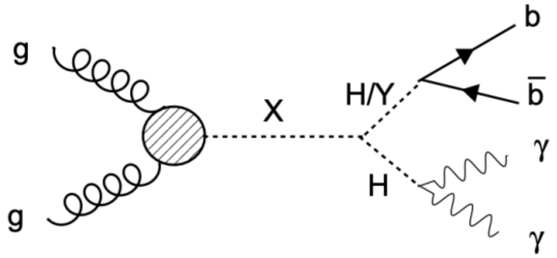
- Multi-class NN used, 4x background classes + 1 signal class
- Output is 5 scores, yi, that sum to 1
- Allocate events to categories based on largest y_i
- In each category fit maximum y_i as discriminating variable



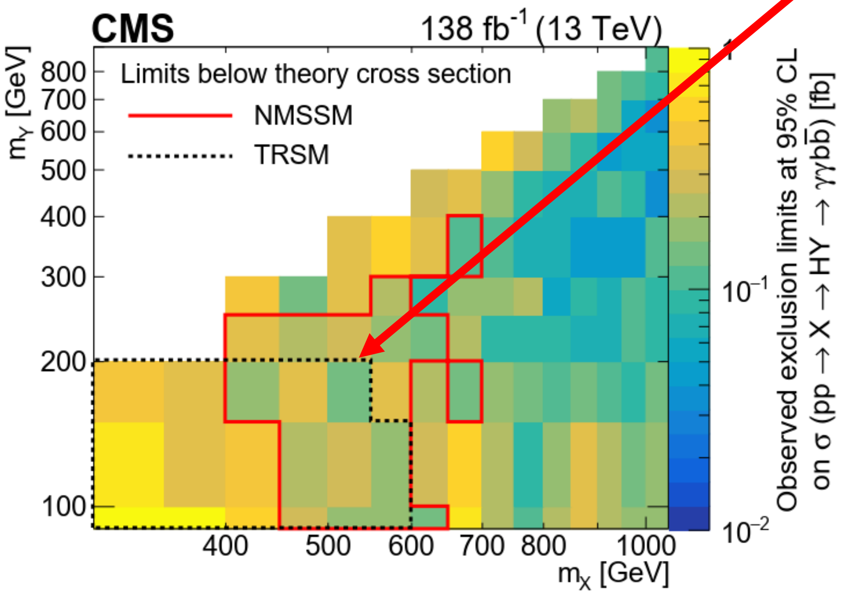
m_H (GeV)

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

NMSSM: search for $H(A) \to h_{125} h(a)_S \to \gamma\gamma bb$ decay

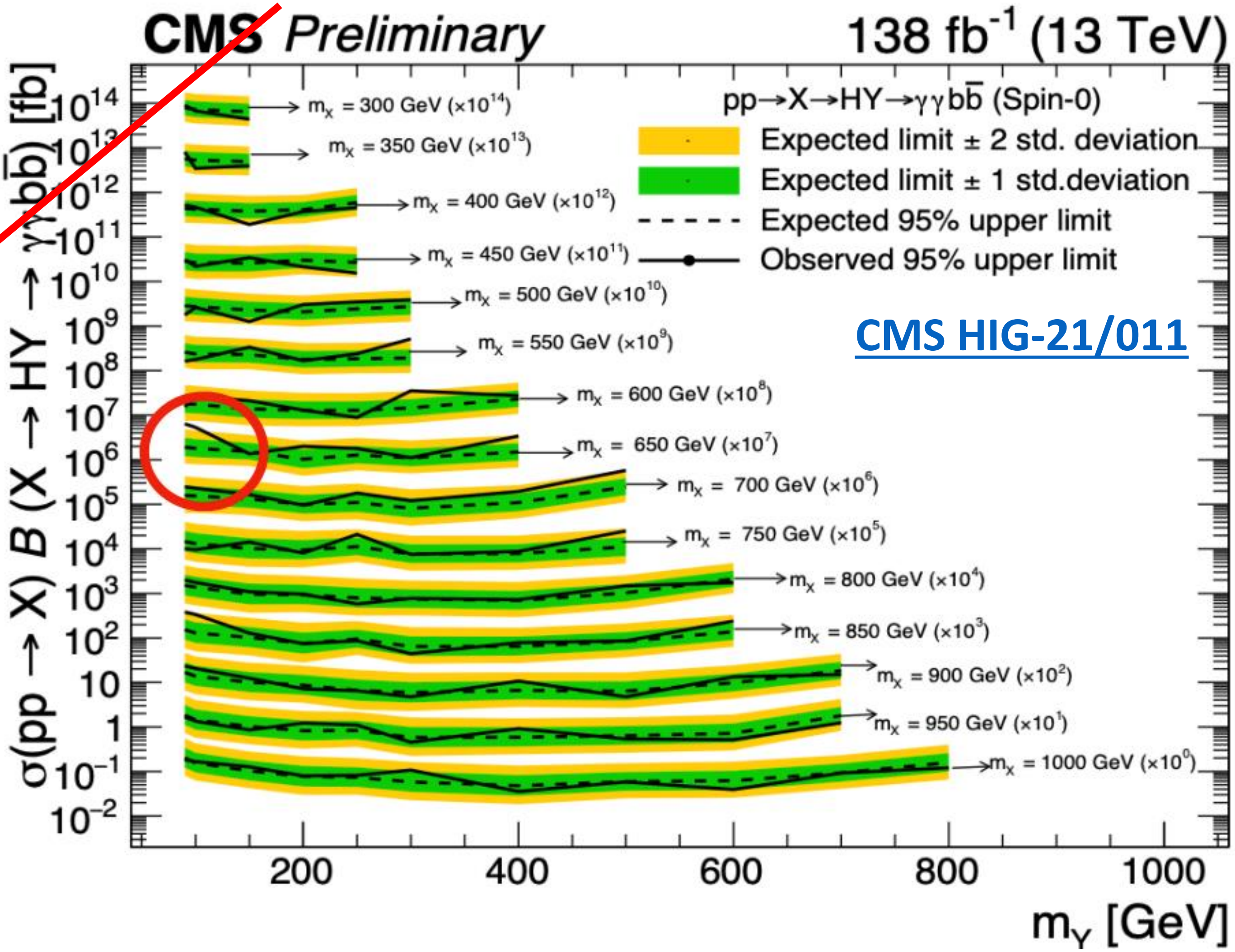


- Largest excess for m_Y=90 GeV, m_X = 650 GeV
  - Local (global) significance of 3.8 (2.8)σ @ m_Y=90 GeV



- **300 < $m_{H(A)}$ < 1000 GeV, $m_{h(a)}$ < 800 GeV**

already sensitive to NMSSM



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

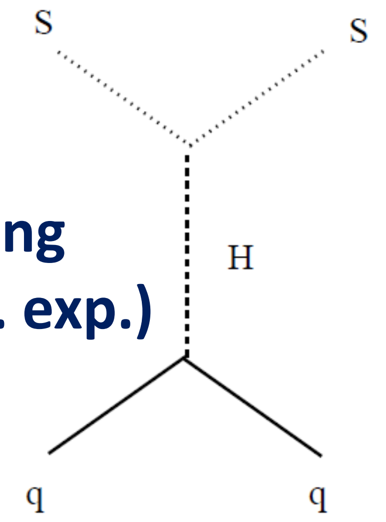
Connection between LHC H->inv. and direct DM searches

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

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

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

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



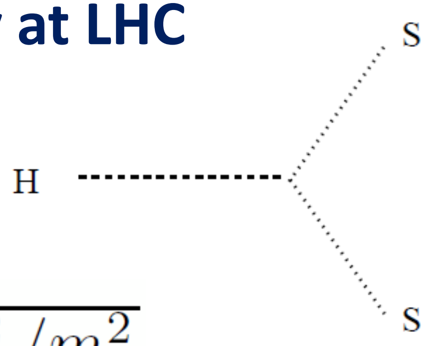
where f_N – Higgs-nucleon coupling

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

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

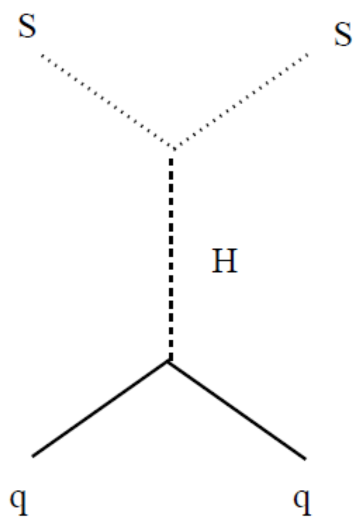
$$\Gamma^{\rm inv}_{h\to \chi\chi} = \frac{\lambda^2_{hff} v^2 m_h \beta_f^3}{32\pi \Lambda^2}, \quad \text{where } \beta_X = \sqrt{1-4M_X^2/m_h^2}$$

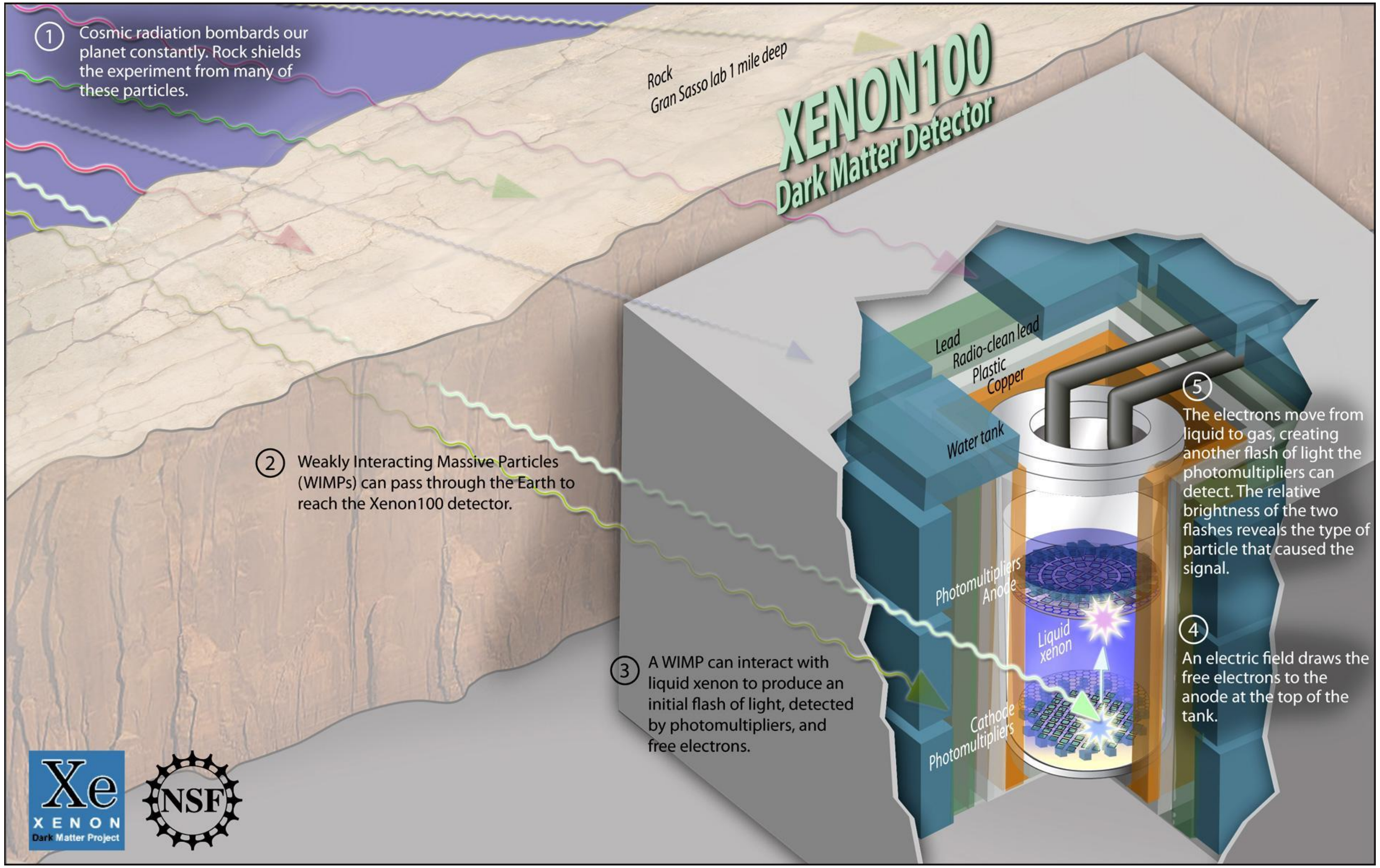
H->invisible decay at LHC



A. Djouadi et. al. arXiv:1112.3299

DM (WIMP) detection on Earth with XENON experiment



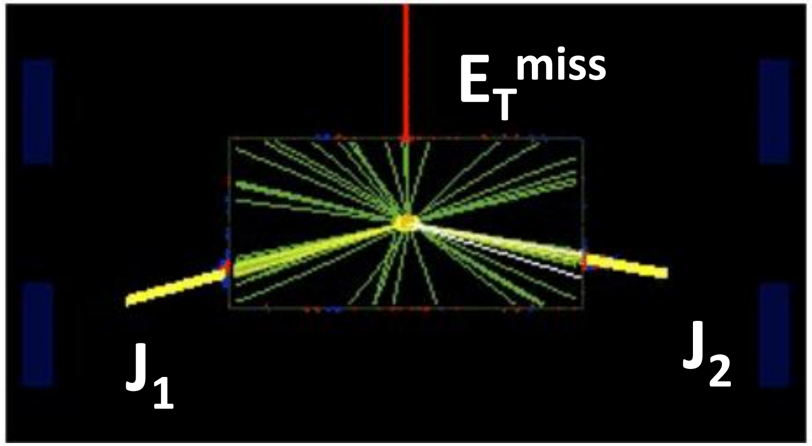


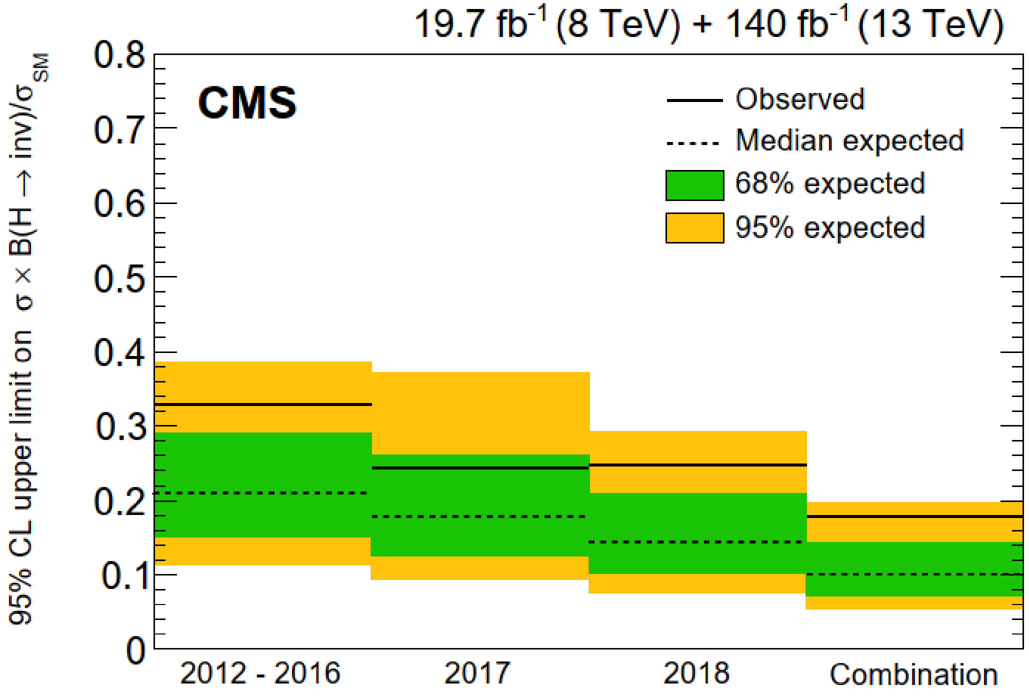
Start data taking in 2007 at Gran Sasso in Italy. Current XENON100 – 165 L xenon. Plan for 1000 L

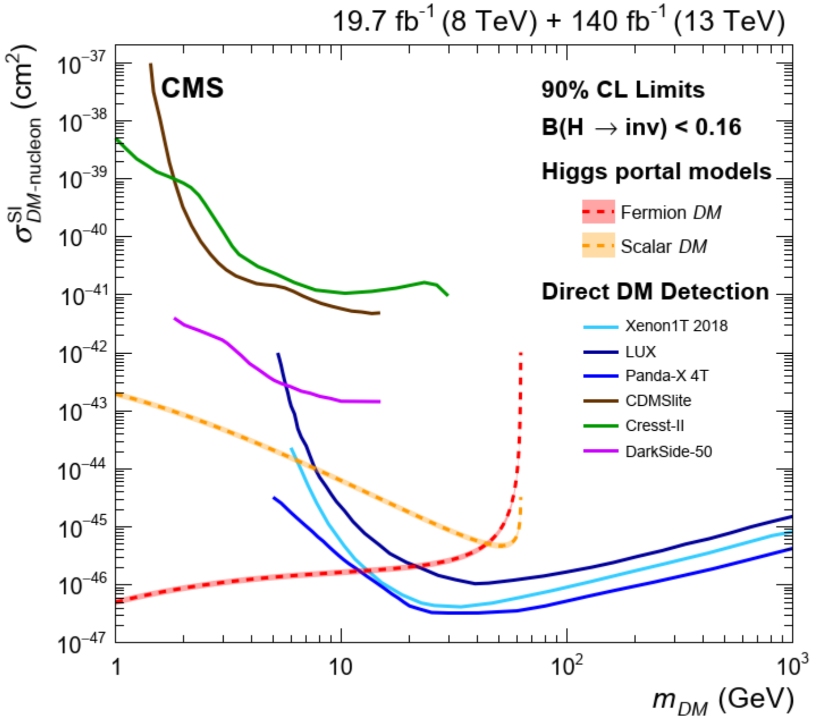
most sensitive mode qq'→qq'h (VBF h)

[arXiv:2201.11585]

Observed (expected) BR(H→inv)< 0.18 (0.10) at 95 % CL







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

Result is already interesting for MSSM and will be interesting for NMSSM with HL-LHC measurements

- **MSSM**

A. Djouadi et al, arXiv:1211.4004

30 ≤ $m_{\chi 1}$ ≤ 60 GeV

$\Omega_{\rm DM}h^2 = 0.1188 \pm 0.0010,$

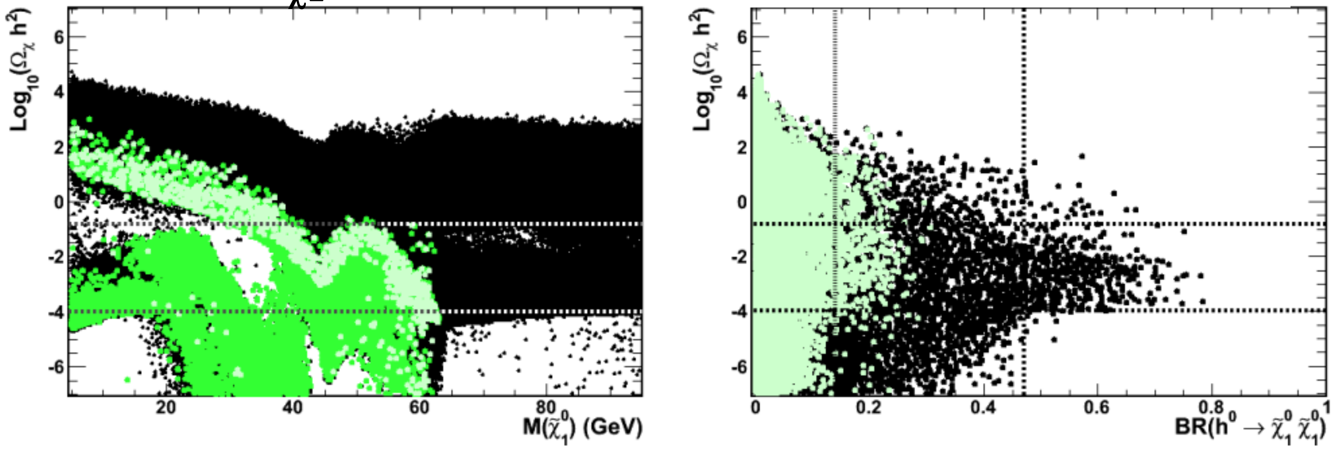


Figure 4: The neutralino relic density $\log_{10}(\Omega_\chi h^2)$ as a function of $M_{\chi_1^0}$ (left) and $\mathrm{BR}(h \to \chi_1^0\chi_1^0)$ (right) for the accepted set of pMSSM points (black dots), those with $\mathrm{BR}(h \to \chi_1^0\chi_1^0) \geq 15\%$ (green dots) and those compatible 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].

- **NMSSM**

U. Ellwanger et al, arXiv:1806.09478

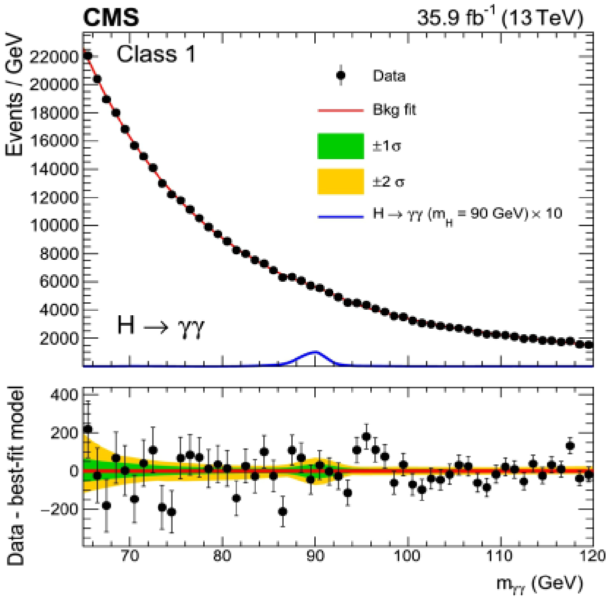
Scenarios with light neutralino 1

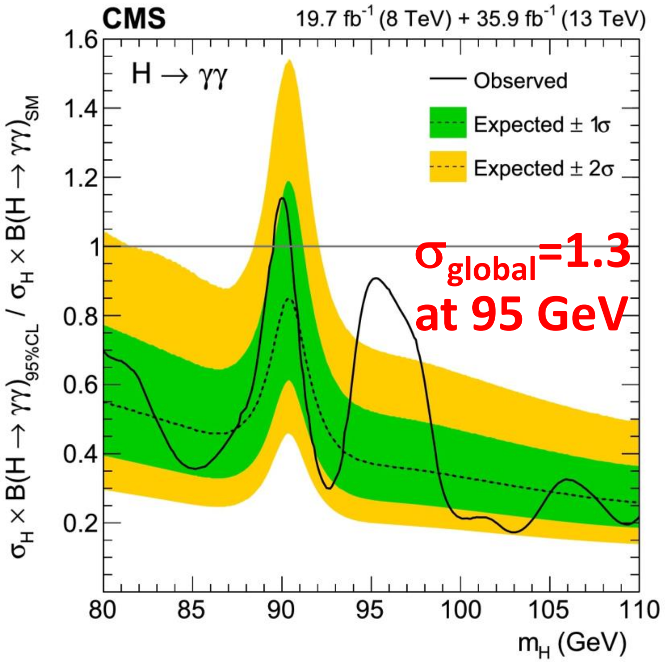
	P1	P2	P3
$M_{\chi_1^\pm}$	265	261	219
$M_{\chi_1^0}$	3.2	40	62
$M_{\chi_2^0}$	250	244	206
$M_{\chi_3^0}$	285	278	236
M_{H_1}	56	35	59
M_{A_1}	76	78	63

In a such scenarious BR h→invisible can reach 8 % .*Ulrich Ellwanger, private communication*

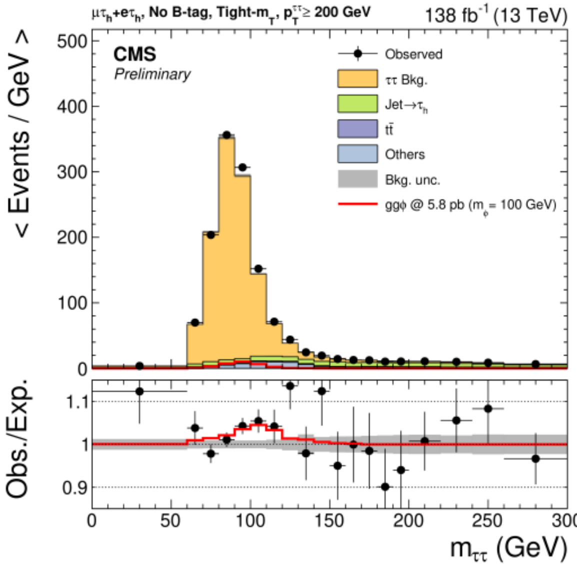
Some excitements at the end:
event excesses observed in CMS in searches for BSM Higgs bosons

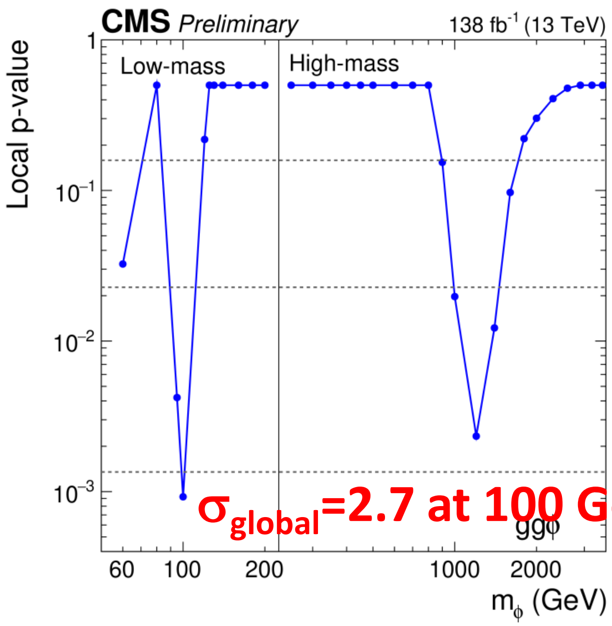
• Light X→γγ



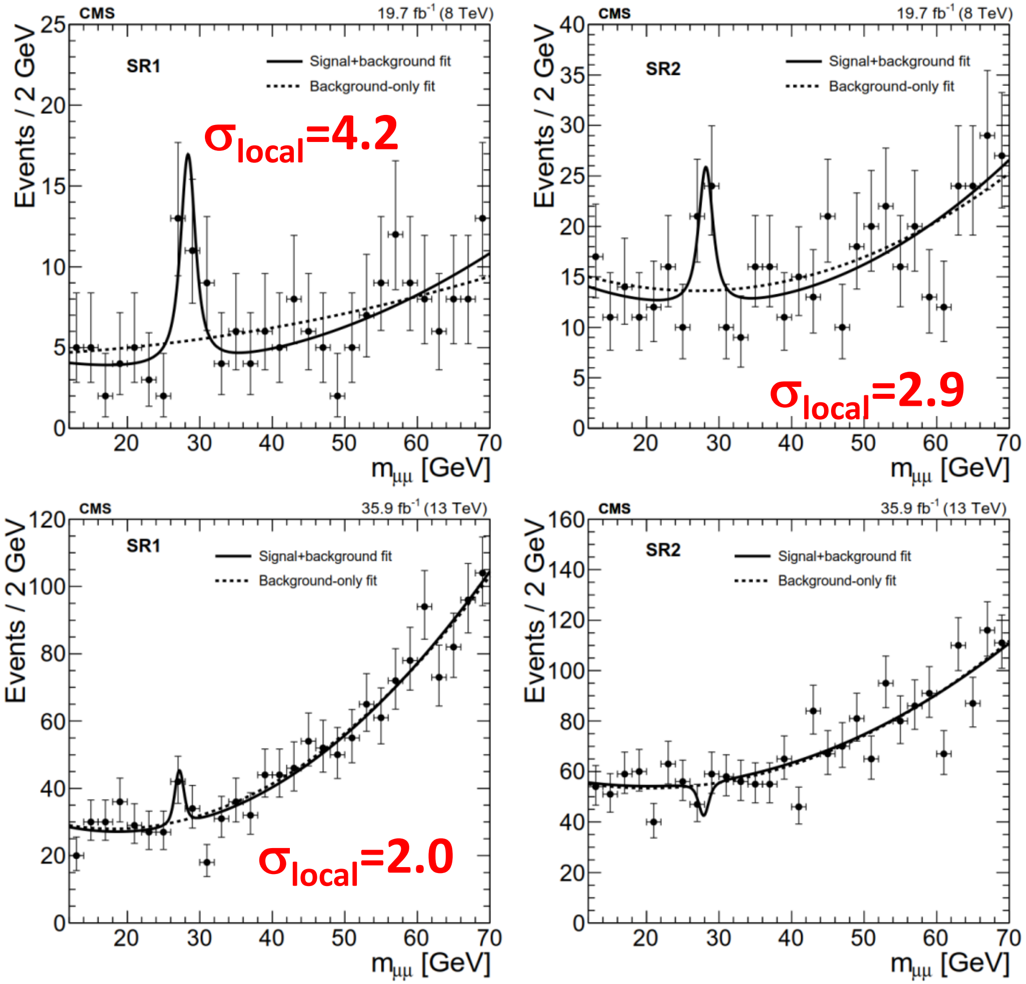


• Light X→ττ





• Light X→μμ



Conclusions

- **very reach physics program for searches for non-SM physics in Higgs boson sector at LHC**
- **we expect to have an another discovery after h_{125} with Run II and Run III or HL-LHC data**

THE END

BSM analyses of h_{125}

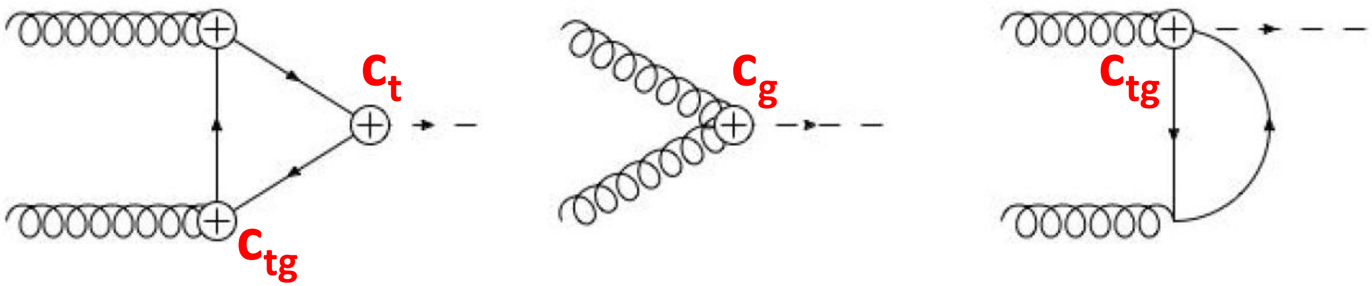
- **measurement of h_{125} transverse momentum**
  - **with a goal to identify deviations from SM prediction**

Non SM contributions into gg→h_{125} production

SM Effective Field Theory approach

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

- Spira at al. arXiv:1612.00283, arXiv:1806.08832, arXiv:2109.02987



C_{tg} is chromomagnetic dipole operator that modifies the coupling between gluons and the top quark, with and without the Higgs boson at the same vertex.

Figure 1: Feynman diagrams contributing to $gg \to H$ production at LO. The possible insertions of dimension-six operators are marked by a cross in a circle.

$$\frac{c_1}{\Lambda^2}\mathcal{O}_1 \;\to\; \frac{\alpha_s}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu},$$

$$\frac{c_2}{\Lambda^2}\mathcal{O}_2 \;\to\; \frac{m_t}{v}(1 - c_t) h \bar{t} t,$$

$$\frac{c_3}{\Lambda^2}\mathcal{O}_3 \;\to\; c_{tg}\frac{g_S m_t}{2v^3}(v + h) G^a_{\mu\nu}(\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c),$$

at NLO

$$c_t(Q^2) = c_t(\mu_0^2) + \frac{24}{5}\frac{m_t^2(\mu_0^2)}{v^2} c_{tg}(\mu_0^2)\left\{\left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu_0^2)}\right)^{\frac{5}{6\beta_0}} - 1\right\},$$

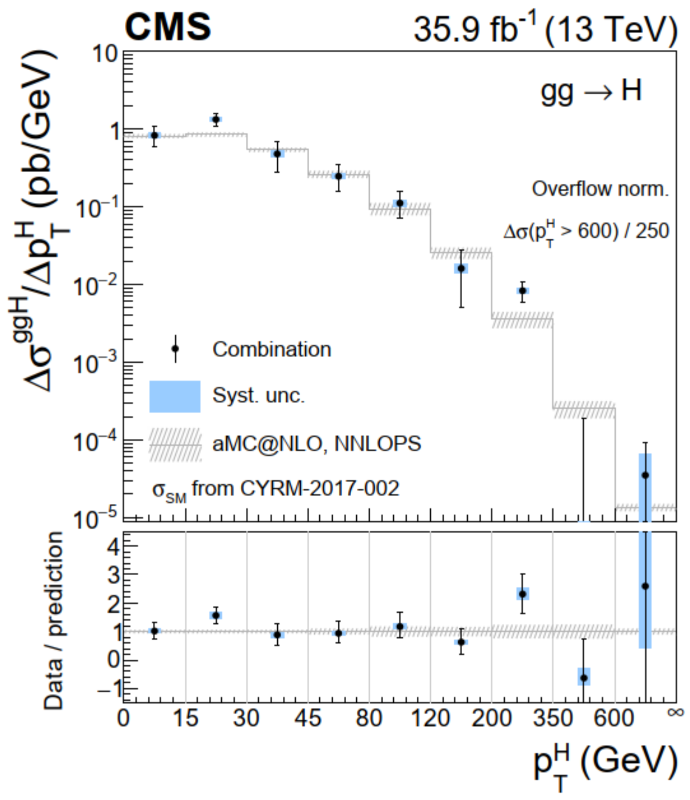
$$c_{tg}(Q^2) = c_{tg}(\mu_0^2)\left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu_0^2)}\right)^{-\frac{7}{6\beta_0}},$$

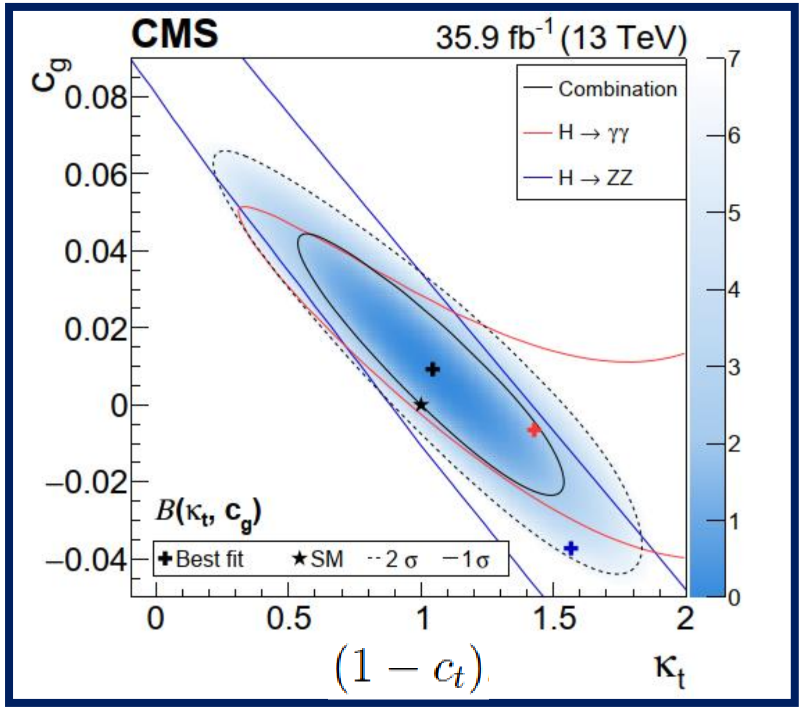
$$c_g(Q^2) = \frac{\beta_0 + \beta_1 \alpha_s(Q^2)/\pi}{\beta_0 + \beta_1 \alpha_s(\mu_0^2)/\pi}\left\{c_g(\mu_0^2) - \frac{3\pi}{5 - 6\beta_0}\frac{m_t^2(\mu_0^2)}{v^2}\frac{c_{tg}(\mu_0^2)}{\alpha_s(\mu_0^2)}\left[\left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu_0^2)}\right)^{\frac{5}{6\beta_0}-1} - 1\right]\right\}$$

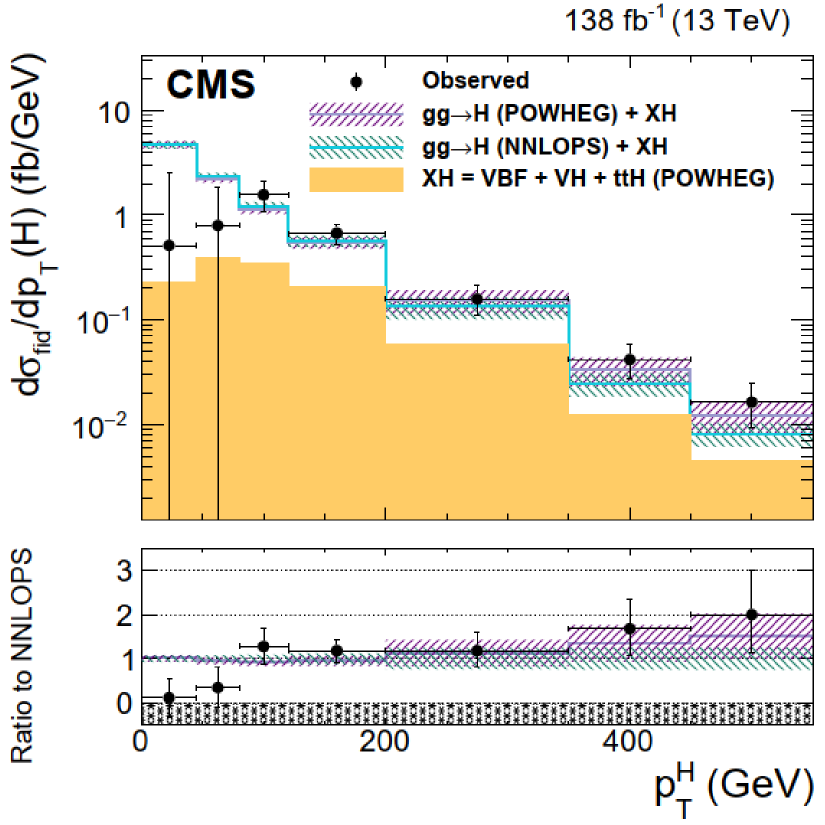
$$\sigma \approx |12 c_g + c_t|^2 \sigma_{SM} \quad (HTL)$$

Recent CMS measurements of p_T^{h125} in Run II

- arXiv:1812.06504, 2016 data
- arXiv:2107.11486, full Run II







scale dependence of c_g, k_t for every p_T^{h125} bin is neglected, LO SM EFT

No significant deviations from SM in p_T^{h125} is found

BSM analyses of h_{125}

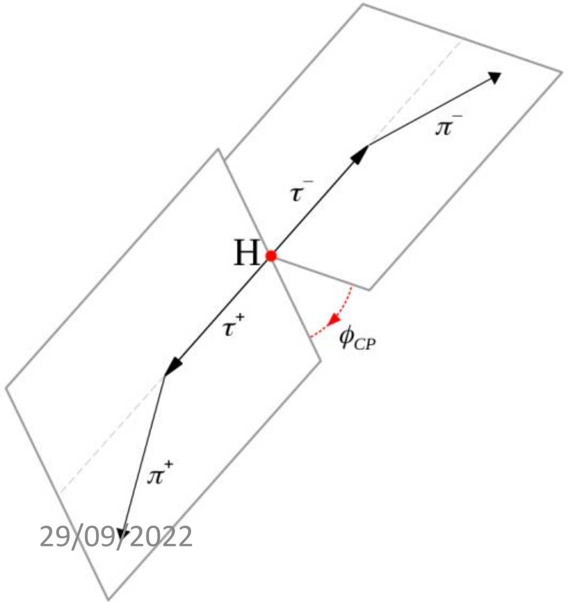
- **measurements of CP property of Higgs boson**

through Higgs boson decays

decays to fermions, ττ

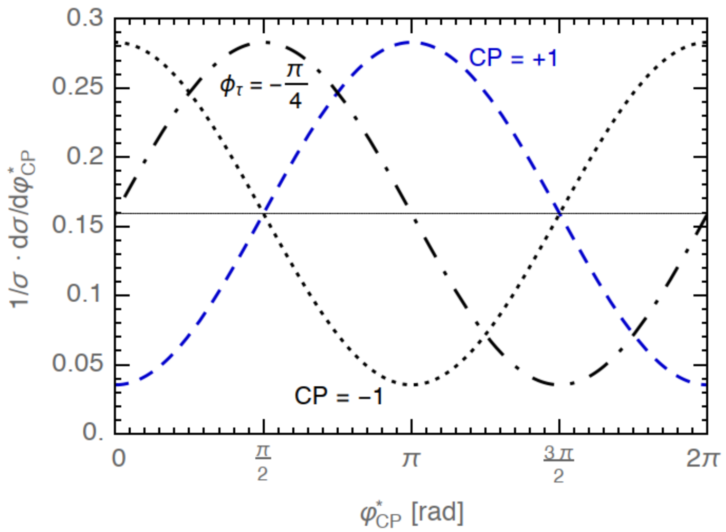
- A. Djouadi review arXiv:hep/ph-0503172 at the end of Section 2.1.4
- M. Kramer et all arXiv:hep-ph/9404280
- Z. Was et al, arXiv:1608.02609
- S. Berge et al, arXiv:1510.03850

Denoting the spin vectors of the fermion f and the antifermion $\bar{f}$ in their respective rest frames by s and $\bar{s}$, respectively, [the $\hat{z}$-axis oriented in the f flight direction], the spin dependence of the decay probability is given by [4]

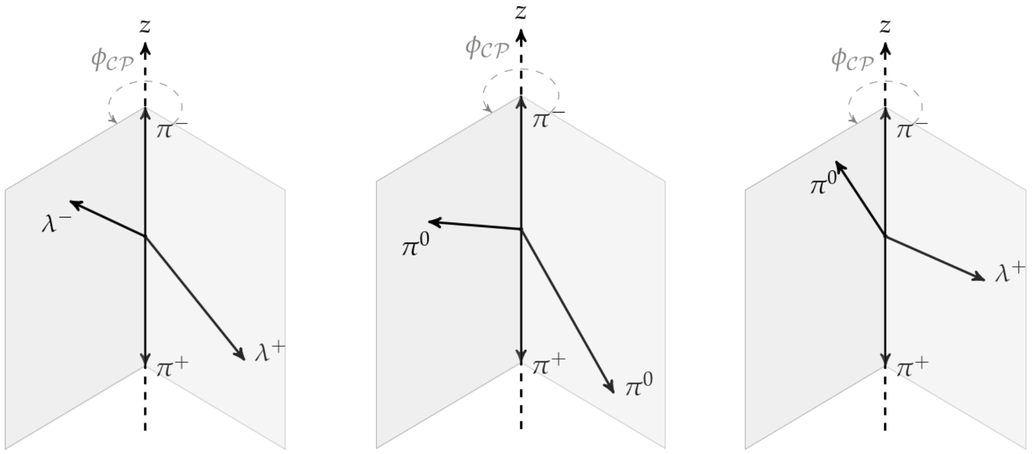


$$\Gamma(H,A \to f\bar{f}) \sim 1 - s_z\bar{s}_z \pm s_\perp \bar{s}_\perp$$

$$\frac{1}{\Gamma}\frac{d\Gamma(H,A)}{d\phi^*} = \frac{1}{2\pi}\left[1 \mp \frac{\pi^2}{16}\cos\phi^*\right]$$

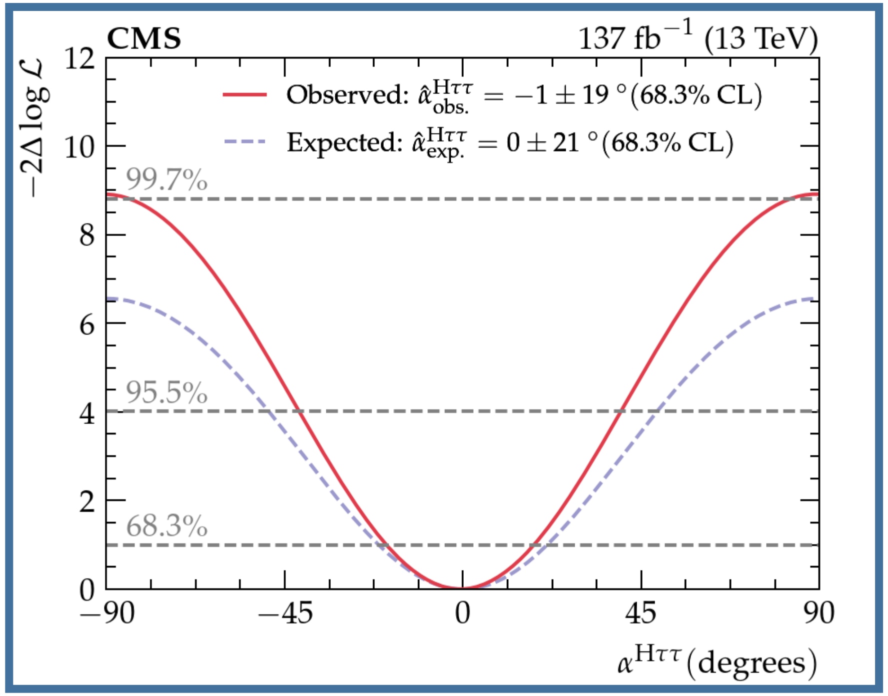


New CMS result on CP properties of $h_{125}\tau\tau$ effective coupling, arXiv:2110.04836



$$\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau).$$

$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau},$$



Relation to mixing angle α:

$$\frac{d\Gamma}{d\phi_{CP}}(H \to \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

S. Berge at al, arXiv:1410.6362
S. Berge at al, arXiv:1108.0670

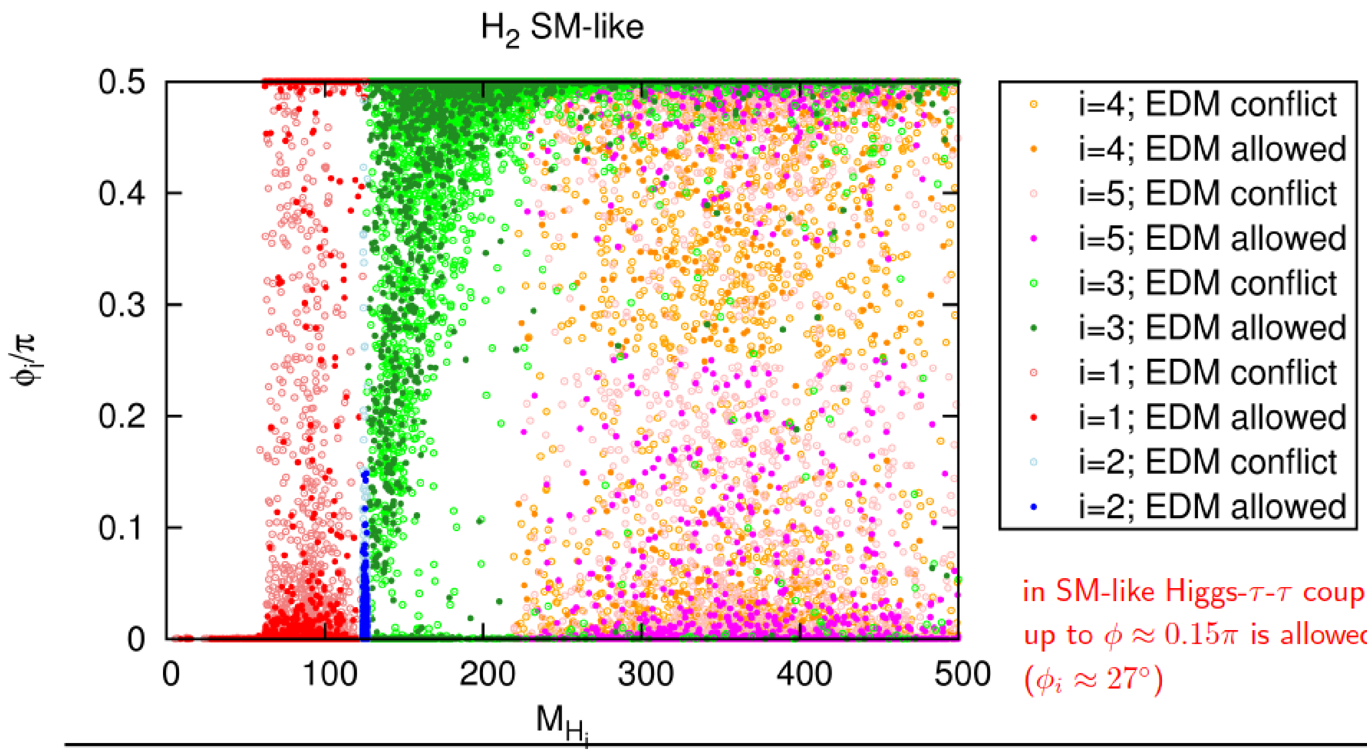
This measurement is interesting for NMSSM

in SM-like Higgs-τ-τ couplg up to $\phi \approx 0.15\pi$ is allowed ($\phi_i \approx 27°$)

Not interesting for MSSM, since large mass difference between h_{125} and A ($m_A \geq 500$ GeV) therefore very small CP mixing

$\mathcal{CP}$ Violation in $\tau^+\tau^-$ Decays

[King,MMM,Nevzorov,Walz,1508.03255]



in SM-like Higgs-τ-τ couplg up to $\phi \approx 0.15\pi$ is allowed ($\phi_i \approx 27°$)

M.M.Mühlleitner, 3 March 2020, CMS meeting

Expected Accuracy at the LHC:**and HL-LHC** [Berge,Bernreuther,Kirchner, 2015]

$\sqrt{s} = 14$ TeV, $\int \mathcal{L} = 150$ fb^{-1}, 500 fb^{-1}, 3 ab^{-1}: $\Delta\phi_i^\tau = 15°, 9°, 4°$

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 $v_1^2 + v_2^2 = v^2 \approx (246)^2\ \mathrm{GeV}^2$

Higgs potential

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

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

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

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

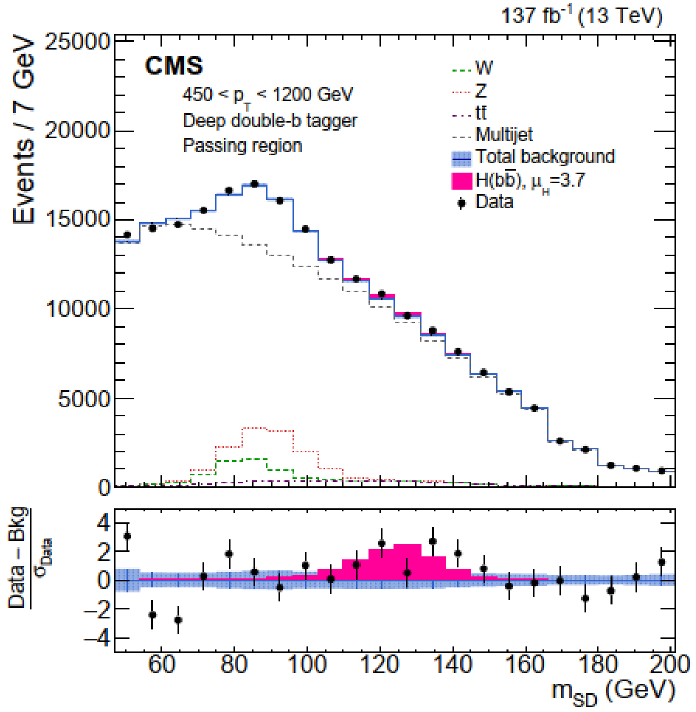
	Φ_1	Φ_2	t_R	b_R	τ_R	t_L, b_L, ν_L, e_L
Type I	$+$	$-$	$-$	$-$	$-$	$+$
Type II	$+$	$-$	$-$	$+$	$+$	$+$
Type X (lepton specific)	$+$	$-$	$-$	$-$	$+$	$+$
Type Y (flipped)	$+$	$-$	$-$	$+$	$-$	$+$

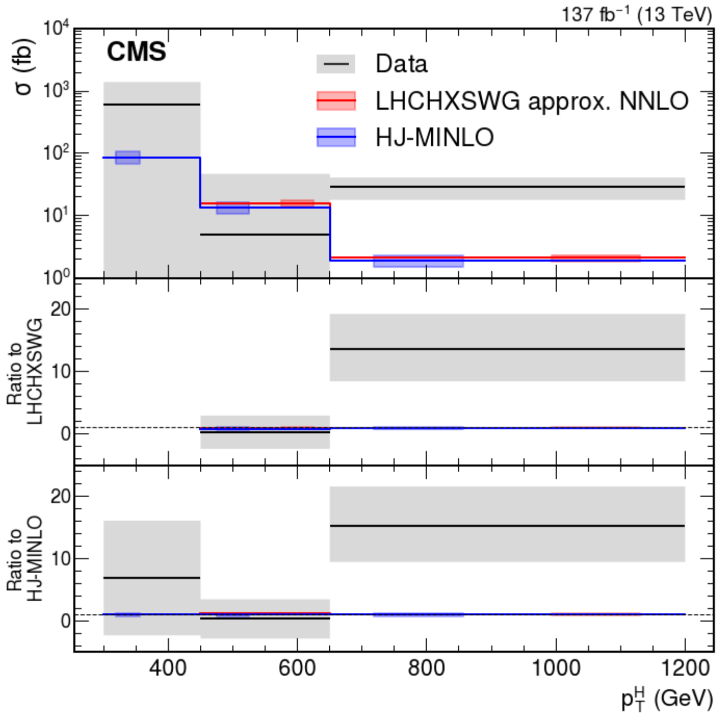
	u-type	d-type	leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

same as in MSSM (→ Type II)

A first attempt to measure $h_{125} \rightarrow bb$ selecting high p_T bb events

- arXiv:2006.13251 (ATLAS, arXiv:2111.08340)





An excess is seen for Higgs boson p_T > 650 GeV with a local significance of 2.6 σ with respect to the SM expectation including the Higgs boson.

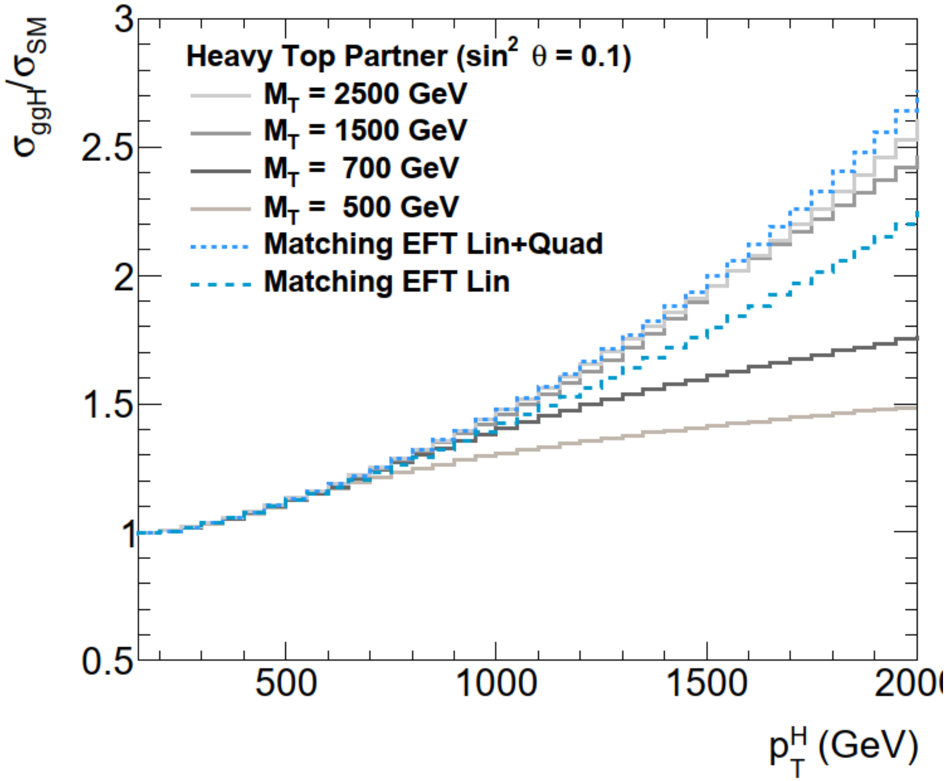
Validity range of SMEFT

- **comparison of p_T^{h125} in SMEFT and an explicit model (example of heavy top partner model). From Spira et al. arXiv:2109.02987**
  - **qualitatively, the matched SMEFT spectrum reproduces that of the model up to $p_T^H \leq M_T$ while at higher p_T^H values, where the model spectrum depends explicitly on M_T^2 mass terms, the SMEFT description breaks down.**

$$y_t = \sqrt{2}\,\frac{m_t}{v}\cos^2\theta \qquad y_T = \sqrt{2}\,\frac{M_T}{v}\sin^2\theta\,. \tag{8}$$

In the limit $M_T \to \infty$ the top partner can be integrated out and the model is matched to the SMEFT with the following Wilson coefficients:

$$\begin{aligned} c_g &= \frac{\sin^2\theta}{12}\,,\\ c_t &= \cos^2\theta\,,\\ c_{tg} &= 0. \end{aligned} \tag{9}$$

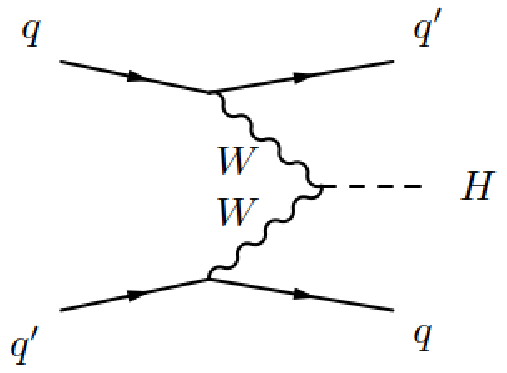


Value of c_g (c_t) obtained from the fit of p_T^{h125} depends on the upper end of the the fit range ! It gives correct value if the upper end is not significantly larger than M_T. *But M_T is not known…*

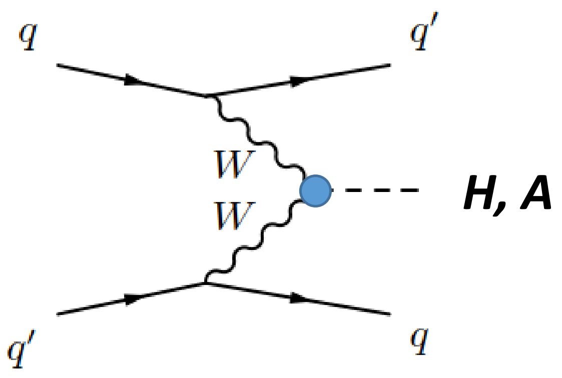
through production mechanism

- arXiv:hep-ph/0105325 Plehn, Raiwater, Zeppenfeld
  arXiv:1301.4965 Djouadi, Melado
- arXiv:hep-ph/0703202
  Klamke, Zeppenfeld

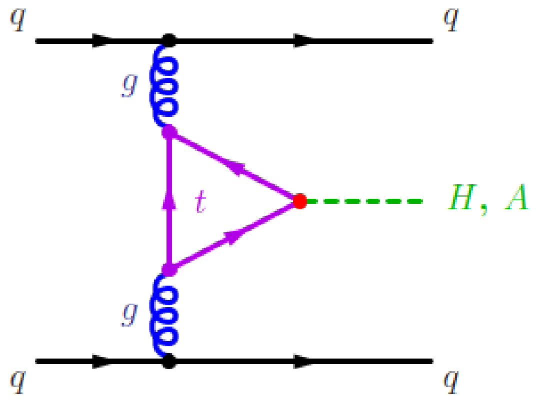
SM tree level



BSM. Only loop induces → suppressed



BSM is not suppressed as in VVH



$$\Gamma^{\rm SM}_{\mu\nu} = -g M_V\, g_{\mu\nu}$$

$$\Gamma^{\rm BSM}_{\mu\nu}(p,q) = \frac{g}{M_V}\left[\lambda\,(p\cdot q\, g_{\mu\nu} - p_\nu q_\mu) + \lambda'\, \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma\right]$$

$$T^{\mu\nu} = a_2\,(q_1\cdot q_2\, g^{\mu\nu} - q_1^\nu q_2^\mu) + a_3\, \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

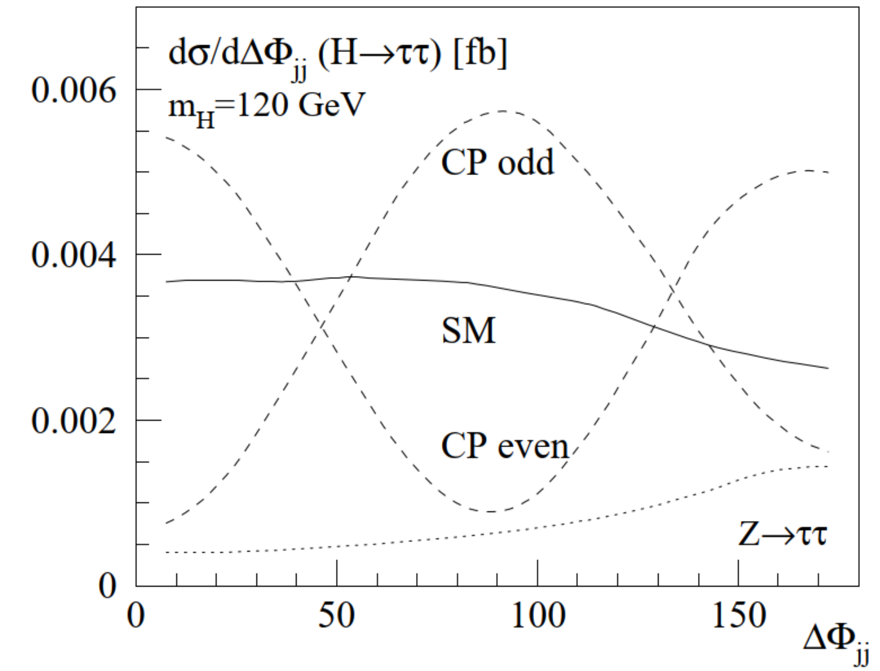
$$a_2 = \frac{y_t}{y_t^{SM}}\cdot\frac{\alpha_s}{3\pi v}, \qquad a_3 = -\frac{\tilde{y}_t}{y_t^{SM}}\cdot\frac{\alpha_s}{2\pi v}$$

The distribution of the azimuthal angle between the two jets in Hjj events can be used to determine the tensor structure of the HVV and effective ggH coupling

$\Delta\phi_{jj}$ reflect CP structure of VVH and ggH couplings

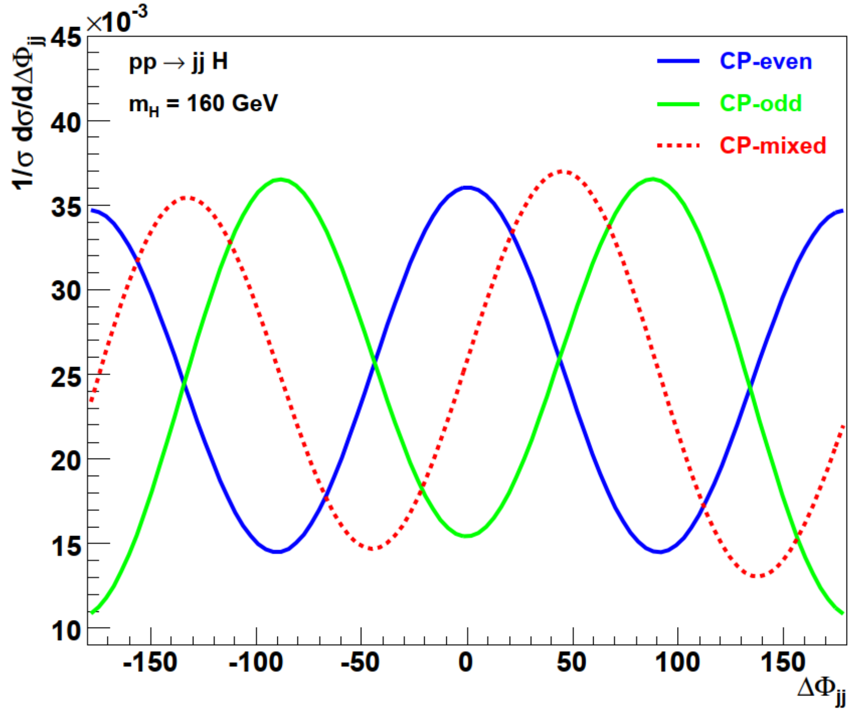
- arXiv:hep-ph/0105325
  Plehn, Raiwater, Zeppenfeld

qq→qqh$_{125}$



- arXiv:hep-ph/0703202
  Klamke, Zeppenfeld

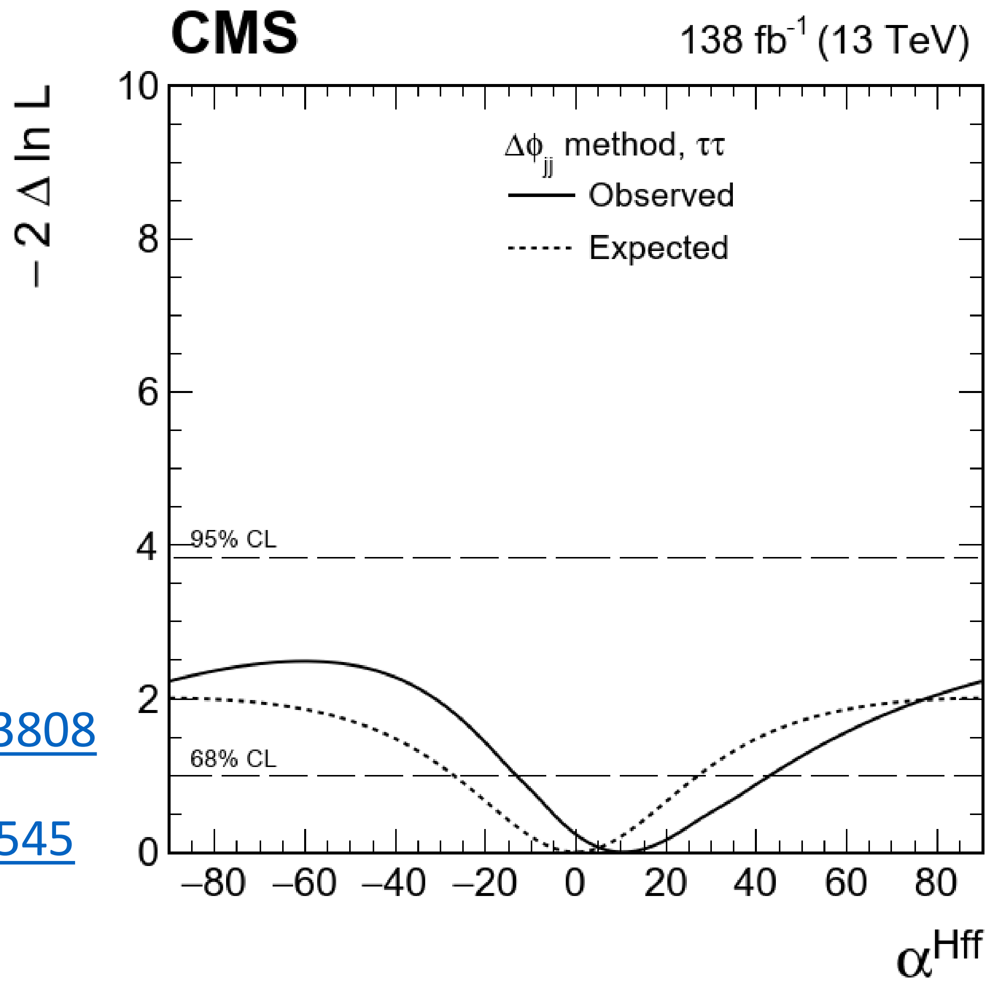
gg→h$_{125}$+jj



New CMS result on CP properties of ggh_{125} effective coupling (HIG-20-007)

- **assuming top quark dominates in ggh_{125} loop**

$$\alpha^{\mathrm{Hff}} = \tan^{-1}\left(\frac{\widetilde{\kappa}_{\mathrm{f}}}{\kappa_{\mathrm{f}}}\right)$$



ATLAS: ggH coupling with H-WW, 36 fb^{-1} arXiv:2109.13808

ATLAS: ttH coupling with H->γγ, 139fb^{-1} arXiv:2004.04545

Implication for complex Two Higgs Doublet Model (C2HDM)

D. Fontes at al, arXiv:1502.01720

$$\tan\phi_t = -c_\beta/s_1 \tan\alpha_2$$

Together with other production modes involving tth_{125} coupling and with $\tau\tau h_{125}$ coupling this measurement will be used to extract fundamental parameters of Complex Two Higgs Doublet Model where CP is explicitly broken

A complex 2HDM

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

and CP is explicitly and not spontaneously broken

$$<\Phi_1> = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \quad <\Phi_2> = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

- m^2_{12} and λ_5 real — 2HDM
- m^2_{12} and λ_5 complex — C2HDM

➡ $\tan\beta = \frac{v_2}{v_1}$ ratio of vacuum expectation values

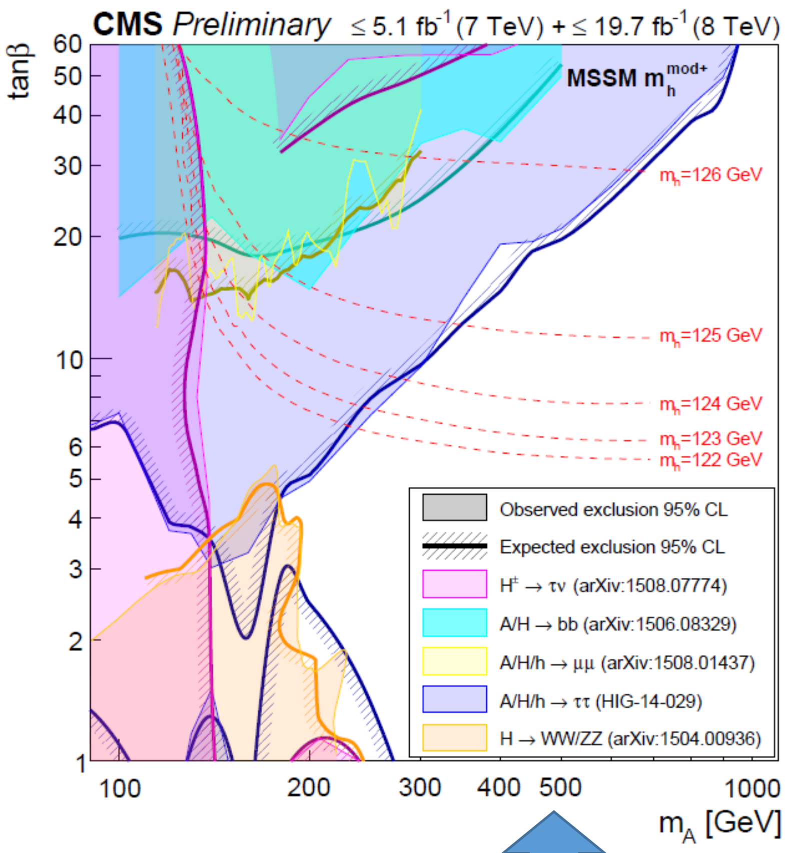
➡ 2 charged, $H^\pm$, and 3 neutral
CP-conserving - h, H and A
CP-violating - h_1, h_2 and h_3

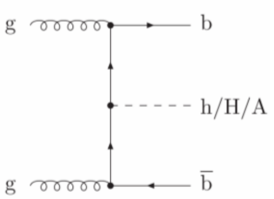
➡ rotation angles in the neutral sector
CP-conserving - α
CP-violating - α_1, α_2 and α_3

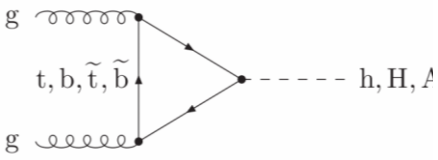
➡ soft breaking parameter
CP-conserving - m^2_{12}
CP-violating - $\mathrm{Re}(m^2_{12})$

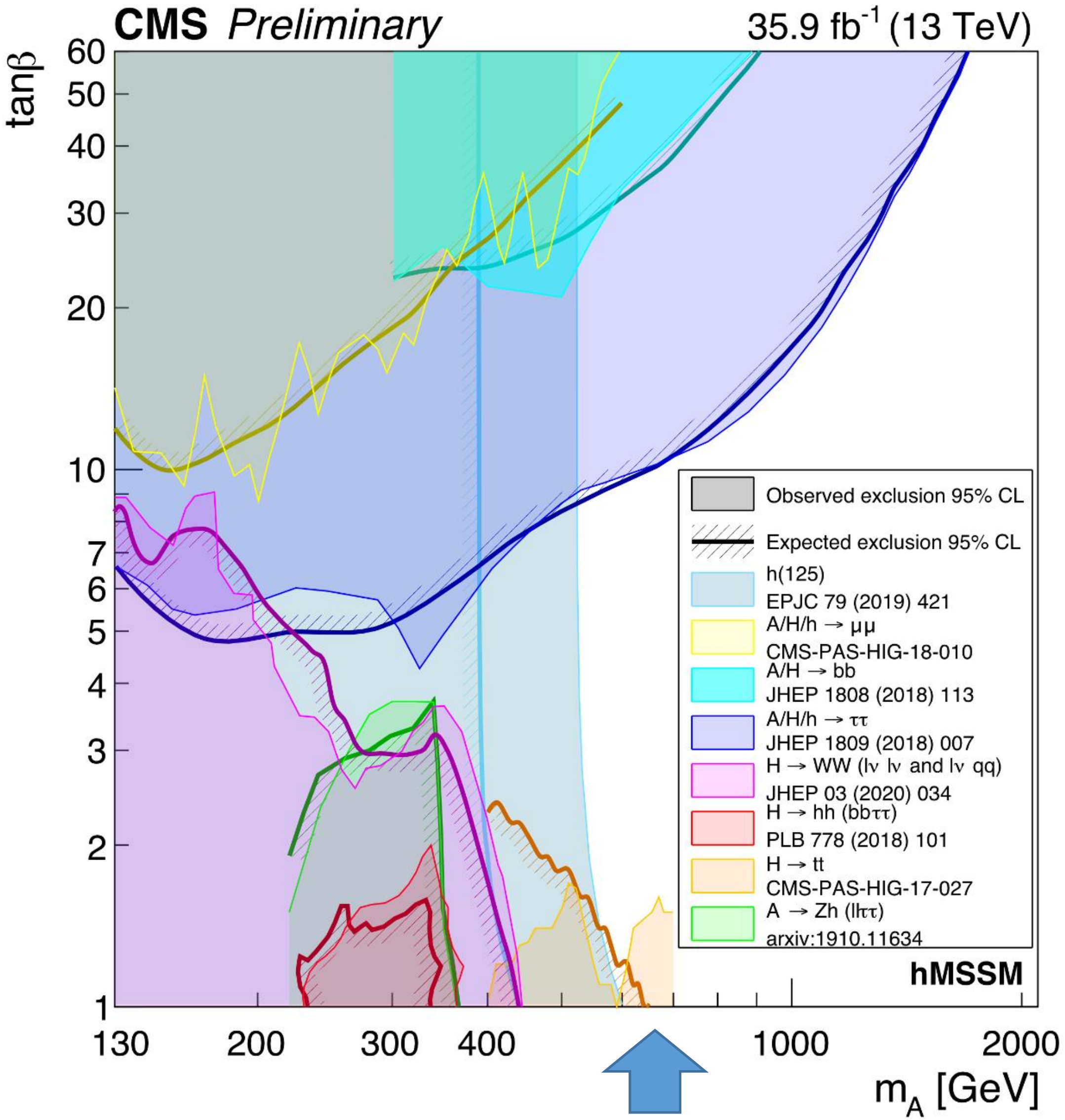
From Rui Santos talk at CMS Higgs meeting March 3rd, 2020

The search strategy and status for MSSM









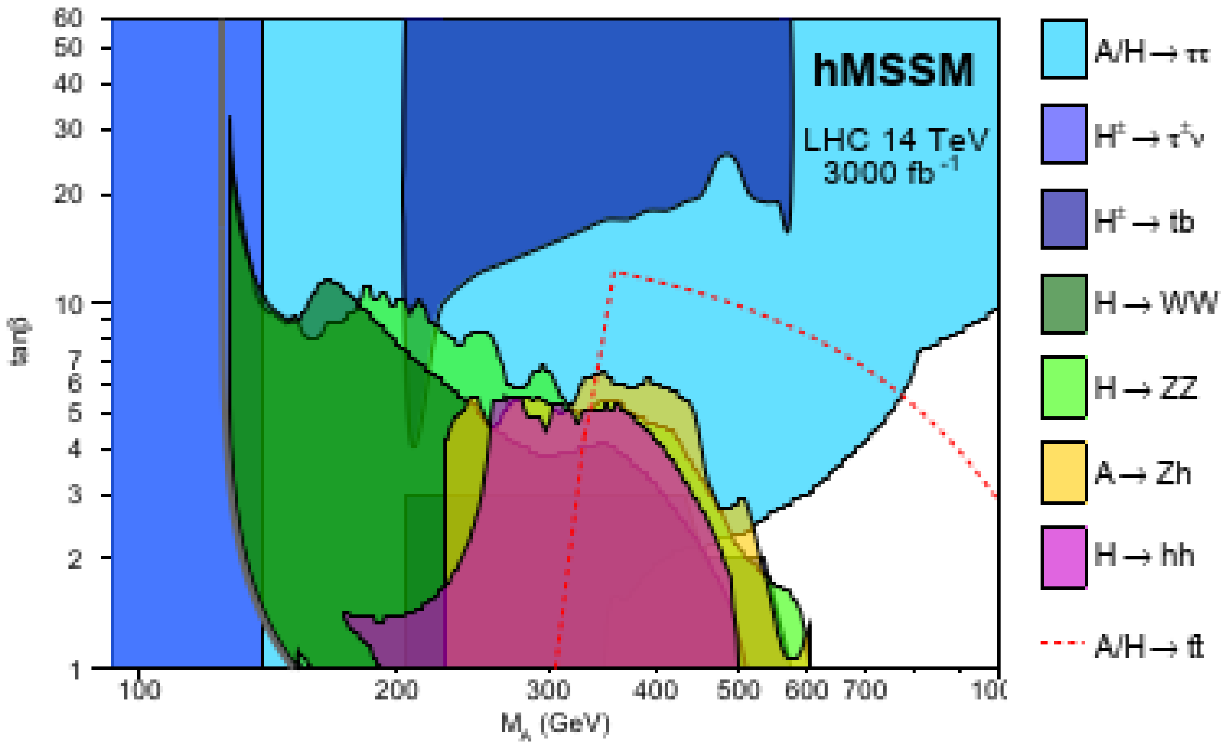
Access this region with H/A->χχ, H/A->tt

and continue searches for A/H->ττ

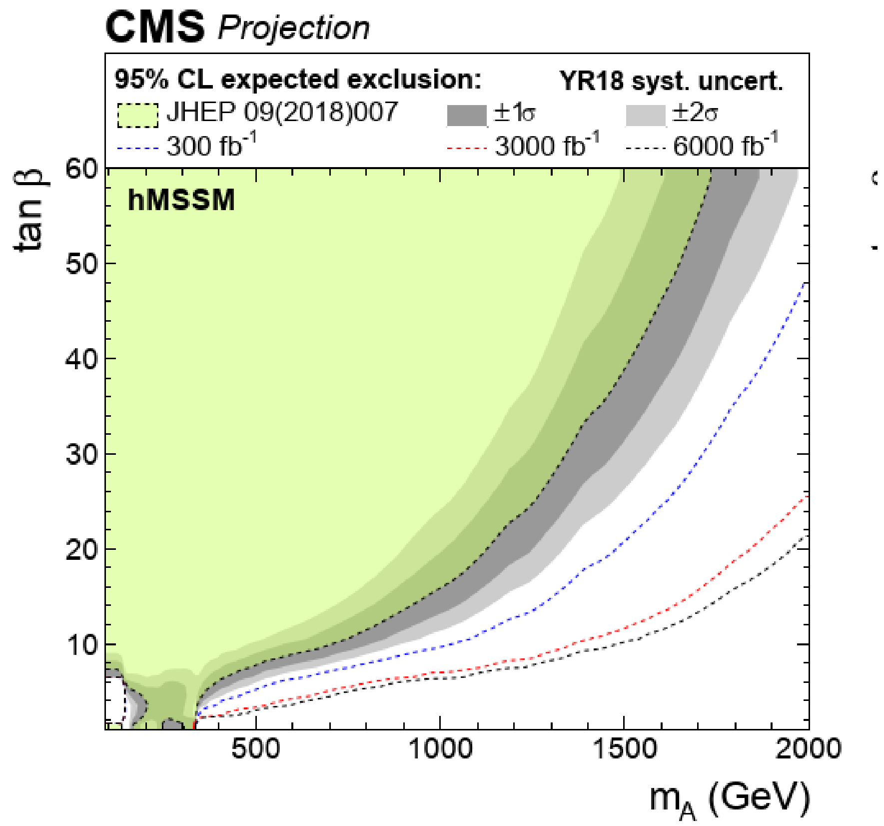
new CMS result for A/H→tt

Prospects for HL-LHC in (h)MSSM

A. Djouadi et al [arXiv:1502.05653]



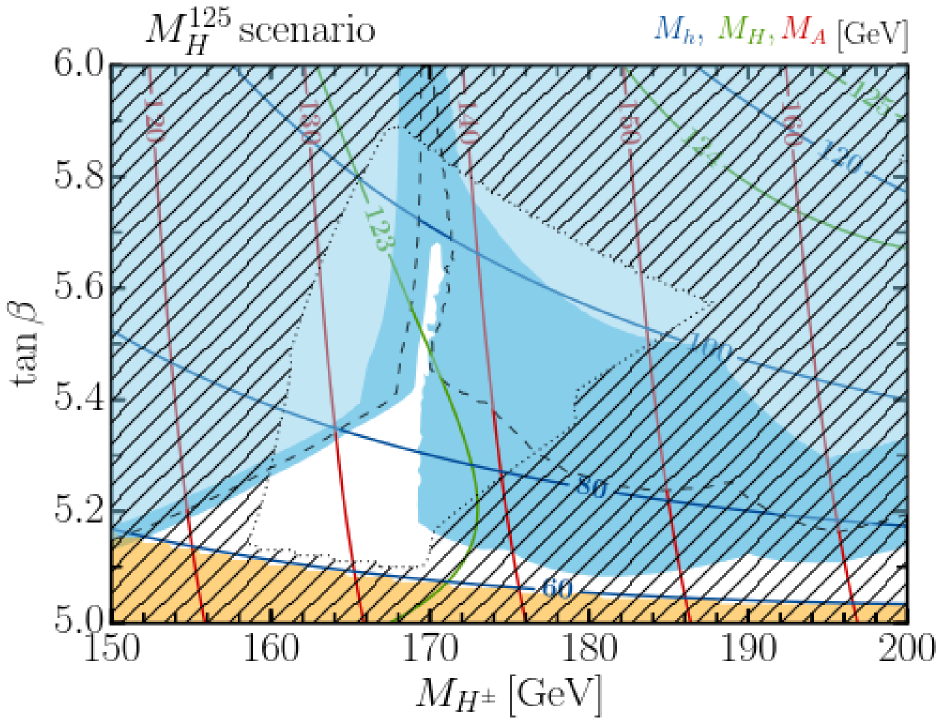
with ττ mode (FTR-19-001)



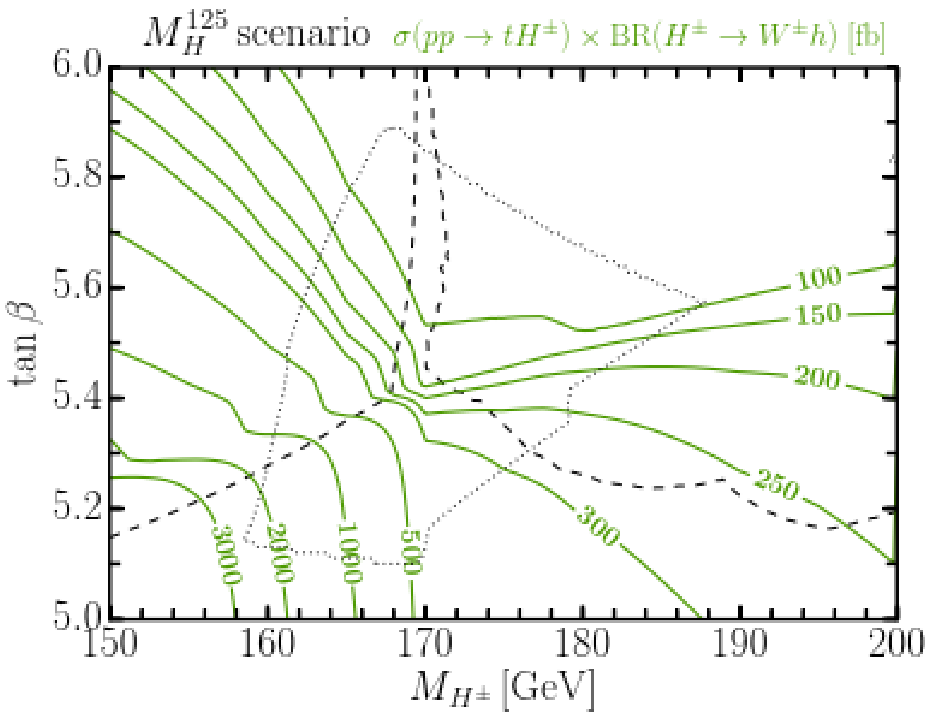
can searches for H/A->χχ and H/A->tt close a “white gap” ?

Caveat, m_H^{125} scenario:

- **In a very restricted region of MSSM parameter space Higgs 125 GeV is associated with H (M_H^{125}), while m_h < 125 GeV**



One should look at H⁺->Wh decays to exclude this scenario



arXiv:1808.07542

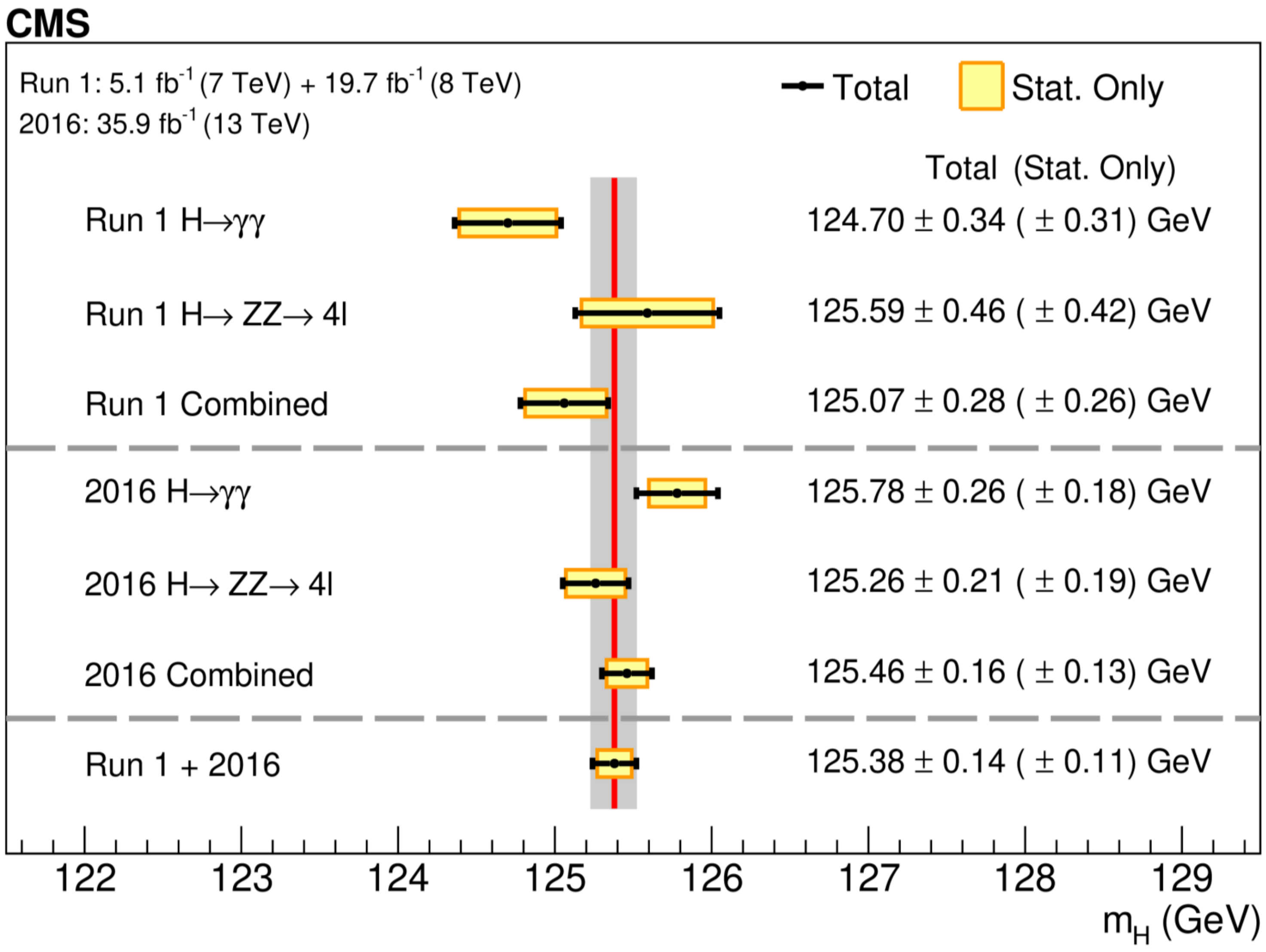
MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios for Run 2 and Beyond

Henning Bahl[a], Elina Fuchs[b], Thomas Hahn[a], Sven Heinemeyer[c,d,e], Stefan Liebler[f], Shruti Patel[f,g], Pietro Slavich[h], Tim Stefaniak[i], Carlos E.M. Wagner[j,k,l], Georg Weiglein[i]

Доклад посвящается Виталию Сергеевичу Кафтанову

03.12.1931, Москва — 14.09.2006, Варна

Latest CMS h_{125} mass measurement



ATLAS CONF Note

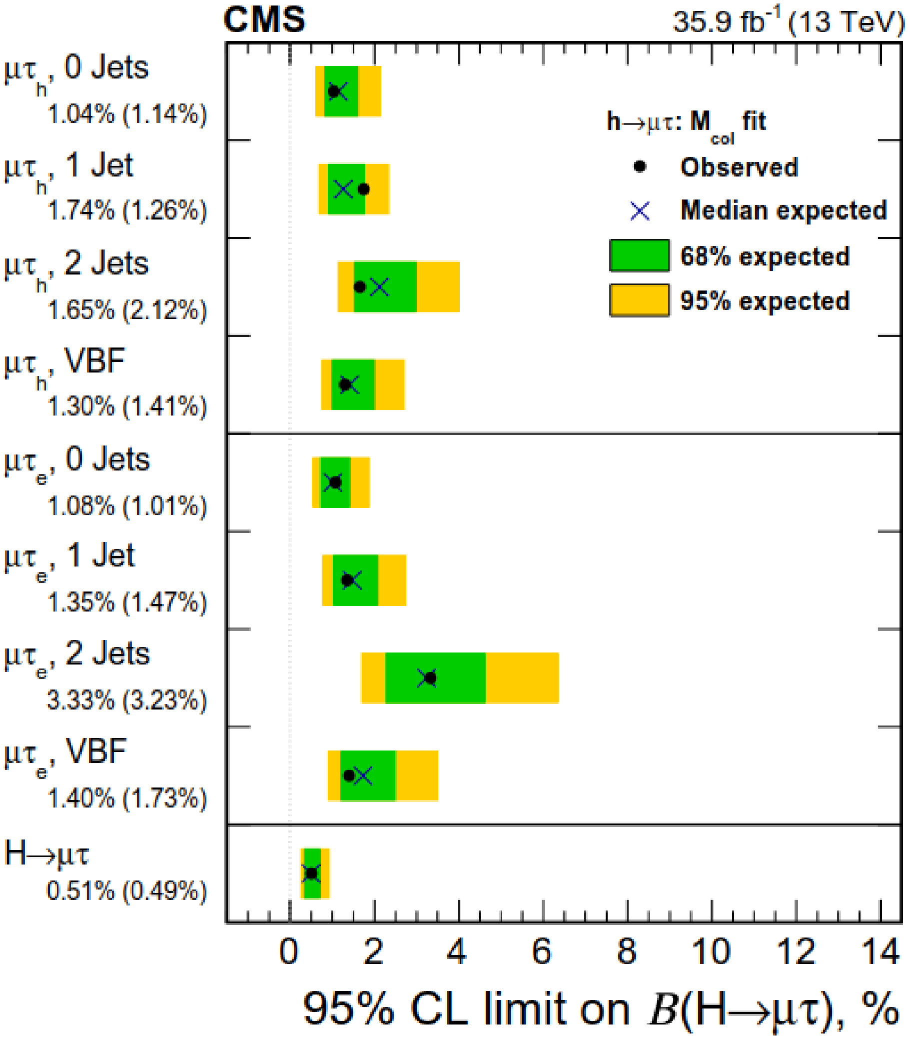
ATLAS-CONF-2020-052

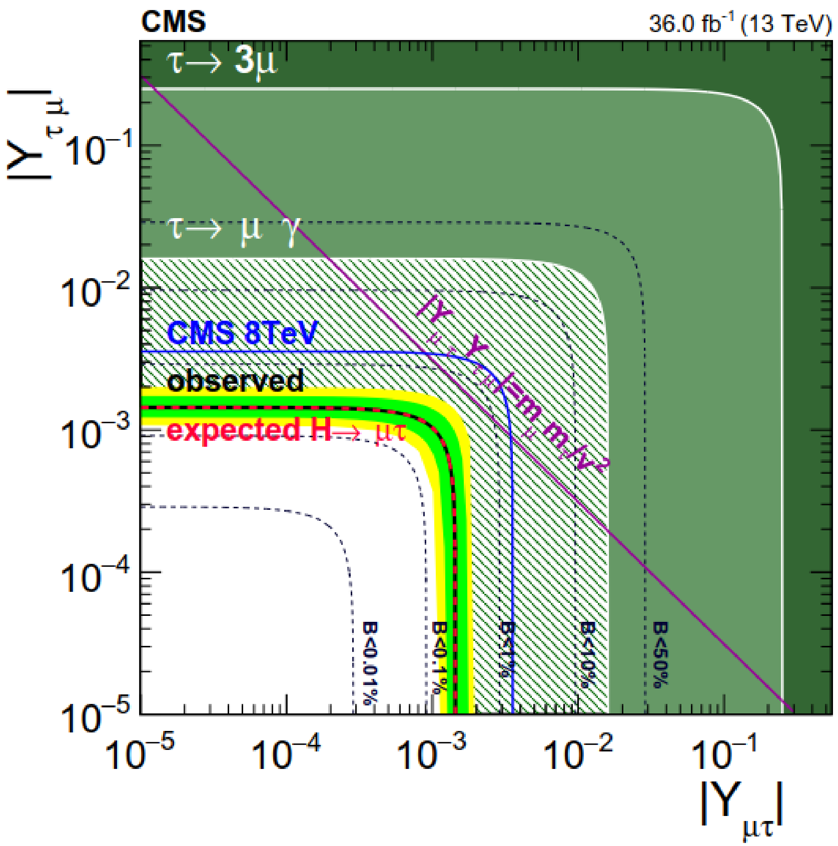
12th March 2021

Combination of searches for invisible Higgs boson decays with the ATLAS experiment

assuming Higgs boson production according to the SM. An upper limit on the invisible Higgs boson branching ratio of $\mathcal{B}_{H\to\mathrm{inv}} < 0.13$ ($0.12^{+0.05}_{-0.04}$) is observed (expected) at the 95% CL. A statistical combination of this result with the combination of direct $H \to$ inv searches using up to 4.7 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV and up to 20.3 fb^{-1} at 8 TeV collected in Run 1 of the LHC yields an observed (expected) upper limit of $\mathcal{B}_{H\to\mathrm{inv}} < 0.11$ ($0.11^{+0.04}_{-0.03}$) at the 95% CL. The combined Run 1+2 result is translated into upper limits on the WIMP-nucleon scattering cross section for Higgs portal models. The derived limits on $\sigma_{\mathrm{WIMP}\text{-}N}$ range down to 10^{-45} cm^2 and 2×10^{-47} cm^2 in the scalar and Majorana fermion WIMP scenarios, respectively, highlighting the complementarity of DM searches at the LHC and direct detection experiments.

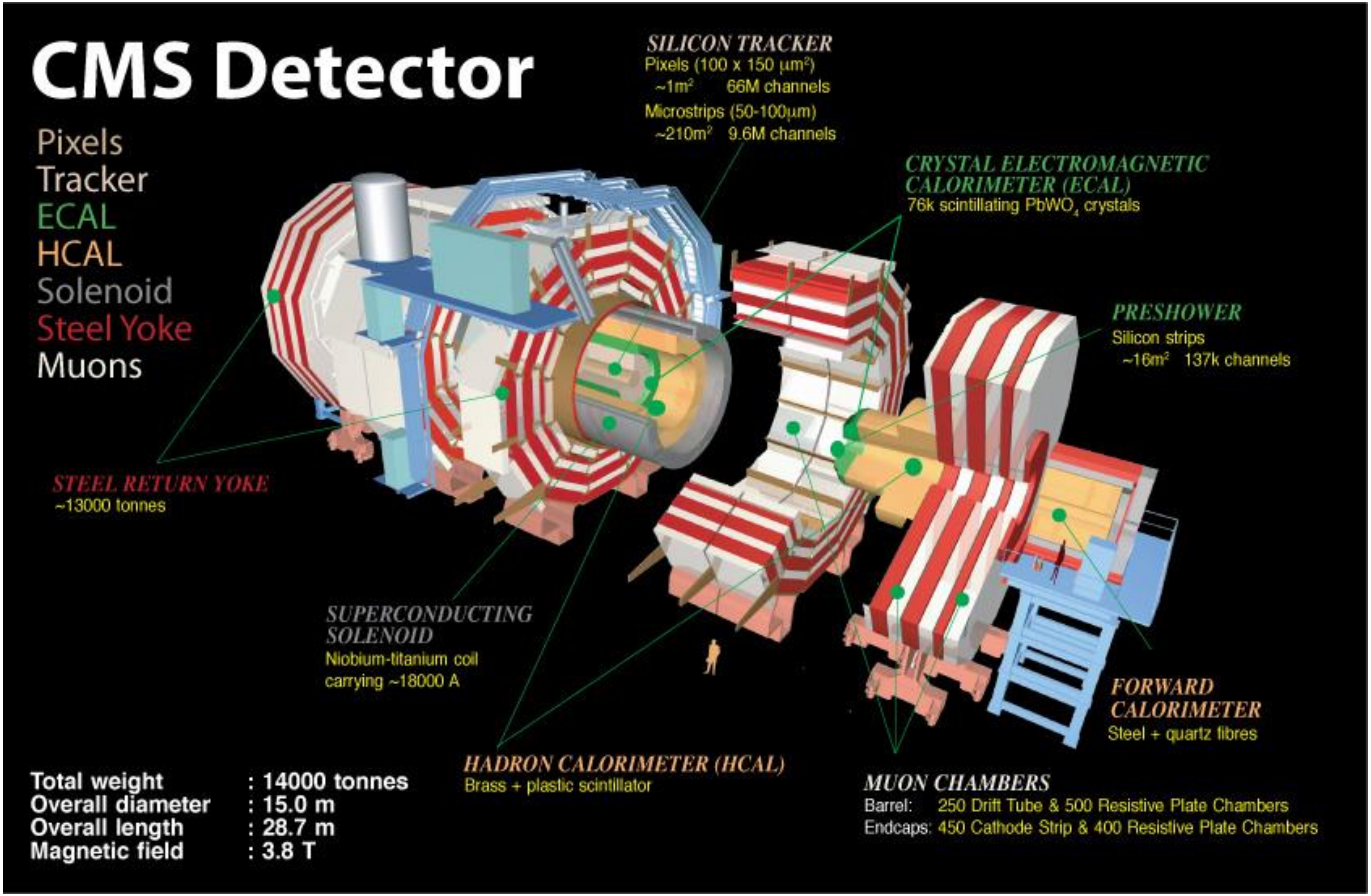
Non-SM h decays: *LFV with h→$\mu\tau$*





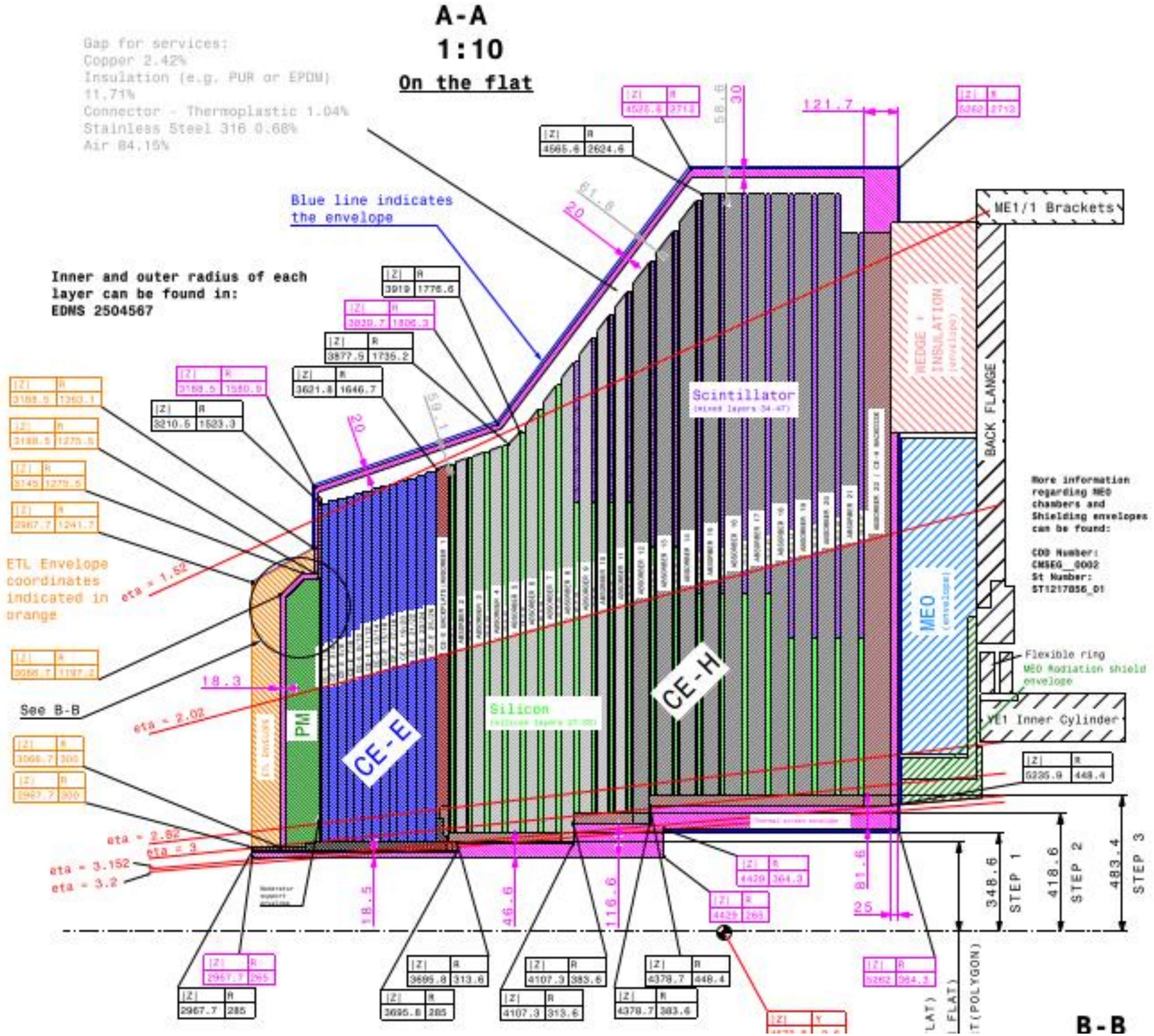
Access seen with 8 TeV, 20 fb^{-1} data is not confirmed for 13 TeV, 36 fb^{-1}

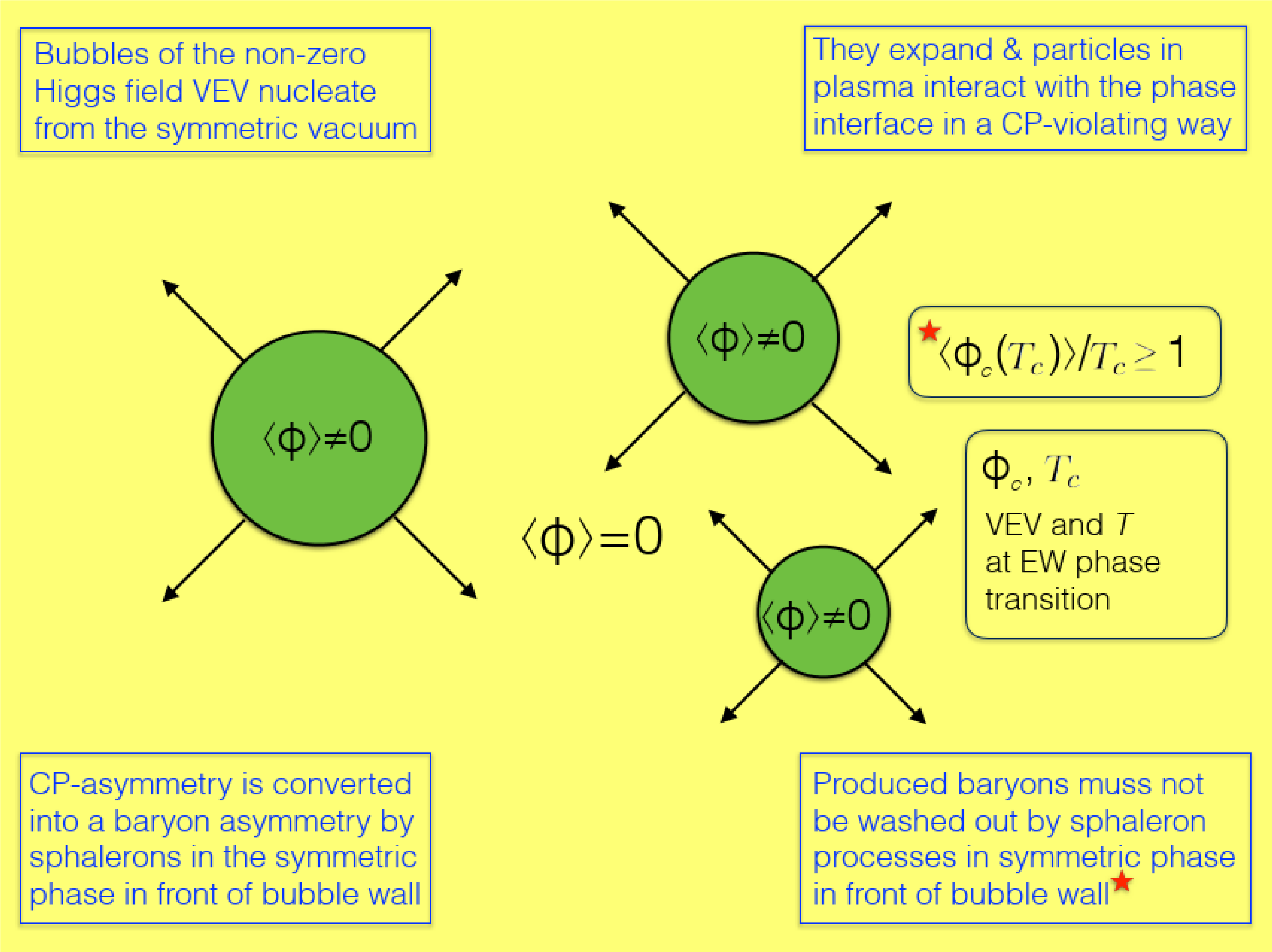
JHEP 06 (2018) 001


CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² 66M channels
Microstrips (50-100μm)
~210m² 9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² 137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
MUON CHAMBERS
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Excellent prospect for forward jet reconstruction at HL-LHC:

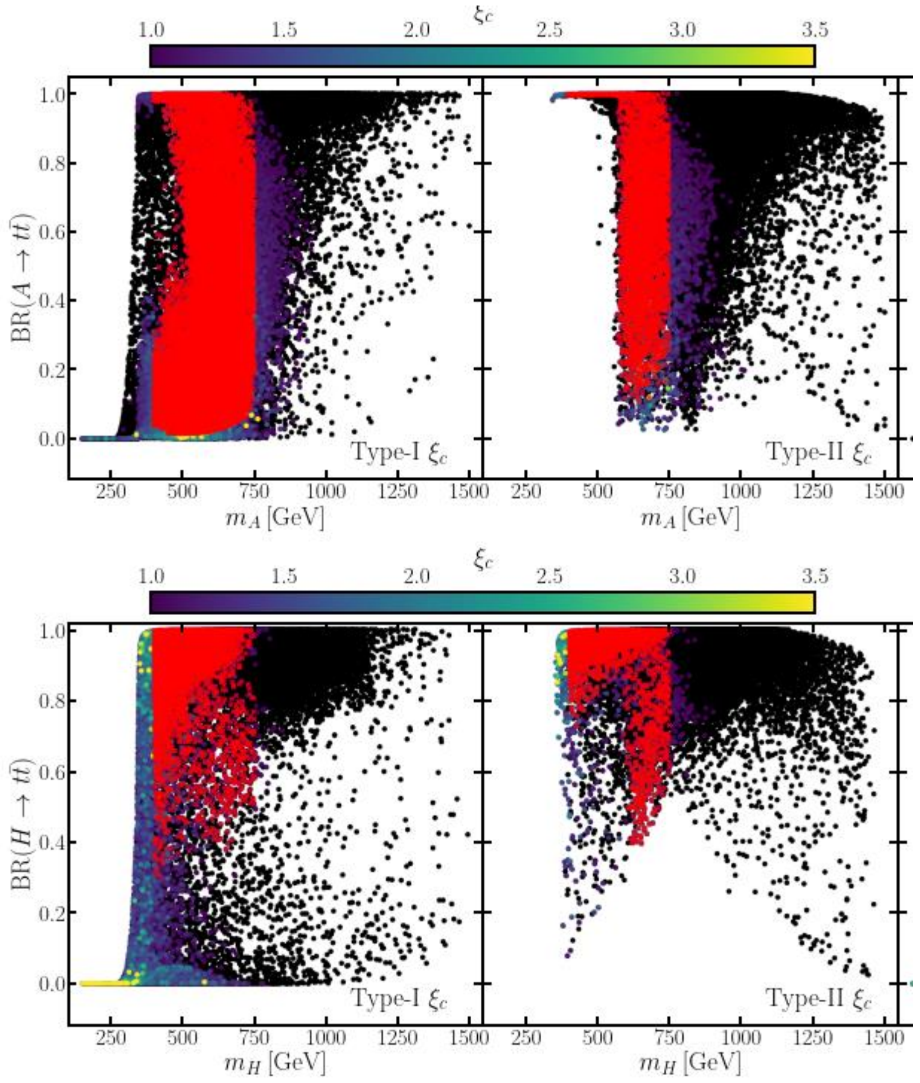
CMS HGCAL (tracker) up to $|\eta| \approx 3.0\ (4.0)$




Bubbles of the non-zero Higgs field VEV nucleate from the symmetric vacuum
They expand & particles in plasma interact with the phase interface in a CP-violating way
$\langle\phi\rangle\neq 0$
$\langle\phi\rangle\neq 0$
$\langle\phi\rangle\neq 0$
$\langle\phi\rangle = 0$
$\langle\phi_c(T_c)\rangle/T_c \geq 1$
ϕ_c, T_c
VEV and T at EW phase transition
CP-asymmetry is converted into a baryon asymmetry by sphalerons in the symmetric phase in front of bubble wall
Produced baryons muss not be washed out by sphaleron processes in symmetric phase in front of bubble wall

2HDM signatures as an evidance for EWPT to be searched at HL-LHC

Red points can be probed at HL-LHC with A/H→tt



Electroweak phase transition in the 2HDM: collider and gravitational wave complementarity

Dorival Gonçalves,[1] Ajay Kaladharan,[1] and Yongcheng Wu[1]

[arXiv:2108.05356]

- **continue with A→ZH→llbb search, however is restricted by $m_H < 2m_t$, when H→tt is open**
- **Search for heavy A(H)→tt and $H^{\pm}$→tb**

Prospects for Higgs p_T at LH-LHC

- **CMS FTR-18-011**

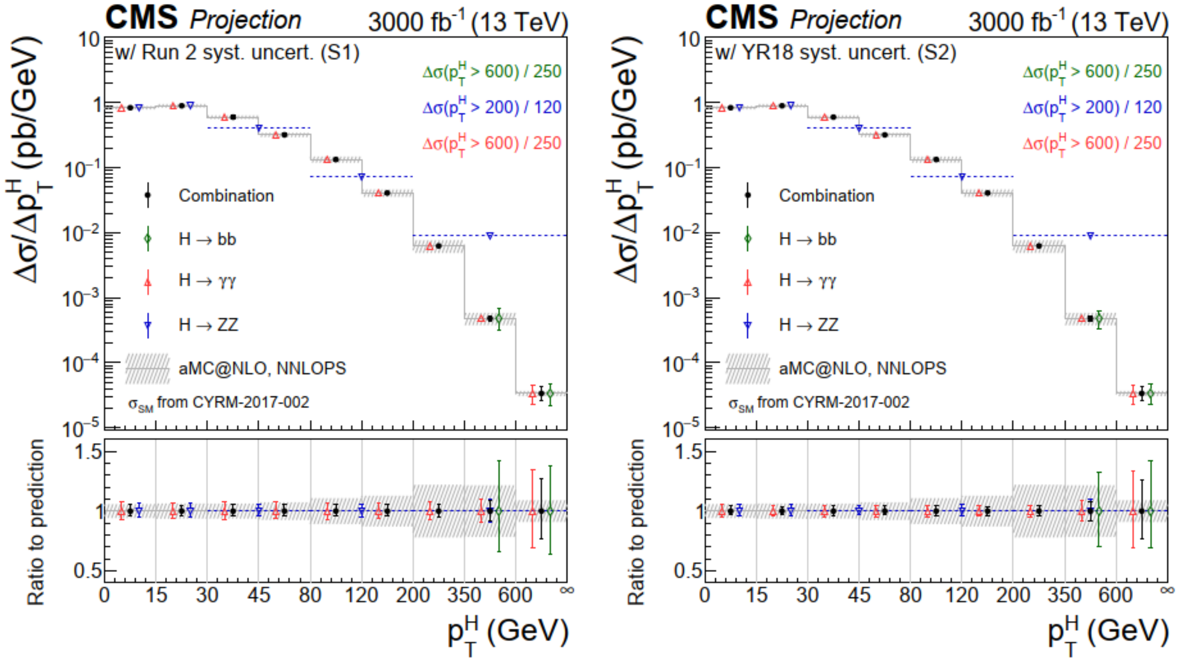
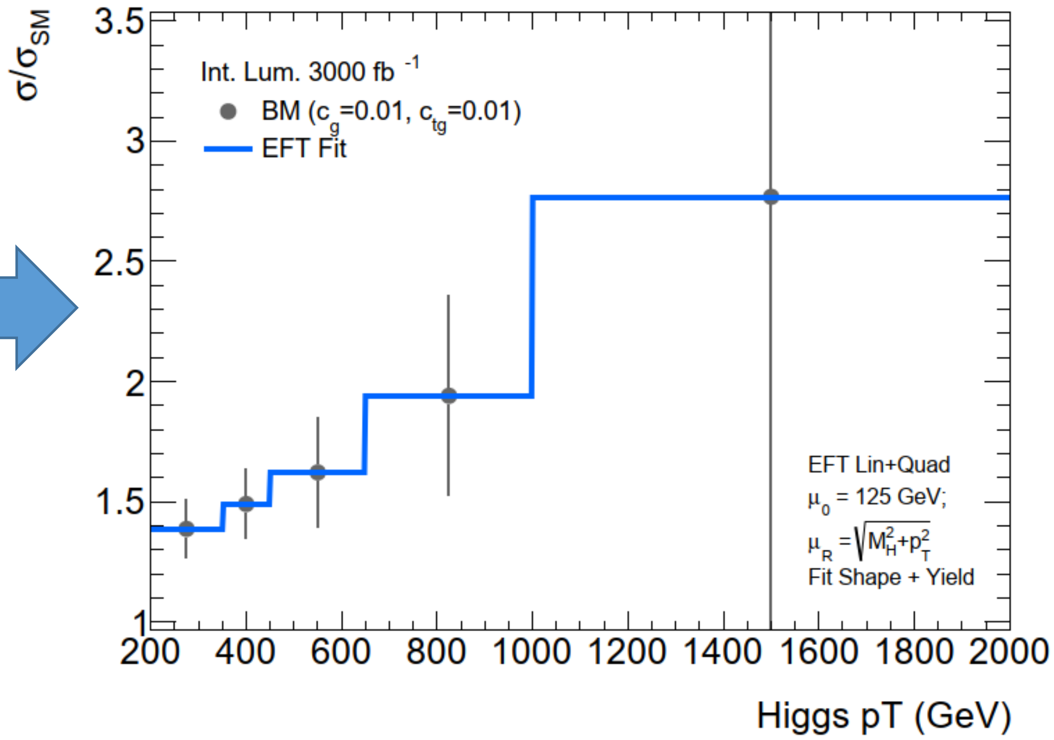


Figure 14: Projected differential cross section for the $p_T(H)$ spectrum at an integrated luminosity of 3000 fb^{-1}, under S1 (left, with Run 2 systematic uncertainties [41]) and S2 (right, with YR18 systematic uncertainties).

- Spira et al. arXiv:2109.02987 TH test of EFT input

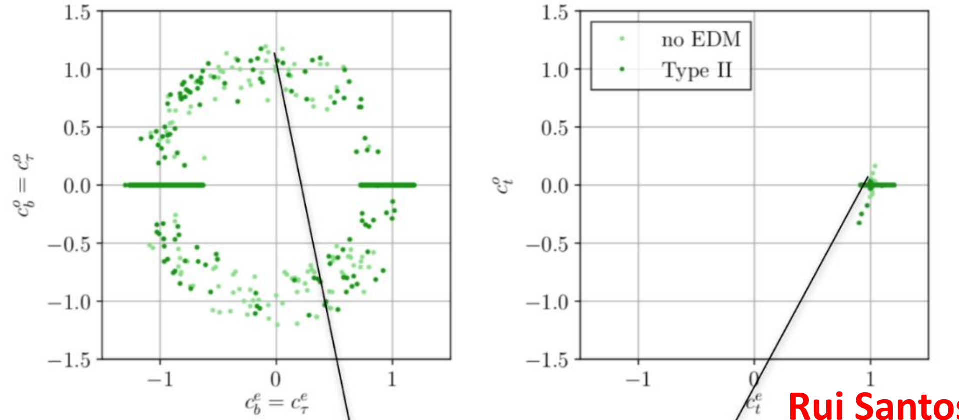


The chromomagnetic dipole operator can be tested also in the top sector:
arXiv:1910.03606, CMS: arXiv:1811.06625, arXiv:2012.04120

$$\frac{c_3}{\Lambda^2}\mathcal{O}_3 \quad \to \quad c_{tg}\frac{g_S m_t}{2v^3}(v+h)G^a_{\mu\nu}(\bar{t}_L\sigma^{\mu\nu}T^a t_R + h.c)\,,$$

This measurement is very interesting in 2HDM !

The strange case of CP-violation in a complex 2HDM



$$Y_{C2HDM} = a_F + i\gamma_5 b_F$$

$$b_U \approx 0; \ a_D \approx 0$$

A Type II model where H_2 is the SM-like Higgs

Rui Santos, private communication

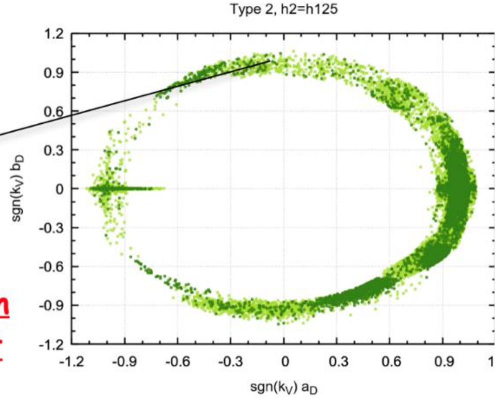
With the new EDM result

Find two particles of the same mass one decaying to tops as CP-even

$$h_2 = H; pp \to Ht\bar{t}$$

and the other decaying to taus as CP-odd

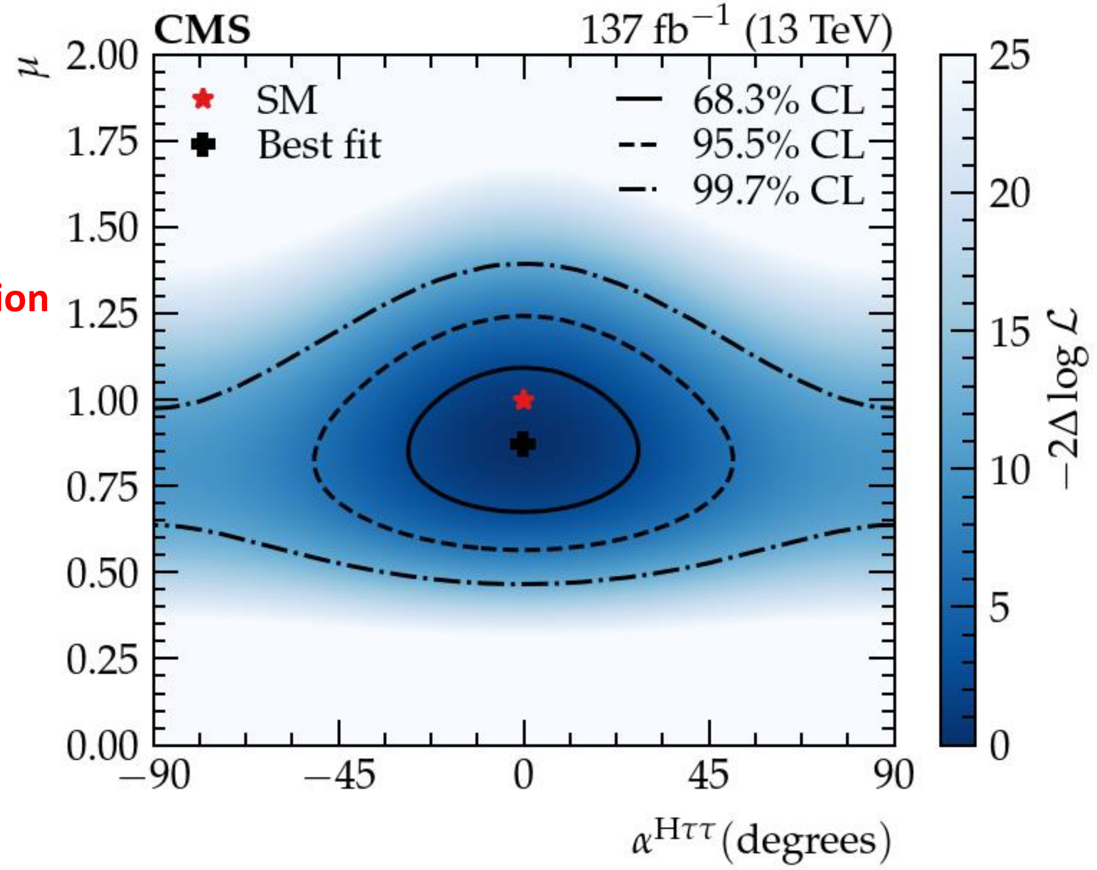
$$h_2 = A \to \tau^+\tau^-$$



Probing one Yukawa coupling is not enough! And I have chosen values in agreement with the most recent EDM measurement

FONTES, MÜHLLEITNER, ROMÃO, RS, SILVA, WITTBRODT, JHEP 1802 (2018) 073.

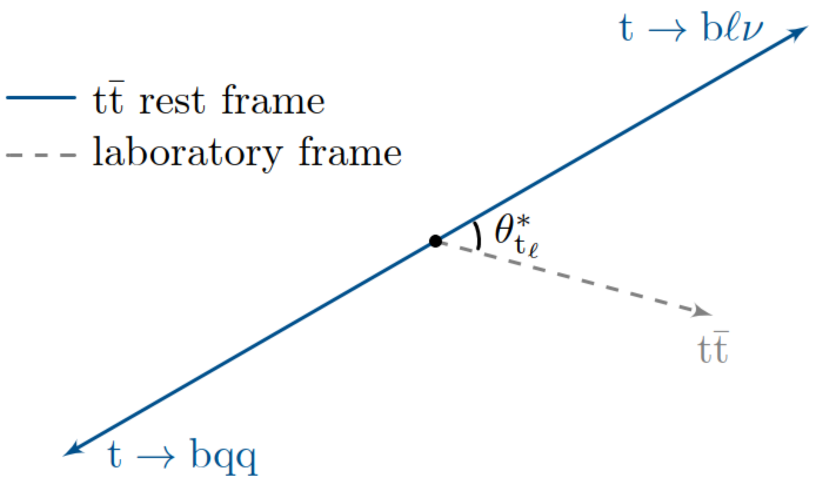
Exclude scenario when $h_2(h_{125})$ is SM like but decay to tt~ as CP-even and to ττ as CP-odd

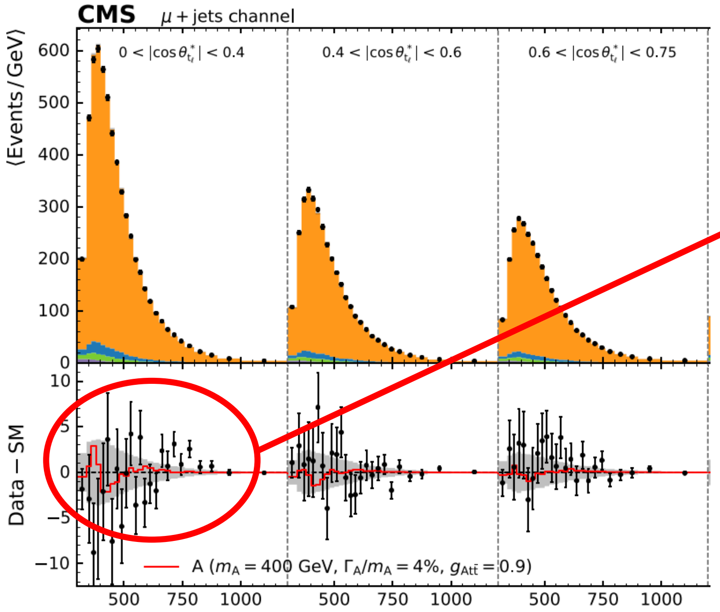


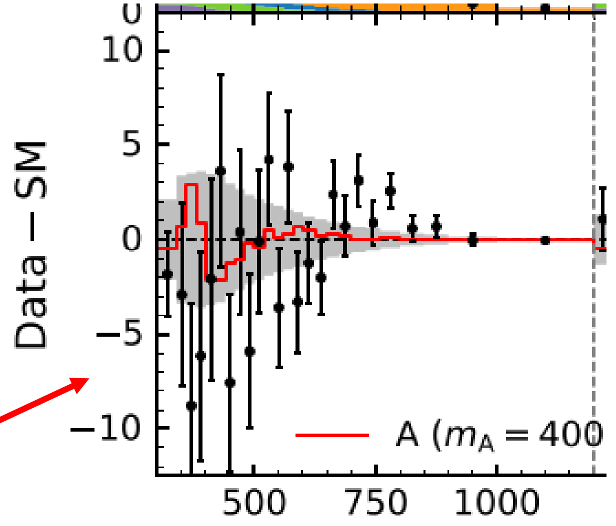
JHEP 1802 (2018) 073

New: first CMS result on low tanβ, large m_A MSSM channel H/A→**tt (I)** (arXiv:1908.01115)

- **semileptonic and di-lepton topology selected**
- **interference effect between gg→H(A)→tt signal ($^3P_0(^1S_0)^*$ state) and gg→tt (mixture of states) background produce peak-dip structure in di-top system mass distribution**
  - K. J. F. Gaemers and F. Hoogeveen, Phys. Lett. B 146 (1984) 347
  - D. Dicus, A. Stange, and S. Willenbrock, arXiv:hep-ph/9404359
  - W. Bernreuther, M. Flesch, and P. Haberl, arXiv:hep-ph/9709284
- **exploit difference in spin correlations. Fit m_{tt} in bins of $\cos\theta^*_{tl}$**



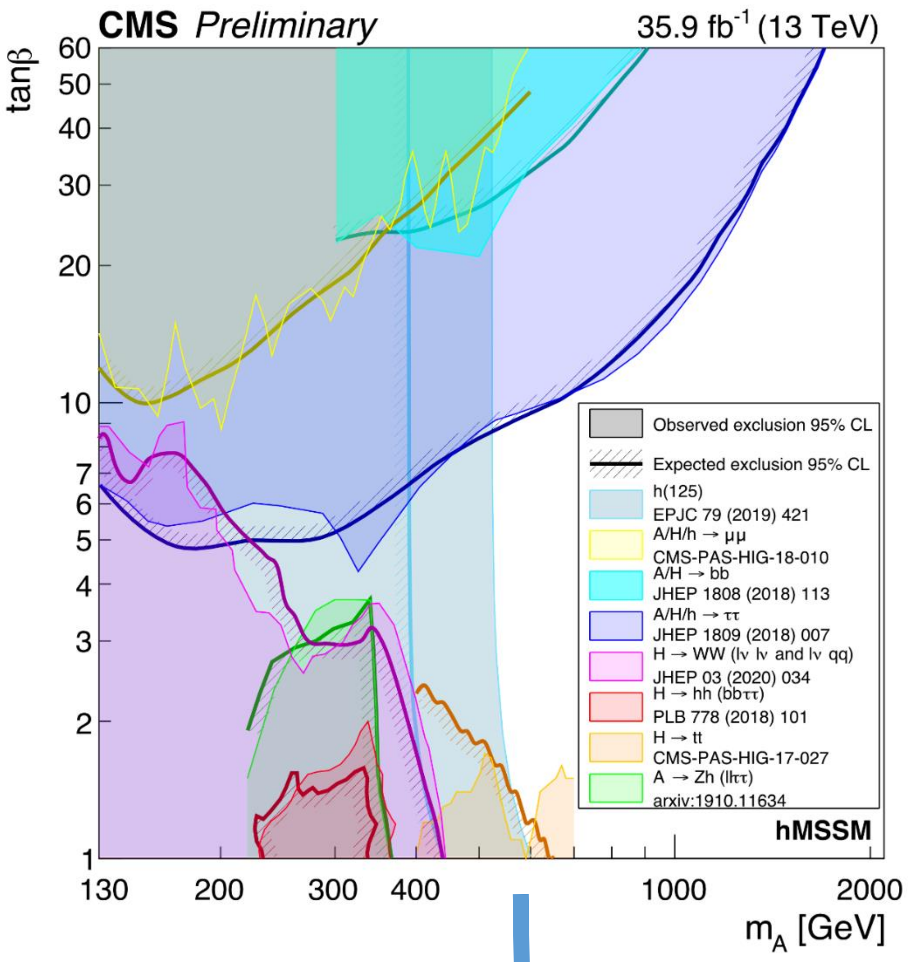


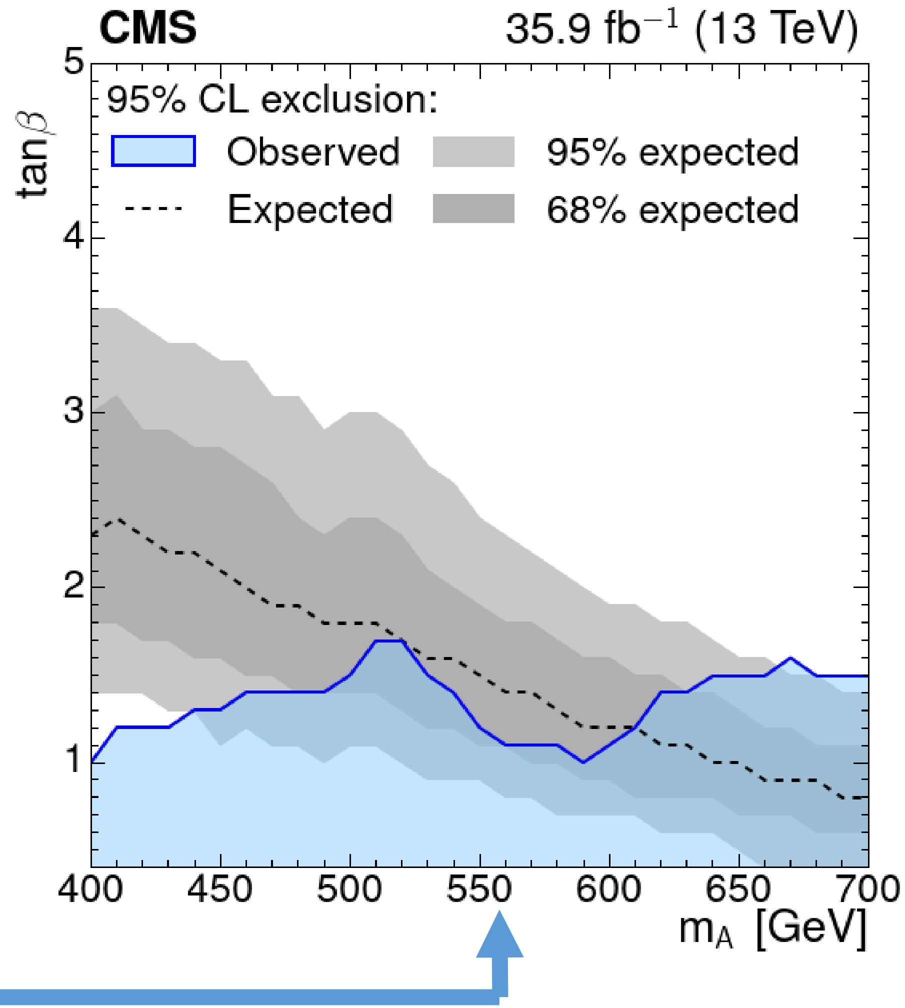


m_{tt} [GeV]

* $^{2S+1}L_J$, J=|S|+|L|, …|S|-|L|

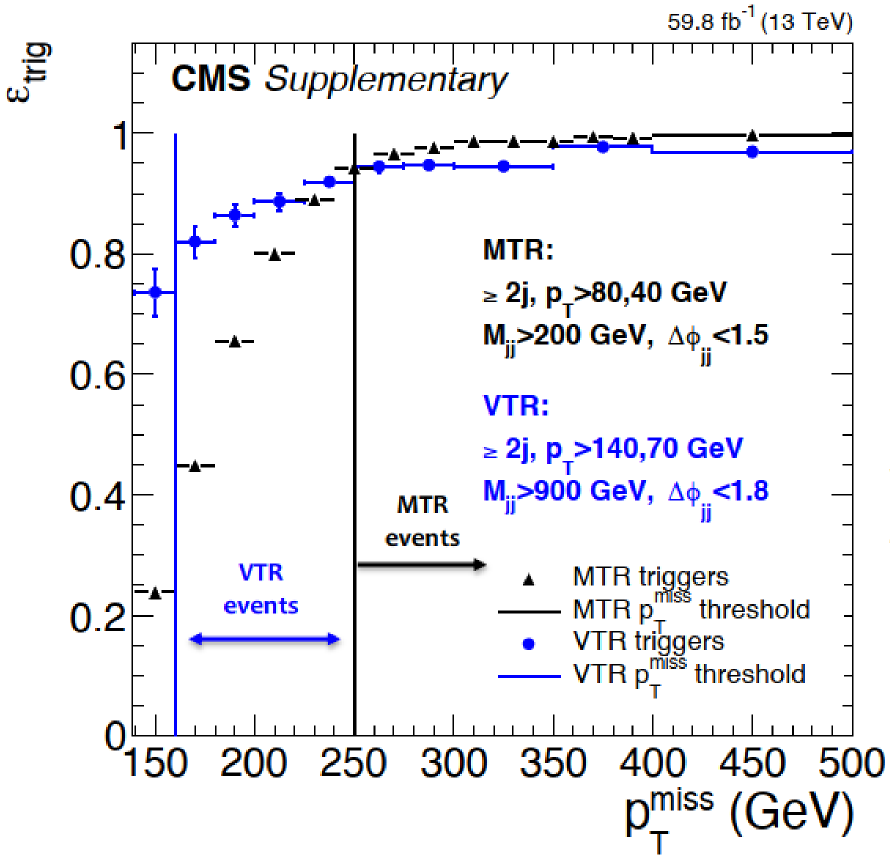
New: first CMS result on low tanβ, large m_A MSSM channel H/A→**tt (II)**





Trigger on the most sensitive mode VBF h→invis

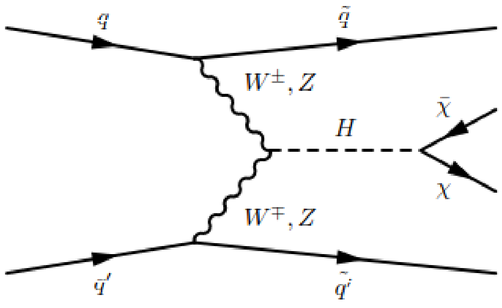
Event selection (online)



Event triggers require large missing momentum + jets

- **MTR** (missing-momentum trigger) target high p_T^{miss} events
- **NEW for 2017/2018: VTR** (VBF-trigger) provides improved efficiency at lower p_T^{miss} (improves sensitivity by ~8%)

Events separated into two regions (MTR & VTR) based on reconstructed p_T^{miss} and jet/M_{jj} requirements

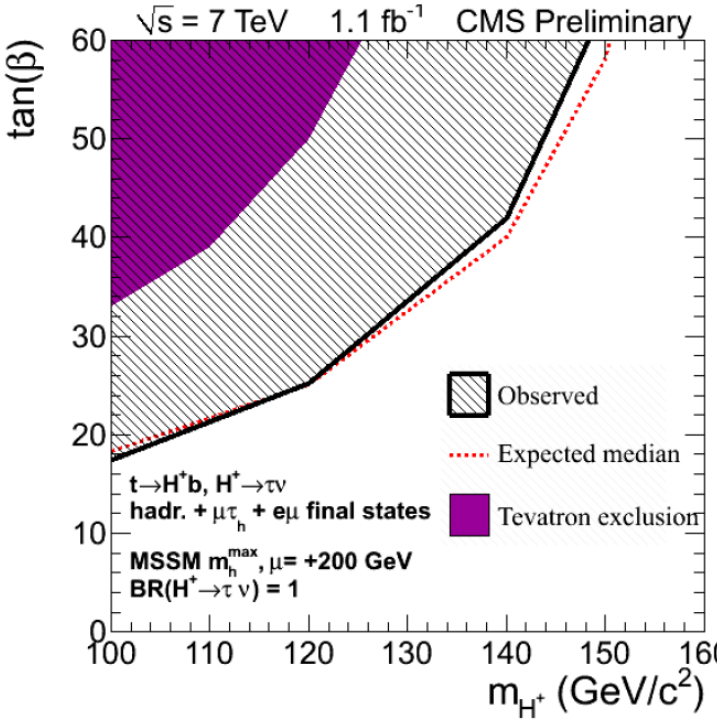


Using refined alignment/calibration for 2017/2018 analysis
→ Substantial performance gain for forward jets!

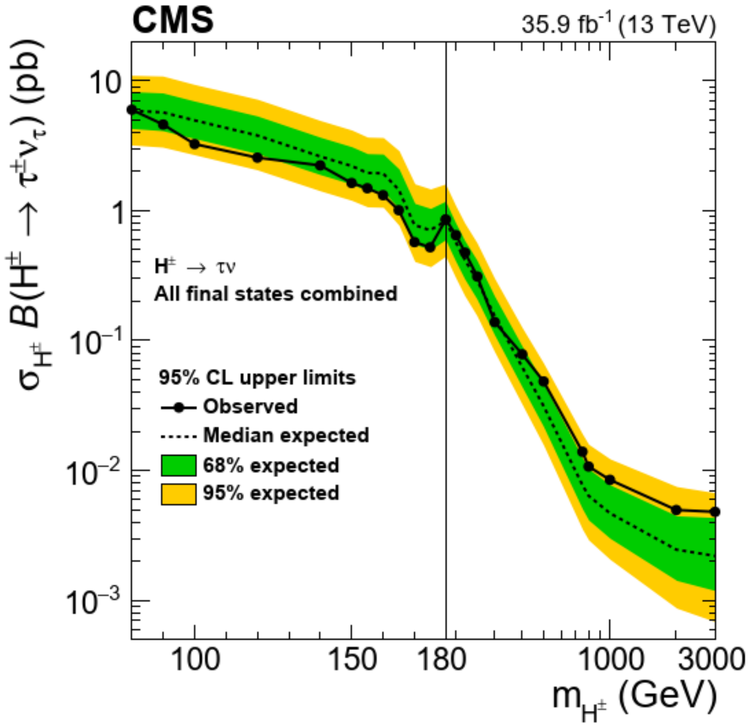
Slide from Nick Wardle talk at Higgs2021

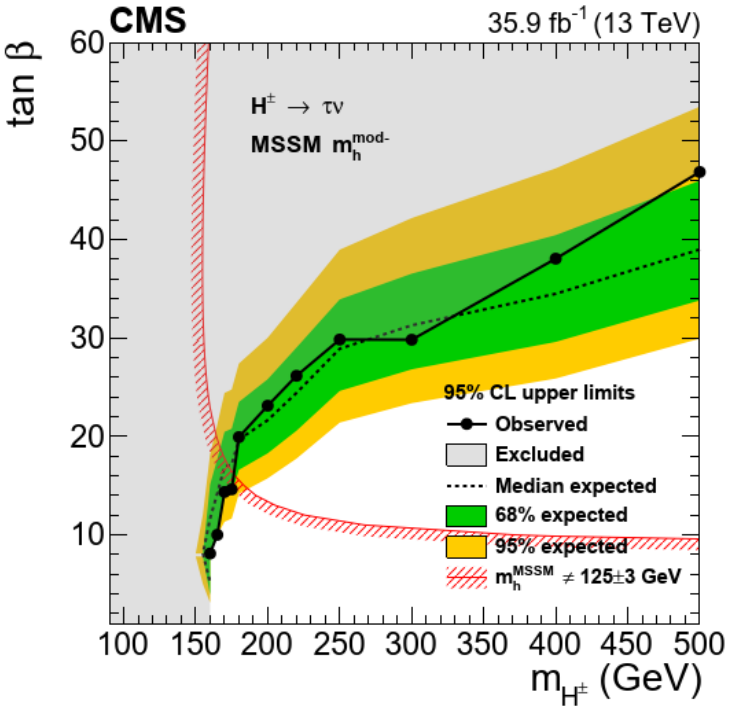
From 2011 to 2022 in MSSM charged Higgs searches

CMS PAS HIG-11-008

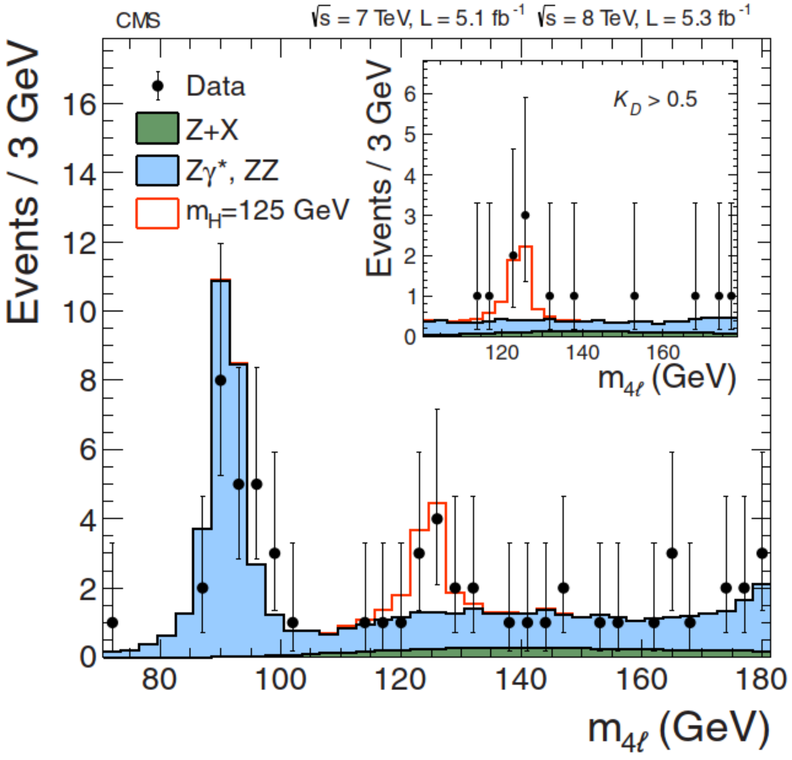


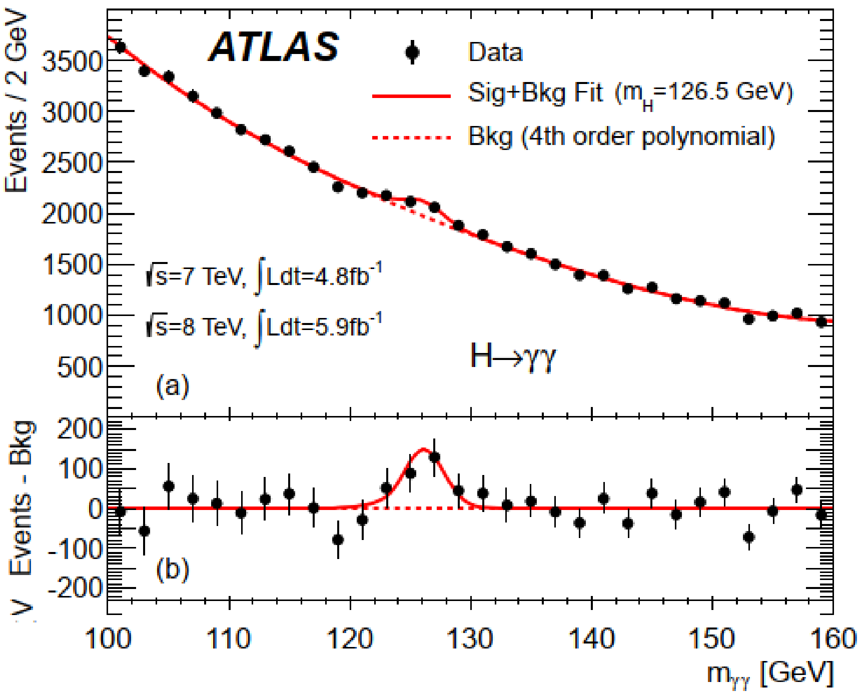
arXiv:1903.04560



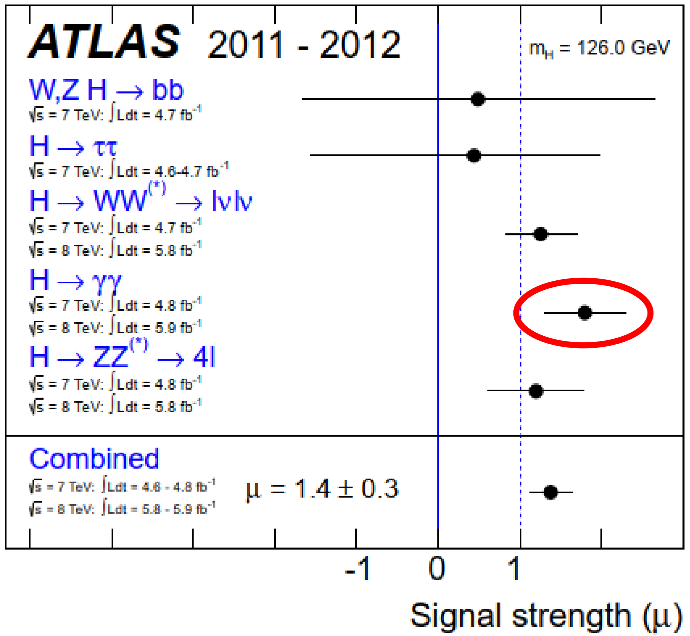


Discovery papers, 2012



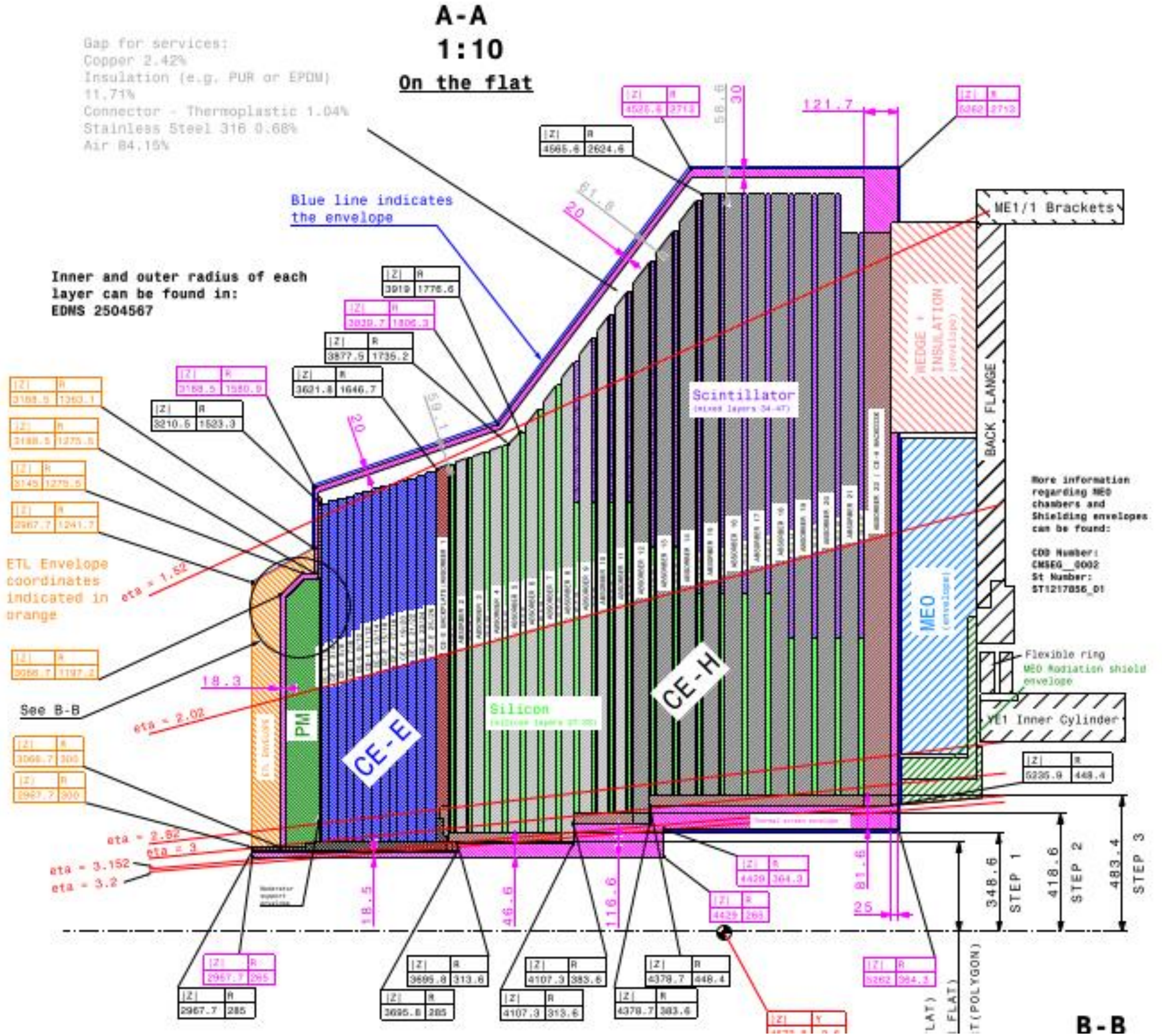


Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.8	3.2
$\tau\tau$ + bb	2.4	0.5
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0



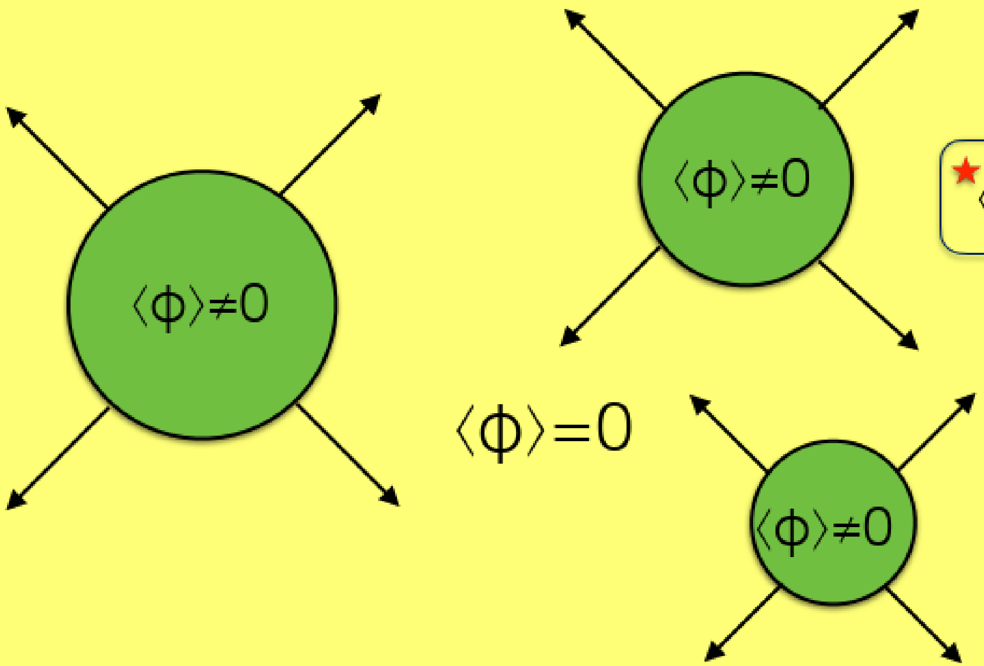
Excellent prospect for forward jet reconstruction at HL-LHC:

CMS HGCAL (tracker) up to |η| ≈ 3.0 (4.0)



Bubbles of the non-zero Higgs field VEV nucleate from the symmetric vacuum

They expand & particles in plasma interact with the phase interface in a CP-violating way



★ $\langle \phi_c(T_c) \rangle / T_c \gtrsim 1$

ϕ_c, T_c
VEV and T at EW phase transition

CP-asymmetry is converted into a baryon asymmetry by sphalerons in the symmetric phase in front of bubble wall

Produced baryons muss not be washed out by sphaleron processes in symmetric phase in front of bubble wall★

BSM Higgs 12 years later in ATLAS and CMS

LHC Days in Split 2022

A. Nikitenko,

Kurchatov Institute, Moscow, Russia

also Imperial College, London, UK