

# Physics (BSM) at LHC

ATLAS, CMS, LHCb

**A. Nikitenko,**

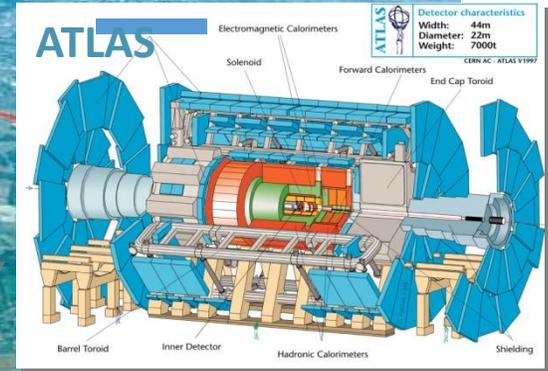
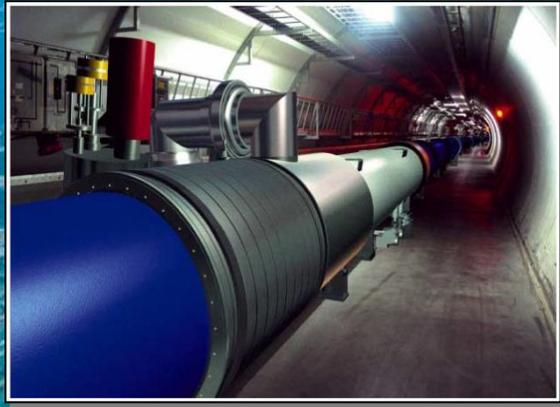
**JINR, Dubna, Russia,**

**also Imperial College, London, UK**

**Novosibirsk, March, 2026**

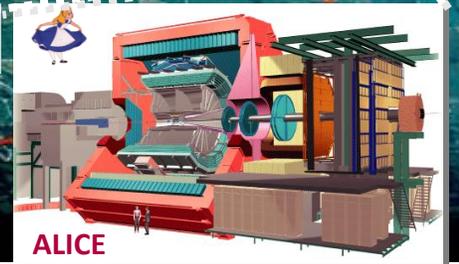
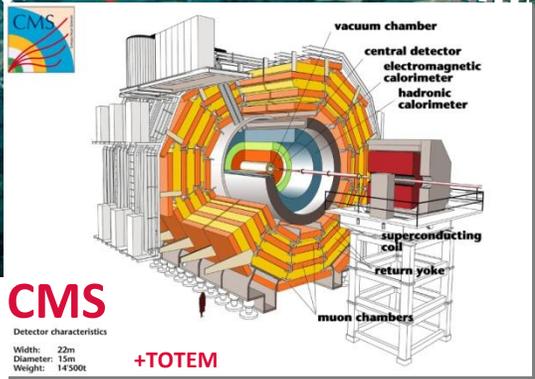
pp, B-Physics,  
CP Violation

LHC : 27 km long  
100m underground



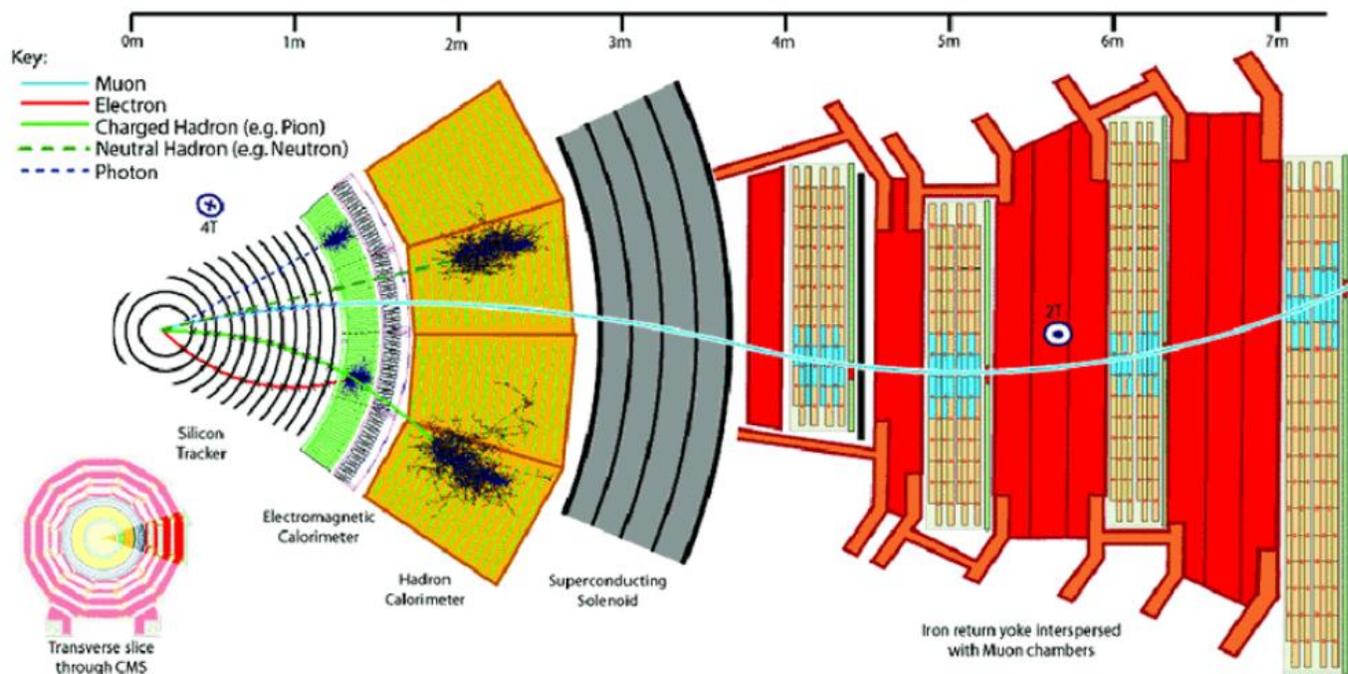
General Purpose,  
pp, heavy ions

Heavy ions, pp

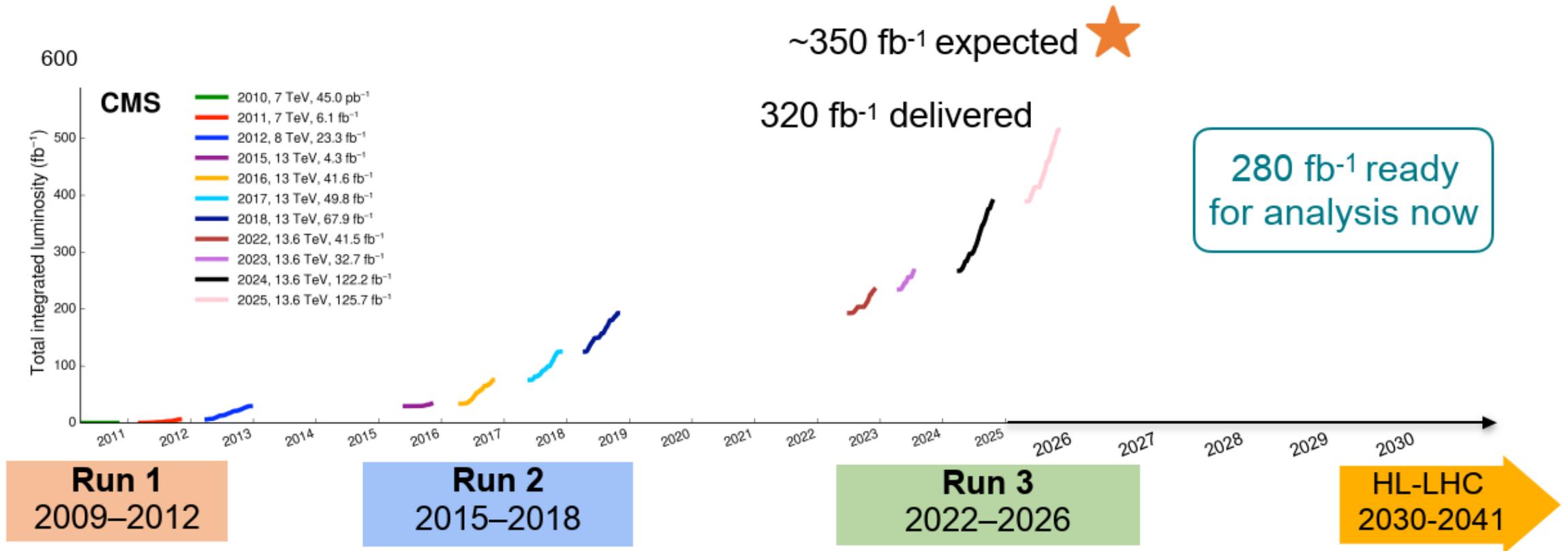


# X-Y view of Compact Muon Solenoid

- Level 1 muon trigger uses muon stations only (RPC, DT, CSC).
- High Level Trigger combines tracker and muon station information



# Accumulated luminosity (CMS)



# CERN, June 2012.

## Higgs boson discovery



In 2012 SUSY people were happy to say:

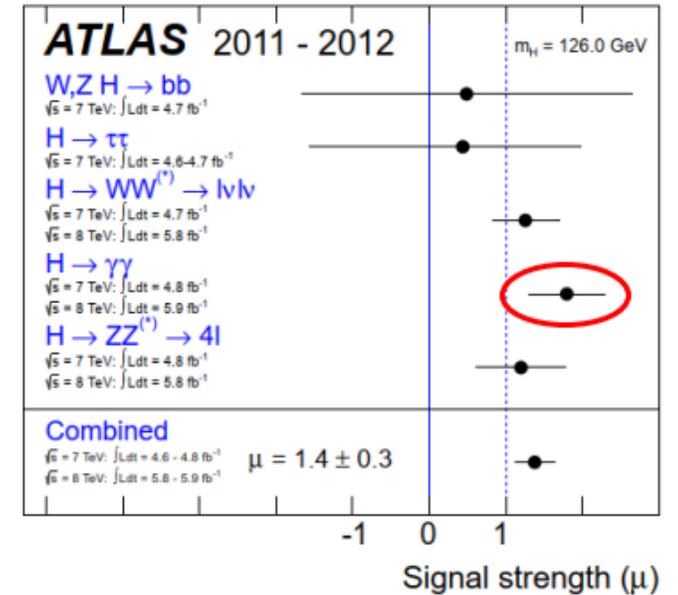
$h_{125}$  is the first discovered SUSY particle

CMS

Decay mode/combination	Expected ( $\sigma$ )	Observed ( $\sigma$ )
$\gamma\gamma$	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

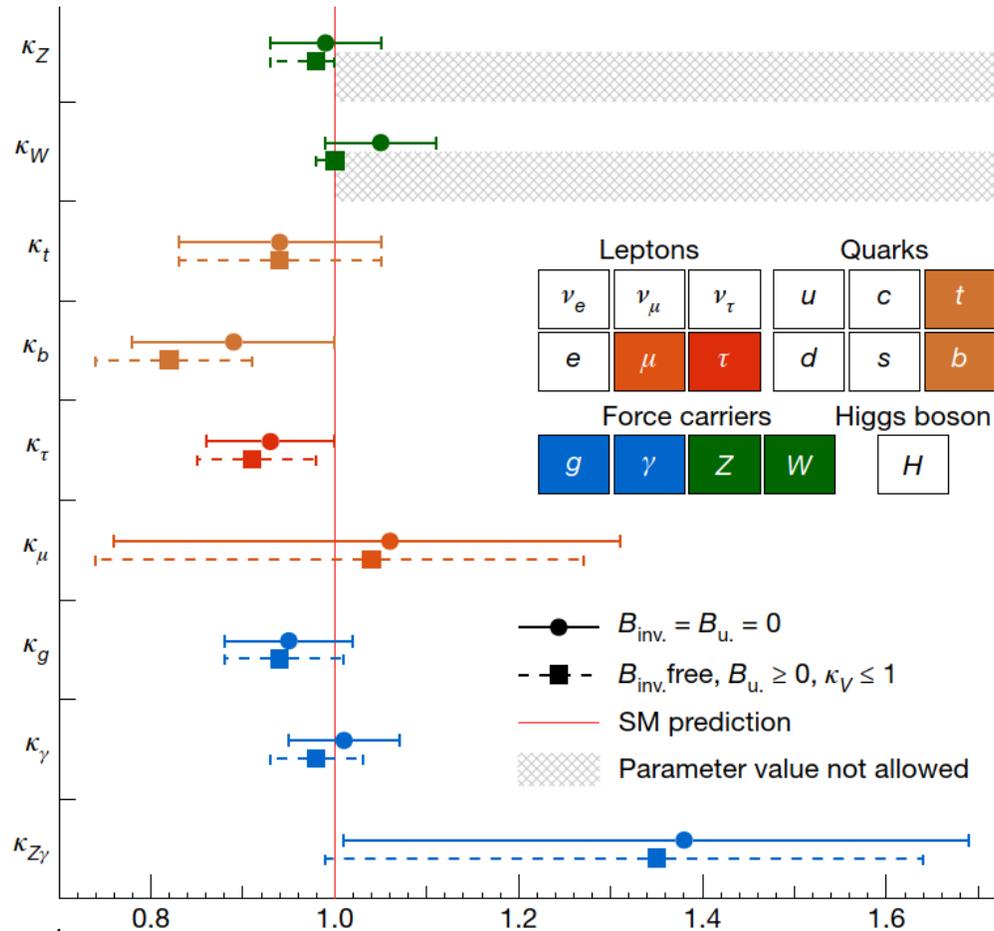


Two SUSY-Gurus



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

# Summary of coupling strength modifiers for $h_{125}$

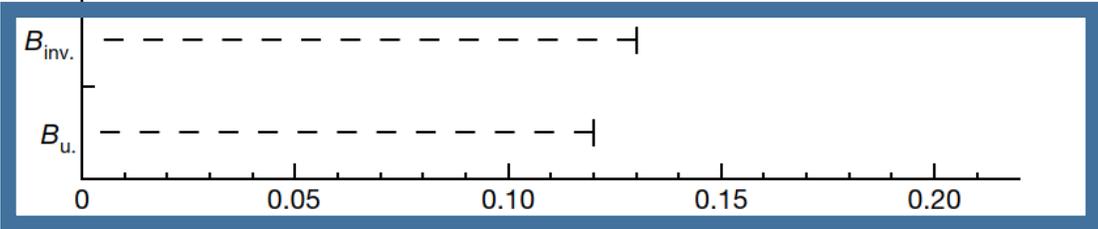


$B_i$  – probability to decay to invisible mode ( $h_{125} \rightarrow \text{DM DM}$ )  
 $B_u$  – probability to decay to yet undetected BSM modes  
 $h_{125} \rightarrow \mu\tau, hh, \dots + \text{unknown/undetactable}$

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

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

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



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

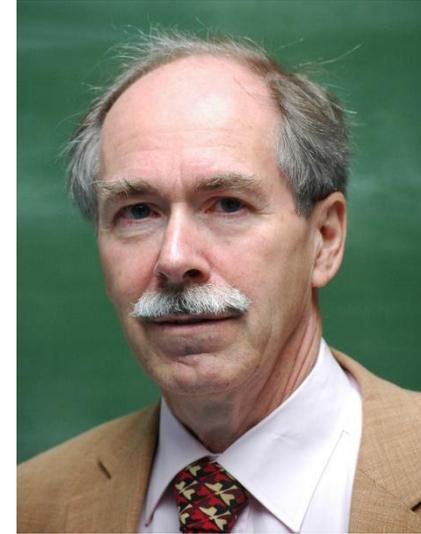
Gerard 't Hooft  
Institute for Theoretical Physics  
Utrecht University  
the Netherlands

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



# BSM physics with Higgs bosons

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

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



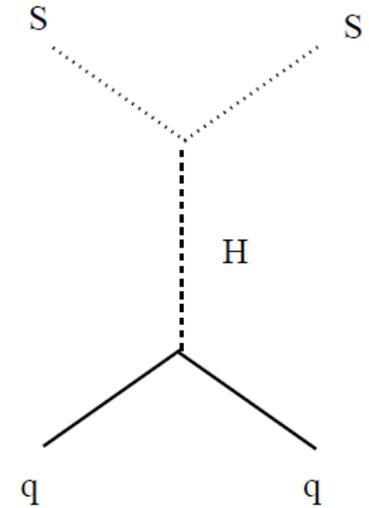
# Connection between LHC H->inv. and direct DM searches”

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

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

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

**DM-nucleon scattering  
(LUX-ZEPLIN, PandaX-4T, ...)**



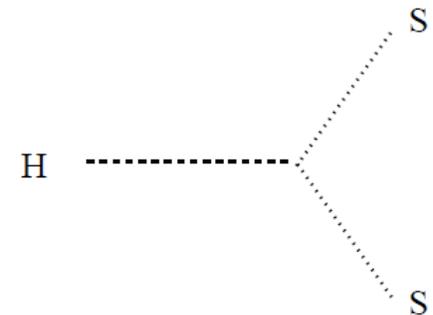
where  $f_N$  – Higgs-nucleon coupling

$$\Gamma_{h \rightarrow SS}^{\text{inv}} = \frac{\lambda_{hSS}^2 v^2 \beta_S}{64\pi m_h},$$

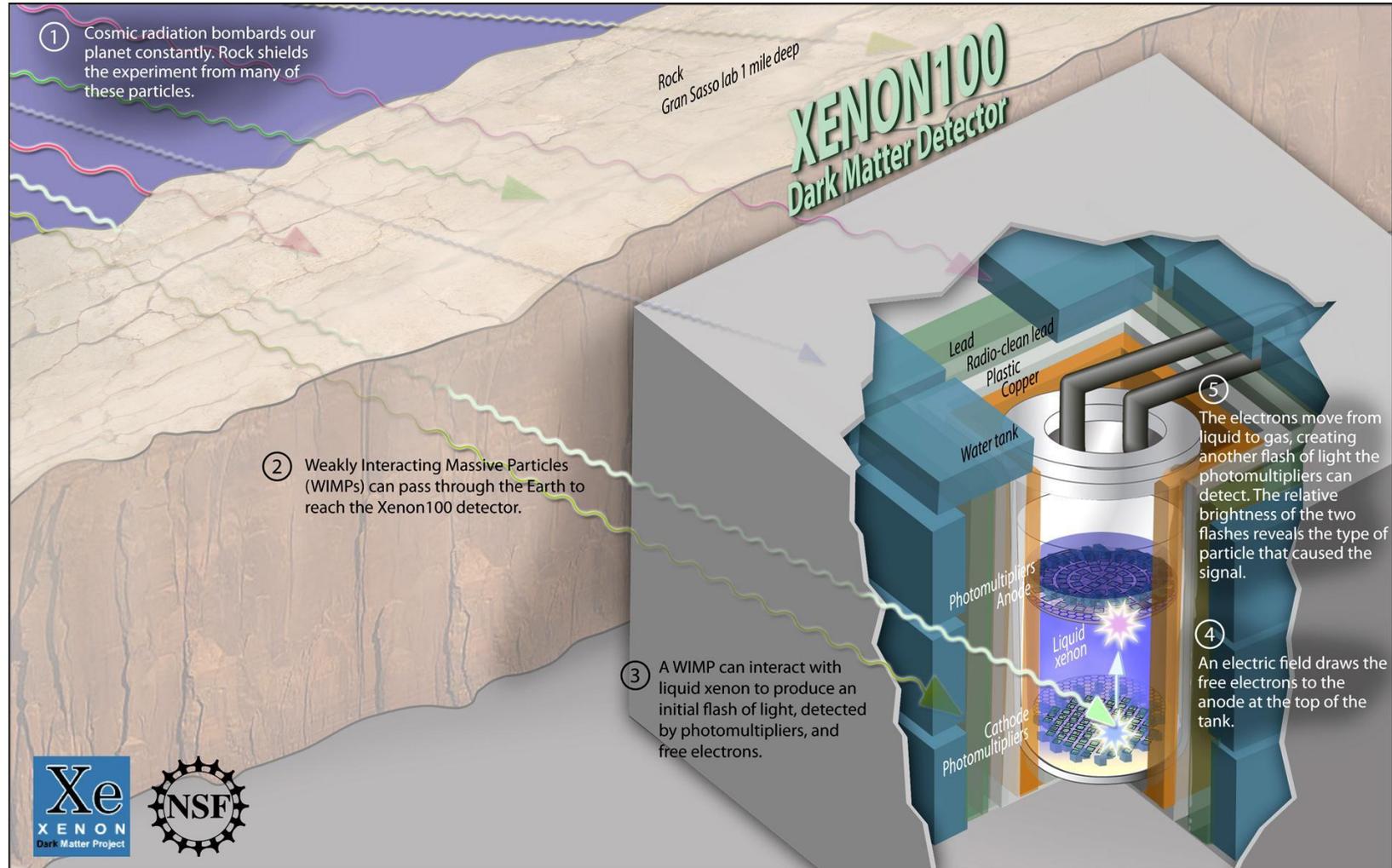
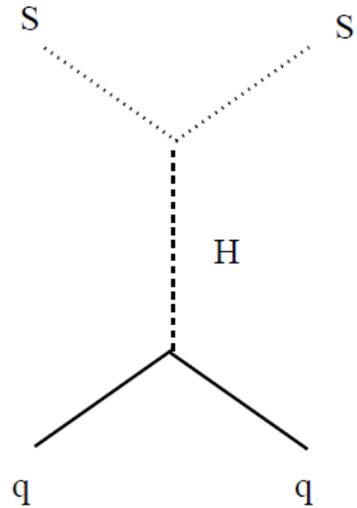
$$\Gamma_{h \rightarrow VV}^{\text{inv}} = \frac{\lambda_{hVV}^2 v^2 m_h^3 \beta_V}{256\pi M_V^4} \left( 1 - 4 \frac{M_V^2}{m_h^2} + 12 \frac{M_V^4}{m_h^4} \right)$$

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

**H->invisible decay at LHC**



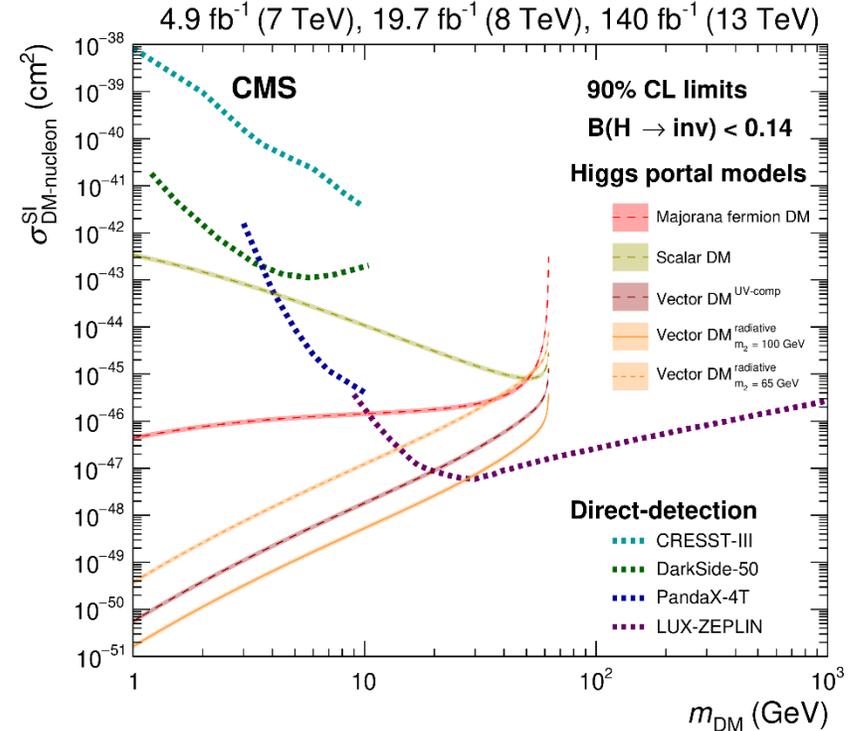
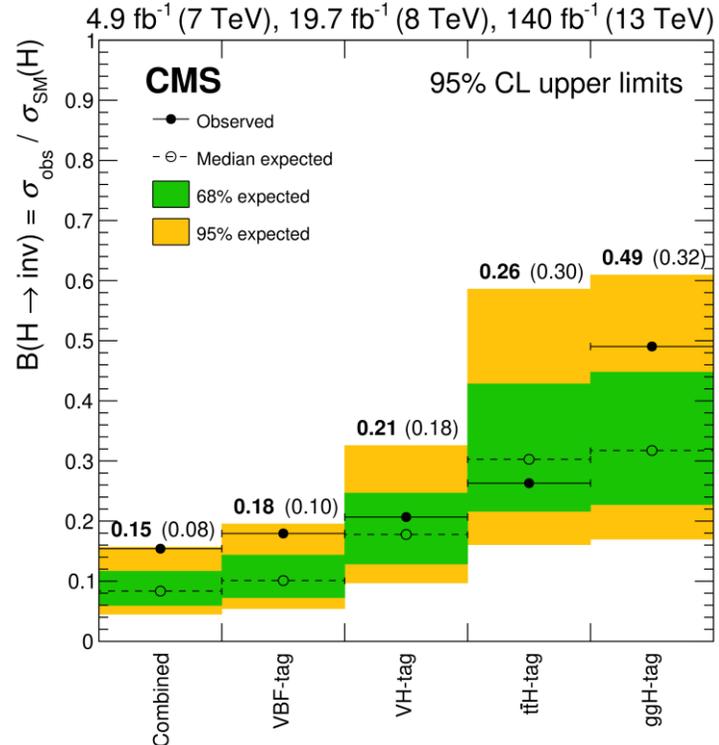
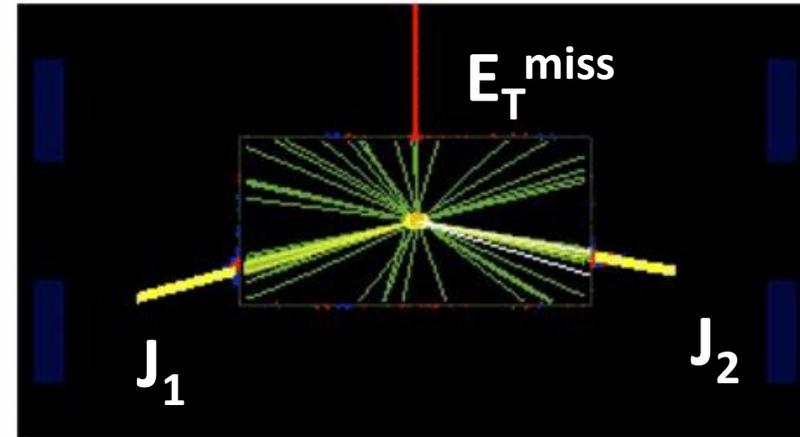
# DM (WIMP) detection on Earth with XENON experiment



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

# most sensitive mode $qq' \rightarrow qq'h$ (VBF h)

[Eur. Phys. J. C 83 \(2023\) 933](#)



**Expect to reach  $\approx 4\%$  at HL-LHC with 3 ab<sup>-1</sup> (FTR-19-001)**

# How it is compared with MSSM and NMSSM predictions

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

- interesting in NMSSM

U. Ellwanger et al, [arXiv:2403.16884](https://arxiv.org/abs/2403.16884)

Scenarios with light neutralino 1

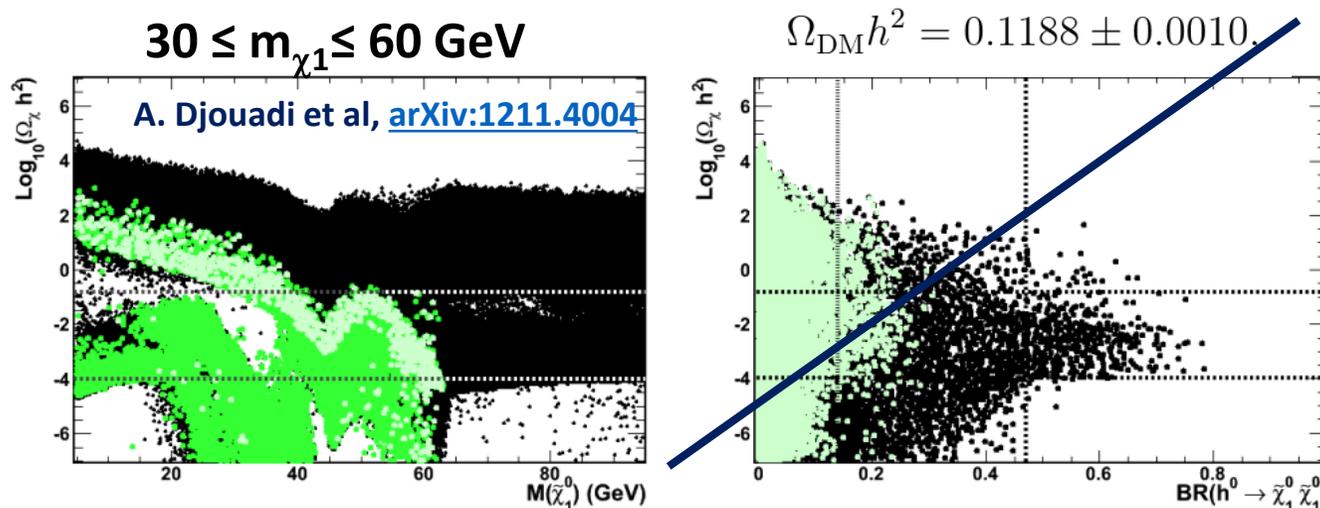


Figure 4: The neutralino relic density  $\log_{10}(\Omega_\chi h^2)$  as a function of  $M_{\chi_1^0}$  (left) and  $\text{BR}(h \rightarrow \chi_1^0 \chi_1^0)$  (right) for the accepted set of pMSSM points (black dots), those with  $\text{BR}(h \rightarrow \chi_1^0 \chi_1^0) \geq 15\%$  (green dots)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

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

**BR  $h \rightarrow$  invisible can reach  $\approx 10-15\%$  due to destructive interferences among processes mediated by the CP-even scalars.**

*Cyril Hugonie, private communication*

latest update in R. Godbole et al. [arXiv:2402.07991](https://arxiv.org/abs/2402.07991),  $\text{BR}(h \rightarrow \chi_1 \chi_1) < 0.1\%$

# Additional Higgs bosons

in MSSM

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

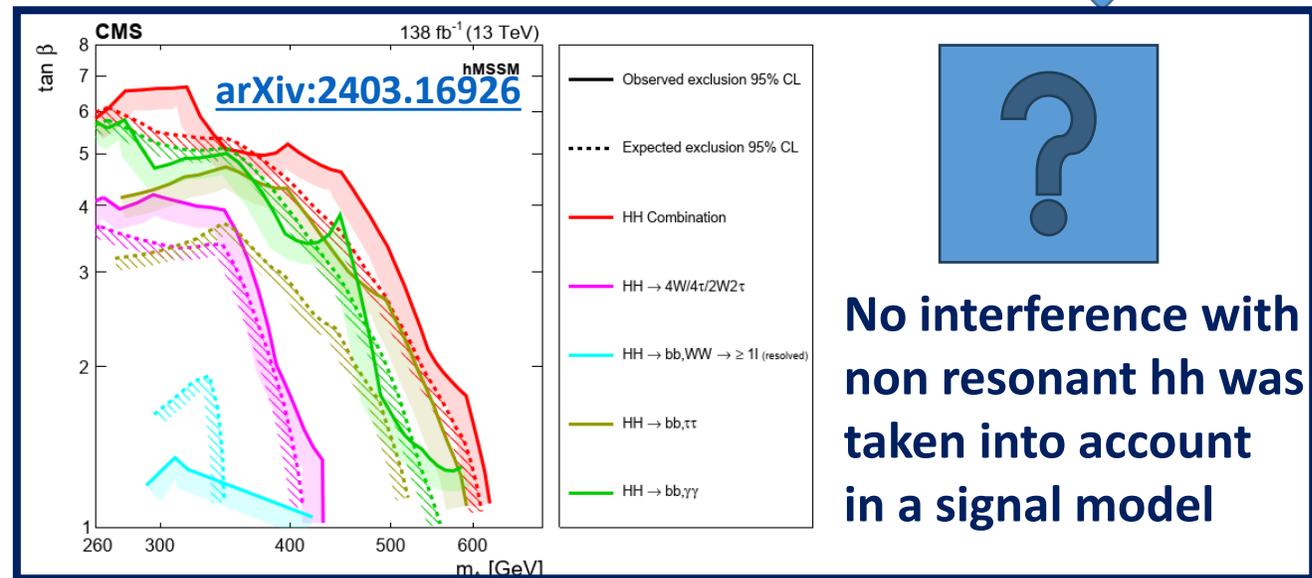
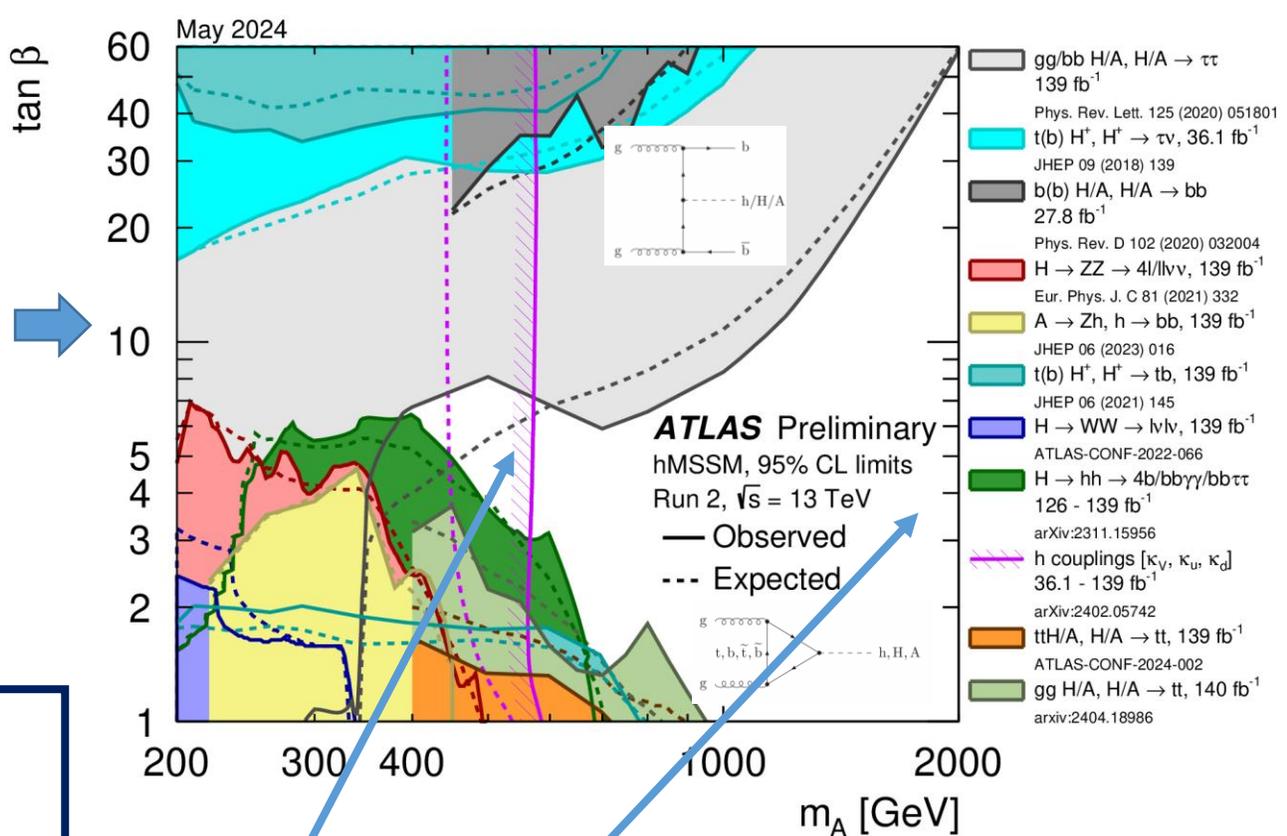
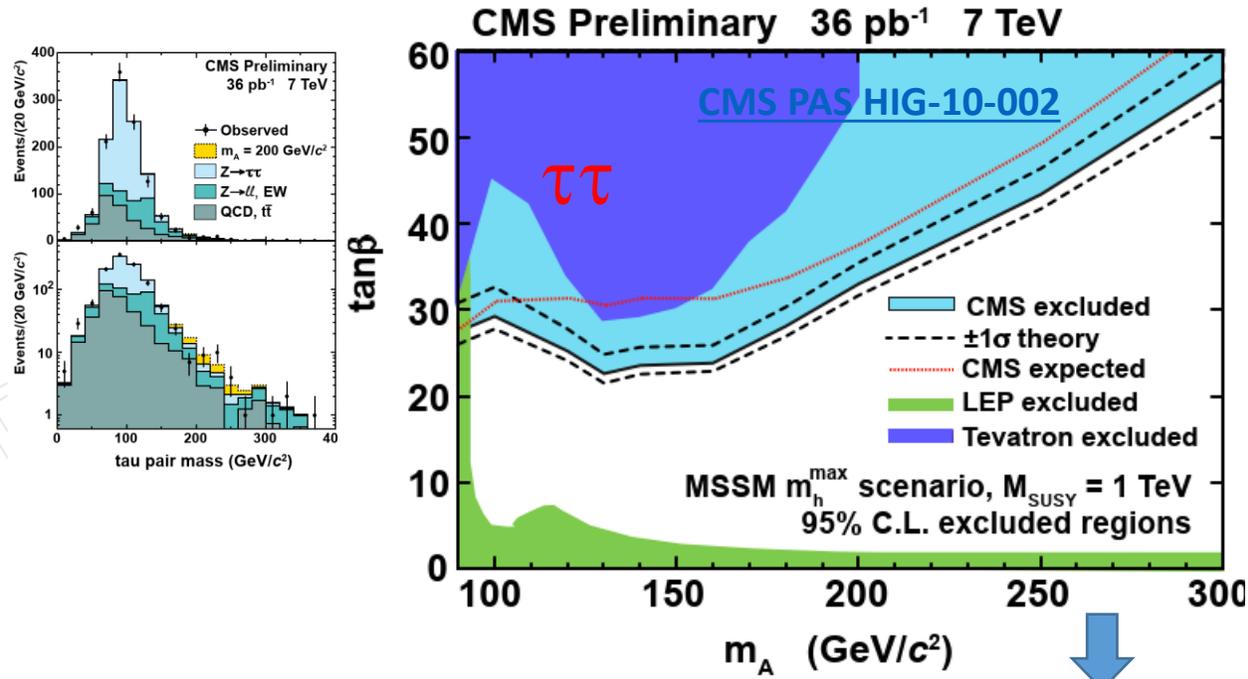
most probably  $h$  (not  $H$ ) is discovered  $h_{125}$

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  $\rightarrow \chi\chi$  still to be done (even in hMSSM: [arXiv:2311.04033](https://arxiv.org/abs/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:

$m_h, m_H, m_A, m_{H^\pm}, \alpha, \tan\beta, m_{12}$  (soft  $Z_2$  symmetry ( $\Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow -\Phi_2$ ) breaking parameter)

$m_{12} \neq 0$  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](https://arxiv.org/abs/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	$\cot\beta$	$-\cot\beta$	$\cot\beta$	$\tan\beta$

$c_{\beta-\alpha}$

$HW^+W^-$

$HZZ$

$ZAh$

$W^\pm H^\mp h$

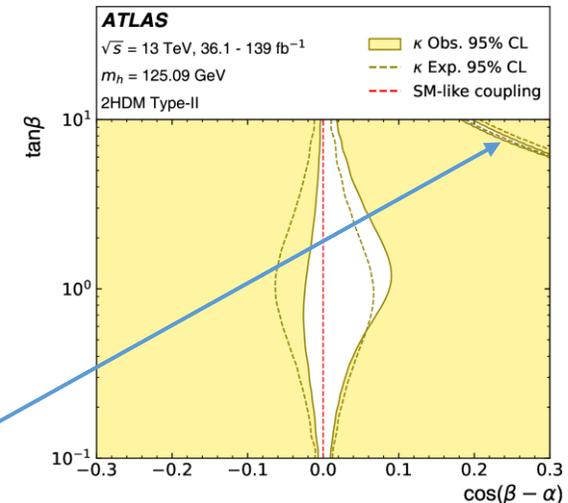
$s_{\beta-\alpha}$

$hW^+W^-$

$hZZ$

$ZAh$

$W^\pm H^\mp H$



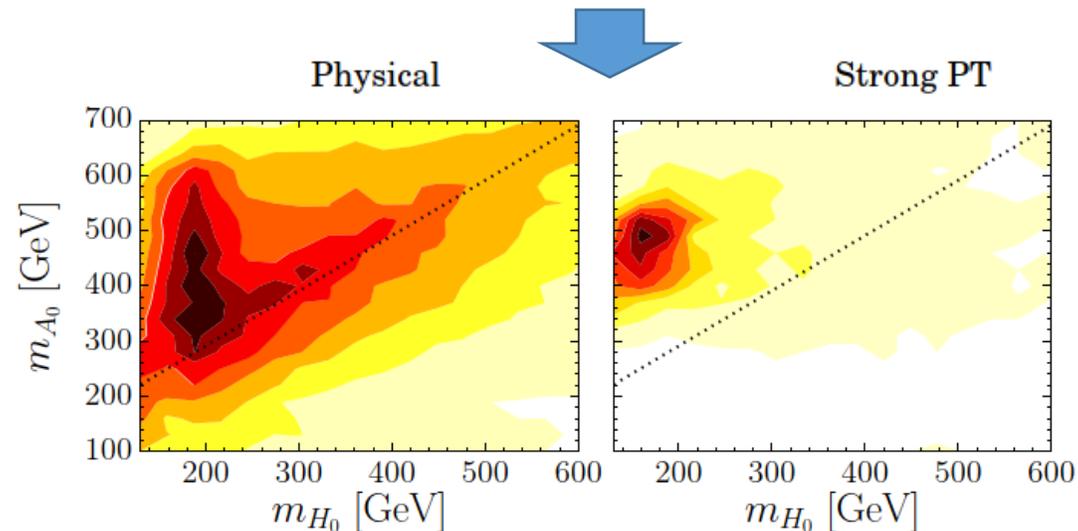
wrong sign Yukawa coupling ( $C_D \approx -1, C_V = C_U \approx 1$ ) scenario,  $\sin(\beta+\alpha) \approx 1$ , can be excluded or confirmed with  $h \rightarrow \gamma\gamma$  at HL-LHC,  $3 \text{ ab}^{-1}$

# Analysis which does not make a sense in MSSM but does in 2HDM: $A \rightarrow ZH$ , $h=h_{125}$

- contrary to MSSM
  - A-boson can have a small mass
  - $m_A \not\approx m_H$  at large masses
- $A \rightarrow ZH$  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 et al, [arXiv:1612.04086](#)



2HDM Type I  
Promising fast  
sim. result for  
 $l\bar{l}b\bar{b}$  final state,  
 $m_A=400$  GeV  
 $m_H=180$  GeV.  
 $\sigma=5$  at  $L=40\text{fb}^{-1}$   
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  $\langle \Phi \rangle \neq 0$  and get system jumping from false to truth vev minimum

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

[M. Quiros, Helv. Phys. Acta 67 \(1994\) 451.](#)

[G.D. Moore, Phys. Rev. D 59 \(1999\) 014503.](#)

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

M. E. Shaposhnikov

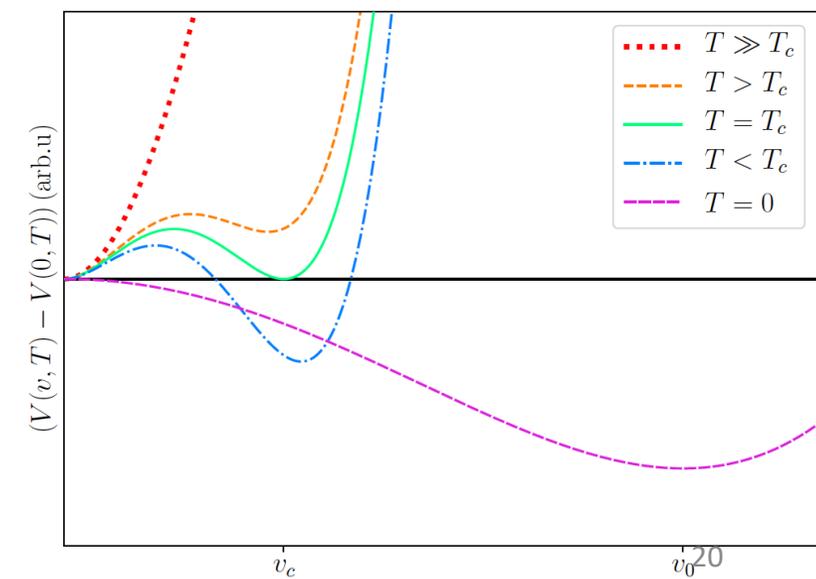
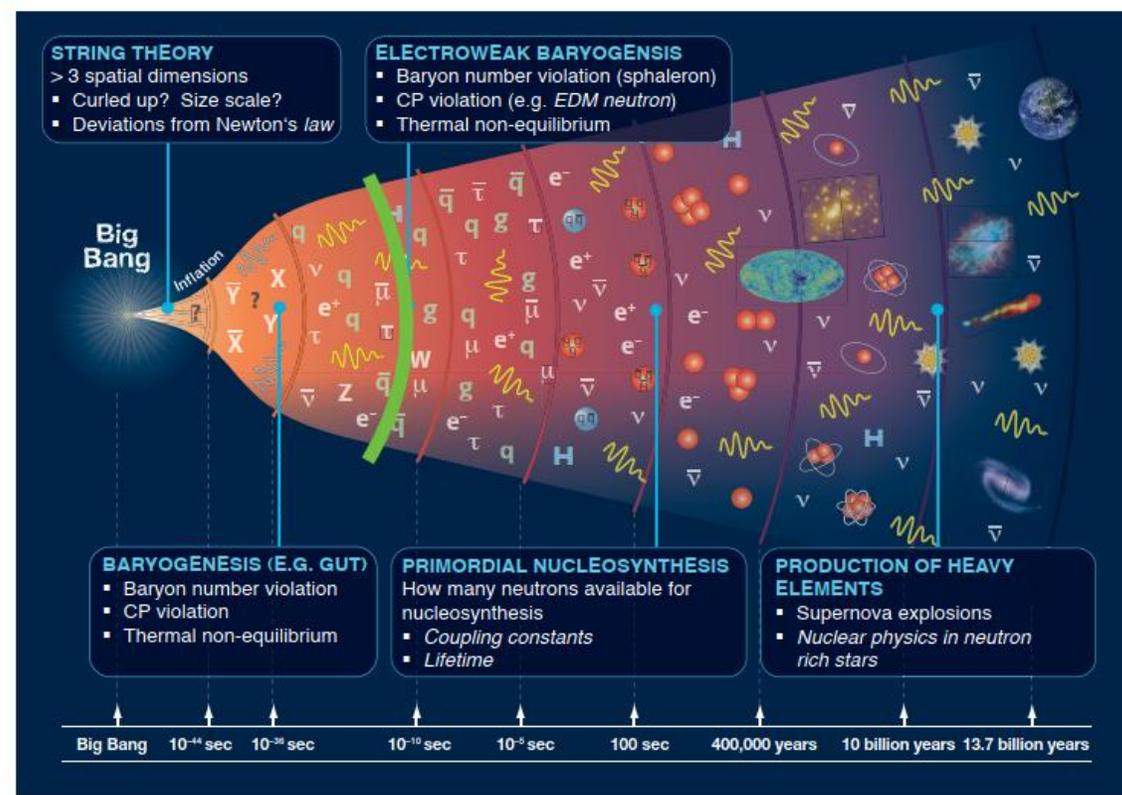
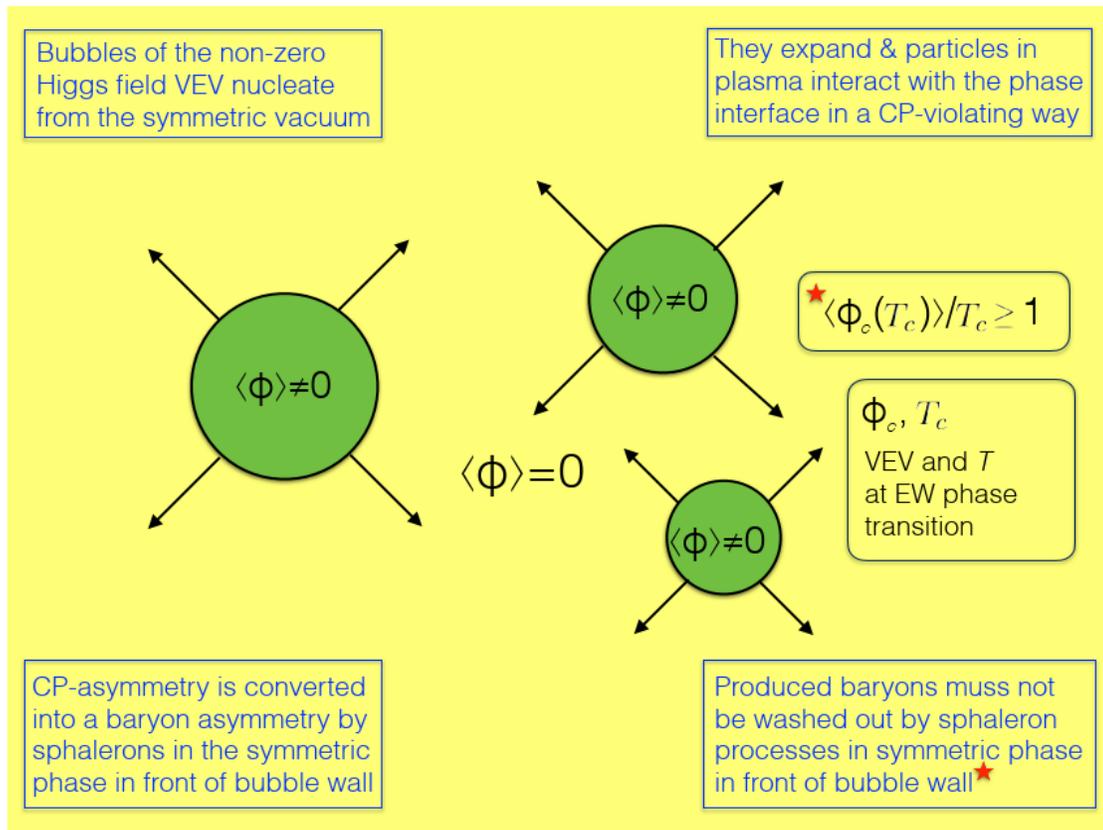
*Institute of Nuclear Research, Academy of Sciences of the USSR*

(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:  $10 \text{ GeV} \lesssim m_H \lesssim 60 \text{ GeV}$ . The sign of the baryon asymmetry is determined by the sign of the CP breaking in the decays of  $K^0$  mesons.

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.



## Condition for EWPT to be of strong first-order:

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

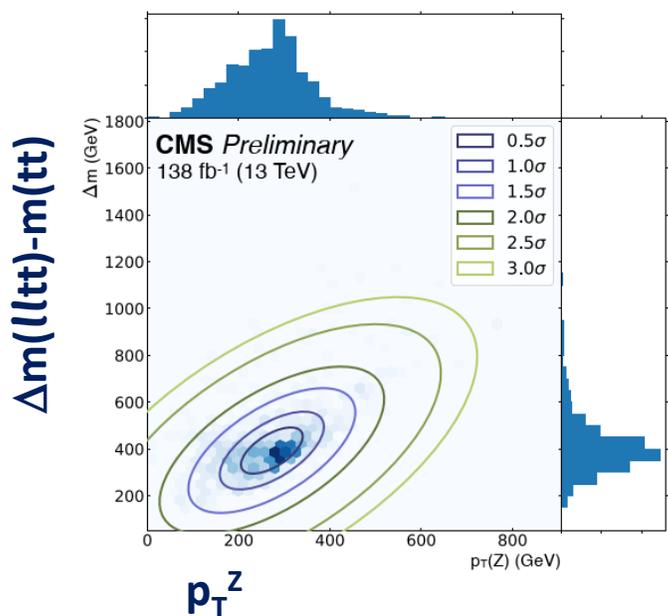
where  $v_c \equiv \sqrt{\omega_1^2 + \omega_2^2}|_{T_c}$  is the Higgs VEV at the critical temperature  $T_c$ , which is defined when the would-be true vacuum and false vacuum are degenerate.

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

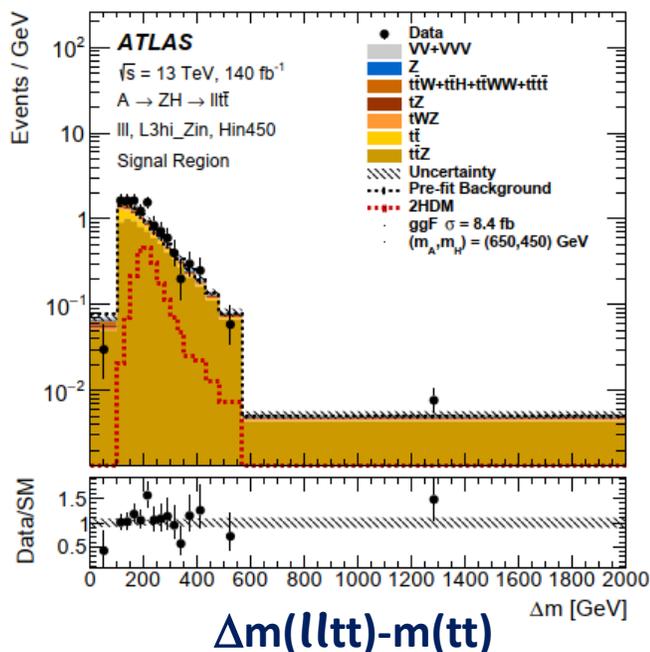
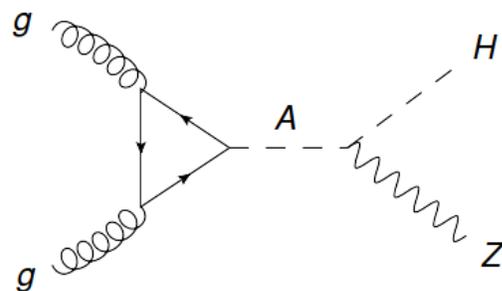
# $A \rightarrow ZH \rightarrow \ell^+ \ell^- tt$ analyses and interpretation

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

semileptonic  $tt \rightarrow \ell \nu jjb$   
**ATLAS:arXiv:2311.04033**

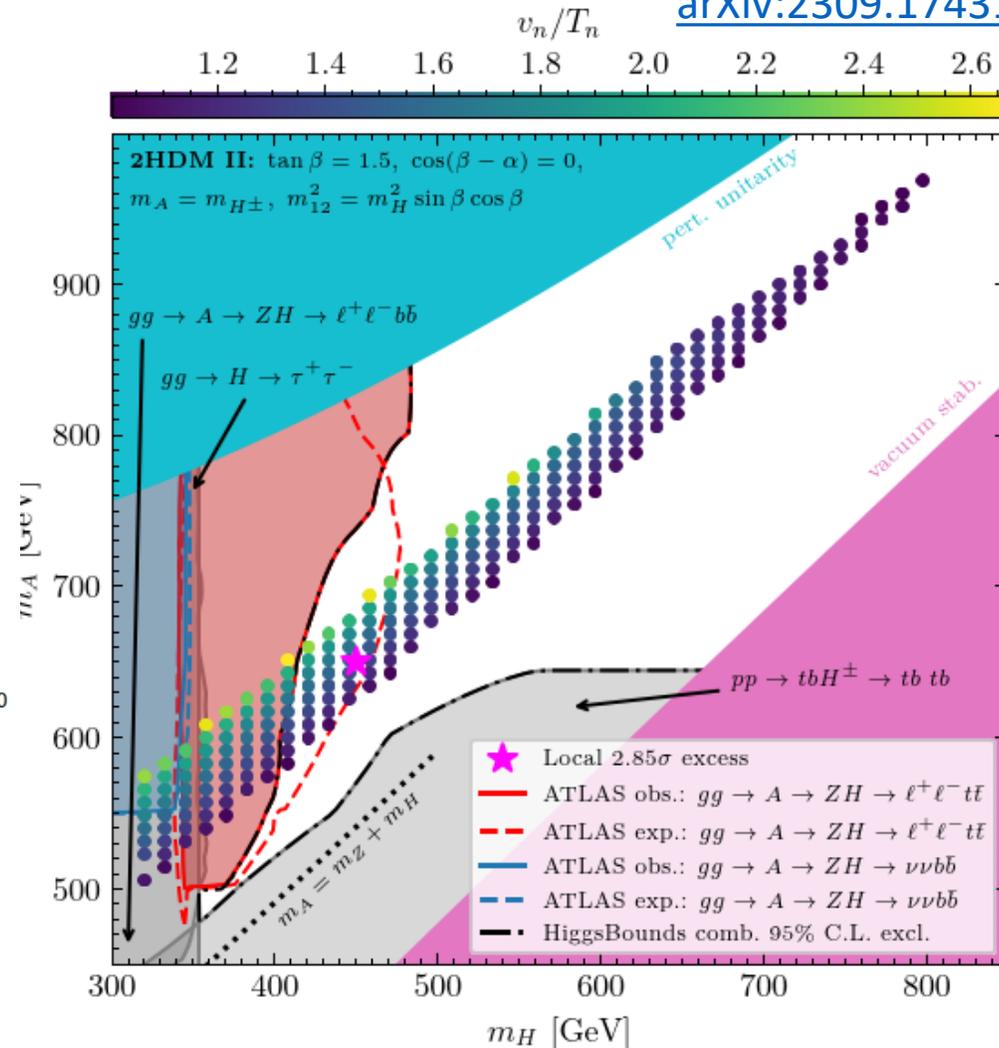


The largest excess over the SM background prediction, amounting to a local significance of  $2.85 \sigma$ , is observed in the  $\ell+\ell-tt$  channel, for the signal hypothesis corresponding to  $(m_A, m_H) = (650, 450) \text{ GeV}$ .



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

Thomas Biekötter<sup>1\*</sup>, Sven Heinemeyer<sup>2†</sup>, Jose Miguel No<sup>2,3‡</sup>,  
 Kateryna Radchenko<sup>4§</sup>, María Olalla Olea Romacho<sup>5¶</sup> and Georg Weiglein<sup>4,6||</sup>  
[arXiv:2309.17431](https://arxiv.org/abs/2309.17431)



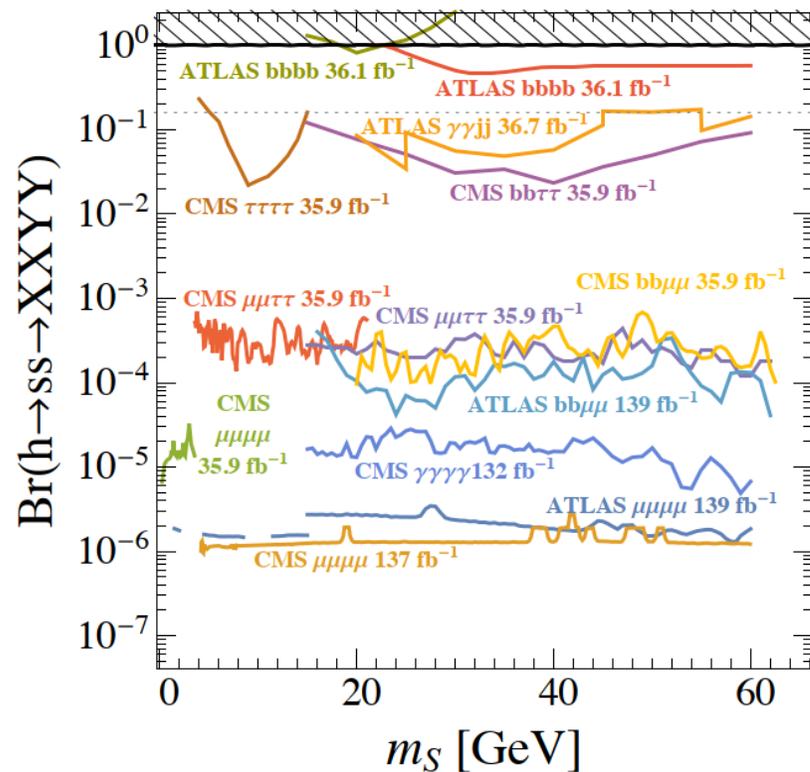
# Searches for the light scalars from $h_{125} \rightarrow aa \rightarrow xx yy$ decays

**NMSSM, 2HDM+S, ...**

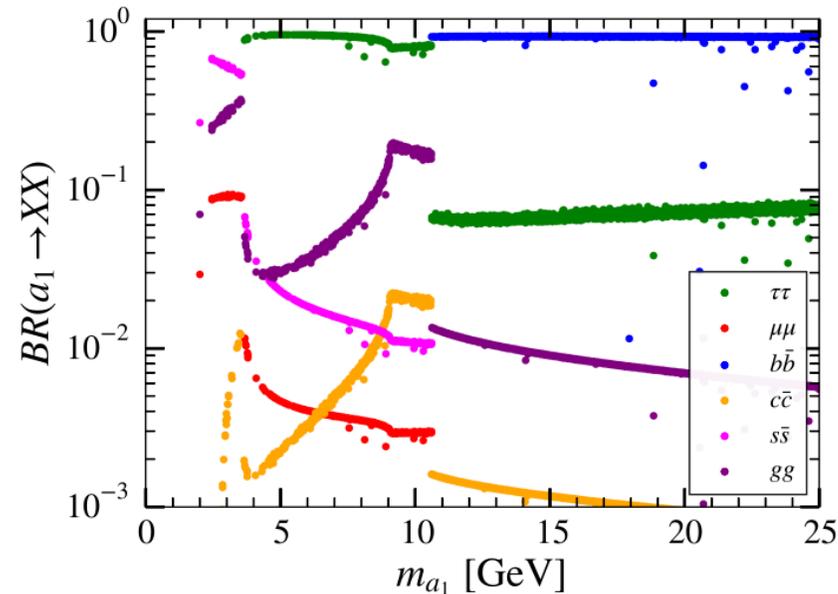
# CMS and ATLAS searches for $h_{125} \rightarrow ss \rightarrow xxyy$ on one plot

M. Carena et al arXiv:2203.08206

see also M. Cepeda et al arXiv:2111.12751

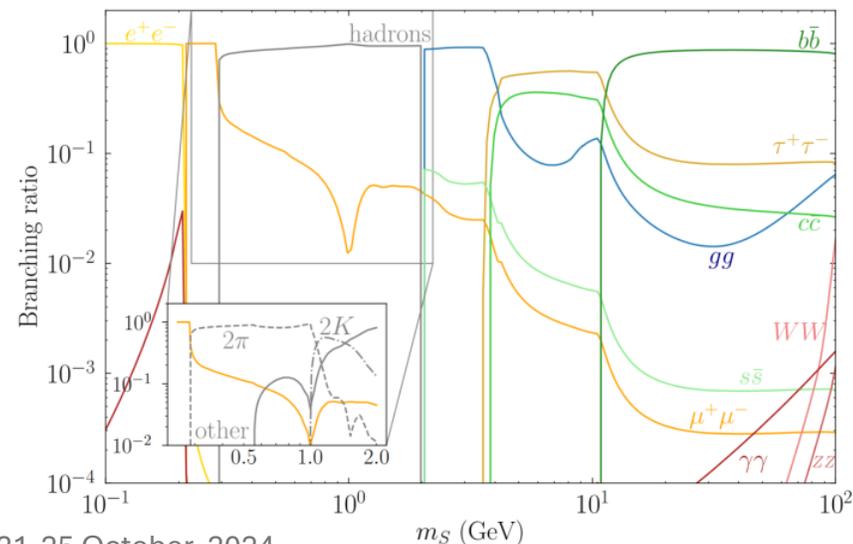


R. Aggleton et al, arXiv:1609.06089 Br's in NMSSM



M. Carena et al arXiv:2203.08206

Br's in  $h_{125}$ +singlet model



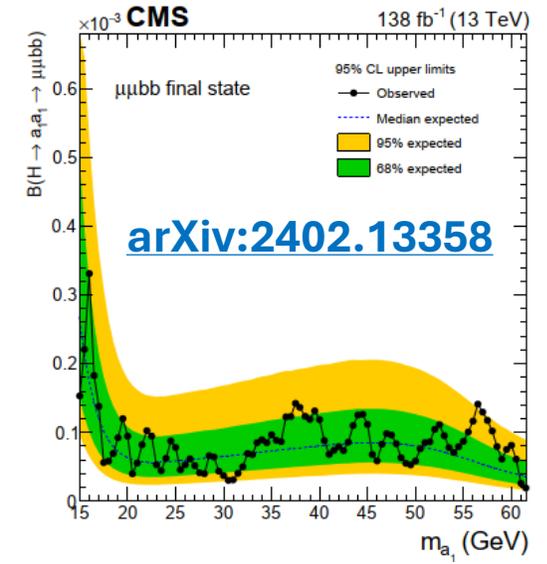
## Recent ATLAS analyses of 2024

- $h_{125} \rightarrow aa \rightarrow 4\gamma$
- $h_{125} \rightarrow Za \rightarrow ll\gamma\gamma$

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

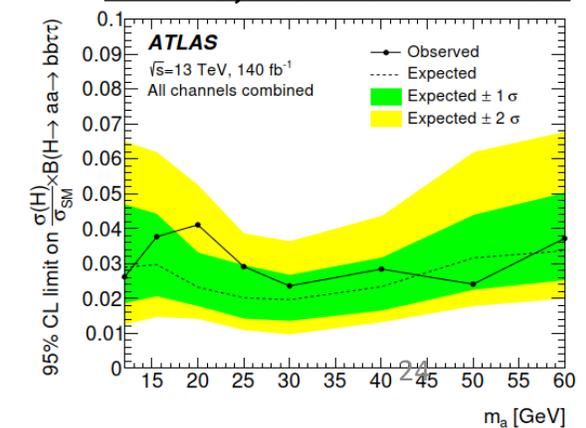
R. Aggleton et al, arXiv:1609.06089

M. Carena et al arXiv:2203.08206

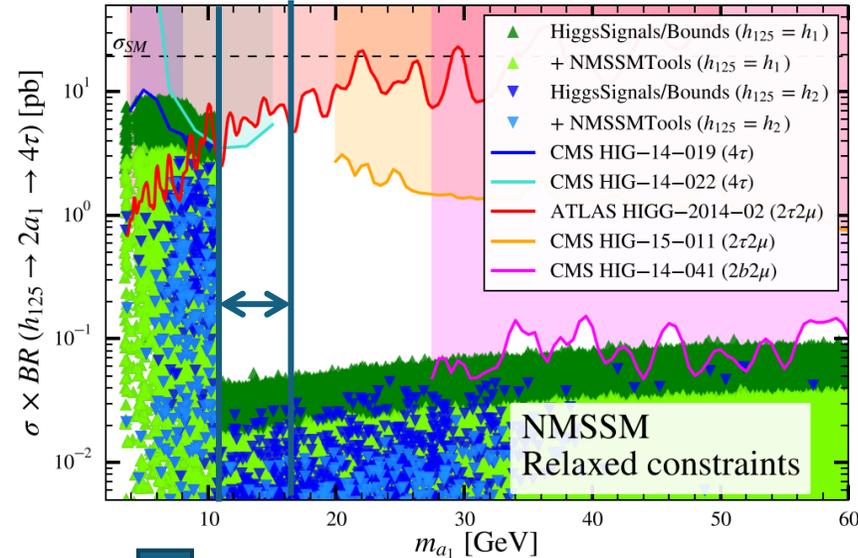


mass range,  $m_a \approx 10-15$  GeV was not accessible.  $\mu\mu(\tau)bb$  could do it using a «fat jet», with two b-quarks inside.

arXiv:2407.01335  
ATLAS, DeXTer method



Observed exclusion limits ( $\sqrt{s} = 8$  TeV)

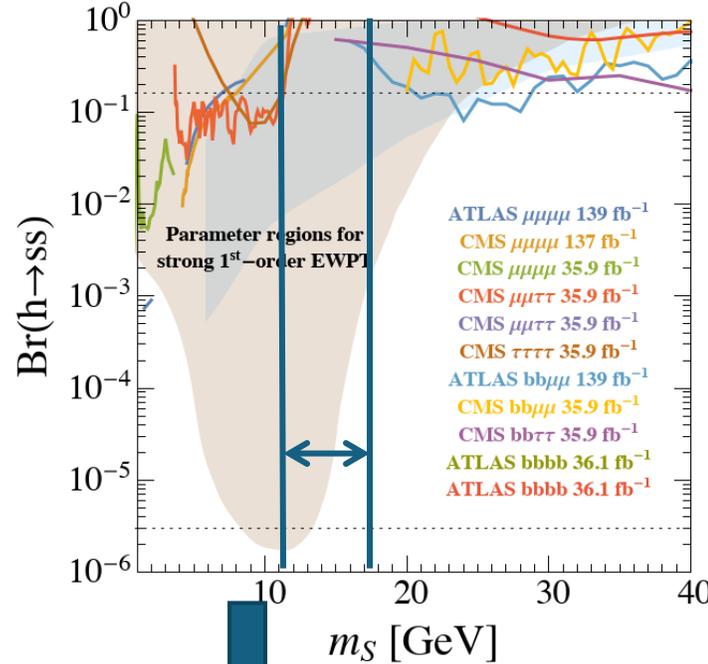


already sensitive to NMSSM

this plot need to be updated for

13 TeV (Run II) analyses. CMS:

- $\mu\mu bb$ : arXiv:2402.13358 –  $m_a$  range is 20-60 GeV
- $\tau\tau bb$ : arXiv:2402.13358 –  $m_a$  range is 15-60 GeV
- $\mu\mu\tau\tau$ : arXiv:2005.08694 –  $m_a$  range is 3.6-21 GeV
- $\tau\tau\tau\tau$ : arXiv:1907.07235 –  $m_a$  range is 4.0-15 GeV
- $\mu\mu\mu\mu$ : arXiv:1812.00380 –  $m_a$  range is 0.25-8.5 GeV
- $bbbb$ : arXiv:2403.10341 –  $m_a$  range is 15-60 GeV



**h125+singlet model**

Already sensitive to parameter regions for strong 1<sup>st</sup> order EWPT

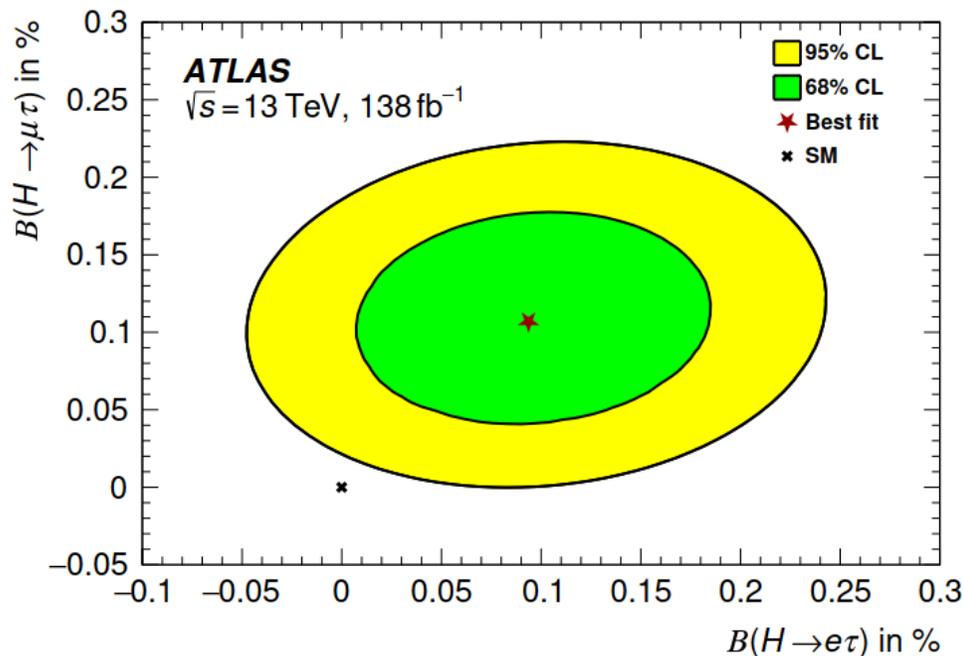
# Search for FCNC

# FCNC in Higgs sector: $h_{125} \rightarrow \mu\tau, e\tau$

ATLAS

[JHEP07\(2023\)166](#)

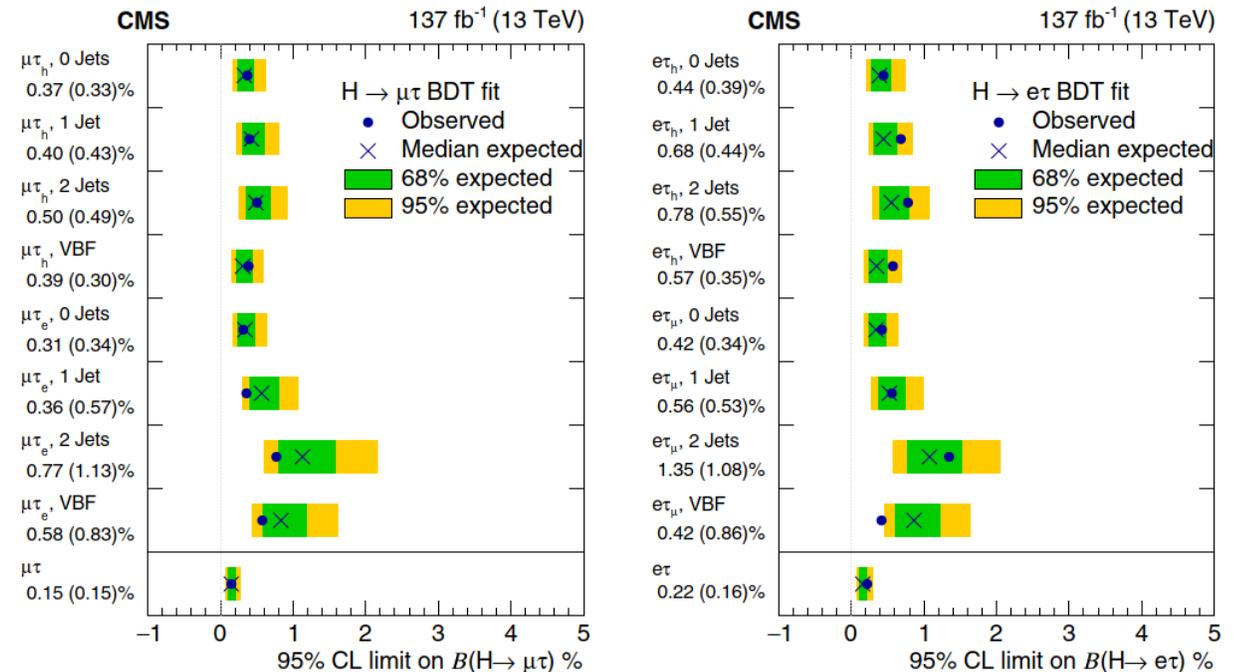
$B(H \rightarrow \mu\tau) - B(H \rightarrow e\tau)$   
 measured is  $(0.25 \pm 0.10)\%$ ,  
 compatible with zero within  
 $2.5\sigma$



CMS

[PHYSICAL REVIEW D 104, 032013 \(2021\)](#)

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



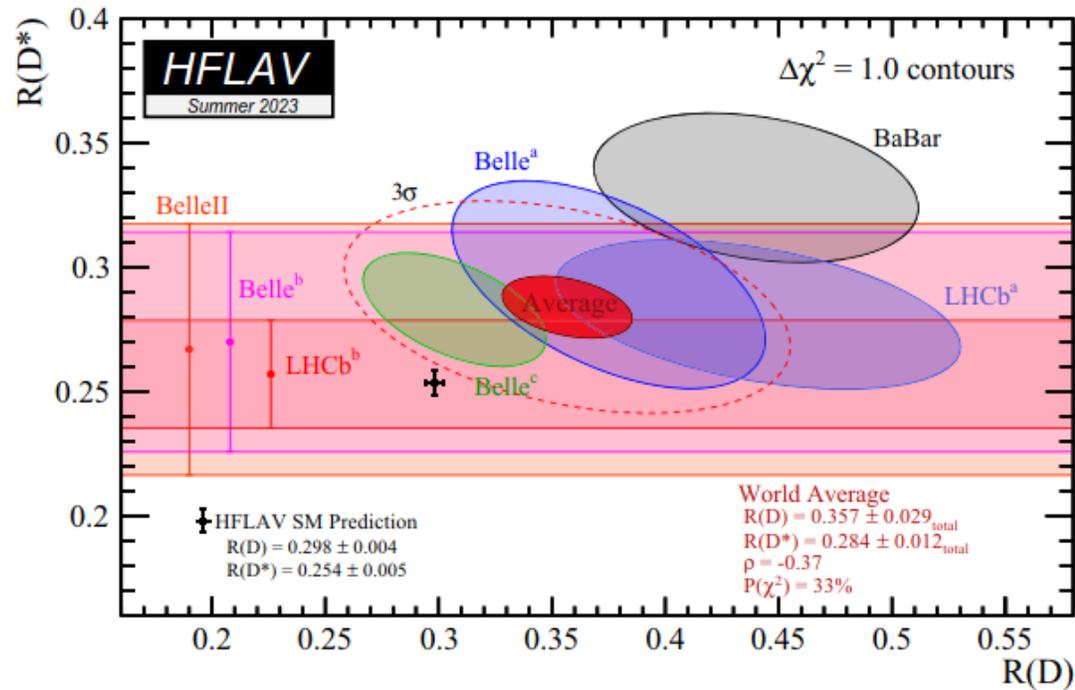
# Lepton Number Violation in B-decays (LHCb)

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

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

# Testing lepton universality ratios

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

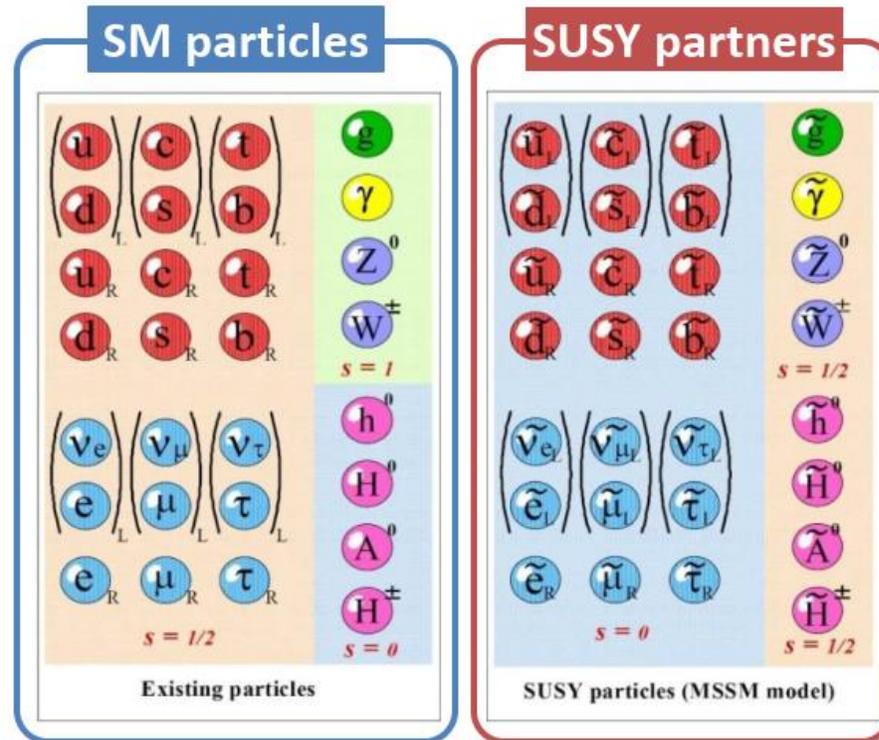


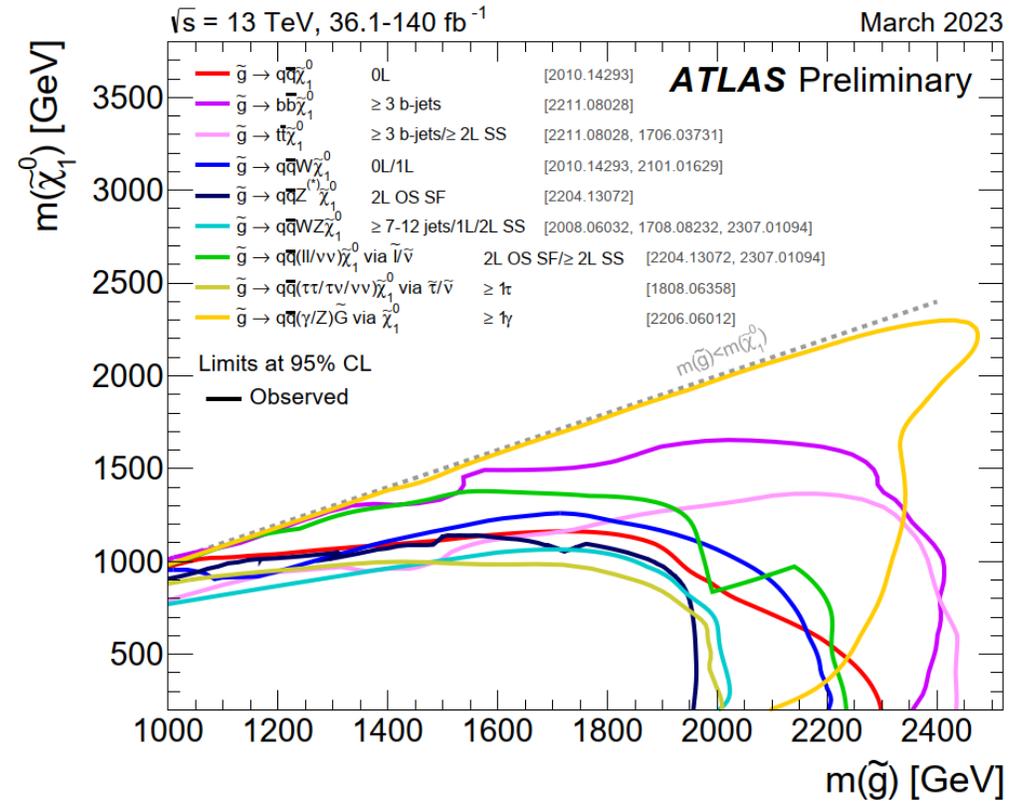
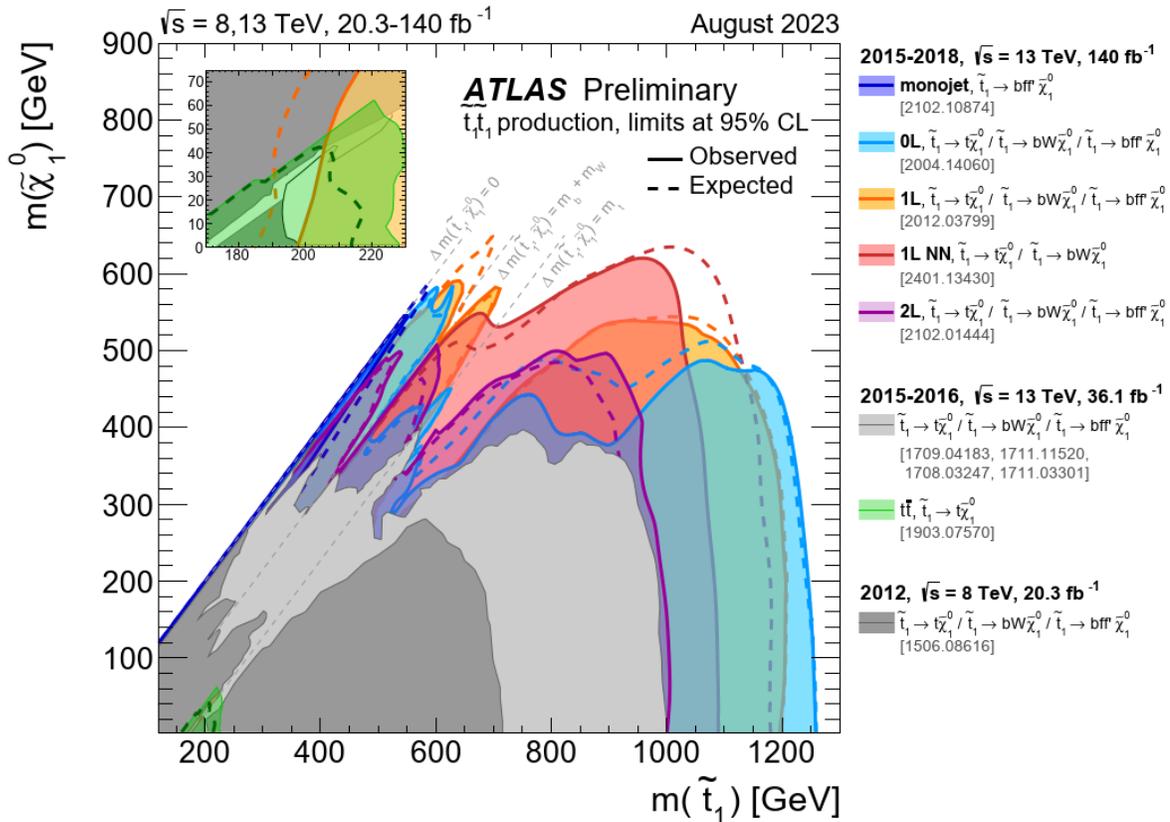
The combined average is  
3.3σ tension with the  
Standard Mode

$$\mathcal{R}(D^*) \equiv \mathcal{B}(\bar{B} \rightarrow D^* \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B} \rightarrow D^* \ell^- \bar{\nu}_\ell)$$

$$\mathcal{R}(D) \equiv \mathcal{B}(\bar{B} \rightarrow D \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B} \rightarrow D \ell^- \bar{\nu}_\ell)$$

# Search for SUSY



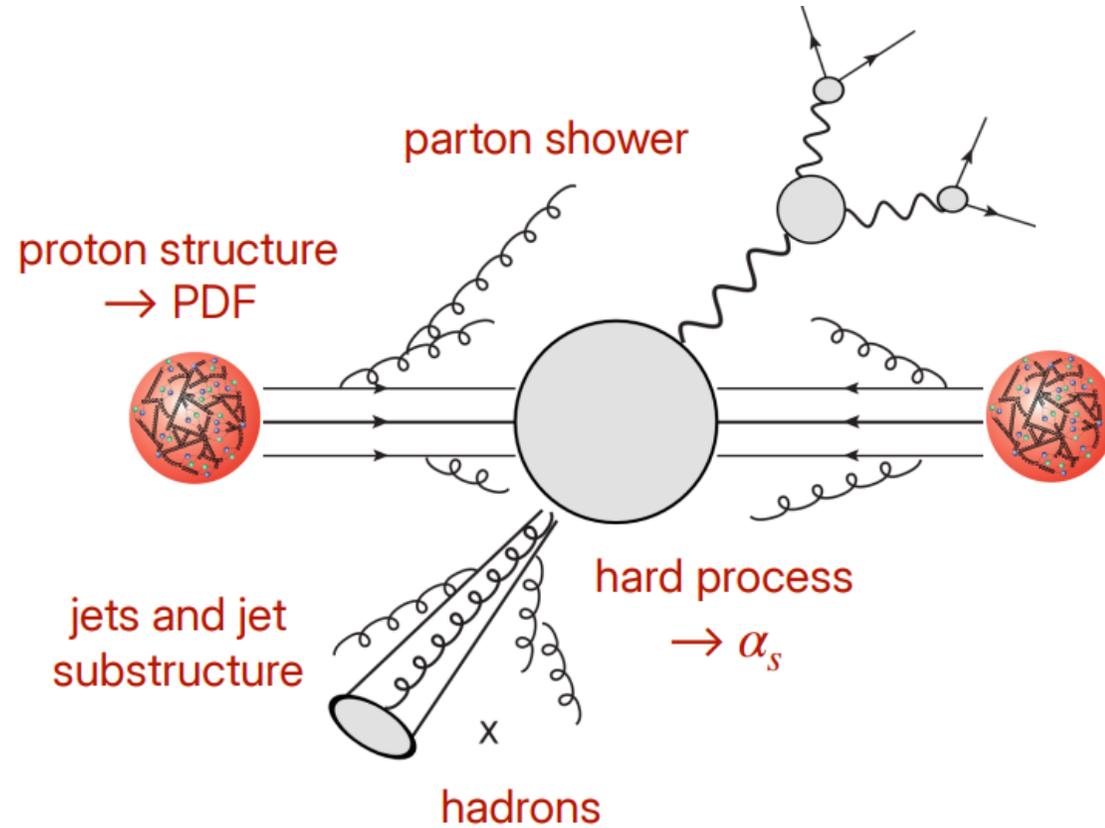


**Exclusion reached:**

- $\leq 2 \text{ TeV}$  for gluino
- $\leq 1 \text{ TeV}$  for stop

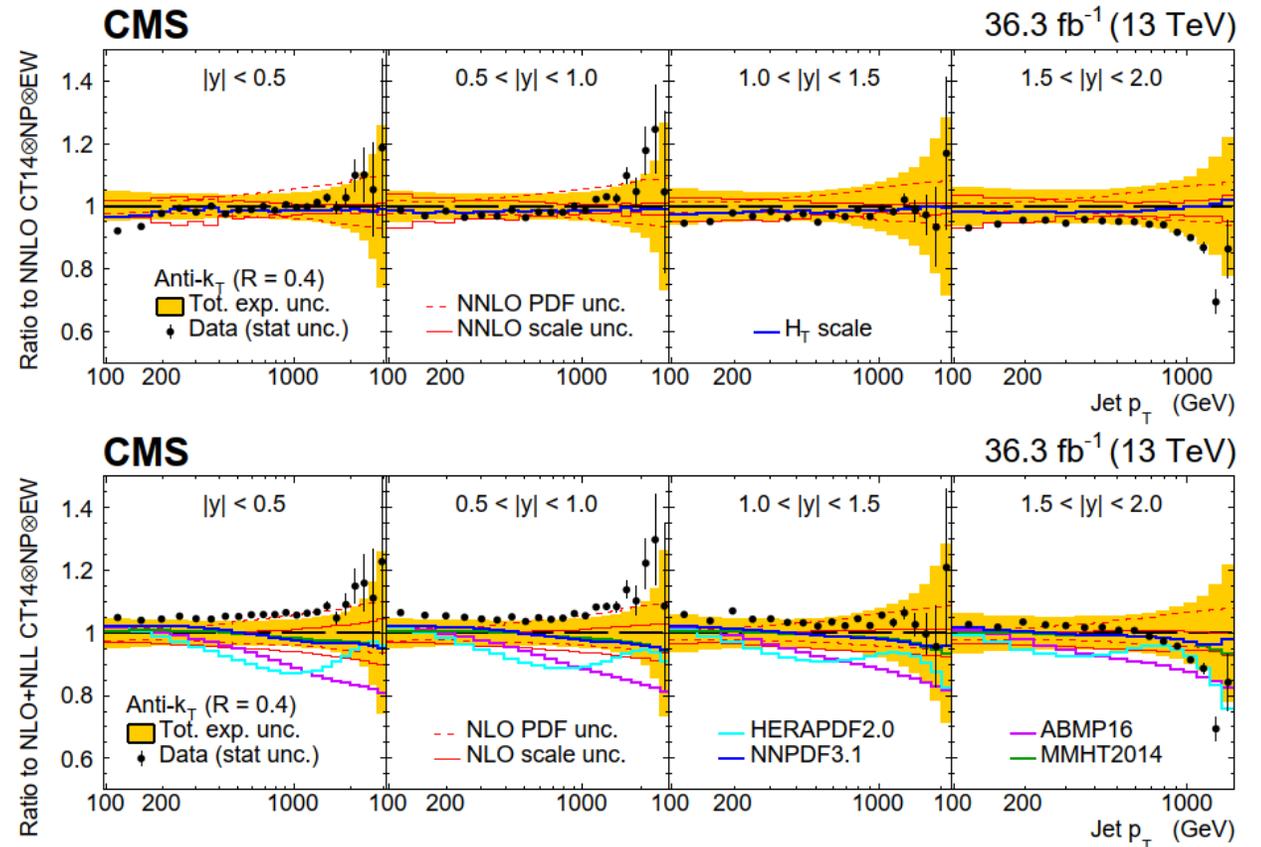
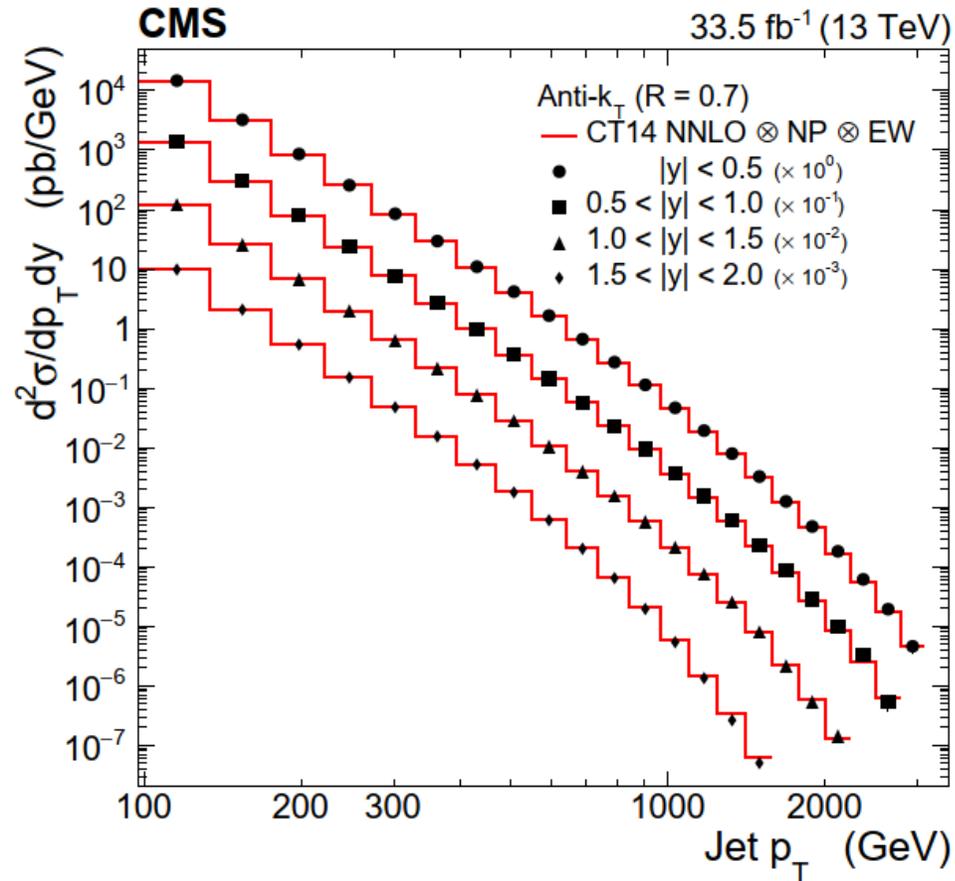
[ATL-PHYS-PUB-2024-014](#)

# QCD



# Inclusive jet production cross-section measurement

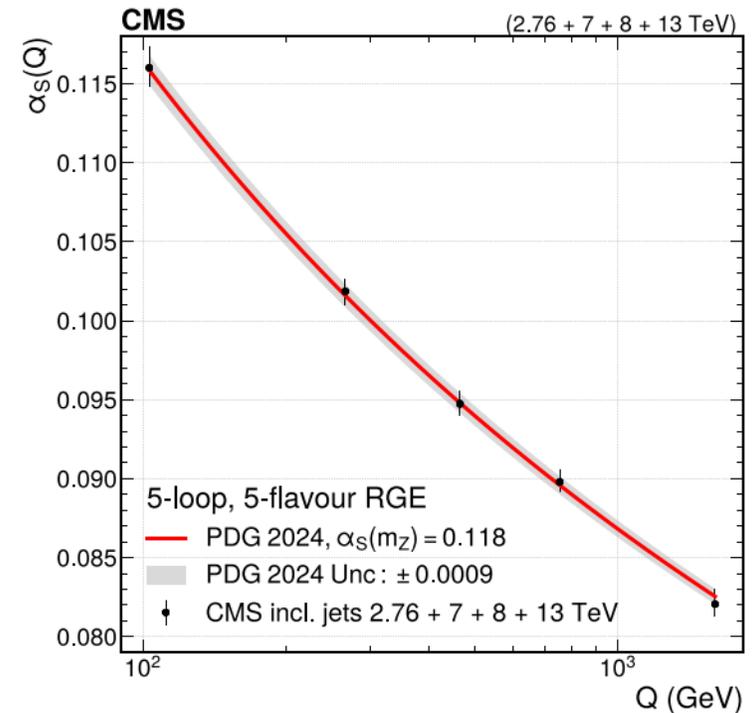
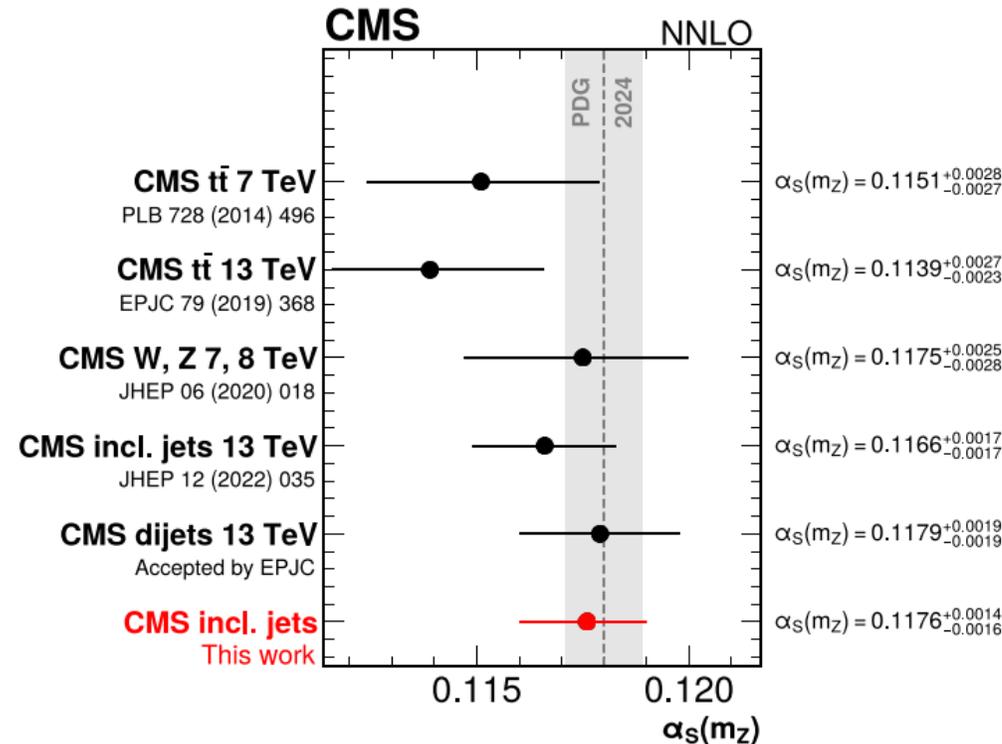
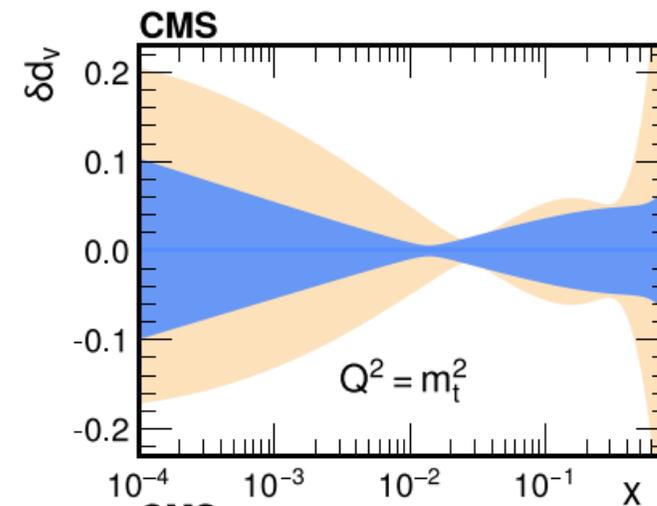
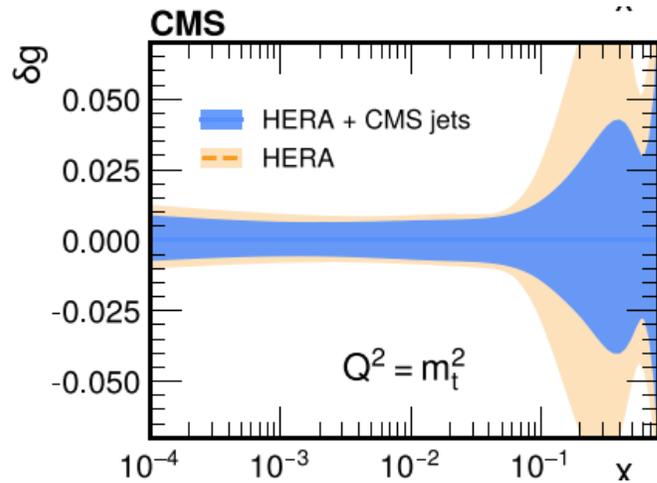
[arXiv:2111.10431](https://arxiv.org/abs/2111.10431)



- good agreement with data over 11<sup>th</sup> order of magnitude !

# Simultaneous fit of $\alpha_s$ and PDF using Run II inclusive jet production data

[arXiv:2412.16665](https://arxiv.org/abs/2412.16665)



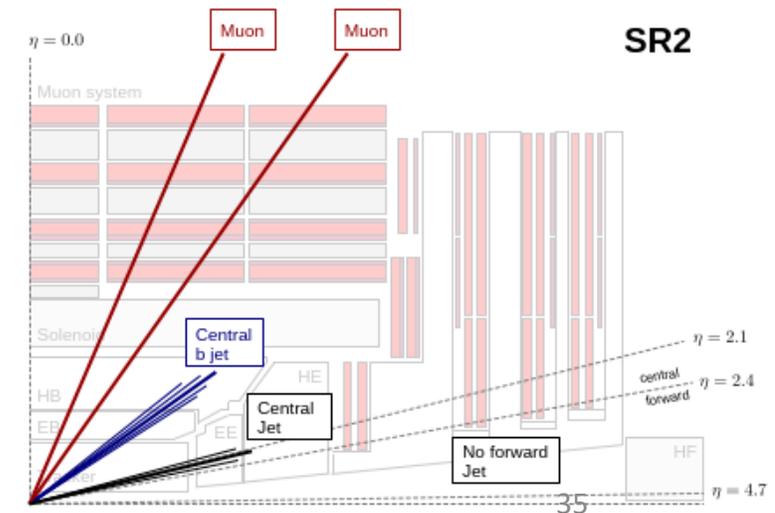
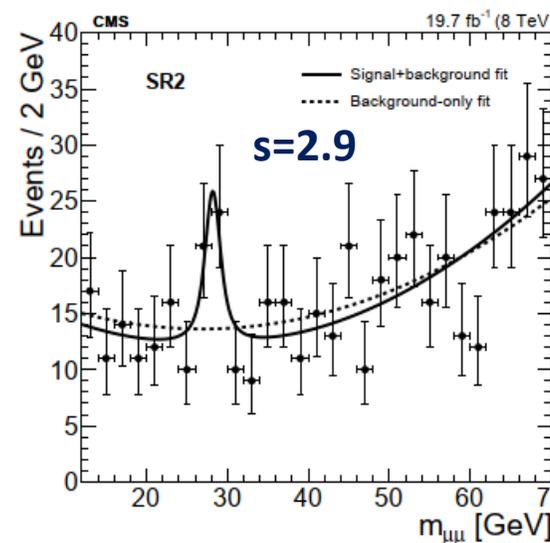
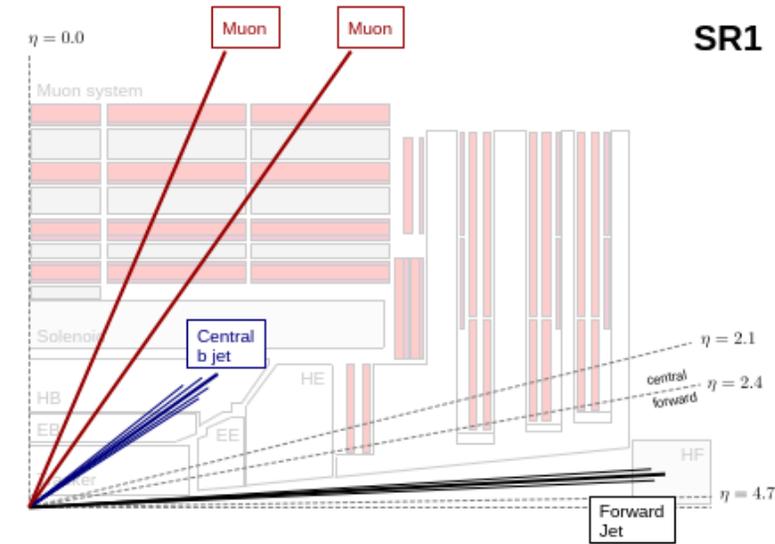
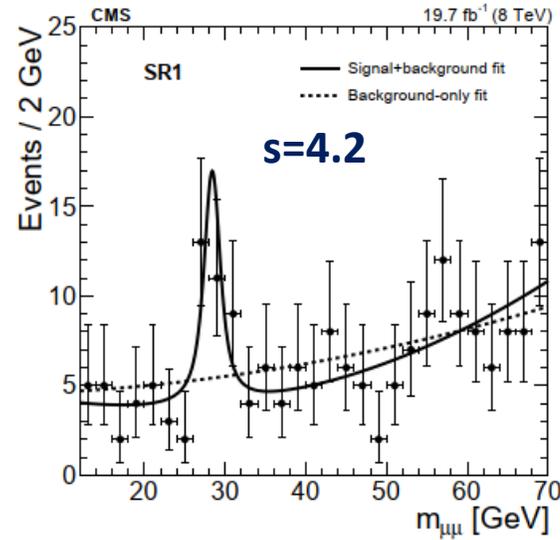
$$xq_i(x) = A_i x^{B_i} (1-x)^{C_i} P_i(x),$$

$$Q_0^2 = 1.9 \text{ GeV}^2,$$

**Excitement at the end:**  
**event excess observed in CMS**  
**in Run 1 with significance 4.8**

# 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.
- combined significance is 4.8



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

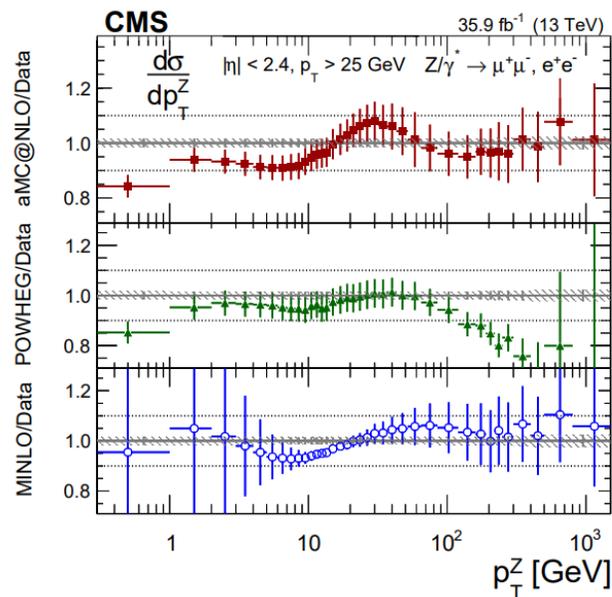
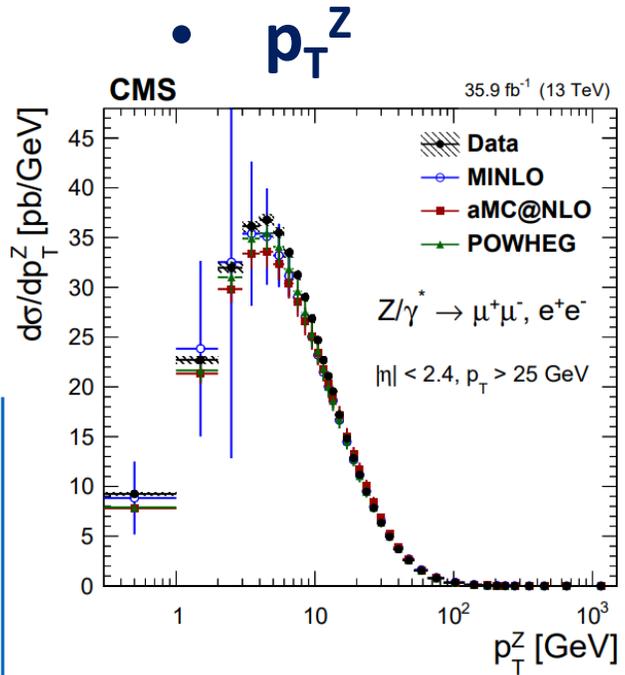
# Conclusions

- **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**

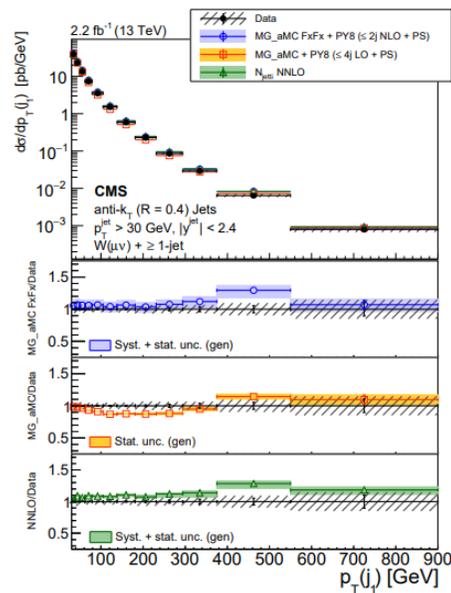
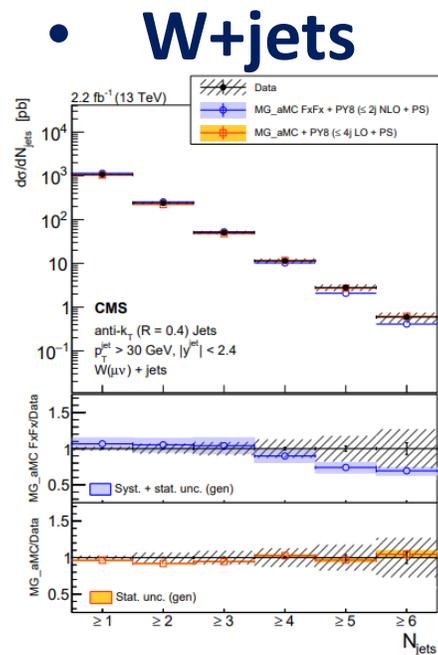
**THE END**

# Z/W+jets production cross-section measurement

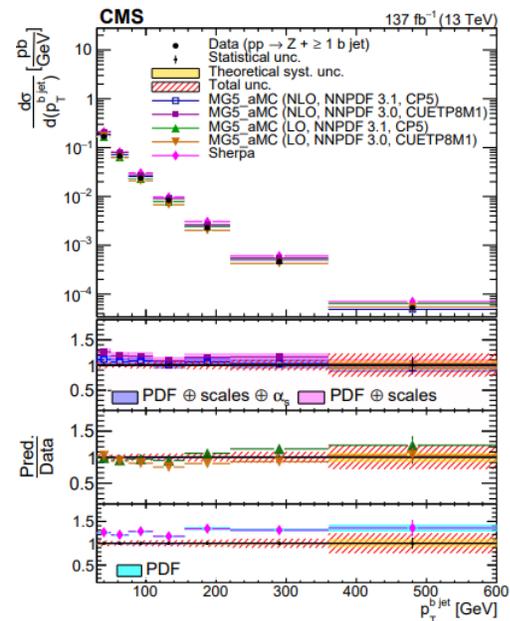
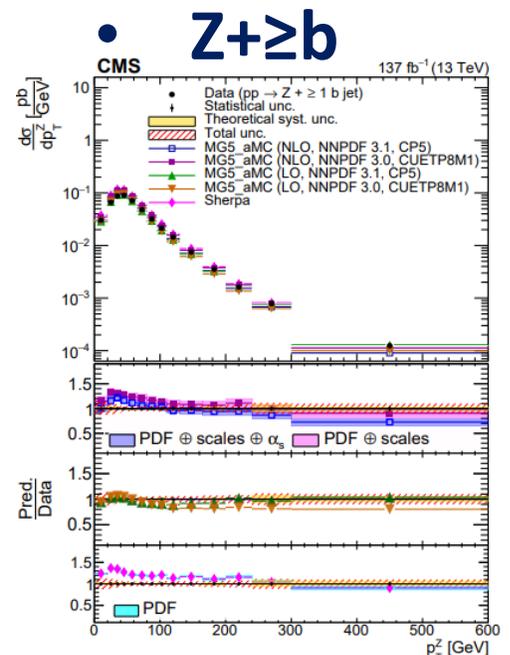
[arXiv:1909.04133](https://arxiv.org/abs/1909.04133)



[arXiv:1707.05979](https://arxiv.org/abs/1707.05979)



[arXiv:2112.09659](https://arxiv.org/abs/2112.09659)



# Summary

## ATLAS SUSY Searches\* - 95% CL Lower Limits

July 2024

ATLAS Preliminary

$\sqrt{s} = 13$  TeV

Model	Signature	$\int \mathcal{L} dt$ [fb <sup>-1</sup> ]	Mass limit	Reference			
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 $e, \mu$ mono-jet	$E_T^{miss}$ 140 $E_T^{miss}$ 140	$\tilde{q}$ [1x, 6x Degen.] 1.0 $\tilde{q}$ [8x Degen.] 0.9	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	2101.14293 2102.10874	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 $e, \mu$	$E_T^{miss}$ 140	$\tilde{g}$ 2.3 Forbidden 1.15-1.95	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{g}) = 1000$ GeV	2101.14293 2101.14293	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 $e, \mu$	2-6 jets	$E_T^{miss}$ 140	$\tilde{g}$ 2.2	$m(\tilde{\chi}_1^0) < 600$ GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(t\bar{t})\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	$E_T^{miss}$ 140	$\tilde{g}$ 2.2	$m(\tilde{\chi}_1^0) < 700$ GeV	2204.13072
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 $e, \mu$	7-11 jets	$E_T^{miss}$ 140	$\tilde{g}$ 1.97	$m(\tilde{\chi}_1^0) < 600$ GeV	2008.06032
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	SS $e, \mu$	6 jets	$E_T^{miss}$ 140	$\tilde{g}$ 1.15	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	2307.01094
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 $e, \mu$ SS $e, \mu$	3 $b$ 6 jets	$E_T^{miss}$ 140 $E_T^{miss}$ 140	$\tilde{g}$ 2.45 $\tilde{g}$ 1.25	$m(\tilde{\chi}_1^0) < 500$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	2211.08028 1909.08457
$3^{rd}$ gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 $e, \mu$	2 $b$	$E_T^{miss}$ 140	$\tilde{b}_1$ 1.255 $\tilde{b}_1$ 0.68	$m(\tilde{\chi}_1^0) < 400$ GeV 10 GeV $< \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b\tilde{h}\tilde{\chi}_1^0$	0 $e, \mu$ 2 $\tau$	6 $b$ 2 $b$	$E_T^{miss}$ 140 $E_T^{miss}$ 140	Forbidden 0.23-1.35 $\tilde{b}_1$ 0.13-0.85	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	1908.03122 2103.08189
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 $e, \mu$	$\geq 1$ jet	$E_T^{miss}$ 140	$\tilde{t}_1$ 1.25	$m(\tilde{\chi}_1^0) = 1$ GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 $e, \mu$	3 jets/1 $b$	$E_T^{miss}$ 140	Forbidden 1.05	$m(\tilde{\chi}_1^0) = 500$ GeV	2012.03799, 2401.13430
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau b\nu, \tau_1 \rightarrow \tau G$	1-2 $\tau$	2 jets/1 $b$	$E_T^{miss}$ 140	Forbidden 1.4	$m(\tilde{\tau}_1) = 800$ GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 $e, \mu$ 0 $e, \mu$	2 $c$ mono-jet	$E_T^{miss}$ 36.1 $E_T^{miss}$ 140	$\tilde{t}_1$ 0.85 $\tilde{t}_1$ 0.55	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	1805.01649 2102.10874
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	1-2 $e, \mu$	1-4 $b$	$E_T^{miss}$ 140	$\tilde{t}_1$ 0.067-1.18	$m(\tilde{\chi}_2^0) = 500$ GeV	2006.05880
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$	1 $b$	$E_T^{miss}$ 140	Forbidden 0.86	$m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	2006.05880	
EW direct	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via WZ	Multiple $l/\nu$ $ee, \mu\mu$	$\geq 1$ jet	$E_T^{miss}$ 140 $E_T^{miss}$ 140	$\tilde{\chi}_1^+ / \tilde{\chi}_2^0$ 0.96 $\tilde{\chi}_1^+ / \tilde{\chi}_2^0$ 0.205	$m(\tilde{\chi}_1^0) = 0$ , wino-bino $m(\tilde{\chi}_1^+) - m(\tilde{\chi}_2^0) = 5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$ via WW	2 $e, \mu$		$E_T^{miss}$ 140	$\tilde{\chi}_1^+ / \tilde{\chi}_1^0$ 0.42	$m(\tilde{\chi}_1^0) = 0$ , wino-bino	1908.08215
	$\tilde{\chi}_1^+ \tilde{\chi}_3^0$ via Wh	Multiple $l/\nu$		$E_T^{miss}$ 140	$\tilde{\chi}_1^+ / \tilde{\chi}_3^0$ 1.06	$m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$ via $\tilde{t}_1/\tilde{\nu}$	2 $e, \mu$		$E_T^{miss}$ 140	$\tilde{\chi}_1^+ / \tilde{\chi}_1^0$ 1.0	$m(\tilde{t}_1, \tilde{\nu}) = 0.5(m(\tilde{t}_1^+) + m(\tilde{\chi}_1^0))$	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 $\tau$		$E_T^{miss}$ 140	$\tilde{\tau}$ [R] 0.35, 0.5	$m(\tilde{\chi}_1^0) = 0$	2402.00603
	$\tilde{t}_L \tilde{t}_L, \tilde{t}_L \rightarrow t\tilde{\chi}_1^0$	2 $e, \mu$	0 jets	$E_T^{miss}$ 140	$\tilde{t}_L$ 0.7	$m(\tilde{\chi}_1^0) = 0$	1908.08215
	$\tilde{t}_L \tilde{t}_L, \tilde{t}_L \rightarrow t\tilde{\chi}_1^0$	$ee, \mu\mu$	$\geq 1$ jet	$E_T^{miss}$ 140	$\tilde{t}_L$ 0.26	$m(\tilde{t}_L) - m(\tilde{\chi}_1^0) = 10$ GeV	1911.12606
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow hG/ZG$	0 $e, \mu$ 4 $e, \mu$ 0 $e, \mu$ 2 $e, \mu$	$\geq 3$ $b$ 0 jets $\geq 2$ large jets $\geq 2$ jets	$E_T^{miss}$ 140 $E_T^{miss}$ 140 $E_T^{miss}$ 140 $E_T^{miss}$ 140	$\tilde{H}$ 0.94 $\tilde{H}$ 0.55 $\tilde{H}$ 0.45-0.93 $\tilde{H}$ 0.77	$BR(\tilde{H} \rightarrow hG) = 1$ $BR(\tilde{H} \rightarrow ZG) = 1$ $BR(\tilde{H} \rightarrow ZG) = 1$ $BR(\tilde{H} \rightarrow ZG) = BR(\tilde{H} \rightarrow hG) = 0.5$	2401.14922 2103.11684 2108.07586 2204.13072	
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{miss}$ 140	$\tilde{\chi}_1^\pm$ 0.66 $\tilde{\chi}_1^\pm$ 0.21	Pure Wino Pure higgsino	2201.02472 2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_T^{miss}$ 140	$\tilde{g}$ 2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	pixel dE/dx		$E_T^{miss}$ 140	$\tilde{g}$ [r(g) = 10 ns] 2.2	$m(\tilde{\chi}_1^0) = 100$ GeV	2205.06013
	$\tilde{\tau}, \tilde{\tau} \rightarrow t\tilde{G}$	Displ. lep		$E_T^{miss}$ 140	$\tilde{\tau}, \mu$ 0.74 $\tilde{\tau}$ 0.36 $\tilde{\tau}$ 0.36	$\tau(\tilde{\tau}) = 0.1$ ns $\tau(\tilde{\tau}) = 0.1$ ns $\tau(\tilde{\tau}) = 10$ ns	ATLAS-CONF-2024-011 ATLAS-CONF-2024-011 2205.06013
RPV	$\tilde{\chi}_1^+ \tilde{\chi}_1^- / \tilde{\chi}_2^0, \tilde{\chi}_1^\pm \rightarrow Zl + \ell\ell\ell$	3 $e, \mu$		140	$\tilde{\chi}_1^+ / \tilde{\chi}_1^-$ [BR(Z $\tau$ )=1, BR(Z $e$ )=1] 0.625, 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^+ \tilde{\chi}_1^- / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 $e, \mu$	0 jets	$E_T^{miss}$ 140	$\tilde{\chi}_1^+ / \tilde{\chi}_2^0$ [ $A_{133} \neq 0, A_{124} \neq 0$ ] 0.95, 1.55	$m(\tilde{\chi}_1^0) = 200$ GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$	$\geq 8$ jets		140	$\tilde{g}$ [ $m(\tilde{\chi}_1^0) = 50$ GeV, 1250 GeV] 1.6, 2.34	Large $A_{112}$	2401.16333
	$\tilde{u}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple		36.1	$\tilde{u}$ [ $A_{231} = 2e-4, 1e-2$ ] 0.55, 1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{u}, \tilde{t} \rightarrow b\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow bbs$	$\geq 4b$		140	Forbidden 0.95	$m(\tilde{\chi}_1^0) = 500$ GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 $b$		36.7	$\tilde{t}_1$ [qq, bs] 0.42, 0.61		1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow qt$	2 $e, \mu$ 1 $\mu$	2 $b$ DV	140 136	$\tilde{t}_1$ 0.4-1.85 $\tilde{t}_1$ [1e-10 < $A_{231}^b < 1e-8, 3e-10 < A_{231}^b < 3e-9$ ] 1.0, 1.6	$BR(\tilde{t}_1 \rightarrow b\tilde{c}/b\tilde{s}) > 20\%$ $BR(\tilde{t}_1 \rightarrow q\tilde{u}) = 100\%, \cos\theta_1 = 1$	2406.18367 2003.11956	
$\tilde{\chi}_1^+ \tilde{\chi}_2^0 / \tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^\pm \rightarrow bbs$	1-2 $e, \mu$	$\geq 6$ jets	140	$\tilde{\chi}_1^\pm$ 0.2-0.32	Pure higgsino	2106.09609	

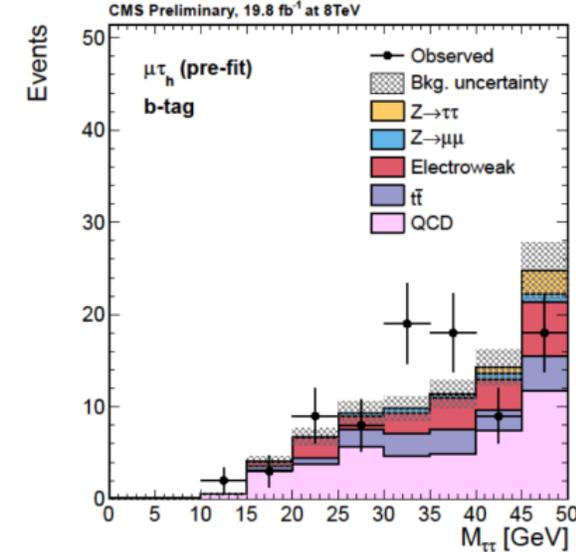
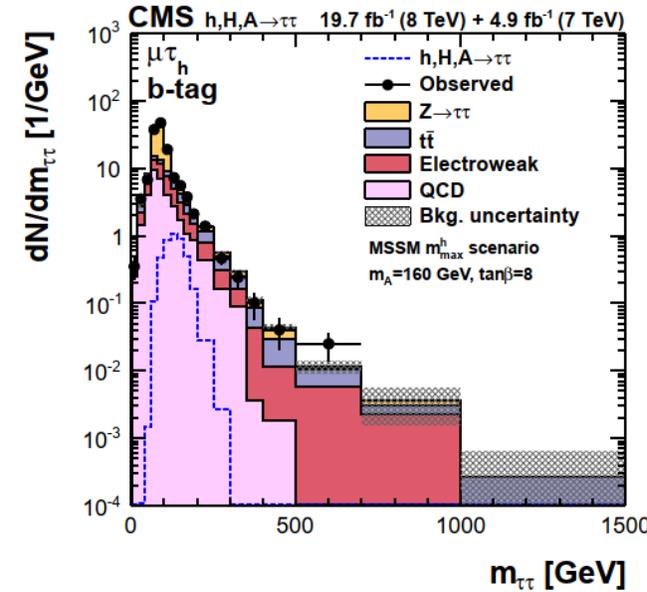
\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

# 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](#)

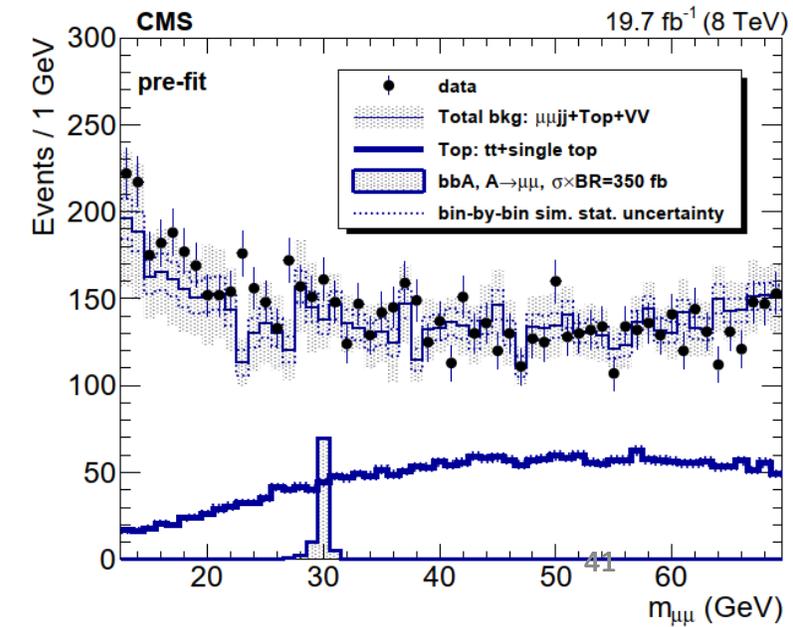
JHEP 10 (2014) 160

zoom at low mass

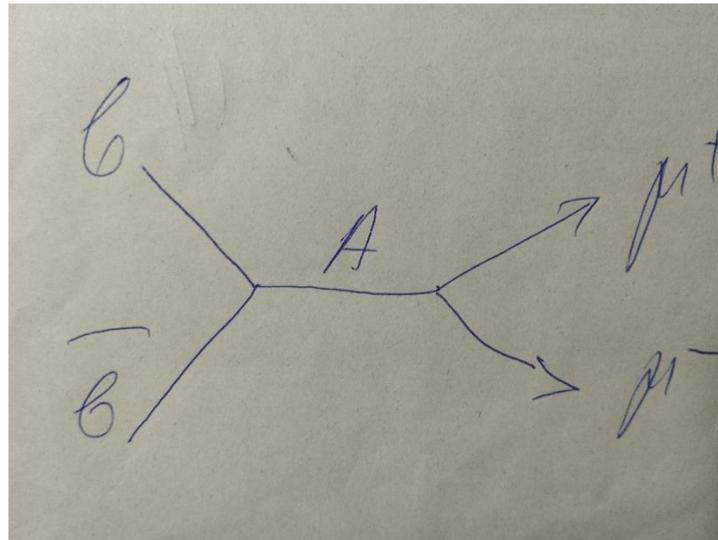


$m_{\tau\tau}$  [GeV]

JHEP 11 (2017) 010



41



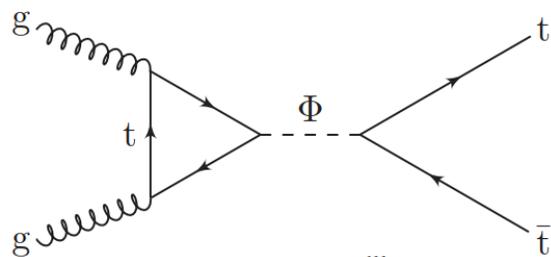
3870170003

## Selections

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

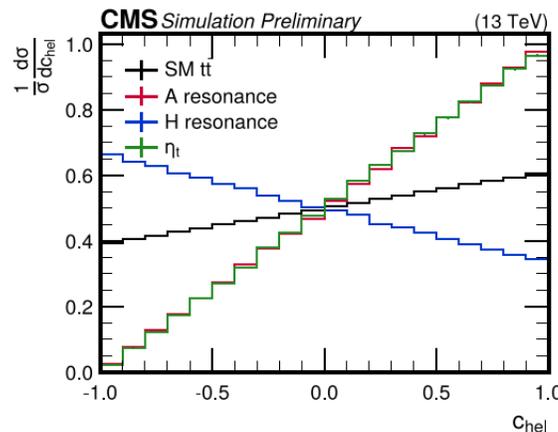
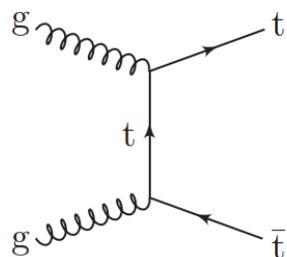
# Search for $A/H \rightarrow t\bar{t}$ in CMS ([arXiv:2507.05119](https://arxiv.org/abs/2507.05119))

- toponium ([arXiv:2104.01927](https://arxiv.org/abs/2104.01927)) or pseudoscalar Higgs boson observation at  $\approx 2m_t$  mass near threshold ?



$$\mathcal{L}_{\text{Yukawa,A}} = ig_{A t \bar{t}} \frac{m_t}{v} \bar{t} \gamma_5 t A,$$

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



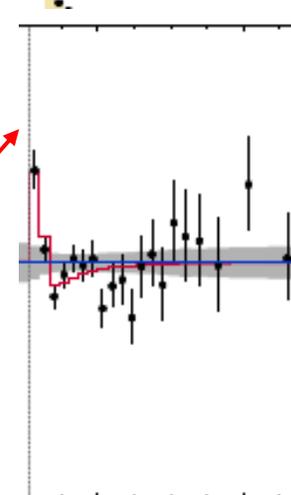
**Postfit (BG + A/H)**    + A(365, 2%),  $g_A = 0.75 \pm 0.03$     + H(365, 2%),  $g_H = 0.0 \pm 0.27$      Uncertainty

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

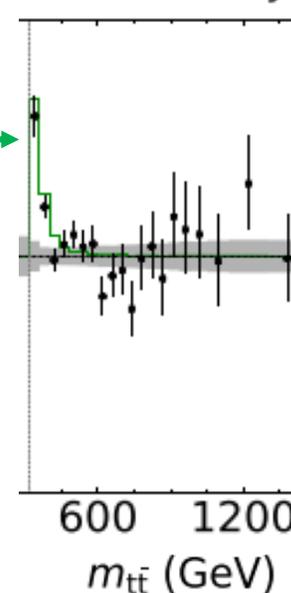
• The  $\eta_t$  mass and width are set to 343 and 7 GeV, respectively.

Ratio to background

$\frac{1}{\sigma} \frac{d\sigma}{dC_{hel}} < 1$   
 $\frac{1}{\sigma} \frac{d\sigma}{dC_{hel}} < 1$



Uncertainty



- for  $\eta_t$  only fit  $\sigma(\eta_t) = 7.1$  pb (11 % error) agrees with  $\sigma_{th} = 6.43$  pb
- for single  $\Phi$  only fit the best significance ( $> 5$ ) for A with  $m_A = 365$  GeV,  $\Gamma_A = 2\%$
- for single  $\Phi$  only fit with  $\eta_t$  included as bkg. with floating  $\sigma(\eta_t)$  no excess is found

# Search for Dark Matter in the framework of Inert Doublet Model using $\mu^+\mu^-(e^+e^-)+p_T^{\text{miss}}$ topology

SM-like Higgs:

$$\phi_S = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + h + i\xi) \end{pmatrix}$$

IDM

$$\phi_D = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

New particles:  $H^\pm, H, A$

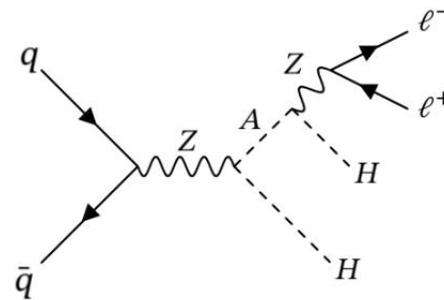
[arXiv:1508.01671](https://arxiv.org/abs/1508.01671)

- scalar H is Dark Matter particle
- free parameters of iDM:

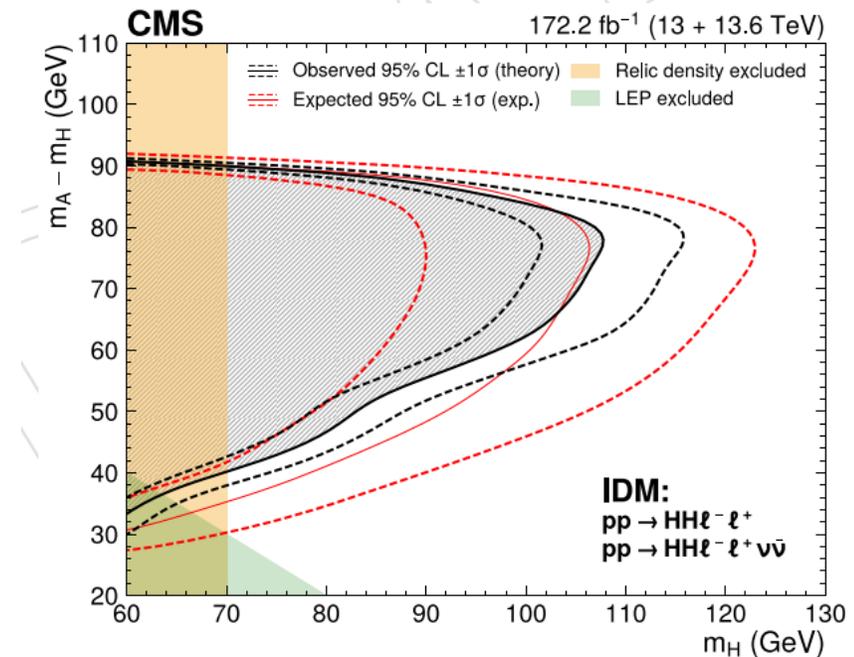
$$m_A, m_{H^+}, m_H, \lambda_{345}$$

•  $pp \rightarrow \mu^+\mu^-HH$

- $qq' \rightarrow Z^* \rightarrow AH$  plus  $qq' \rightarrow Zh^*, qq' \rightarrow Z^* \rightarrow Zh^*$



mass of di-lepton pair must be less than  $m_Z$  to suppress large DY bkg.



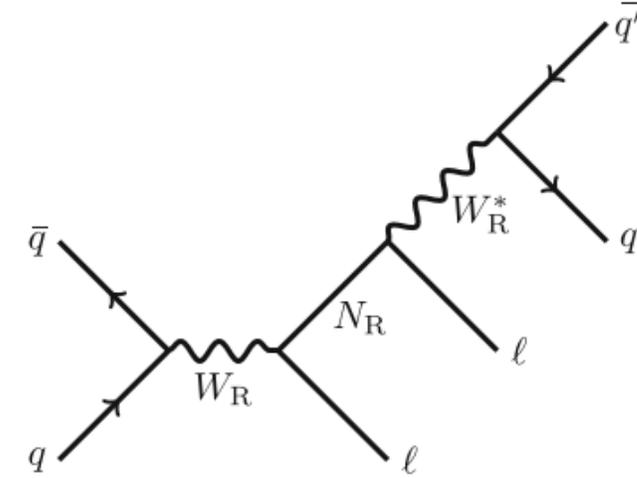
# Mijorana neutrino.

## 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

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

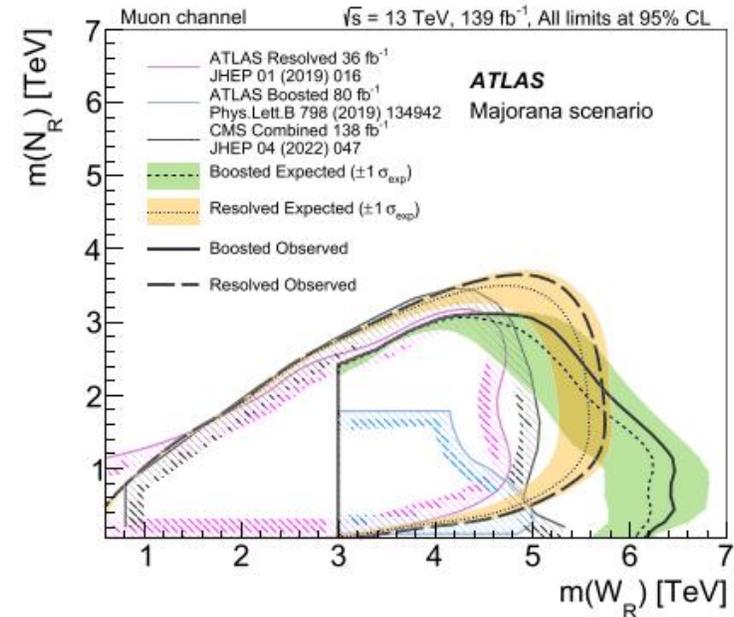
$$M_D \propto \langle \Phi \rangle = v = \text{scale of } W_L$$

$$M_N \propto \langle \Delta_R \rangle = v_R = \text{scale of } W_R$$

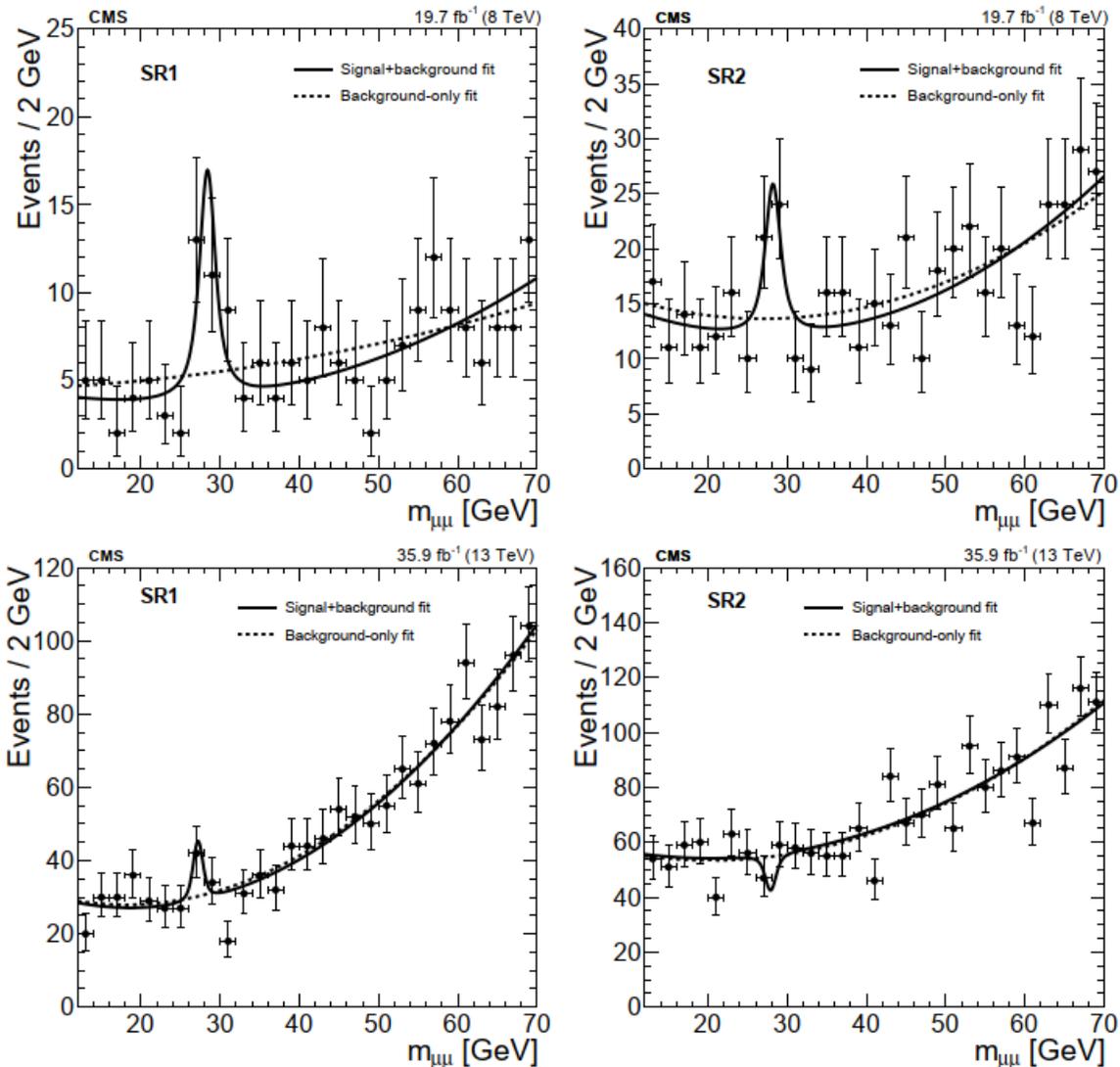
$$m_\nu \propto \frac{M_{W_L}^2}{M_{W_R}}$$

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

[Eur. Phys. J. C 83 \(2023\) 1164](#)



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



Event category	SR1	SR2
$m_X$ (GeV)	$28.4 \pm 0.6$	$28.2 \pm 0.7$
$\Gamma_{\mu\mu}$ (GeV)	$1.9 \pm 1.3$	$1.9 \pm 1.1$

$\sqrt{s}$ (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)	$28.3 \pm 0.4$		$27.2 \pm 0.6$	
$\Gamma_{\mu\mu}$ (GeV)	$1.8 \pm 0.8$		$0.7 \pm 1.0$	
$N_S$	$22.0 \pm 7.6$	$22.8 \pm 9.5$	$14.5 \pm 9.3$	$-14.9 \pm 10.1$

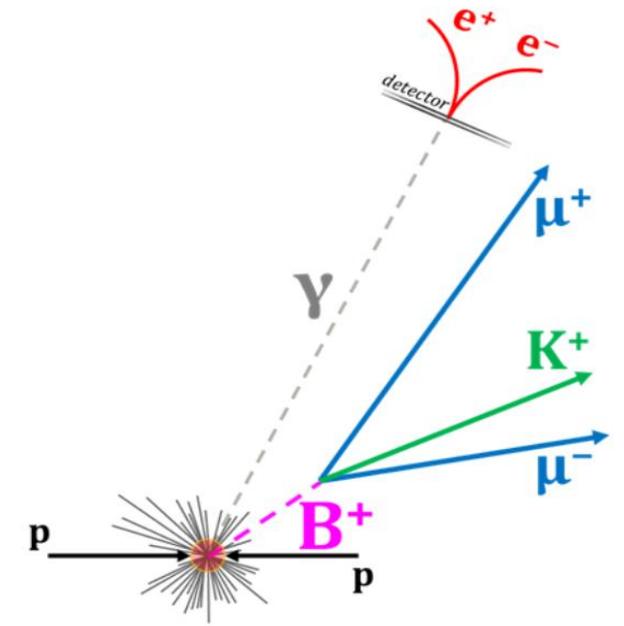
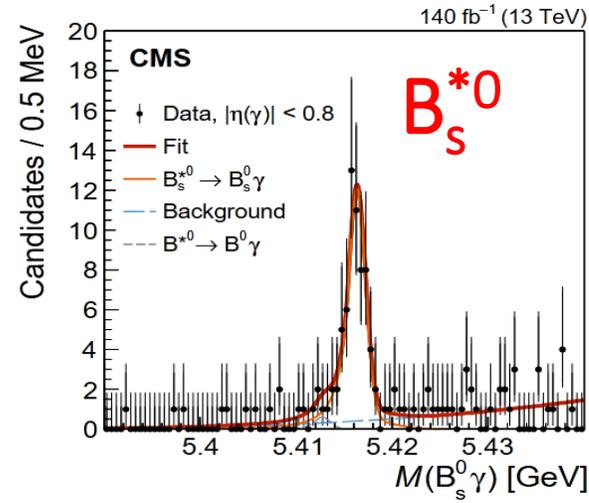
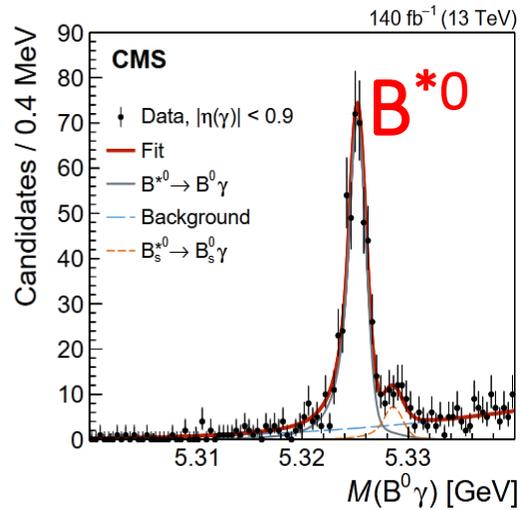
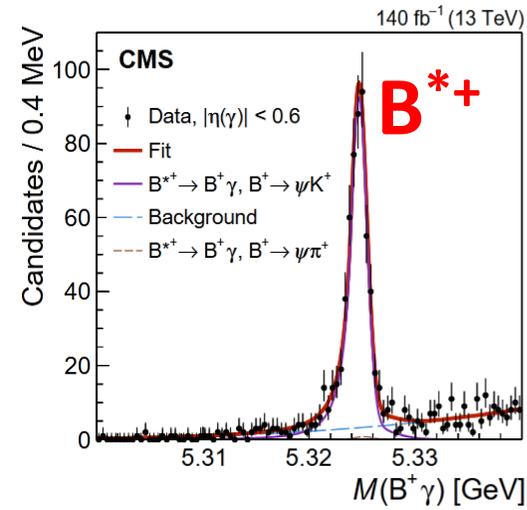
**M. Mangano: no observation at 13 TeV might be explained by the increase of tt background by a factor of 3.3**

# Searches for processes with Lepton Number Violation

**FCNC forbidden in SM imposing  $Z_2$  symmetry**

[Sheldon L. Glashow and Steven Weinberg Phys. Rev. D \*\*15\*\*, 1958](#)

# First full reconstruction of B\* mesons



**The 3 vector B meson states have never been reconstructed previously (only indirect previous measurements exist)**

**Main challenge:** very low-pt  $\gamma$  emitted in  $B^* \rightarrow B\gamma$  decays

**In this work, the 3 states reconstructed fully exclusively for the 1<sup>st</sup> time!**

Using conversion photons for soft  $\gamma$  detection allows to go as low as  $p_T(\gamma) \sim 300$  MeV

Precision of mass measurements – order of magnitude better than PDG (current world-averages)

Publication: [CMS-BPH-24-011](#), [arXiv:2508.05820](#), accepted to Phys.Rev.Lett

CMS Physics Briefing: [cms.cern/news/b-mesons-are-excited-finally-show](#)

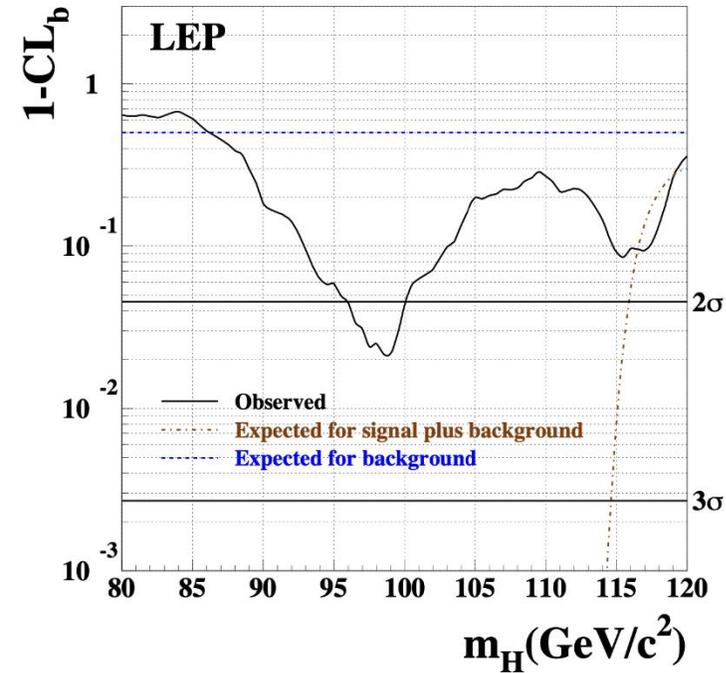
Presentations:

- LHCP2025 (Taiwan): S. Polikarpov, *Recent results in heavy flavour physics from CMS*
- Lomonosov 2025 (Moscow): S. Polikarpov, *Spectroscopy of charm and beauty at CMS*
- Presented by others at: LHCC 162, QFTHEP 2025, EPS-HEP2025, ICNFP 2025

Parameter	Value
1 $\Delta m(B^{*+}) \equiv m(B^{*+}) - m(B^+)$	$45.277 \pm 0.039 \pm 0.027$ MeV
2 $\Delta m(B^{*0}) \equiv m(B^{*0}) - m(B^0)$	$45.471 \pm 0.056 \pm 0.028$ MeV
3 $\Delta m(B_s^{*0}) \equiv m(B_s^{*0}) - m(B_s^0)$	$49.407 \pm 0.132 \pm 0.041$ MeV
4 $m(B^{*+})$	$5324.69 \pm 0.04 \pm 0.03 \pm 0.07$ MeV
5 $m(B^{*0})$	$5325.19 \pm 0.06 \pm 0.03 \pm 0.08$ MeV
6 $m(B_s^{*0})$	$5416.34 \pm 0.13 \pm 0.04 \pm 0.10$ MeV
7 $m(B^{*0}) - m(B^{*+})$	$0.50 \pm 0.07 \pm 0.01 \pm 0.05$ MeV
8 $m(B_s^{*0}) - m(B^{*+})$	$91.66 \pm 0.14 \pm 0.03 \pm 0.12$ MeV
9 $m(B_s^{*0}) - m(B^{*0})$	$91.15 \pm 0.14 \pm 0.03 \pm 0.12$ MeV
10 $m(B_s^{*0}) - \frac{1}{2} [m(B^{*0}) + m(B^{*+})]$	$91.40 \pm 0.13 \pm 0.03 \pm 0.12$ MeV
11 $\Delta m(B^{*0}) - \Delta m(B^{*+})$	$0.19 \pm 0.07 \pm 0.01$ MeV
12 $\Delta m(B_s^{*0}) - \Delta m(B^{*+})$	$4.13 \pm 0.14 \pm 0.03$ MeV
13 $\Delta m(B_s^{*0}) - \Delta m(B^{*0})$	$3.94 \pm 0.14 \pm 0.03$ MeV
14 $\Delta m(B_s^{*0}) - \frac{1}{2} [\Delta m(B^{*0}) + \Delta m(B^{*+})]$	$4.03 \pm 0.13 \pm 0.03$ MeV
15 $\Delta m(B^{*0}) / \Delta m(B^{*+})$	$1.0043 \pm 0.0015 \pm 0.0002$
16 $\Delta m(B_s^{*0}) / \Delta m(B^{*+})$	$1.0912 \pm 0.0031 \pm 0.0007$
17 $\Delta m(B_s^{*0}) / \Delta m(B^{*0})$	$1.0866 \pm 0.0031 \pm 0.0007$
18 $2 \Delta m(B_s^{*0}) / [\Delta m(B^{*+}) + \Delta m(B^{*0})]$	$1.0889 \pm 0.0030 \pm 0.0007$

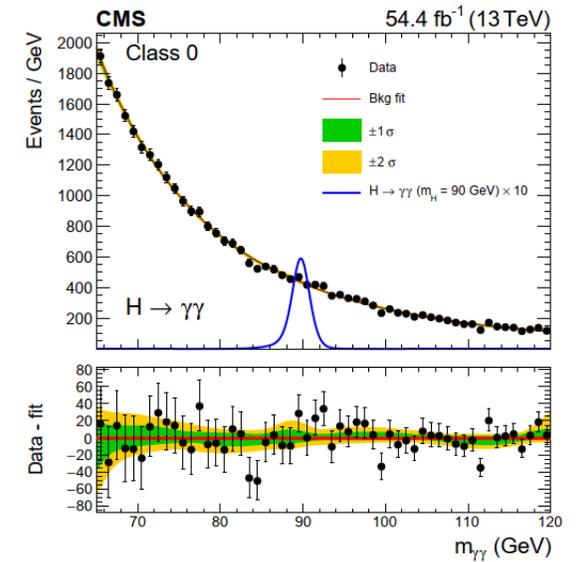
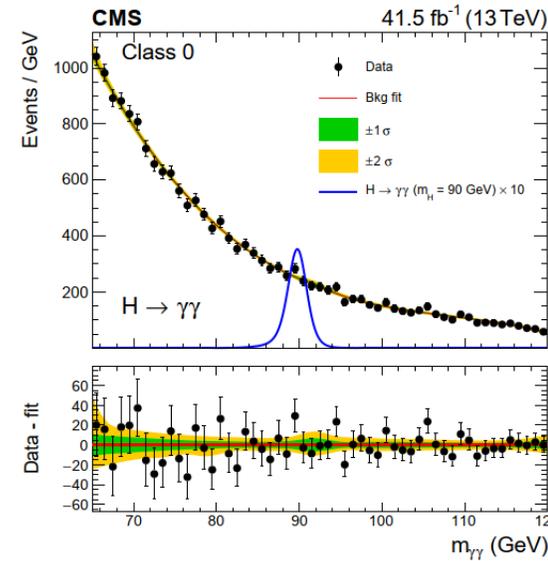
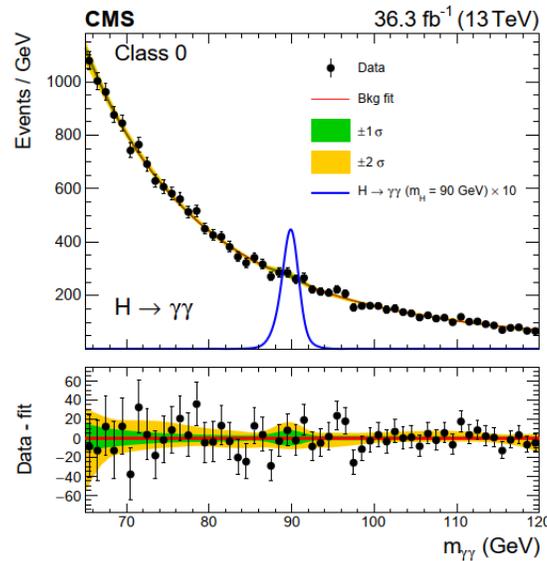
# h95 GeV

[Phys. Lett. B 565 \(2003\) 61–75](#)

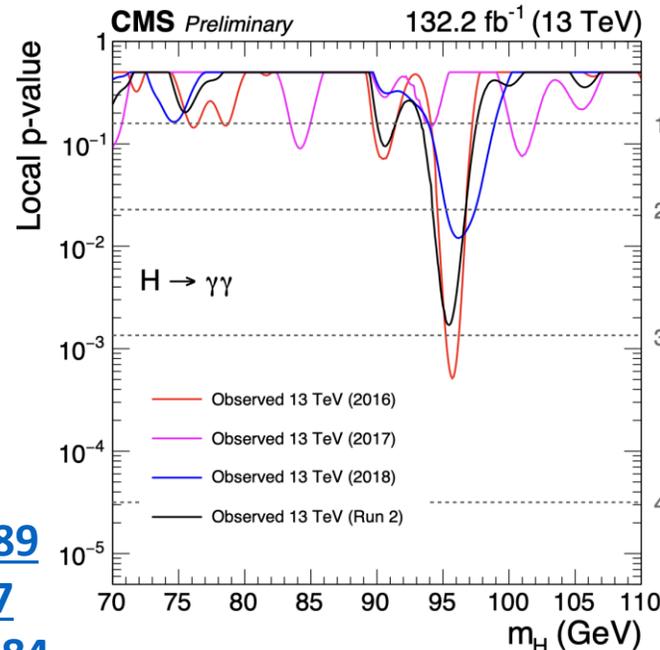


**CMS: event classification according to di-photon BDT score (Class 0, 1, 2) + VBF in 2017, 2018**  
Class 0 has a largest sensitivity

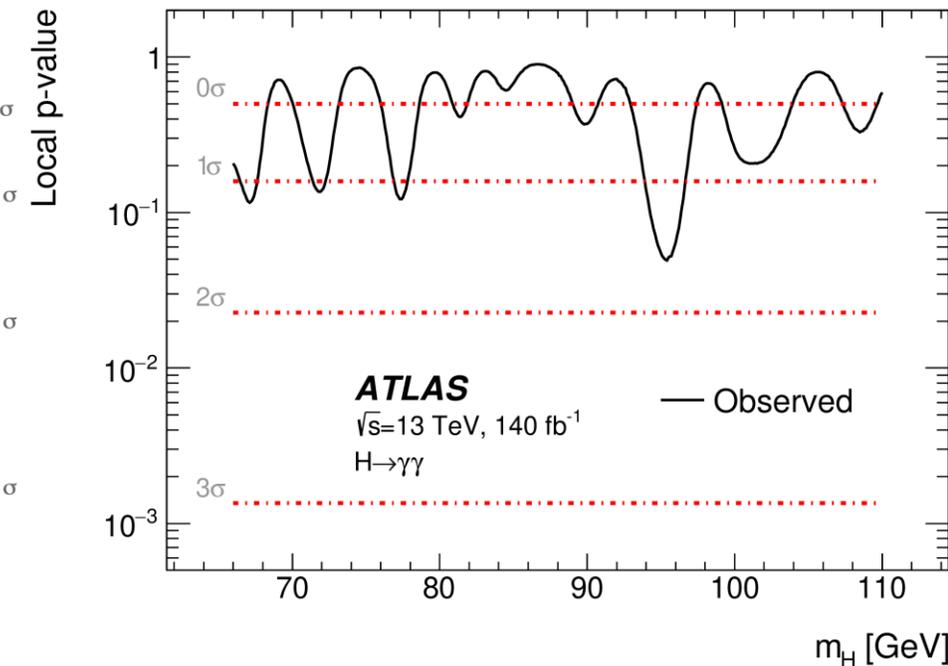
can be explained in S2HDM, [arXiv:2306.03889](#)  
can be explained in 2HDM, [JHEP11\(2023\)017](#)  
can be explained in NMSSM, [arXiv:2403.16884](#)



[arXiv:2405.18149](#)



[arXiv:2407.07546](#)



# Two Higgs Doublet Model (I)

Consider two complex EW doublets

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

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

## Higgs potential

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

parameters  $\lambda_6, \lambda_7 = 0$  as result of  $Z_2$  symmetry imposed to avoid FCNC ( $\Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow -\Phi_2$ )

**Soft  $Z_2$  symmetry breaking:  $m_{12} \neq 0$**

**$m_{12} \neq 0$  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

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

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

	$\Phi_1$	$\Phi_2$	$t_R$	$b_R$	$\tau_R$	$t_L, b_L, \nu_L, e_L$
Type I	+	-	-	-	-	+
Type II	+	-	-	+	+	+
Type X (lepton specific)	+	-	-	-	+	+
Type Y (flipped)	+	-	-	+	-	+

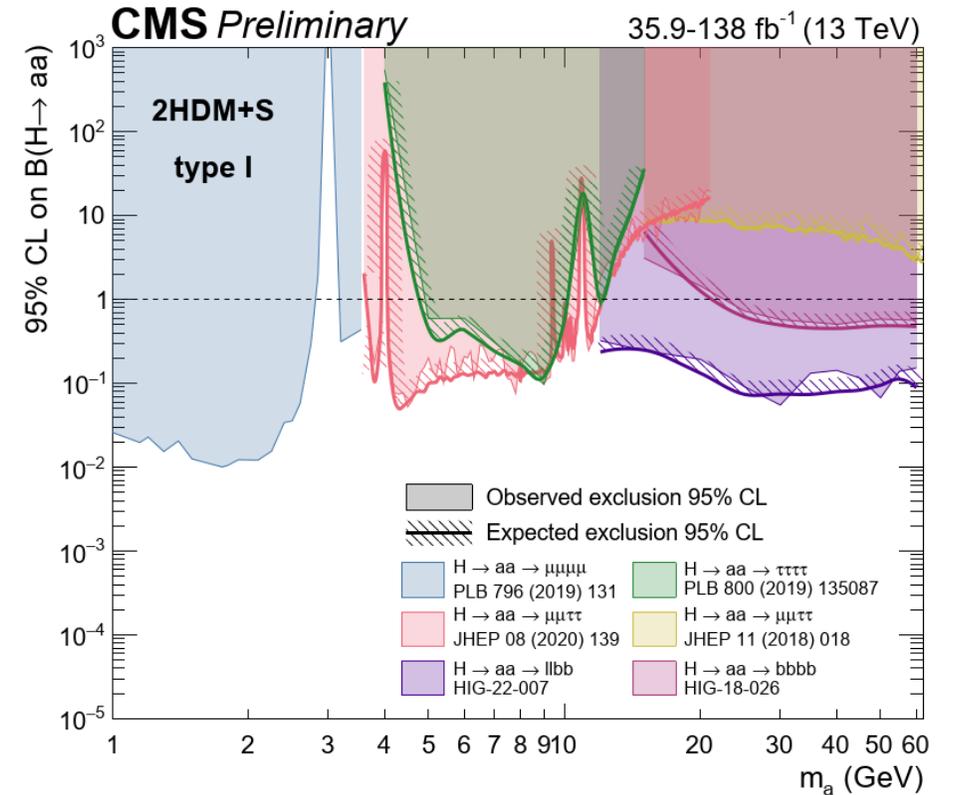
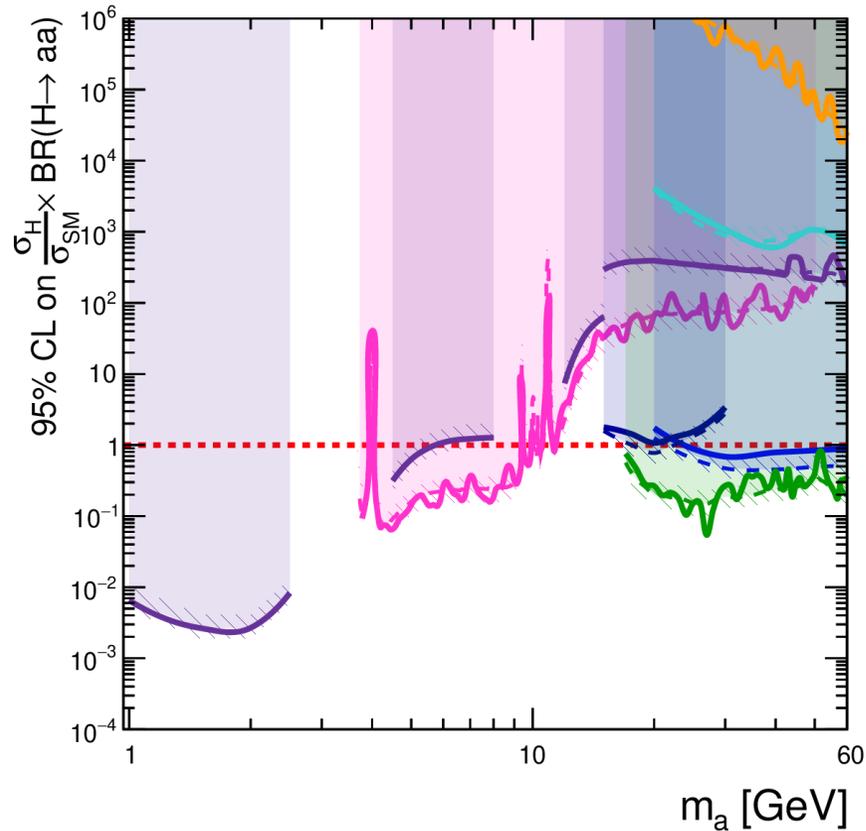


	$u$ -type	$d$ -type	leptons
Type I	$\Phi_2$	$\Phi_2$	$\Phi_2$
Type II	$\Phi_2$	$\Phi_1$	$\Phi_1$
Lepton-specific	$\Phi_2$	$\Phi_2$	$\Phi_1$
Flipped	$\Phi_2$	$\Phi_1$	$\Phi_2$

same as in MSSM



# 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  $\eta_c, \eta_b$  states ( $h \rightarrow \eta_b \eta_c \rightarrow aa, \eta_b a \rightarrow aa, \dots$ ). [U. Haisch et al. arXiv:1802.02156](https://arxiv.org/abs/1802.02156)

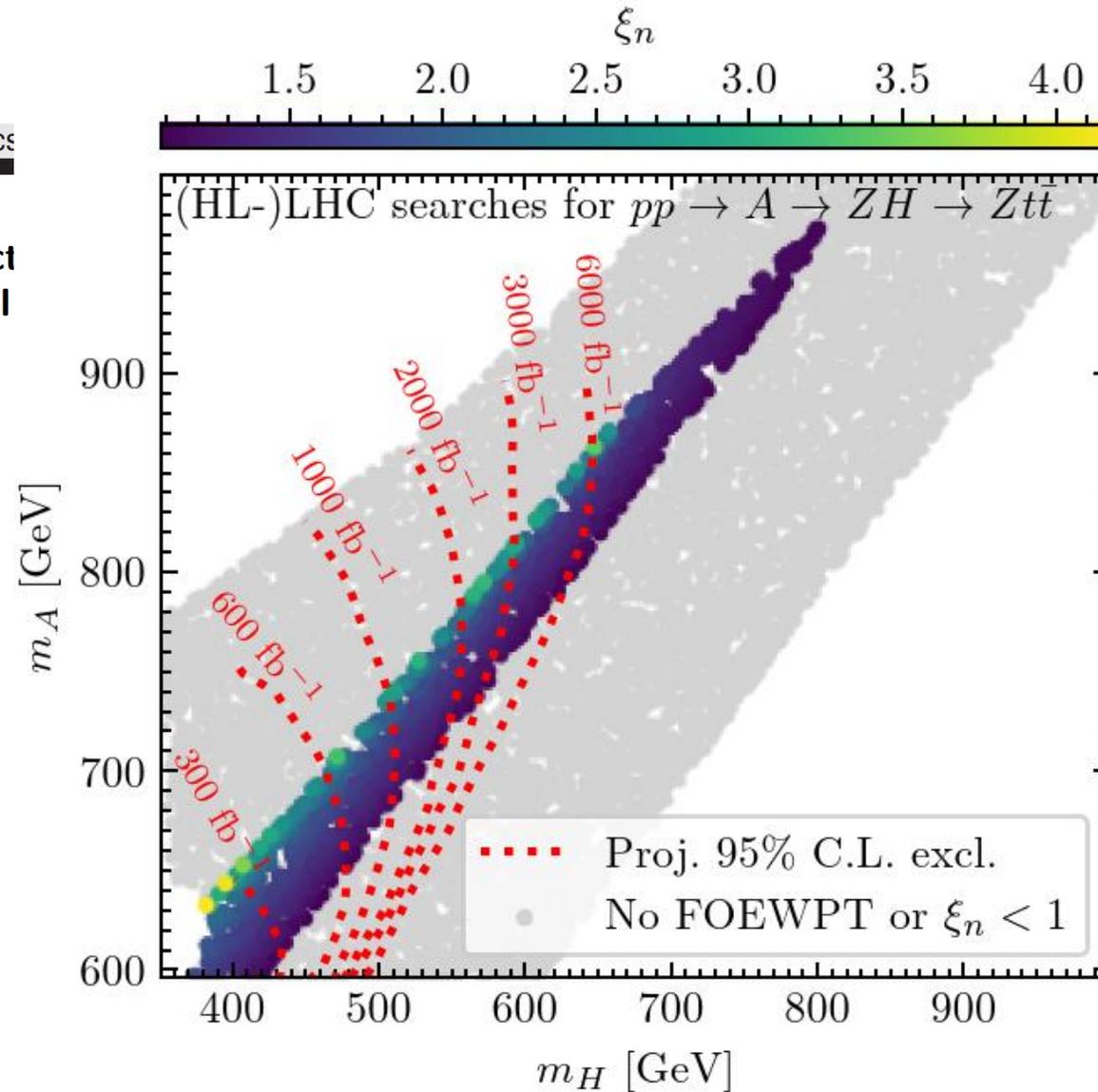
# Prospects for $A \rightarrow ZH \rightarrow l^+ l^- tt$ at HL-LHC

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

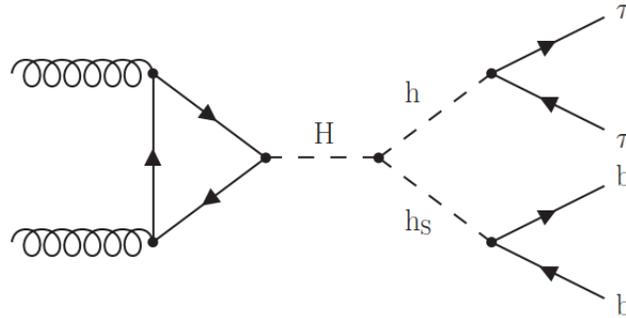
Thomas Biekötter,<sup>a</sup> Sven Heinemeyer,<sup>b</sup> José Miguel No,<sup>b,c</sup>  
María Olalla Olea-Romacho<sup>a</sup> and Georg Weiglein<sup>a,d</sup>

[JCAP 03\(2023\) 031](#)



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

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



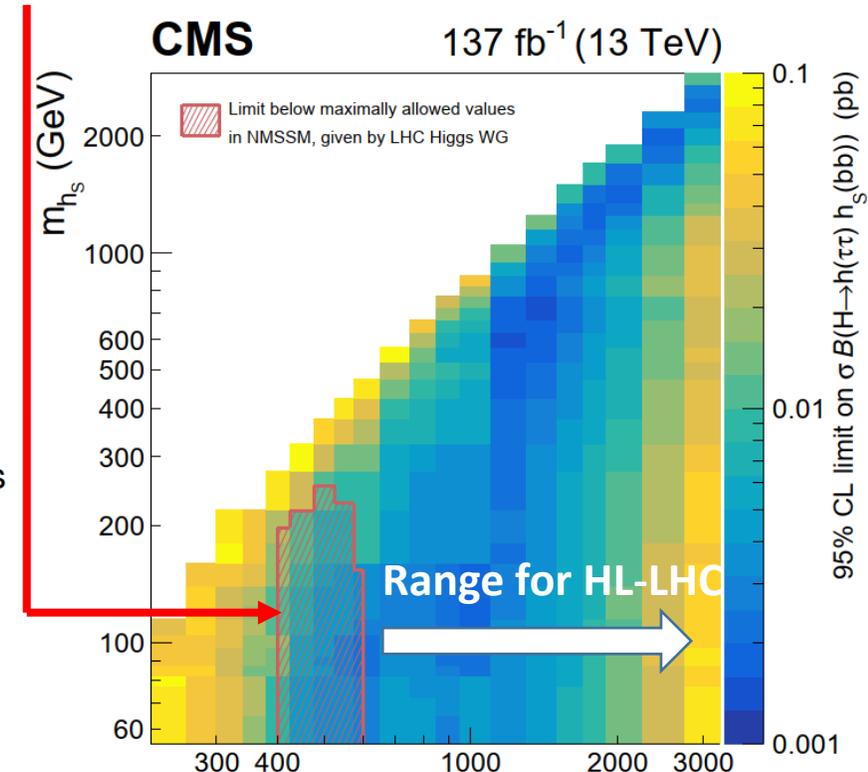
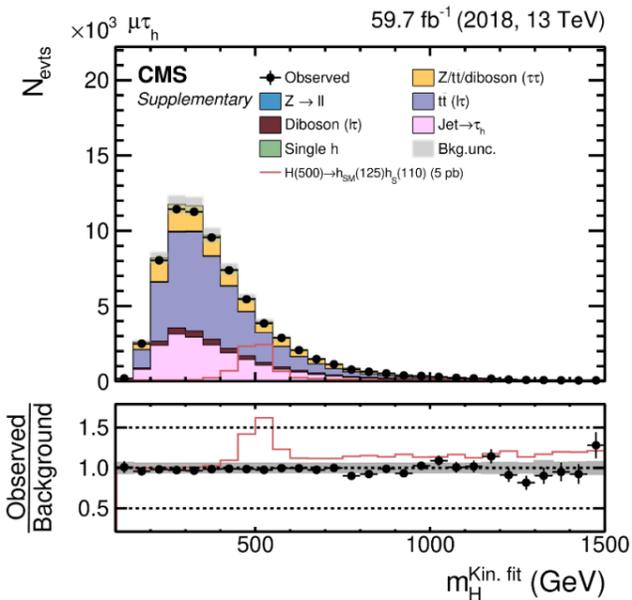
[arXiv:2106.10361](https://arxiv.org/abs/2106.10361)

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,  $y_i$ , that sum to 1
- Allocate events to categories based on largest  $y_i$
- In each category fit maximum  $y_i$  as discriminating variable

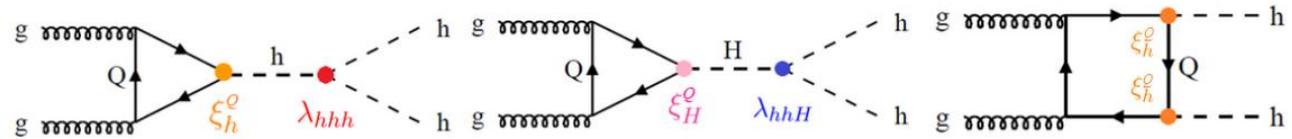
for  $m_H < 400$  GeV B physics kills most of the benchmark  $m_H$  (GeV) points (Ulrich Ellwanger, private communication)



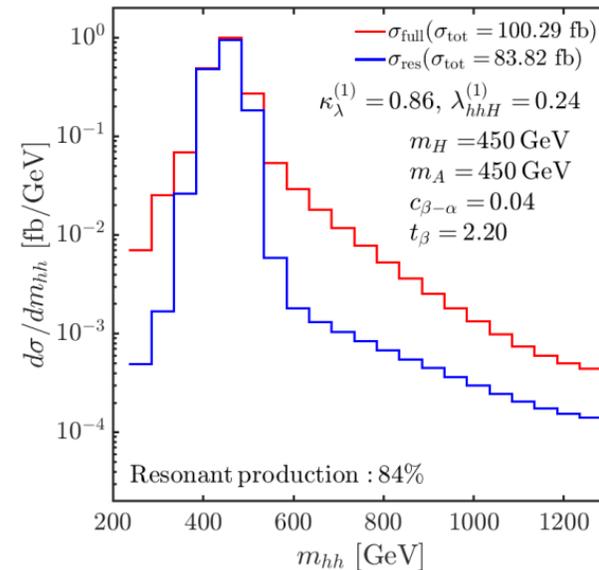
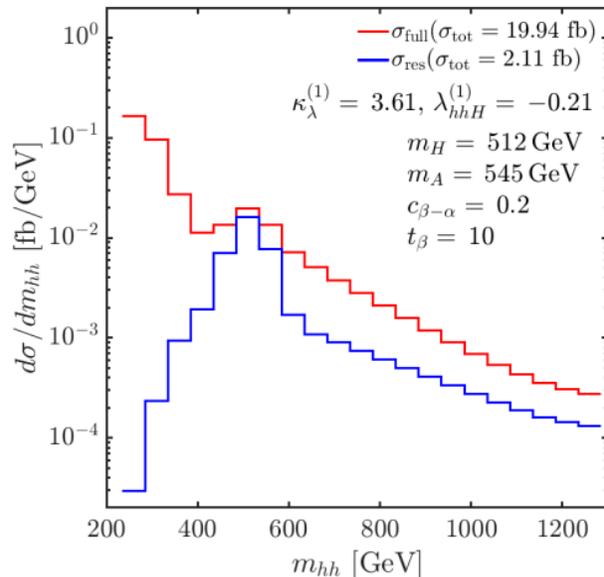
Do not show  $H \rightarrow h_{125} h_{125}$  CMS and ATLAS results since signal model taken in the analyses does not take into account interference with non resonant hh production

- Importance of taking into account non-resonance production

- S. Heinemeier et al. [arXiv:2403.14776](https://arxiv.org/abs/2403.14776)
- T. Robens et al. [arXiv:2409.06651](https://arxiv.org/abs/2409.06651)



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



# 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<sub>μ</sub>-2 anomaly ([arXiv:2104.10175](https://arxiv.org/abs/2104.10175))

Four possible Z<sub>2</sub> charge assignments that forbid tree-level Higgs-mediated FCNC effects in the 2HDM

	Φ <sub>1</sub>	Φ <sub>2</sub>	t <sub>R</sub>	b <sub>R</sub>	τ <sub>R</sub>	t <sub>L</sub> , b <sub>L</sub> , ν <sub>L</sub> , e <sub>L</sub>
Type I	+	-	-	-	-	+
Type II	+	-	-	+	+	+
Type X (lepton specific)	+	-	-	-	+	+
Type Y (flipped)	+	-	-	+	-	+

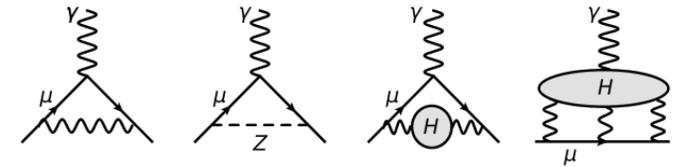
## Couplings of Higgs particles to quarks and leptons

	u-type	d-type	leptons	ξ <sub>A</sub> <sup>u</sup>	ξ <sub>A</sub> <sup>d</sup>
type I	Φ <sub>2</sub>	Φ <sub>2</sub>	Φ <sub>2</sub>	cot β	-cot β
type II	Φ <sub>2</sub>	Φ <sub>1</sub>	Φ <sub>1</sub>	cot β	tan β
type III (lepton-specific)	Φ <sub>2</sub>	Φ <sub>2</sub>	Φ <sub>1</sub>	cot β	-cot β
type IV (flipped)	Φ <sub>2</sub>	Φ <sub>1</sub>	Φ <sub>2</sub>	cot β	tan β



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

SM contribution to magnetic momentum of muon

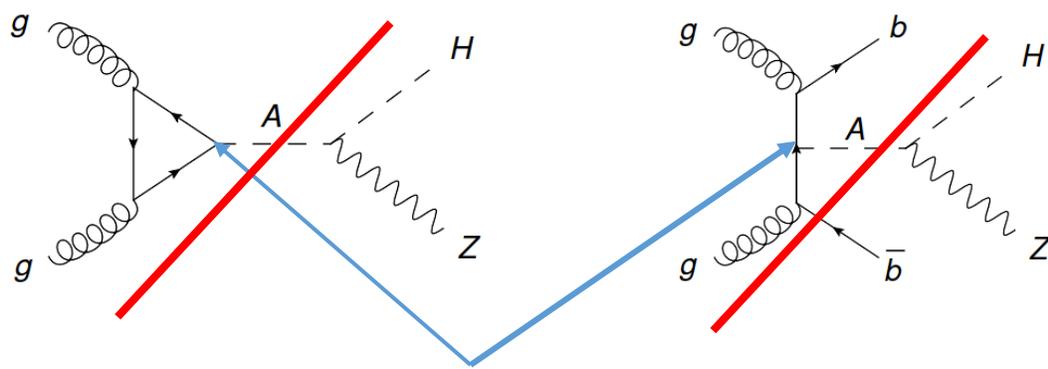


$$\Delta a_{\mu}^{\text{obs}} = a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = 251(59) \times 10^{-11}$$

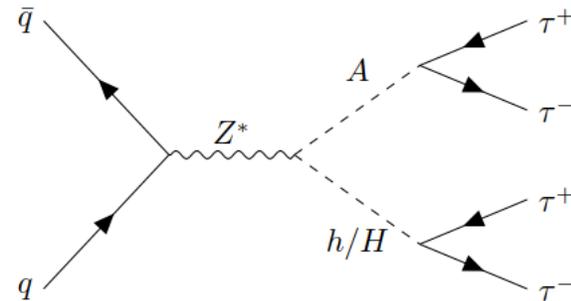
4.2 σ deviation from SM, in 2HDM φ<sup>0</sup>, A, H<sup>±</sup> contribute to loop

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

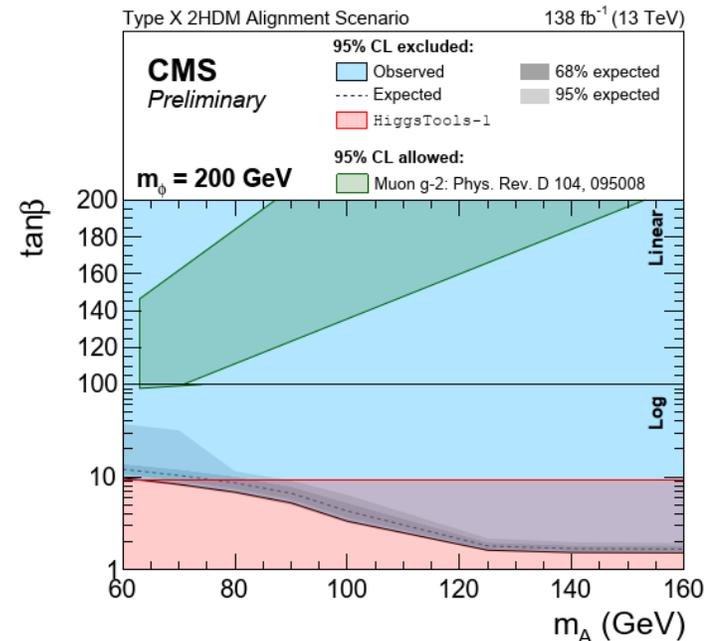
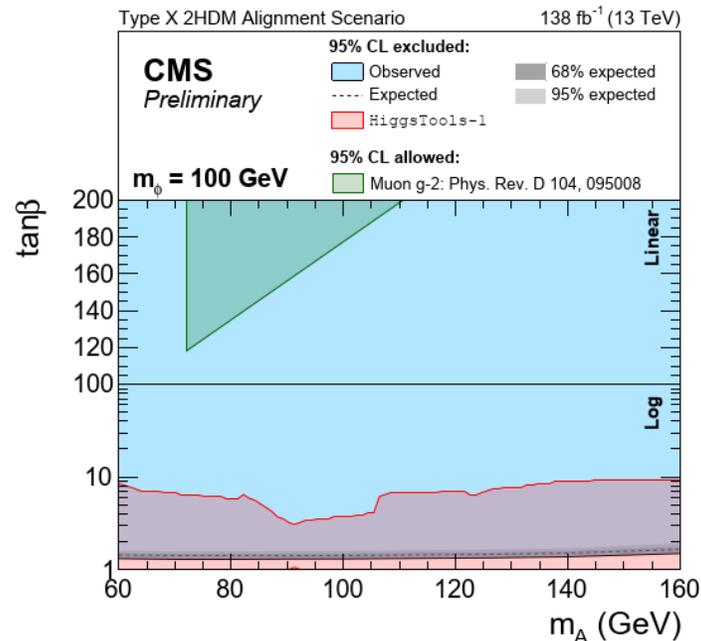
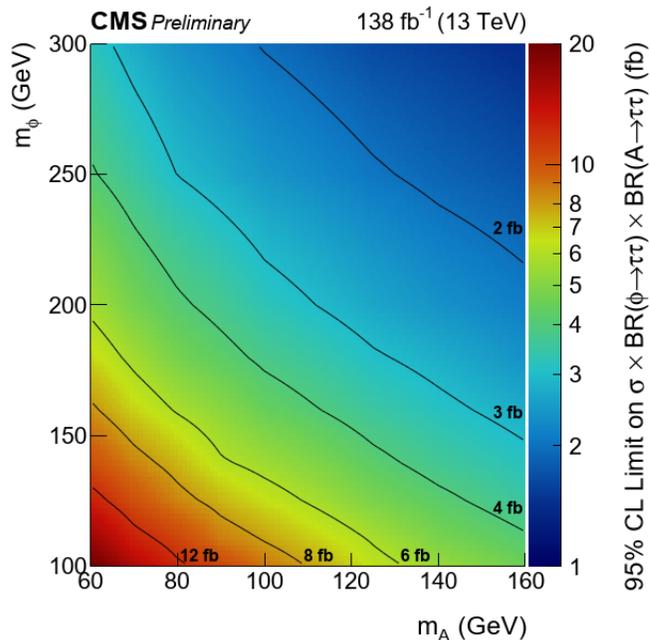
normal scenario (NS)	inverted scenario (IS)
$h_{\text{SM}} = h, \quad \varphi^0 = H$	$h_{\text{SM}} = H, \quad \varphi^0 = h$
$y_f^{h_{\text{SM}}} = 1, \quad s_{\beta-\alpha} = 1$	$y_f^{h_{\text{SM}}} = 1, \quad c_{\beta-\alpha} = 1$
$y_t^A = -y_t^{\varphi^0} = \frac{1}{t_{\beta}}, \quad y_{\ell}^A =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



$$\xi_A^t = -\xi_A^b = 1/\tan\beta$$



$$\xi_{AZ\phi} \approx 1, \xi_A^\tau = \xi_\phi^\tau = \tan\beta$$



- search excludes the allowed region for the  $g_\mu$ -2 anomaly with a Type III 2HDM
- a complete exclusion of the type III 2HDM for many of the mass points scanned.

# limits on the anomalous electromagnetic moments of the $\tau$ lepton [\(Rep. Prog. Phys. 87 \(2024\) 107801\)](#)

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

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

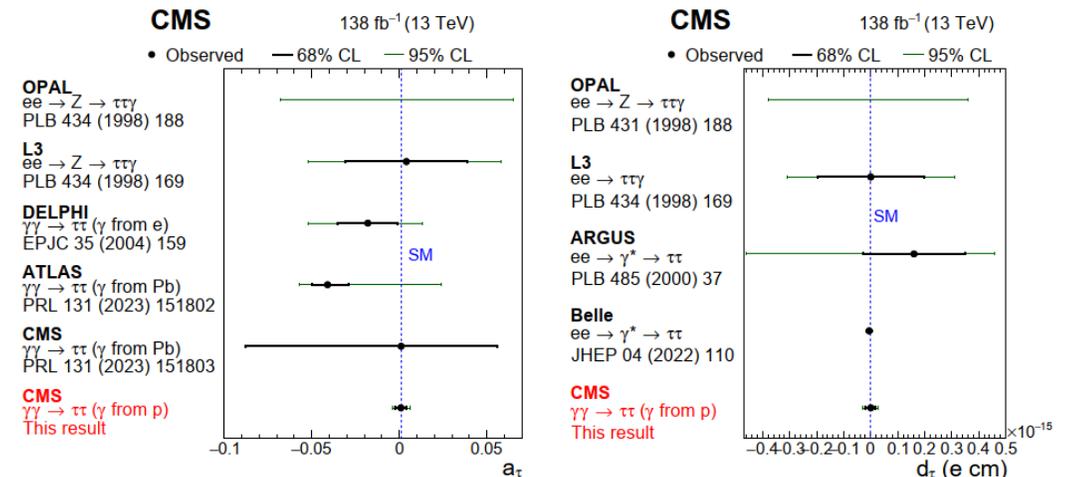
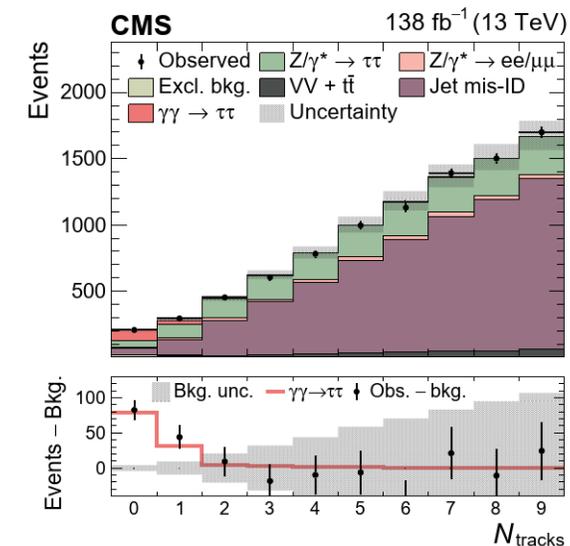
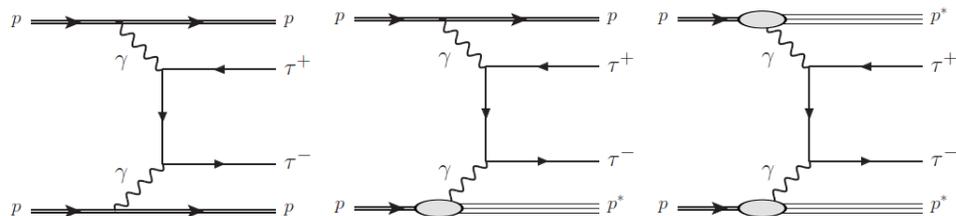
$$F_2(0) = a_\ell \equiv (g_\ell - 2)/2 \text{ and } F_3(0) = -2md_\ell/e,$$

the gyromagnetic ratio  $g_\ell$  is a constant term that relates the magnetic moment of the lepton to its spin, and  $d_\ell$  is the lepton anomalous electric dipole moment.

$$a_\tau = 1.17721 \pm 0.00005 \times 10^{-3}$$

in the SM ([arXiv:hep-ph/0701260](#))

$$d_\tau = -7.3 \times 10^{-38} \text{ e cm in SM ([arXiv:2003.08195](#))}$$

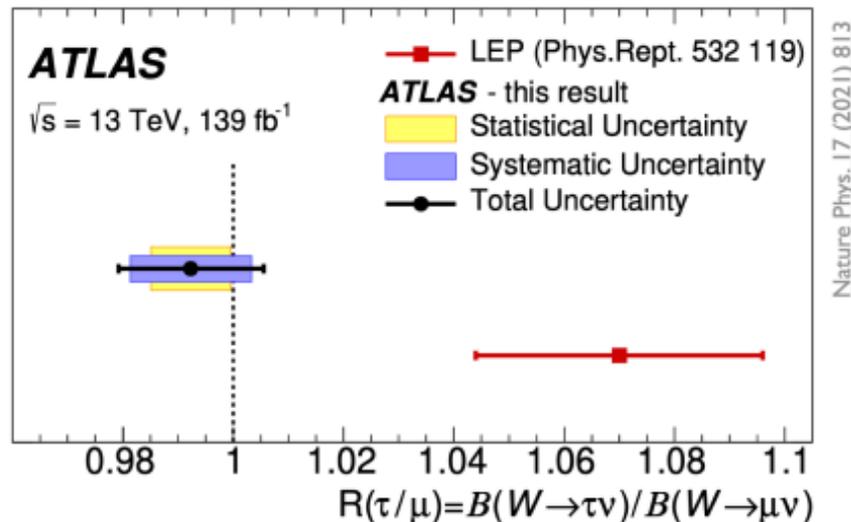


# Lepton Universality in W decays

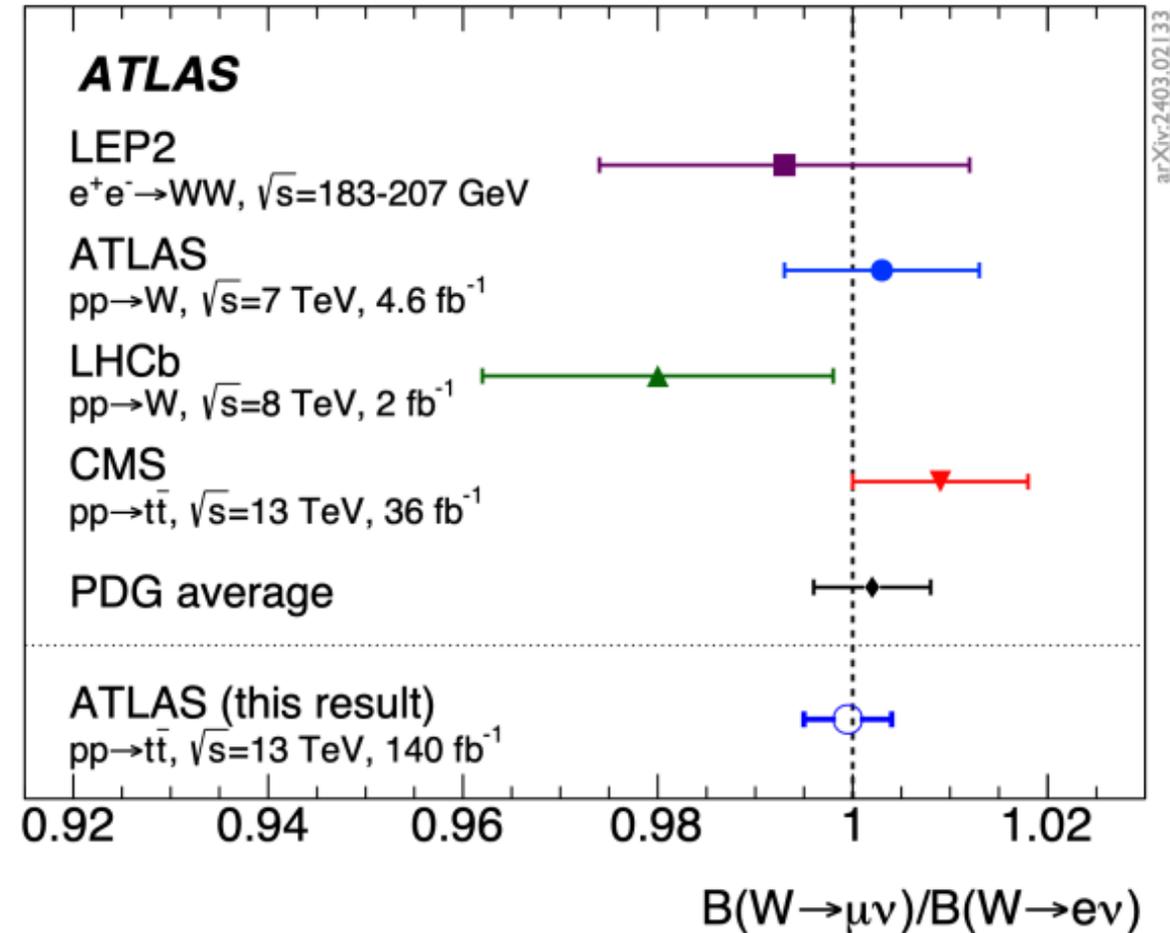
Recent result from ATLAS: W decays to electrons and muons from top-pair events

- 2x improvement on single-experiment precision

[Nature Phys. 17 \(2021\) 813](#)



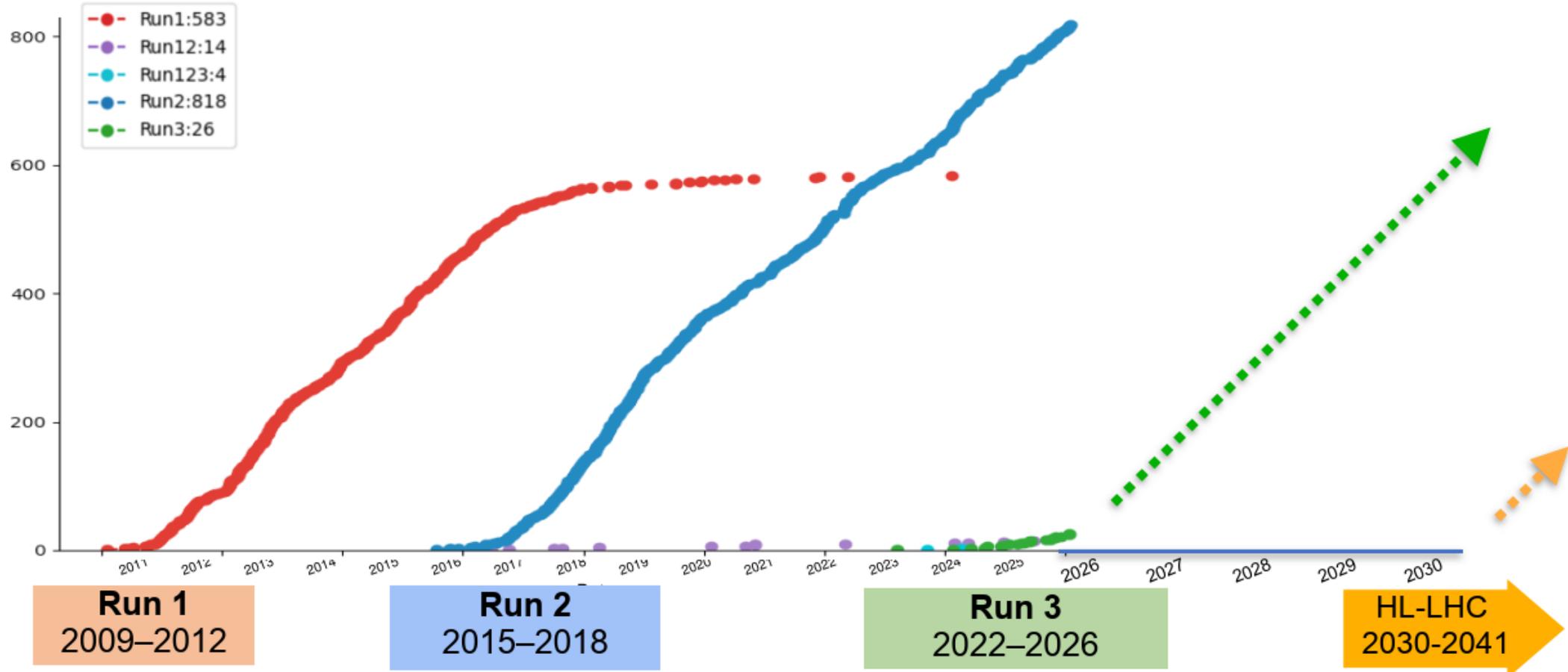
Nature Phys. 17 (2021) 813



arXiv:2403.02133

# Publications

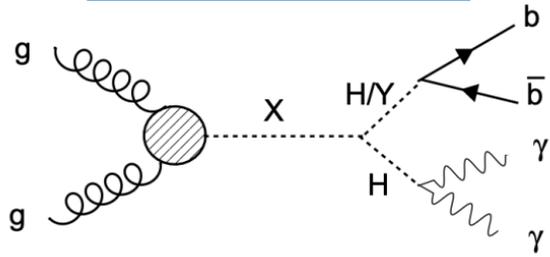
<https://mia-tosi.web.cern.ch>



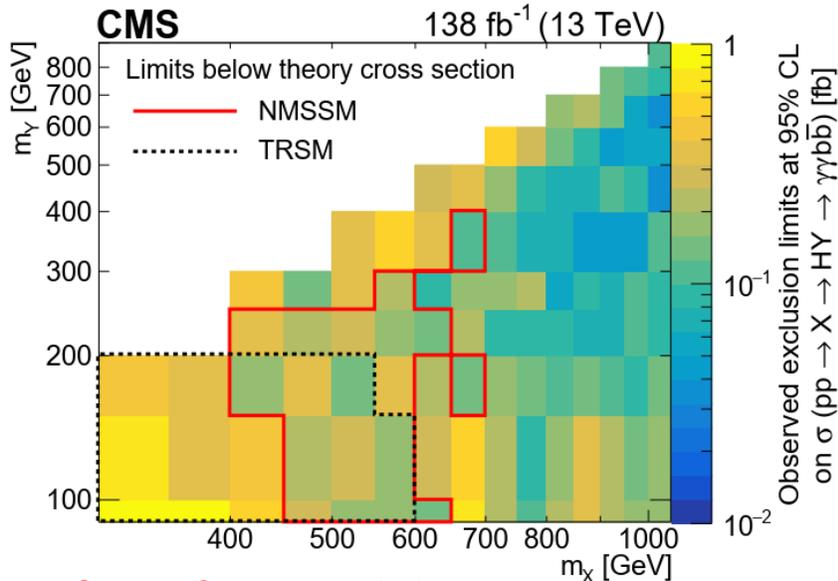
searches for  
 $H(A) \rightarrow h_{125} h(a)_S$  decays

# search for $H(A) \rightarrow h_{125} h(a)_s \rightarrow \gamma\gamma bb$

[arXiv:2310.01643](https://arxiv.org/abs/2310.01643)



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



already sensitive to NMSSM

# Combination assuming SM BR

$h_{125} \rightarrow \gamma\gamma, \tau\tau, bb$  [arXiv:2403.16926](https://arxiv.org/abs/2403.16926)

