

## Carlos' 60th birthday at HH22:



# Discoveries through the Higgs Boson(s)

*Sven Heinemeyer, IFT (CSIC, Madrid)*

Chicago, 05/2023

- Two joint papers (out of many)
- BSM Higgs physics (what connects us)
- I found  $\gtrsim 100$  photos
  - will show only a tiny fraction ;-)
  - (→ 3 intermezzi)
  - ... surprisingly few photos in which Marcela or Carlos are working ...

## My first recollection . . .

DESY Theory workshop in 1996(?)

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with common interests,  
with the same passion (for BSM Higgs physics),  
and that we will have many interesting(?) papers together (cit. av.  $\gtrsim 300$ )

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Even the age difference goes to zero ...

## The earliest photo that I found: Uli's birthday party in Naperville 2004



## Now for the two papers:

Inspire: a carena, m. and wagner, c. and heinemeyer → 23 (9) results

The first and the last:

### Reconciling the Two-Loop Diagrammatic and Effective Field Theory Computations of the Mass of the Lightest $\mathcal{CP}$ -even Higgs Boson in the MSSM

M. Carena <sup>§,†</sup>, H.E. Haber <sup>‡</sup>, S. Heinemeyer <sup>‡</sup>,

W. Hollik <sup>¶</sup>, C.E.M. Wagner <sup>†,\*‡</sup> and G. Weiglein <sup>†</sup>

<sup>§</sup> FERMILAB, Batavia, IL 60510-0500 USA

<sup>†</sup> CERN, TH Division, CH-1211 Geneva 23, Switzerland

<sup>#</sup> Santa Cruz Inst. for Part. Phys., Univ. of California, Santa Cruz, CA 95064 USA

<sup>‡</sup> DESY Theorie, Notkestrasse 85, 22603 Hamburg, Germany

<sup>¶</sup> Institut für Theoretische Physik, Univ. of Karlsruhe, 76128 Karlsruhe, Germany

<sup>\*</sup> High Energy Physics Division, Argonne National Lab., Argonne, IL 60439 USA

<sup>‡</sup> Enrico Fermi Institute, Univ. of Chicago, 5640 Ellis, Chicago, IL 60637 USA

#### Abstract

The mass of the lightest  $\mathcal{CP}$ -even Higgs boson of the minimal supersymmetric extension of the Standard Model (MSSM) has previously been computed including  $\mathcal{O}(\alpha\alpha_s)$  two-loop contributions by an on-shell diagrammatic method, while approximate analytic results have also been obtained via renormalization-group-improved effective potential and effective field theory techniques. Initial comparisons of the corresponding two-loop results revealed an apparent discrepancy between terms that depend logarithmically on the supersymmetry-breaking scale, and different dependences of the non-logarithmic terms on the squark mixing parameter,  $X_t$ . In this paper, we determine the origin of these differences as a consequence of different renormalization schemes in which both

arXiv:2012.15629v3 [hep-ph] 17 May 2021

### Higgs-mass predictions in the MSSM and beyond

P. Slavich<sup>a</sup> and S. Heinemeyer<sup>b,c,d</sup> (eds.),

E. Bagnaschi<sup>e</sup>, H. Bahl<sup>f</sup>, M.Goodsell<sup>a</sup>, H.E. Haber<sup>g</sup>, T. Hahn<sup>h</sup>, R. Harlander<sup>i</sup>, W. Hollik<sup>h</sup>, G. Lee<sup>j,k,l</sup>, M. Mühlleitner<sup>m</sup>, S. Paßehr<sup>i</sup>, H. Rzebak<sup>n</sup>, D. Stöckinger<sup>o</sup>, A. Voigt<sup>p</sup>, C.E.M. Wagner<sup>q,r,s</sup> and G. Weiglein<sup>f</sup>, B.C. Allanach<sup>t</sup>, T. Biekötter<sup>f</sup>, S. Borowka<sup>u,†</sup>, J. Braathen<sup>f</sup>, M. Carena<sup>r,s,v</sup>, T.N. Dao<sup>w</sup>, G. Degrassi<sup>x</sup>, F. Domingo<sup>y</sup>, P. Drechsel<sup>f,†</sup>, U. Ellwanger<sup>z</sup>, M. Gabelmann<sup>m</sup>, R. Gröber<sup>aa</sup>, J. Klappert<sup>i</sup>, T. Kwasnitza<sup>o</sup>, D. Meuser<sup>f</sup>, L. Mihaila<sup>bb,†</sup>, N. Murphy<sup>cc,†</sup>, K. Nickel<sup>y,†</sup>, W. Porod<sup>dd</sup>, E.A. Reyes Rojas<sup>ee</sup>, I. Sobolev<sup>f</sup> and F. Staub<sup>m,†</sup>

Predictions for the Higgs masses are a distinctive feature of supersymmetric extensions of the Standard Model, where they play a crucial role in constraining the parameter space. The discovery of a Higgs boson and the remarkably precise measurement of its mass at the LHC have spurred new efforts aimed at improving the accuracy of the theoretical predictions for the Higgs masses in supersymmetric models. The “*Precision SUSY Higgs Mass Calculation Initiative*” (KUTS) was launched in 2014 to provide a forum for discussions between the different groups involved in these efforts. This report aims to present a comprehensive overview of the current status of Higgs-mass calculations in supersymmetric models, to document the many advances that were achieved in recent years and were discussed during the KUTS meetings, and to outline the prospects for future improvements in these calculations.

They have more in common than one may think . . .

Reconciling the Two-Loop Diagrammatic and  
Effective Field Theory Computations of the Mass  
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**Abstract**

The mass of the lightest  $\mathcal{CP}$ -even Higgs boson of the minimal supersymmetric extension of the Standard Model (MSSM) has previously been computed including  $\mathcal{O}(\alpha\alpha_s)$  two-loop contributions by an on-shell diagrammatic method, while approximate analytic results have also been obtained via renormalization-group-improved effective potential and effective field theory techniques. Initial comparisons of the corresponding two-loop results revealed an apparent discrepancy between terms that depend logarithmically on the supersymmetry-breaking scale, and different dependences of the non-logarithmic terms on the squark mixing parameter,  $X_t$ . In this paper, we determine the origin of these differences as a consequence of different renormalization schemes in which both

⇒ note the arXiv number!

⇒ the second paper in the new millennium

(modulo 2000 vs. 2001)

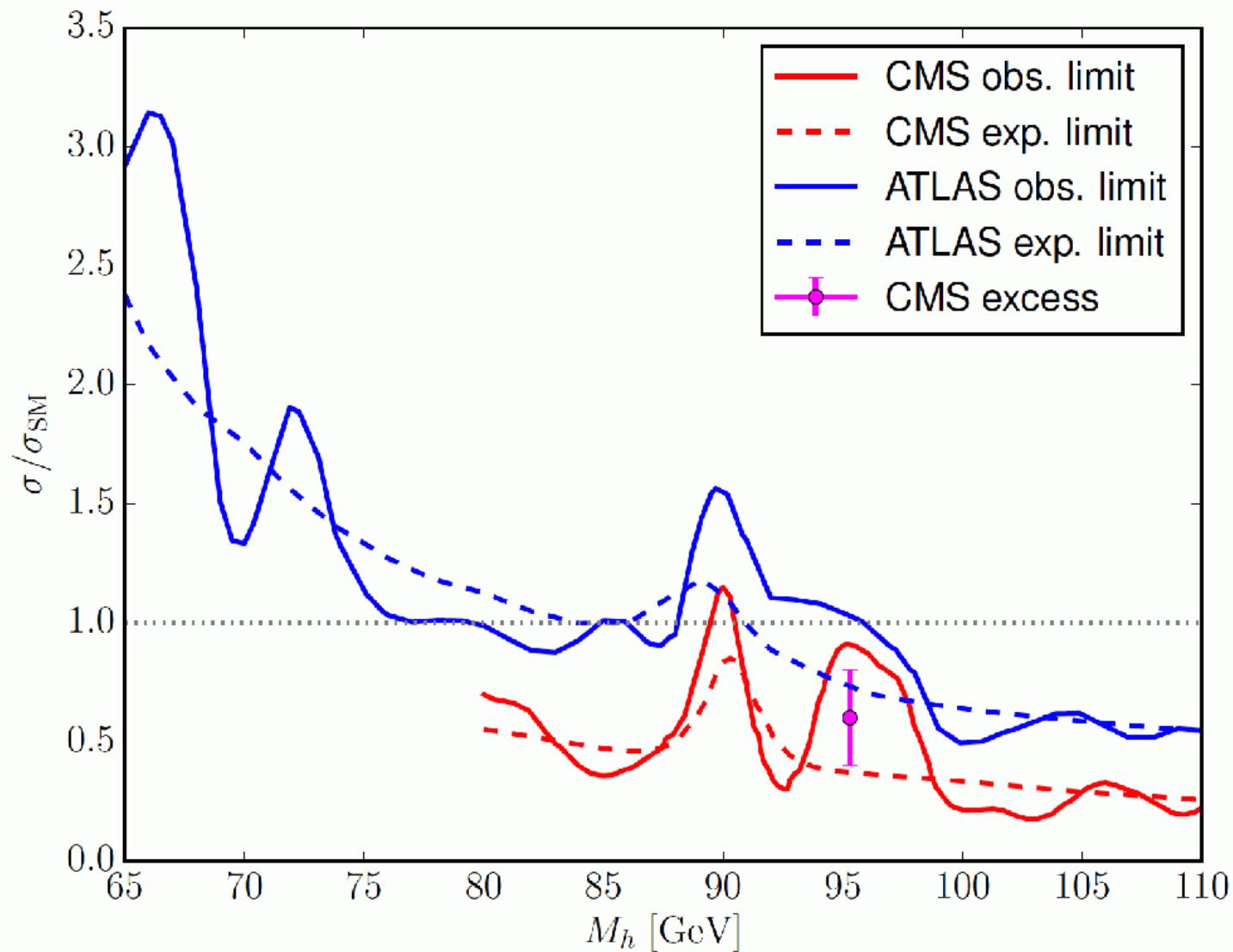
## Light BSM Higgs bosons



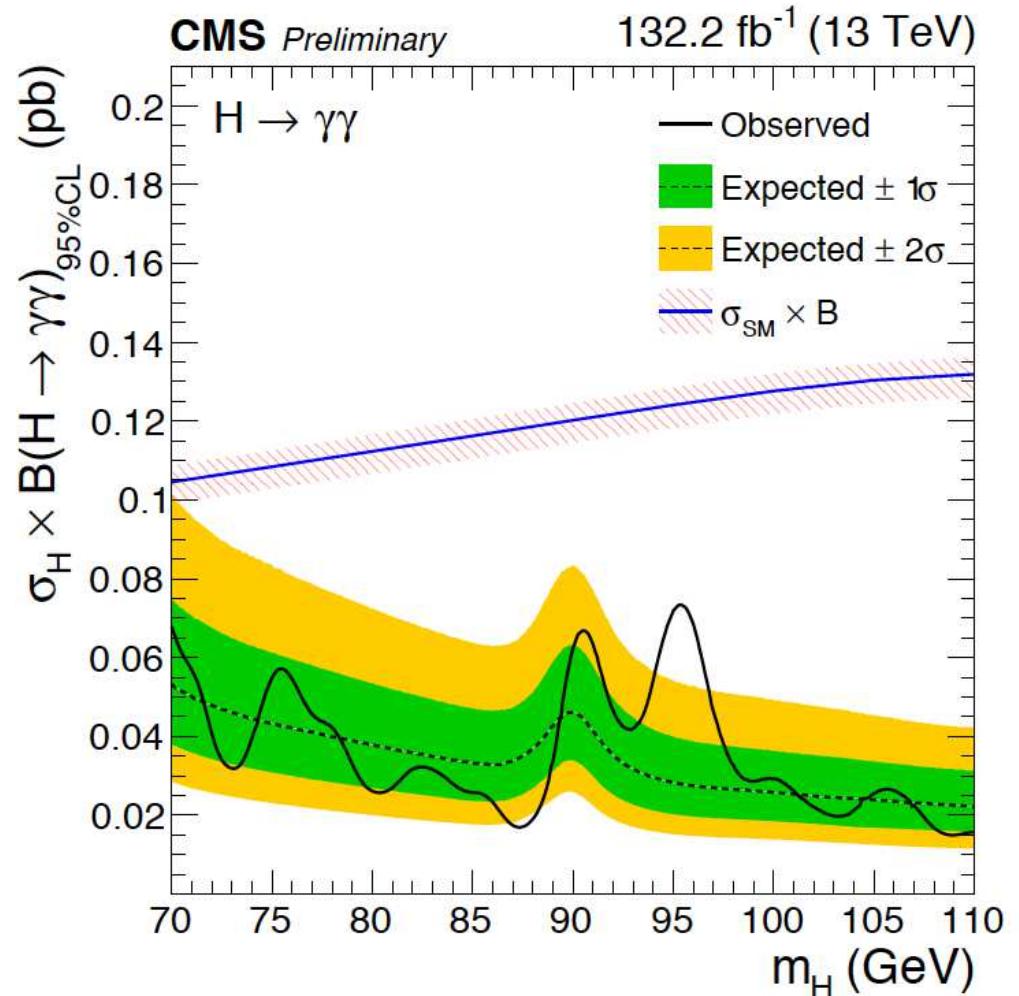
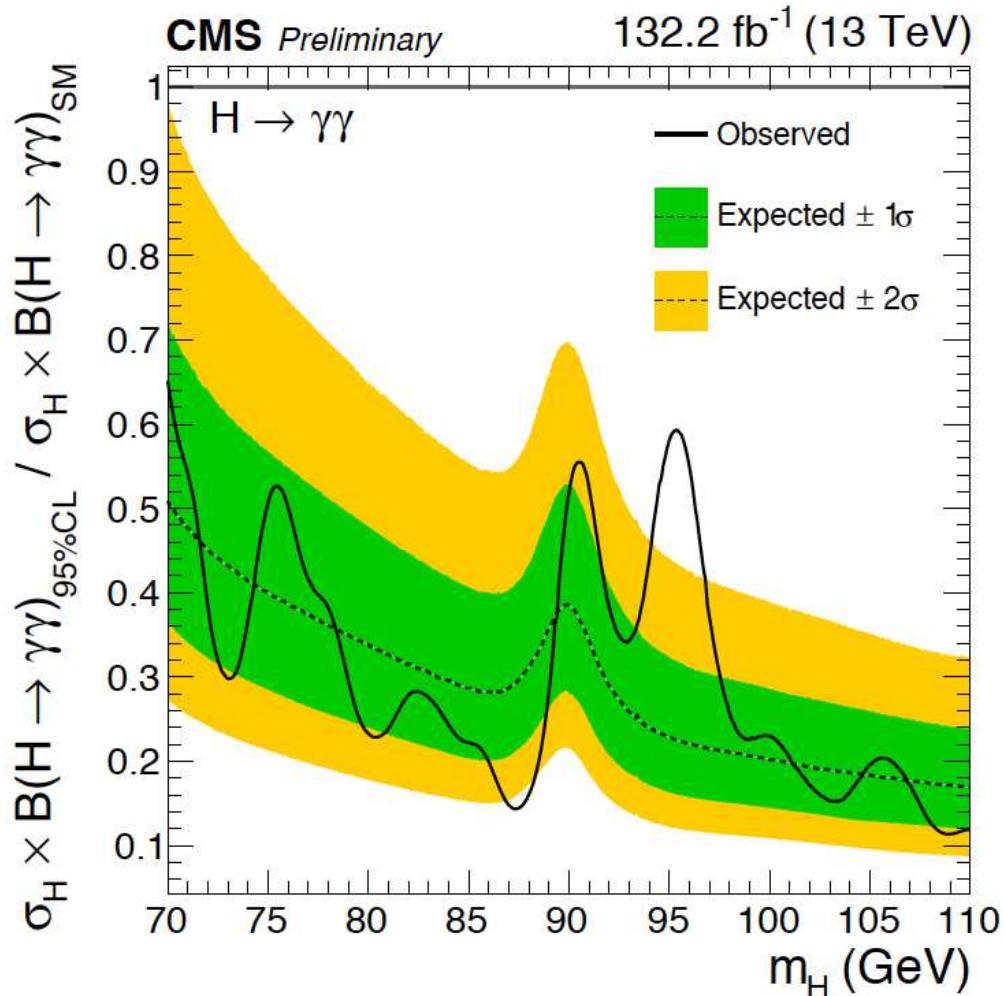
## Case study: Search for $pp \rightarrow \phi \rightarrow \gamma\gamma$ : excess at $m_\phi \sim 95$ GeV

[CMS '17, ATLAS '18, S.H., T. Stefaniak '18]

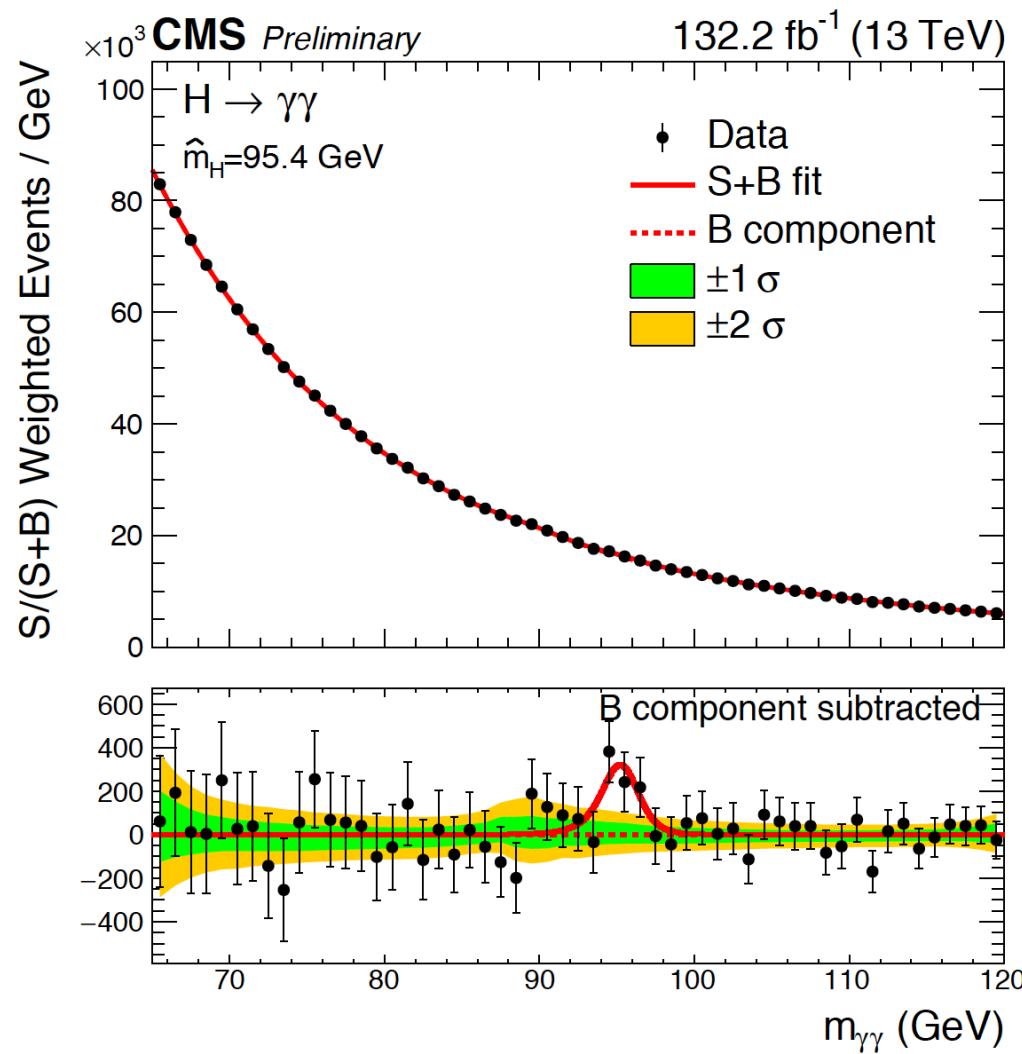
$$\mu_{\text{CMS}} = 0.6 \pm 0.2$$



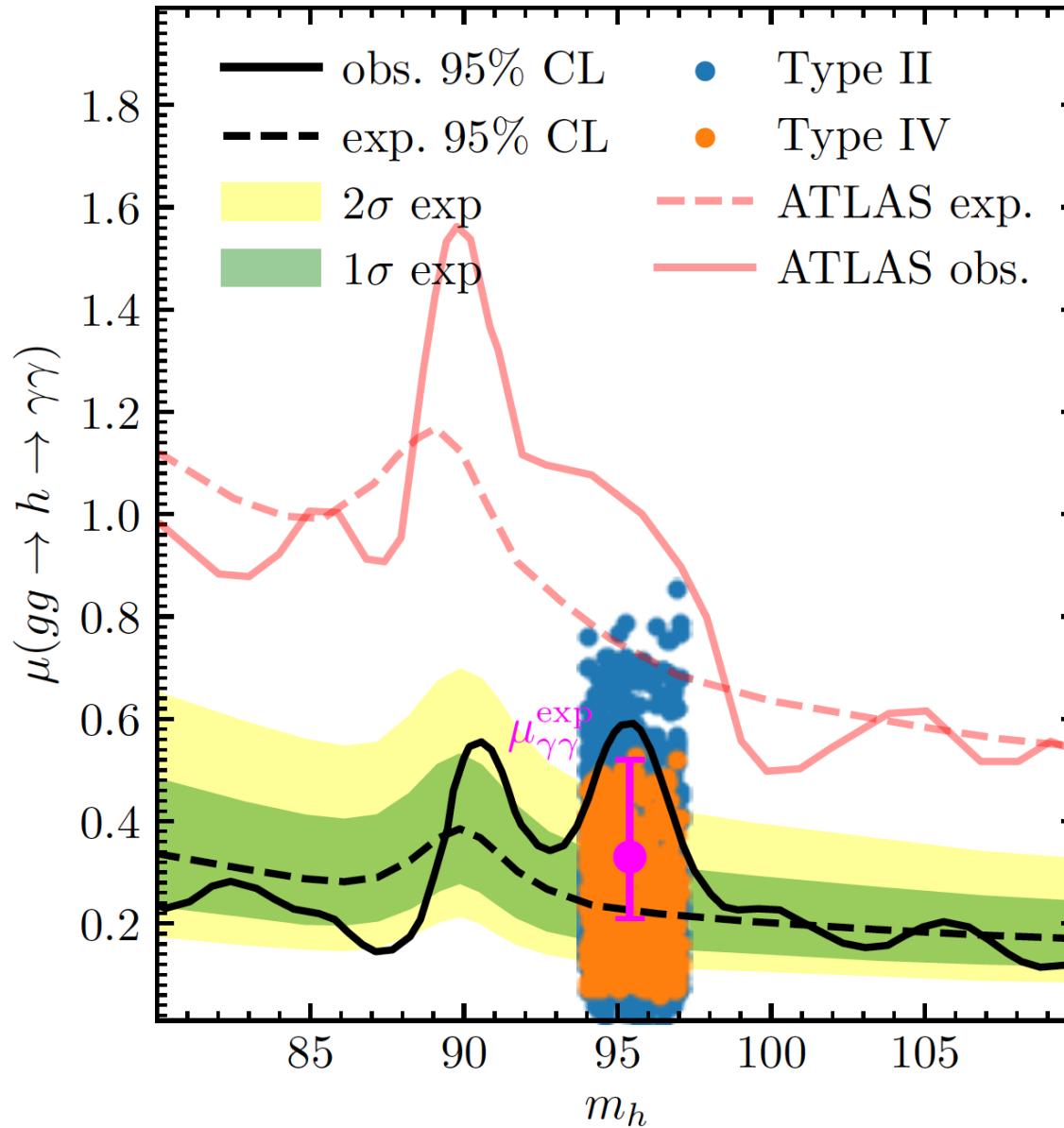
→ if there is something, it would look exactly like this!



$$\mu_{\gamma\gamma} = [\sigma(gg \rightarrow h_{95}) \times \text{BR}(h_{95} \rightarrow \gamma\gamma)]_{\text{exp/SM}} = 0.33^{+0.19}_{-0.12}$$



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⇒ ATLAS update expected for May/June '23 ...

Last week . . .



TUESDAY, MAY 23



10:42 PM

## Searches for BSM scalars - ATLAS

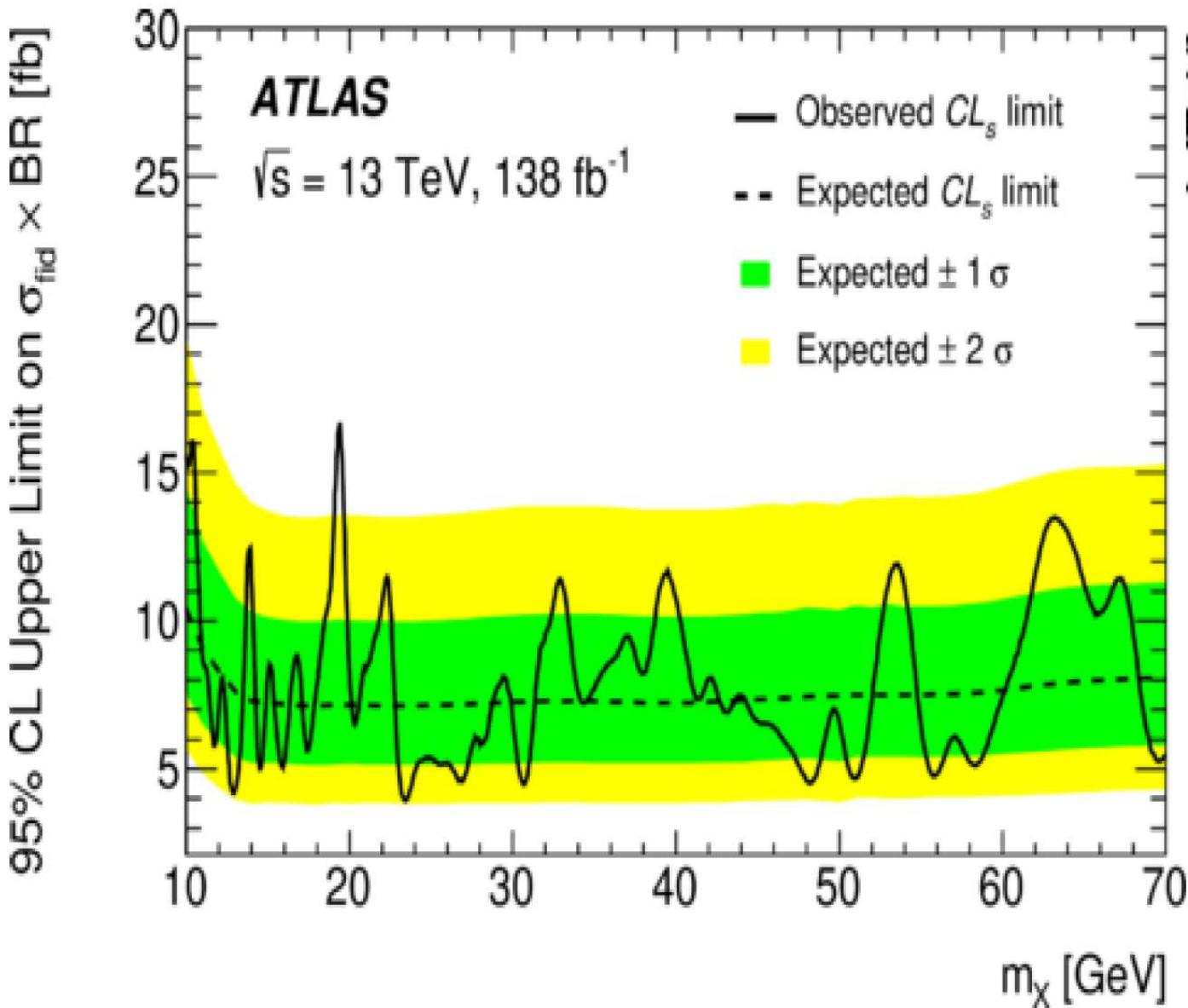
Speaker: Nicholas Kyriacou



Nick\_Kyriacou\_LHC...

## ATLAS latest low-mass $\gamma\gamma$ results:

## ATLAS latest low-mass $\gamma\gamma$ results:



→ only for  $m_{\gamma\gamma} \leq 70$  GeV    ARGH!

⇒ I need a break

## Intermezzo I: first workshop photos: LCWS 2006 Vancouver



## Intermezzo I: first workshop photos: LCWS 2006 Vancouver



## Intermezzo I: first HDays 2009



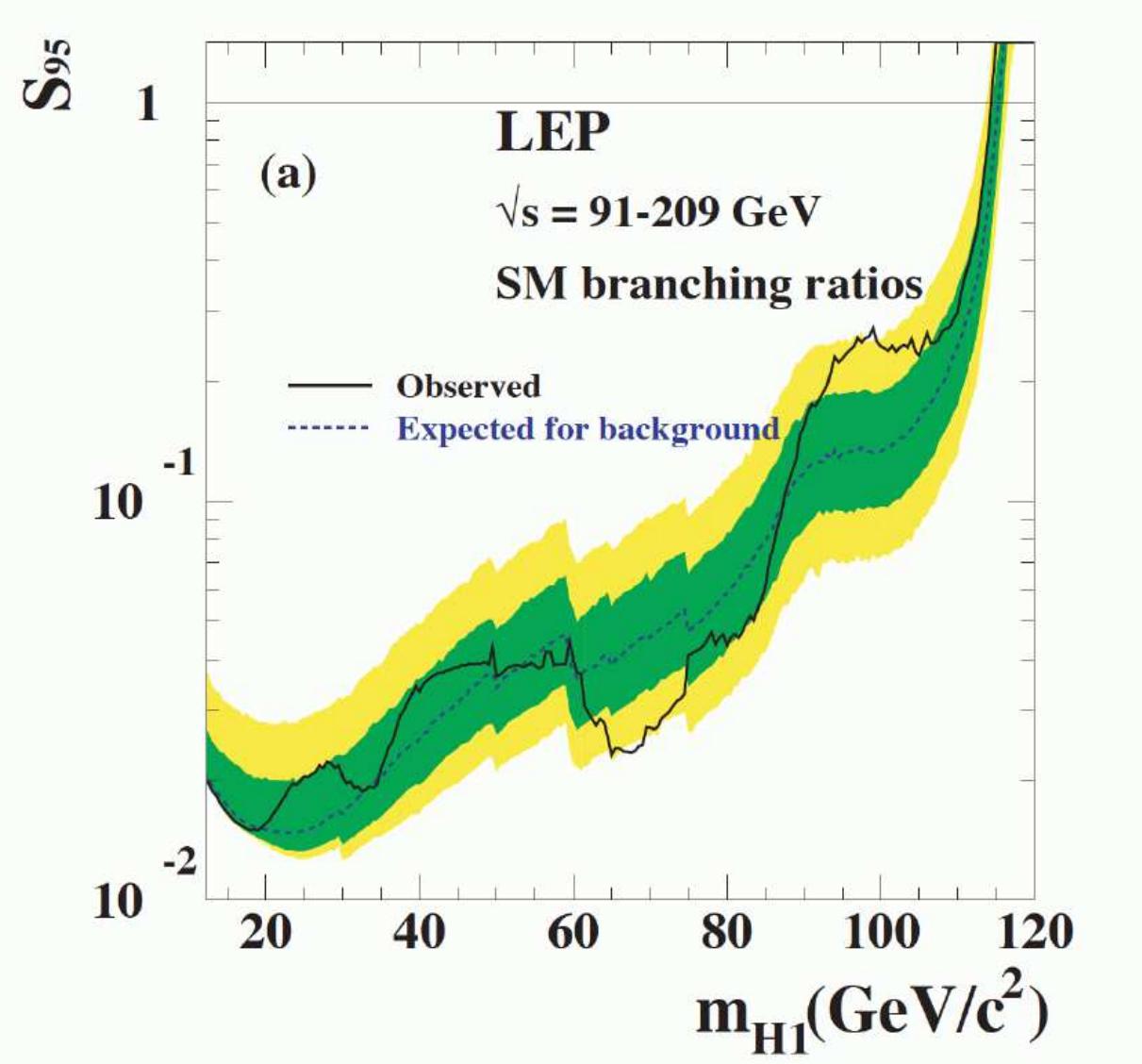
## Intermezzo I: Aspen 2013



## End of intermezzo I: SUSY 2014



## Remember the LEP excess?



$$\mu_{bb}(98 \text{ GeV}) = [\sigma(e^+e^- \rightarrow Zh) \times BR(h \rightarrow b\bar{b})]_{\text{exp/SM}} = 0.117 \pm 0.057$$

## S2HDM:

Three neutral  $\mathcal{CP}$ -even Higgses:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}, \quad R = \begin{pmatrix} c_{\alpha_1}c_{\alpha_2} & s_{\alpha_1}c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1}s_{\alpha_2}s_{\alpha_3} + s_{\alpha_1}c_{\alpha_3}) & c_{\alpha_1}c_{\alpha_3} - s_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_2}s_{\alpha_3} \\ -c_{\alpha_1}s_{\alpha_2}c_{\alpha_3} + s_{\alpha_1}s_{\alpha_3} & -(c_{\alpha_1}s_{\alpha_3} + s_{\alpha_1}s_{\alpha_2}c_{\alpha_3}) & c_{\alpha_2}c_{\alpha_3} \end{pmatrix}$$

Coupling to fermions: (same pattern as in 2HDM)

	$u$ -type ( $c_{h_i tt}$ )	$d$ -type ( $c_{h_i bb}$ )	leptons ( $c_{h_i \tau\tau}$ )
type I	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$
type II	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
type III (lepton-specific)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
type IV (flipped)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

“Physical” input parameters:

$$\alpha_{1,2,3}, \quad \tan \beta, \quad v, \quad v_S, \quad m_{h_{1,2,3}}, \quad m_A, \quad M_{H^\pm}, \quad m_\chi, \quad m_{12}^2$$

Needed to fit the two excesses:  $m_{h_1} \sim 95$  GeV,  $m_{h_2} \sim 125$  GeV

- $c_{h_1 VV}^2$  strongly reduced for  $\mu_{\text{LEP}}$
- $c_{h_1 bb}$  reduced to enhance  $\text{BR}(h_1 \rightarrow \gamma\gamma)$
- $c_{h_1 tt}$  not reduced for  $\mu_{\text{CMS}}$
- $c_{h_1 \tau\tau}$  possibly reduced to enhance  $\text{BR}(h_1 \rightarrow \gamma\gamma)$

	Decrease $c_{h_1 b\bar{b}}$	No decrease $c_{h_1 t\bar{t}}$	No enhancement $c_{h_1 \tau\bar{\tau}}$
type I	$(\frac{R_{12}}{s_\beta}) \text{:}-)$	$(\frac{R_{12}}{s_\beta}) \text{:}-()$	$(\frac{R_{12}}{s_\beta})$
type II	$(\frac{R_{11}}{c_\beta}) \text{:}-)$	$(\frac{R_{12}}{s_\beta}) \text{:}-)$	$(\frac{R_{11}}{c_\beta})$
type III	$(\frac{R_{12}}{s_\beta}) \text{:}-)$	$(\frac{R_{12}}{s_\beta}) \text{:}-()$	$(\frac{R_{11}}{c_\beta})$
type IV	$(\frac{R_{11}}{c_\beta}) \text{:}-)$	$(\frac{R_{12}}{s_\beta}) \text{:}-)$	$(\frac{R_{12}}{s_\beta})$

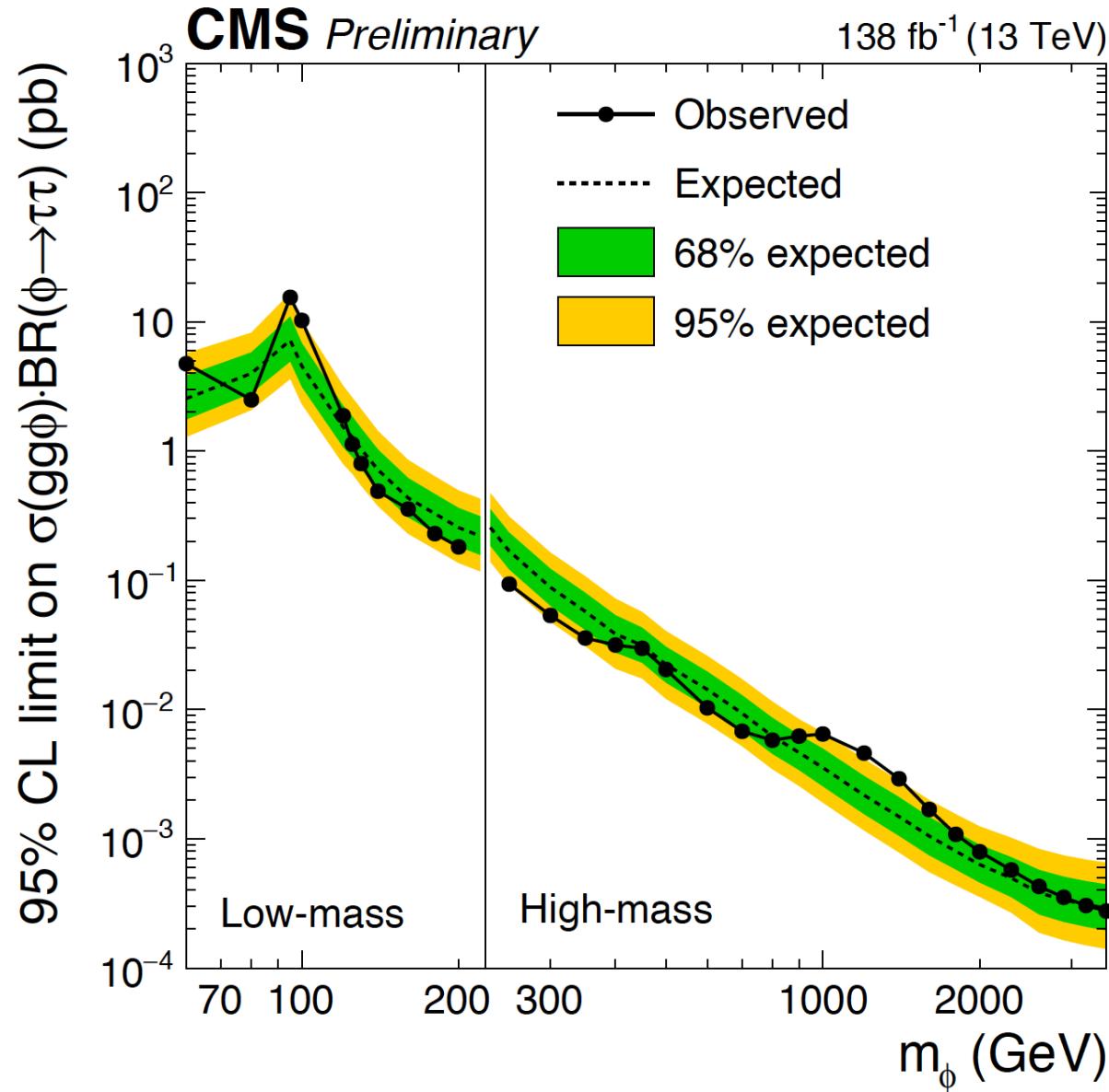
Type II and IV:  $c_{h_1 bb}$  and  $c_{h_1 tt}$  independent

Type II vs. IV:  $c_{h_1 \tau\bar{\tau}}$  can be suppressed or enhanced

⇒ only type II and IV can fit CMS and LEP excesses

## The new $\tau^+\tau^-$ excess

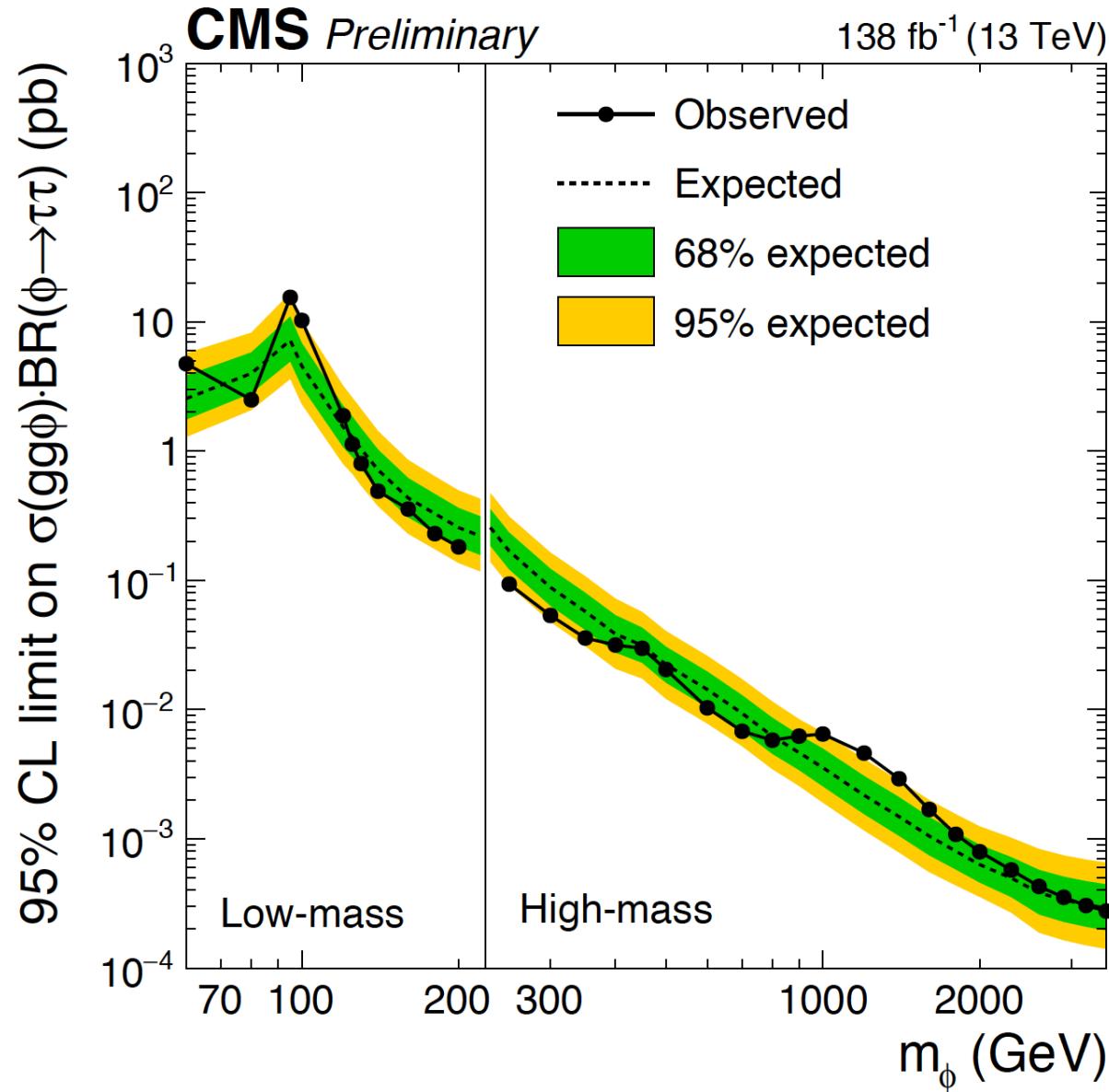
[CMS '22]



Can you spot the excess?

## The new $\tau^+\tau^-$ excess

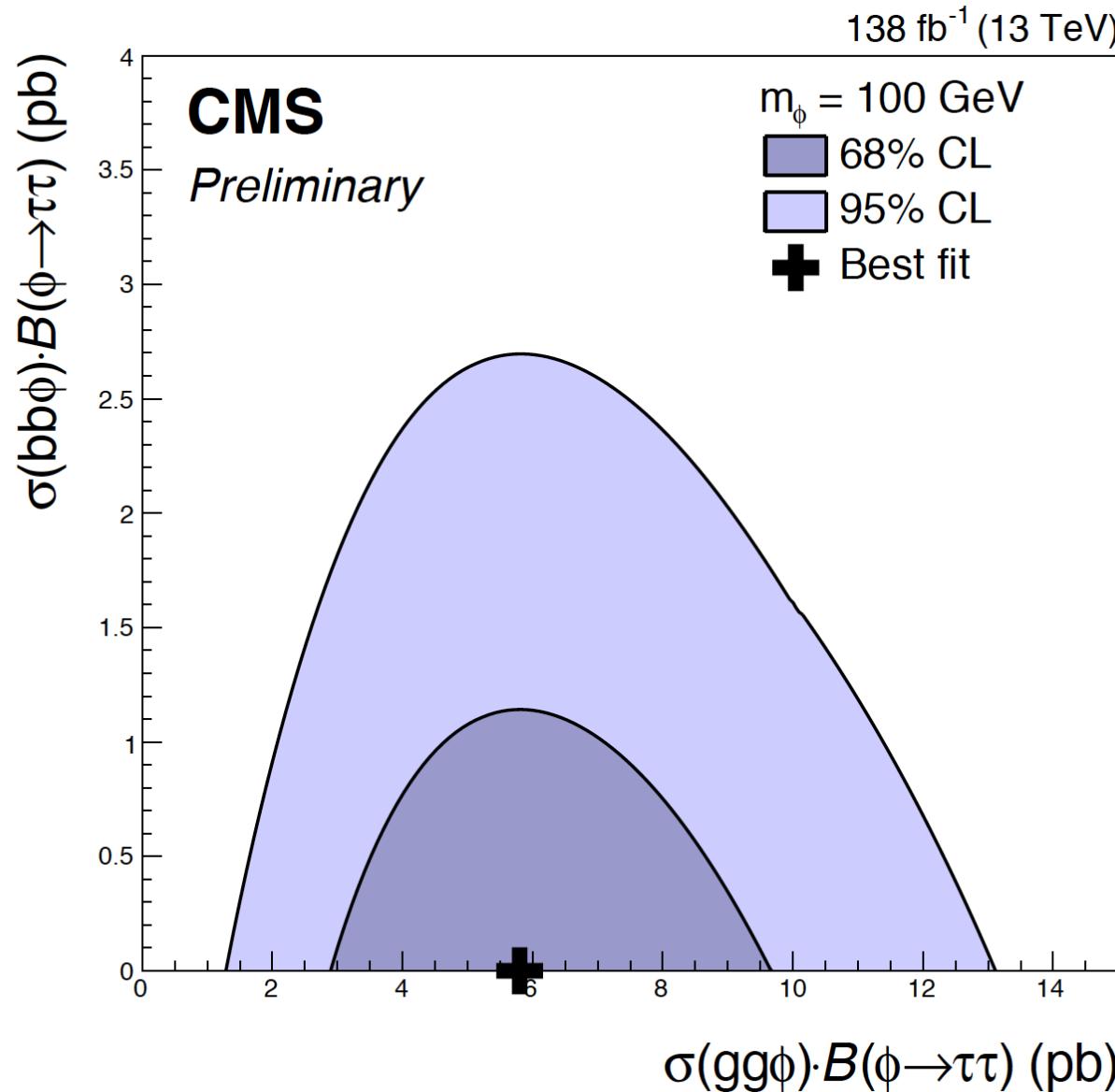
[CMS '22]



Can you spot the excess? At 95 – 100 GeV?

Better visible here, focusing on 100 GeV:

[CMS '22]



⇒ clear excess of  $\sim 3\sigma$  at  $\sim 100$  GeV

Now we have three excesses at  $\sim 95$  GeV

$$\mu_{bb}^{\text{exp}} = 0.117 \pm 0.057, \quad \mu_{\gamma\gamma}^{\text{exp}} = 0.35 \pm 0.12, \quad \mu_{\tau\tau}^{\text{exp}} = 1.2 \pm 0.5$$

corresponding to

$$\mu_{bb}^{\text{exp}} \sim 2\sigma, \quad \mu_{\gamma\gamma}^{\text{exp}} \sim 3\sigma, \quad \mu_{\tau\tau}^{\text{exp}} \sim 2.4\sigma$$

Three (effectively) independent channels

$\Rightarrow$  no LEE (as theorist I am allowed to add naively)

$$\Rightarrow \sim 4.3\sigma$$

$$\chi^2_{95} = \frac{(\mu_{bb}^{\text{theo}} - 0.117)^2}{(0.057)^2} + \frac{(\mu_{\gamma\gamma}^{\text{theo}} - 0.35)^2}{(0.12)^2} + \frac{(\mu_{\tau\tau}^{\text{theo}} - 1.2)^2}{(0.5)^2}$$

Can we fit all excesses together?

$\Rightarrow$  first another break

## Intermezzo II: before the pandemic: HH16



## Intermezzo II: before the pandemic: SUSY16



## Intermezzo II: before the pandemic: HPNP17

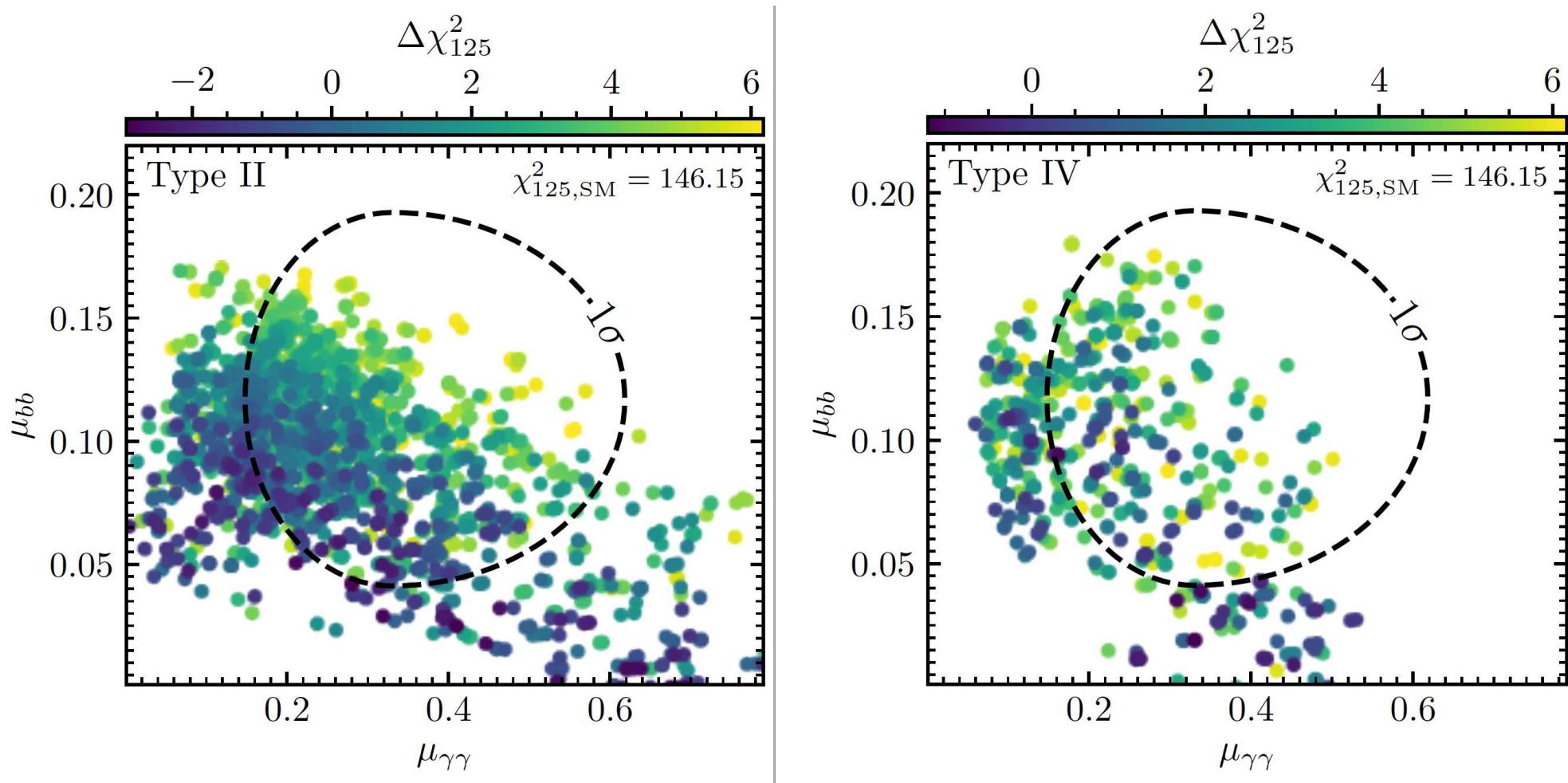


## End of intermezzo II: before the pandemic: HPNP17



## S2HDM type II vs. type IV

[T. Biekötter, S.H., G. Weiglein '23]

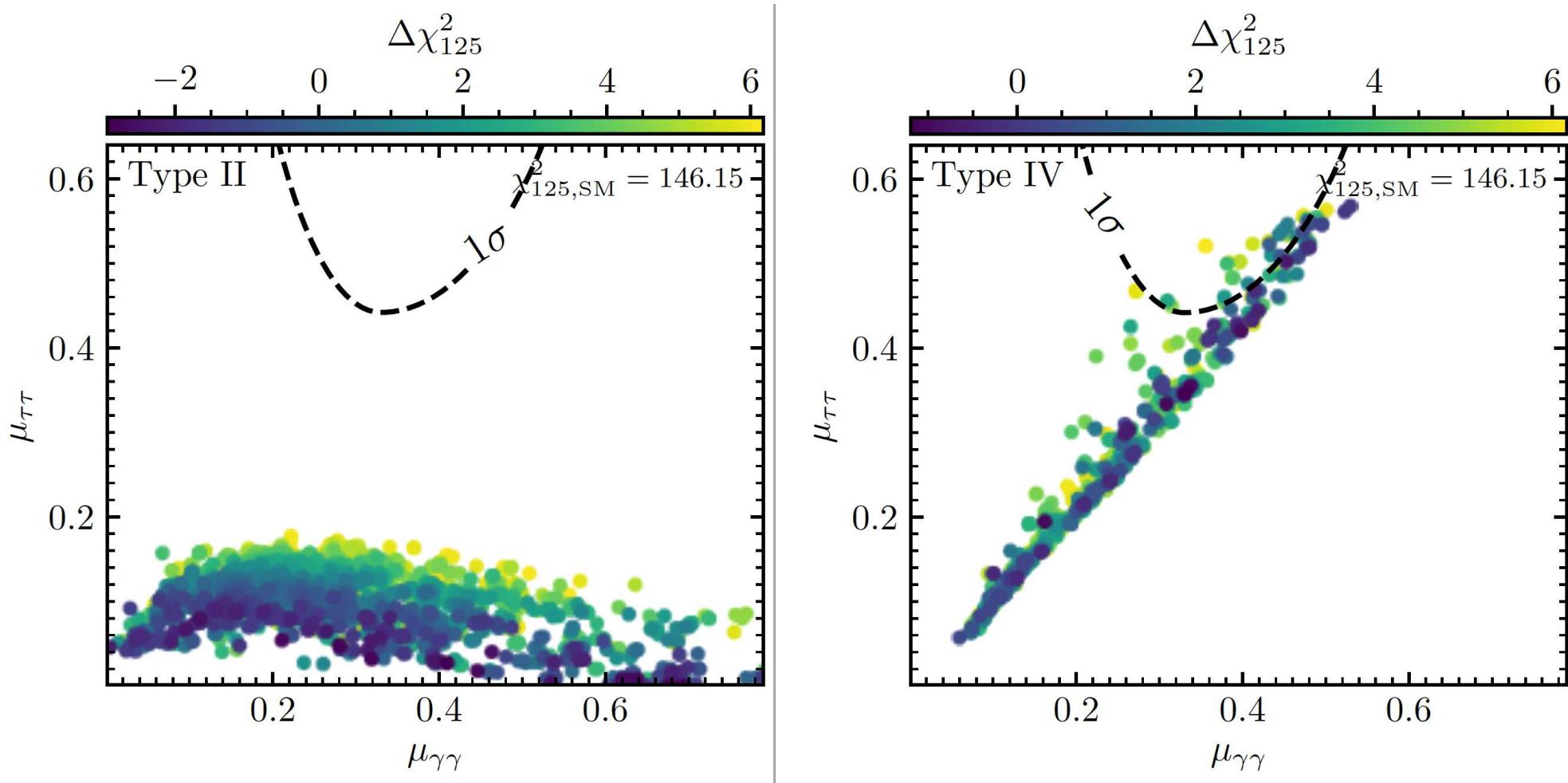


Color coding:  $\chi^2_{125}$  from [HiggsSignals](#)

⇒ both type II and IV can fit the  $\gamma\gamma$  and  $bb$  excesses

## S2HDM type II vs. type IV

[T. Biekötter, S.H., G. Weiglein '23]



Color coding:  $\chi^2_{125}$  from [HiggsSignals](#)

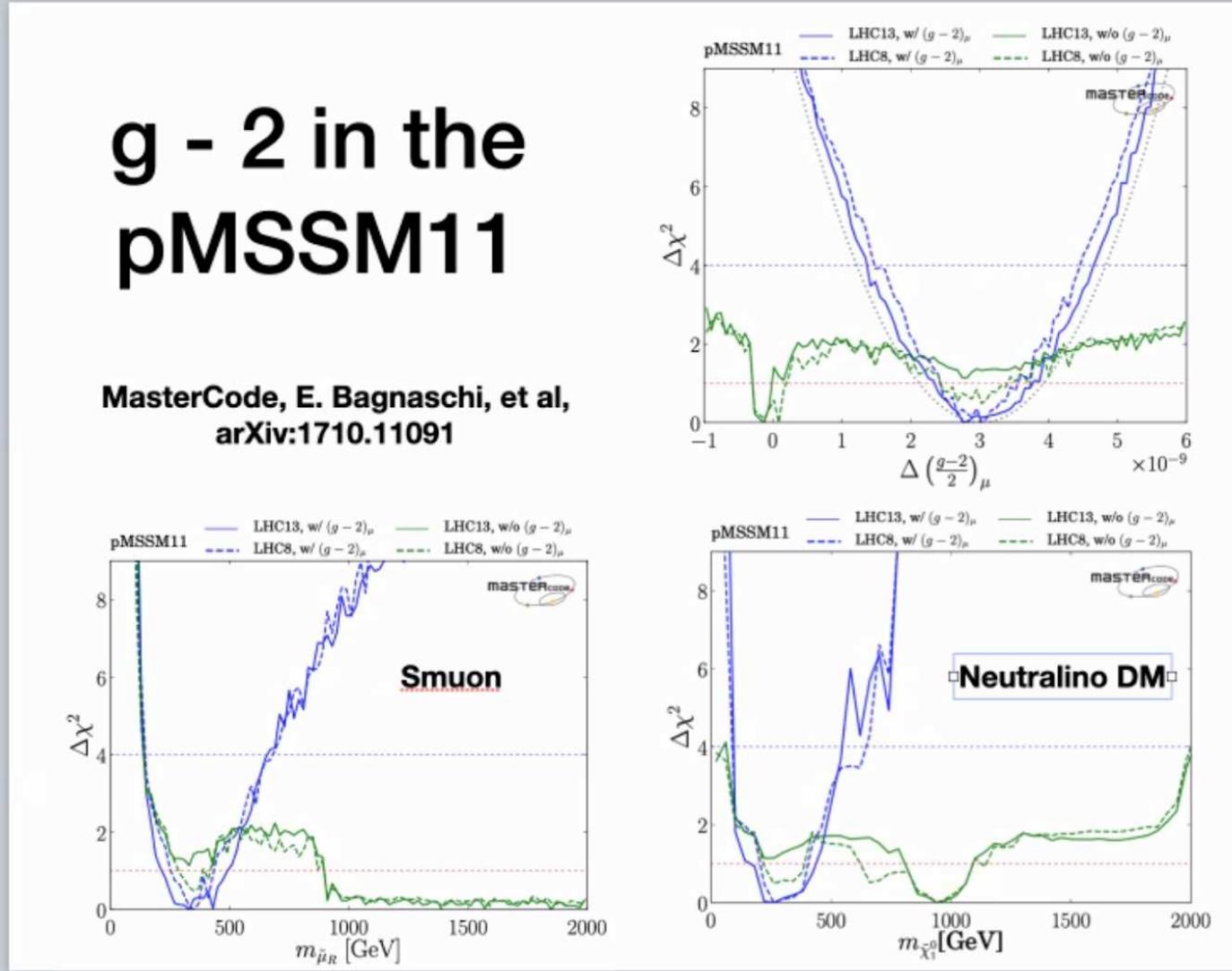
⇒ only type IV can fit marginally the  $\gamma\gamma$  and  $\tau\tau$  excesses

## SUSY realizations

What about SUSY??

⇒ first a final intermezzo

# Intermezzo III: during the pandemic: $(g - 2)_\mu$ with a beer (2021)



## Intermezzo III: after the pandemic: back to normal at HH22



## Intermezzo III: after the pandemic: back to normal at HH22



## Intermezzo III: after the pandemic: women power at HDays22



## Intermezzo III: HDays22: the Marcela-Rule



## End of intermezzo III: HDays22: the $\gamma\gamma$ bet



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  - $\mu\nu$ SSM
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**Q:** Can the models fit the excesses **despite** the additional SUSY constraints on the Higgs sector **???**

## What about the NMSSM?

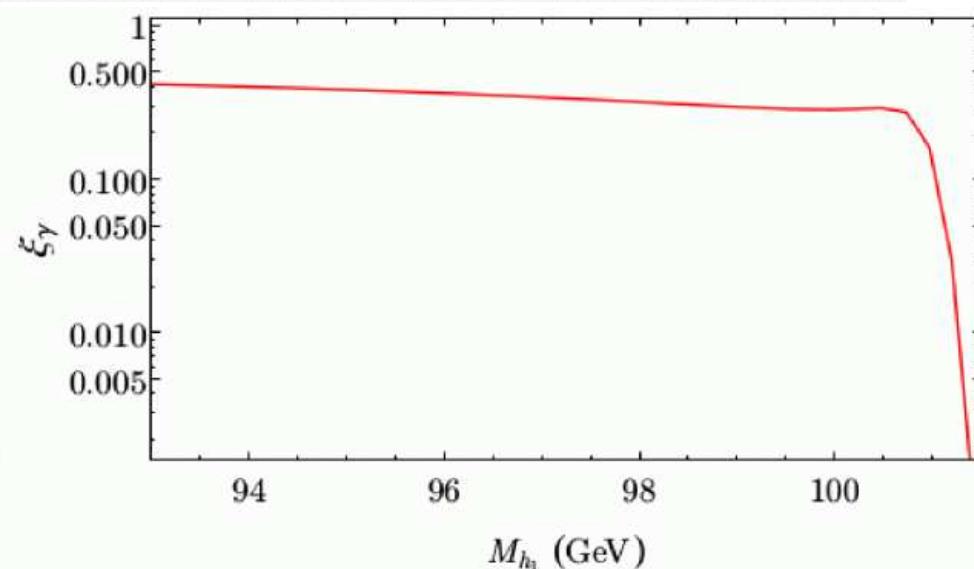
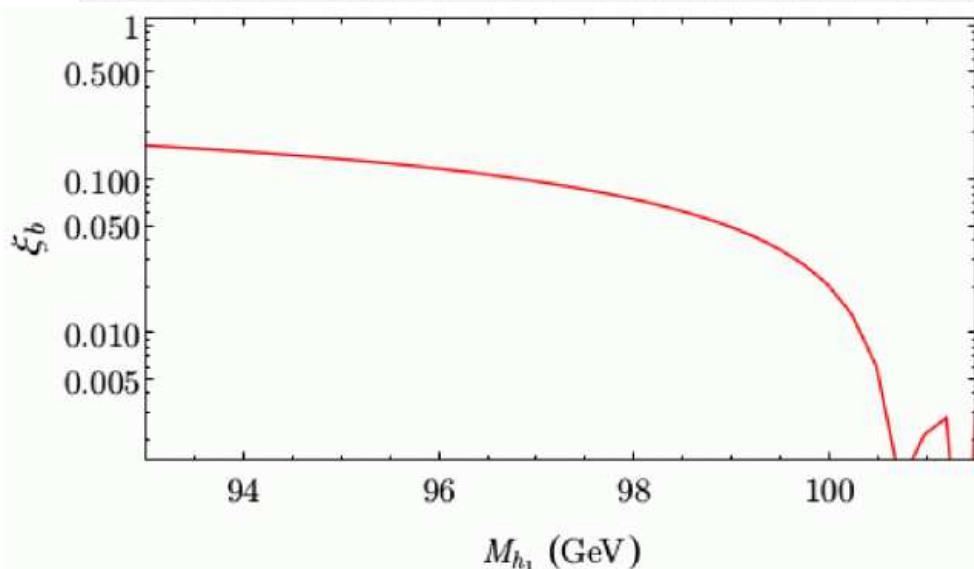
[F. Domingo, S.H., S. Passeehr, G. Weiglein '18]

Parameters:

$\lambda = 0.6$ ,  $\kappa = 0.035$ ,  $\tan \beta = 2$ ,  $\mu_{\text{eff}} = (397 + 15x) \text{ GeV}$ ,  $M_{H^\pm} = 1 \text{ TeV}$ ,  
 $A_\kappa = -325 \text{ GeV}$ ,  $M_{\text{SUSY}} = 1 \text{ TeV}$ ,  $A_t = A_b = 0$

$$\xi_b \equiv \frac{\Gamma[h_1 \rightarrow ZZ] \cdot \text{BR}[h_1 \rightarrow b\bar{b}]}{\Gamma[H_{\text{SM}}(M_{h_1}) \rightarrow ZZ] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \rightarrow b\bar{b}]} \sim \frac{\sigma[e^+e^- \rightarrow Z(h_1 \rightarrow b\bar{b})]}{\sigma[e^+e^- \rightarrow Z(H_{\text{SM}}(M_{h_1}) \rightarrow b\bar{b})]}$$

$$\xi_\gamma \equiv \frac{\Gamma[h_1 \rightarrow gg] \cdot \text{BR}[h_1 \rightarrow \gamma\gamma]}{\Gamma[H_{\text{SM}}(M_{h_1}) \rightarrow gg] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \rightarrow \gamma\gamma]} \sim \frac{\sigma[gg \rightarrow h_1 \rightarrow \gamma\gamma]}{\sigma[gg \rightarrow H_{\text{SM}}(M_{h_1}) \rightarrow \gamma\gamma]}.$$



⇒ both excesses can be fitted simultaneously well with new  $\mu_{\gamma\gamma}$ !

## What about the $\mu\nu$ SSM?

$\mu\nu$ SSM: [D. Lopez-Fogliani, C. Muñoz '06]

$\mu\nu$ SSM: NMSSM + well motivated RPV (in simple terms)  
⇒ EW scale seesaw to reproduce the neutrino data

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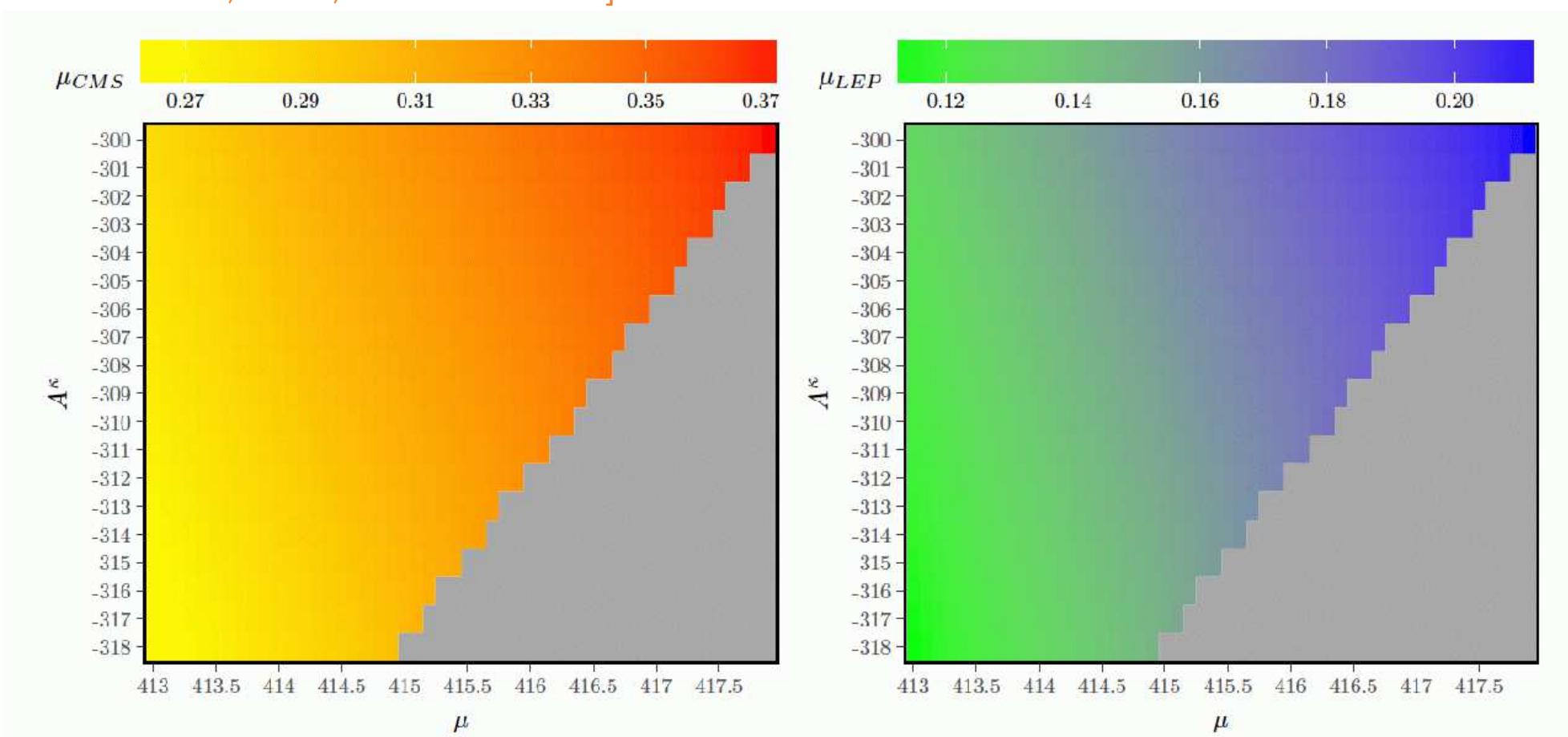
Can the  $\mu\nu$ SSM explain the two excesses?

[T. Biekötter, S.H., C. Muñoz '17]

$v_{iL}$	$Y_i^\nu$	$A_i^\nu$	$\tan \beta$	$\mu$	$\lambda$	$A^\lambda$	$\kappa$	$A^\kappa$	$M_1$
$\sqrt{2} \cdot 10^{-5}$	$10^{-7}$	-1000	2	[413; 418]	0.6	956.035	0.035	[-300; -318]	100
$M_2$	$M_3$	$m_{\tilde{Q}_{iL}}^2$	$m_{\tilde{u}_{iR}}^2$	$m_{\tilde{d}_{iR}}^2$	$A_1^u$	$A_{2,3}^{u,d}$	$(m_e^2)_{ii}$	$A_{33}^e$	$A_{11,22}^e$
200	1500	$800^2$	$800^2$	$800^2$	0	0	$800^2$	0	0

# Can the $\mu\nu$ SSM explain the two excesses?

[T. Biekötter, S.H., C. Muñoz '17]

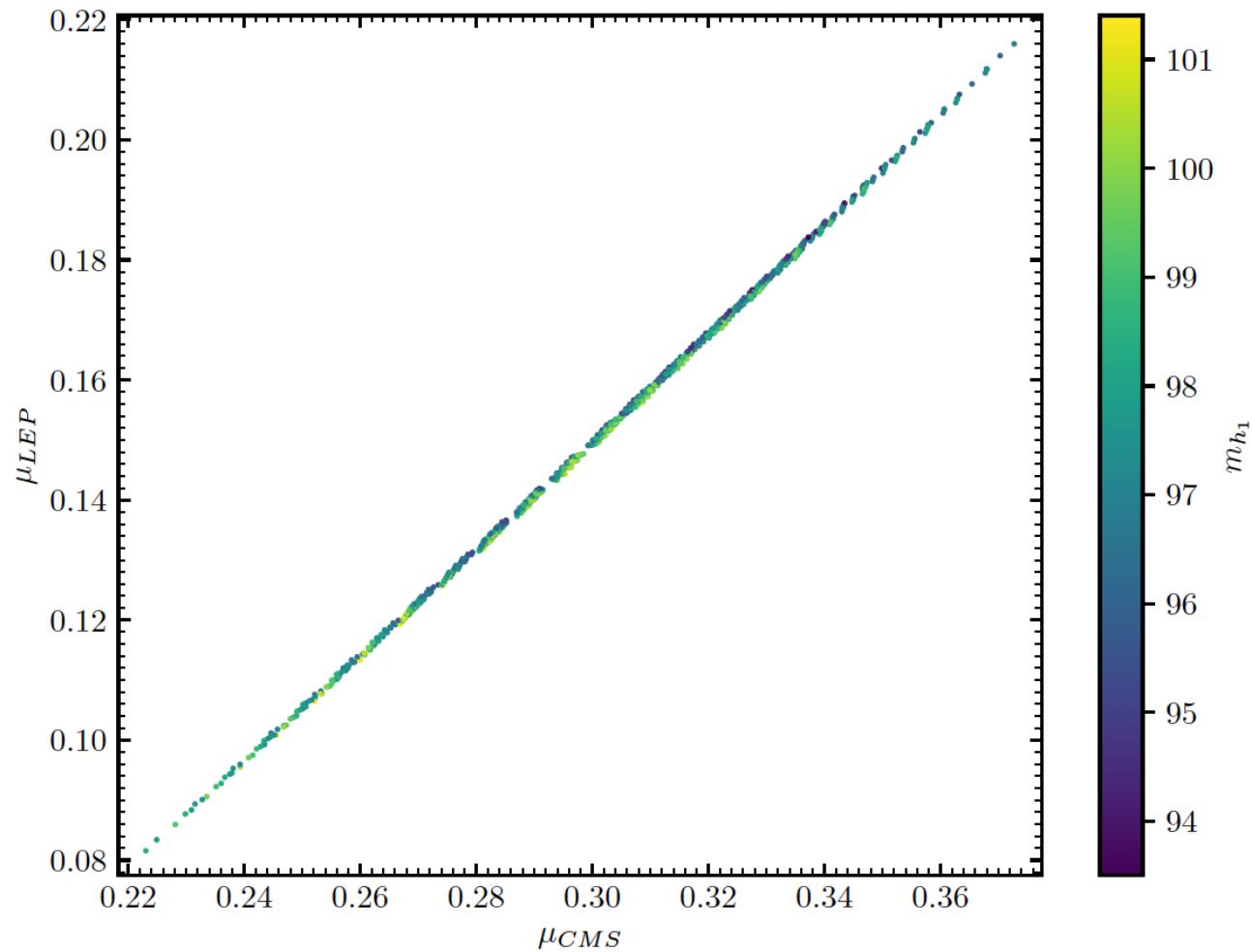


⇒ Yes! :-)

using the new  $\mu_{\gamma\gamma}$ !

# Why does SUSY prefer the new $\mu_{\gamma\gamma}$ ?

[*T. Biekötter, S.H., C. Muñoz '19*]



⇒ SUSY enforces strong correlation!

⇒ LEP excess enforces  $\mu_{\gamma\gamma} \lesssim 0.35$

And very finally: a photo from SUSY'09 . . .



. . . that introduces the second paper

Howie and Marcela as a model for the poster of the KUTS workshop series:

# Katharsis of Ultimate Theory Standards

11<sup>th</sup> meeting: 20-22 November 2019 (MPI Munich)

Precise Calculation of

(N)



Higgs Boson masses

Local organizers: T. Hahn, W. Hollik

Organized by:  
M. Carena, H. Haber  
R. Harlander, S. Heinemeyer  
W. Hollik, P. Slavich, G. Weiglein

# The final KUTS report: (with topical overlap with the first paper ;-)

## Higgs-mass predictions in the MSSM and beyond

P. Slavich<sup>a</sup> and S. Heinemeyer<sup>b,c,d</sup> (eds.),

E. Bagnaschi<sup>e</sup>, H. Bahl<sup>f</sup>, M. Goodsell<sup>a</sup>, H.E. Haber<sup>g</sup>, T. Hahn<sup>h</sup>, R. Harlander<sup>i</sup>,  
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T.N. Dao<sup>w</sup>, G. Degrassi<sup>x</sup>, F. Domingo<sup>y</sup>, P. Drechsel<sup>f†</sup>, U. Ellwanger<sup>z</sup>, M. Gabelmann<sup>m</sup>,  
R. Gröber<sup>aa</sup>, J. Klappert<sup>i</sup>, T. Kwasnitza<sup>o</sup>, D. Meuser<sup>f</sup>, L. Mihaila<sup>bb†</sup>, N. Murphy<sup>cc†</sup>,  
K. Nickel<sup>y†</sup>, W. Porod<sup>dd</sup>, E.A. Reyes Rojas<sup>ee</sup>, I. Sobolev<sup>f</sup> and F. Staub<sup>m†</sup>

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Predictions for the Higgs masses are a distinctive feature of supersymmetric extensions of the Standard Model, where they play a crucial role in constraining the parameter space. The discovery of a Higgs boson and the remarkably precise measurement of its mass at the LHC have spurred new efforts aimed at improving the accuracy of the theoretical predictions for the Higgs masses in supersymmetric models. The “*Precision SUSY Higgs Mass Calculation Initiative*” (KUTS) was launched in 2014 to provide a forum for discussions between the different groups involved in these efforts. This report aims to present a comprehensive overview of the current status of Higgs-mass calculations in supersymmetric models, to document the many advances that were achieved in recent years and were discussed during the KUTS meetings, and to outline the prospects for future improvements in these calculations.

In 2020 we got it out juuuuust in time :-)

**Happy Birthday, Marcela and Carlos!!**



**One down, four to go!**