"Tell me that you have found no sign of
New Physics again, I dare you.
I double dare you. Tell me
one more goddamn time!"

BSM Higgs Lecture

Sven Heinemeyer, IFT (CSIC, Madrid)

Daejeon, 09-10/2025

1. The SM Higgs & Motivation for BSM Higgs

2. BSM Higgs sectors: RxSM, 2HDM, N2HDM, MSSM, . . .

3. BSM Higgs sectors: collider phenomenology & more

4. Anomalies and possible explanations

BSM Higgs Lecture

Anomalies and possible explanations

Sven Heinemeyer, IFT (CSIC, Madrid)

Daejeon, 09-10/2025

1. When should one consider an anomaly?

2. Indications for flavor violating Higgs decays?

3. Indications for Higgs bosons above 125 GeV?

4. Indications for Higgs bosons below 125 GeV?!

1. When should one consider an anomaly?

How to search for BSM physics?

There are two complementary ways:

1. Direct searches

– direct production of BSM particles at (high-energy) colliders

– obvious at high $\sqrt{s}$, but also lower $\sqrt{s}$ is possible

– mostly at pp colliders

– also (future) e^+e^- colliders have a chance
(clean environment, uncolored particles)

2. Indirect searches

– high precision measurement of “SM processes” ($(g-2)_\mu$, flavor, . . .)

– search for processes forbidden/suppressed in the SM

– possible at high and low $\sqrt{s}$

– high precision required on the experimental and theoretical side

How to search for BSM physics?

There are two complementary ways:

1. Direct searches

$\Rightarrow$ excesses observed at $\sim$ 96 GeV in BSM Higgs searches

$\Rightarrow$ excesses observed at $\sim$ 152 GeV in SM Higgs measurements

– models with “only” extended Higgs sectors (N2HDM)

– SUSY models with (naturally) extended Higgs sectors (NMSSM)

– models with Higgs triplets

2. Indirect searches

$\Rightarrow$ measurement of flavor violating Higgs decays

– more complex SUSY models (NHSSM)

– . . . ??

Indications for new physics at the LHC? $\boxed{\Rightarrow \text{personal take!}}$

Q: when should we take an anomaly seriously?

Indications for new physics at the LHC?

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Q: when should we take an anomaly seriously?

C1: ATLAS and CMS should see the same
(or at least something compatible)

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(or at least something compatible)
$\Rightarrow$ 99.x% of all anomalies are killed by that

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C2: Non-weird models should be able to explain the anomaly
in non-weird parts of the parameter space

Indications for new physics at the LHC?

$\boxed{\Rightarrow \text{personal take!}}$

Q: when should we take an anomaly seriously?

C1: ATLAS and CMS should see the same
(or at least something compatible)
$\Rightarrow$ 99.x% of all anomalies are killed by that

C2: Non-weird models should be able to explain the anomaly
in non-weird parts of the parameter space

Counter examples:

– 750 GeV excess
$\Rightarrow$ no non-weird model could explain this in a non-weird part of the parameter space

– Flavor anomalies
$\Rightarrow$ no non-weird model could explain this

There are many^2 anomalies around

SUSY24 (final talk): Wagner's rule:

Quote:
"Any anomaly can be explained by RPV SUSY"

There are many^2 anomalies around

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Corollary:
"And the explanation is wrong."

There are many^2 anomalies around

SUSY24 (final talk): Wagner's rule:

Quote:
"Any anomaly can be explained by RPV SUSY"

Corollary:
"And the explanation is wrong."

Second corollary by S.H.:
The situation changes if C2 is fulfilled

Three interesting anomalies

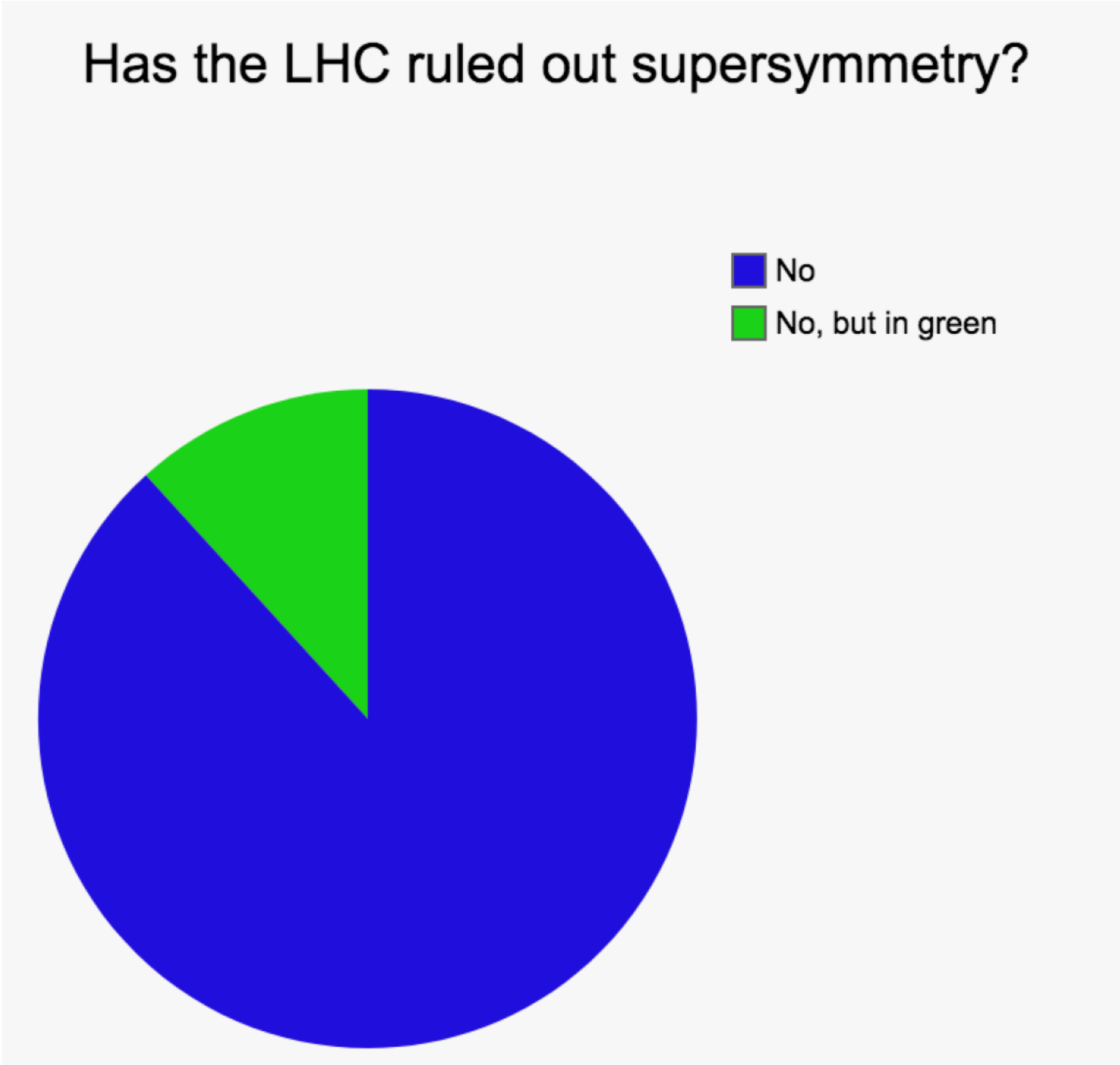
1. Lepton flavor violating Higgs decays:
   $h \to \tau\,\mu$, $h \to \tau\,e$

2. h_{125} measurements with results up to 160 GeV ("side band analysis")
   Indications for h_{152}??

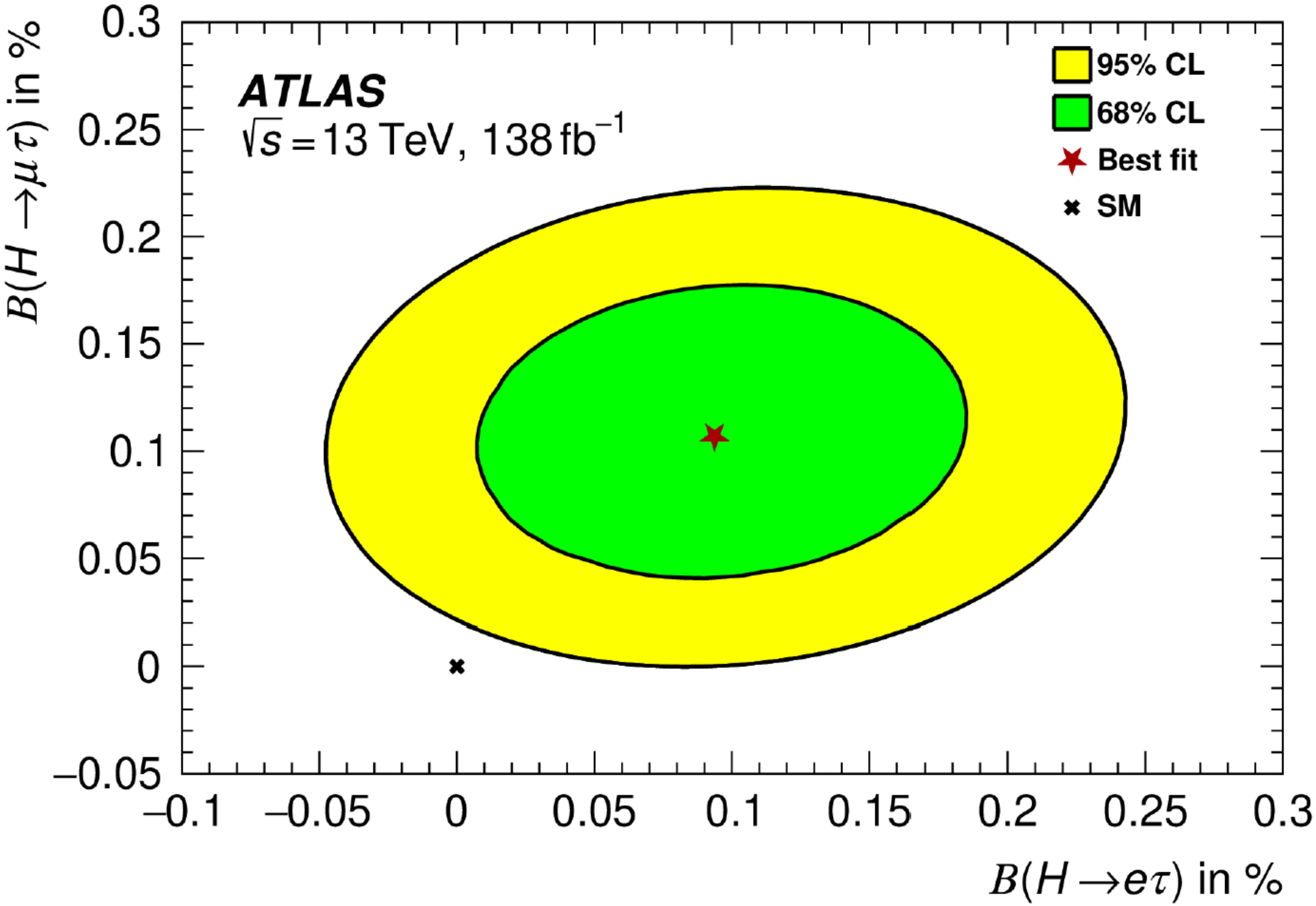
3. Low mass Higgs searches:
   $pp \to \phi \to \gamma\gamma$

$\Rightarrow$ ordered according to my personal preference (3 the most)
(on what I would bet more money (3 the most))

2. Indications for flavor violating Higgs decays?



Anomalie II: excesses $h \to \tau\,\mu$, $h \to \tau\,e$



$\Rightarrow$ non-contradicting limits from CMS

Explanation in the Non-holomorphic MSSM (NHSSM):

[*M. Rehman, S.H. '24*]

$$-\mathcal{L}^{\rm NH}_{\rm soft} \;=\; T'^{D}_{ij} h_2 \tilde{d}^*_{Ri} \tilde{q}_{Lj} + T'^{U}_{ij} h_1 \tilde{u}^*_{Ri} \tilde{q}_{Lj} + T'^{E}_{ij} h_2 \tilde{e}^*_{Ri} \tilde{l}_{Lj} + \mu' \tilde{h}_1 \tilde{h}_2 .$$

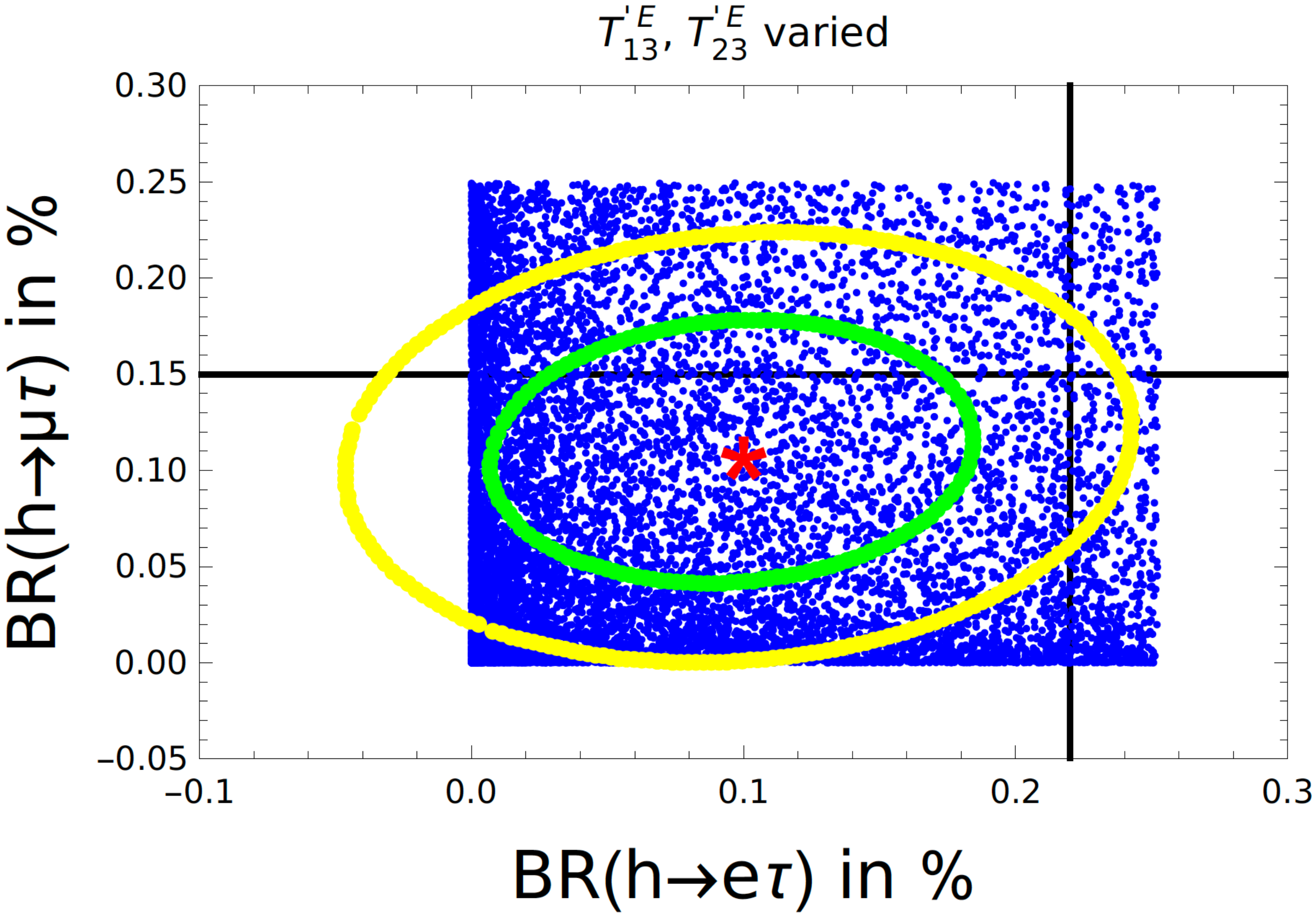
Other important limits:

Process	Limit	Process	Limit
$\mathrm{BR}(\mu \to e\gamma)$	4.2×10^{-13}	$\mathrm{BR}(\mu \to 3e)$	1.0×10^{-12}
$\mathrm{CR}(\mu - e, \mathrm{Au})$	7.0×10^{-13}	$\mathrm{CR}(\mu - e, \mathrm{Ti})$	4.3×10^{-13}
$\mathrm{BR}(\tau \to e\gamma)$	3.3×10^{-8}	$\mathrm{BR}(\tau \to 3e)$	2.7×10^{-8}
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8}	$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8}
$\mathrm{BR}(h \to e\mu)$	6.1×10^{-5}	$\mathrm{BR}(h \to e\tau)$	2.2×10^{-3}
$\mathrm{BR}(h \to \mu\tau)$	1.5×10^{-3}		

Explanation in the Non-holomorphic MSSM (NHSSM):

[*M. Rehman, S.H. '24*]

⇒ variation of two NH terms:



⇒ perfect description, in agreement with all other limits

One word of caution:

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I cheated a bit

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I cheated a bit - as many BSM physicists do . . .

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The difference: I tell you :-)

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$\Rightarrow$ NH terms that have to be introduced and varied

$$-\mathcal{L}_{\rm soft}^{\rm NH} \;=\; T_{ij}^{\prime D} h_2 \tilde{d}_{Ri}^{*} \tilde{q}_{Lj} + T_{ij}^{\prime U} h_1 \tilde{u}_{Ri}^{*} \tilde{q}_{Lj} + T_{ij}^{\prime E} h_2 \tilde{e}_{Ri}^{*} \tilde{l}_{Lj} + \mu' \tilde{h}_1 \tilde{h}_2 .$$

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$\Rightarrow$ but there are many^2 more, all kept at zero!

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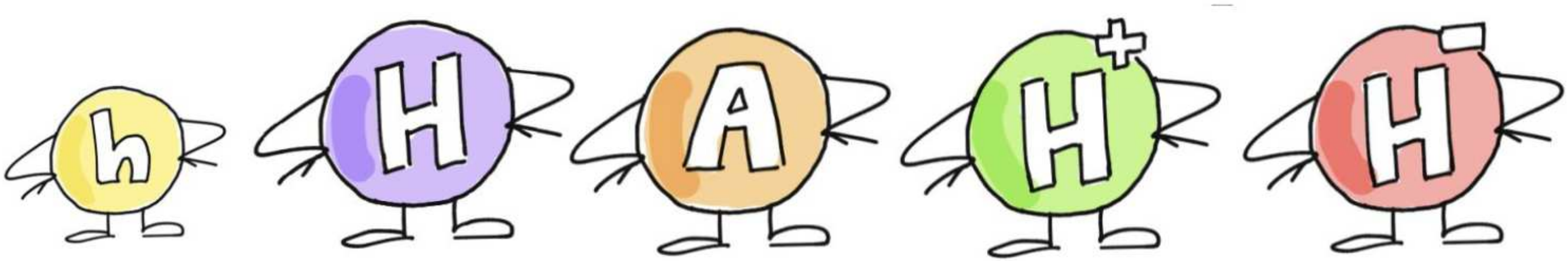
$\Rightarrow$ but there are many^2 more, all kept at zero!

$\Rightarrow$ if they had the same size, many limits would be violated

$\Rightarrow$ and I do not know a symmetry that gives me only the desired terms . . .

3. Indications for Higgs bosons above 125 GeV?



[K. Radchenko]

Indications for heavy BSM Higgs bosons?

$\Rightarrow$ there aren MANY search channels

– $pp \to X$ (traditional method)
– $pp \to Y \to h_{125}X$
– $pp \to h_{125} + X$ sideband analysis
– ...

$\Rightarrow$ there are (correspondingly?!) many anomalies

Indications for heavy BSM Higgs bosons?

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- ...

⇒ there are (correspondingly?!) many anomalies

Focus on one anomaly/indication:

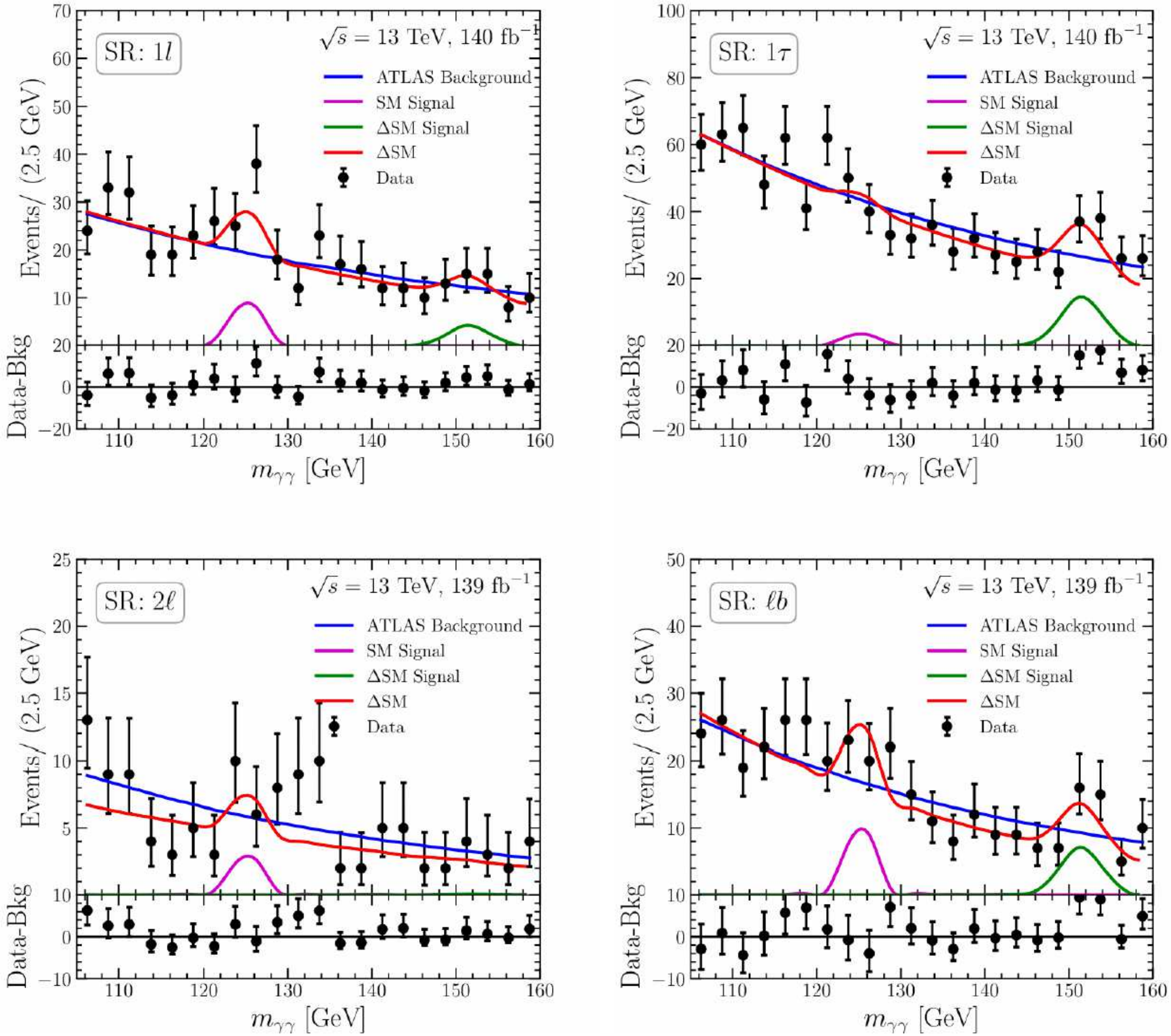
$pp \to h_{125} + X$ sideband analysis

[A. Crivellin, B. Mellado et al. '24, '25]

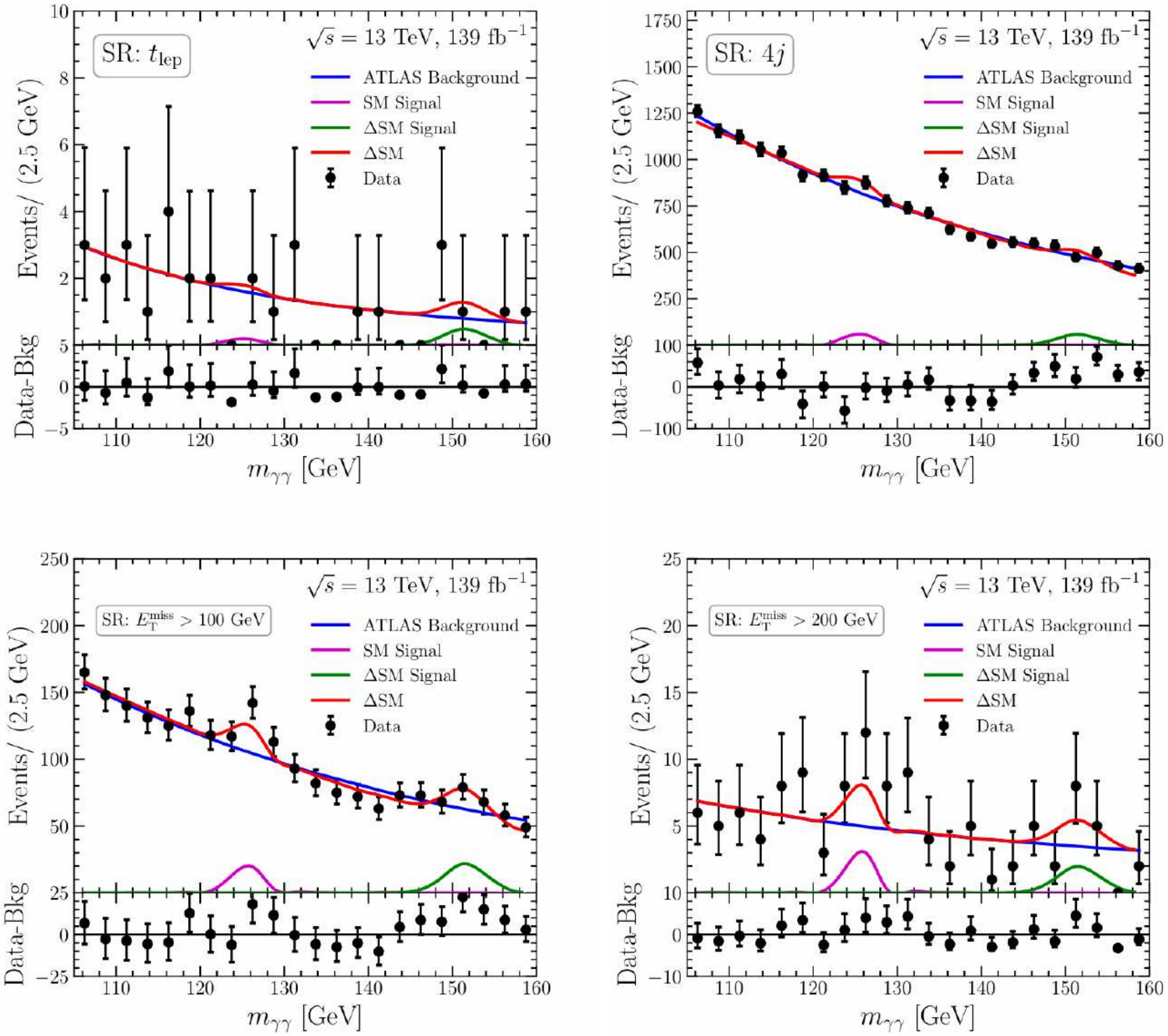
⇒ $\sim 4 - 5\,\sigma$ claimed

⇒ "true experimental" analysis still missing

$pp \to h_{125} + X$ sideband analysis (4 SRs I) [*ATLAS '24*]

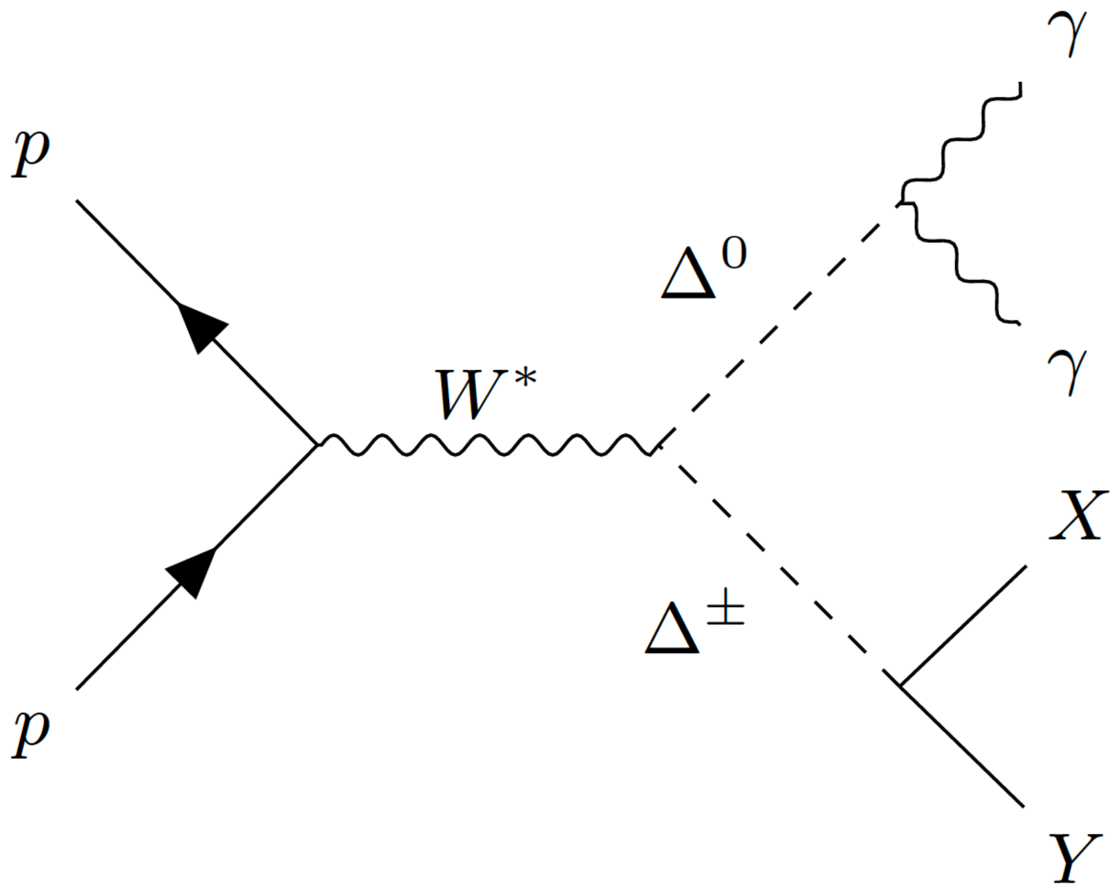


$pp \to h_{125} + X$ sideband analysis (4 SRs II) [ATLAS '24]



“Suggested” BSM contribution:

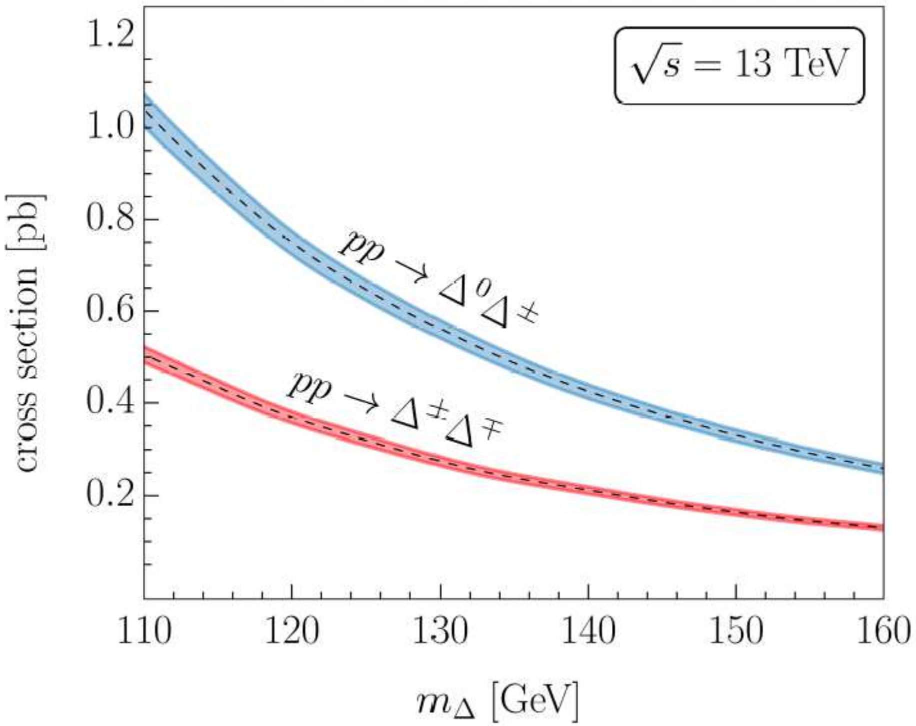
[*A. Crivellin, B. Mellado et al. ’24, ’25*]

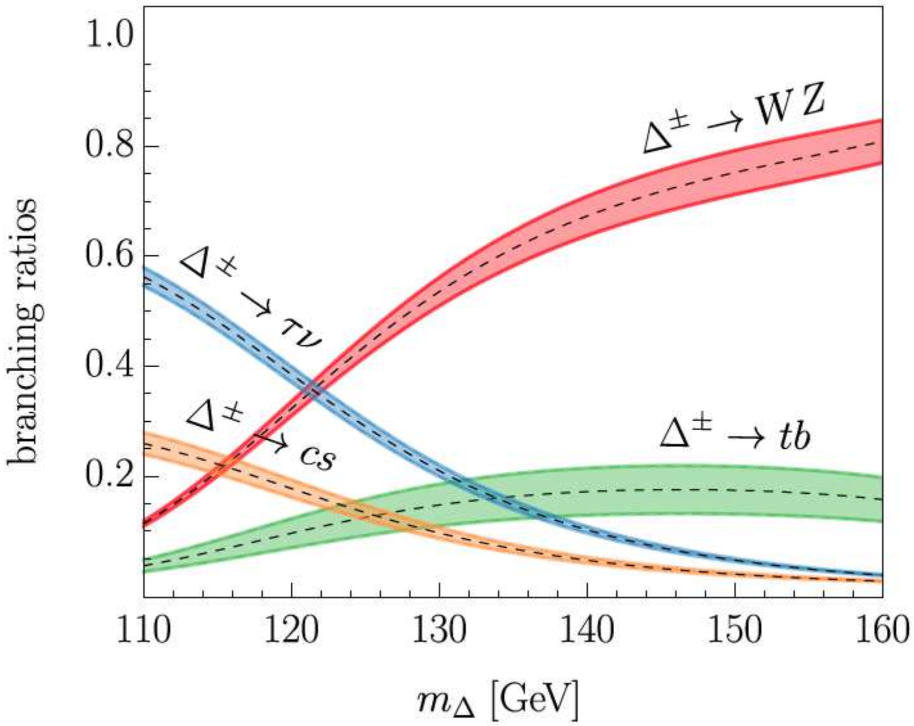


$m_{\Delta^0} \approx 152$ GeV, Δ^0 from a $Y = 0$ triplet

$m_{\Delta^\pm} \approx 152$ GeV also from the $Y = 0$ triplet

"Model prediction" for production and decay: [A. Crivellin, B. Mellado et al. '24, '25]





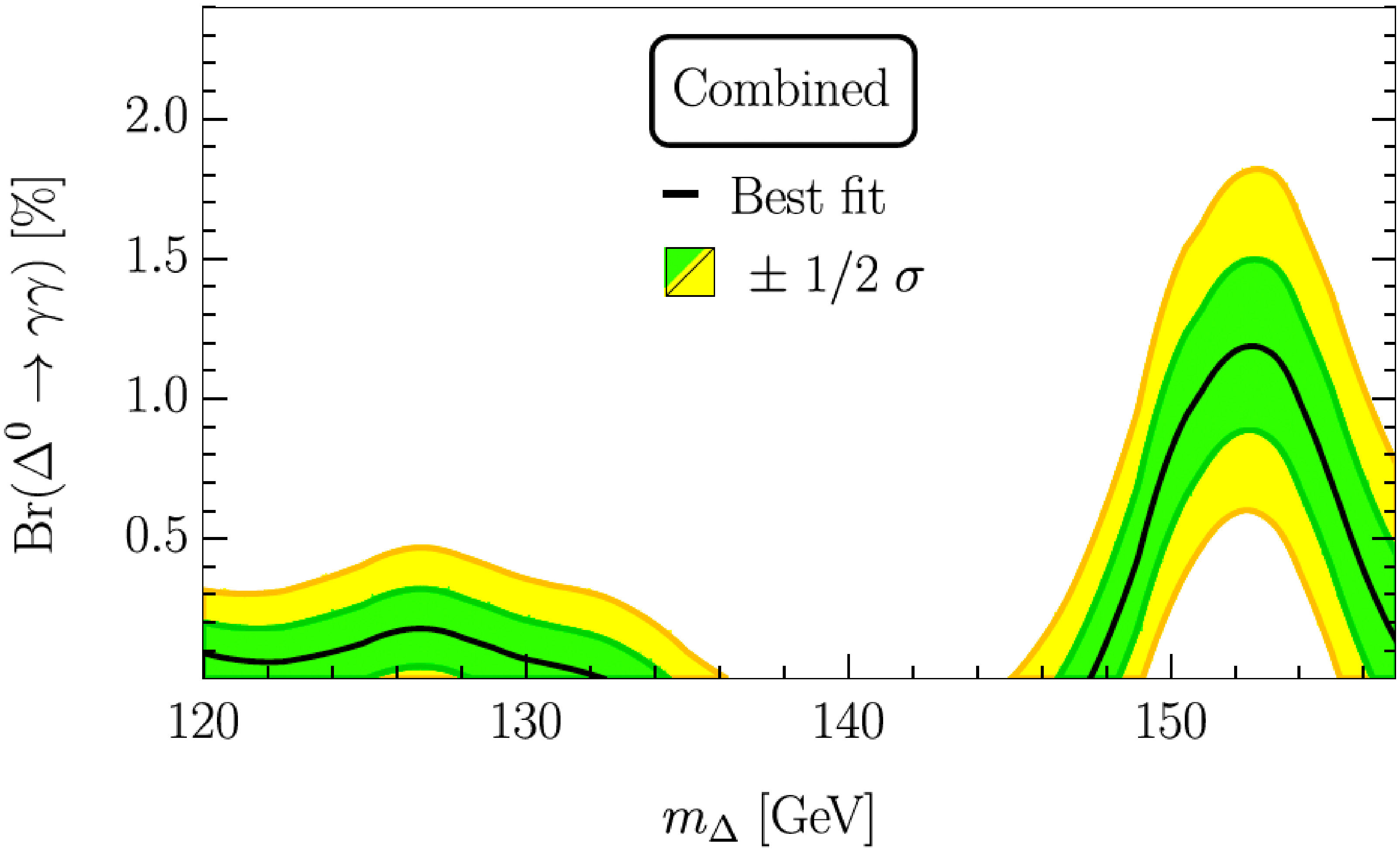
$\Rightarrow$ combined analysis of various SRs

$\Rightarrow$ significance for $\Delta^0 \to \gamma\gamma$

$\Rightarrow$ preferred values for BR($\Delta^0 \to \gamma\gamma$)

Final result for BR($\Delta^0 \to \gamma\gamma$):

[A. Crivellin, B. Mellado et al. '24, '25]



$\Rightarrow$ evidence for $\Delta^0_{152} \to \gamma\gamma$ with more than $4\,\sigma$

$\Rightarrow$ UV-complete model realization?

$\Rightarrow$ "true experimental" analysis still missing

4. Indications for Higgs bosons below 125 GeV?!

LHC Seminar

Measurement of Higgs boson production and search for new resonances in final states with photons and Z bosons

by Chiara Arcangeletti (INFN e Laboratori Nazionali di Frascati (IT))

Tuesday 6 Jun 2023, 11:00 → 12:00 Europe/Zurich

500/1-001 - Main Auditorium (CERN)

Full Run 2 ATLAS result for low-mass Higgs search in $pp \to \phi \to \gamma\gamma$

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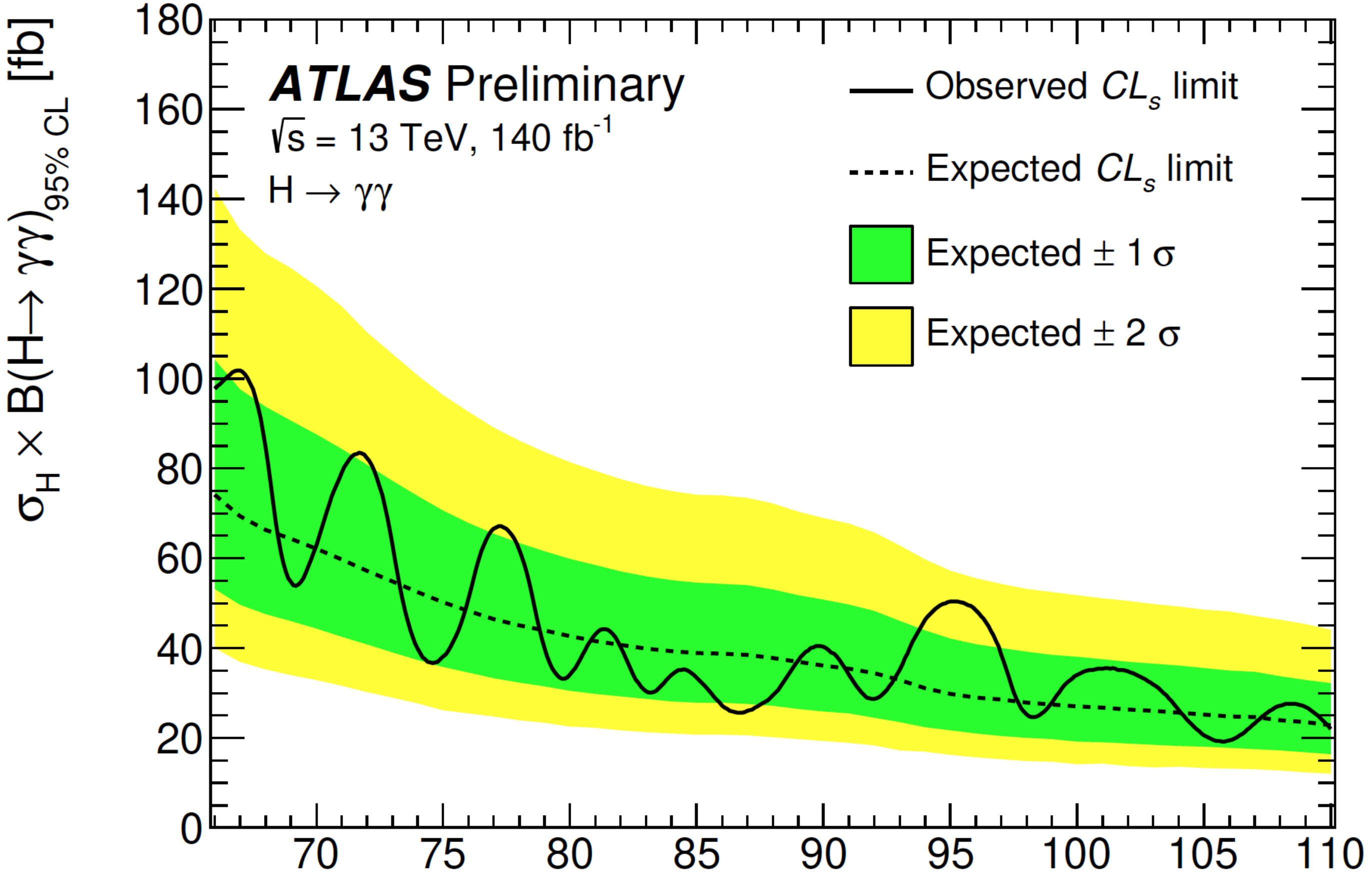
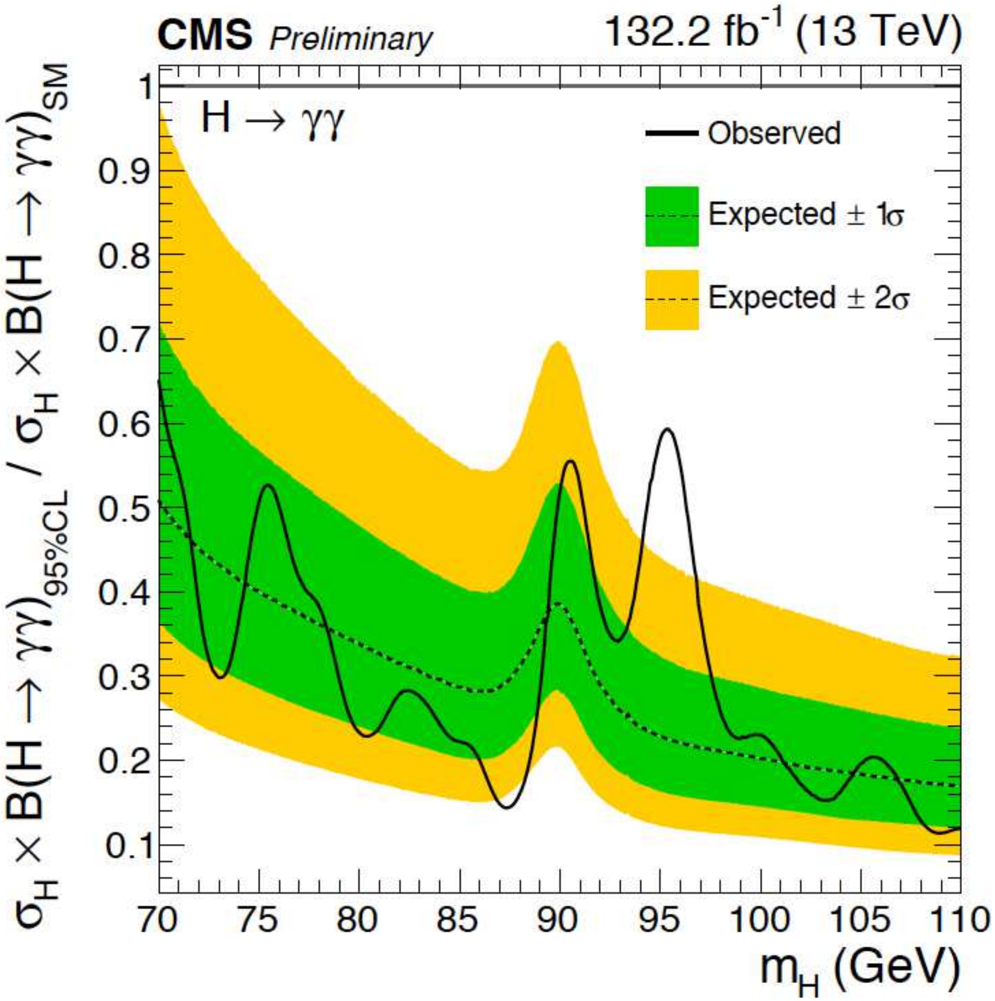
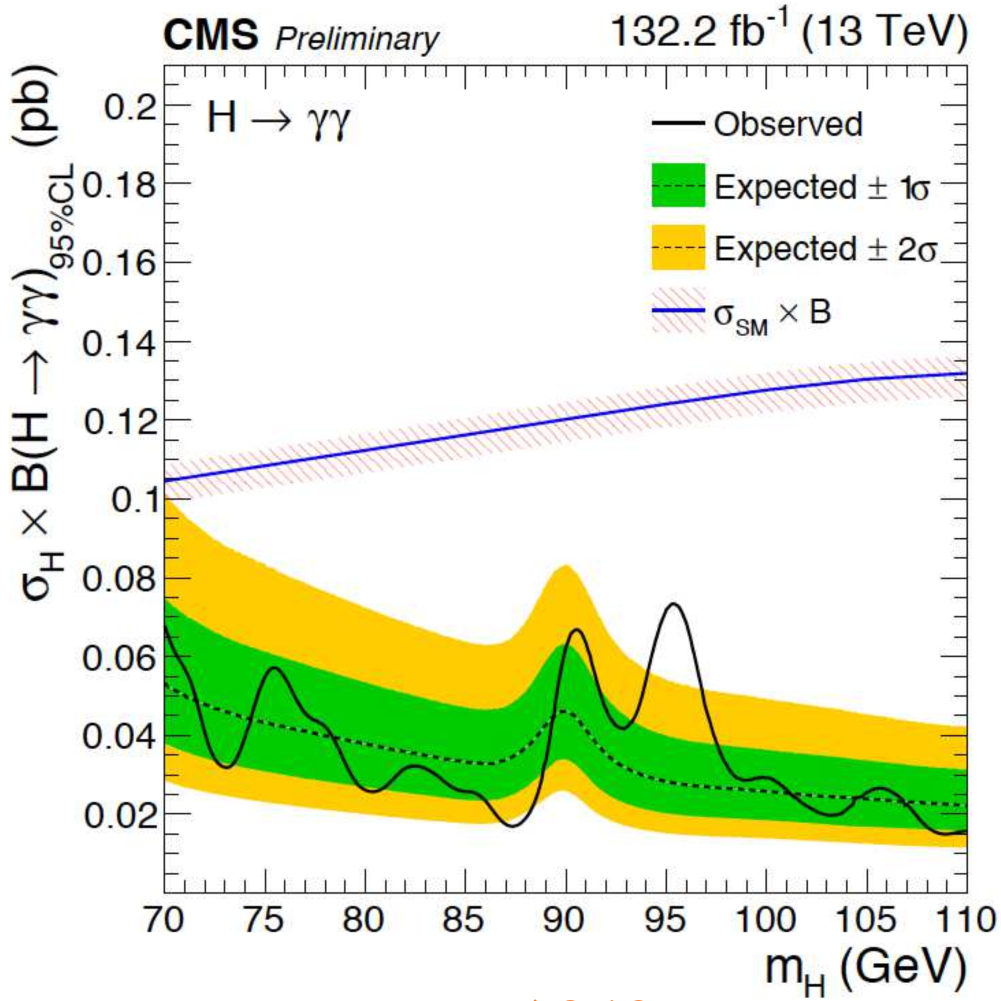


$\Rightarrow$ higest "excess" at 95.4 GeV

Full Run 2 results from CMS: excess at 95.4 GeV [CMS '23]



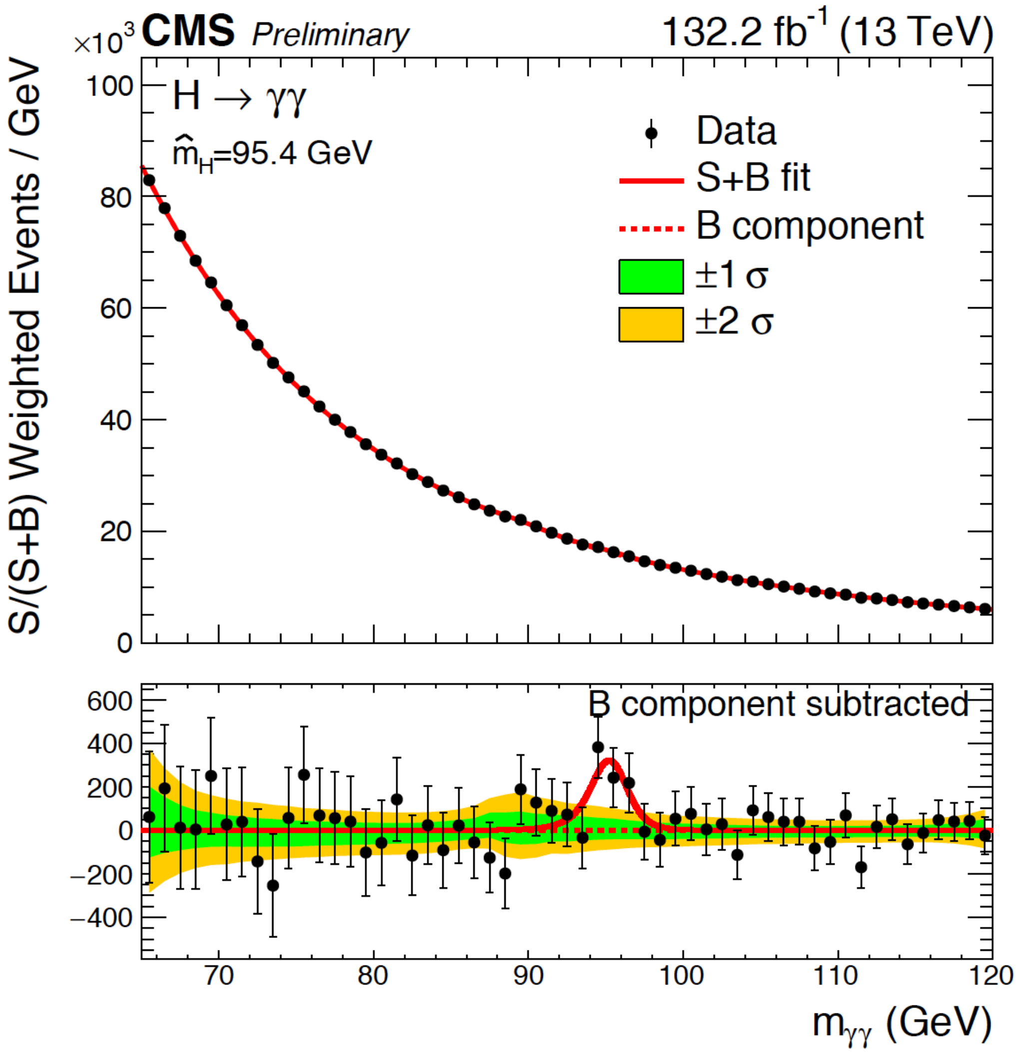


$$\mu_{\gamma\gamma}^{\text{CMS}} = [\sigma(gg \to h_{95}) \times \text{BR}(h_{95} \to \gamma\gamma)]_{\text{exp/SM}} = 0.33^{+0.19}_{-0.12}\ (2.9\,\sigma)$$

$$\mu_{\gamma\gamma}^{\text{ATLAS}} = 0.18 \pm 0.10\ (1.7\,\sigma)$$

Full Run 2 results from CMS:

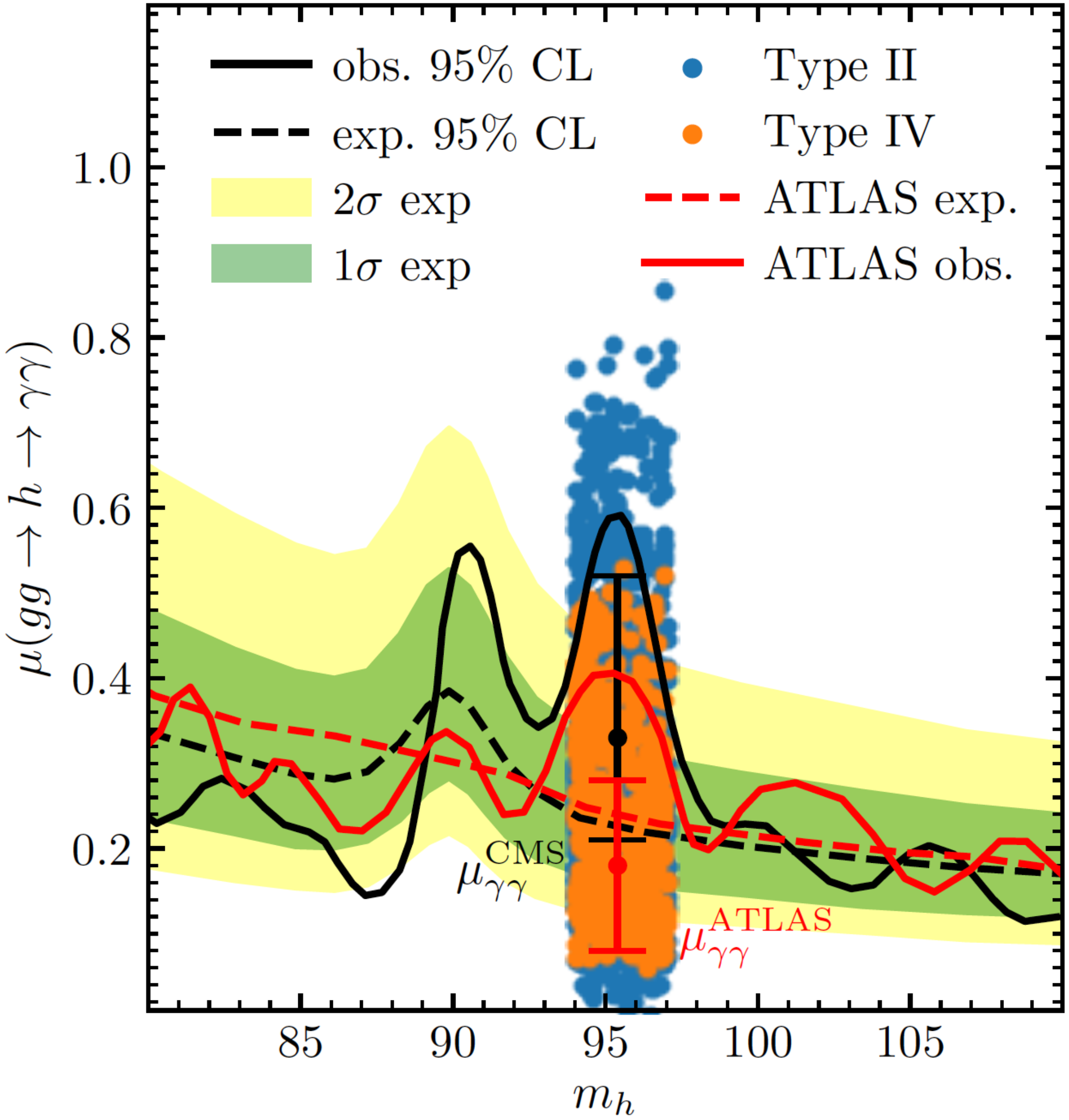
[CMS '23]



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

New CMS/ATLAS comparison:

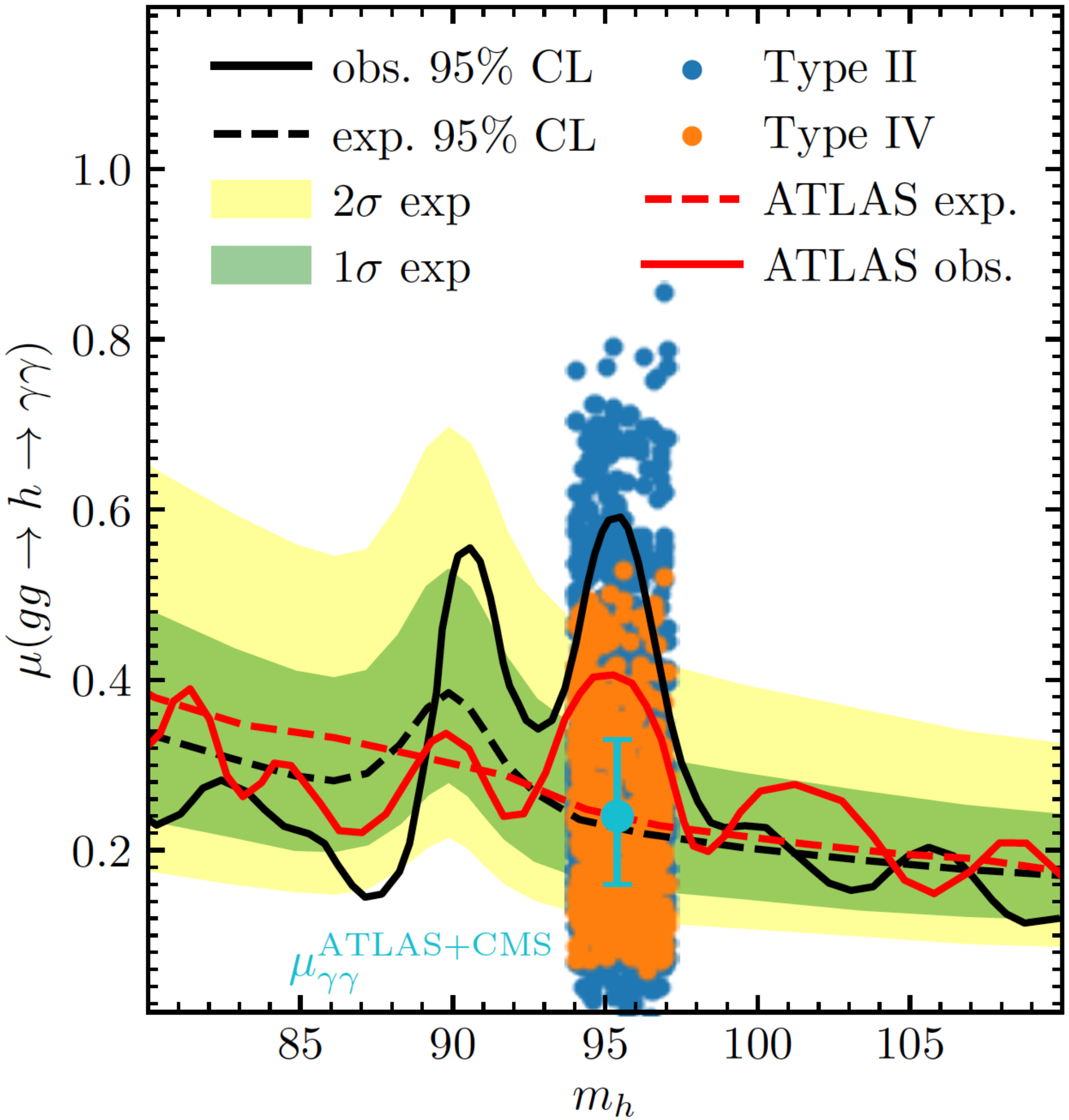
[*T. Biekötter, S.H., G. Weiglein '23*]



$\Rightarrow$ agreement between ATLAS and CMS!

New CMS/ATLAS comparison:

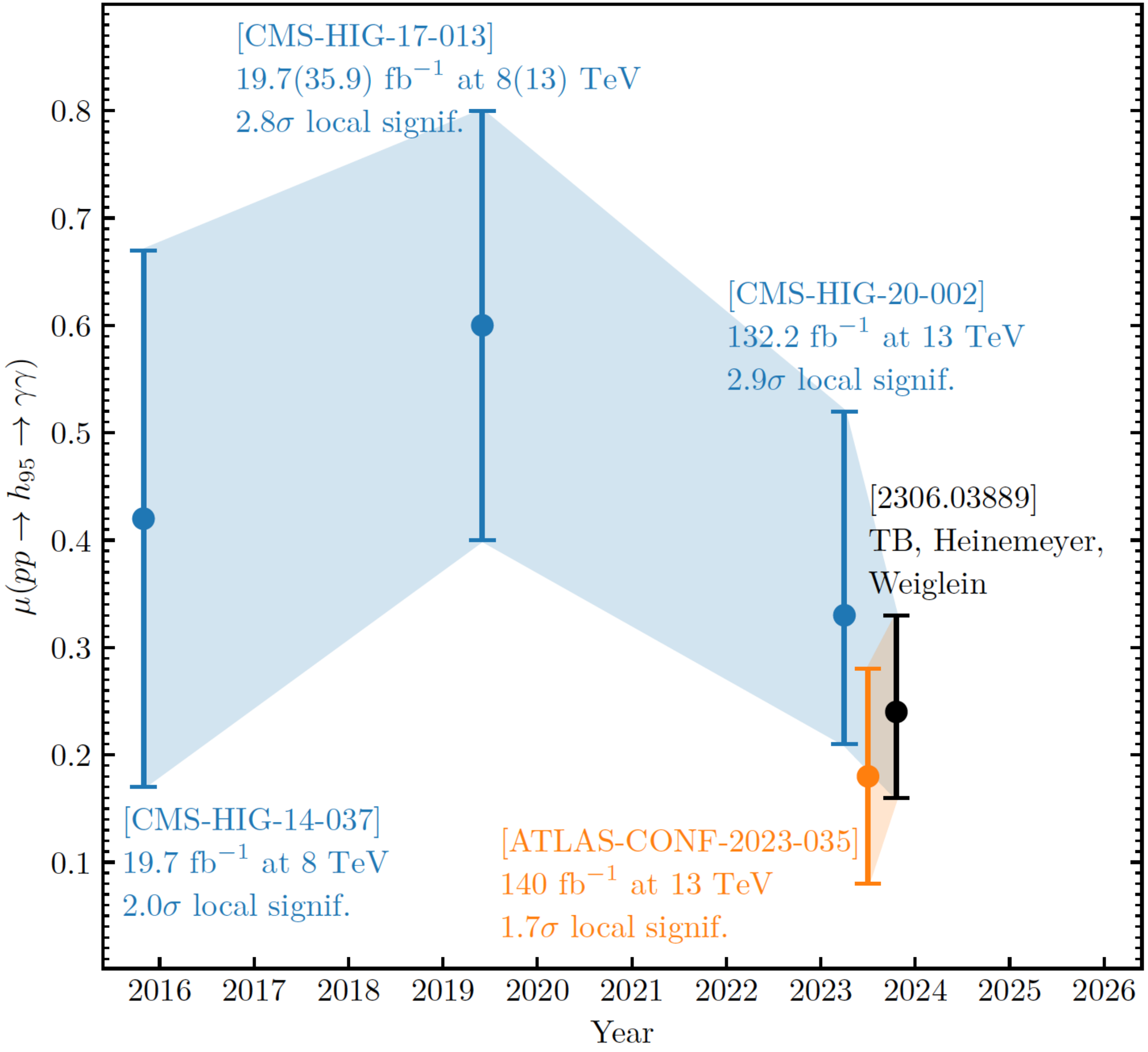
[*T. Biekötter, S.H., G. Weiglein '23*]



$\Rightarrow$ ATLAS and CMS: $\mu_{\gamma\gamma} = 0.24^{+0.09}_{-0.08}$ $(3.1\,\sigma)$ - which is called "evidence"

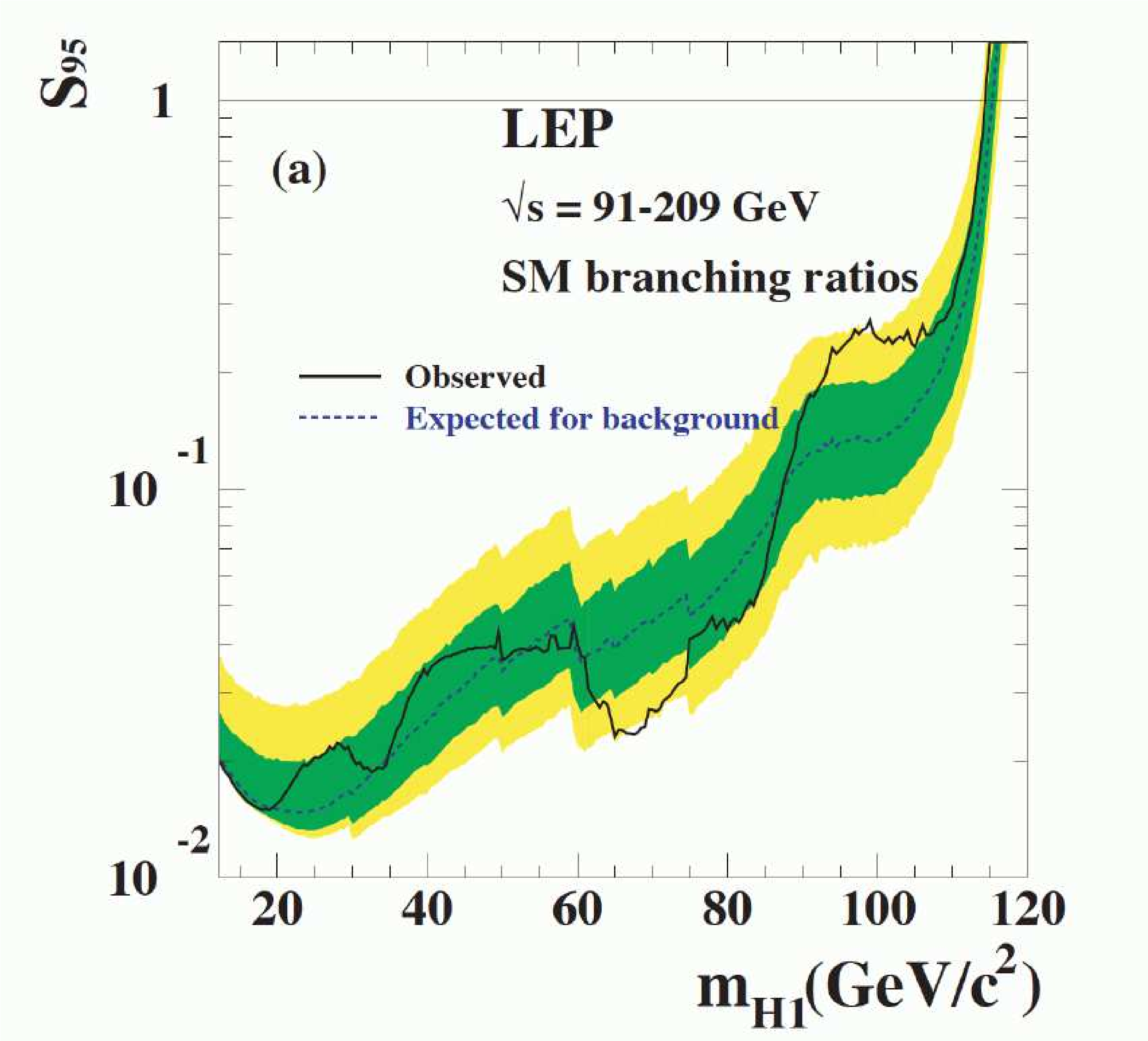
Road to discovery:

[T. Biekötter, S.H., G. Weiglein '23]



$\Rightarrow$ note the reduction of $\mu_{\gamma\gamma}$ over time!

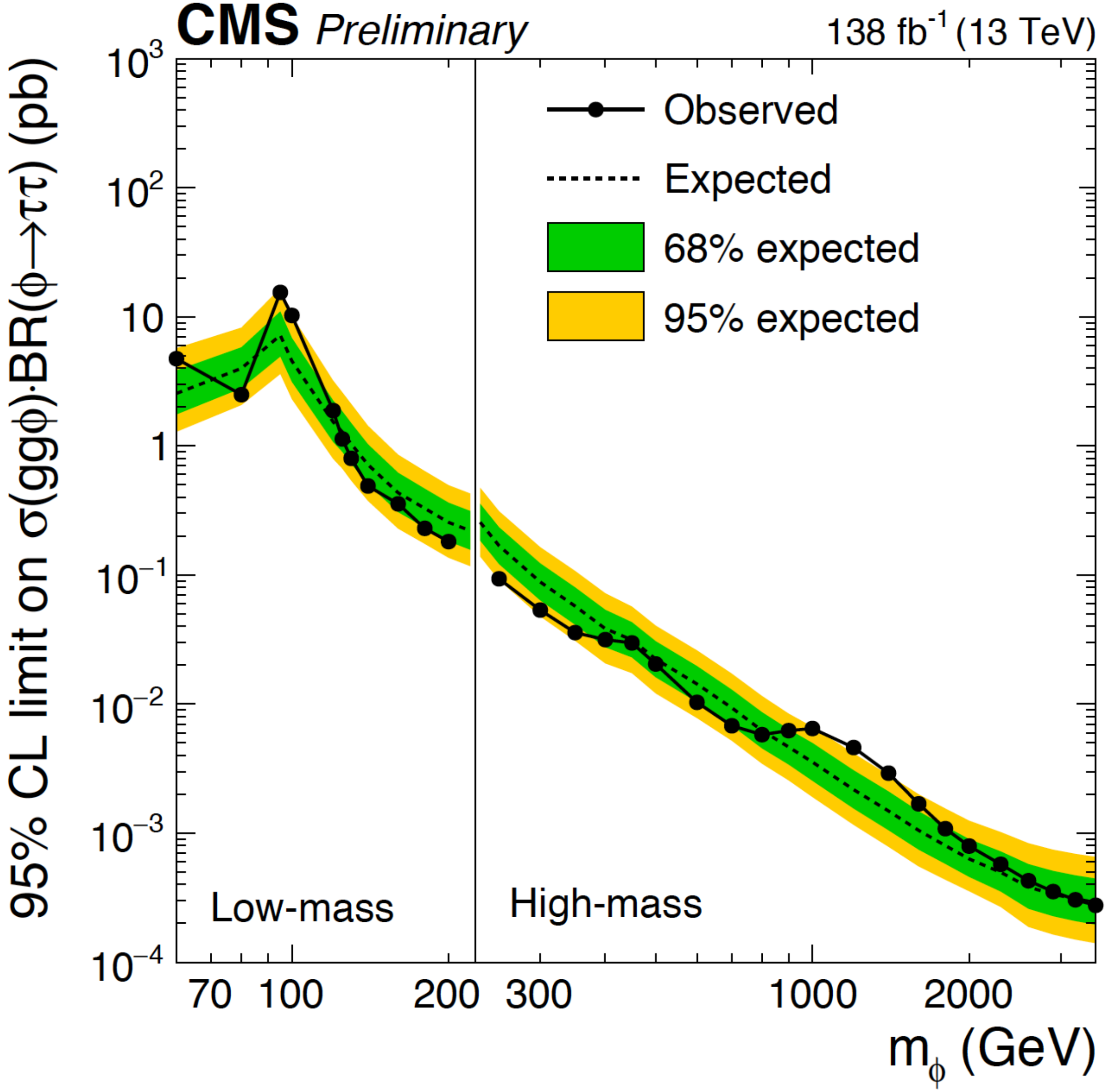
Remember the LEP excess?



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

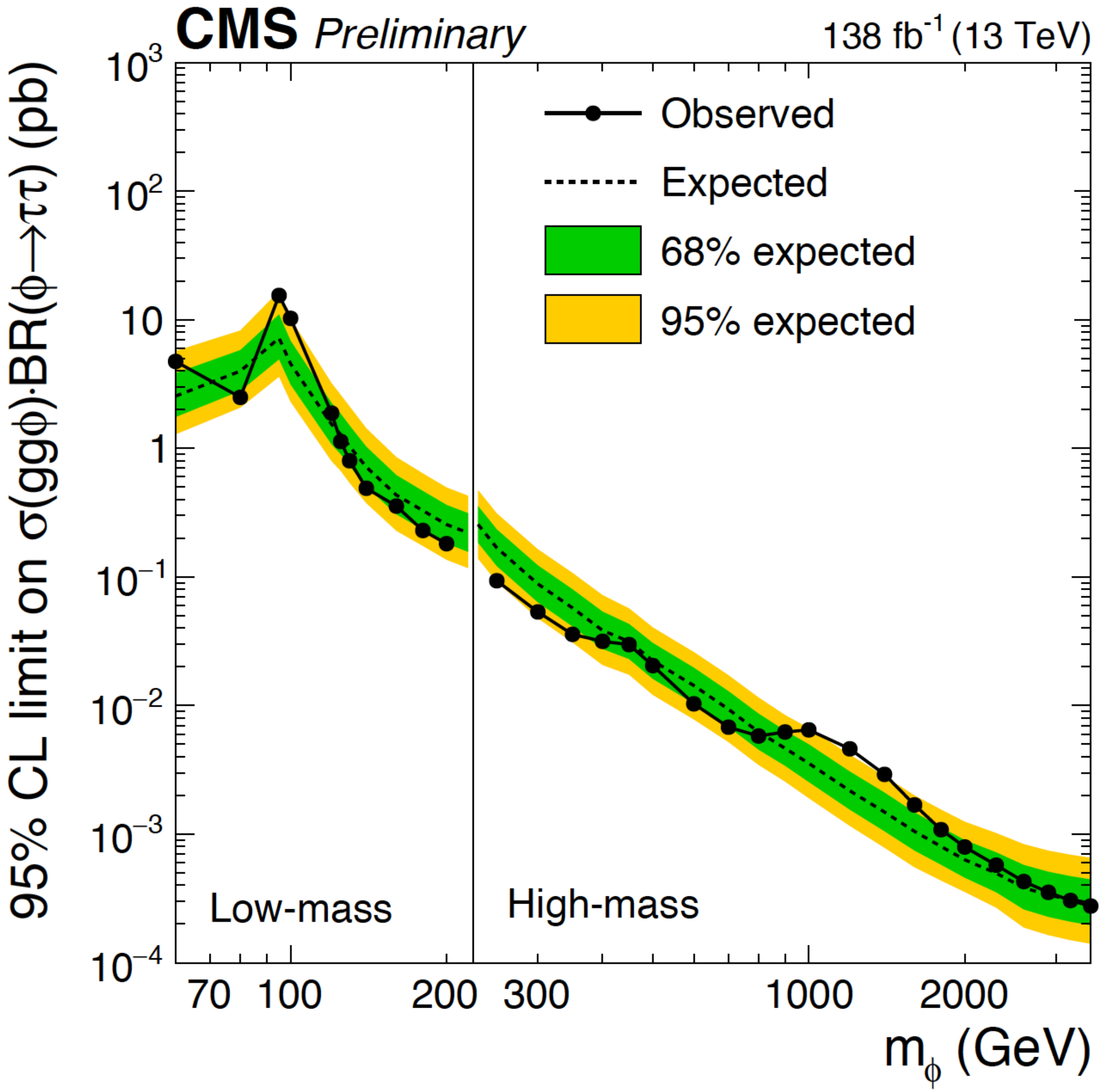
One more at the LHC: the $\tau^+\tau^-$ excess

[CMS '22]



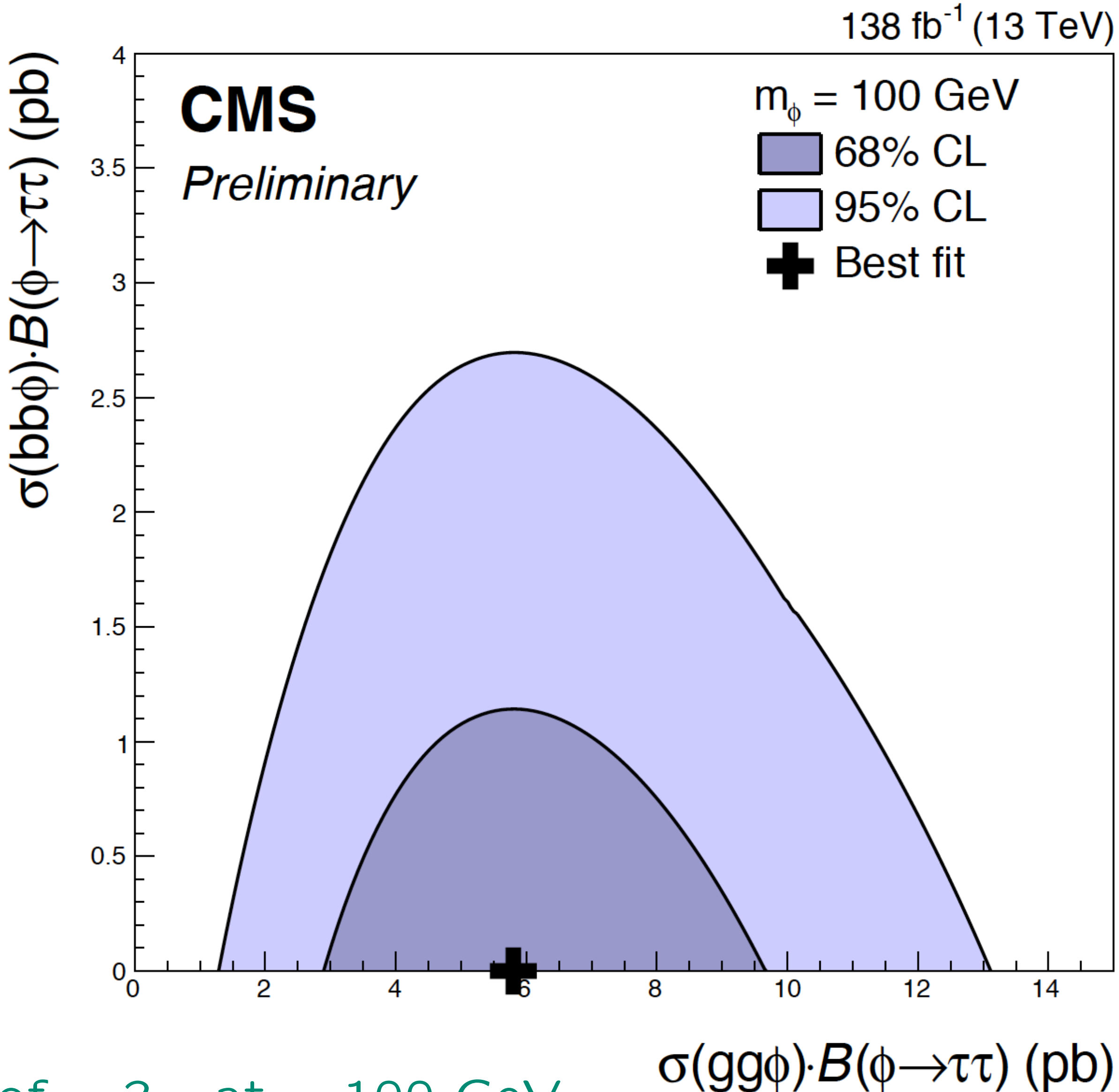
Can you spot the excess?

One more at the LHC: the $\tau^+\tau^-$ excess



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

Better visible here, focusing on 100 GeV: [*CMS '22*]



$\Rightarrow$ clear excess of $\sim 3\,\sigma$ at $\sim$ 100 GeV

$\Rightarrow$ at $\sim$ 95 GeV: $\mu_{\tau\tau} = 1.2 \pm 0.5$ caveat: limits from $t\bar{t}\phi\,/\,Z\phi$, $\phi \to \tau\tau$

Now we have three (two?) excesses at ~ 95 GeV

$$\mu_{bb}^{\text{exp}} = 0.117 \pm 0.057, \quad \mu_{\gamma\gamma}^{\text{exp}} = 0.24^{+0.09}_{-0.08}, \quad \mu_{\tau\tau}^{\text{exp}} = 1.2 \pm 0.5$$

corresponding to

$$\mu_{bb}^{\text{exp}} \sim 2\,\sigma, \quad \mu_{\gamma\gamma}^{\text{exp}} \sim 3.1\,\sigma, \quad \mu_{\tau\tau}^{\text{exp}} \sim 2.4\,\sigma$$

Three (two) (effectively) independent channels

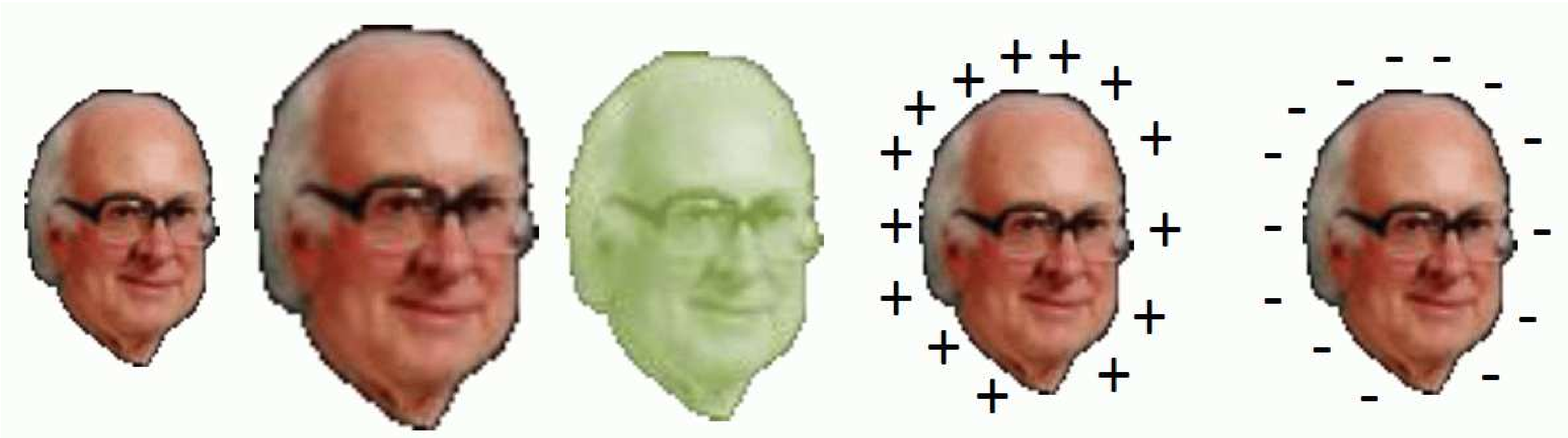
$\Rightarrow$ no LEE (as theorist I am allowed to add naively)

$$\boxed{\Rightarrow \sim 4.6\,(3.7)\,\sigma}$$

$$\chi^2_{95} = \frac{(\mu_{bb}^{\text{theo}} - 0.117)^2}{(0.057)^2} + \frac{(\mu_{\gamma\gamma}^{\text{theo}} - 0.24)^2}{(0.08)^2} + \frac{(\mu_{\tau\tau}^{\text{theo}} - 1.2)^2}{(0.5)^2}$$

Can we fit all excesses together?

Possible model interpretation



Are there non-weird models that can explain these indications
in a non-weird part of the parameter space?

h95: UV-complete models

Authors	Model	arXiv	Excesses	Comments
Cao, Guo, He et al.	nNMSSM	1612.08522	$bb + \gamma\gamma$	
Fox, Weiner	2HDM	1710.07649	$bb + (\gamma\gamma)$	
Haisch, Malinauskas	2HDM	1712.06599	$bb + (\gamma\gamma)$	
TB, Heinemeyer, Muñoz	$\mu\nu$SSM	1712.07475	$bb + \gamma\gamma$	EW seesaw
Liu, Liu, Wagner, Wang	$U(1)_{L_\mu - L_\tau}$	1805.01476	$bb + \gamma\gamma$	B-anomalies
Domingo, Heinemeyer, Paßehr, Weiglein	NMSSM	1807.06322	$bb + \gamma\gamma$	
Hollik, Liebler, Moortgat-Pick et al.	μNMSSM	1809.07371	$bb + \gamma\gamma$	Inflation
TB, Chakraborti, Heinemeyer	N2HDM	1903.11661	$bb + \gamma\gamma$	
Cline, Toma	pNG + squarks	1906.02175	$bb + \gamma\gamma$	DM
Choi, Hui Im, Sik Jeong et al.	gNMSSM	1906.03389	$bb + \gamma\gamma$	
Cao, Jia, Yue et al.	nNMSSM	1908.07206	$bb + \gamma\gamma$	Type-I seesaw
Aguilar-Saavedra, Joaquim	SM + $U(1)_{Y'}$	2002.07697	$bb + \gamma\gamma$	
TB, Olea-Romacho	S2HDM	2108.10864	$bb + \gamma\gamma$	DM, GC excess
TB, Grohsjean, Heinemeyer et al.	NMSSM	2109.01128	$\gamma\gamma$	400 GeV excess
Heinemeyer, Lika, Moortgat-Pick et al.	2HDM+s	2112.11958	$bb + \gamma\gamma$	
TB, Heinemeyer, Weiglein	N2HDM	2203.13180	$bb + (\tau\tau) + \gamma\gamma$	
TB, Heinemeyer, Weiglein	N2HDM	2204.05975	$bb + (\tau\tau) + \gamma\gamma$	CDF M_W
Benbrik, Boukidi, Moretti et al.	A2HDM-III	2204.07470	$bb + \gamma\gamma$	LFV

Green: 2HDM(+X), blue: Susy, red: Extra charged fields

h95: UV-complete models

Authors	Model	arXiv	Excesses	Comments
TB, Heinemeyer, Weiglein	S2HDM	2303.12018	$bb + (\tau\tau) + \gamma\gamma$	DM
Azevedo, TB, Ferreira	C2HDM	2305.19716	$bb + \tau\tau + \gamma\gamma$	
Bonilla, Carcamo, Kovalenko et al.	Left-Right model	2305.11967	$\gamma\gamma$	DM
TB, Heinemeyer, Weiglein	S2HDM	2306.03889	$bb + (\tau\tau) + \gamma\gamma$	DM
Escribano, Martín Lozano, Vicente	Scotogenic	2306.03735	$bb + \gamma\gamma$	DM, ν masses
Belyaev, Benbrik, Boukidi et al.	A2HDM	2306.09029	$bb + (\tau\tau) + \gamma\gamma$	
Ashanuman, Banik, Coloretti et al.	$Y = 0$ triplet	2306.15722	$\gamma\gamma$	CDF M_W
Aguilar-Saavedra, Camara et al.	UN2HDM	2307.03768	$(\tau\tau)$, $\gamma\gamma$	
Dutta, Lahiri, Li et al.	2HDMS	2308.05653	$bb + \gamma\gamma$	
Ellwanger, Hugonie	NMSSM	2309.07838	$bb + (\gamma\gamma)$	
Cao, Jia, Lian et al.	gNMSSM	2310.08436	$bb + \gamma\gamma$	DM
Borah, Mahapatra Paul et al.	2HDM+$U(1)_{L_\mu - L_\tau}$	2310.11953	$\gamma\gamma$	DM, gm2, CDF
Arcadi, Busoni, Cabo-Almeida et al.	2HDM+s/a	2311.14486	$(bb) + \gamma\gamma + (\tau\tau)$	
Ahriche	GM	2312.10484	$bb + \gamma\gamma + (\tau\tau)$	
Coloretti, Crivellin, Mellado	2HDM+S+triplet	2312.17314	$\gamma\gamma$	h_{151}, h_{400}
Cao, Lian	gNMSSM	2402.15847	$bb + \gamma\gamma$	DM, gm2
Kalinowski, Kotlarski	MRSSM	2403.08720	$bb + \gamma\gamma$	DM

Green: 2HDM(+X), blue: Susy, red: Extra charged fields

h95: UV-complete models

Authors	Model	arXiv	Excesses	Comments
Ellwanger, Hugonie	NMSSM	2403.16884	$bb + \gamma\gamma$	DM, gm2
Ellwanger, Hugonie, King, Moretti	NMSSM	2404.19338	$bb + \gamma\gamma$	DM, $\chi^0\chi^\pm$ excess
Benbrik, Boukidi, Moretti	A2HDM	2405.02899	$bb + \gamma\gamma + \tau\tau$	$h_{95} + A_{95}$
Arhrib, Phan, Tran, Yuan	gauged 2HDM	2405.03127	$bb + (\gamma\gamma)$	$h_{125} \to Zy$ excess
Lian	NMSSM	2406.10969	$bb + \gamma\gamma$	DM
Gao, Ma, Xu	2HDM+S	2408.03705	$bb + \gamma\gamma$	BAU

Green: 2HDM(+X), blue: Susy, red: Extra charged fields

Possible model: **N2HDM** [**S2HDM** similar with complex singlet]

Fields:

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

Potential:

$$\begin{aligned} V \ = \ & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ & +\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned}$$

Z_2 symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$, $\Phi_S \to \Phi_S$

Z_2' symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to \Phi_2$, $\Phi_S \to -\Phi_S$ (broken by $v_S \Rightarrow$ no DM)

Physical states: h_1, h_2, h_3 ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

Extension of the Z_2 symmetry to fermions determines four types:

	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II (SUSY type)	Φ_2	Φ_1	Φ_1
type III (lepton-specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

$\Rightarrow$ exactly as in 2HDM

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 massive gauge bosons: (identical for all four types)

	$c_{h_i VV} = c_\beta R_{i1} + s_\beta R_{i2}$
h_1	$c_{\alpha_2} c_{\beta-\alpha_1}$
h_2	$-c_{\beta-\alpha_1} s_{\alpha_2} s_{\alpha_3} + c_{\alpha_3} s_{\beta-\alpha_1}$
h_3	$-c_{\alpha_3} c_{\beta-\alpha_1} s_{\alpha_2} - s_{\alpha_3} s_{\beta-\alpha_1}$

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 (SUSY type)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
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:

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

Needed to fit the $\gamma\gamma$ and $b\bar{b}$ excesses: $m_{h_1} \sim 95$ GeV, $m_{h_2} \sim 125$ GeV

- $c^2_{h_1VV}$ strongly reduced for $\mu_{b\bar{b}}$
- c_{h_1bb} reduced to enhance BR$(h_1 \to \gamma\gamma)$
- c_{h_1tt} not reduced for $\mu_{\gamma\gamma}$

	Decrease $c_{h_1b\bar{b}}$	No decrease $c_{h_1t\bar{t}}$	No enhancement $c_{h_1\tau}$
type I	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{12}}{s_\beta})$
type II (SUSY type)	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{11}}{c_\beta})$
type III	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{11}}{c_\beta})$
type IV	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$

Type II and IV: c_{h_1bb} and c_{h_1tt} independent

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

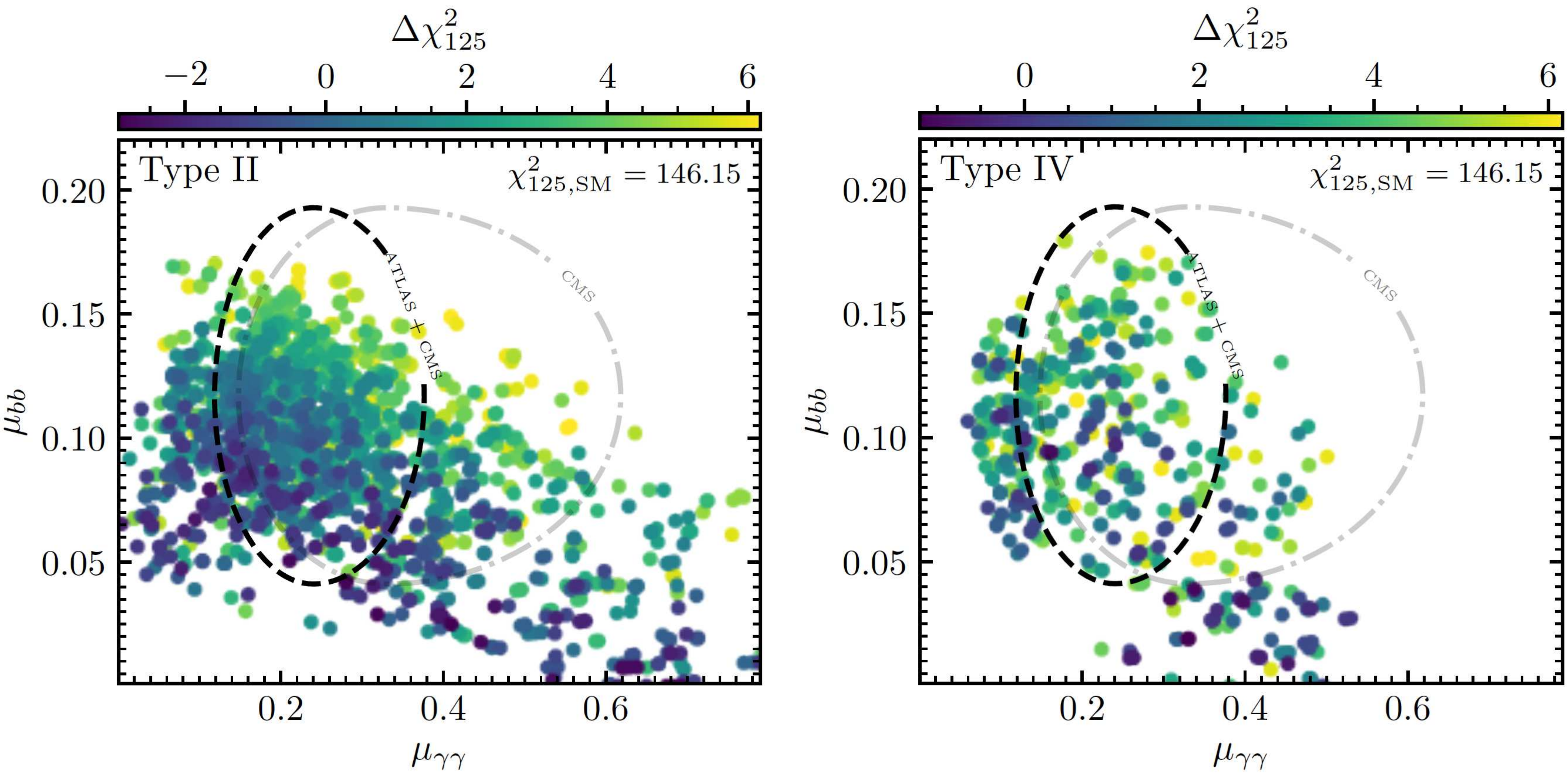
$\Rightarrow$ only type II and IV can fit the $\gamma\gamma$ and $b\bar{b}$ excesses

$\Rightarrow$ $\tau\tau$ excess may decide between type II and IV

$\Rightarrow$ Parameter scan $\Rightarrow$ ScannerS/s2hdmTools

Constraints:

- Tree-level perturbativity $\Rightarrow$ ScannerS/s2hdmTools
- Minimum of potential is global minimum $\Rightarrow$ ScannerS/s2hdmTools
  . . . or sufficiently long-lived $\Rightarrow$ Evade
- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds
- SM-like Higgs properties
  $\Rightarrow$ HiggsSignals (N2HDECAY/s2hdmTools, SusHi) $\Rightarrow$ χ^2_{125}
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso bounds
- Electroweak precision data (T and S) $\Rightarrow$ ScannerS/s2hdmTools

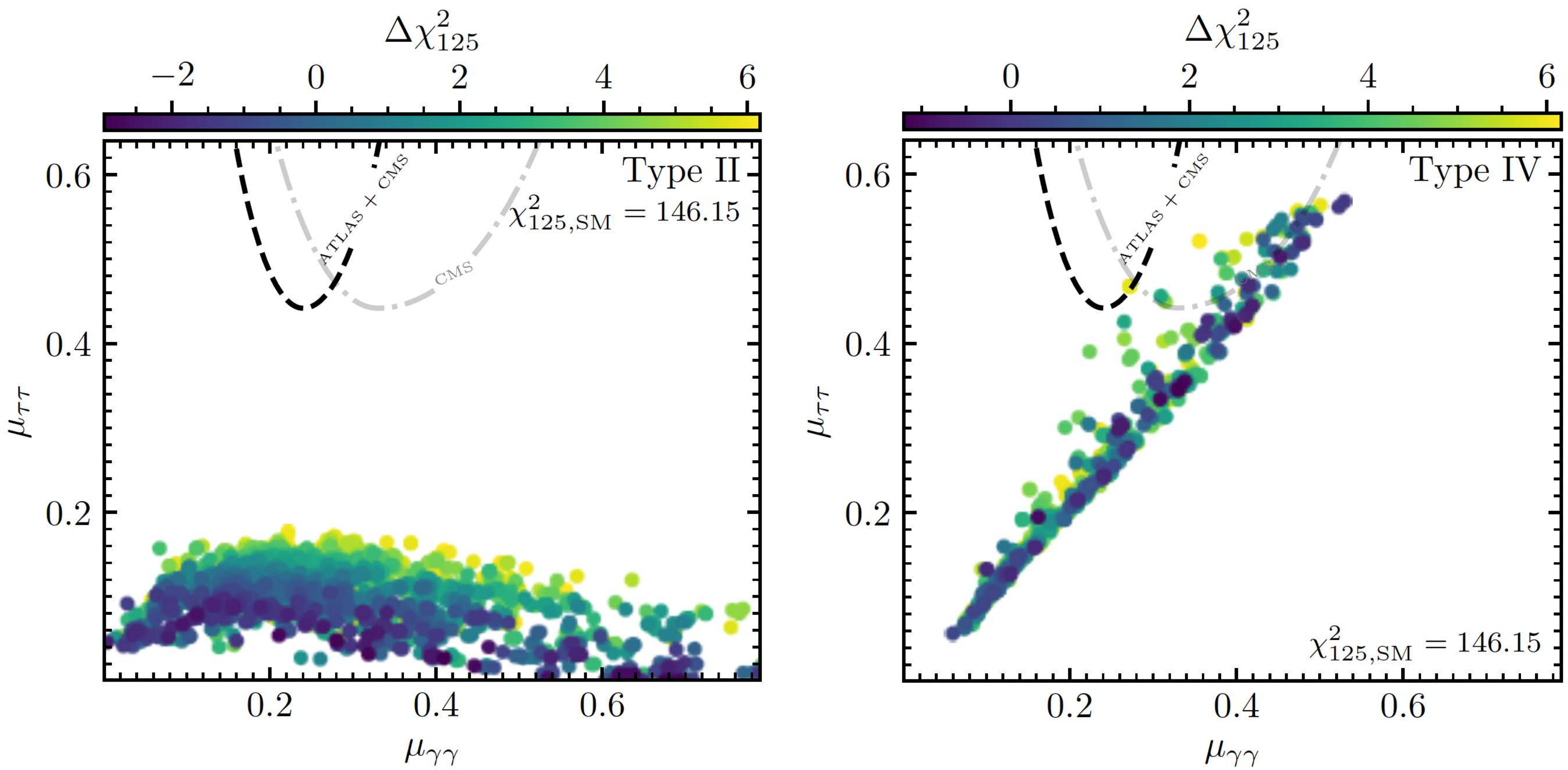


Color coding: χ^2_{125} from HiggsSignals

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

S2HDM type II vs. type IV

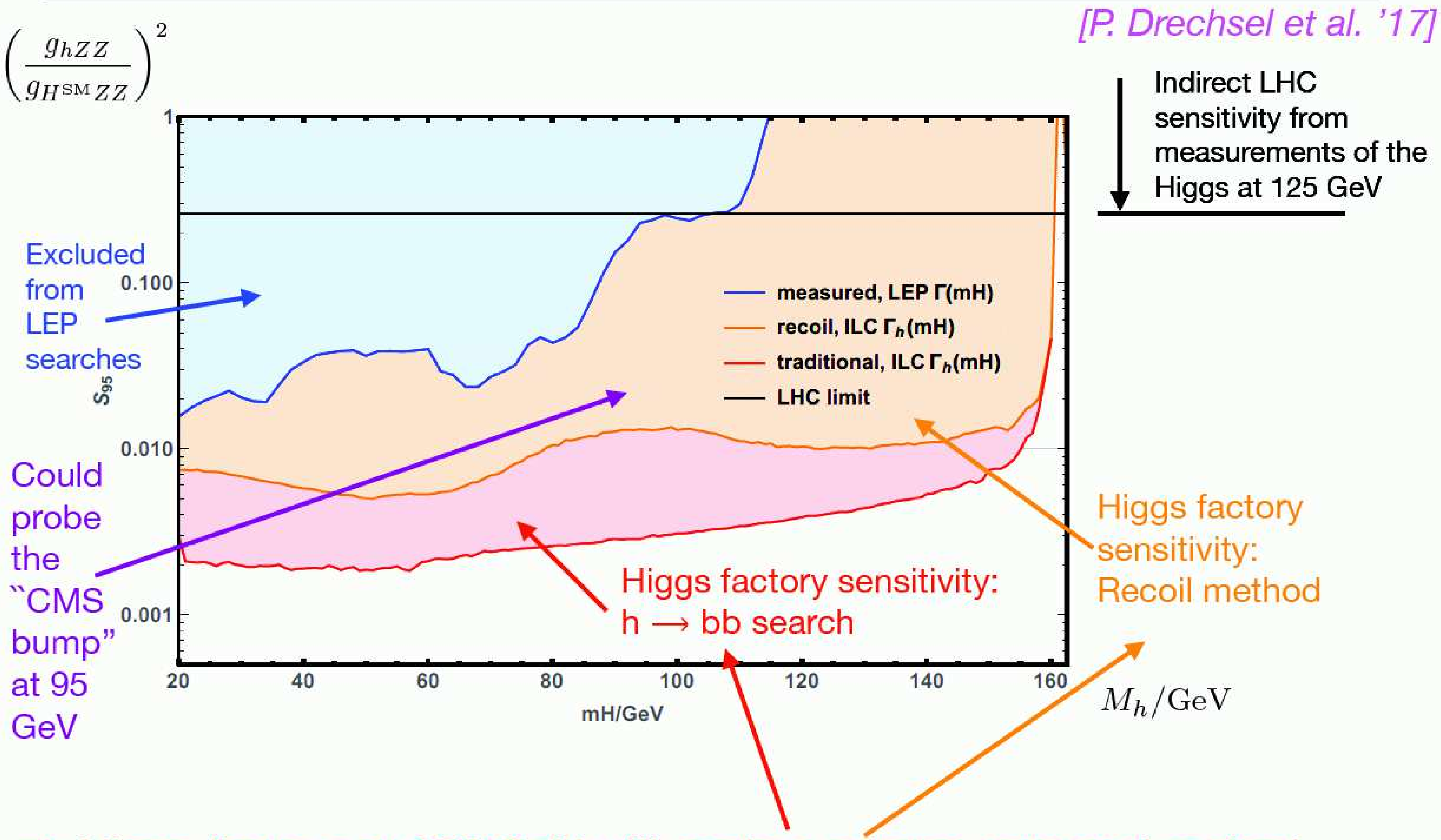
[T. Biekötter, S.H., G. Weiglein '23]



Color coding: χ^2_{125} from HiggsSignals

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

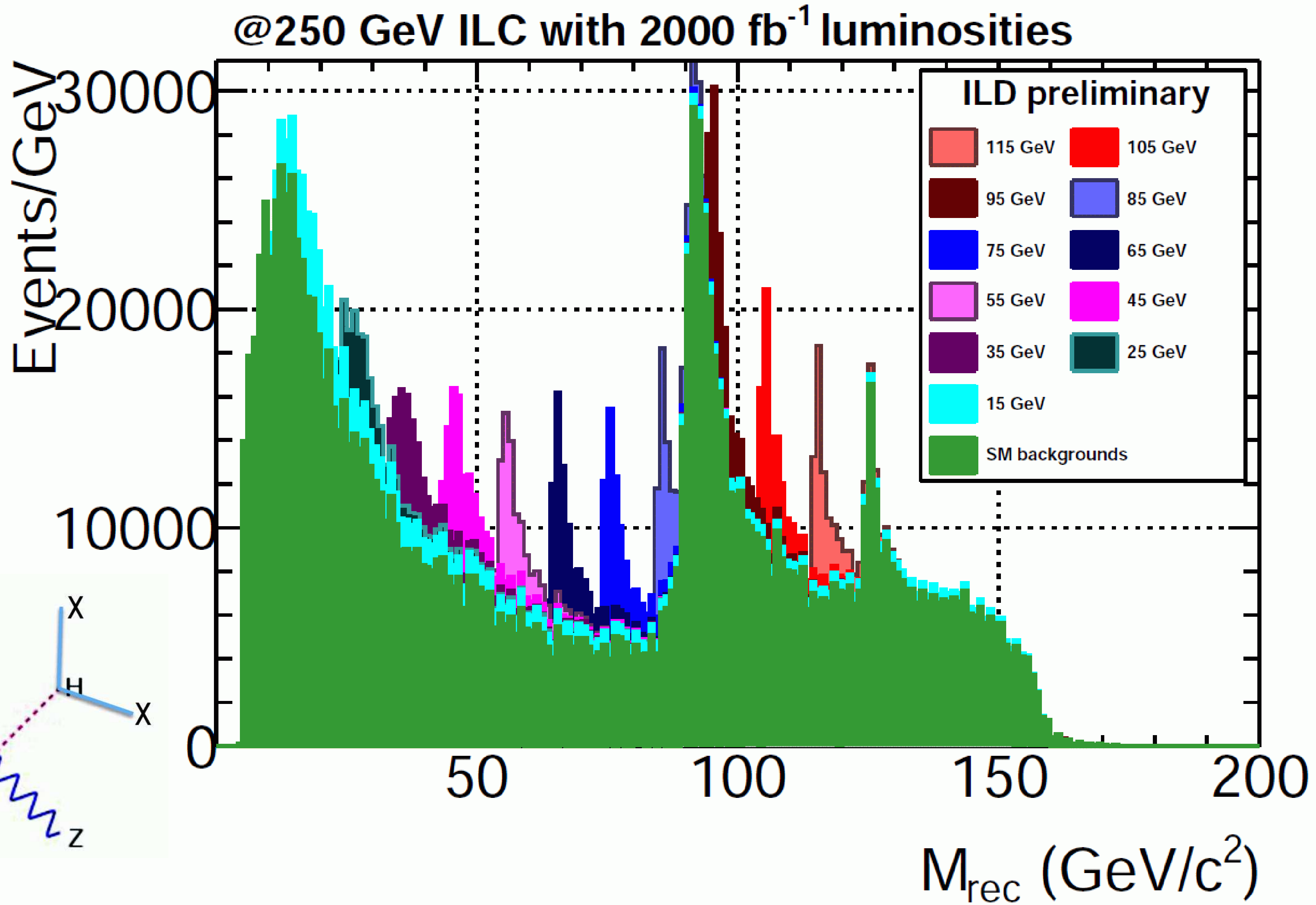
Example for discovery potential for new light states: Sensitivity at 250 GeV with 500 fb^{-1} to a new light Higgs

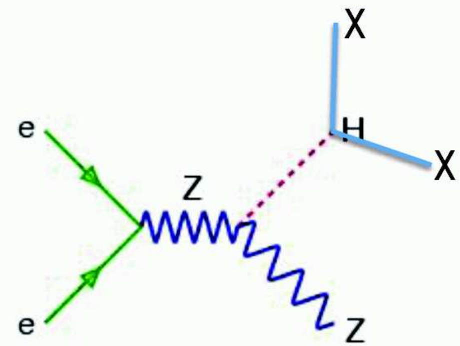


⇒ Higgs factory at 250 GeV will explore a large untested region!

[*Taken from G. Weiglein '18*]

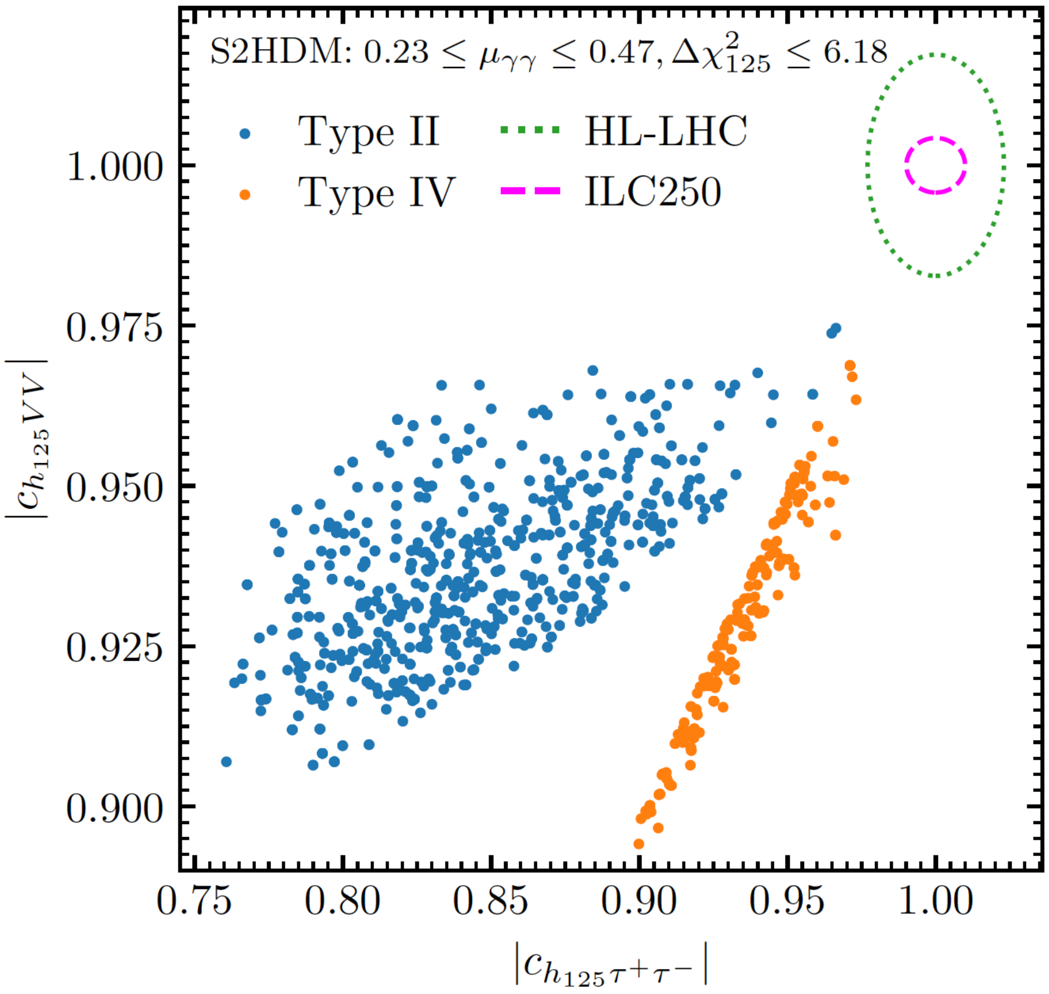
Search for invisibly decaying light Higgses via recoil method: [*Y. Wang et al. '18*]





h_{125} coupling measurements at the HL-LHC/ILC

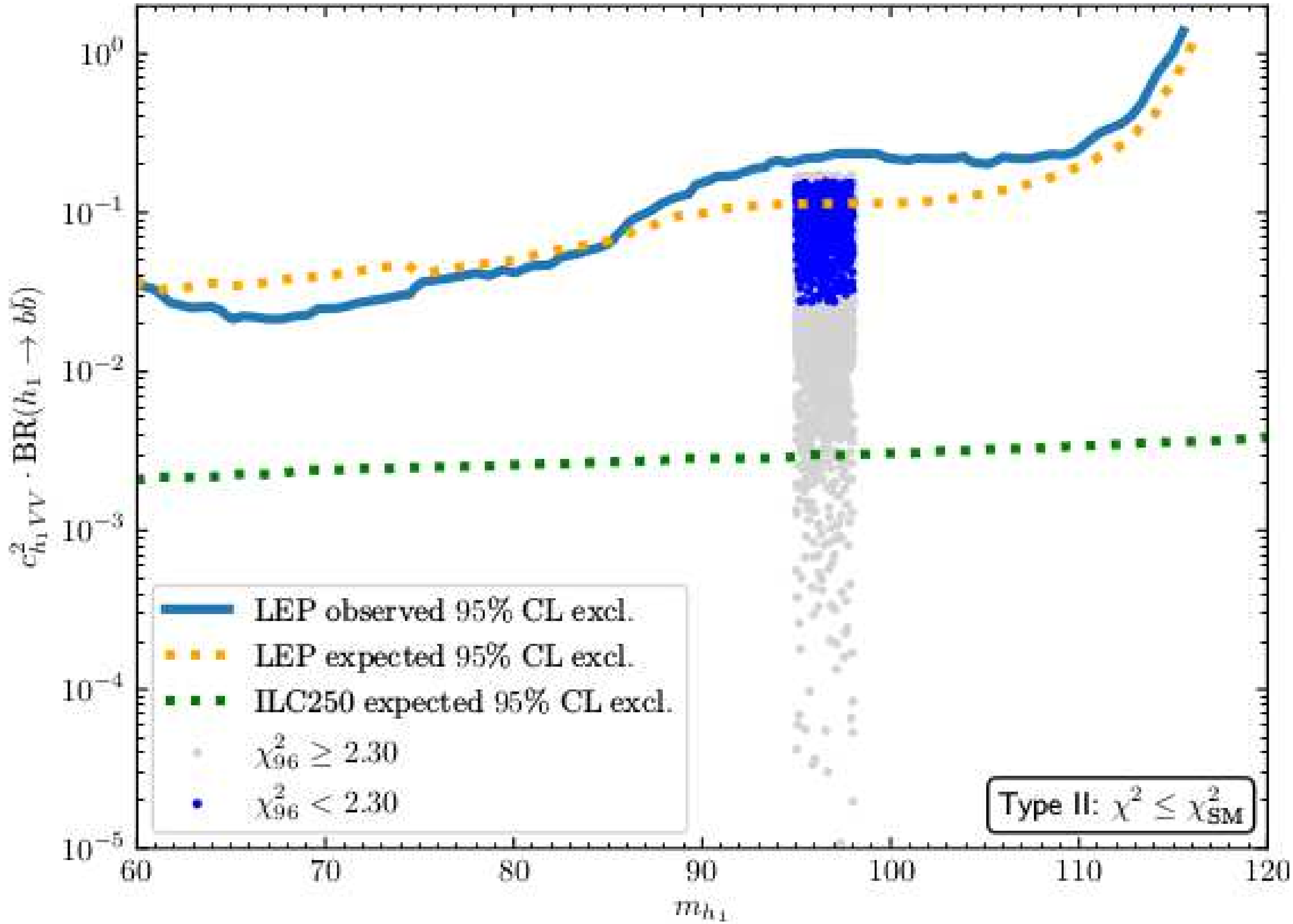
[*T. Biekötter, S.H., G. Weiglein '23*]



$\Rightarrow$ both types show some deviation from SM

Production of the light Higgs at the ILC:

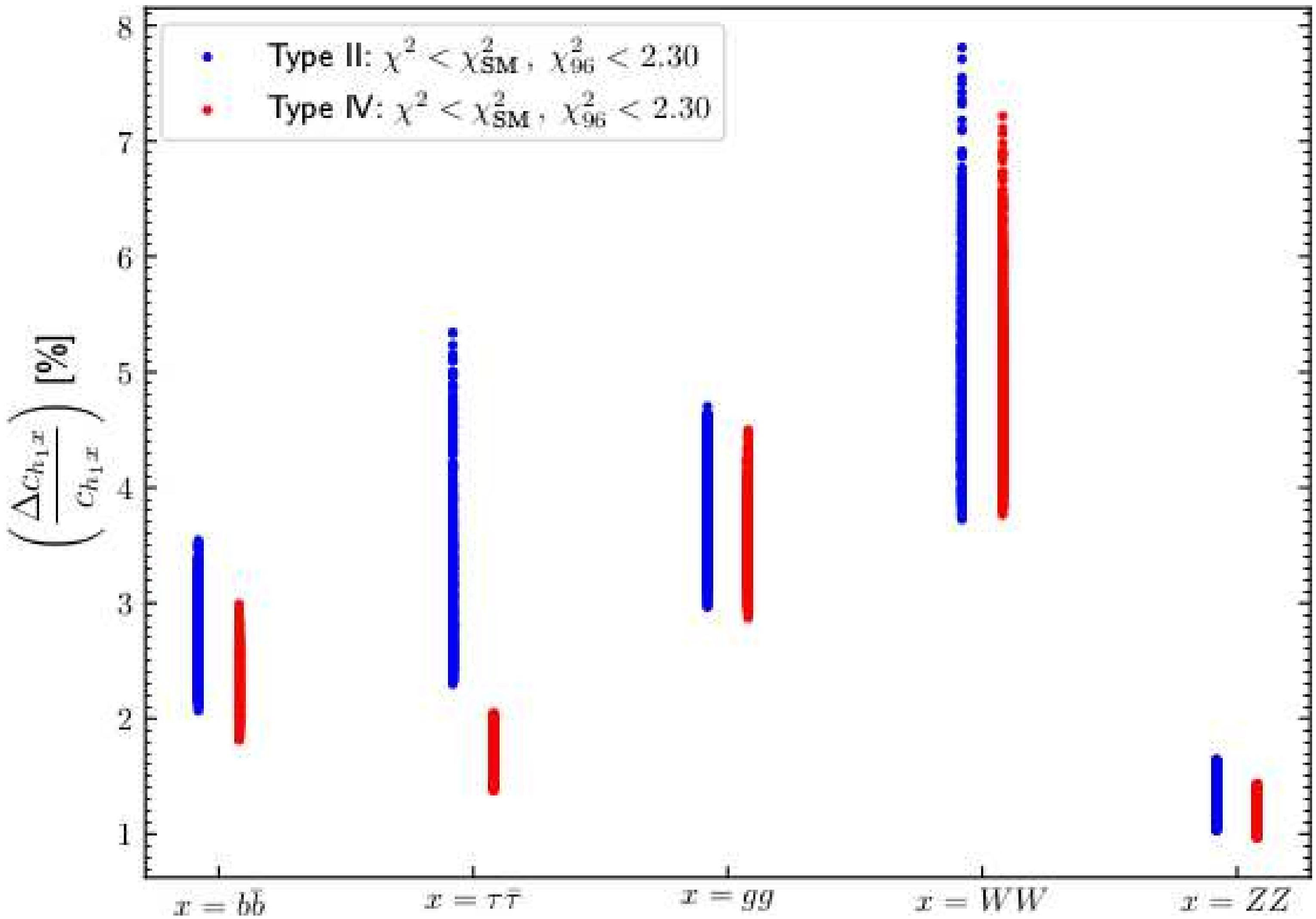
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



⇒ new state easily in the reach of the ILC ⇒ coupling measurements

h_{95} coupling measurements at the HL-LHC/ILC

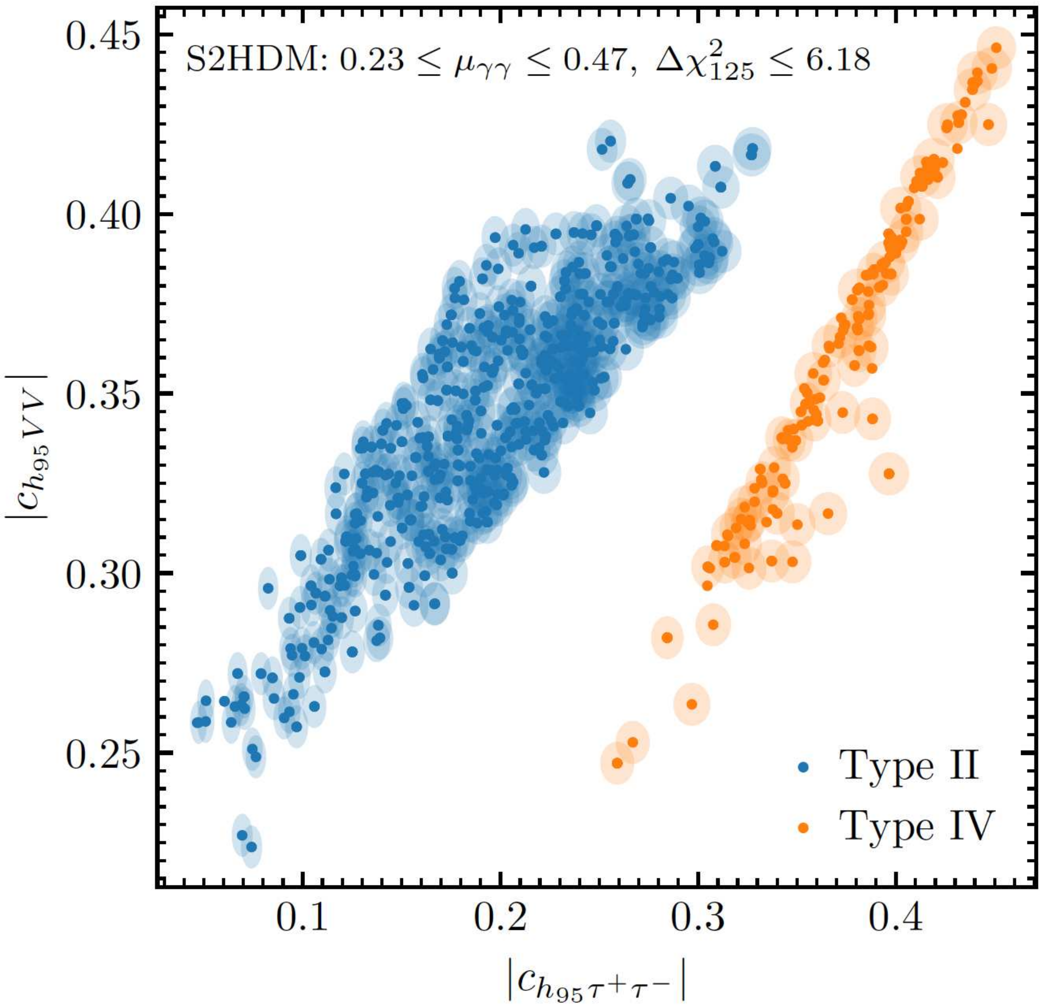
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



$\Rightarrow$ clear difference in $g_{h_{95}\tau\tau}$ as expected

h_{95} coupling measurements at the HL-LHC/ILC

[*T. Biekötter, S.H., G. Weiglein '23*]



$\Rightarrow$ models clearly distinguishable!

SUSY realizations

What about SUSY??

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$\Rightarrow$ type II is needed for SUSY

$\Rightarrow$ $\tau\tau$ excess most strongly in contradiction with other measurements

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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 **???**

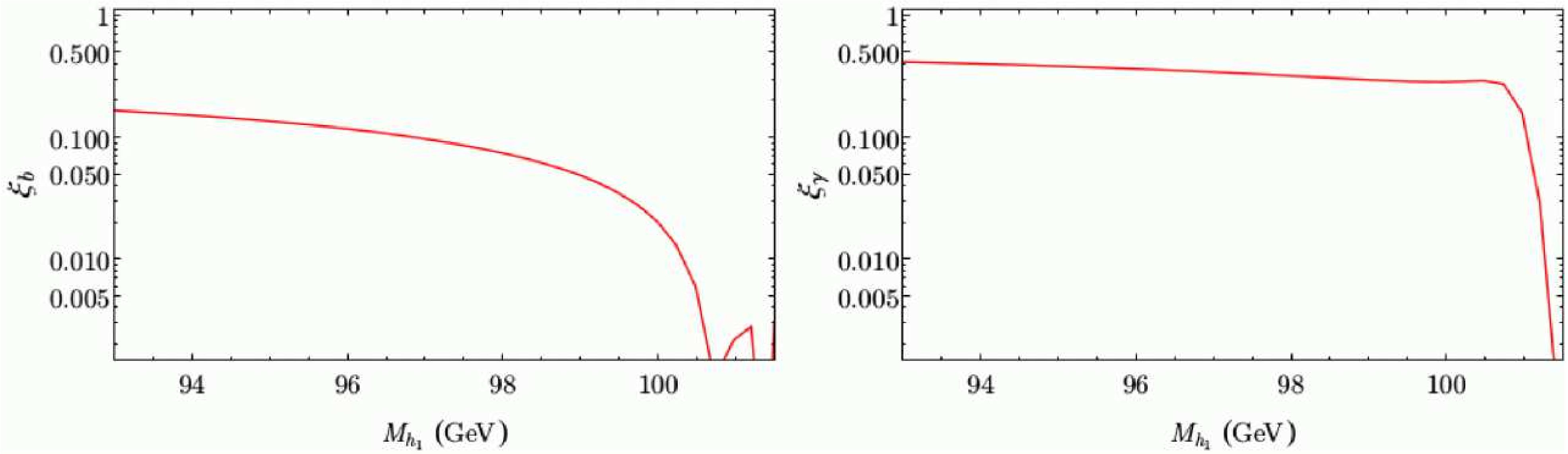
 [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

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

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

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



$\Rightarrow$ 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)
$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

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

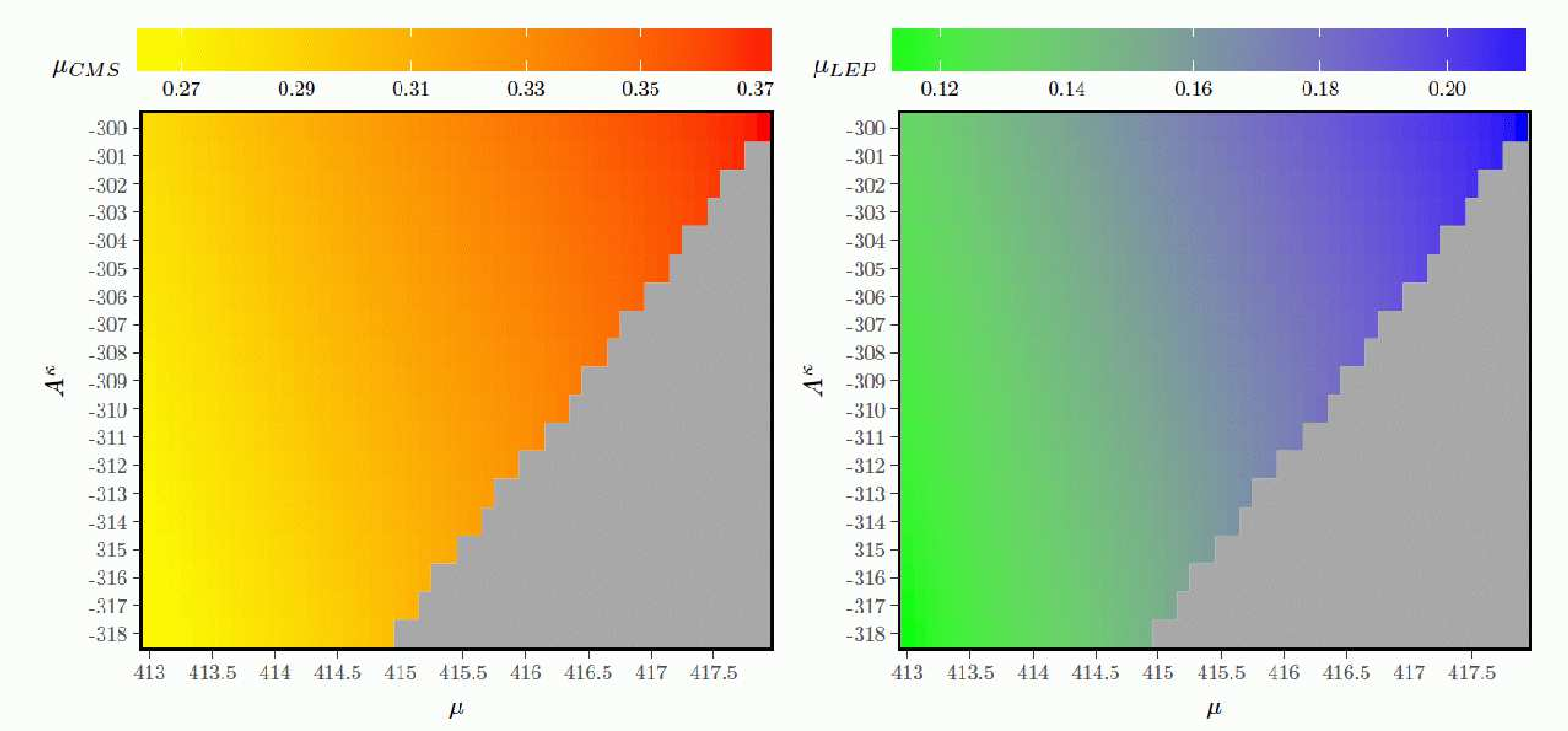
[*T. Biekötter, S.H., C. Muñoz '17*]

v_{iL}	Y_i^ν	A_i^ν	$\tan\beta$	μ	λ	A^λ	κ	A^κ	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	$m^2_{\widetilde{Q}_{iL}}$	$m^2_{\widetilde{u}_{iR}}$	$m^2_{\widetilde{d}_{iR}}$	A_1^u	$A_{2,3}^{u,d}$	$(m^2_{\widetilde{e}})_{ii}$	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*]

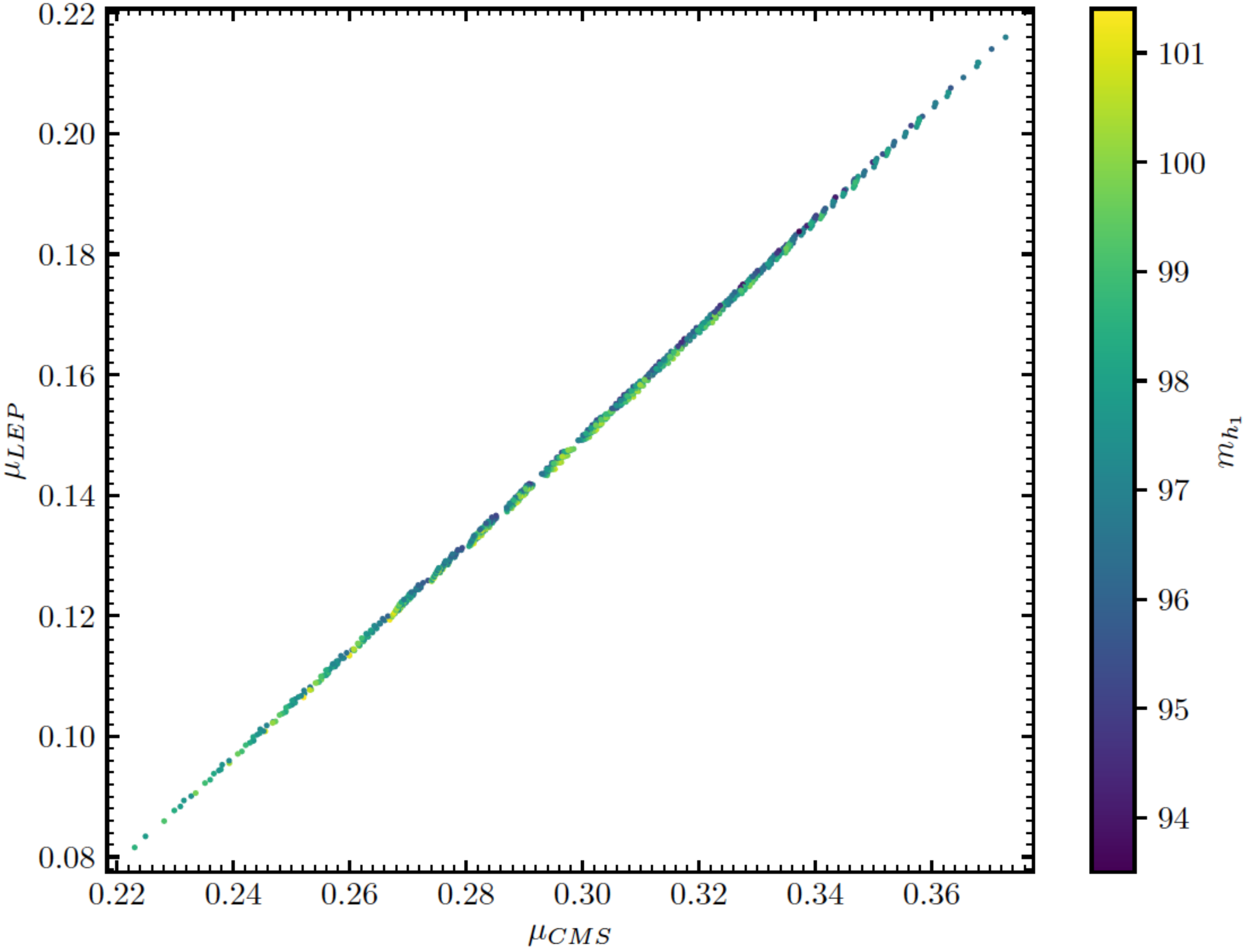


$\Rightarrow$ Yes! :-)

using the <u>new</u> $\mu_{\gamma\gamma}$!

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

[*T. Biekötter, S.H., C. Muñoz '19*]



$\Rightarrow$ SUSY enforces strong correlation!

$\Rightarrow$ LEP excess enforces $\mu_{\gamma\gamma} \lesssim 0.35$ - EXACTLY AS OBSERVED NOW! :-)

Final model analysis: Georgi-Machacek Model (GM)

Field content:

In the GM model, the SM Higgs doublet ϕ with a complex triplet χ (hypercharge $Y = 1$) and a real triplet ξ ($Y = 0$). These fields are represented as:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}, \quad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix}. \tag{2.33}$$

Neutral fields:

$$\phi^0 = \frac{1}{\sqrt{2}}(v_\phi + \phi_r^0 + i\phi_i^0), \quad \chi^0 = v_\chi + \frac{1}{\sqrt{2}}(\chi_r^0 + i\chi_i^0), \quad \xi^0 = v_\chi + \xi_r^0.$$

Three neutral $\mathcal{CP}$-even Higgs bosons:

$$h^0 = \cos\alpha\, \phi^{0,r} - \sin\alpha \left(\frac{1}{\sqrt{3}}\chi^{0,r} + \sqrt{\frac{2}{3}}\,\xi^{0,r} \right),$$

$$H^0 = \sin\alpha\, \phi^{0,r} + \cos\alpha \left(\frac{1}{\sqrt{3}}\chi^{0,r} + \sqrt{\frac{2}{3}}\,\xi^{0,r} \right),$$

$$H_5^0 = \sqrt{\frac{2}{3}}\,\xi^{0,r} - \frac{1}{\sqrt{3}}\chi^{0,r},$$

$\Rightarrow$ choose $m_h = 95.4$ GeV, $m_H = 125$ GeV

Why GM?

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GM contains doubly charged Higgs bosons

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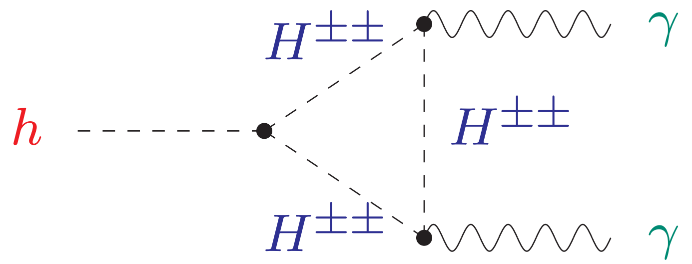
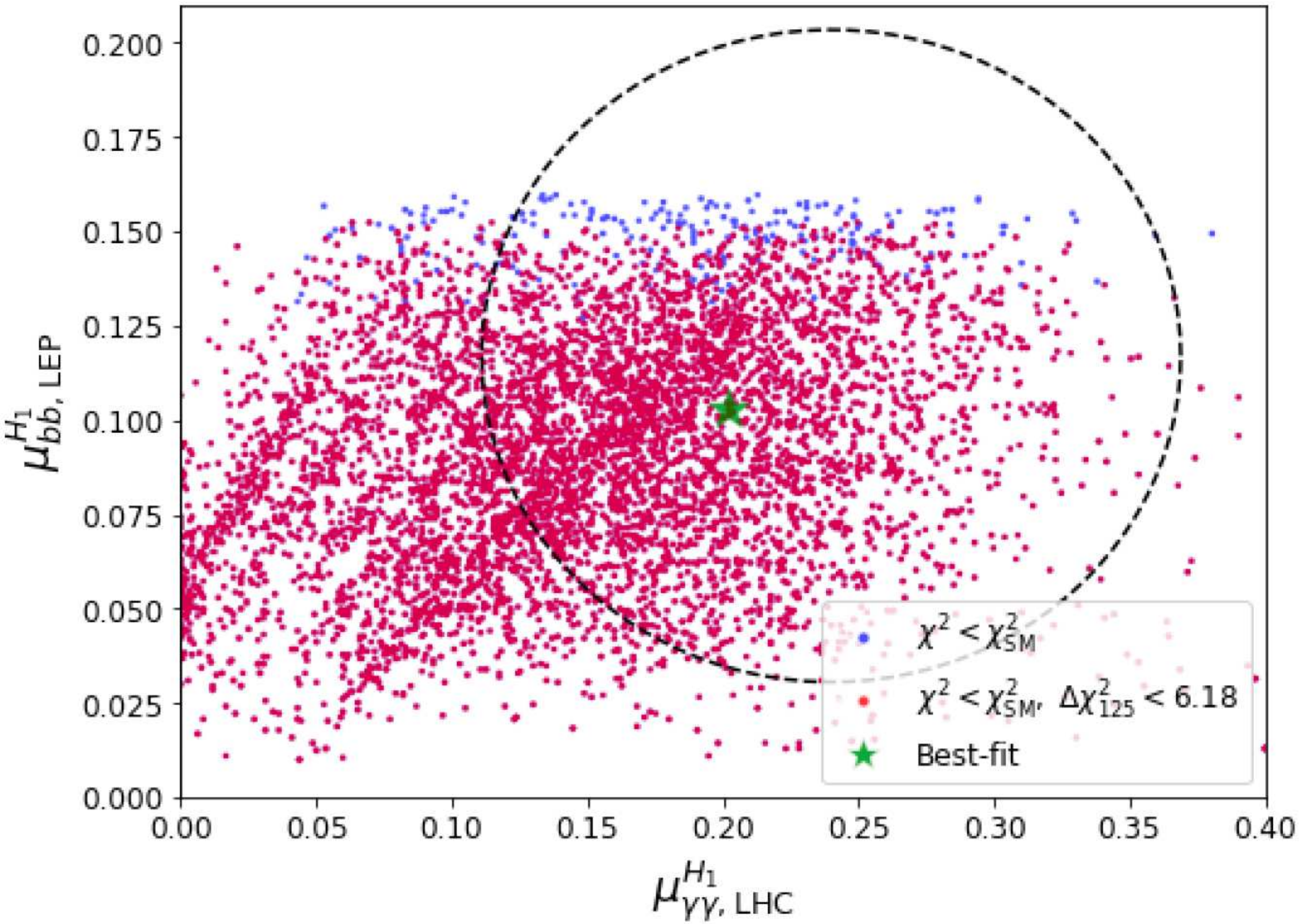
GM contains doubly charged Higgs bosons



$\Rightarrow$ important enhancement of BR($h \to \gamma\gamma$)

$\Rightarrow$ to match $\mu_{\gamma\gamma}^{\rm exp} \sim 0.24$

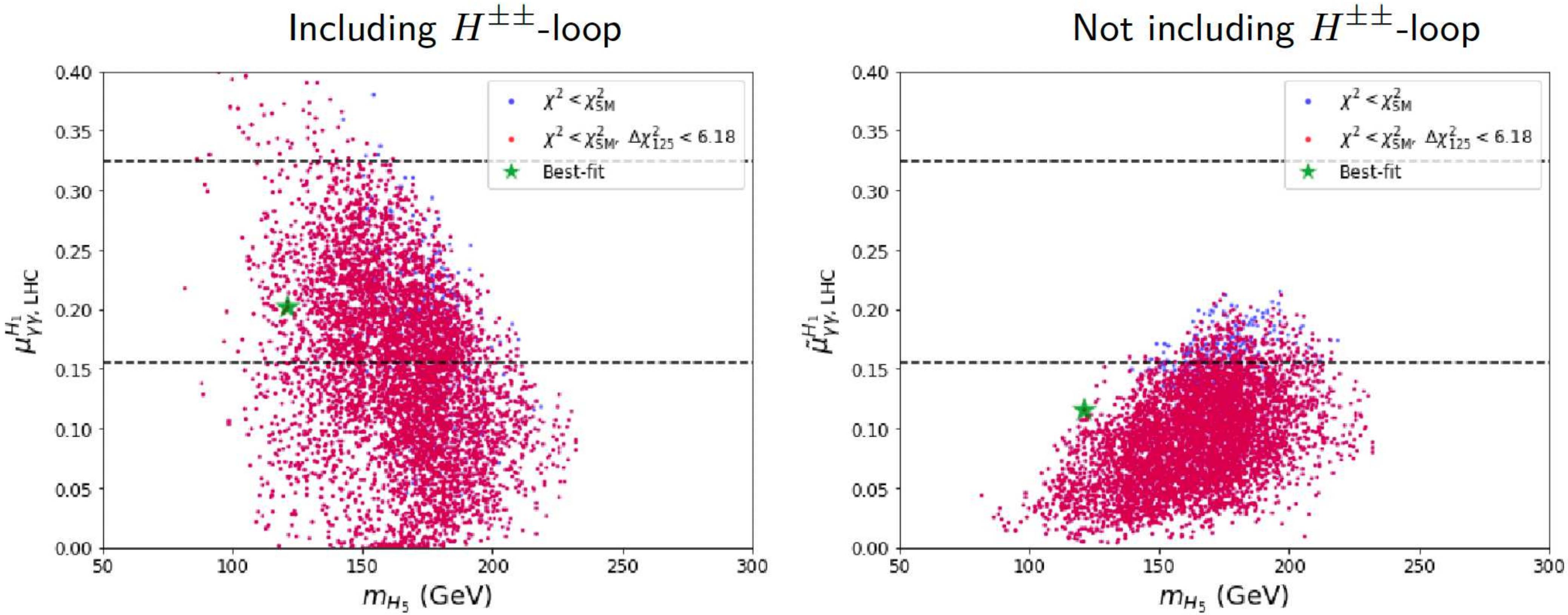
Parameter scan: can we fit $\mu_{\gamma\gamma}$ and μ_{bb}? [T.K. Chen, C.W. Chiang, S.H., G. Weiglein '23]



$\Rightarrow$ both excesses are described well

Relevance of $H^{\pm\pm}$:

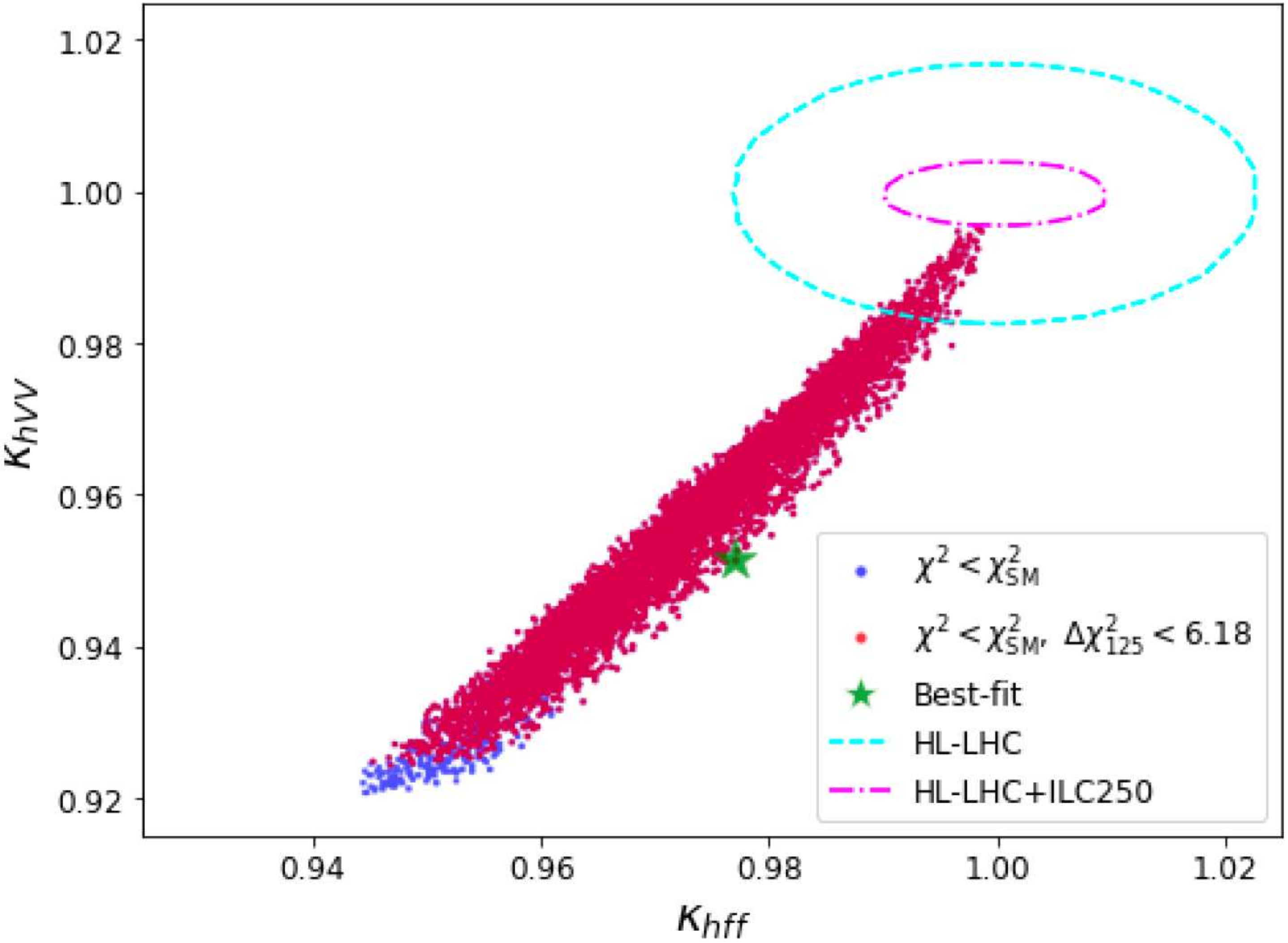
[T.K. Chen, C.W. Chiang, S.H., G. Weiglein '23]



$\Rightarrow$ doubly charged Higgs is very important!

Future tests: h_{125}:

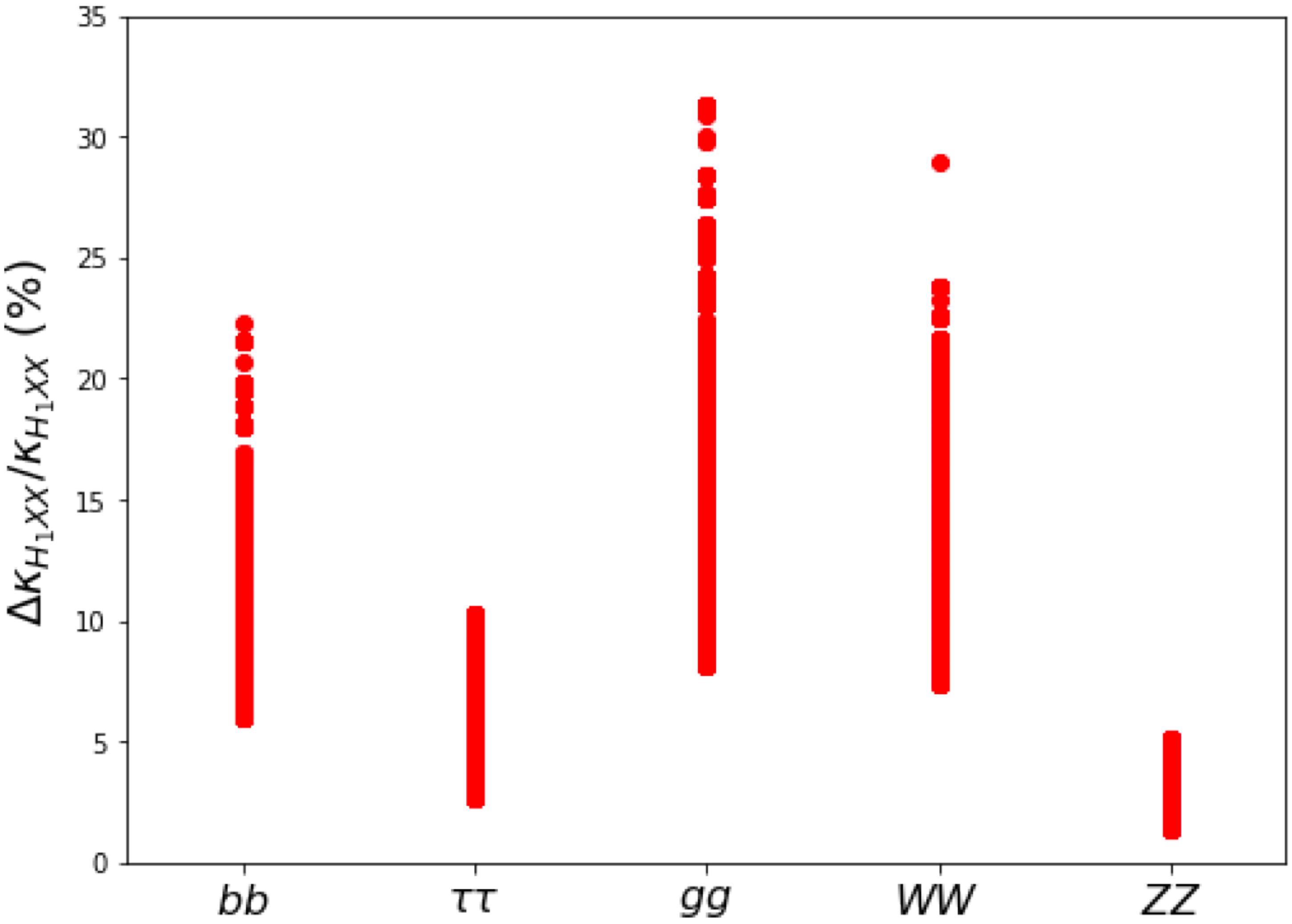
[T.K. Chen, C.W. Chiang, S.H., G. Weiglein '23]



$\Rightarrow$ part of the parameter space shows relevant deviations

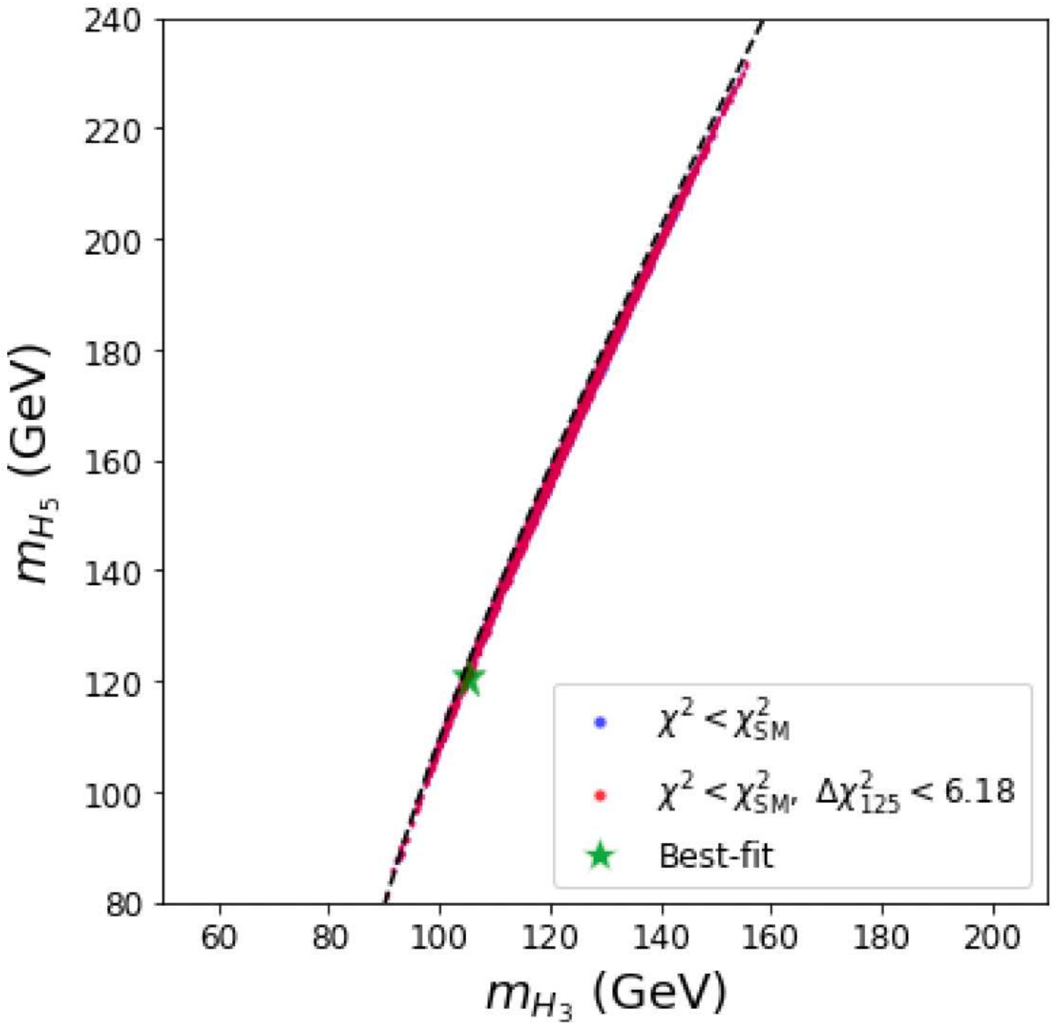
Future tests: h_{95}:

[T.K. Chen, C.W. Chiang, S.H., G. Weiglein '23]



$\Rightarrow$ precision coupling measurement possible

Note the favored mass scales: [T.K. Chen, C.W. Chiang, S.H., G. Weiglein '23]



$\Rightarrow$ Other Higgs bosons naturally found around $\sim$ 150 GeV

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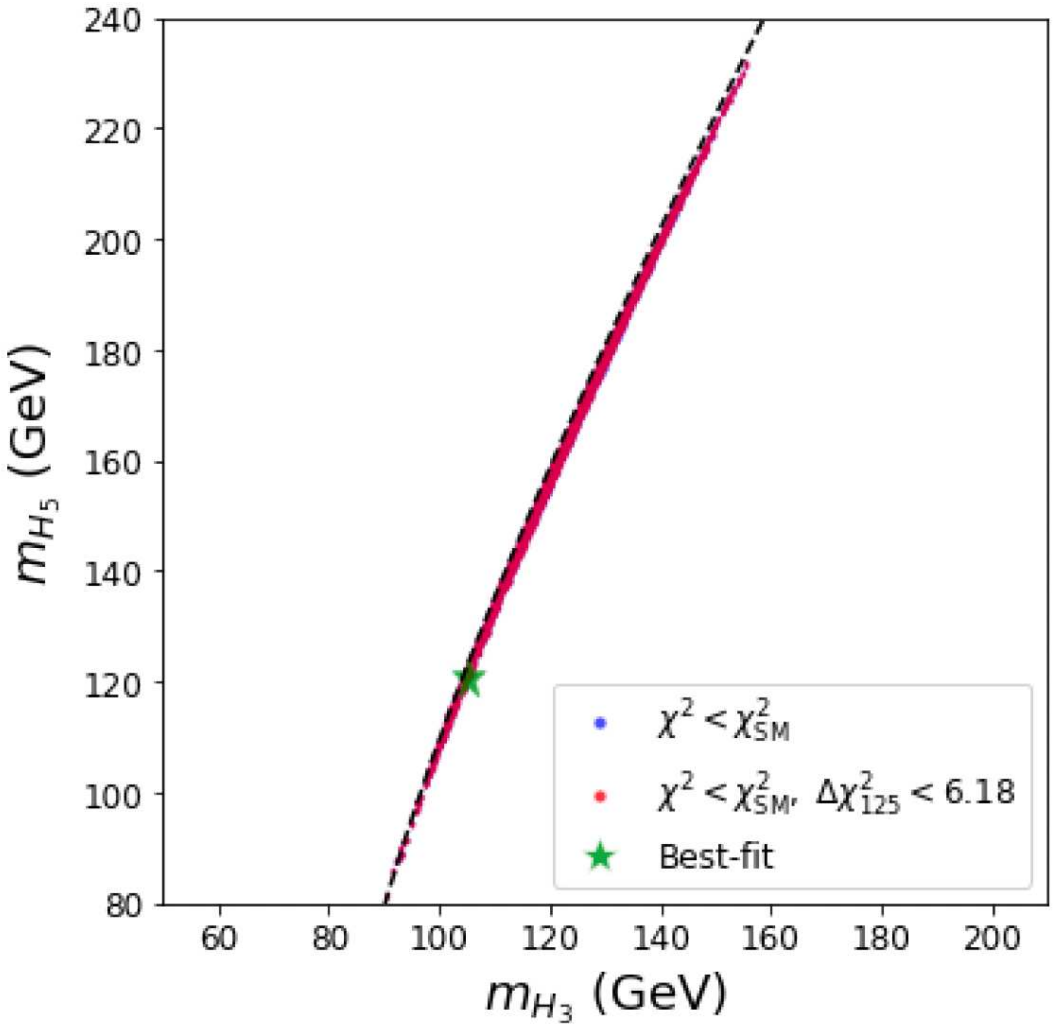

⇒ Other Higgs bosons naturally found around $\sim$ 150 GeV

⇒ can GM also fit the excesses around $\sim$ 152 GeV?

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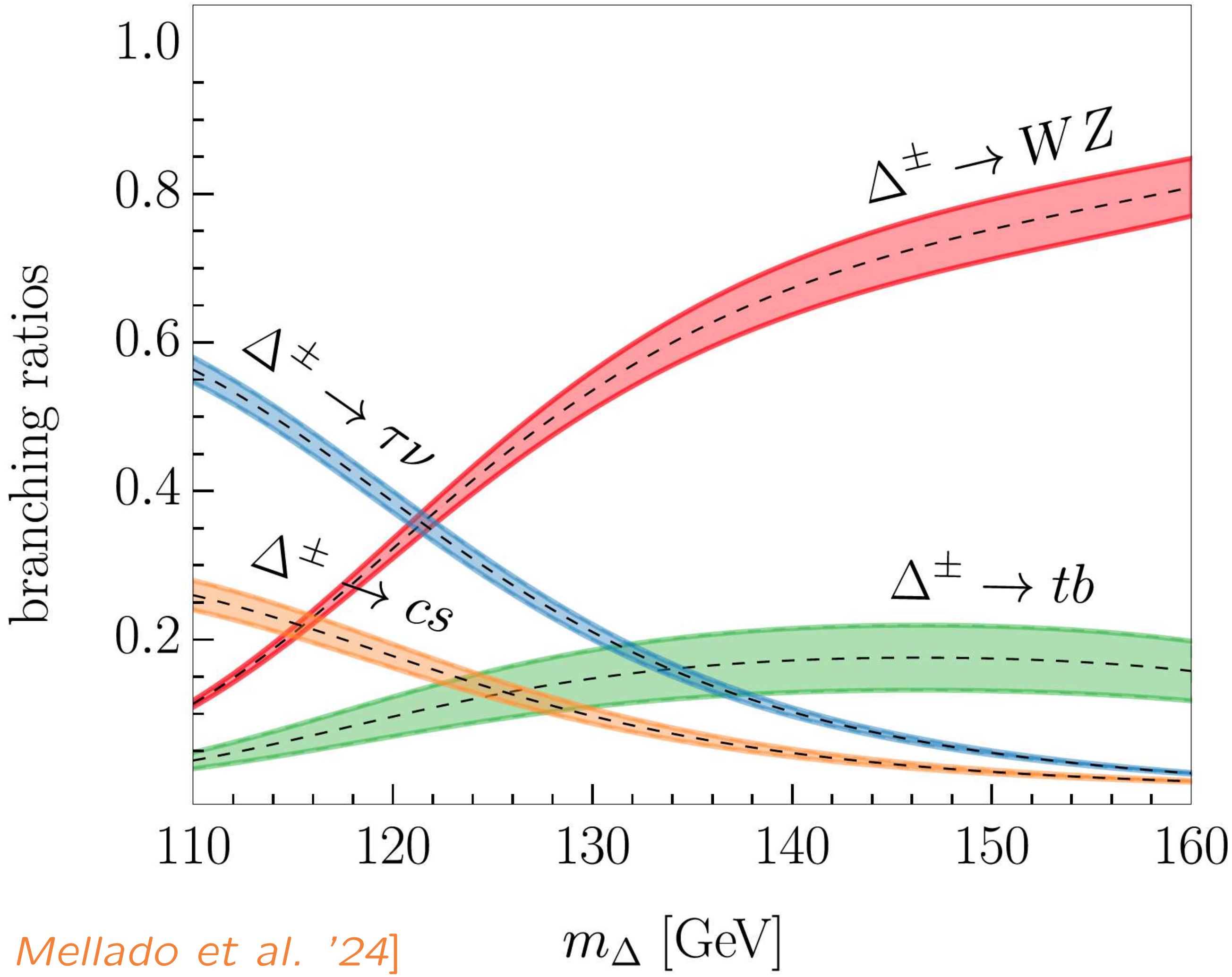


[*A. Crivellin, B. Mellado et al. '24*]

⇒ No! GM cannot produce this kind of "mixed BRs"

Solution: minimally extended GM:

[*Taken from T.K. Chen '25*]

Why (m)eGM?

TKC, Chiang, Yagyu, 2303.09294

- ❖The presence of $H^{\pm\pm}$ provides **potential enhancements in the di-photon signals**, as suggested by the previous stats.
- ❖The tree-level ρ **is not seriously spoiled**, as protected by the **(approximate) $SO(4)$ symmetry** in the (me)GM model.
- ❖The **GM model itself is too restrictive**: the scalar **couplings to WW and ZZ are of a fixed ratio** → cannot satisfy the H-152 signatures ($WW \gg ZZ$).

→ The **meGM model breaks this restriction benignly** by adding "perturbations" to the GM model.

Our treatment of SR's

[*Taken from T.K. Chen '25*]

Signal Regions (SR's)

ATLAS, 2301.10486
ATLAS, 2405.20040
Ashanujjaman, Banik, Coloretti, *et al.*, 2411.18618

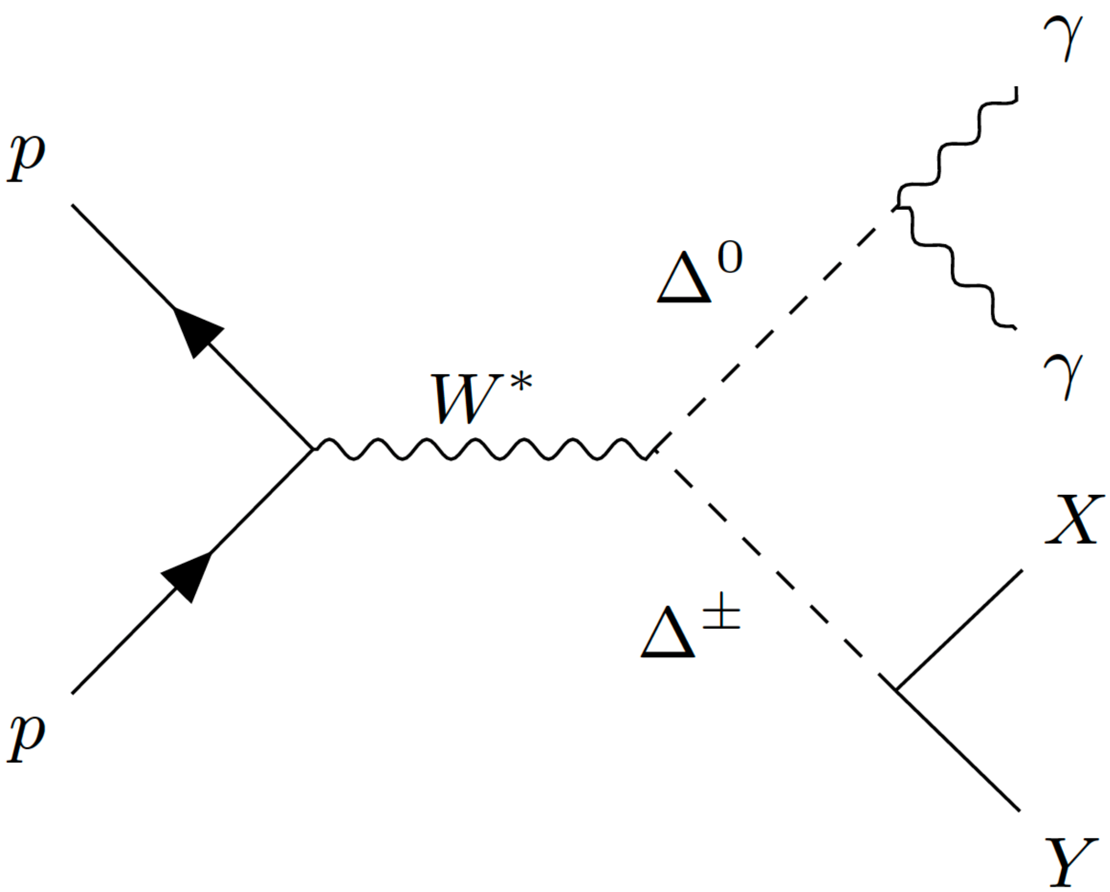
- Combining 2301.10486 and 2405.20040, 2411.18618 identified **eight relevant SR's** in which the charged Drell-Yan process will contribute to the excesses at 152 GeV. The WH and VBF processes also contribute only to these SR's.
- To properly address the statistics, we further **include the other twelve irrelevant SR's**, analyzing a total of **20 SR's**.
  → The overall χ^2 will become worse due to this.
- For each the SR, we fit the two bins at ~151 and 154 GeV (three of them only have one), making it a total of **37 bins**.

SM: $\chi^2/\mathrm{dof} \approx 43/37$

$\Rightarrow$ not good, but this also does not look like a $\sim 4\sigma$ excess

Add meGM contribution:

[T.K. Chen, C.W. Chiang, S.H., G. Weiglein PREL.]

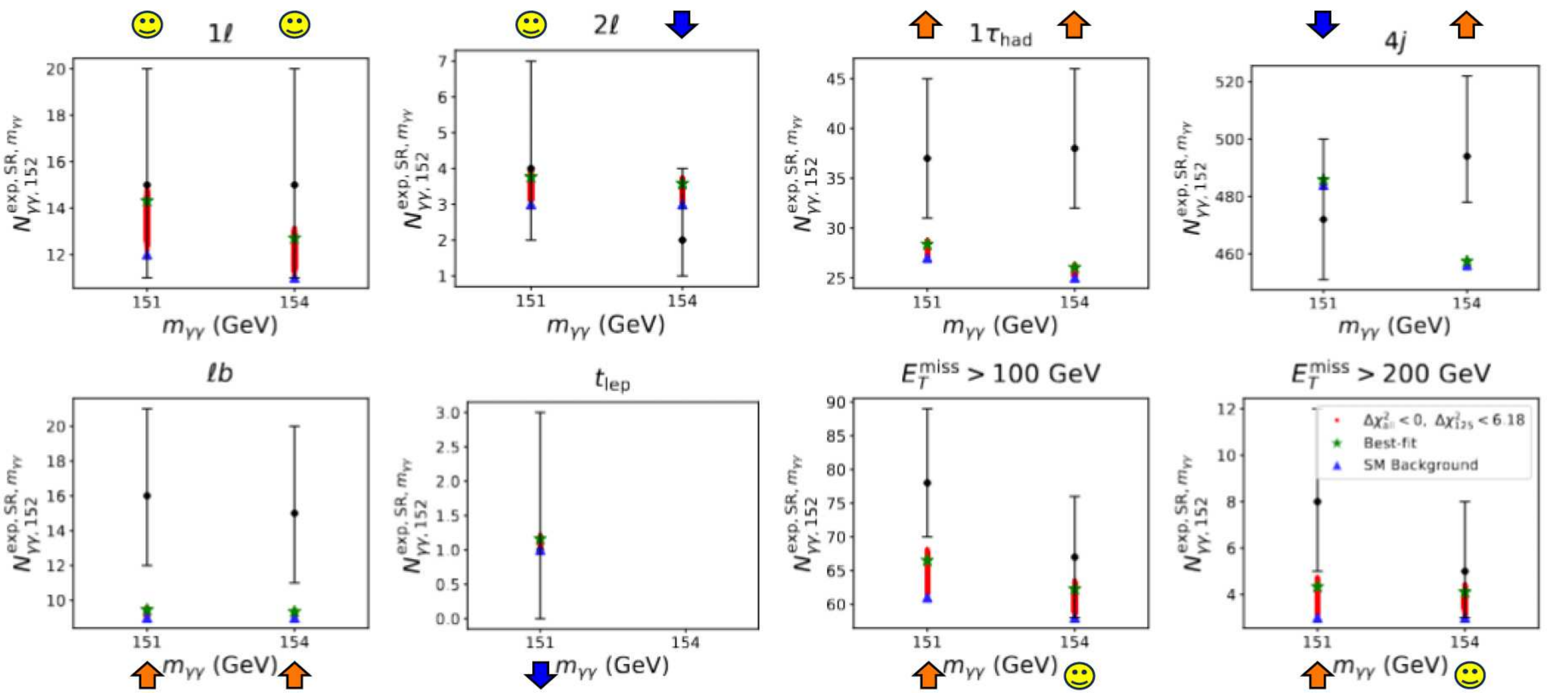


$m_{\Delta^0} \approx 152$ GeV, mixed state (H_3)

$m_{\Delta^\pm} \approx 152$ GeV also mixed state

The "8 selected SR's":

[T.K. Chen, C.W. Chiang, S.H., G. Weiglein, PREL.]

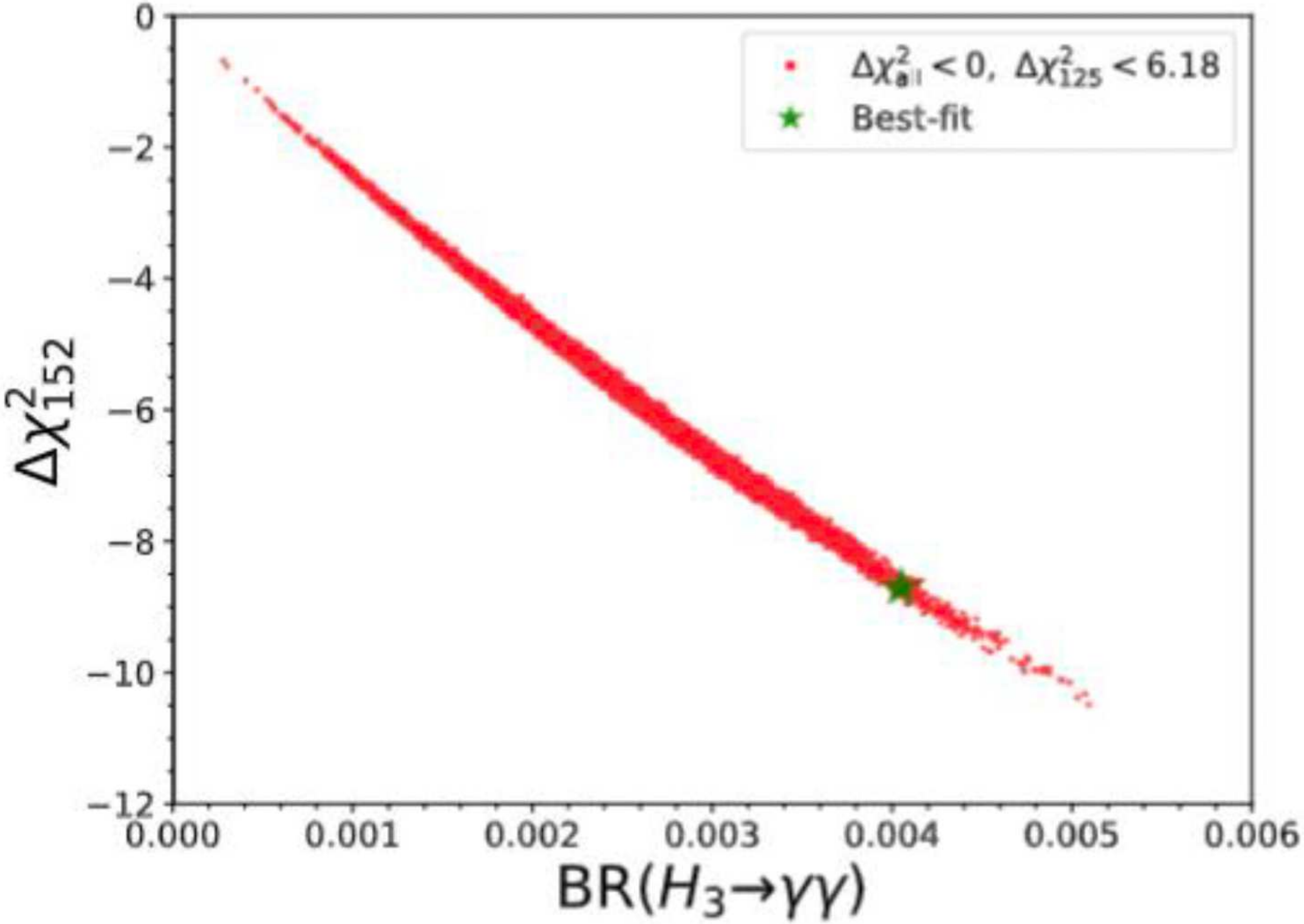


⇒ most SR's become better

⇒ 3 become worse (but "look ok")

Improvement in χ^2:

[T.K. Chen, C.W. Chiang, S.H., G. Weiglein, PREL.]



SM: $\chi^2/\mathrm{dof} \approx 43/37$

GM: $\chi^2/\mathrm{dof} \approx 33/37 \Rightarrow$ (relevantly?) better

A final word:

The LHC discovered a Higgs, the last particle predicted by the SM

But nothing since . . .

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$\Rightarrow$ Very likely that it manifests itsel at the (HL-)LHC!

$\Rightarrow$ there are many anomalies, some which fulfil all the criteria

but many will go away (experience . . .)

A final word:

The LHC discovered a Higgs, the last particle predicted by the SM

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NO: We know for sure: the SM is incomplete ⇒ we need new physics!

⇒ Very likely that it manifests itsel at the (HL-)LHC!

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We will see Physics Beyond the SM! LET'S GO EXPLORING!


Further Questions?