Karlsruher Institut für Technologie

Scalar extensions of the SM and recent discrepencies

Based on [2203.13180], [2204.05975] and [2208.14466] in collaboration with
Sven Heinemeyer, José Miguel No, María Olalla Olea Romacho, Georg Weiglein

57th Rencontres de Moriond: EW Interactions and Unified Theories

24th of March 2023

Thomas Biekötter

The SM Higgs sector

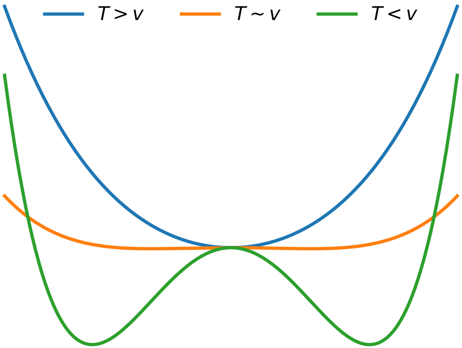
EW symmetry unbroken in early universe

$\downarrow$

Cross-over transition at $T \sim v$

$\downarrow$

EW symmetry broken at $T = 0$



Minimal parametrization of EW symmetry breaking

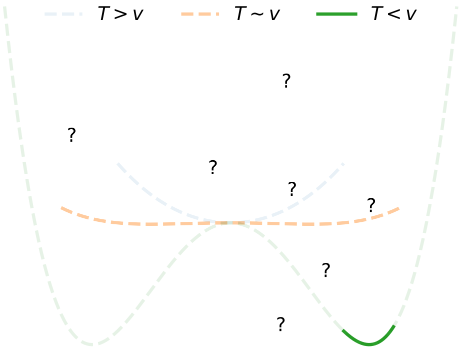
The SM Higgs sector

Consequences:

→ One physical scalar particle

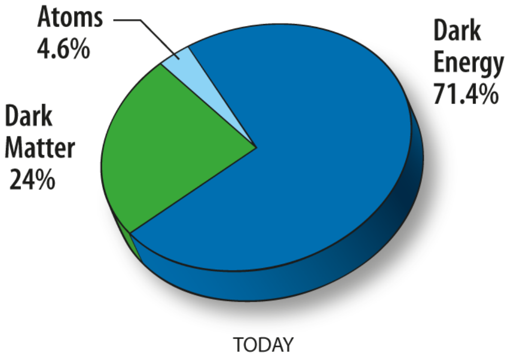
→ Couplings ∼ Mass

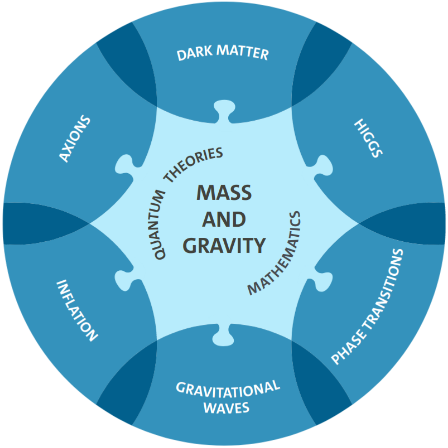
→ No CP violation in Higgs potential



Any departure from these predictions → BSM physics

Why extended Higgs sector?





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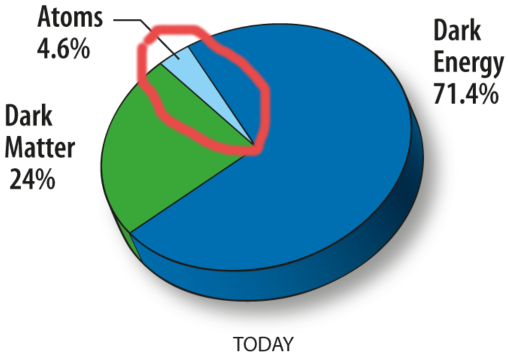
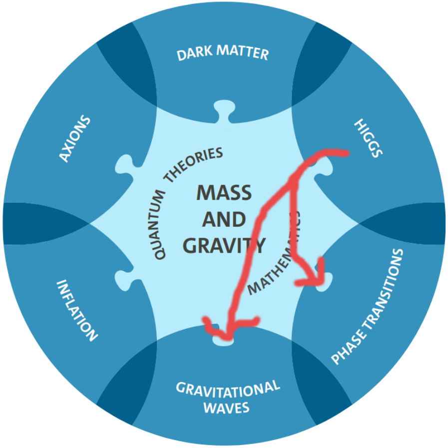


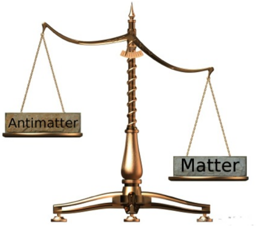


Matter-antimatter asymmetry

SM prediction: We do not exit: $\frac{n_b}{n_\gamma} \sim 6 \cdot 10^{-19}$

Observations: We exist: $\frac{n_b}{n_\gamma} \sim 6 \cdot 10^{-10}$

[BBN, CMB]



[D0, Fermilab]

Baryon Asymmetry of the Universe (BAU) $\rightarrow$ Sakharov conditions

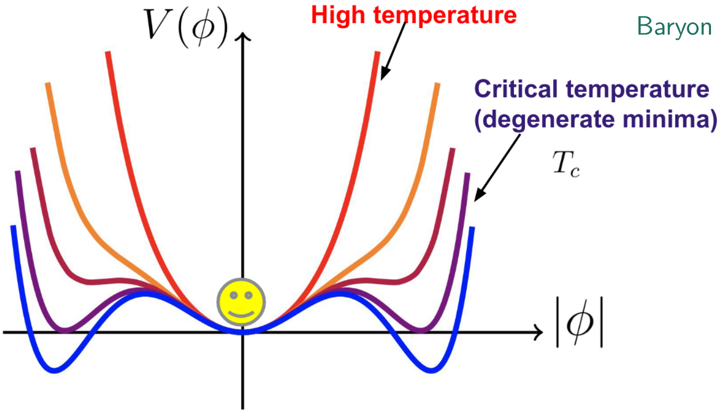
1. B violation
2. Loss of thermal equilibrium
3. C and CP violation

Electroweak baryogenesis: Requires BSM around the EW scale

EW baryogenesis

1st-order electroweak phase transition

[Slide: Olalla Olea, Susy2021]

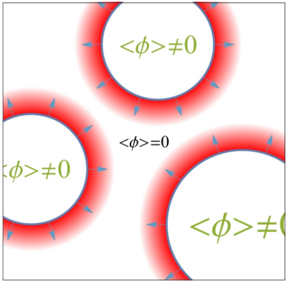


Currently probed at the LHC

Baryon number preservation criterion:

$$\frac{v}{T} \gtrsim 1$$

[Kuzmin, Rubakov, Shaposhnikov, Phys.Lett.B 155 (1985) 36]

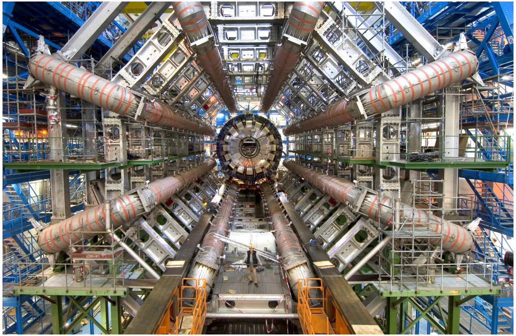


[José Miguel No]

Gravitational waves

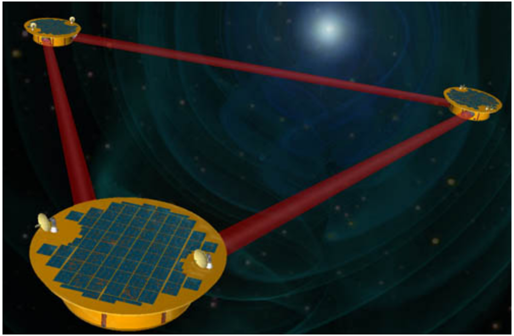
1st-order EWPT gives rise to a primordial stochastic GW background

LHC



[CERN]

LISA



[NASA]

Complementarity: Colliders $\leftrightarrow$ GW detectors

The (next-to) 2HDM

N2HDM = **2HDM**(ϕ_1, ϕ_2) + Real Scalar Singlet(ϕ_s)

Scalar tree-level potential

$$V_{\text{tree}} = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}]$$
$$\left(+\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2\right)$$

Extension of Z_2 ($\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$) to Yukawa sector $\Rightarrow$ 4 types of the **(N)2HDM**

Type-II/IV(flipped): u_R coupled to Φ_2, d_R coupled to Φ_1, ℓ_R coupled to Φ_1/Φ_2

EW vacuum:

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}, \quad \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad \langle\Phi_S\rangle = v_S/\sqrt{2} \quad \in \mathbb{R} \quad \tan\beta := v_2/v_1$$

Scalar spectrum: CP-even scalars h_1/h, h_2/H, h_3, CP-odd scalar A, charged scalars $H^\pm$

Opportunities?*,**

Cascade decays: 1st-order EWPT smoking gun signature $A \to ZH \to Zt\bar{t}$

h_{125} self coupling: Non-resonant pair production and GW

A scalar at 95 GeV? $gg \to h_{95} \to \gamma\gamma$ (CMS)
$gg \to h_{95} \to \tau^+\tau^-$ (CMS)
$e^+e^- \to Zh_{95} \to Zb\bar{b}$ (LEP)

W-boson mass: CDF measurement and weak isopin breaking

*Personal selection

**At LHC and future e^+e^- collider

1st-order EWPT in 2HDM-II

$[\tan\beta = 3,\ \cos(\beta-\alpha) = 0,\ m_A = m_{H^\pm}]$

Smoking gun at the (HL-)LHC:

$pp \to A \to ZH \to \ell^+\ell^- t\bar{t}$

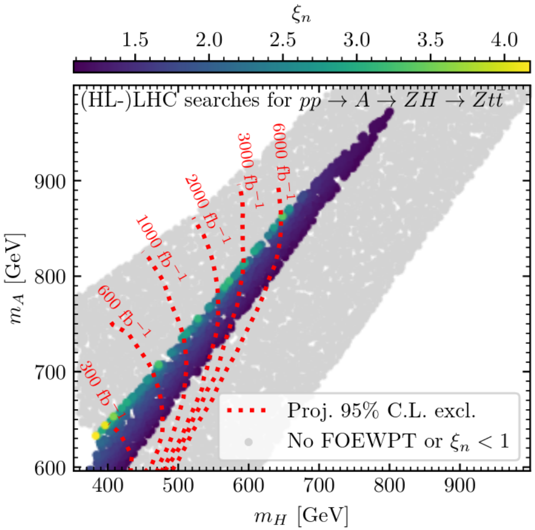
Vital to exploit the $H \to t\bar{t}$ channel

No limits yet!

Red: Extrapolations of projections for $41\ \mathrm{fb}^{-1}$

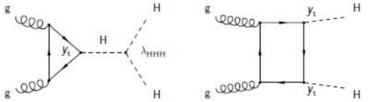
Huge discovery potential (low $\tan\beta$)

[TB, S. Heinemeyer, J. No, O. Olea, G. Weiglein, 2208.14466]



1st-order EWPT in 2HDM-II

Pair production and GW at LISA:

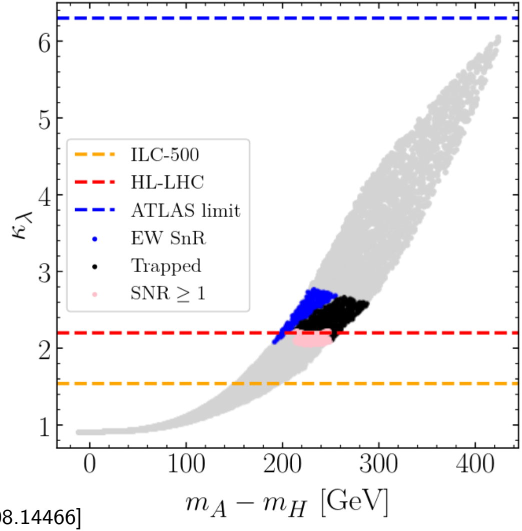


$$\kappa_\lambda = \frac{(\lambda_{hhh}^{2\mathrm{HDM}})^{(1)}}{(\lambda_{hhh}^{\mathrm{SM}})^{(0)}}$$

Expectations at LISA will be shaped by (HL-)LHC results

For points with potentially detectable GW signals:

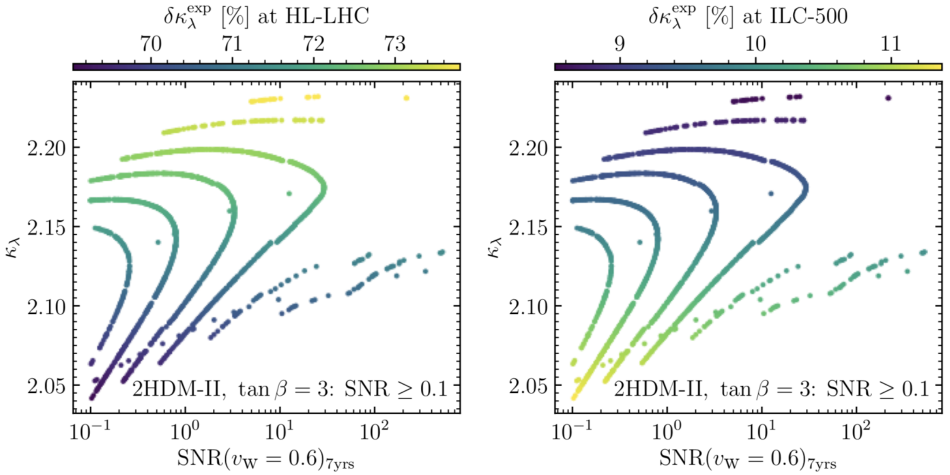
$$\kappa_\lambda \approx 2 \approx \text{exp. HL-LHC limit}$$



[TB, S. Heinemeyer, J. No, O. Olea, G. Weiglein, 2208.14466]

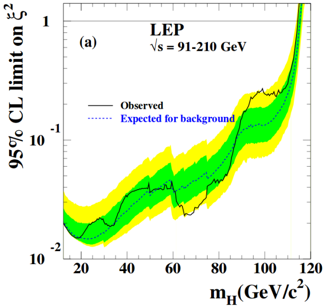
1st-order EWPT in 2HDM-II

Exp. precision on $\kappa_\lambda \approx 2$: (For $\kappa_\lambda = 1 : \delta\kappa_\lambda^{\text{exp}} = 60\%/27\%$ at HL-LHC/ILC-500)



[TB, S. Heinemeyer, J. No, O. Olea, G. Weiglein, 2208.14466]

The 95GeV excesses



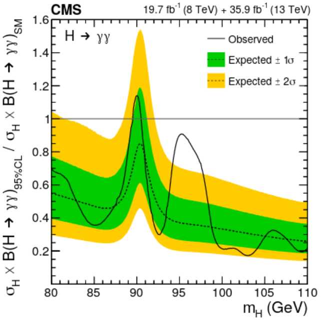
[LEP: hep-ex/0306033]

Local significance: 2.3σ

Extracted signal strength:

$$\mu_{bb}\left(e^+e^- \to Zh \to Zb\bar{b}\right) = 0.117 \pm 0.057$$

[Cao, Guo, He, Wu, Zhang: 1612.08522]



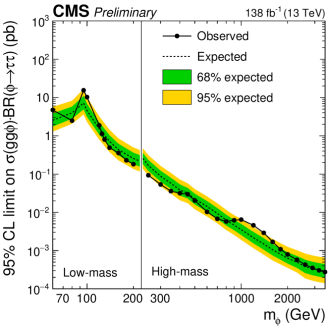
[CMS: 1811.08459]

Local significance: 2.8σ

Extracted signal strength:

$$\mu_{\gamma\gamma}\left(gg \to h \to \gamma\gamma\right) = 0.6 \pm 0.2$$

[CMS: 1811.08459]



[CMS: 2208.02717]

Local significance: 3.1σ

Extracted signal strength:

$$\mu_{\tau\tau}\left(gg \to h \to \tau^+\tau^-\right) = 1.2 \pm 0.5$$

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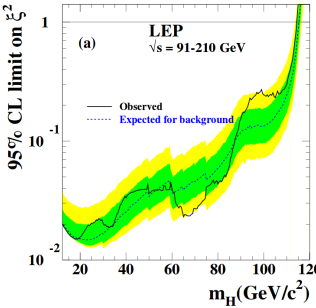

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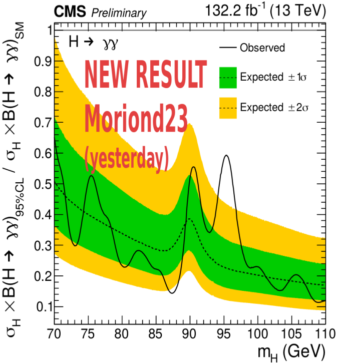
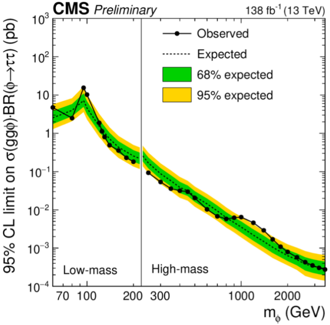


[CMS HIG-20-002]

Local significance: 2.9σ

Extracted signal strength:

$$\mu_{\gamma\gamma}\left(gg \to h \to \gamma\gamma\right) \approx 0.35$$



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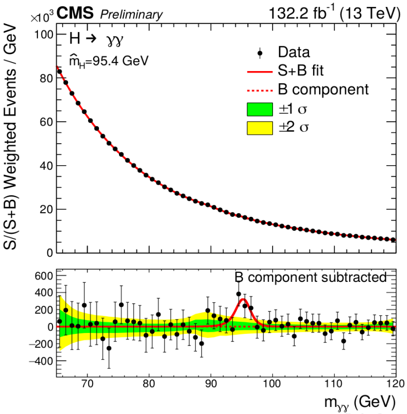
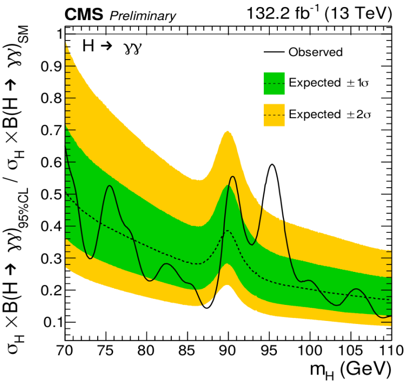
This week's news from CMS





[CMS: CMS HIG-20-002]

Refined analysis (see Susan Gascon-Shotkin's talk), but the excess persists in the updated analysis!

$\approx 3\sigma$ local significance (unchanged), but signal strength reduced

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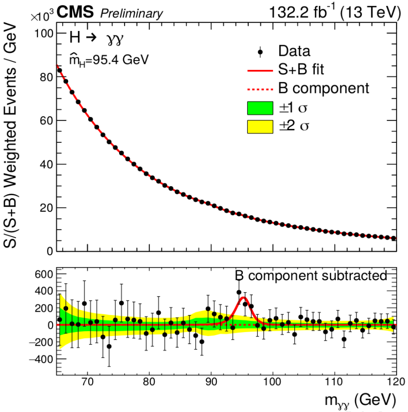

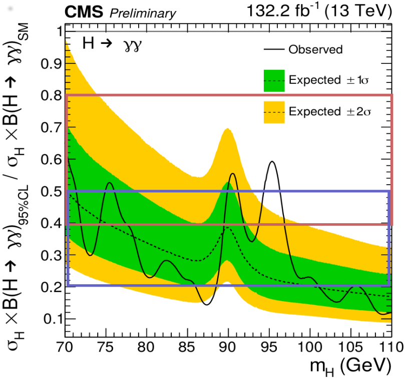

[CMS: CMS HIG-20-002]

$\mu_{\gamma\gamma}^{\text{1st-year Run 2}} = 0.6 \pm 0.2$

$\mu_{\gamma\gamma}^{\text{Full Run 2}} \approx 0.35 \pm 0.12$

[TB, S. Heinemeyer, G. Weiglein, 2303.12018]

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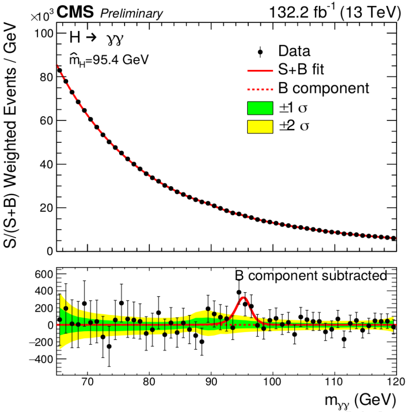

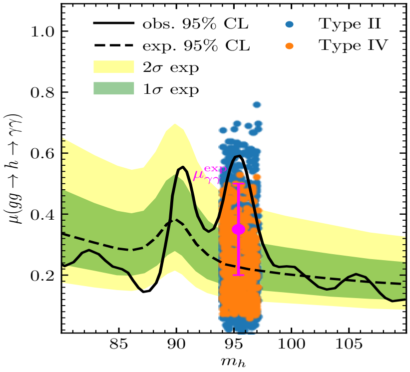

Implications:

[TB, S. Heinemeyer, G. Weiglein, 2303.12018]

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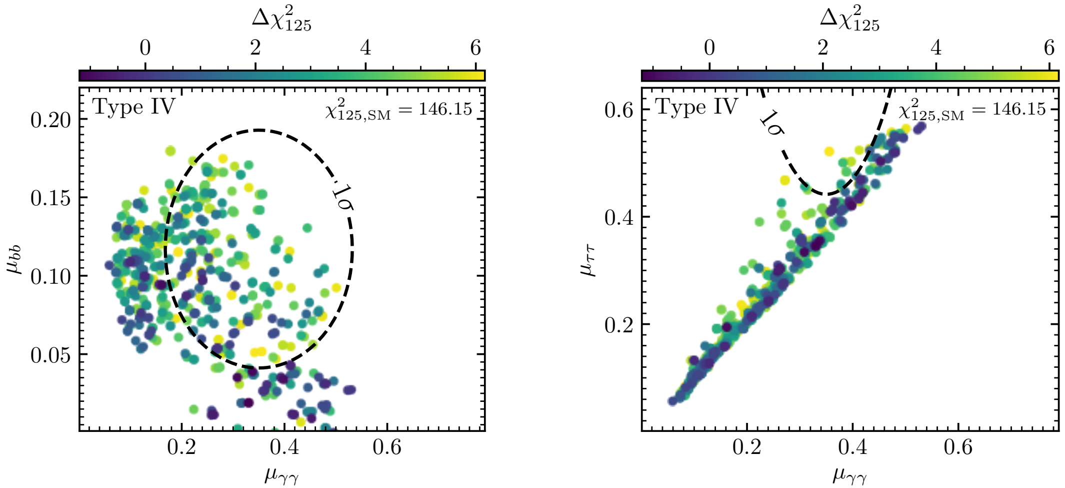
Singlet-extended 2HDM



[TB, S. Heinemeyer, G. Weiglein, 2303.12018]

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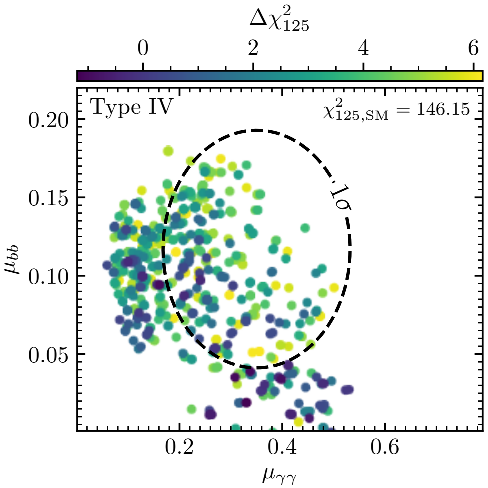
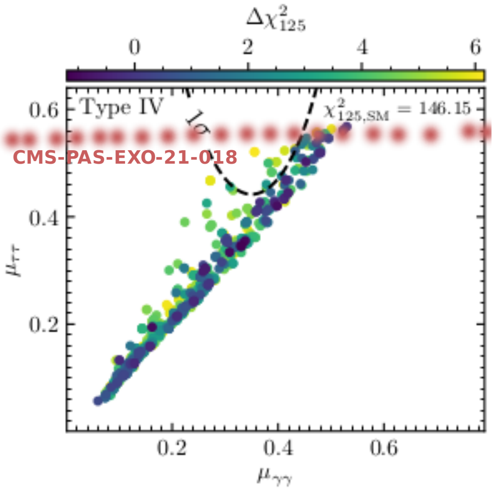
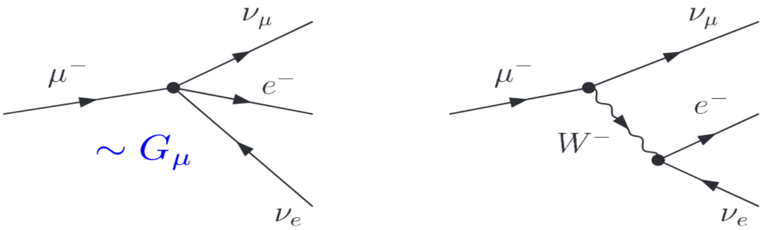




CMS-PAS-EXO-21-018: ttH with $H \to \tau^+\tau^-$

[TB, S. Heinemeyer, G. Weiglein, 2303.12018]

M_W in the SM and beyond



$$\Rightarrow M_W^2 = M_Z^2 \left(\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\alpha\pi}{\sqrt{2} G_\mu M_Z^2}(1 + \Delta r)} \right) = M_W^2(G_\mu, \alpha, M_Z, \Delta r(m_t, m_b, \dots))$$

$$\text{Loop corrections: } \Delta r = \Delta\alpha - \frac{c_w^2}{s_w^2}\Delta\rho + \dots$$

Custodial symmetry: $\rho = 1$ at classical level $\leftarrow$ holds in (N)2HDM

Quantum corrections from isospin splitting: $\Delta\rho \neq 0$

SM: $\Delta\rho \sim (m_t^2 - m_b^2)$ (N)2HDM: $\Delta\rho \sim (m_A^2 - m_{H^\pm}^2)(m_H^2 - m_{H^\pm}^2)$

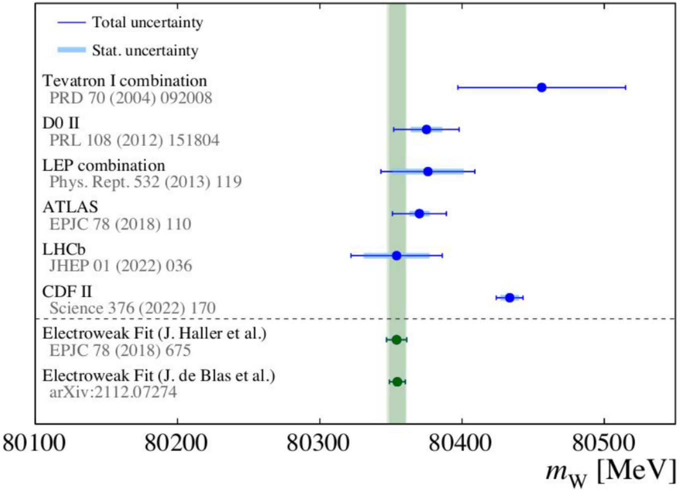
CDF measurement of M_W

What to make of this?

At the moment it is not justified to disregard neither the CDF measurement nor the previous ones

Precision of M_W measurements dominates EW fits in SM and beyond (second most important: $\sin^2\theta_{\rm eff}$)

New PDG average will have significantly inflated uncertainties



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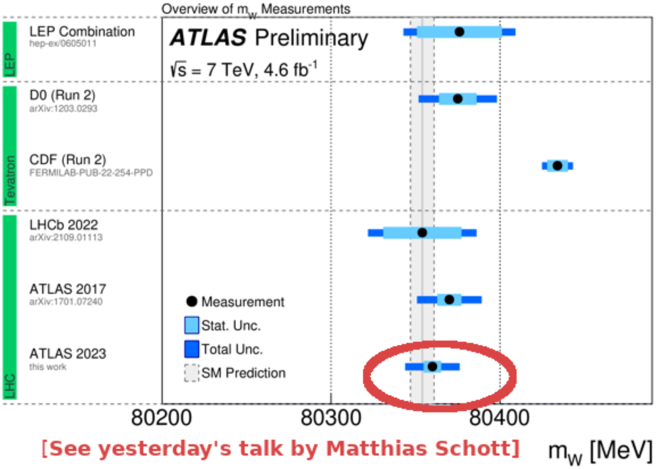
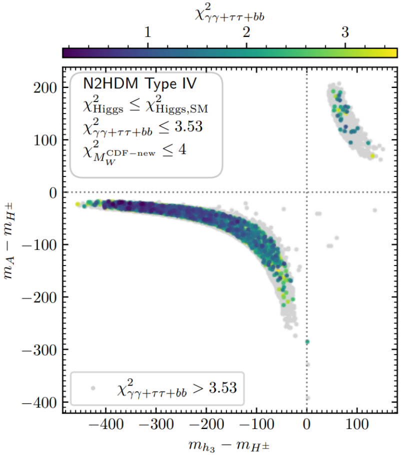


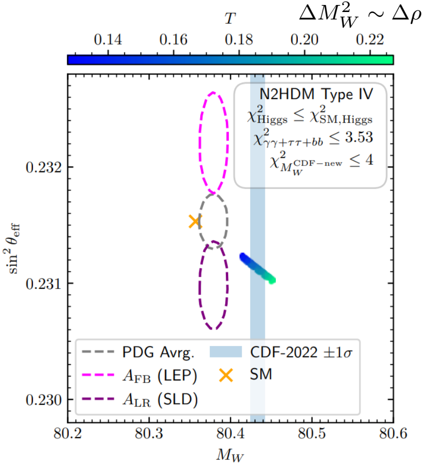
[See yesterday's talk by Matthias Schott]

M_W and a Higgs boson at 95 GeV

$\Delta M_W^2 \sim \Delta\rho = \alpha T$



Coloured points fit excesses at 95 GeV
Preferred mass hierarchy: $m_{h_3} < m_A \approx m_{H^\pm}$



Preference: $\sin^2\theta_{\text{eff}}$ extracted from A_{LR} measured at SLD

[TB, S. Heinemeyer, G. Weiglein, 2204.05975]

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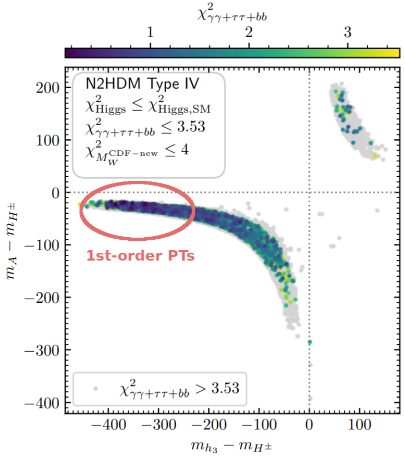

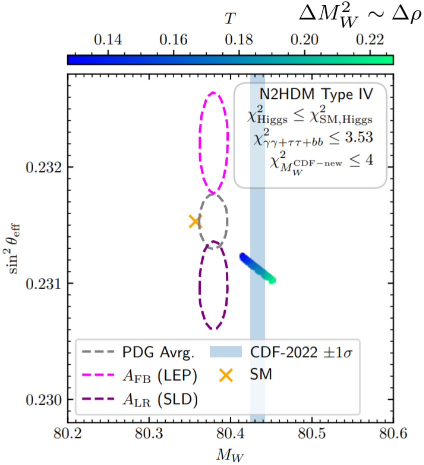

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Conclusions and prospects

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EW baryogenesis smoking gun: Searches are ongoing by CMS (U. Hamburg) and ATLAS (U. Freiburg) [AFAIK]

Self-coupling of h_{125}: 1st-order EWPT in 2HDM $\rightarrow$ Difficult to probe at HL-LHC
$\rightarrow e^+e^-$ collider at $\sqrt{s} = 500$ GeV: $\delta\kappa_\lambda \approx 10\%$ for $\kappa_\lambda \approx 2$

$\mathrm{M_W}$ in 2HDMs: Cannot disregard neither the CDF measurement nor the previous ones
Problem for pheno analyses: EW fits driven by M_W
$\rightarrow$ Conclusions depend on what you choose (average value? ...separate scans?)

Excesses at 95 GeV: Clarification from low-mass di-photon searches with full Run 2 data

Thanks!

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Excesses at 95 GeV: Clarification from ATLAS low-mass di-photon searches with full Run 2 data

Thanks!

ATLAS di-photon search ($80 fb^{-1}$)

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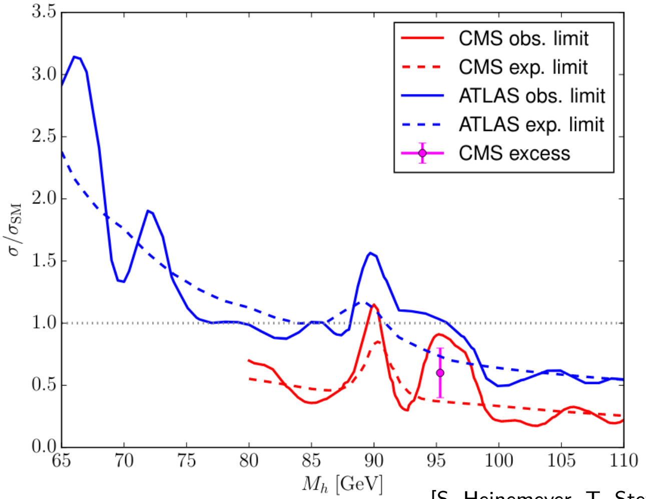
[ATLAS-CONF-2018-025]



[S. Heinemeyer, T. Stefaniak, 1812.05864]

B-number preservation criterion

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Outside the bubbles: Quantum mechanical sphaleron processes create the B-asymmetry

Inside the bubbles: Sphalerons must be suppressed.

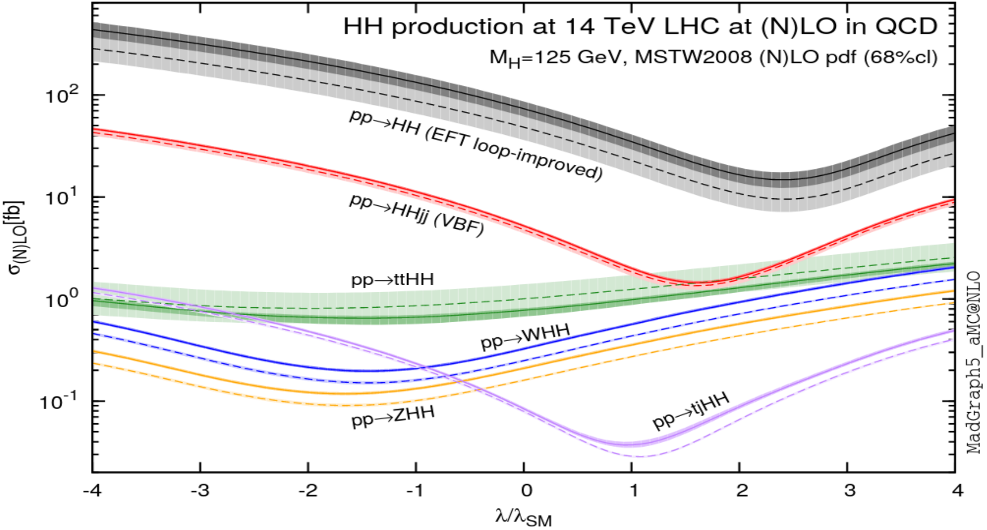
S.Dimopoulos, L. Susskind, Phys.Rev.D 18 (1978) 4500-4509:

> events are really important. The point is that the rates for these processes are of the renormalizable type for T>250 GeV. Thus they can allow the system to return to equilibrium and may wash out any excess which developed at super high temperature.

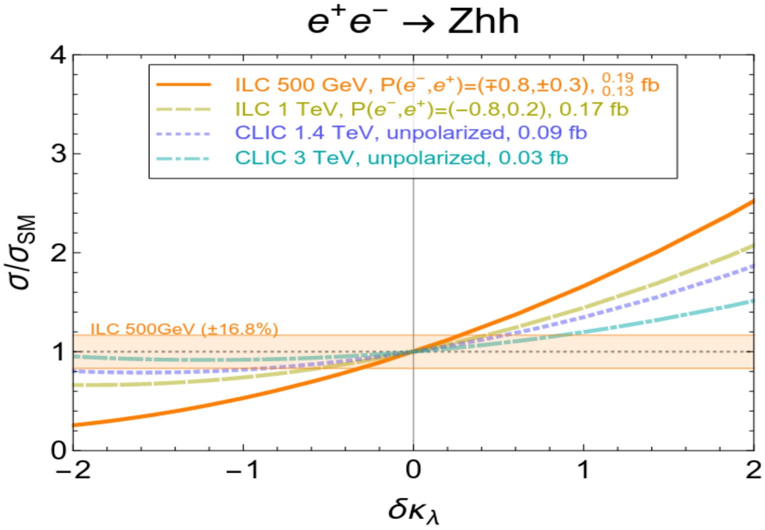
Condition to prevent the washout of the asymmetry: $$\frac{v}{T} \gtrsim 1$$

$\rightarrow$ Strong 1st-order phase transition [Kuzmin, Rubakov, Shaposhnikov, Phys.Lett.B 155 (1985) 36]

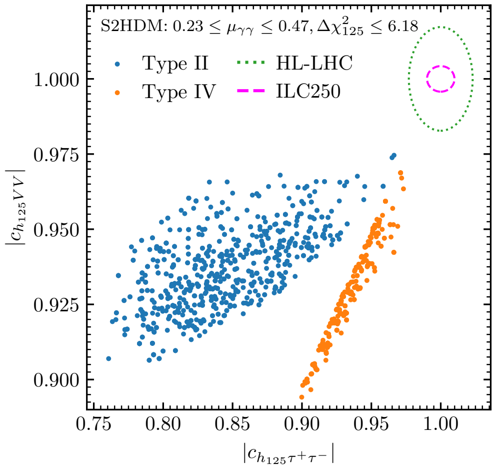
HH pair production at the LHC



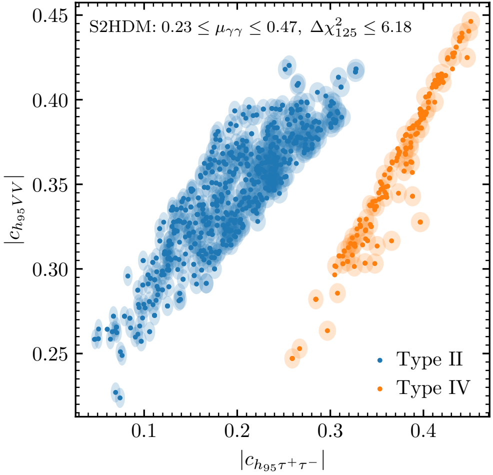
HH pair production at the ILC



h95: Future prospects

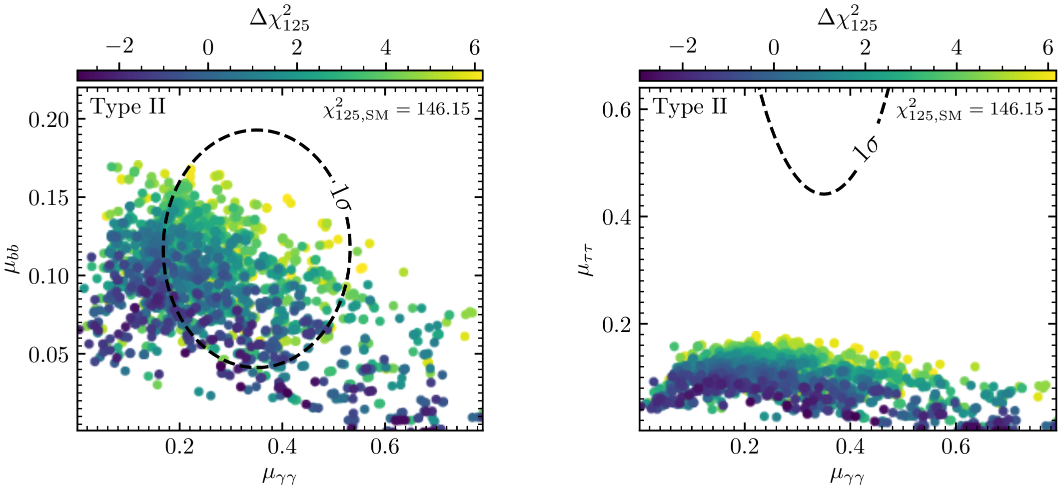


Indirect via h125 couplings



Directly producung h95 at ILC

Singlet-extended 2HDM



[TB, S. Heinemeyer, G. Weiglein, 2303.12018]