Where is SUSY?

Georg Weiglein,

DESY & UHH, 03 / 2023

Universität Hamburg
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CLUSTER OF EXCELLENCE
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DESY.

Introduction: many open questions of particle physics

Discovered Higgs boson: what is the underlying physics?
We have a description of the known particles and their interactions, but we do not know the underlying dynamics

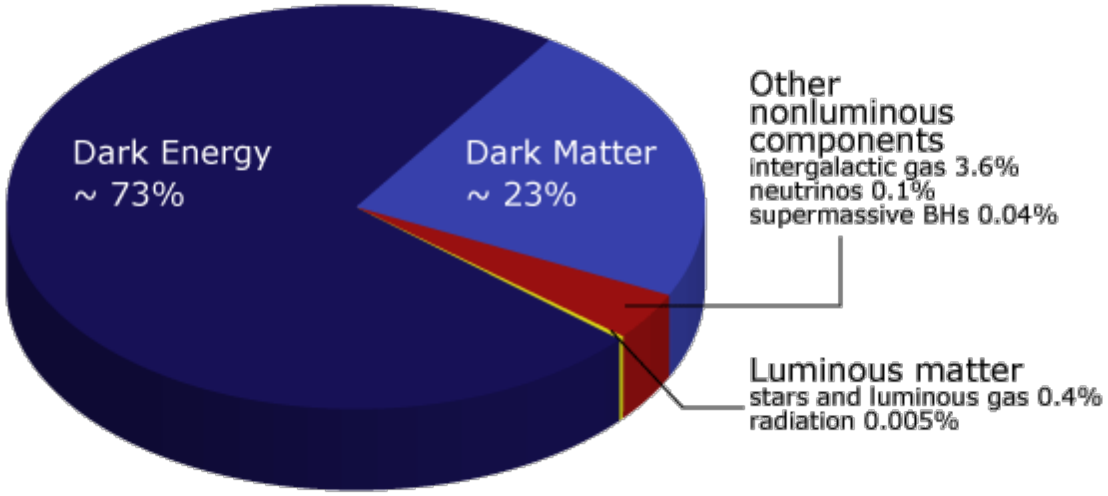
``Hierarchy problem": the puzzle of the Higgs mass, $M_H \approx 125$ GeV
All other elementary particle masses are ``protected" from physics at much higher scales (gravity, …) by known symmetries.
But what protects M_H?

Explanation for the imbalance between matter and anti-matter in the universe?

Connection to dark matter and dark energy and to the phase of inflation in the early universe?

Many open questions of particle physics

- Nature of the ``dark sector” of the universe?

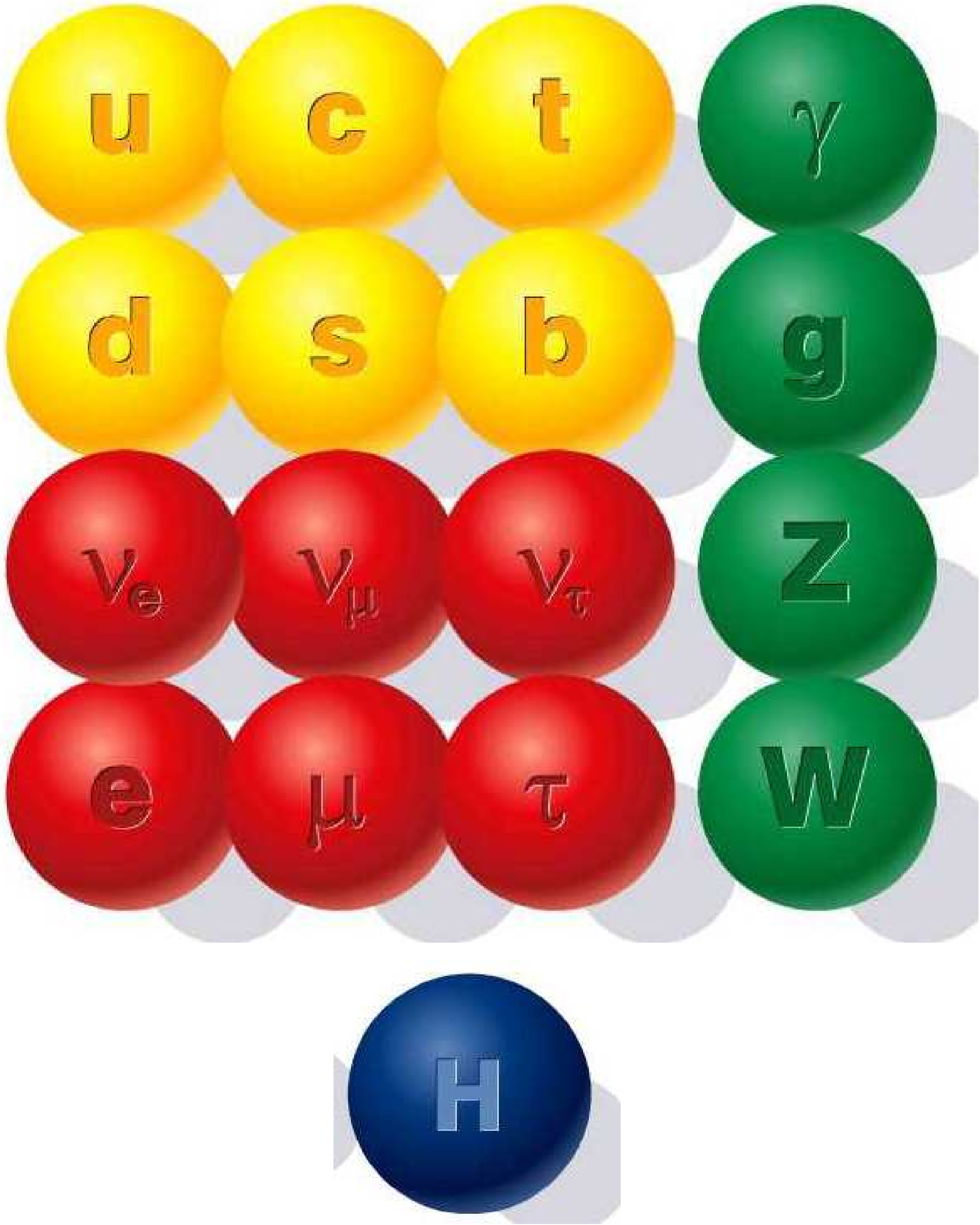


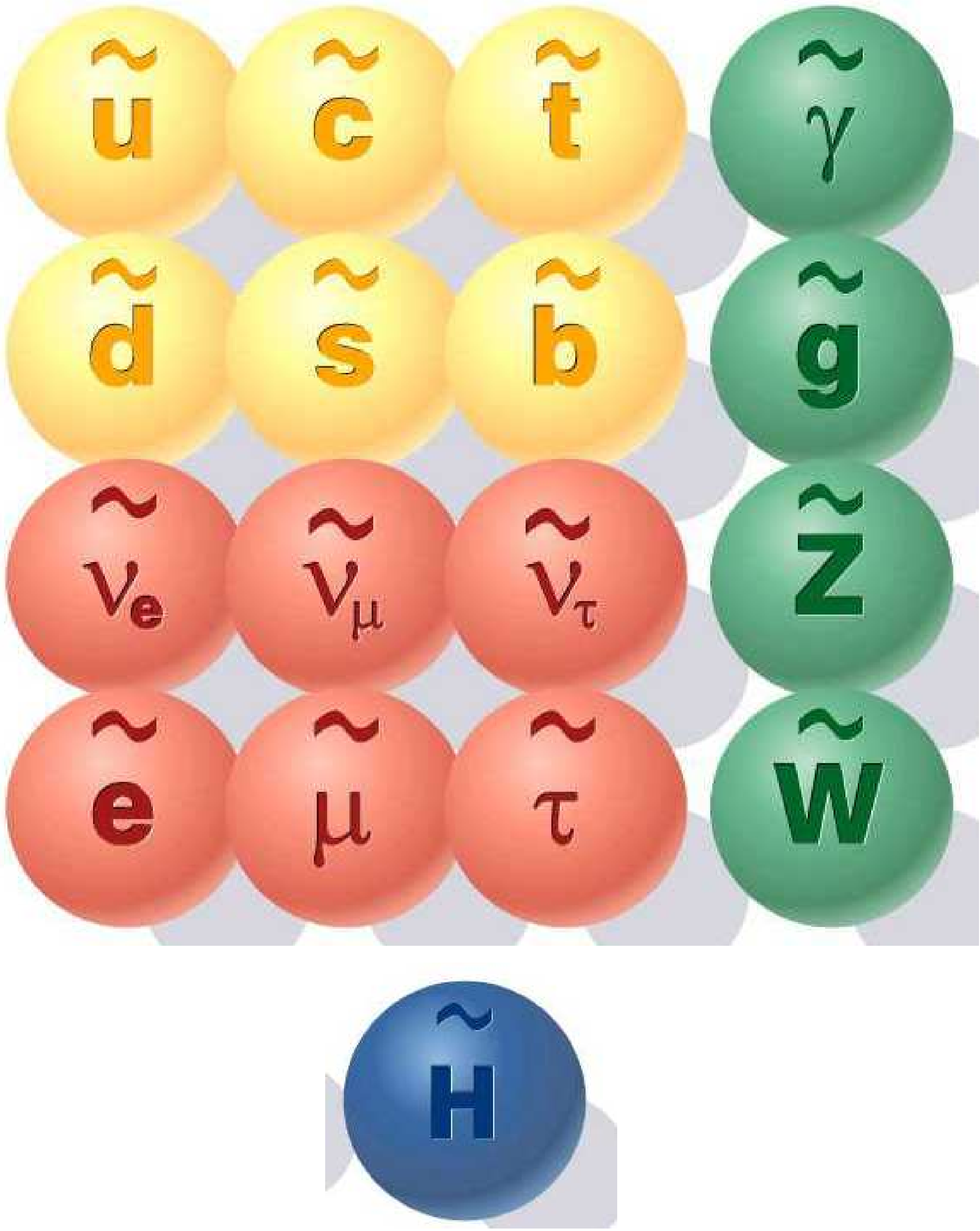
- Origin of the observed patterns of flavour (quarks, neutrino physics)?
- How is gravity related to the quantum world? Quantum structure of space-time? Are there more than three dimensions of space?
- Unification of the fundamental interactions of nature?
- …

⇒ Strong motivation for BSM physics

Particularly attractive possibility addressing many of the open questions: supersymmetry (SUSY)

Supersymmetry: fermion ⟷ boson symmetry,
leads to compensation of large quantum corrections





The minimal supersymmetric extension of the Standard Model (MSSM)

Superpartners for Standard Model particles:

$\left[u, d, c, s, t, b\right]_{L,R}$ $\left[e, \mu, \tau\right]_{L,R}$ $\left[\nu_{e,\mu,\tau}\right]_{L}$ Spin $\frac{1}{2}$

$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R}$ $\left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R}$ $\left[\tilde{\nu}_{e,\mu,\tau}\right]_{L}$ Spin 0

$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0}$ Spin 1 / Spin 0

$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4}$ Spin $\frac{1}{2}$

Two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

Exact SUSY $\Leftrightarrow m_{\mathrm{e}} = m_{\tilde{\mathrm{e}}}, \ldots$

$\Rightarrow$ SUSY can only be realised as a broken symmetry

MSSM: no particular SUSY breaking mechanism assumed, parameterisation of possible soft SUSY-breaking terms

Supersymmetry (SUSY)

SUSY: unique possibility to connect space–time symmetry (Lorentz invariance) with internal symmetries (gauge invariance):

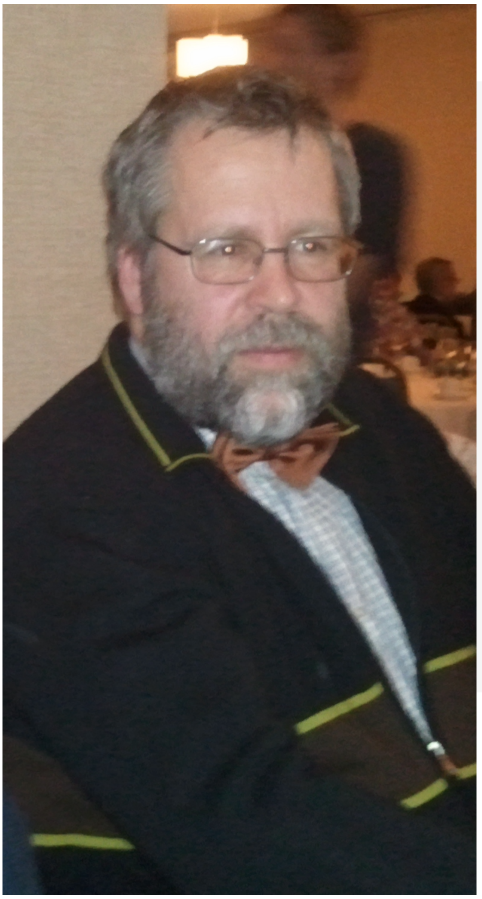
Unique extension of the Poincaré group of symmetries of relativistic quantum field theories in $3+1$ dimensions

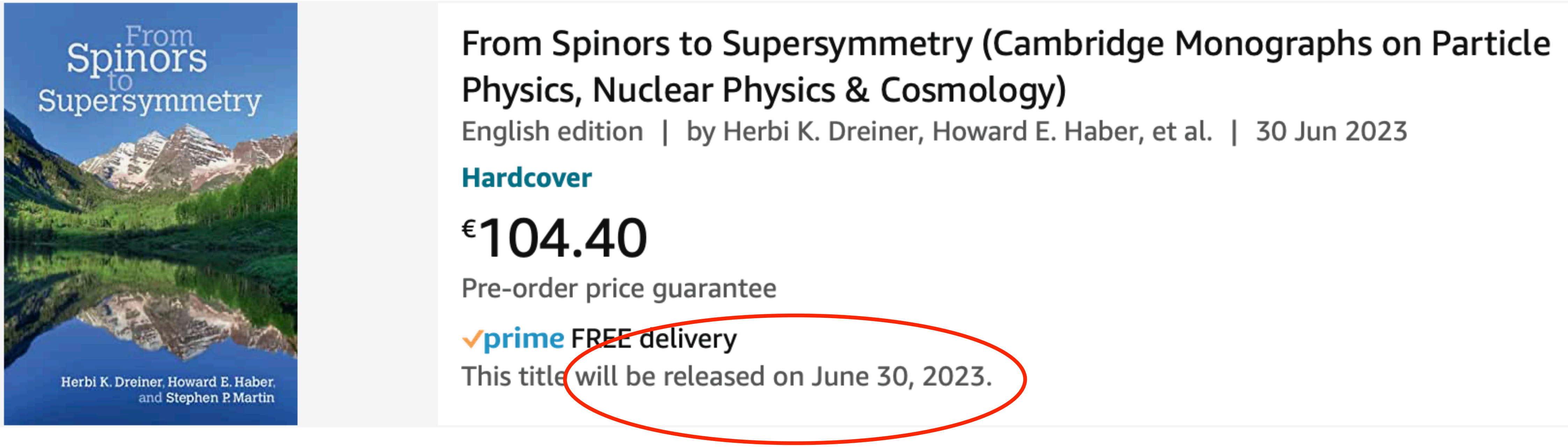
Local SUSY includes gravity, called “supergravity”

Lightest superpartner (LSP) is stable if “R parity” is conserved
$\Rightarrow$ Candidate for cold dark matter in the Universe

Gauge coupling unification, $M_{\mathrm{GUT}} \sim 10^{16}$ GeV
neutrino masses: see-saw scale $\sim .01$–$.1\, M_{\mathrm{GUT}}$

SUSY: ``the book”





From Spinors to Supersymmetry (Cambridge Monographs on Particle Physics, Nuclear Physics & Cosmology)

English edition | by Herbi K. Dreiner, Howard E. Haber, et al. | 30 Jun 2023

Hardcover

€104.40

Pre-order price guarantee

✓prime FREE delivery

This title will be released on June 30, 2023.

Supersymmetry is an extension of the successful Standard Model of particle physics; it relies on the principle that fermions and bosons are related by a symmetry, leading to an elegant predictive structure for quantum field theory. This textbook provides a comprehensive and pedagogical introduction to supersymmetry and spinor techniques in quantum field theory. By utilising the two-component spinor formalism for fermions, the authors provide many examples of practical calculations relevant for collider physics signatures, anomalies, and radiative corrections. They present in detail the component field and superspace formulations of supersymmetry and explore related concepts, including the theory of extended Higgs sectors, models of grand unification, and the origin of neutrino masses. Numerous exercises are provided at the end of each chapter. Aimed at graduate students and researchers, this volume provides a clear and unified treatment of theoretical concepts that are at the frontiers of high energy particle physics.

Print length

1025 pages

SUSY with R-parity violation

Most general gauge-invariant and renormalizable superpotential with chiral superfields of the MSSM:

$$\mathcal{V} = \mathcal{V}_{\text{MSSM}} + \underbrace{\frac{1}{2}\lambda^{ijk} L_i L_j E_k + \lambda'^{ijk} L_i Q_j D_k + \mu'^{i} L_i H_u}_{\text{violate lepton number}} + \underbrace{\frac{1}{2}\lambda''^{ijk} U_i D_j D_k}_{\text{violates baryon number}}$$

If both lepton and baryon number are violated

⇒ rapid proton decay

Minimal choice (MSSM) contains only terms in the Lagrangian with even number of SUSY particles ⇒ additional symmetry: “R parity”

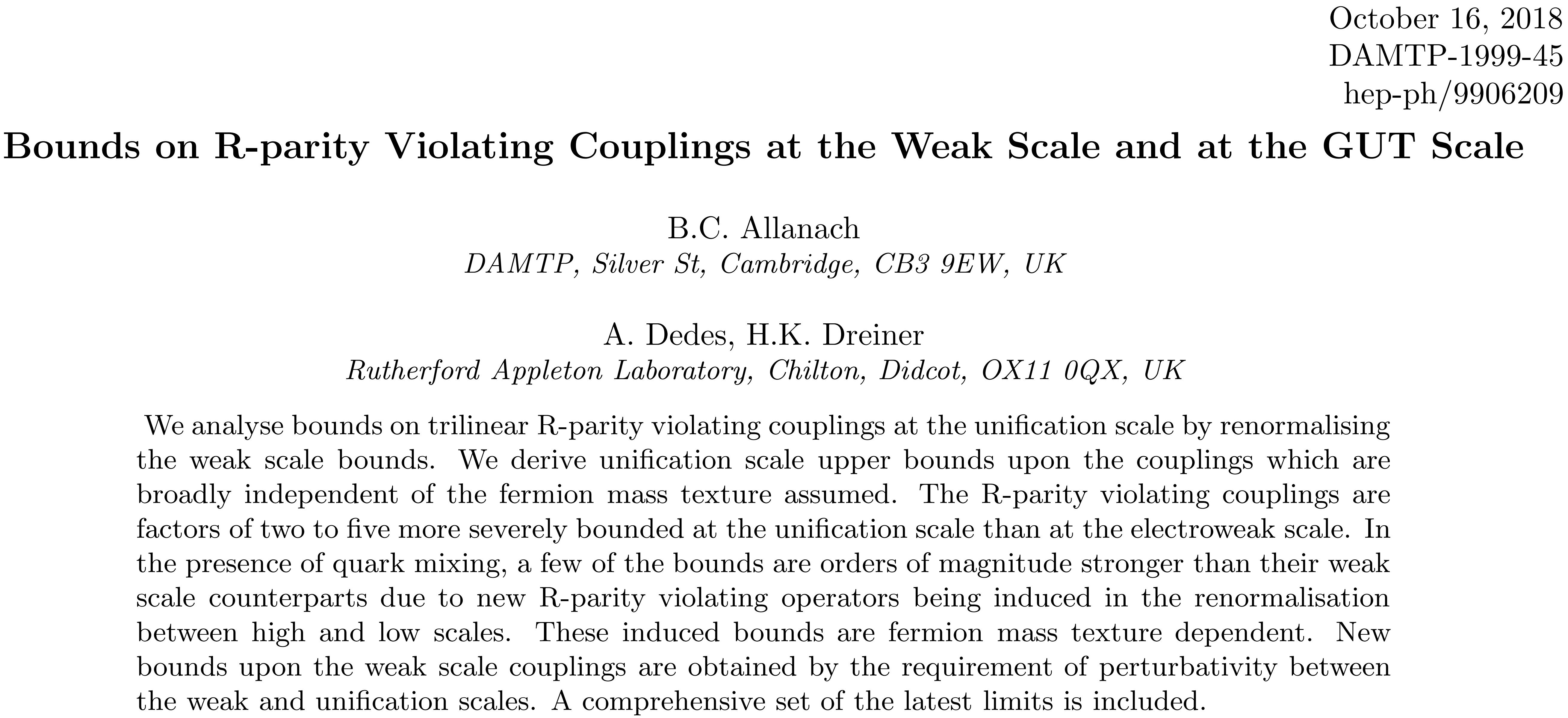
⇒ all SM particles have even R parity, all SUSY particles have odd R parity

SUSY with R-parity violation

R-parity violating SUSY has a very rich phenomenology

Herbi has 47 papers where R-parity violation appears in the title!

SUSY with R-parity violation



October 16, 2018
DAMTP-1999-45
hep-ph/9906209

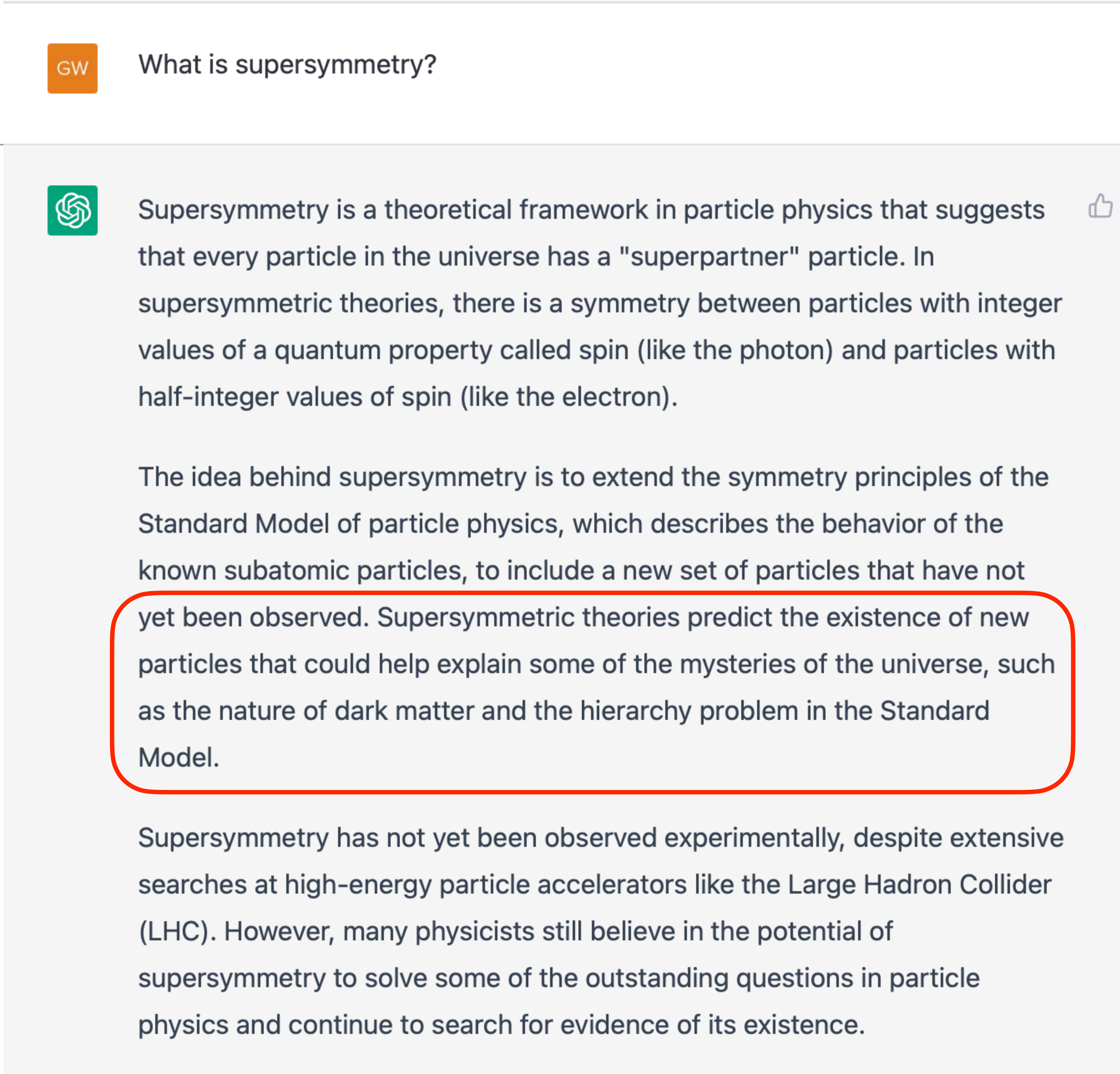
Bounds on R-parity Violating Couplings at the Weak Scale and at the GUT Scale

B.C. Allanach
DAMTP, Silver St, Cambridge, CB3 9EW, UK

A. Dedes, H.K. Dreiner
Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, UK

We analyse bounds on trilinear R-parity violating couplings at the unification scale by renormalising the weak scale bounds. We derive unification scale upper bounds upon the couplings which are broadly independent of the fermion mass texture assumed. The R-parity violating couplings are factors of two to five more severely bounded at the unification scale than at the electroweak scale. In the presence of quark mixing, a few of the bounds are orders of magnitude stronger than their weak scale counterparts due to new R-parity violating operators being induced in the renormalisation between high and low scales. These induced bounds are fermion mass texture dependent. New bounds upon the weak scale couplings are obtained by the requirement of perturbativity between the weak and unification scales. A comprehensive set of the latest limits is included.

ChatGPT:



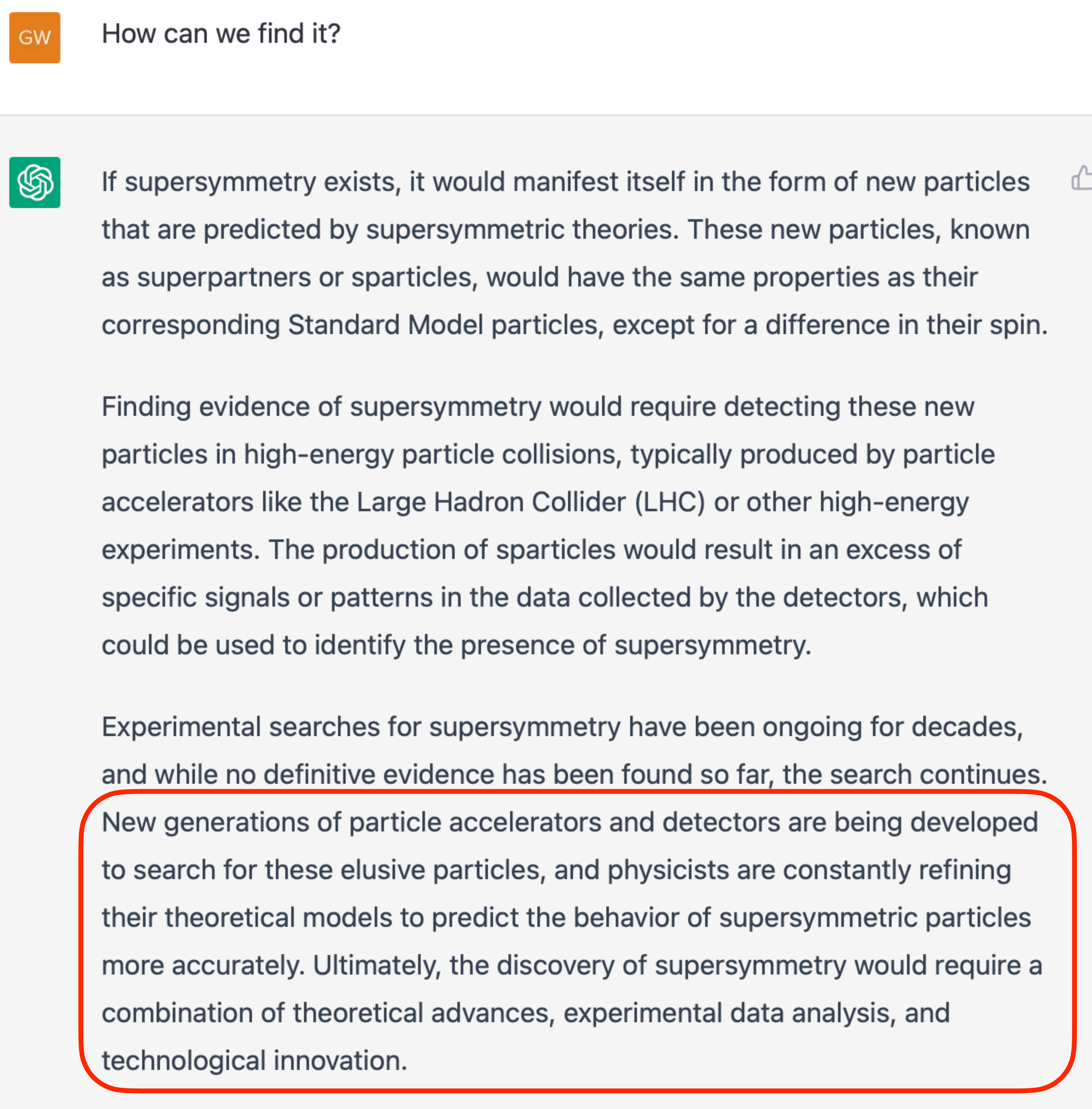
What is supersymmetry?

Supersymmetry is a theoretical framework in particle physics that suggests that every particle in the universe has a "superpartner" particle. In supersymmetric theories, there is a symmetry between particles with integer values of a quantum property called spin (like the photon) and particles with half-integer values of spin (like the electron).

The idea behind supersymmetry is to extend the symmetry principles of the Standard Model of particle physics, which describes the behavior of the known subatomic particles, to include a new set of particles that have not yet been observed. Supersymmetric theories predict the existence of new particles that could help explain some of the mysteries of the universe, such as the nature of dark matter and the hierarchy problem in the Standard Model.

Supersymmetry has not yet been observed experimentally, despite extensive searches at high-energy particle accelerators like the Large Hadron Collider (LHC). However, many physicists still believe in the potential of supersymmetry to solve some of the outstanding questions in particle physics and continue to search for evidence of its existence.

ChatGPT:

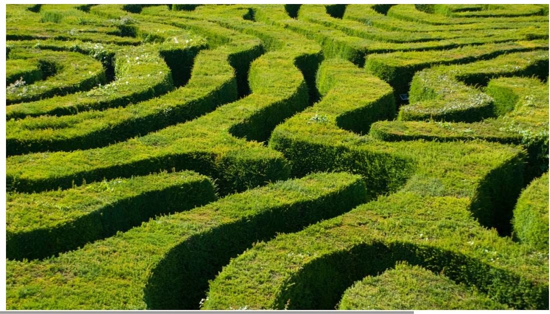


GW How can we find it?

If supersymmetry exists, it would manifest itself in the form of new particles that are predicted by supersymmetric theories. These new particles, known as superpartners or sparticles, would have the same properties as their corresponding Standard Model particles, except for a difference in their spin.

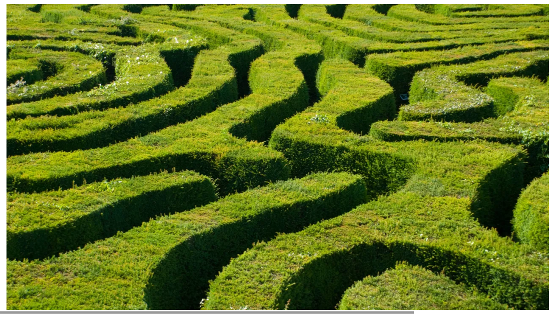
Finding evidence of supersymmetry would require detecting these new particles in high-energy particle collisions, typically produced by particle accelerators like the Large Hadron Collider (LHC) or other high-energy experiments. The production of sparticles would result in an excess of specific signals or patterns in the data collected by the detectors, which could be used to identify the presence of supersymmetry.

Experimental searches for supersymmetry have been ongoing for decades, and while no definitive evidence has been found so far, the search continues. New generations of particle accelerators and detectors are being developed to search for these elusive particles, and physicists are constantly refining their theoretical models to predict the behavior of supersymmetric particles more accurately. Ultimately, the discovery of supersymmetry would require a combination of theoretical advances, experimental data analysis, and technological innovation.



Where is SUSY — nowhere?

Where is SUSY — nowhere?



This is of course a valid possibility, but in comparison with other possible BSM scenarios SUSY offers various attractive features

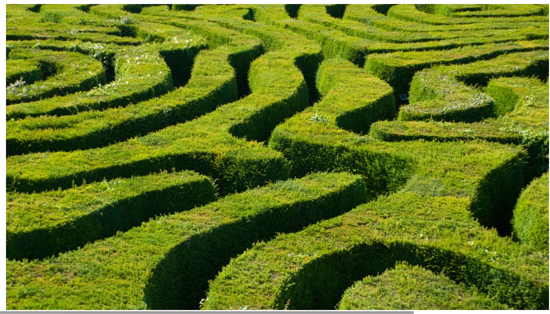
Currently often EFT analyses are performed instead of analyses in specific models; these analyses so far have not provided clear hints towards certain classes of BSM scenarios

Direct SUSY searches: often performed in ``simplified models”
LHC: strong limits on coloured SUSY particles, electroweak SUSY particles can be much lighter

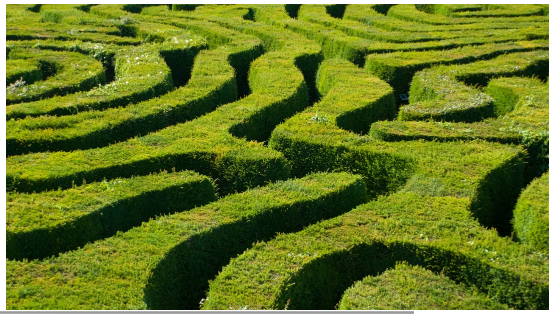
Indirect constraints from electroweak precision observables, etc.: as a renormalisable theory, SUSY can be thoroughly tested (see below)

The mass of the SM-like Higgs boson is a prediction in SUSY, while it is a free parameter in the SM

Where is SUSY — at very high scales?



Where is SUSY — at very high scales?



High-scale SUSY: how to match to the SM?

SM cannot be matched to the MSSM if the scale of the MSSM particles is above about 10^{11} GeV *[G. Giudice, A. Strumia '12]*

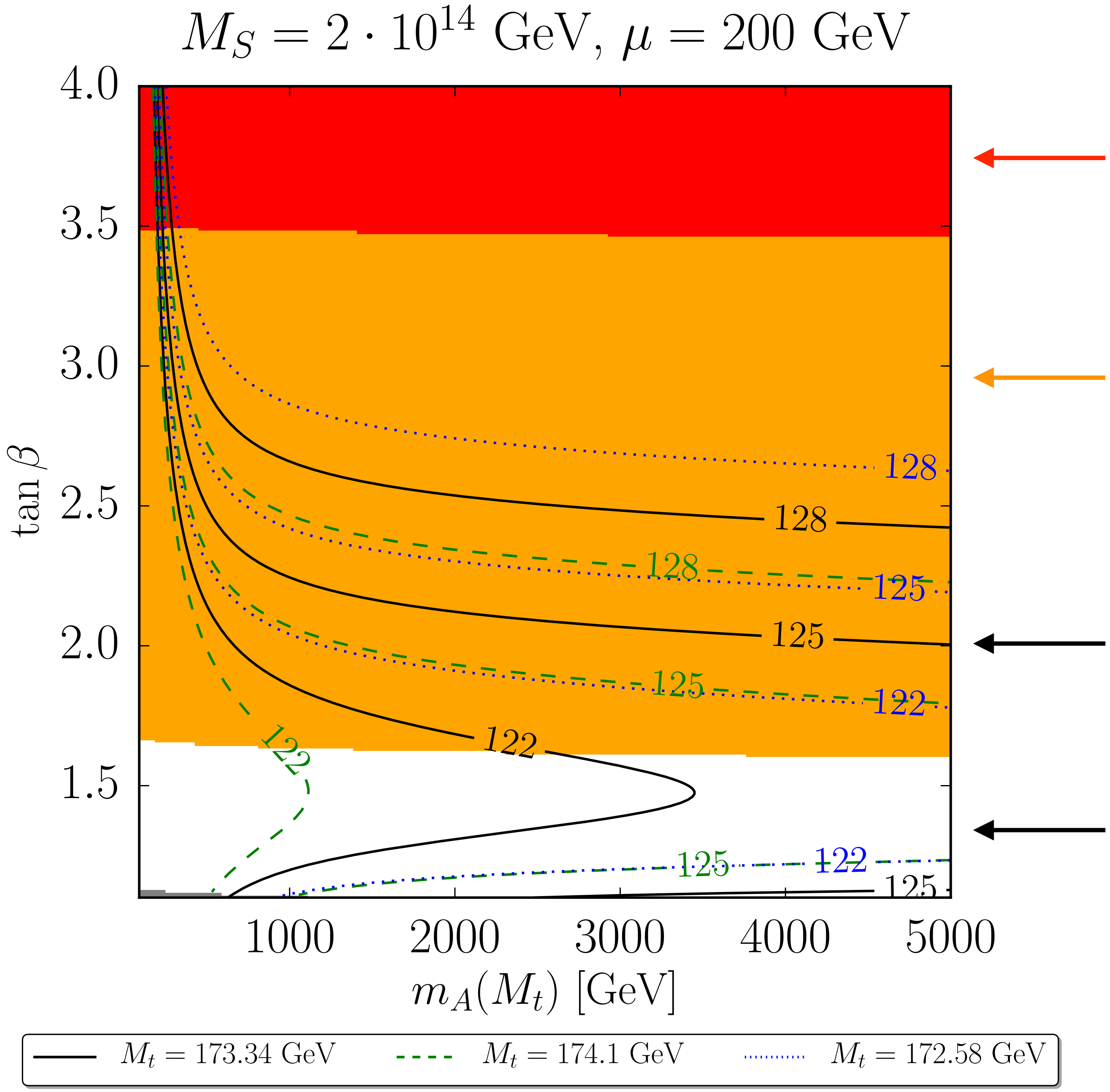
2HDM with and without light higgsinos / gauginos matched to the MSSM at high scale

⇒ Supersymmetric UV completion + stable vacuum + Higgs at 125 GeV works for 2HDM as low-scale model and for 2HDM + light higgsinos

Does not work for split SUSY case (light higgsinos and gauginos)

2HDM + light higgsinos at low scale, other MSSM states at high scale

[E. Bagnaschi, F. Brümmer, W. Buchmüller, A. Voigt, G. W. ’15]



unstable vacuum

meta-stable vacuum

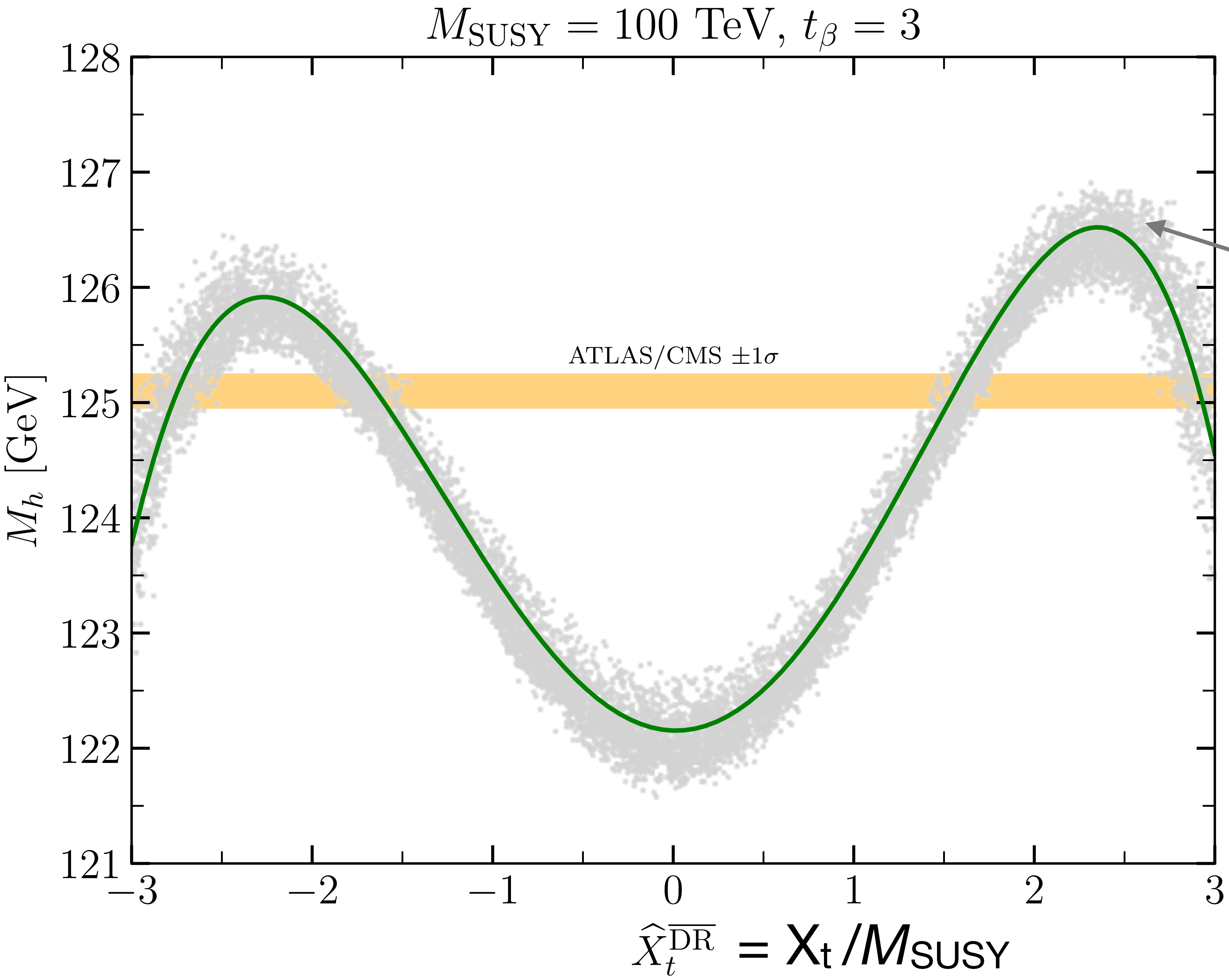
M_h

stable vacuum

⇒ Stable or meta-stable vacuum possible for low tanβ and large M_A

The Higgs-boson mass as a precision observable

Example: M_h prediction for heavy SUSY (M_{SUSY} = 100 TeV)



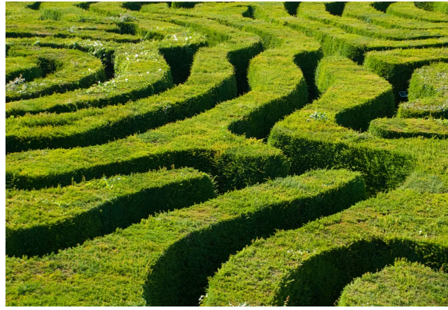
[H. Bahl, J. Braathen, G. W. '22]

Mass parameters and trilinear couplings varied in [1/2 M_{SUSY}, 2 M_{SUSY}]

X_t : mixing in the scalar top sector

⇒ High-precision measurement of the Higgs mass puts important constraints on BSM physics even if new physics scale is very high!

Where is SUSY — maybe not that far away?



Possible hints for light BSM particles:

- Electroweak precision observables, …
- Direct searches
- Global fits

The lightest SUSY particle might be very light!

Bonn-TH-2008-11
DCPT/09/04
DESY 08-190
IPPP/09/02
arXiv:0901.3485 [hep-ph]

Mass Bounds on a Very Light Neutralino

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Arne M. Weber[5¶] and Georg Weiglein[6‖]

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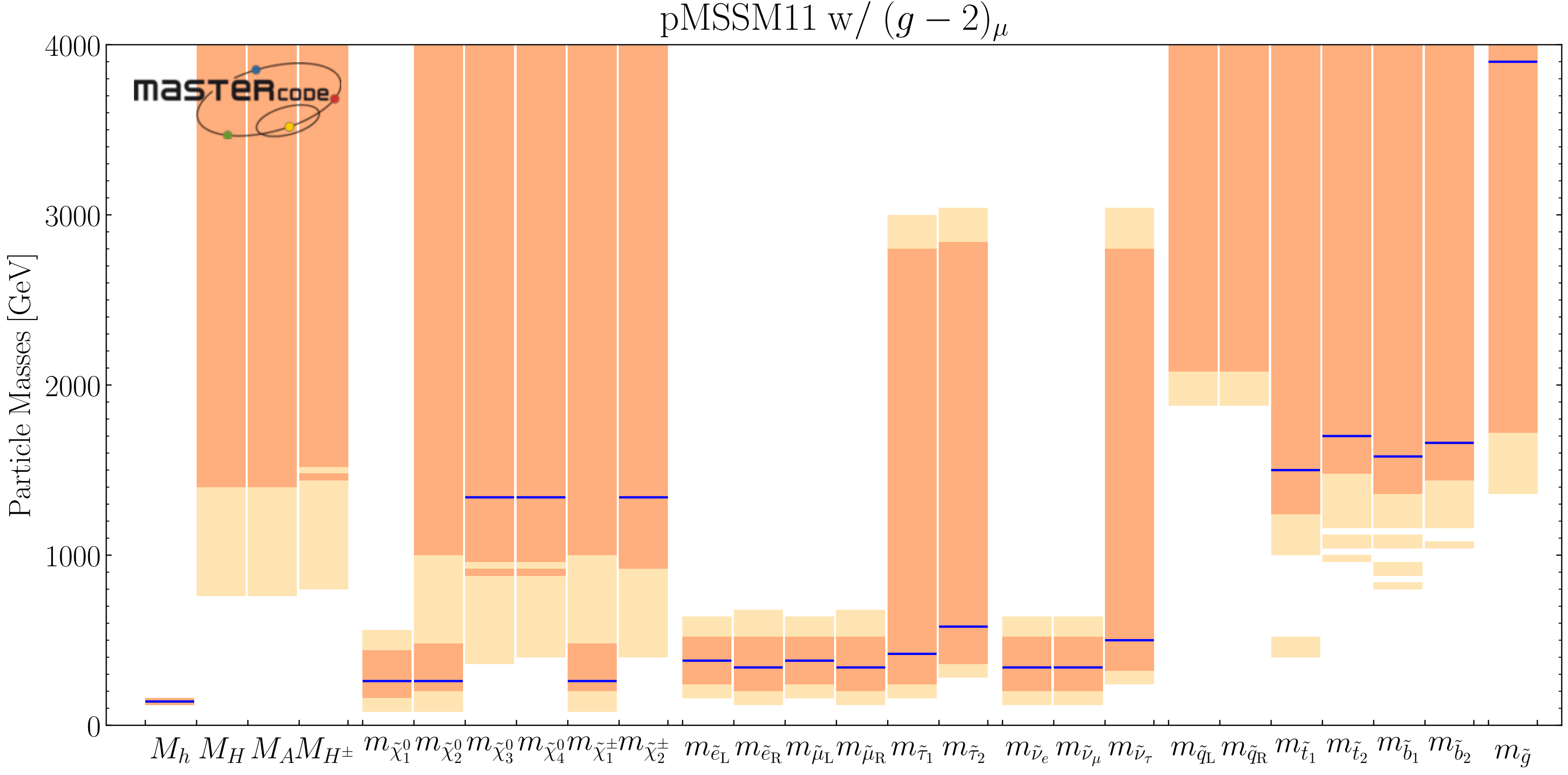
Abstract

Within the Minimal Supersymmetric Standard Model (MSSM) we systematically investigate the bounds on the mass of the lightest neutralino. We allow for non-universal gaugino masses and thus even consider massless neutralinos, while assuming in general that R-parity is conserved. Our main focus is on laboratory constraints. We consider collider data, precision observables, and also rare meson decays to very light neutralinos. We then discuss the astrophysical and cosmological implications. We find that a massless neutralino is allowed by all existing experimental data and astrophysical and cosmological observations.

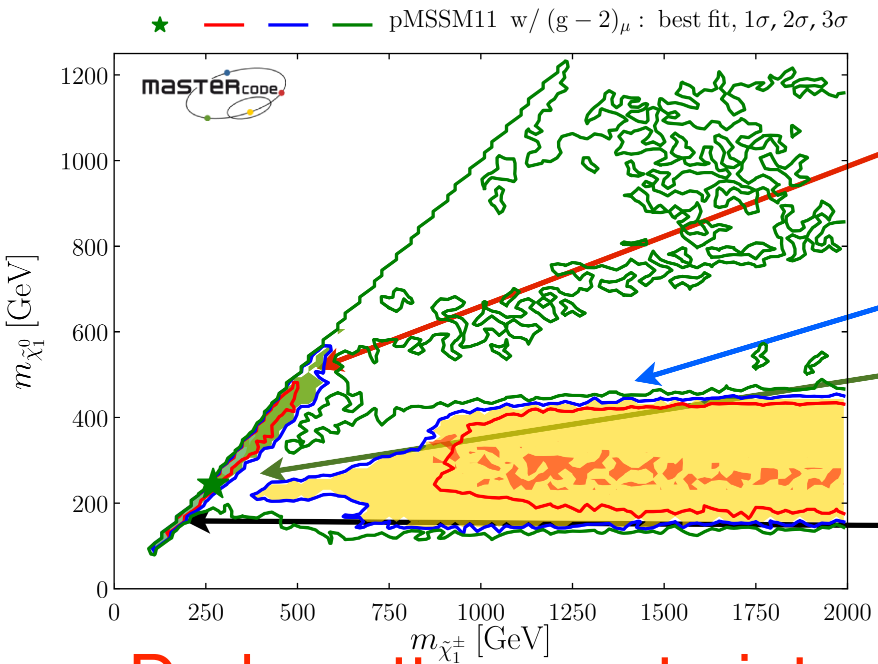
Where are the new particles? Example: global SUSY fit

[E. Bagnaschi et al ’18, 19]

MasterCode: Global fit in the MSSM with 11 parameters



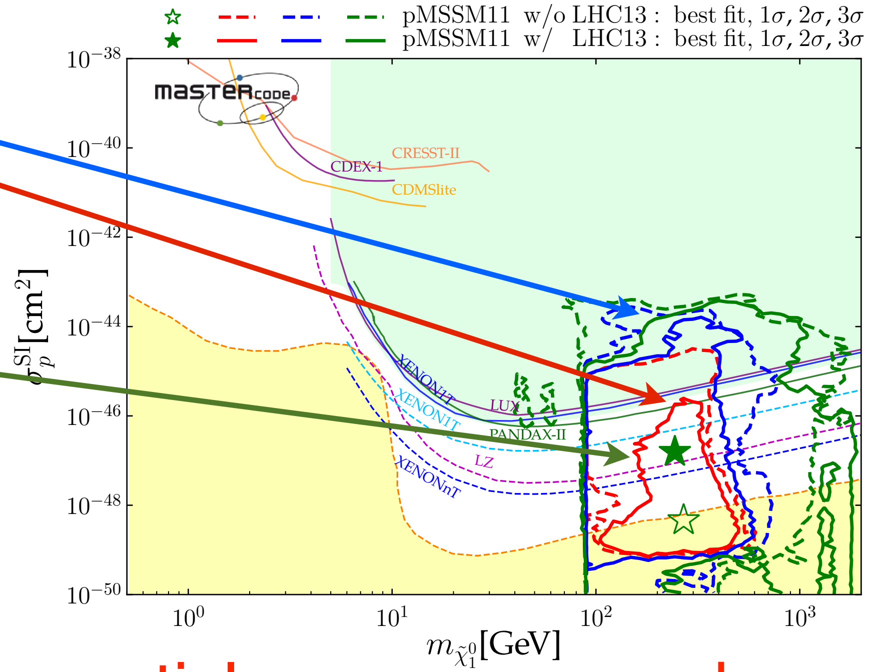
Best fit region and implications for collider and dark matter searches:



68% / 95%
C.L. contours

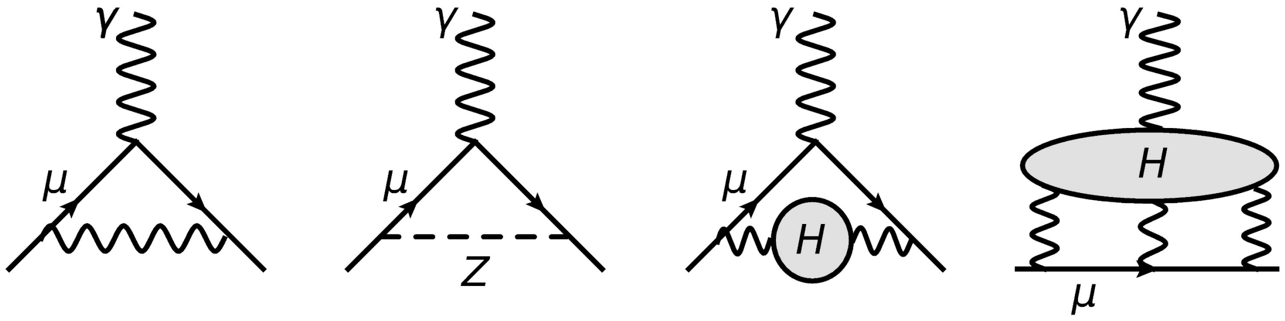
Best fit points

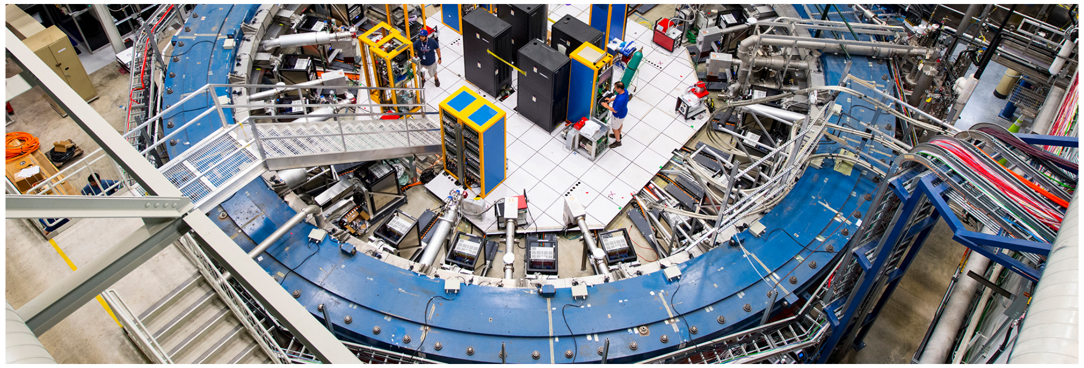
Compressed
spectrum



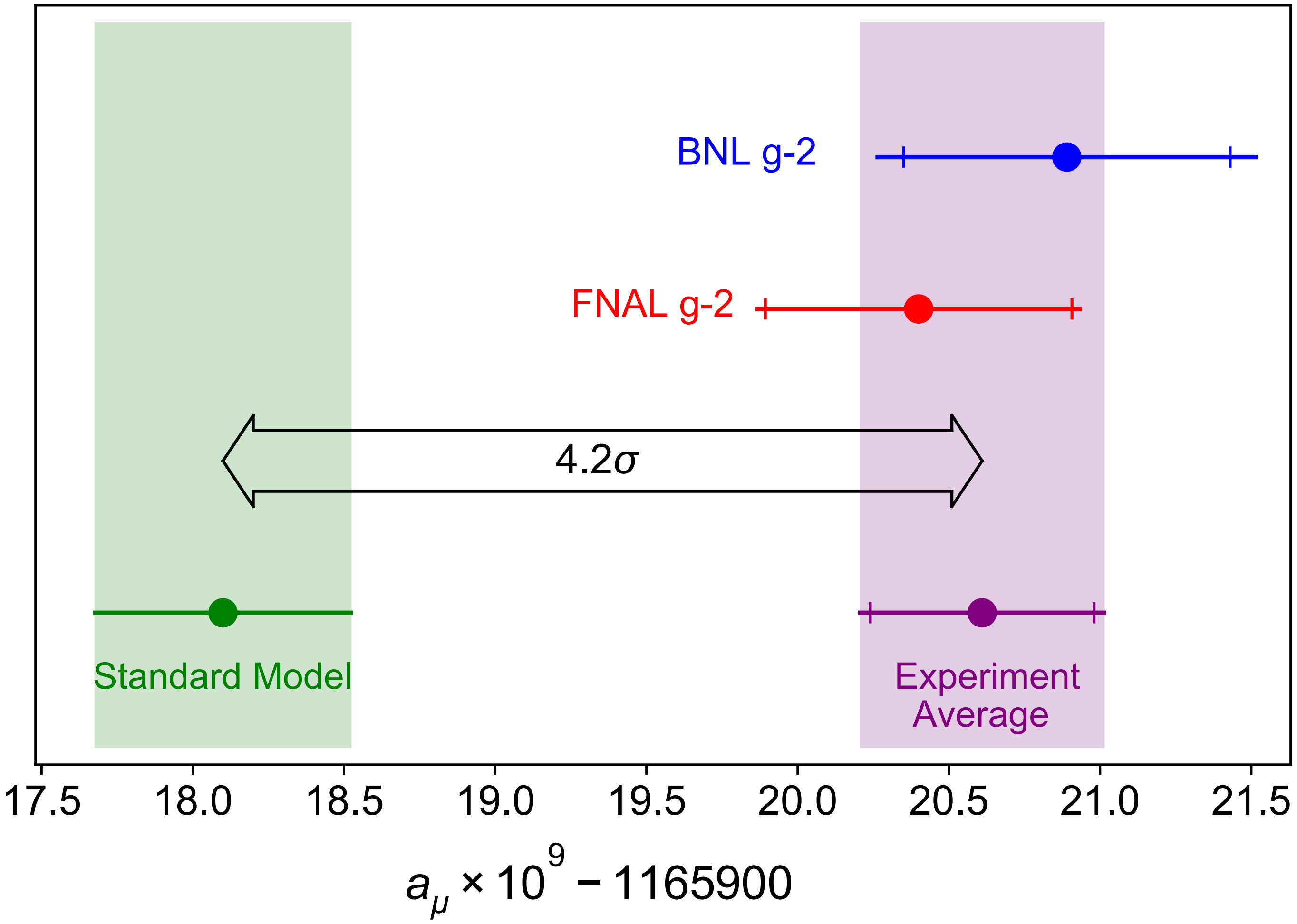
⇒ Dark matter constraint and $(g-2)_\mu$ favour light ew particles, compressed spectra

The anomalous magnetic moment of the muon





$a_\mu \equiv (g-2)_\mu/2$



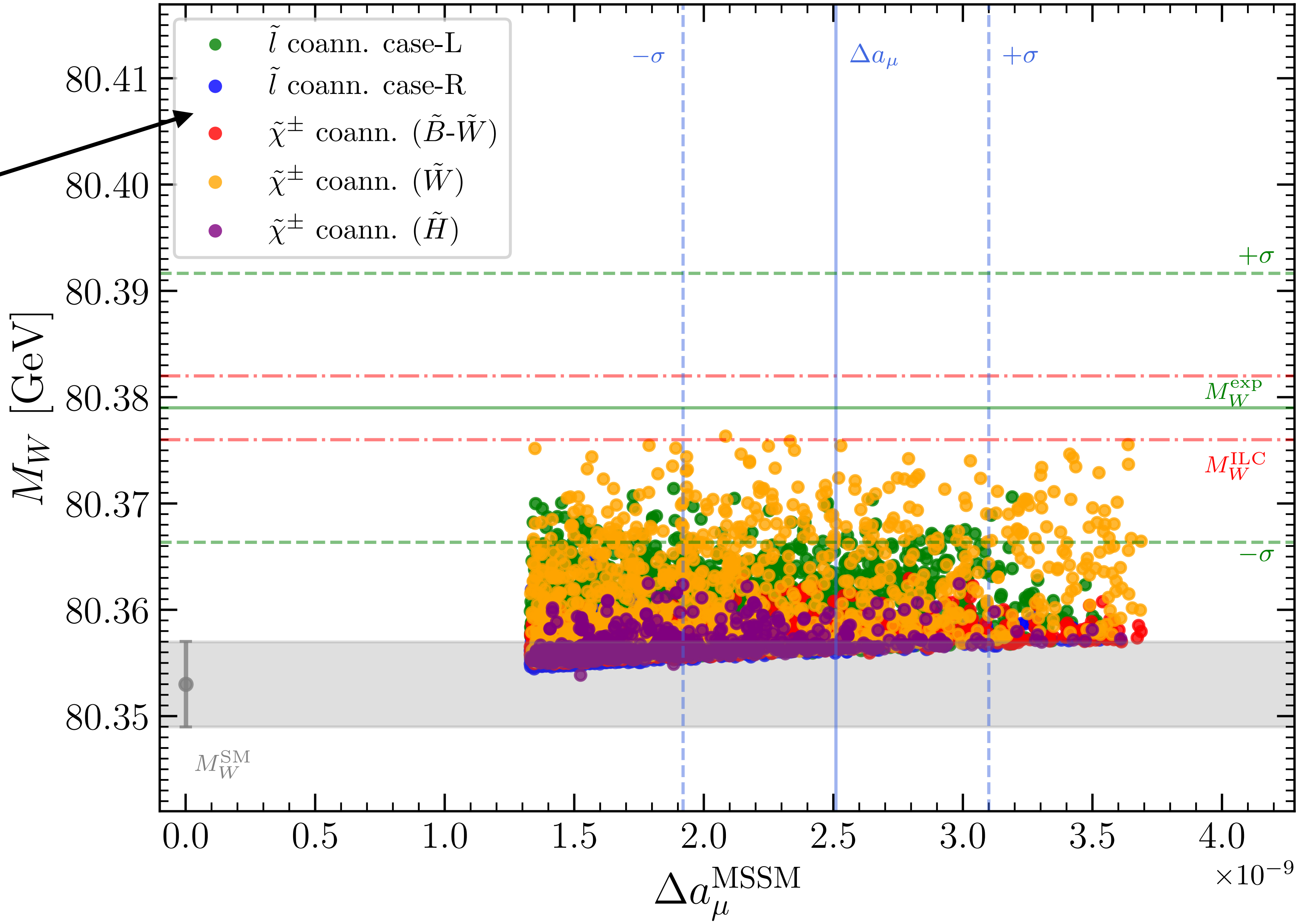
- New FNAL result confirms previous BNL measurement
- Discrepancy from SM prediction: hint for relatively light BSM particles?
- SM prediction: ongoing debate regarding data-driven vs. lattice determinations of the hadronic vacuum polarisation

Muon g–2 and M_W: a hint for light BSM particles?

[E. Bagnaschi, M. Chakraborti, S. Heinemeyer, I. Saha, G. W. '22]

Impact of light electroweak SUSY particles on $g_\mu - 2$, M_W (PDG average) and dark matter relic density (squarks assumed very heavy!)

Different mechanisms for obtaining the right amount of dark matter



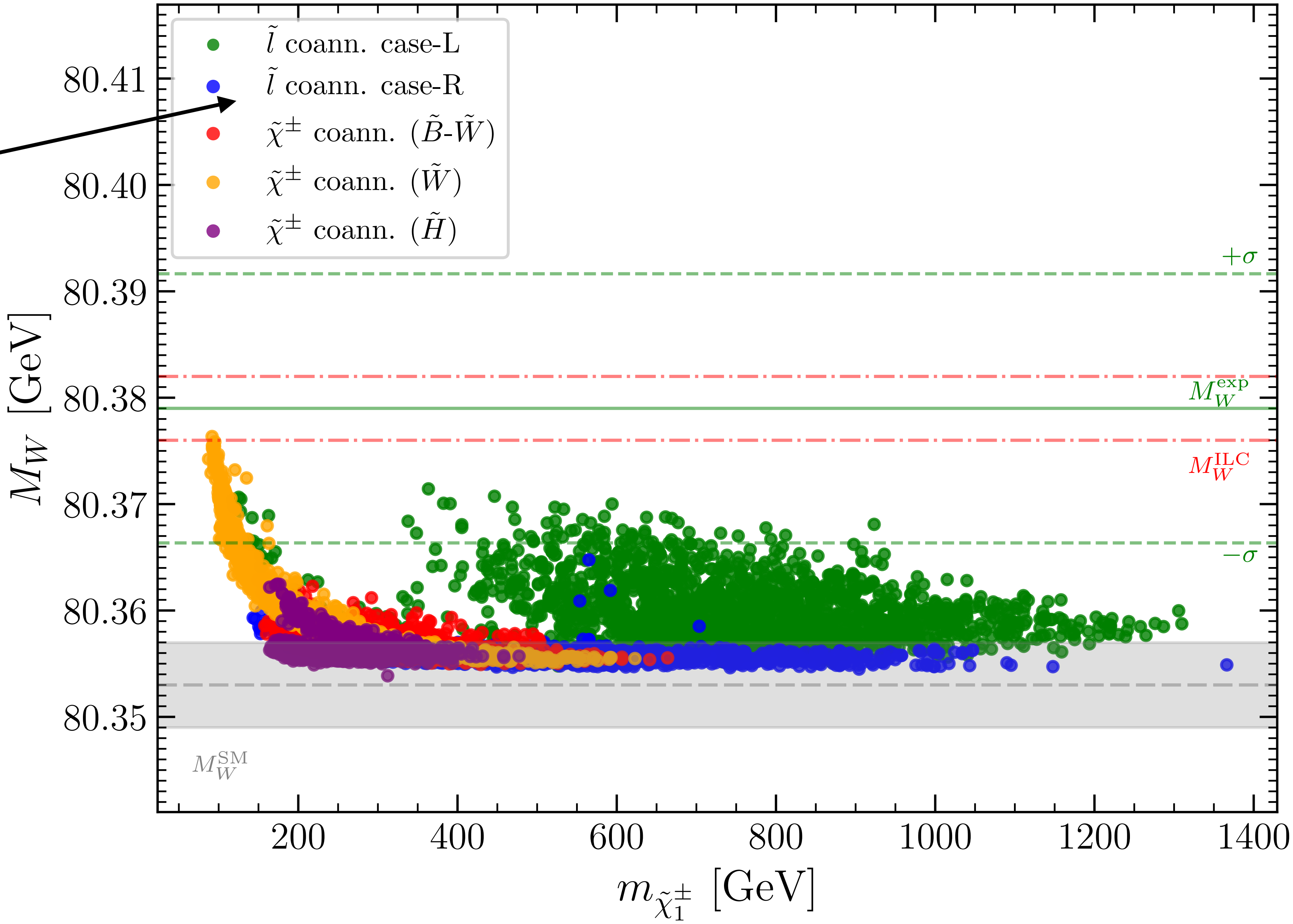
⇒ Improved precision on M_W can probe different dark matter mechanisms

Muon g–2 and M_W: a hint for light BSM particles?

[E. Bagnaschi, M. Chakraborti, S. Heinemeyer, I. Saha, G. W. ’22]

Correlation with the mass of the lightest chargino:

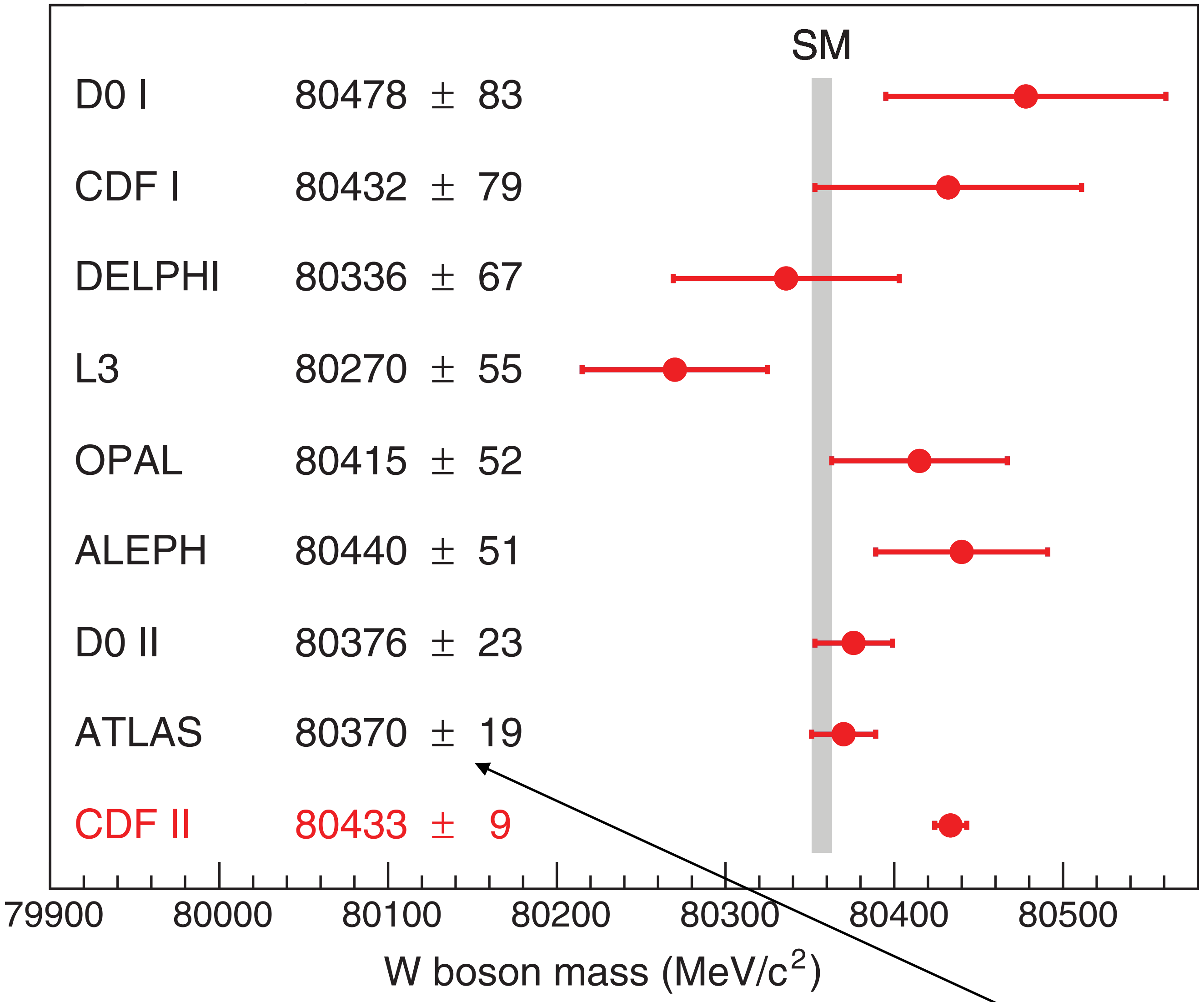
Different mechanisms for obtaining the right amount of dark matter

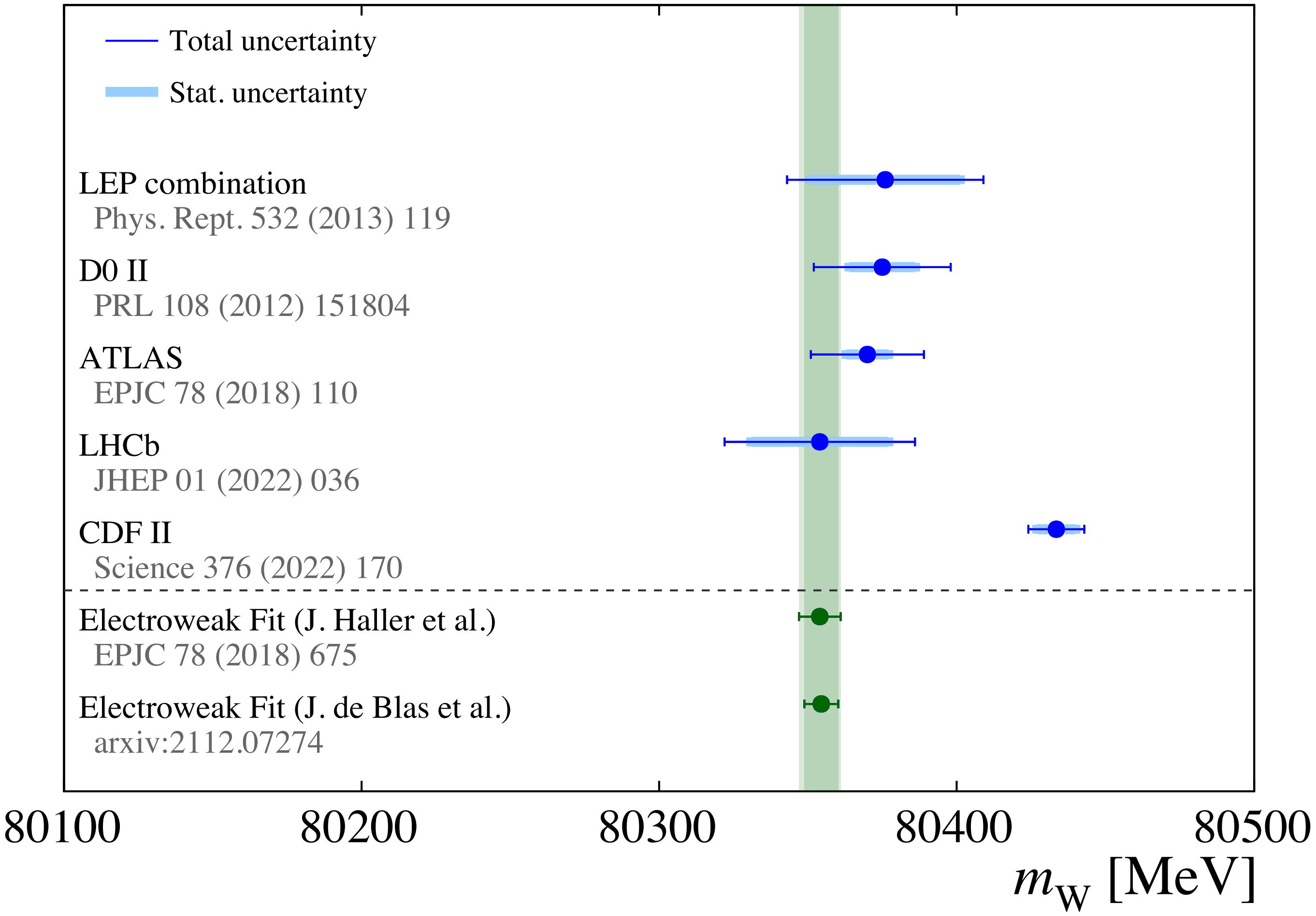


⇒ Possible hints for light charginos can be probed with future searches
Larger values for M_W possible if stops, sbottoms are close to the exp. bounds

Recent result for the W mass from CDF

See ``MWDays23” Workshop at CERN in April!





[CDF Collaboration ’22]

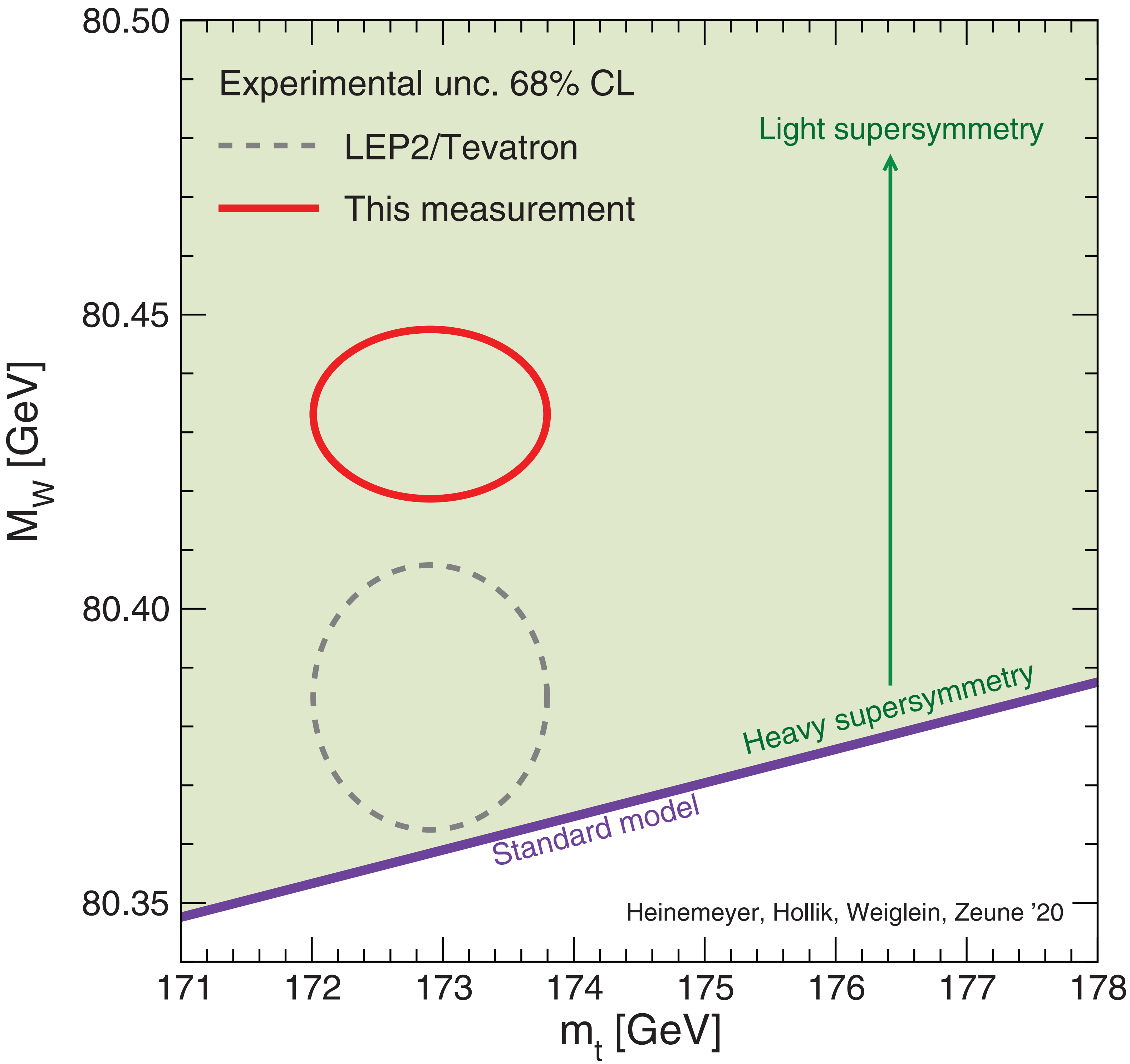
Latest result from ATLAS (reanalysis): 80360 ± 16 *[ATLAS Collaboration ’23]*

⇒ CDF result: large deviation from the SM; very small experimental error
Compatibility of the different M_W measurements? New world average?

New CDF value for M_W: preference for BSM contribution

[CDF Collaboration ’22] *[S. Heinemeyer, W. Hollik, G. W., L. Zeune ’20]*

SM vs. SUSY

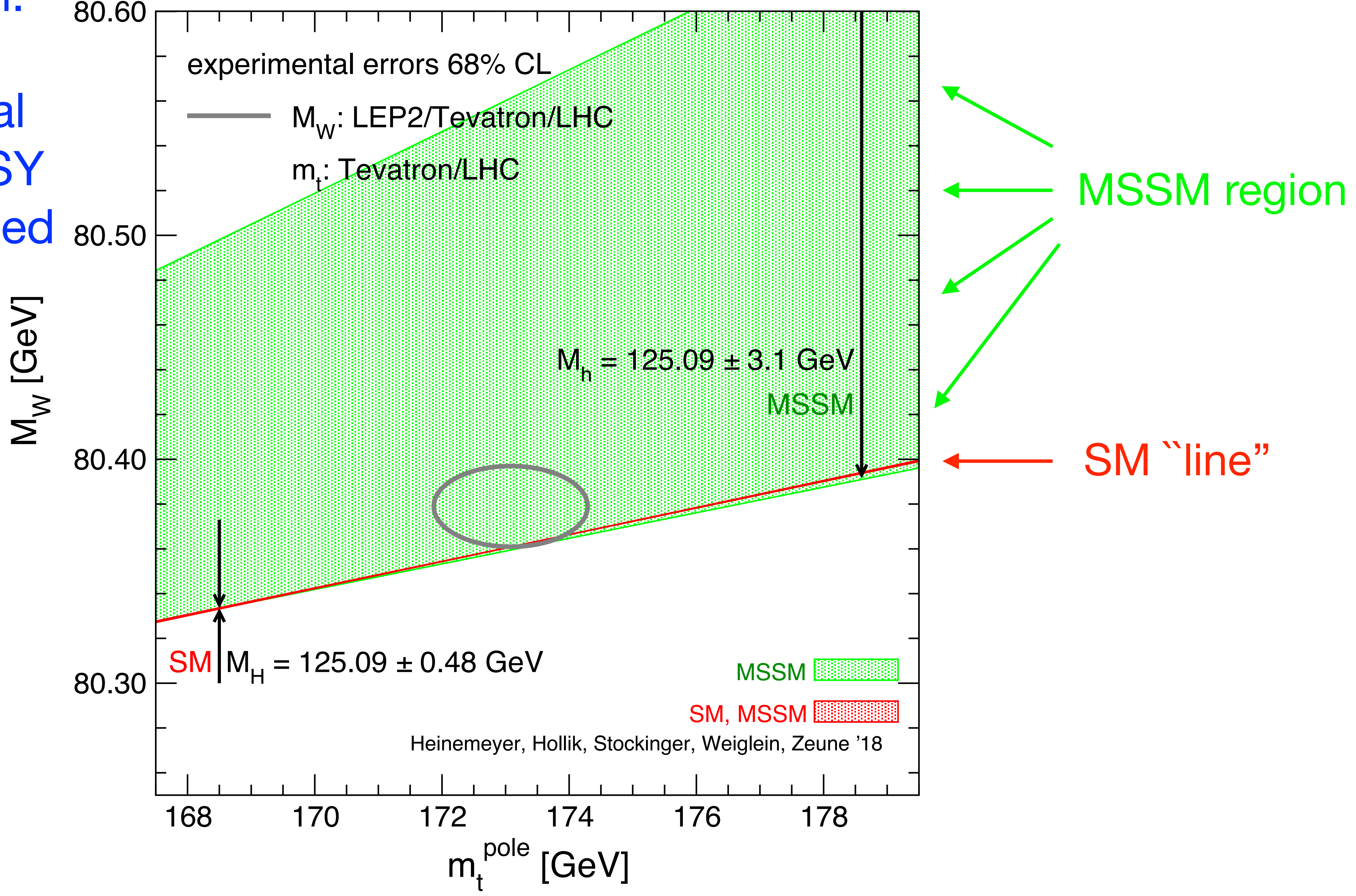


Prediction for M_W in the SM and the MSSM vs. experimental results for M_W and m_t

[S. Heinemeyer, W. Hollik, G. W., L. Zeune '18]

Parameter scan:

No experimental bounds on SUSY particles imposed

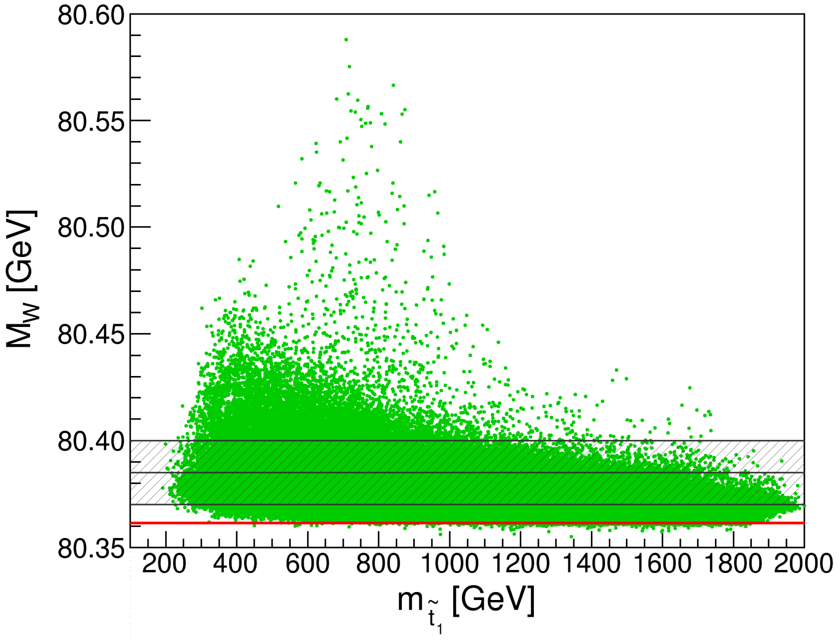


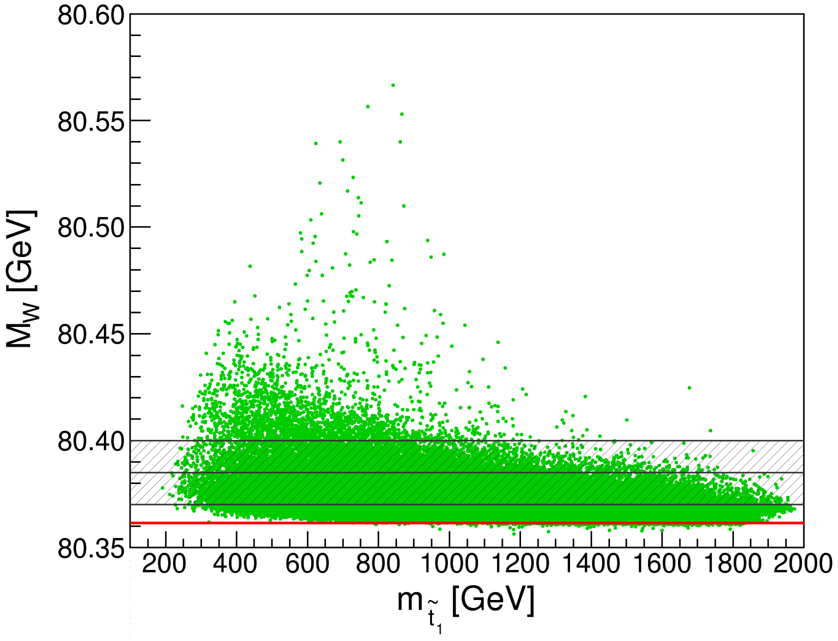
⇒ Large upward shift in M_W possible, large sensitivity to BSM effects

Prediction for M_W in the MSSM depending on the lighter stop mass (parameter scan)

[S. Heinemeyer, W. Hollik, G. W., L. Zeune ’13]

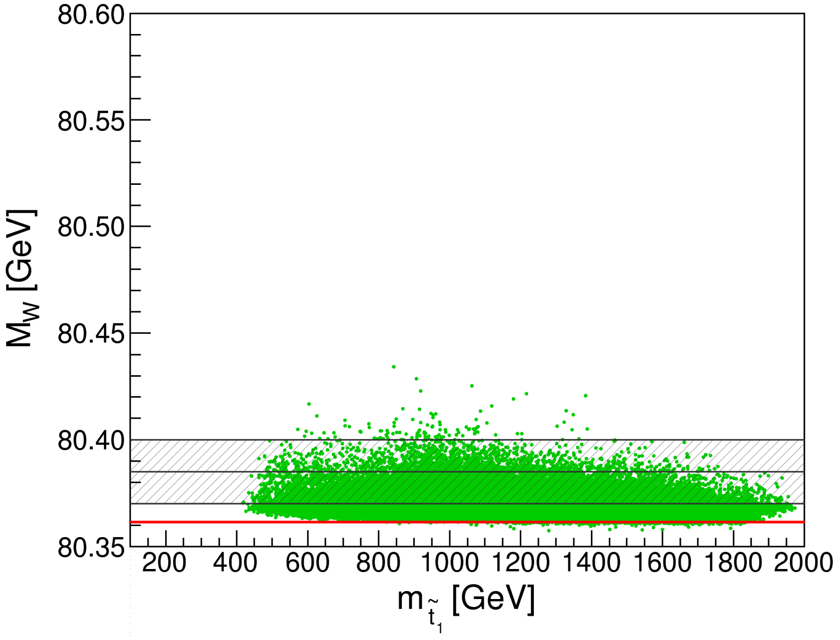
All points

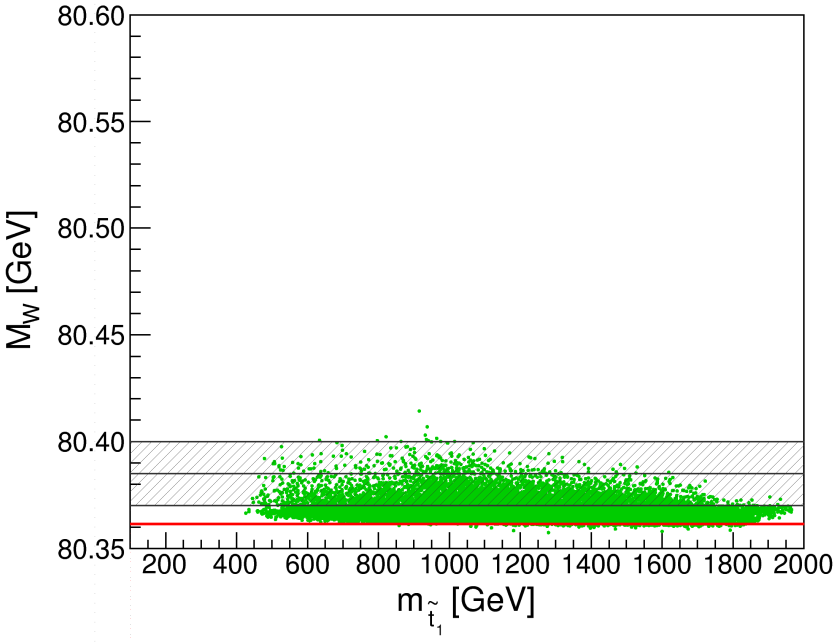




Heavy gluino, heavy first and second generation squarks

+ heavy sbottoms

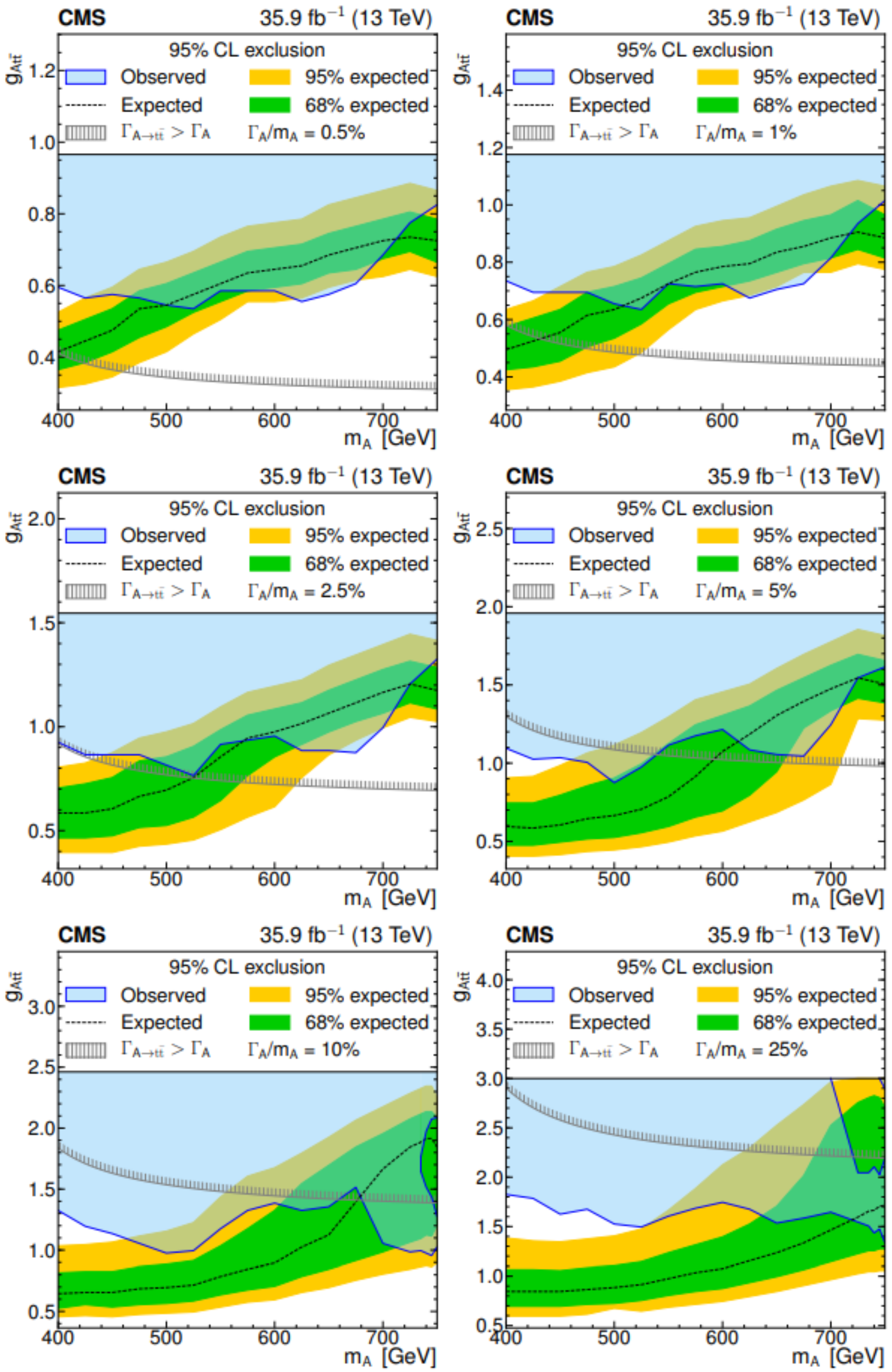




+ heavy sleptons and charginos

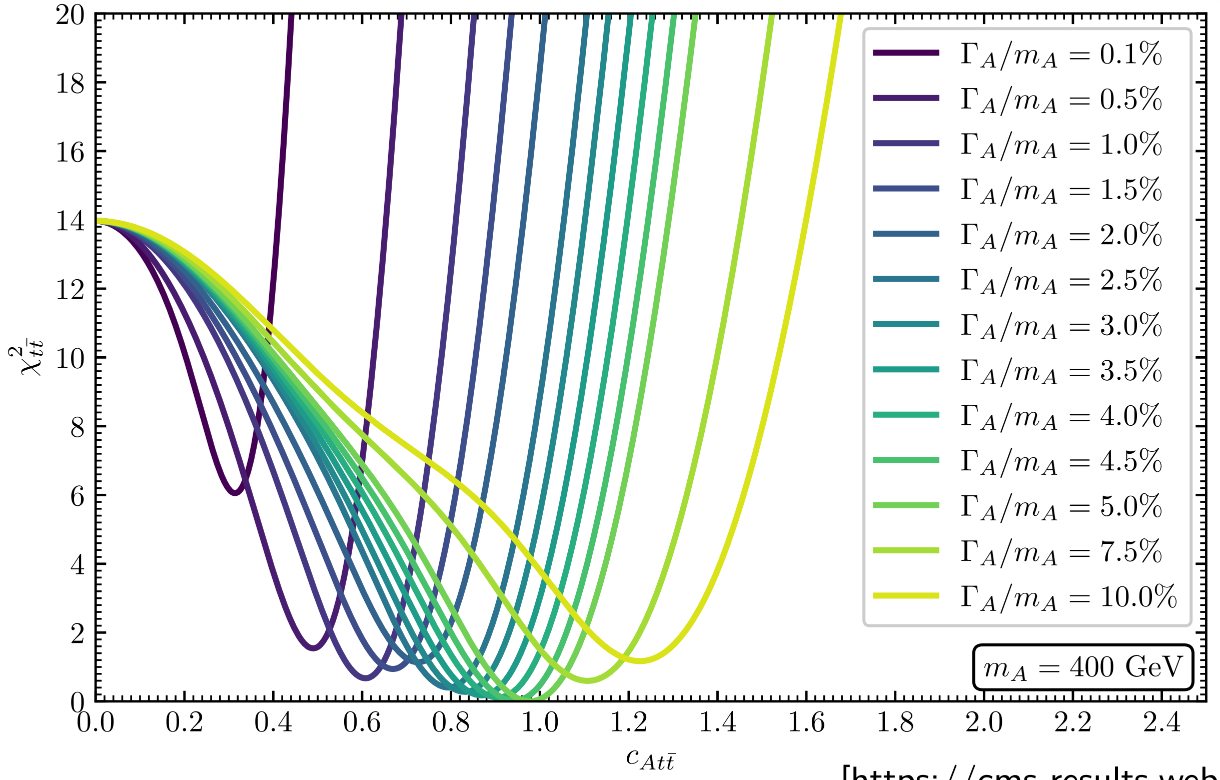
⇒ Sizeable enhancements possible even for relatively heavy SUSY, but values as high as the CDF measurement are disfavoured by exp. constr.

Excess in CMS search for A → tt at about 400 GeV



[CMS: 1908.01115]

[CMS Collaboration '19]



[https://cms-results.web.cern.ch]

Local excess of 3.5σ at ~ 400 GeV
Global significance below 2σ

Consistent with a pseudoscalar Higgs boson at ~ 400 GeV

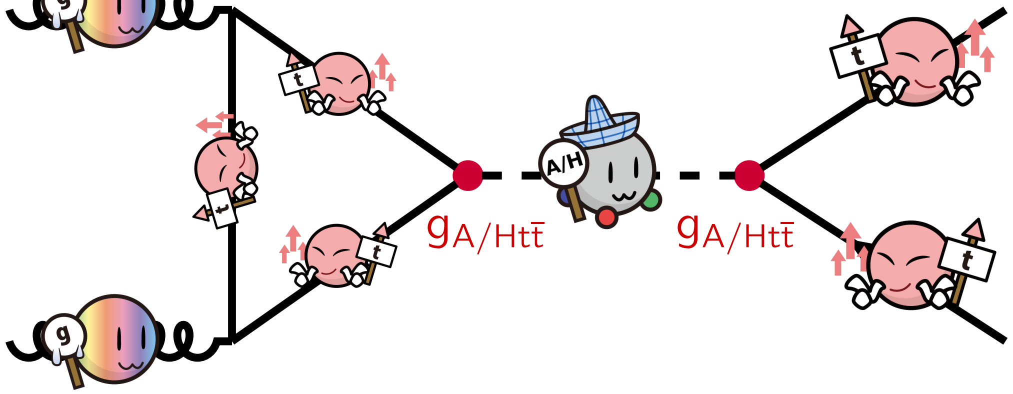
Most significant for $\Gamma_A/m_A = 4\%$ and $c_{At\bar{t}} \sim 1$, but also consistent with slightly different m_A and Γ_A/m_A $\to \chi^2_{t\bar{t}}(m_A, \Gamma_A/m_A, c_{At\bar{t}})$

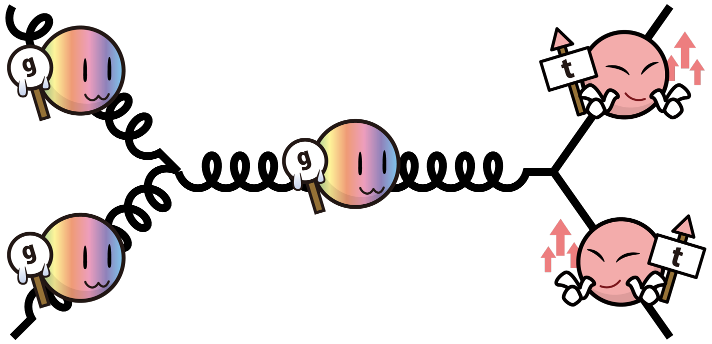
Corresponding ATLAS limits only for $m_A > 500$ GeV and only 8 TeV data

[ATLAS: 1707.06025]

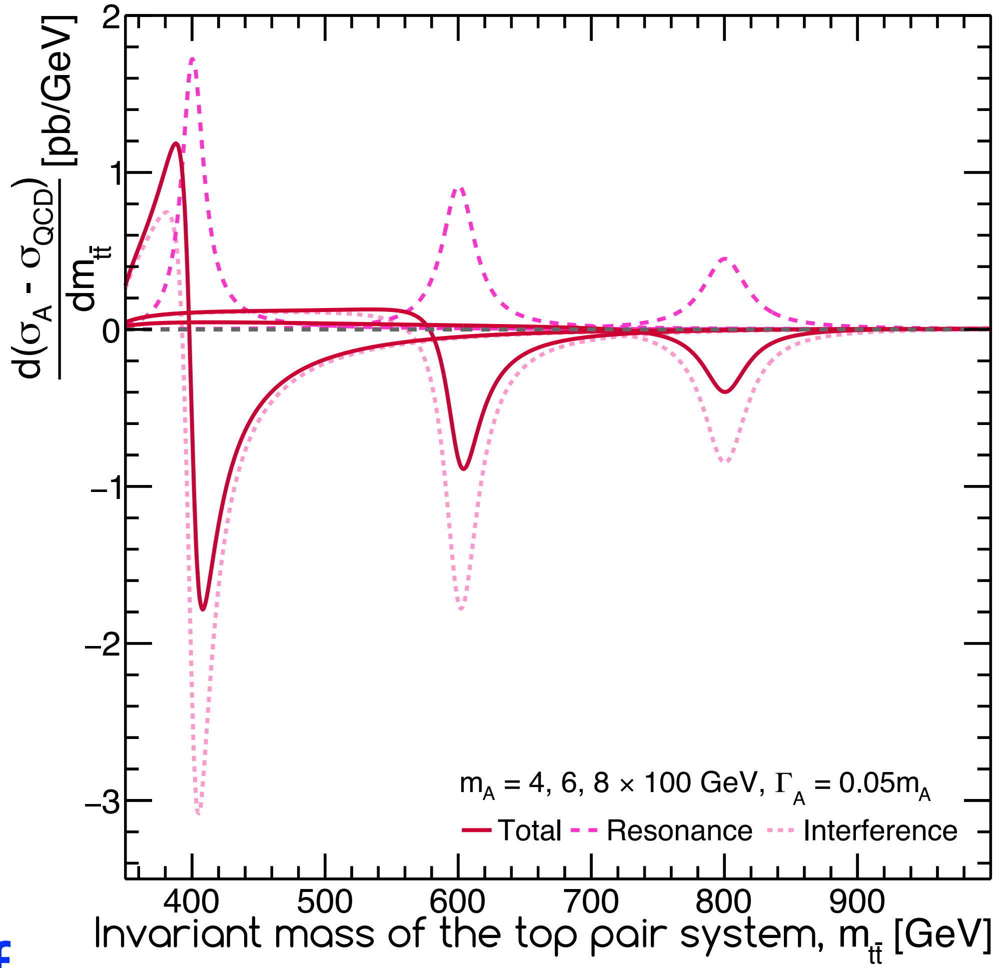
CMS: excess in search for A → tt at about 400 GeV

[A. Anuar '21]





Interference ⇒

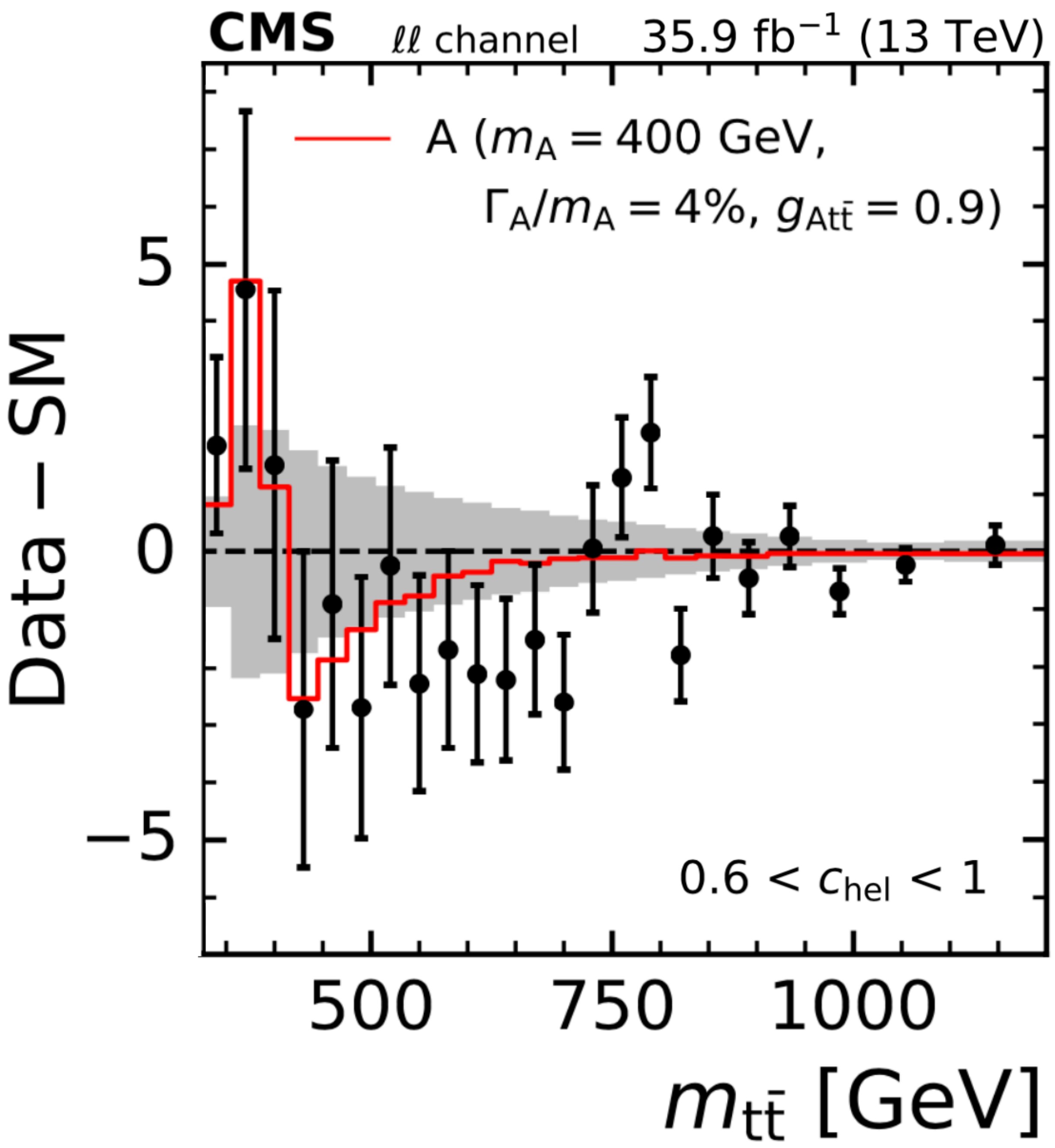


Signal-background interference yields peak-dip structure

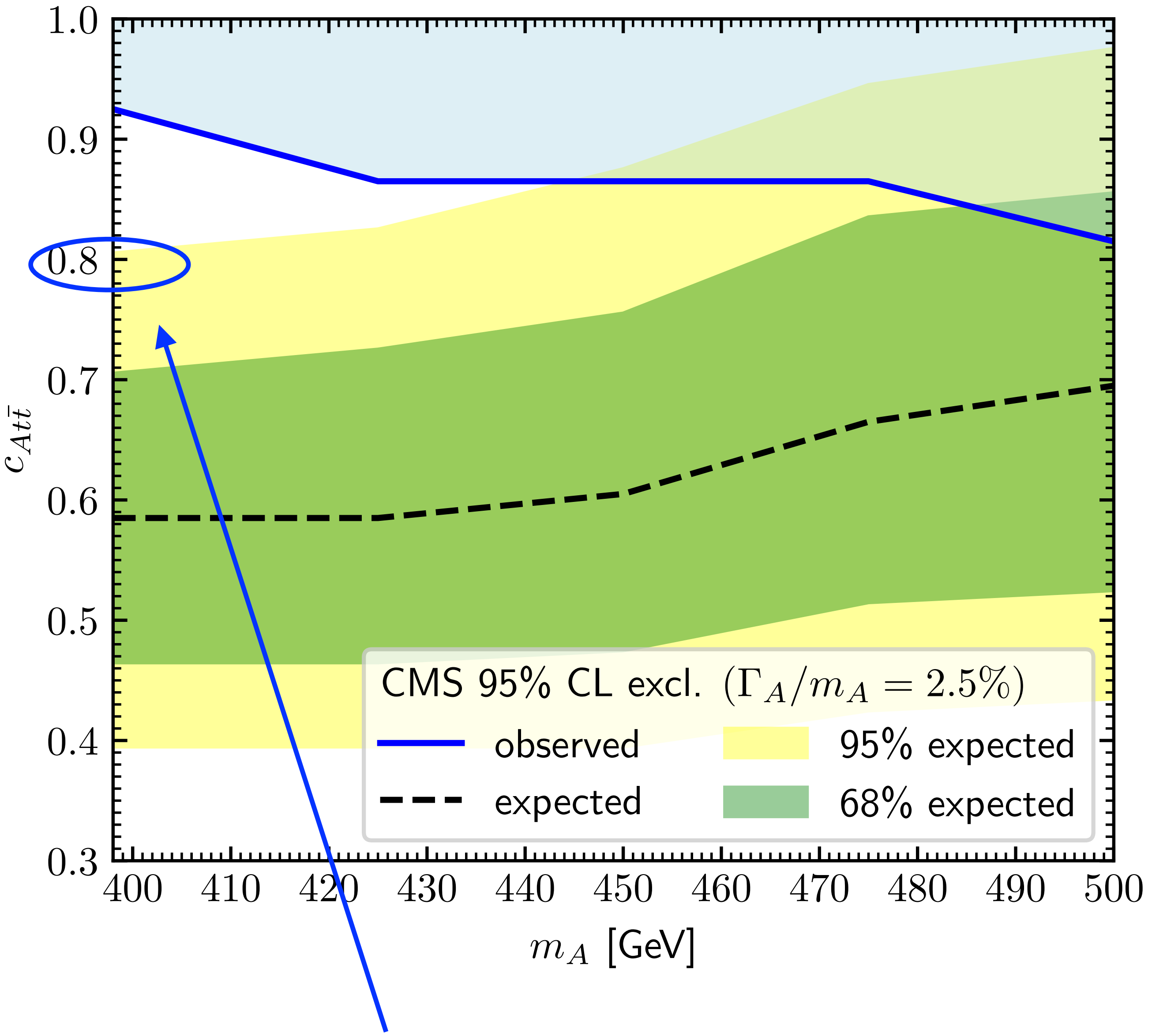
Analysed using angular correlations of the top and anti-top decay products

Search for additional Higgs bosons: H, A → tt

Excess in CMS search at about 400 GeV:



[CMS Collaboration '19]

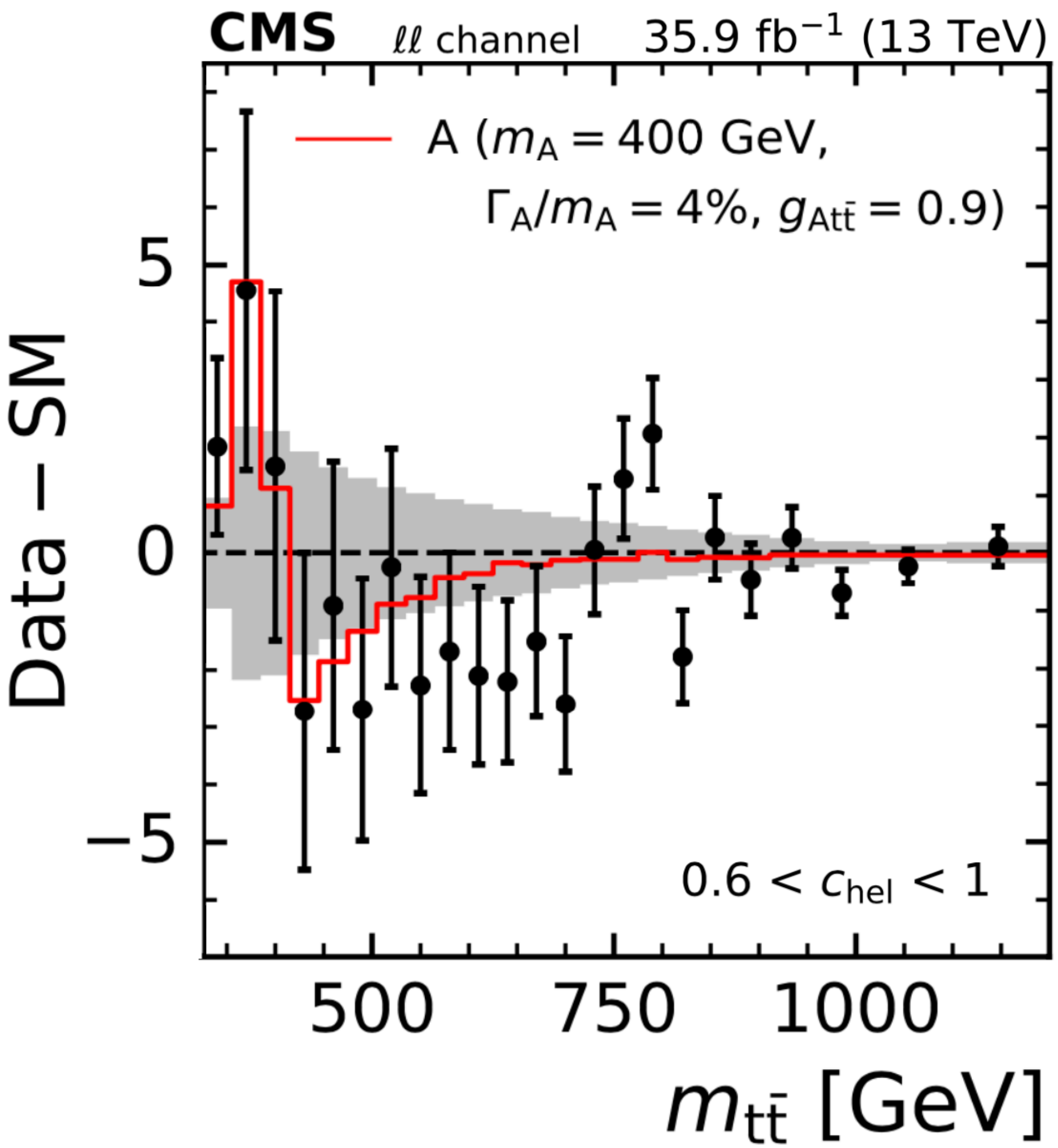


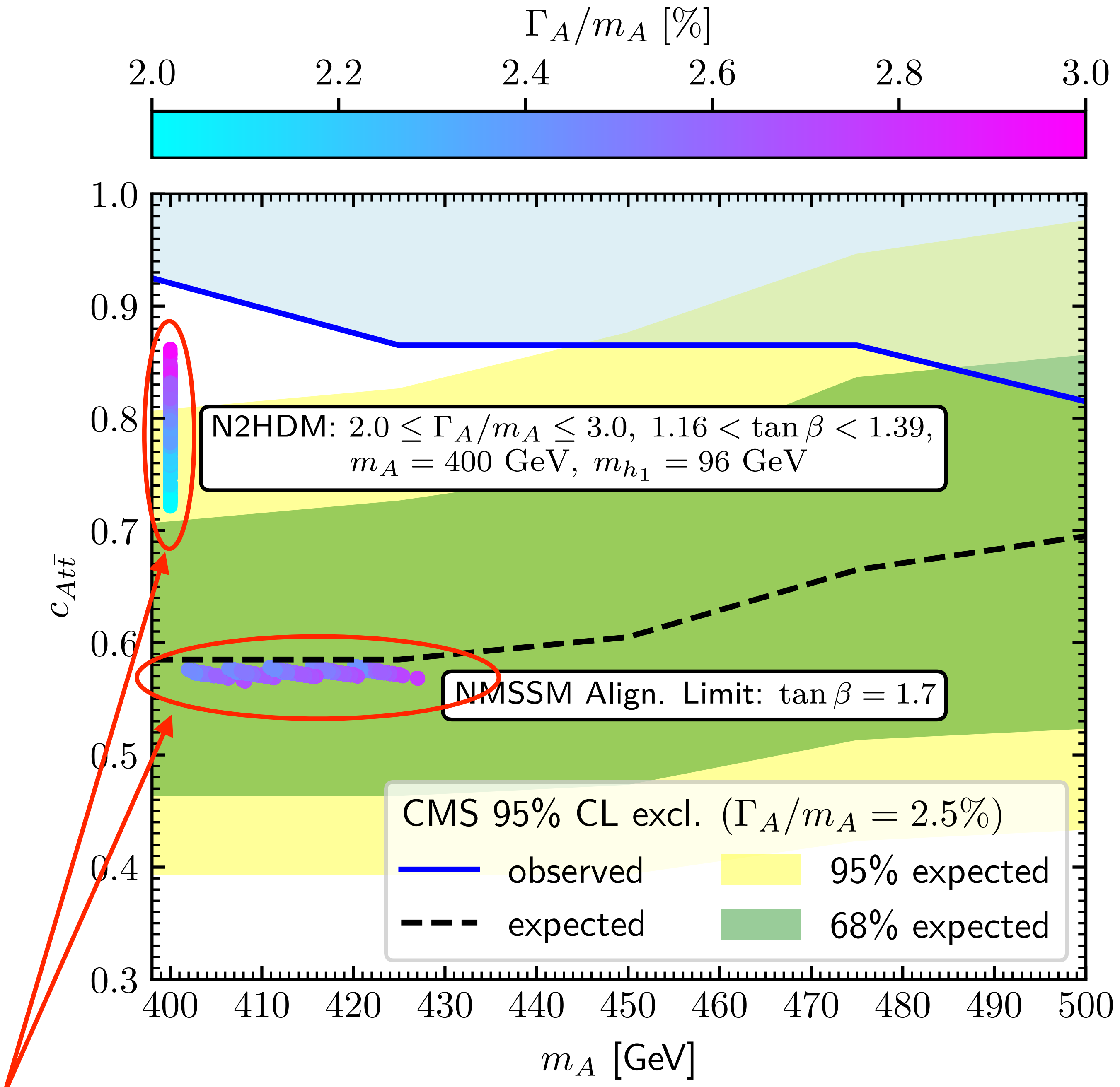
CMS, best fit value for $\Gamma_A/m_A = 2.5\%$

Search for additional Higgs bosons: H, A → tt

[T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. W. '21]

Excess in CMS search at about 400 GeV:





⇒ Good description of the A → tt excess at 400 GeV in models with extended Higgs sectors (N2HDM, NMSSM)

Conclusions

SUSY continues to be among the most attractive frameworks for addressing the unsolved issues of particle physics

SUSY particles may be less far away than some people think …

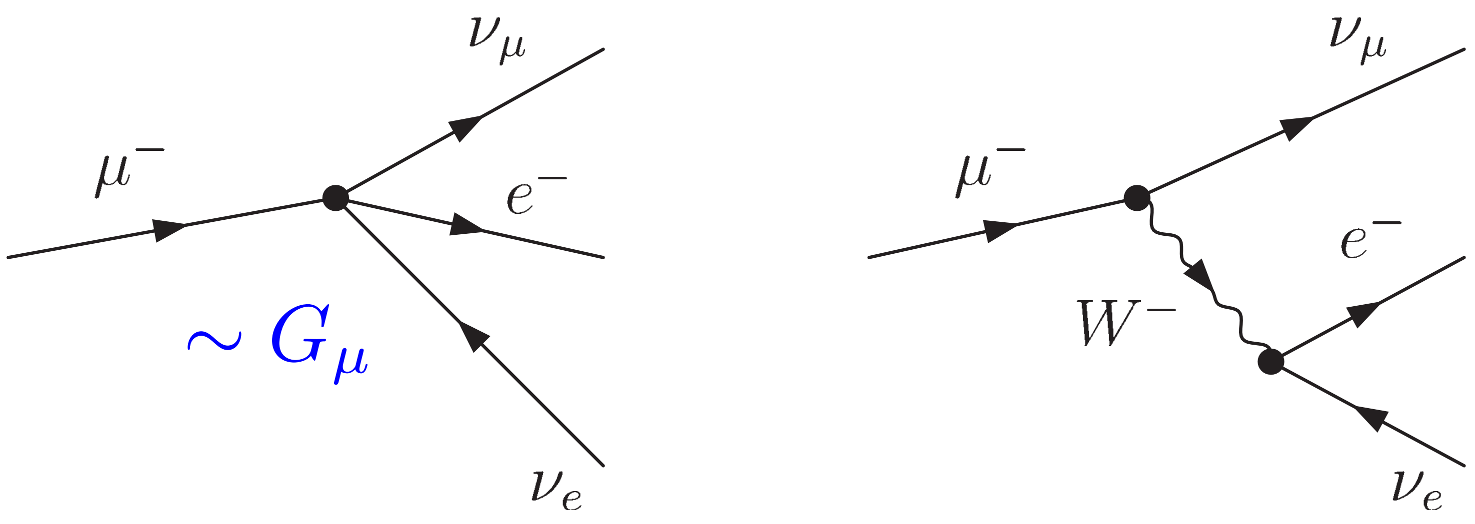
Happy birthday, dear Herbi, …

Happy birthday, dear Herbi, …

… and all the best from Sven & me!

Backup

Theoretical prediction for the W-boson mass from muon decay: relation between M_W, M_Z, α, G_μ



$M_{\rm W}$: Comparison of prediction for muon decay with experiment (Fermi constant G_μ); QED corrections in Fermi model incl. in def. of G_μ

$$\Rightarrow \quad M_{\rm W}^2 \left(1 - \frac{M_{\rm W}^2}{M_{\rm Z}^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_\mu}\left(1 + \Delta r\right),$$

$$\Updownarrow$$

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

loop corrections

$\Rightarrow$ Theo. prediction for $M_{\rm W}$ in terms of $M_{\rm Z}$, α, G_μ, $\Delta r(m_{\rm t}, m_{\tilde{\rm t}}, \ldots)$

Tree-level prediction: $M_W^{\rm tree}$ = 80.939 GeV, $M_W^{\rm exp}$ = 80.379 +- 0.012 GeV

⇒ off by many σ (accuracy of 1.5 x 10^{-4})

BSM predictions for the W-boson mass

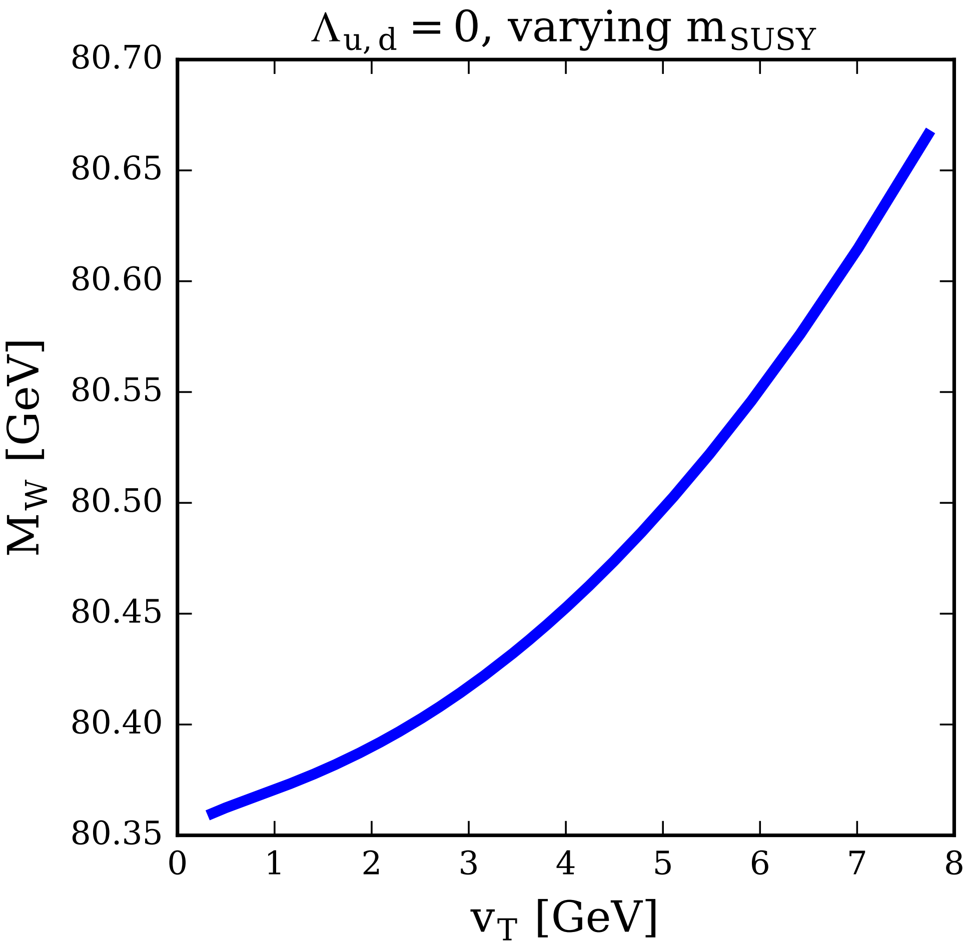
Extended Higgs sectors consisting of doublets and singlets:
custodial symmetry ⇒ $\varrho = 1$ at lowest order

Lowest-order charged Higgs exchange contribution: ~ $(m_\mu \, m_e)/M_W^2$

⇒BSM contributions enter at 1-loop level: $\Delta r(m_i^{SM}, m_j^{BSM}, \ldots)$

Extended Higgs sectors involving triplets:
tree-level contribution from triplet v.e.v. v_T:
$M_W^2 = 1/4 \, g_2^2 \, v^2 + g_2^2 \, v_T^2$

Example: MRSSM



[P. Diessner, G. W. '19]

BSM predictions for the W-boson mass

S, T, U parameters: only BSM contributions taken into account that enter via gauge-boson self-energies (only one-loop contributions), external momentum neglected

$$M_W^2 = M_W^2\big|_{\mathrm{SM}} \left(1 + \frac{s_w^2}{c_w^2 - s_w^2}\Delta r'\right)$$

$$\Delta r' = \frac{\alpha}{s_w^2}\left(-\frac{1}{2}S + c_w^2 T + \frac{c_w^2 - s_w^2}{4 s_w^2} U\right)$$

SM prediction for the experimental values of *M*H, *m*t, …

Global fits to electroweak precision observables:
SM, SM + S, T, U parameters: *GFitter*, …
BSM models (SUSY, …): *MasterCode*, *Gambit*, …
EFT fits

BSM prediction for M_W, example: MSSM, NMSSM

Δr in the MSSM and the NMSSM, treatment of higher-order contributions:
full one-loop + higher orders (SM) + higher orders (SUSY)

$$\Delta r^{\rm (N)MSSM} = \Delta r^{\rm (N)MSSM(\alpha)} + \Delta r^{\rm (N)MSSM(h.o.)}$$

$$\Delta r^{\rm (N)MSSM(h.o.)} = \Delta r^{\rm SM(h.o.)} + \Delta r^{\rm SUSY(h.o.)}$$

⇒ State-of-the art SM prediction recovered in decoupling limit, all available higher-order corrections of SUSY-type included

For light SUSY particles: additional theoretical uncertainty from higher-order SUSY-loop corrections

SUSY higher-order contributions

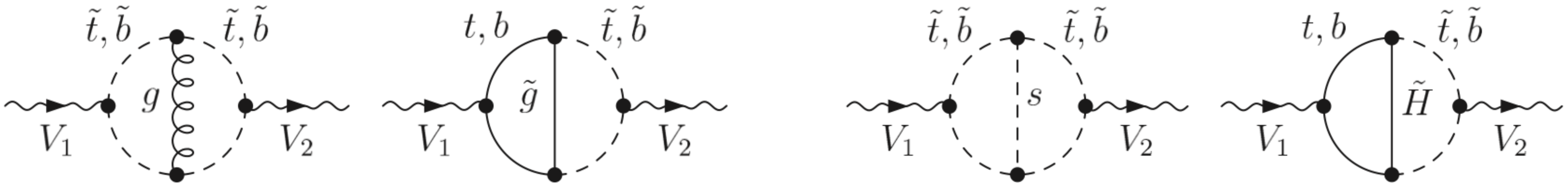
One-loop:

leading contributions from the scalar superpartners of the top and bottom quarks via Δϱ: additional source of isospin splitting

Two-loop:

leading reducible 2-loop corrections, gluon/gluino 2-loop corrections, higgsino 2-loop corrections

$$\Delta r^{\mathrm{SUSY(h.o.)}} = \Delta r^{\mathrm{SUSY}(\alpha^2)}_{\mathrm{red}} - \frac{c_W^2}{s_W^2}\Delta\rho^{\mathrm{SUSY},(\alpha\alpha_s)} - \frac{c_W^2}{s_W^2}\Delta\rho^{\mathrm{SUSY},(\alpha_t^2,\alpha_t\alpha_b,\alpha_b^2)}$$



The effective leptonic weak mixing angle: $\sin^2\theta_{\rm eff}$

Effective leptonic weak mixing angle at the Z-boson resonance:

$$\sin^2\theta_{\rm eff} = \frac{1}{4}\left(1 - \mathrm{Re}\,\frac{g_V}{g_A}\right) = \left(1 - \frac{M_{\rm W}^2}{M_{\rm Z}^2}\right)(1 + \Delta\kappa)$$

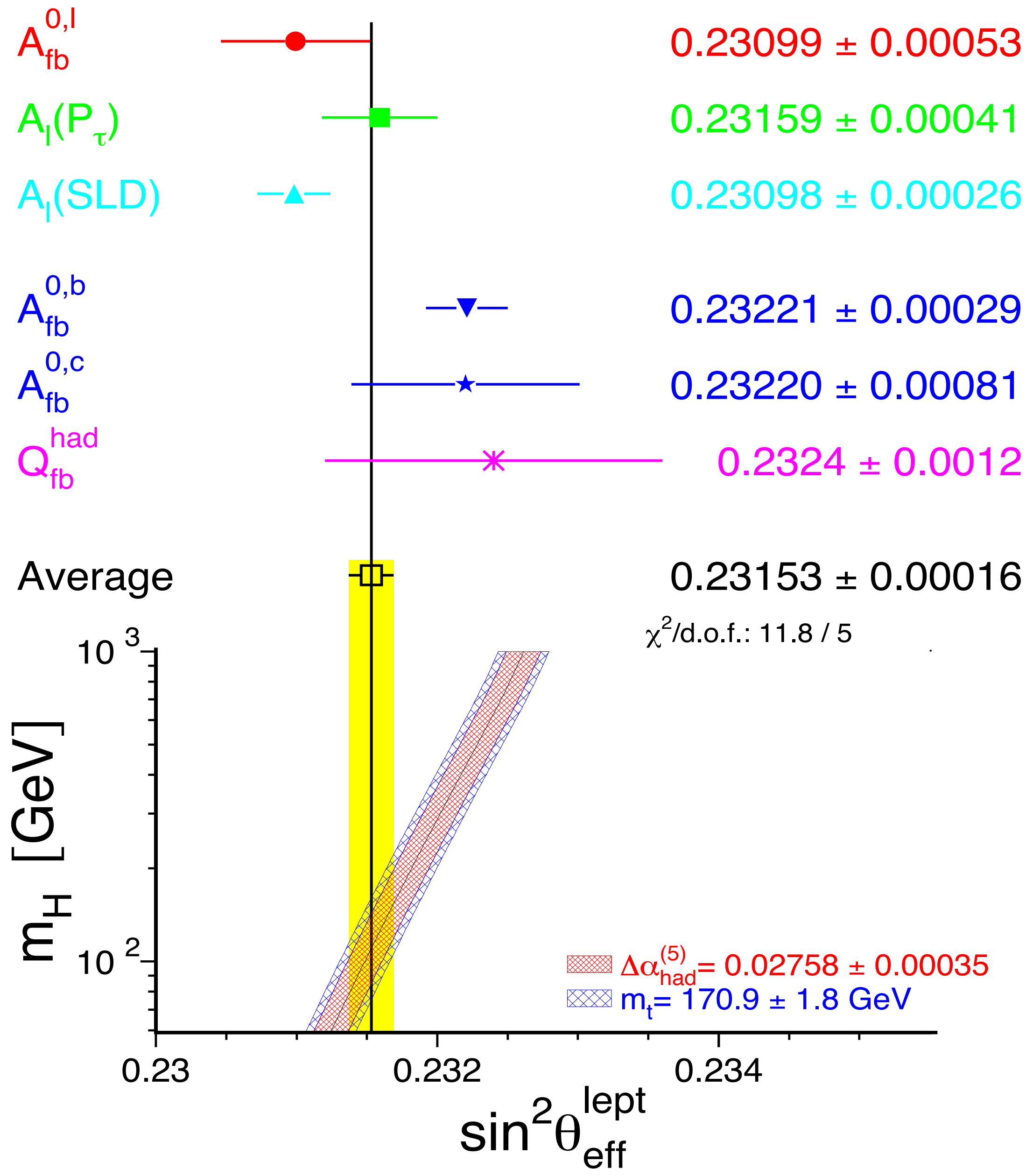
Current experimental value from LEP and SLD:

$\sin^2\theta_{\rm eff} = 0.23153 \pm 0.00016 \Rightarrow$ Accuracy of 0.07%

However: the small experimental error of the world-average is driven by two measurements that are not well compatible with each other: $A_{\rm LR}$ (SLD) and $A_{\rm FB}$ (LEP)

$$\sin^2\theta_{\rm eff}(A_{\rm LR}) = 0.23098 \pm 0.00026, \quad \sin^2\theta_{\rm eff}(A_{\rm FB}) = 0.23221 \pm 0.00029$$

$\sin^2\theta_{\mathrm{eff}}$: unclear experimental situation



[*LEPEWWG '07*]

$\sin^2\theta_{\mathrm{eff}}$ has a high sensitivity to M_{H} and effects of new physics

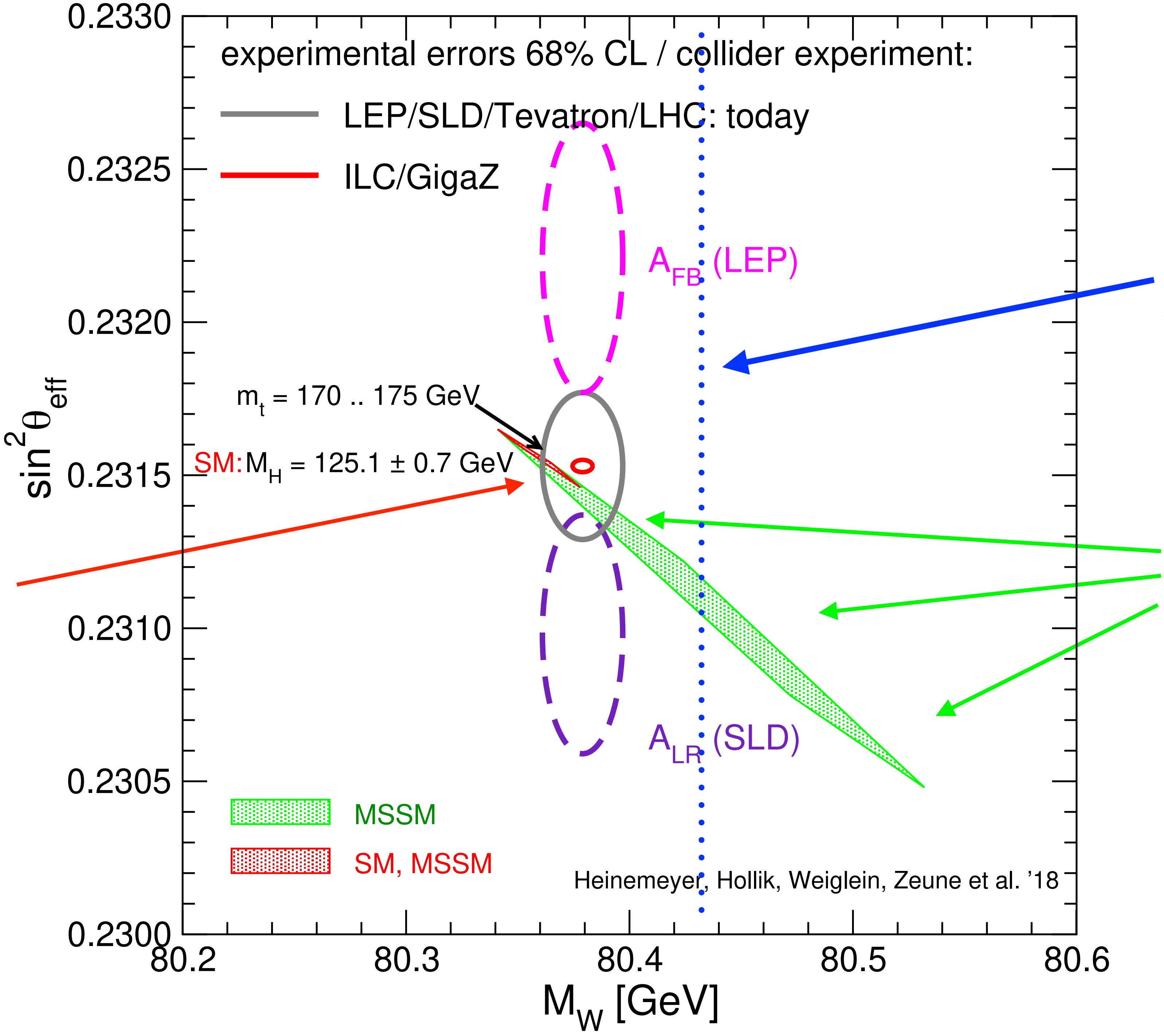
But:
large discrepancy between A_{LR} (SLD) and A_{FB} (LEP),

has big impact on constraints on new physics

Interpretation of constraints from $\sin^2\theta_{\mathrm{eff}}$ is complicated by the fact that the two most precise individual measurements differ from each other by more than 3 σ

Prediction for M_W and $\sin^2\theta_{\rm eff}$ in the SM and MSSM vs. experimental accuracies (before new CDF result)

[S. Heinemeyer, W. Hollik, G. W., L. Zeune ’18]



New CDF value

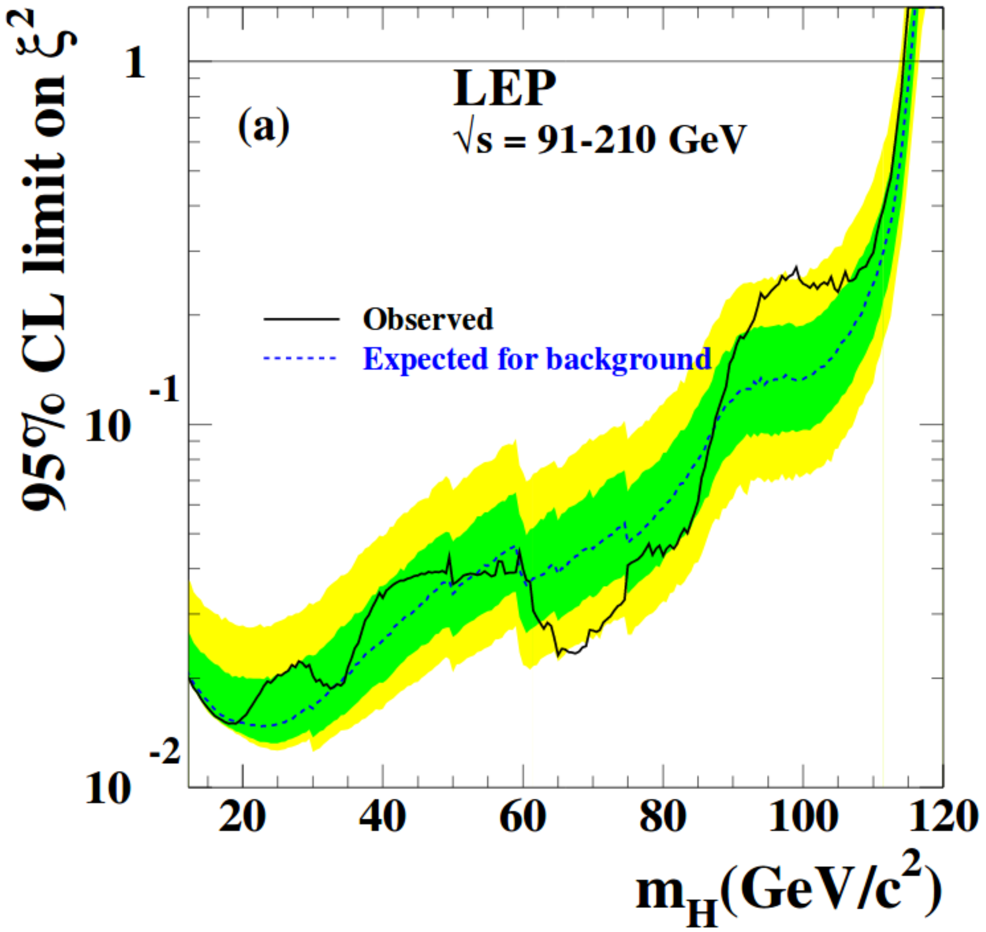
MSSM region

SM ``line”

⇒ M_W and $\sin^2\theta_{\rm eff}$ have high sensitivity for model discrimination

Further hints for an additional light Higgs boson: excesses at about 95 GeV at LEP and CMS

[LEP Higgs Combination '06]

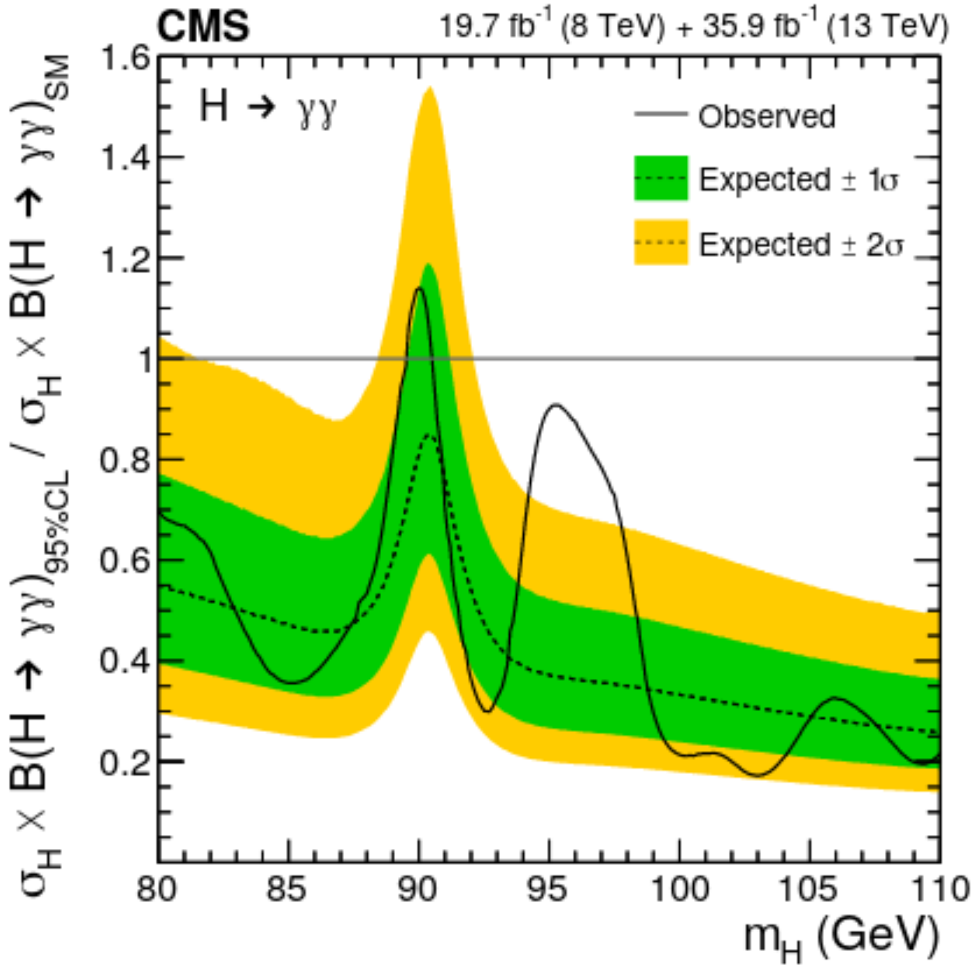


[LEP: hep-ex/0306033]

$\sim 2\sigma$ local excess at 96 - 98GeV

Extracted signal strength:
$\mu_{\rm LEP}\left(e^+e^- \to Zh \to Zb\bar{b}\right) = 0.117 \pm 0.057$
[1612.08522]

[CMS Collaboration '18]



[CMS: 1811.08459]

Run I/II data: Local excess of $\gtrsim 3\sigma$

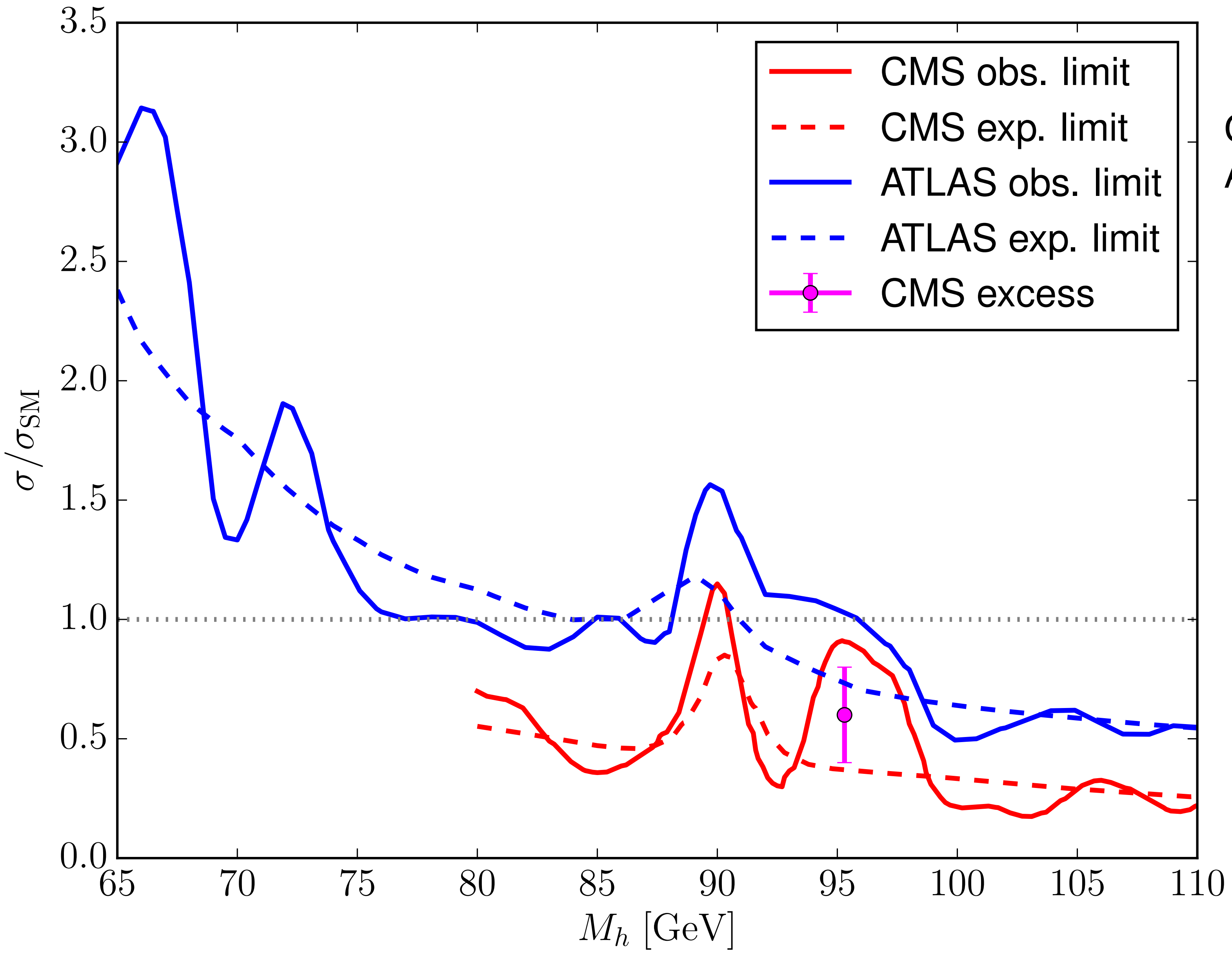
Extracted signal strength:
$\mu_{\rm CMS}\left(gg \to h \to \gamma\gamma\right) = 0.6 \pm 0.2$

$\to \chi^2_{96}(\mu_{\rm LEP}, \mu_{\rm CMS})$ assuming no correlation between $\mu_{\rm LEP}$ and $\mu_{\rm CMS}$

Many model interpretations with common origin of both excesses, including N2HDM and NMSSM

Possible hint for an additional light Higgs boson: CMS excess in $h \longrightarrow \gamma\gamma$ search vs. ATLAS limit

[T. Stefaniak '18]



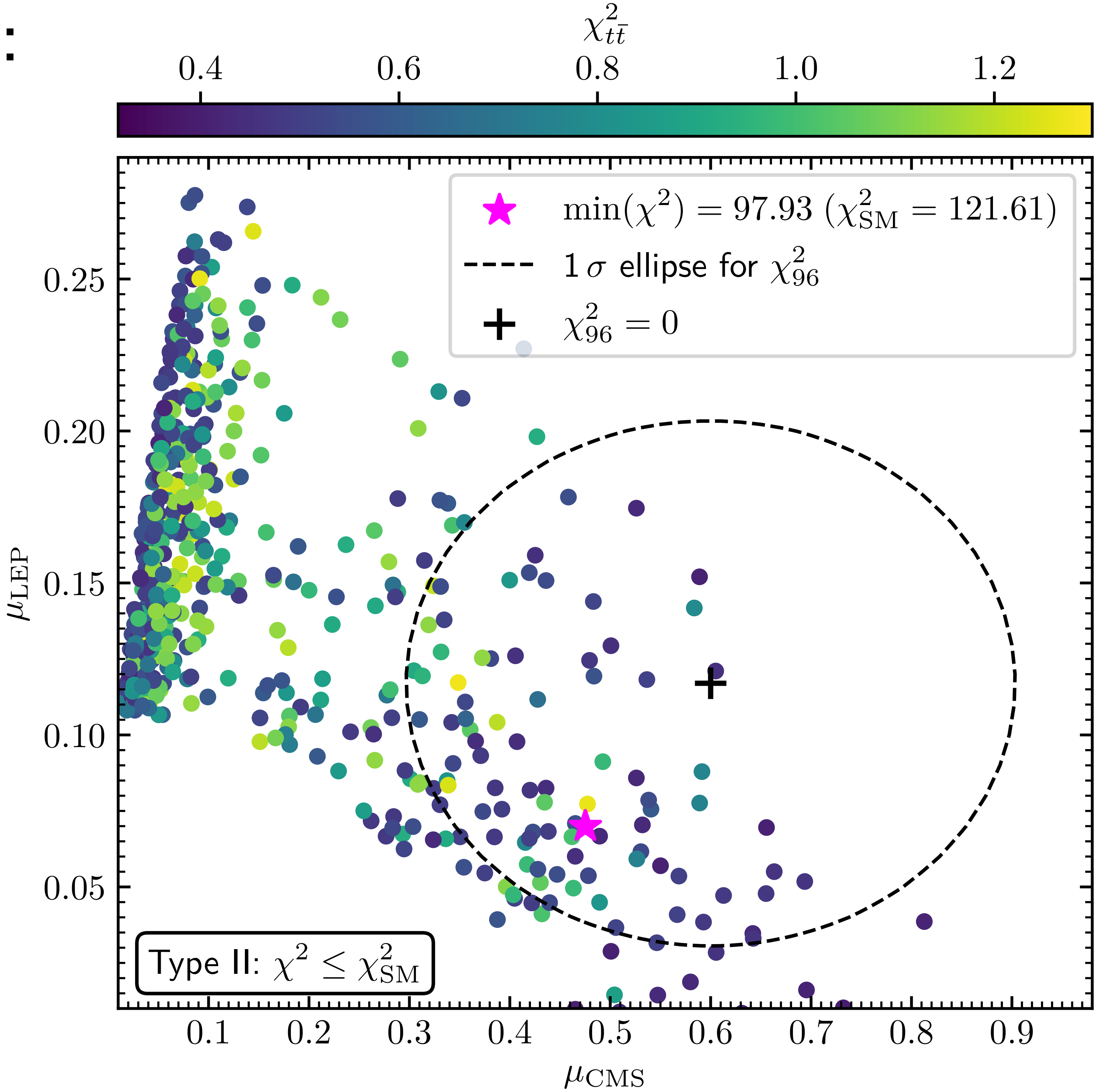
CMS-PAS-HIG 17-013,
ATLAS-CONF-2018-025

Could these excesses in the search for light additional Higgs bosons also be accommodated in the considered models?

Combined interpretation of excesses at 400 GeV (tt) + 95 GeV

[T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. W. ’21]

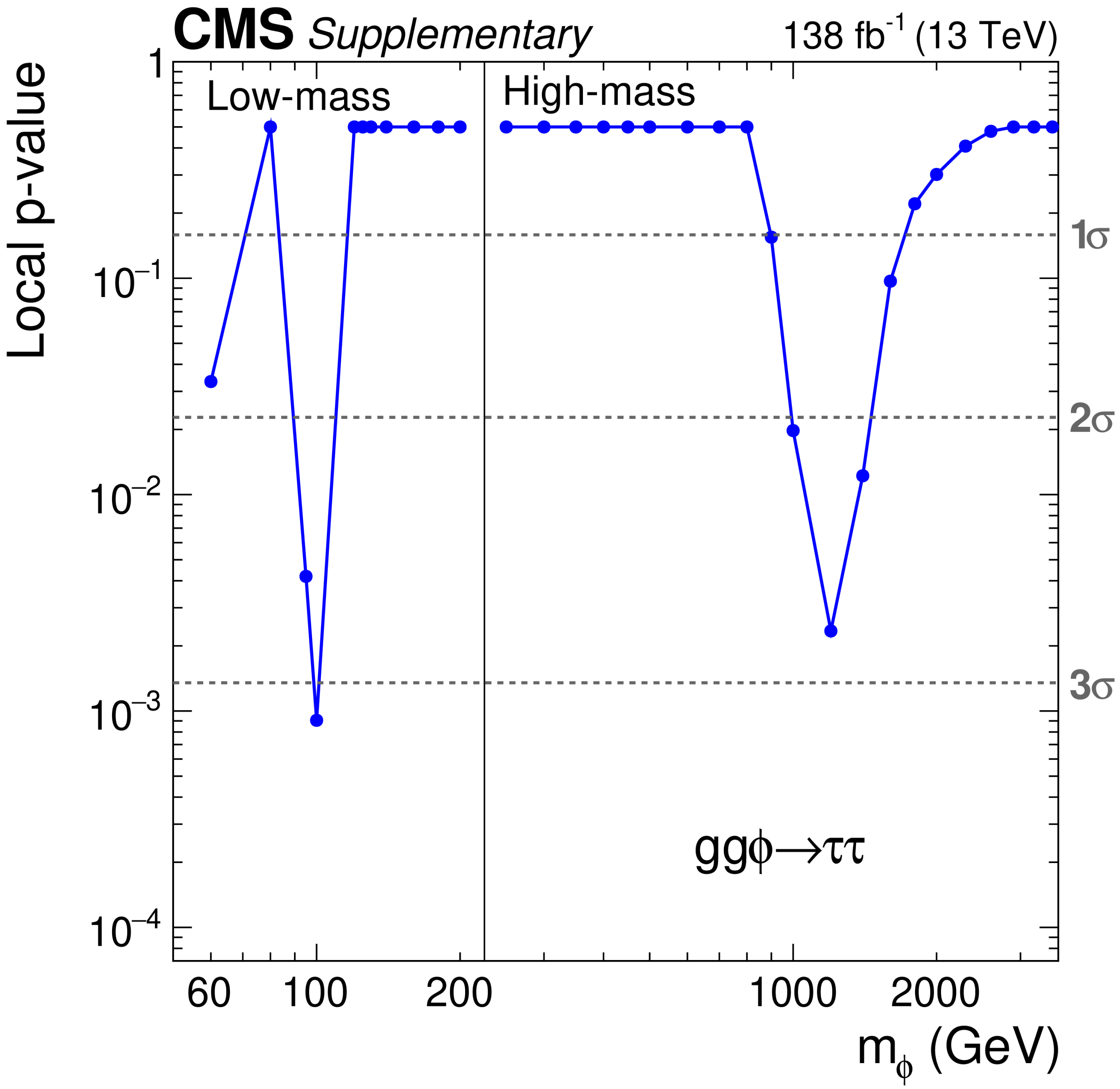
N2HDM, type II:

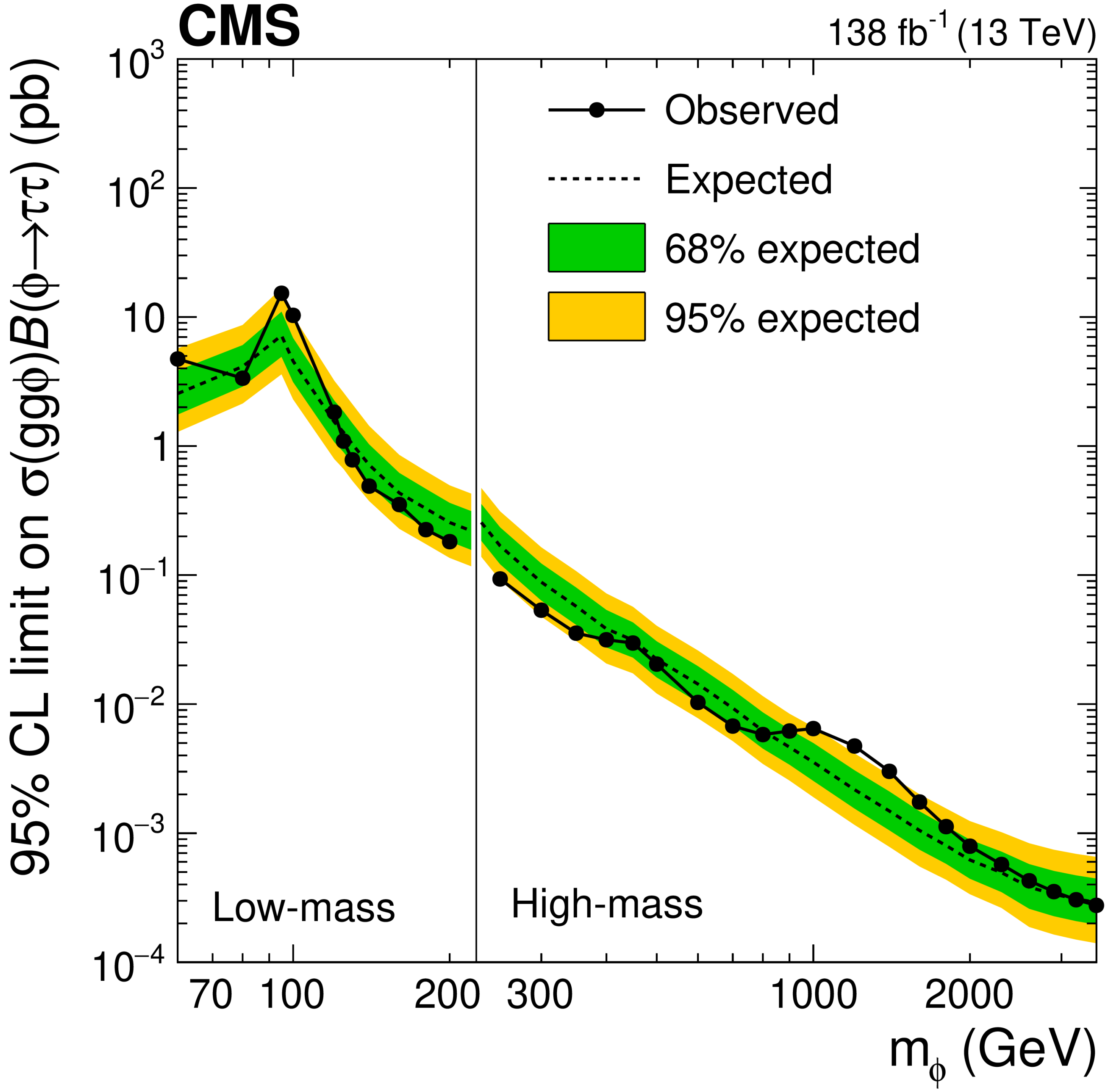


⇒ The A → tt excess at 400 GeV and the CMS $\gamma\gamma$ and LEP excesses at about 95 GeV can be described very well simultaneously!

Recent news: CMS result for the **ττ** channel

[CMS Collaboration '22]





⇒ The low-mass search shows an excess near 95 GeV that is compatible with the one observed in the $\gamma\gamma$ channel at Run I and II

Can the CMS $\gamma\gamma$, CMS $\boldsymbol{\tau\tau}$ and the LEP excess near 95 GeV all be described simultaneously?

Next-to-Two-Higgs doublet model (N2HDM):

[T. Biekötter, S. Heinemeyer, G. W. '22]

$$\begin{aligned} \text{N2HDM} &= \text{SM}(\phi_1) + \text{Second Higgs Doublet}(\phi_2) + \text{Real Scalar Singlet}(\phi_s) \\ &= \text{2HDM}(\phi_1, \phi_2) + \text{Real Scalar Singlet}(\phi_s) \end{aligned}$$

Higgs sector

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

Symmetries: Z_2: $\phi_1 \to \phi_1$, $\phi_2 \to -\phi_2$ and $\phi_s \to \phi_s$, only softly broken by m_{12}^2
Z_2': $\phi_1 \to \phi_1$, $\phi_2 \to \phi_2$ and $\phi_s \to -\phi_s$, spontaneously broken by v_s

Extension of Z_2 to Yukawa sector $\Rightarrow$ 4 types of the (N)2HDM

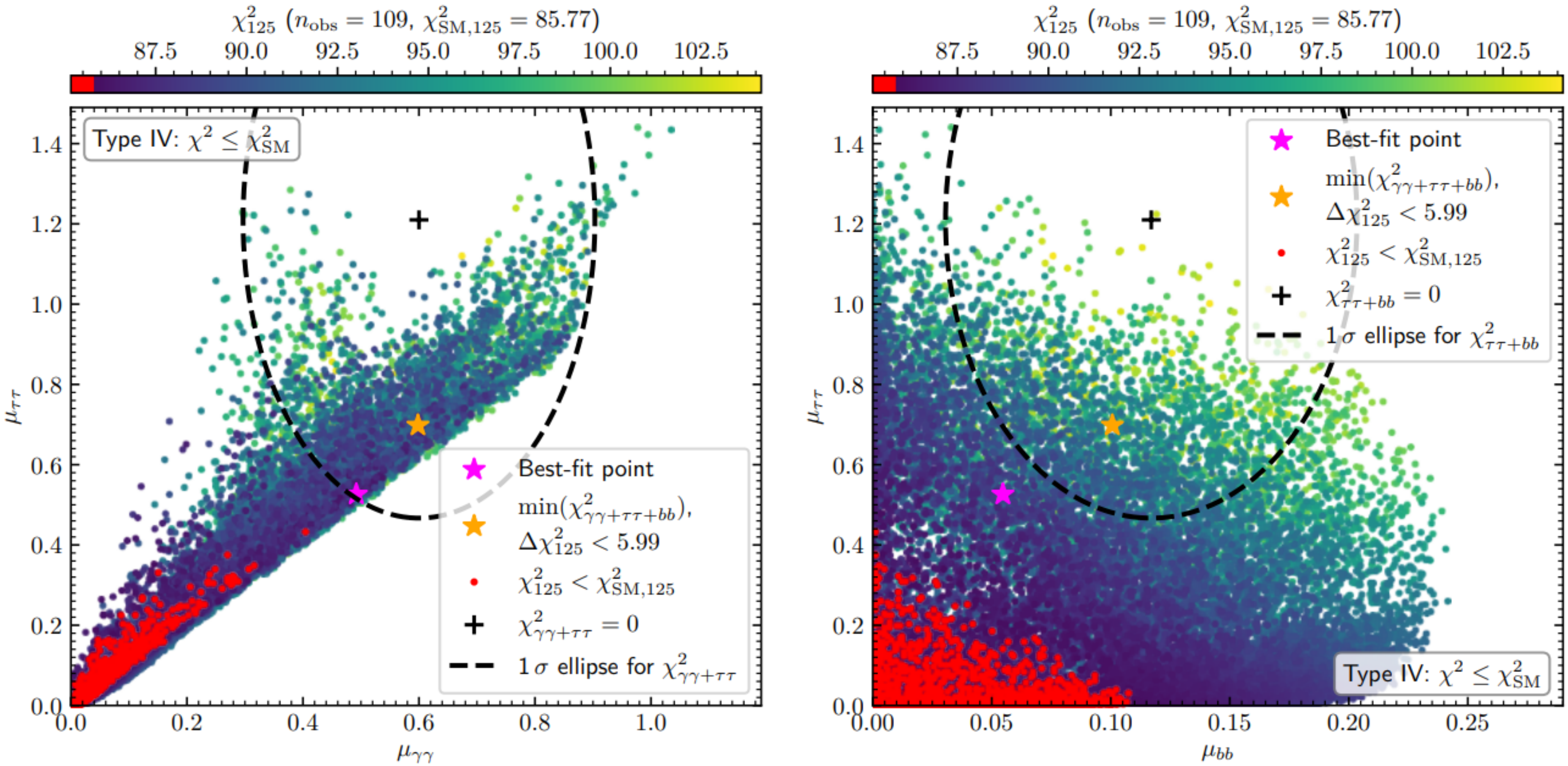
$$-\mathcal{L}_{\text{Yuk}} = \sum_{i=1}^{2} \frac{\sqrt{2}m_f}{v} c_{h_i f\bar{f}} \overline{\Psi}_f \Psi_f h_i$$

Type	u-quarks	d-quarks	leptons
I	ϕ_2	ϕ_2	ϕ_2
II (Susy-like)	ϕ_2	ϕ_1	ϕ_1
III (lepton-specific)	ϕ_2	ϕ_2	ϕ_1
IV (flipped)	ϕ_2	ϕ_1	ϕ_2

N2HDM vs. excesses in Higgs searches near 95 GeV

N2HDM, type IV:

[T. Biekötter, S. Heinemeyer, G. W. '22]

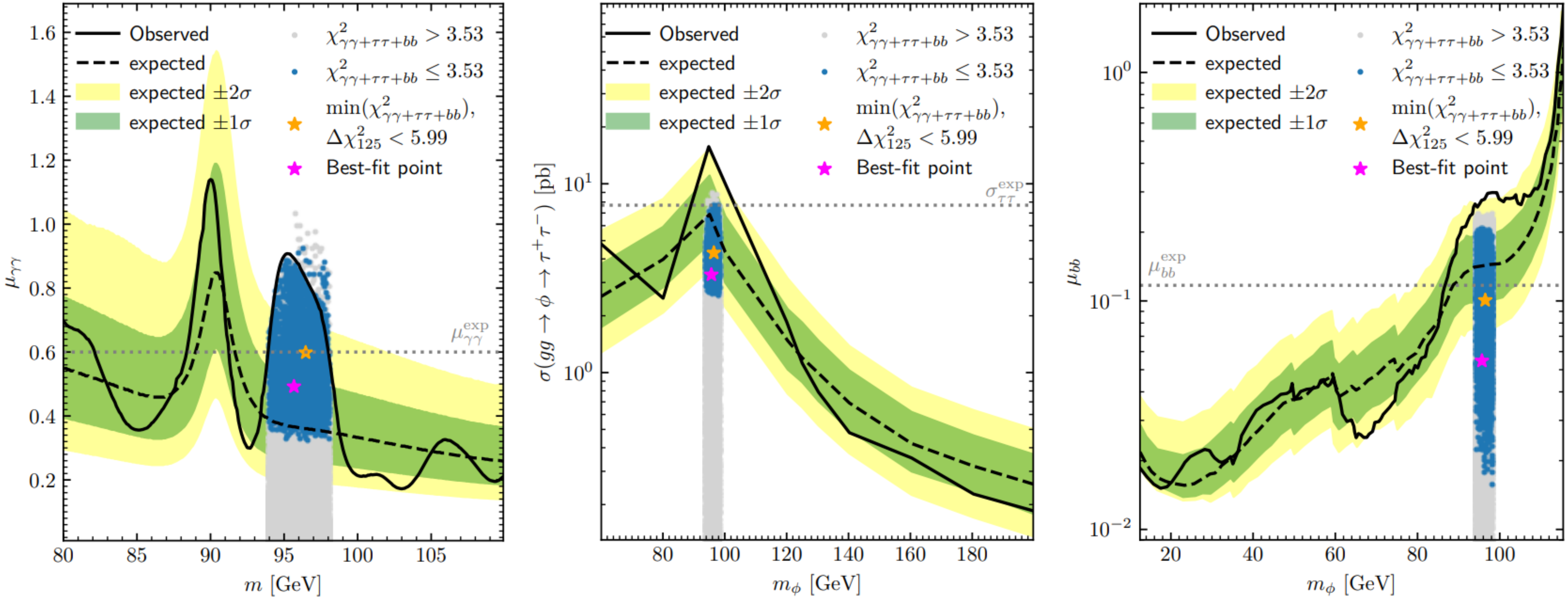


⇒ Good compatibility with all three excesses!

N2HDM vs. excesses in Higgs searches near 95 GeV

N2HDM, type IV:

[T. Biekötter, S. Heinemeyer, G. W. '22]



[2203.13180]

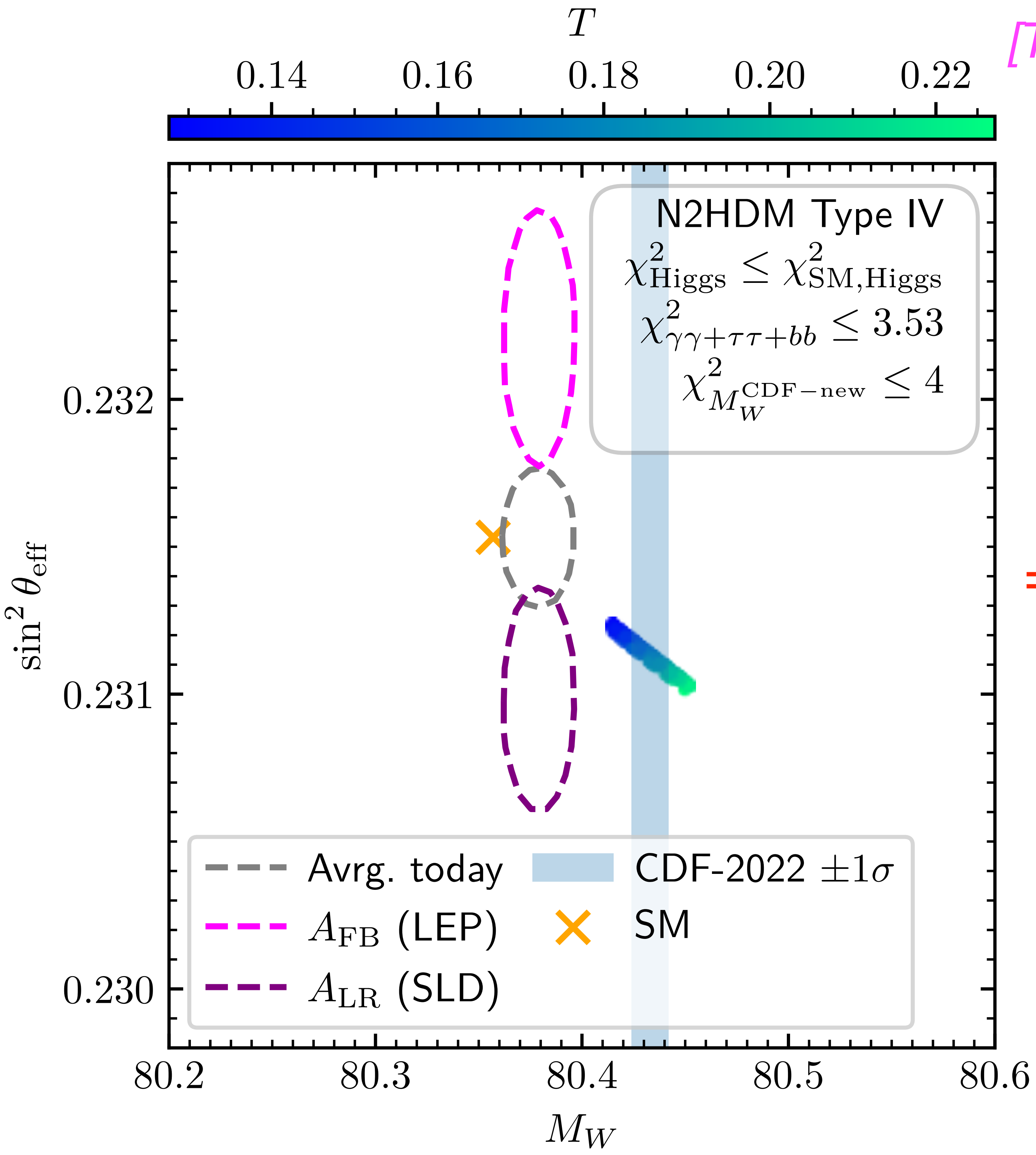
$$\chi^2 = \chi^2_{\gamma\gamma} + \chi^2_{\tau\tau} + \chi^2_{bb} + \chi^2_{125}$$

χ^2_{125}: HiggsSignals

⇒ Good compatibility with all three excesses!

N2HDM: a 95 GeV Higgs and the CDF value of M_W

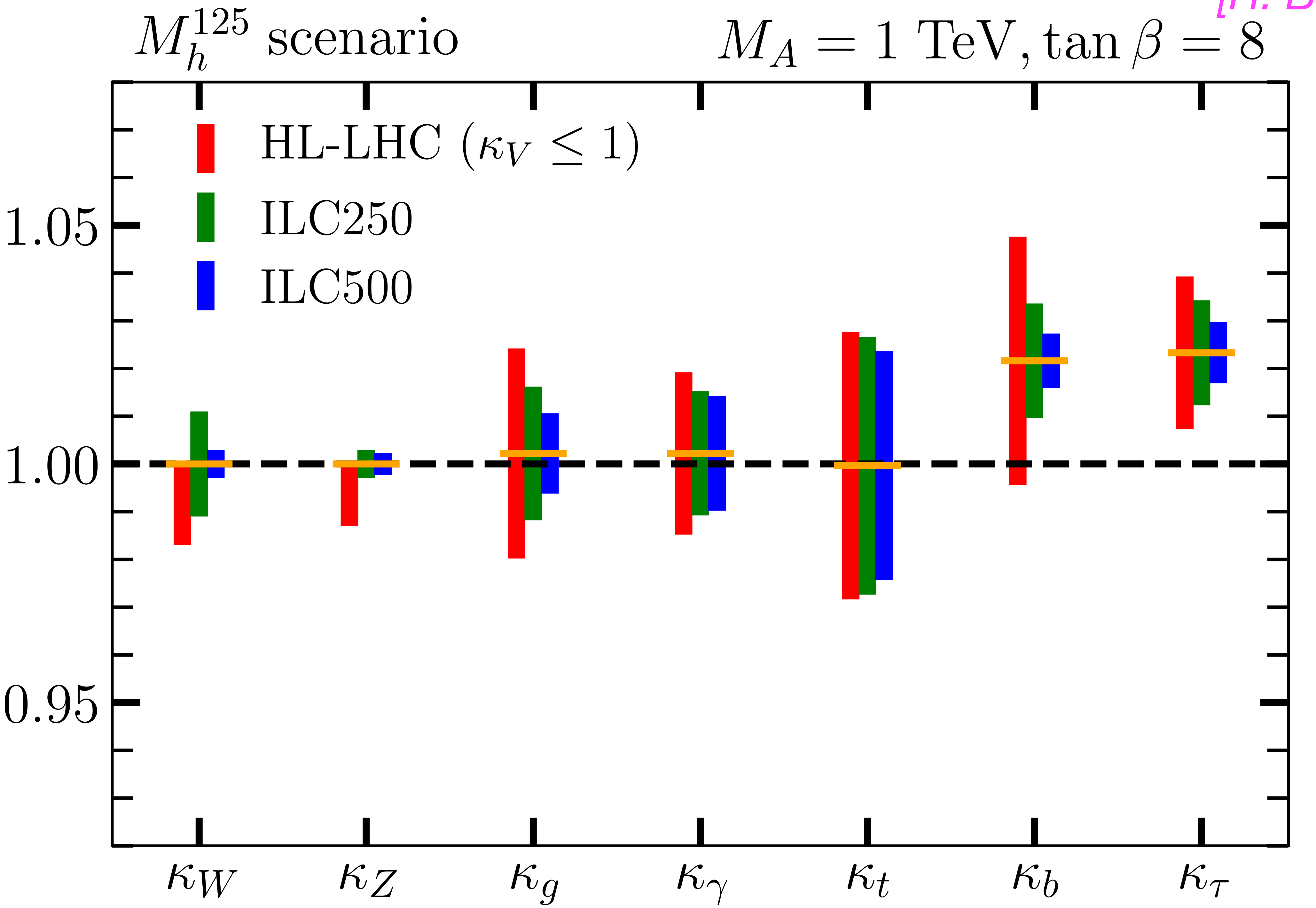
[T. Biekötter, S. Heinemeyer, G. W. '22]



⇒ The N2HDM of type IV can simultaneously accommodate the three excesses in the Higgs searches near 95 GeV and an M_W value that agrees with the new CDF measurement!

Example: heavy SUSY scenario

[H. Bahl et al. ’19]

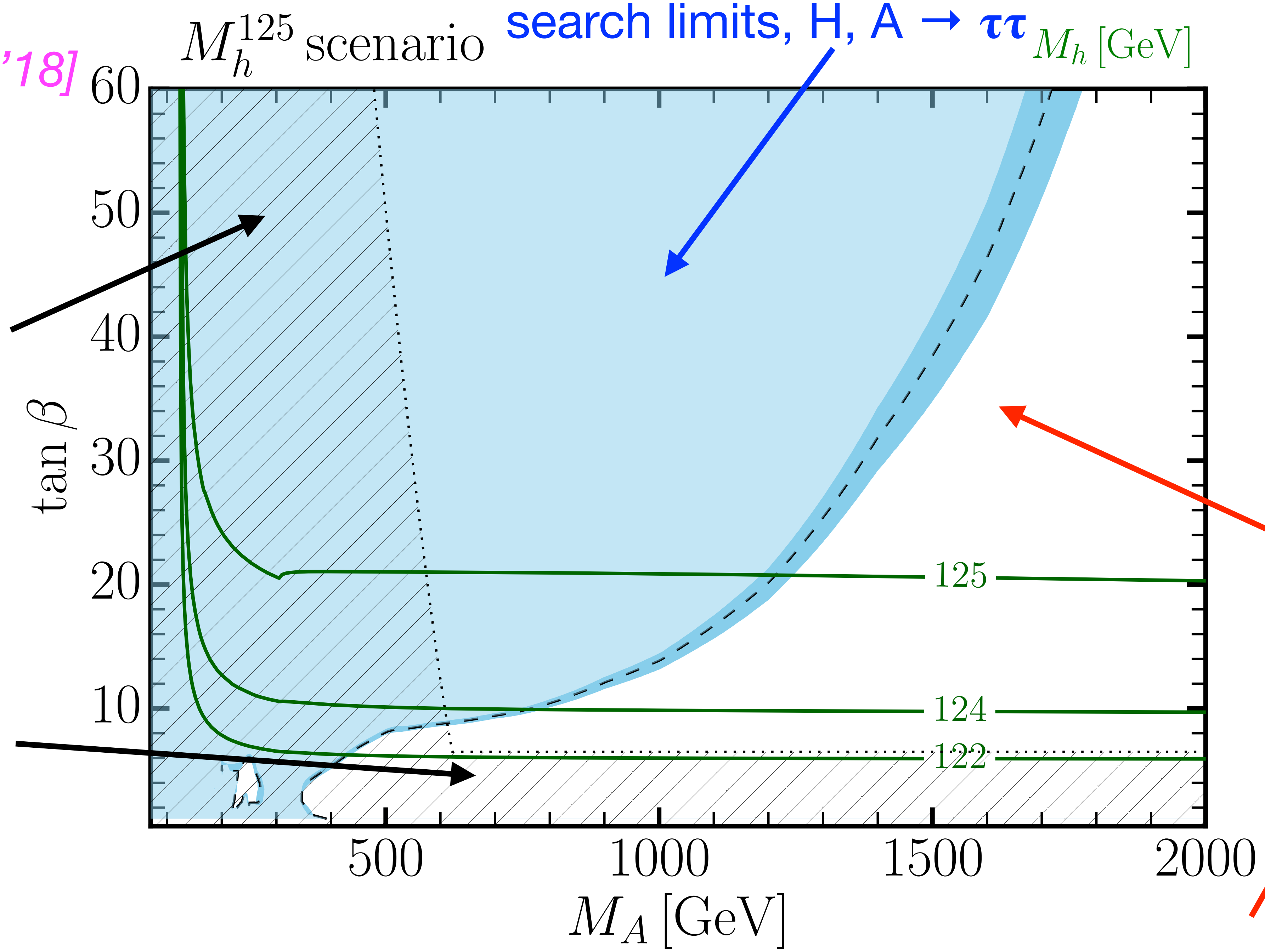


⇒ Precision at 1% level provides large sensitivity for discriminating between different realisations of underlying physics

Higgs physics at the LHC (Run 3, HL-LHC)

Search for additional Higgs bosons (+ vector boson scattering): MSSM example

[H. Bahl et al. '18]



HiggsBounds: area excluded by Higgs search limits, H, A → **ττ**

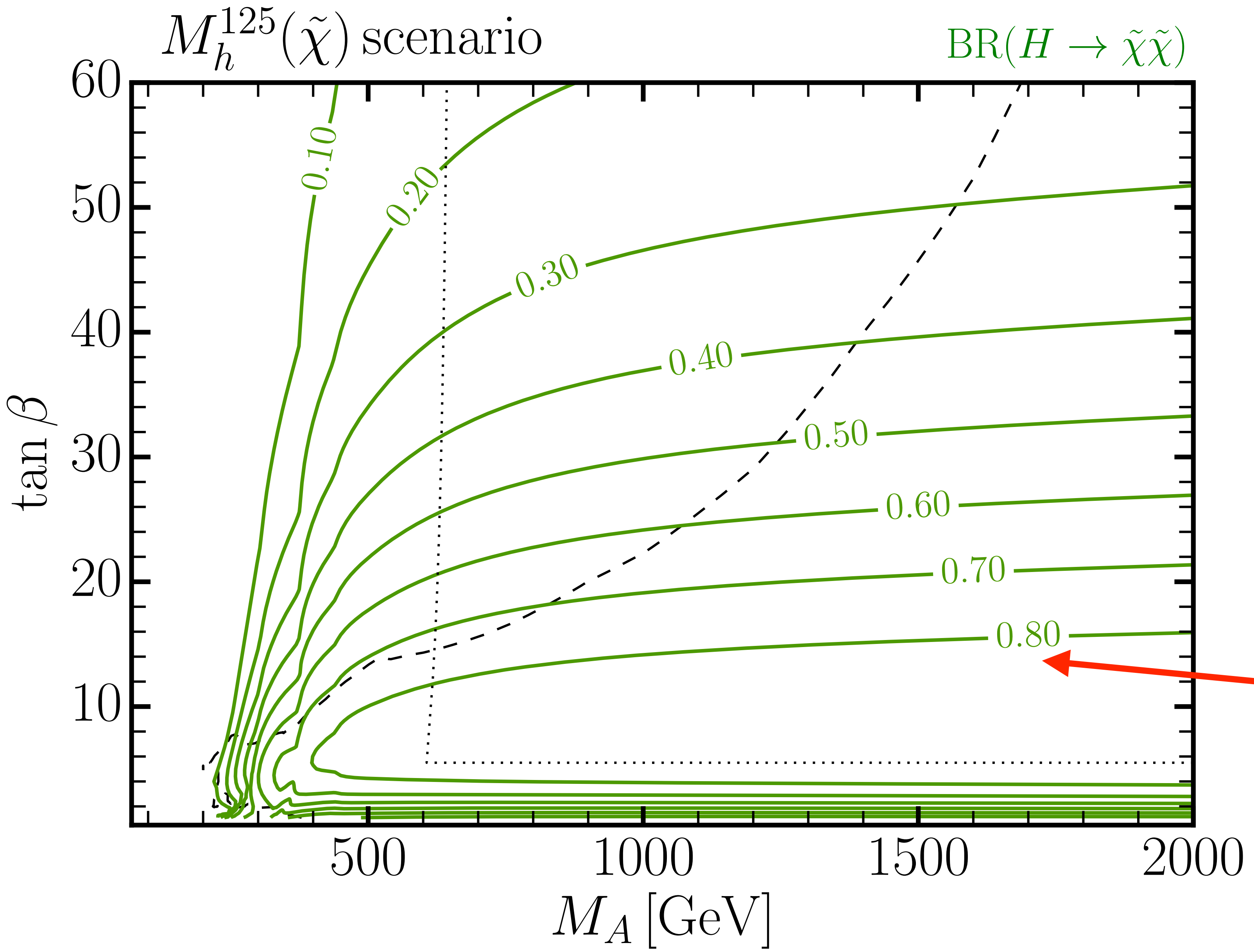
HiggsSignals: area is not compatible with the detected properties of the detected Higgs signal h125 (indirect sensitivity)

Allowed region, could be probed by dedicated searches for H, A → BSM part.

Non-standard decays of heavy Higgses, e.g. $H \to \tilde{\chi}\tilde{\chi}$

[H. Bahl et al. ’18]

Decays of heavy Higgs bosons *H, A* into charginos and neutralinos:



Branching ratios of more than 80% possible!

⇒ Dedicated searches for heavy Higgs decays into SUSY particles could probe the ``LHC wedge” region

Theoretical description: N2HDM and NMSSM

[T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. W. ’21]

Scans in the N2HDM (Higgs sector consists of two doublets and a real singlet) and the NMSSM (MSSM + Higgs singlet + superpartners), taking into account the constraints from collider searches, the signal rates of the Higgs at 125 GeV, flavour physics, electroweak precision observables, vacuum stability and perturbative unitarity

NMSSM with $M_A = 400$ GeV and low tanβ: ``alignment without decoupling” region

$$\chi^2 = \chi^2_{125} + \chi^2_{tt} + \ldots$$

Require: $\chi^2 \leqq \chi^2_{SM}$