Recently at the Chiemsee (Bavaria, Germany):

BSM Higgs Physics and GW: my personal view

Sven Heinemeyer, IFT (CSIC, Madrid)

Hamburg, 11/2025

- Two joint papers out of 100+ (as a bracket)
- BSM Higgs physics and GW
- A little quiz in the end
- I found $\gtrsim$ 1000 photos
  $\rightarrow$ will show only a tiny fraction, mostly from 1997 - 2000 ;-)
  ($\rightarrow$ 3 intermezzi)
  . . . surprizingly few photos in which Georg is working . . .

My first recollection . . .

I started my PhD in 1994 in Karlsruhe with Wolfgang Hollik.

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I could not imagine that he would become my best friend
with common interests,
with the same passion (for BSM Higgs physics),
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and that we would go on honeymoon together (but that's another story)

The earliest photo that I found: RadCor 1998 (Barcelona)

Now for the two papers:

Inspire: `a weiglein and heinemeyer` → 249 (131) results

Very old and quite recent, a theme that connects us for a long^2 time:

(and all of todays speakers are co-authors! :-)

arXiv:hep-ph/0001002v3 13 Jul 2000

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 [§,†], H.E. Haber [♯], S. Heinemeyer [‡],

W. Hollik [¶], C.E.M. Wagner [†,*,♮] and G. Weiglein [†]

[§] FERMILAB, Batavia, IL 60510-0500 USA
[†] CERN, TH Division, CH–1211 Geneva 23, Switzerland
[♯] Santa Cruz Inst. for Part. Phys., Univ. of California, Santa Cruz, CA 95064 USA
[‡] DESY Theorie, Notkestrasse 85, 22603 Hamburg, Germany
[¶] Institut für Theoretische Physik, Univ. of Karlsruhe, 76128 Karlsruhe, Germany
[*] High Energy Physics Division, Argonne National Lab., Argonne, IL 60439 USA
[♮] 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[a] and S. Heinemeyer[b,c,d] (eds.),

E. Bagnaschi[e], H. Bahl[f], M. Goodsell[a], H.E. Haber[g], T. Hahn[h], R. Harlander[i], W. Hollik[h], G. Lee[j,k,l], M. Mühlleitner[m], S. Paßehr[i], H. Rzehak[n], D. Stöckinger[o], A. Voigt[p], C.E.M. Wagner[q,r,s] and G. Weiglein[f],

B.C. Allanach[t], T. Biekötter[f], S. Borowka[u‡], J. Braathen[f], M. Carena[r,s,v], T.N. Dao[w], G. Degrassi[x], F. Domingo[y], P. Drechsel[f‡], U. Ellwanger[z], M. Gabelmann[m], R. Gröber[aa], J. Klappert[i], T. Kwasnitza[o], D. Meuser[f], L. Mihaila[bb‡], N. Murphy[cc‡], K. Nickel[y‡], W. Porod[dd], E.A. Reyes Rojas[ee], I. Sobolev[f] and F. Staub[m‡]

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 . . .

First the first paper: (the second paper comes in the end)

arXiv:hep-ph/0001002v3 13 Jul 2000

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⇒ note the arXiv number!

⇒ the second paper in the new millenium (modulo 2000 vs. 2001)

BSM Higgs Physics and GW

BSM Higgs Physics and GW (large part of our work since ∼2020)

BSM Higgs Physics and GW (large part of our work since ∼2020)

⇒ Why is there more matter than antimatter? ⇒ (EW) baryogenesis

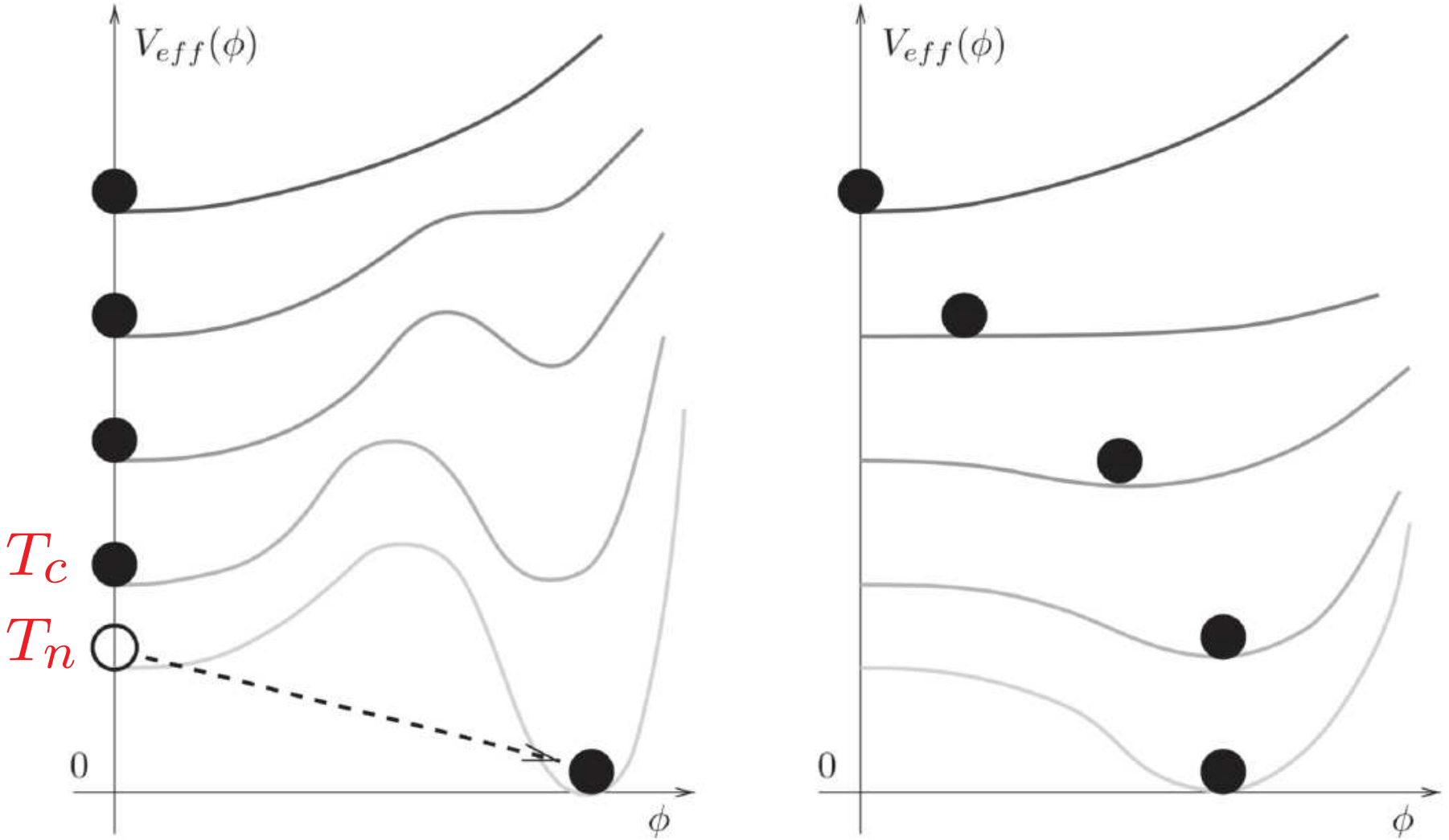
⇒ requires First Order EW Phase Transition (FOEWPT)

FOEWPT not possible in the SM ⇒ BSM Higgs sector required

FOEWPT can cause Gravitational Waves (GW), detectable with LISA, . . .

Phase transition: BSM vs. SM

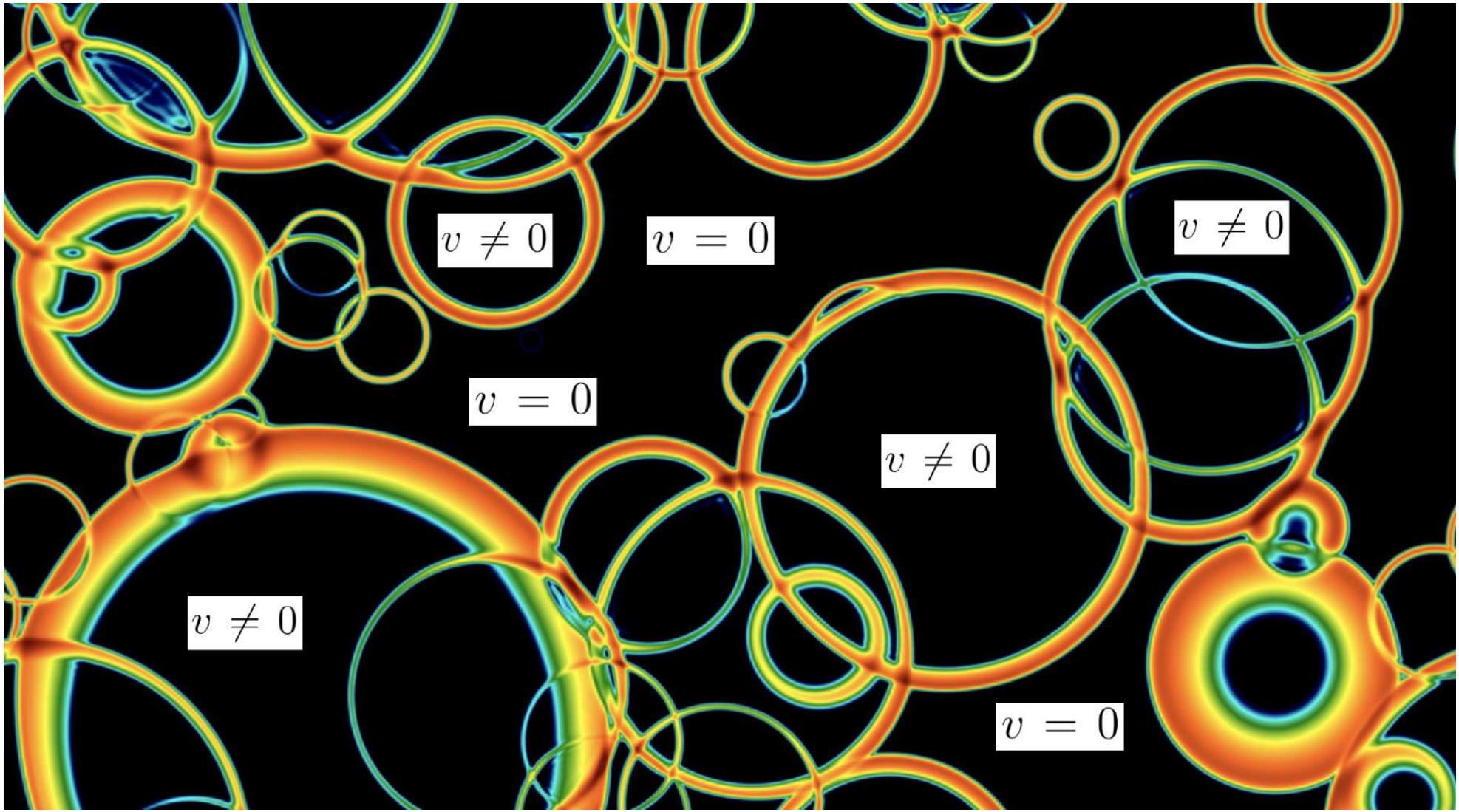
[taken from V. A. Rubakov and D. S. Gorbunov]



$\Rightarrow$ BSM Higgs sector required to realized FOEWPT

Bubble formation can lead to Gravitational Waves

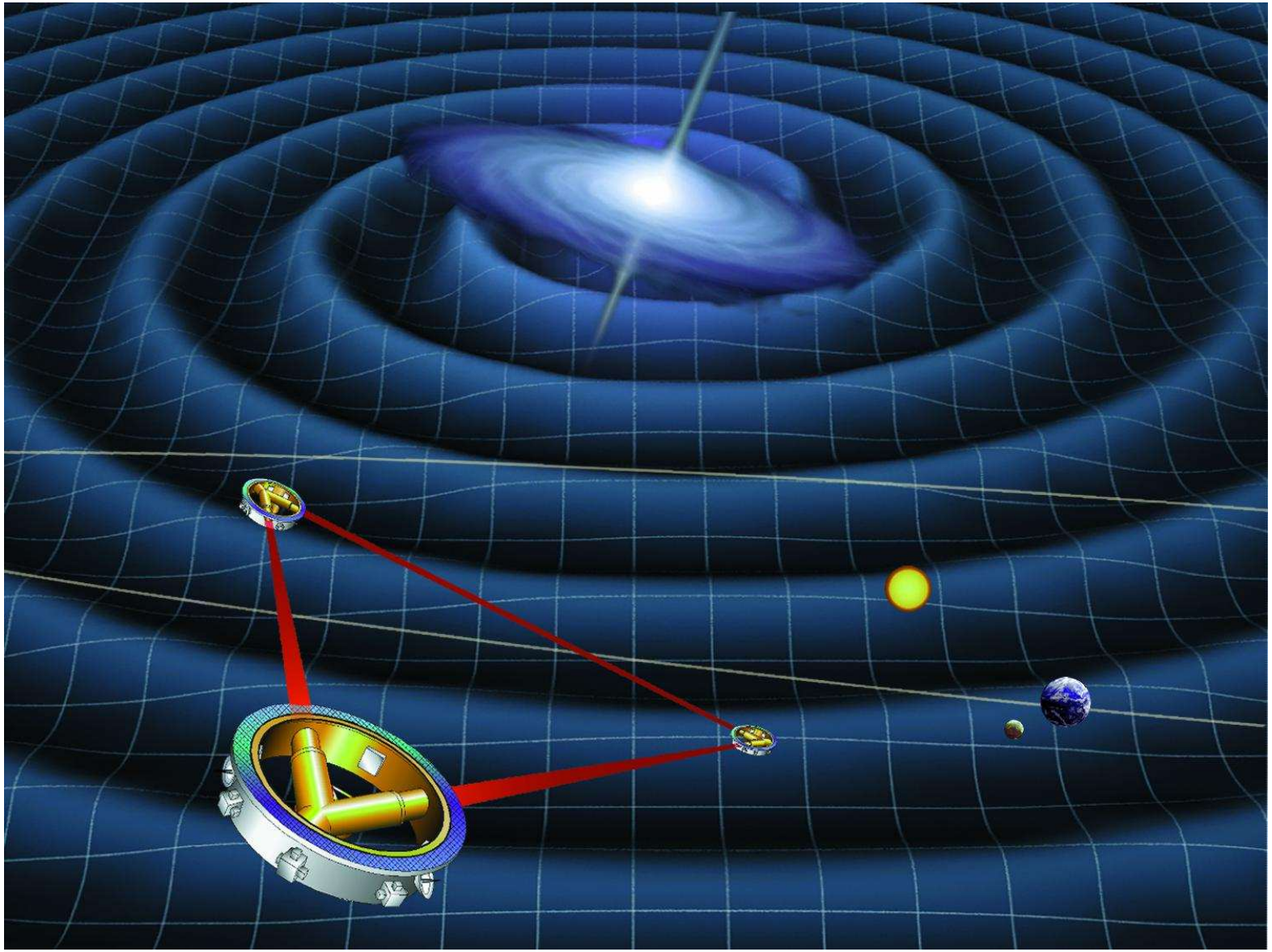
[taken from D. Weir]



$\Rightarrow$ Interesting interplay of Higgs physics and Gravitational Waves!

GW observatory: LISA

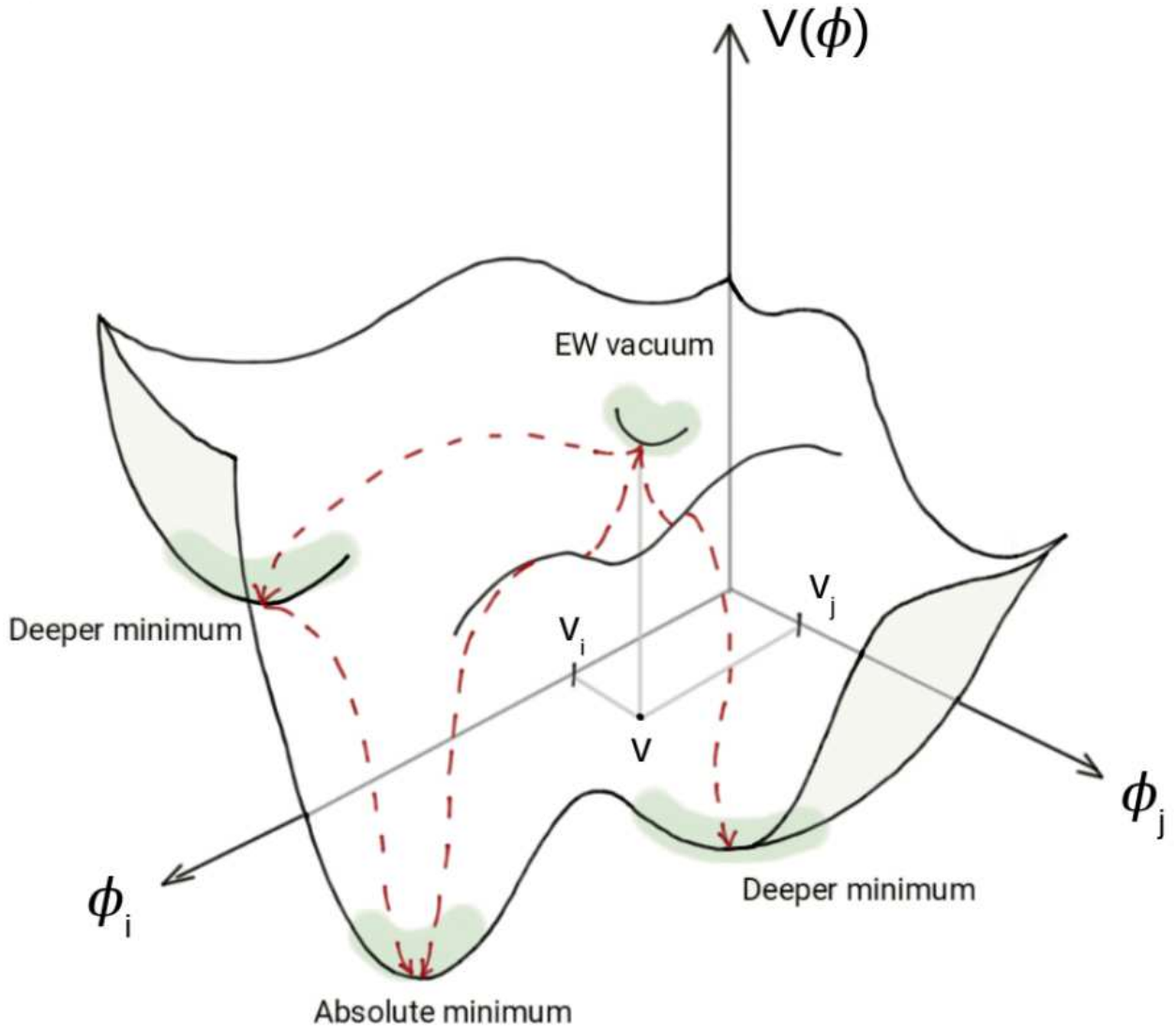
[NASA]



Approved launch date: $\sim$ 2035

BSM Higgs sectors can (should) behave very different from SM Higgs

[*K. Radchenko '24*]



⇒ much more complicated structure, very[2] little known . . .

$\Rightarrow$ FOEWPT in the 2HDM type II? $\Rightarrow$ parameter scan $\Rightarrow$ ScannerS

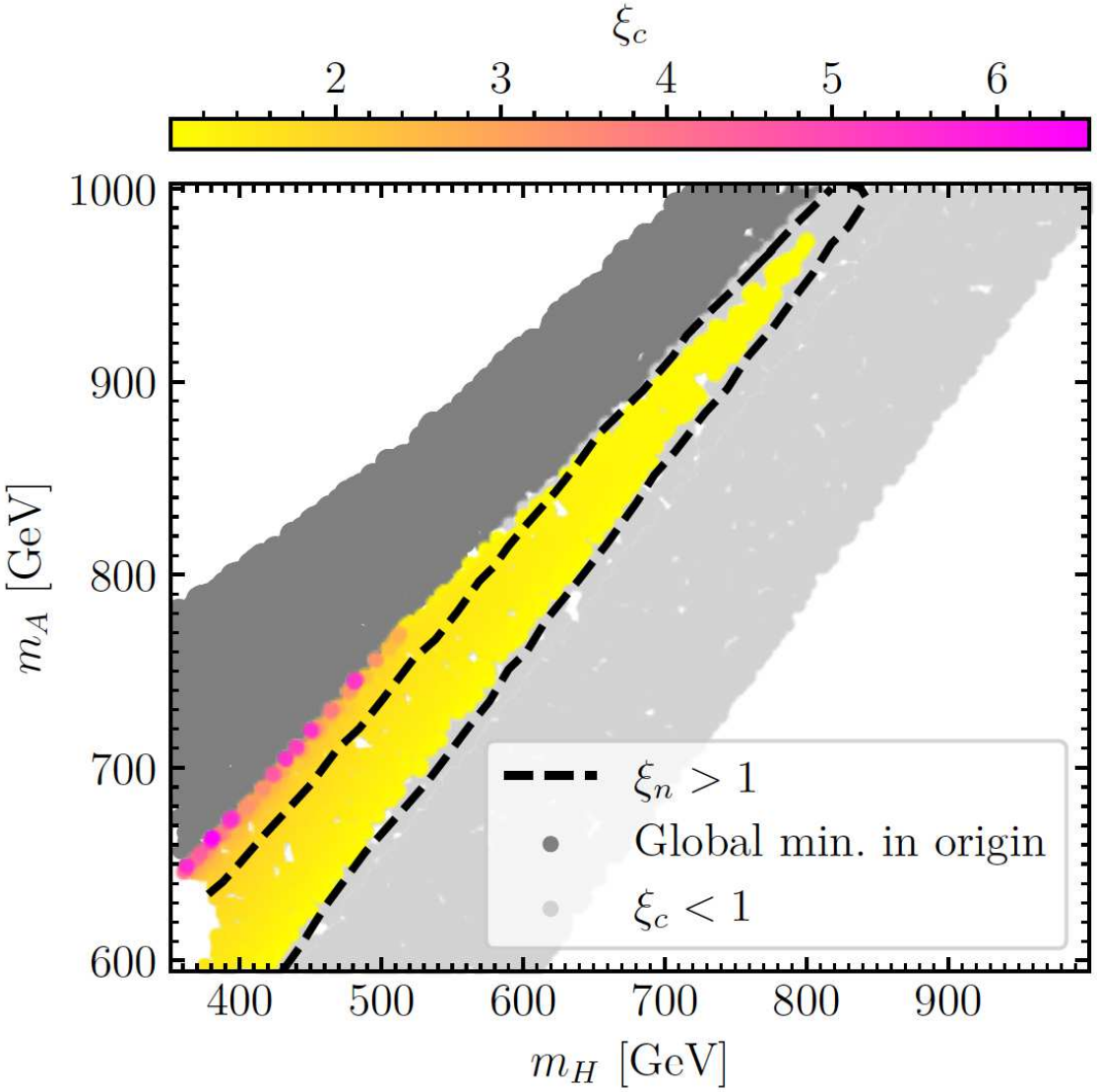
$\tan\beta = 3$, $c_{\beta-\alpha} = 0$, $m_{12}^2 = m_H^2 s_\beta c_\beta$
0.2 TeV $\leq m_H \leq$ 1 TeV, 0.6 TeV $\leq m_A = m_{H^\pm} \leq$ 1.2 TeV

Constraints:

- Tree-level perturbativity $\Rightarrow$ ScannerS
- Minimum of potential is global minimum $\Rightarrow$ ScannerS
  . . . or sufficiently long-lived $\Rightarrow$ Evade
- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds
- SM-like Higgs properties $\Rightarrow$ HiggsSignals (2HDECAY, SusHi)
  $\Rightarrow \chi^2_{125}$ (with $\chi^2_{\text{SM},125} = 84.4$)
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso bounds
- Electroweak precision data (T and S) $\Rightarrow$ ScannerS

GWs in the 2HDM: $\xi_c := v_c/T_c \gtrsim 1$

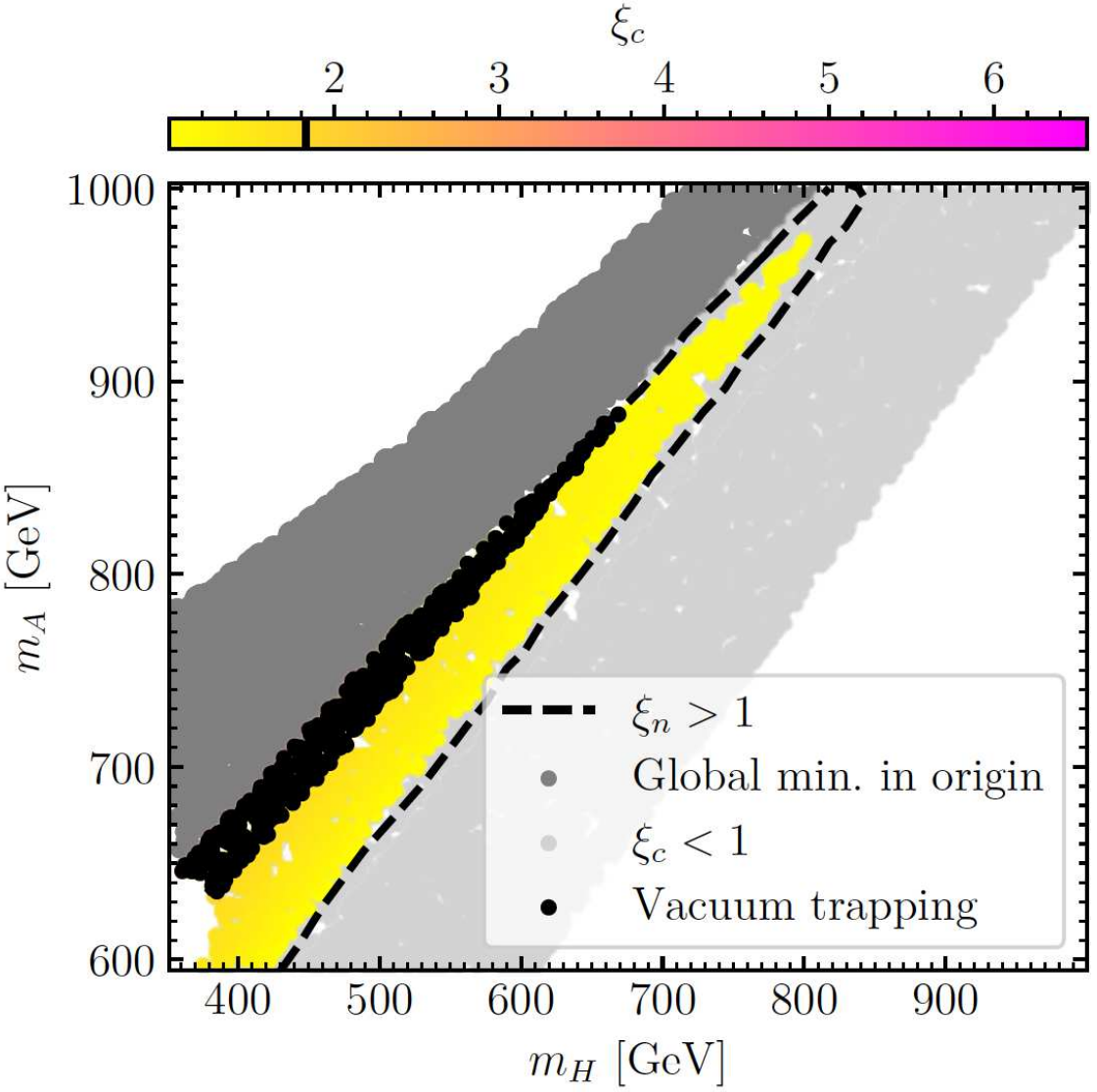
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



$\Rightarrow$ large ξ_c found in the 2HDM $\Rightarrow$ strong GW signal?

GWs in the 2HDM: $\xi_n := v_n/T_n \gtrsim 1$

[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



⇒ Thanks to Georg there are less GWs: forbidden by vacuum trapping

Intermezzo I: first workshop photos (DESY Theory WS 1998, my flat)

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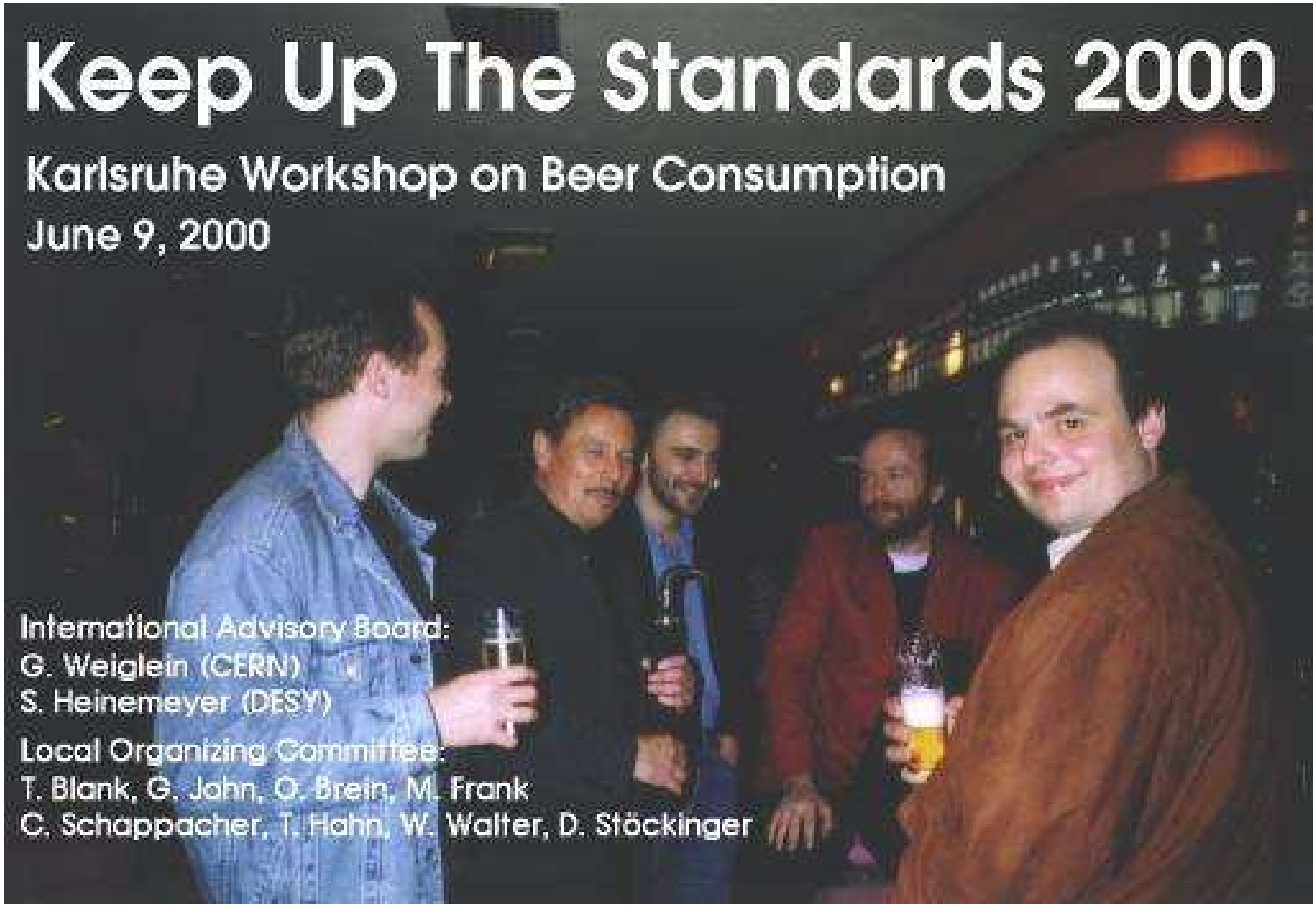
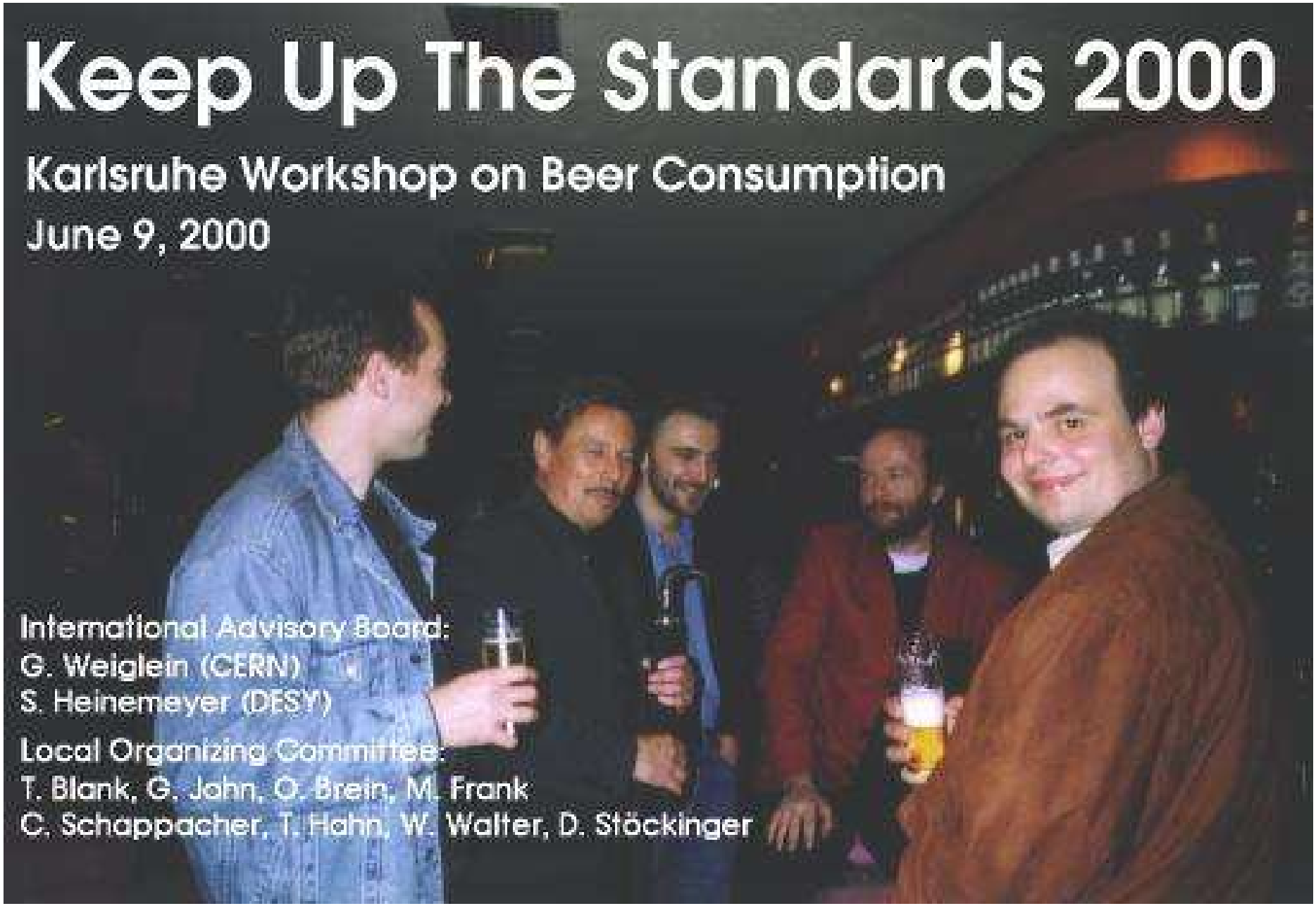
Intermezzo I: first workshop photos (LCWS 1999, Sitges)

Intermezzo I: first workshop photos (LCWS 1999, Sitges)

Intermezzo I: KUTS

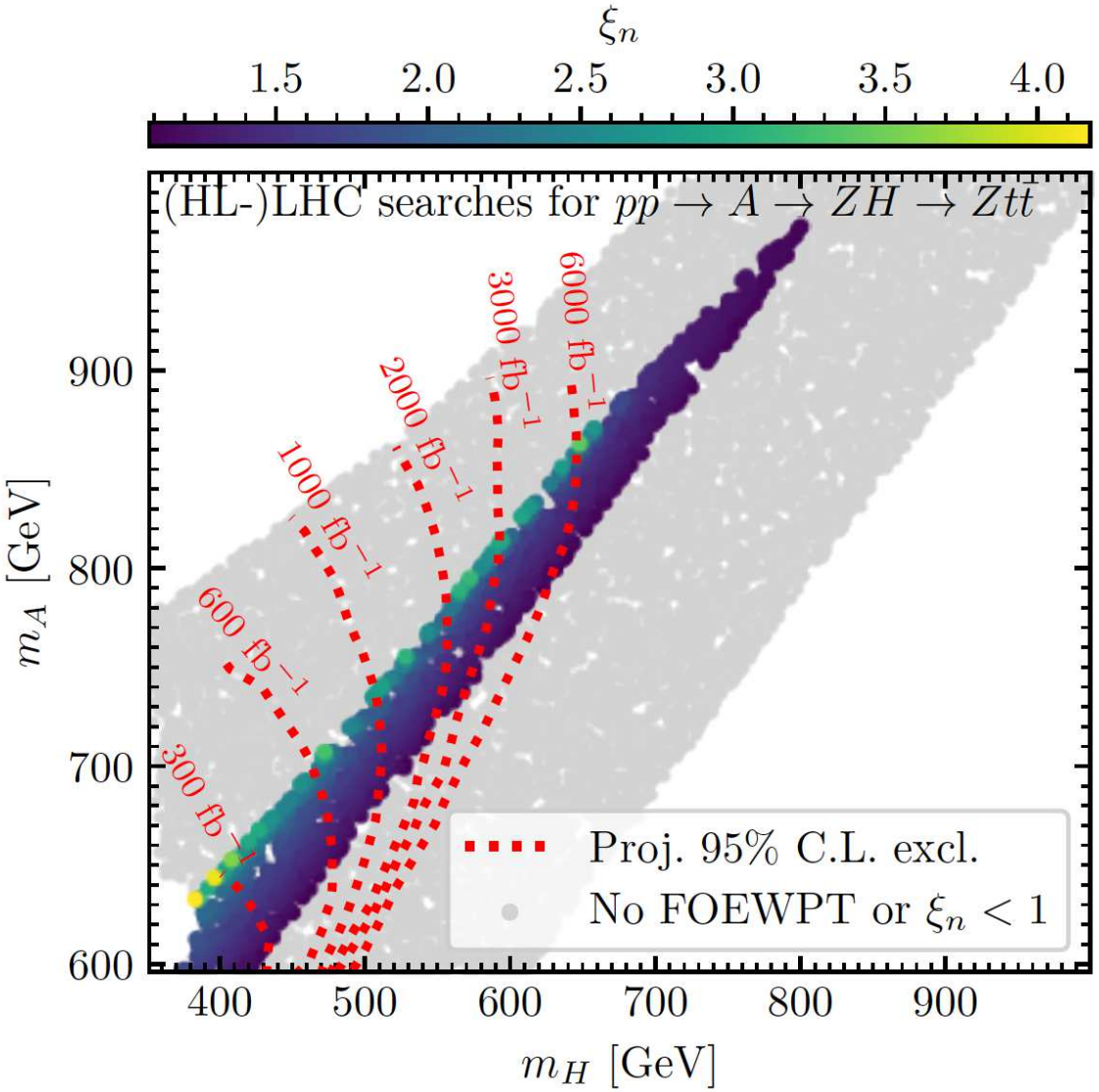



Keep Up The Standards 2000
Karlsruhe Workshop on Beer Consumption
June 9, 2000
International Advisory Board:
G. Weiglein (CERN)
S. Heinemeyer (DESY)
Local Organizing Committee:
T. Blank, G. Jahn, O. Brein, M. Frank
C. Schappacher, T. Hahn, W. Walter, D. Stöckinger

BSM Higgs physics and GW II:

[T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22]

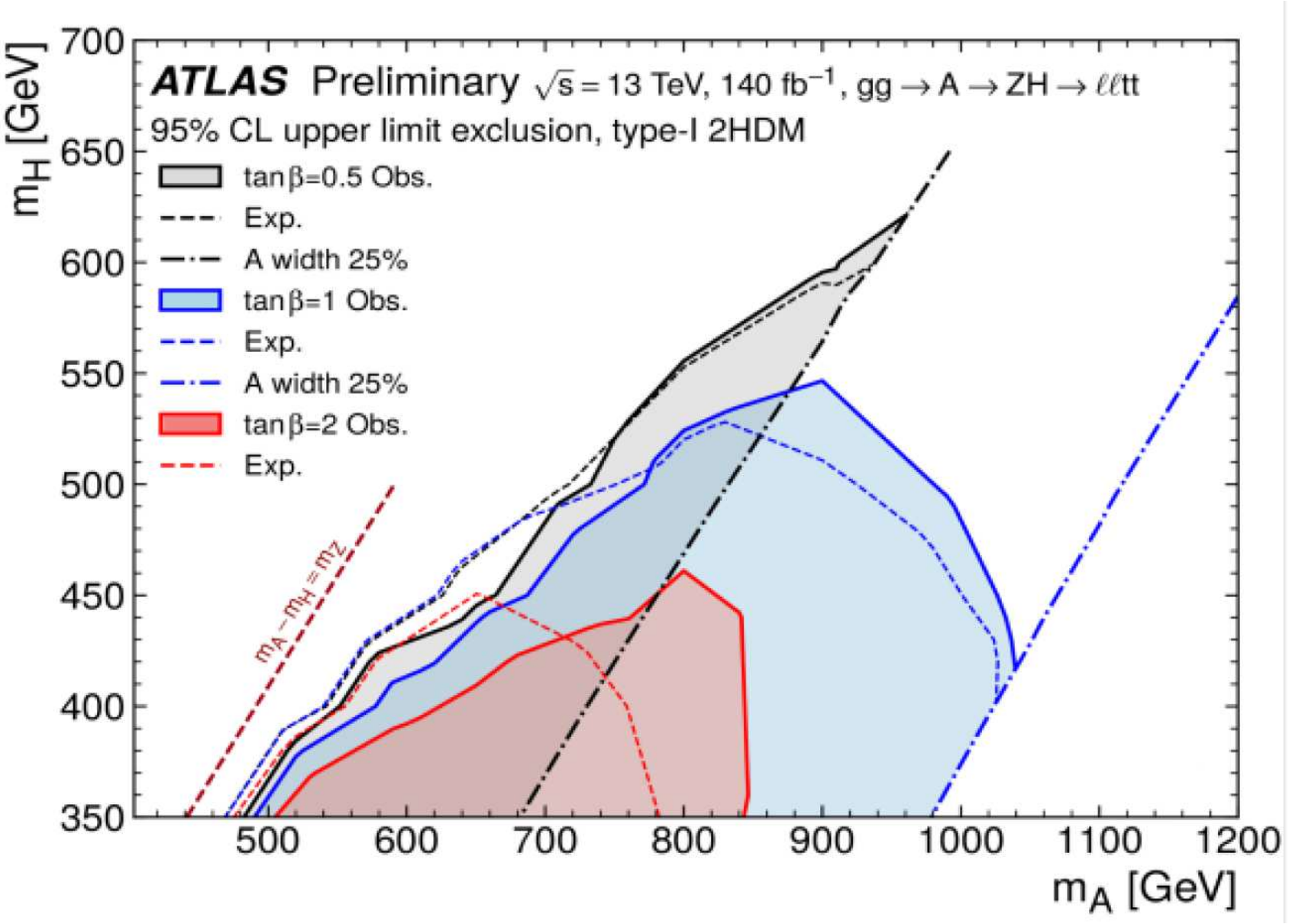
Smoking gun signature: gap between m_A and m_H $\Rightarrow$ $pp \to A \to ZH \to Zt\bar{t}$



$\Rightarrow$ GW zone can be covered at the HL-LHC

Finally: experimental results from ATLAS at LHCP23

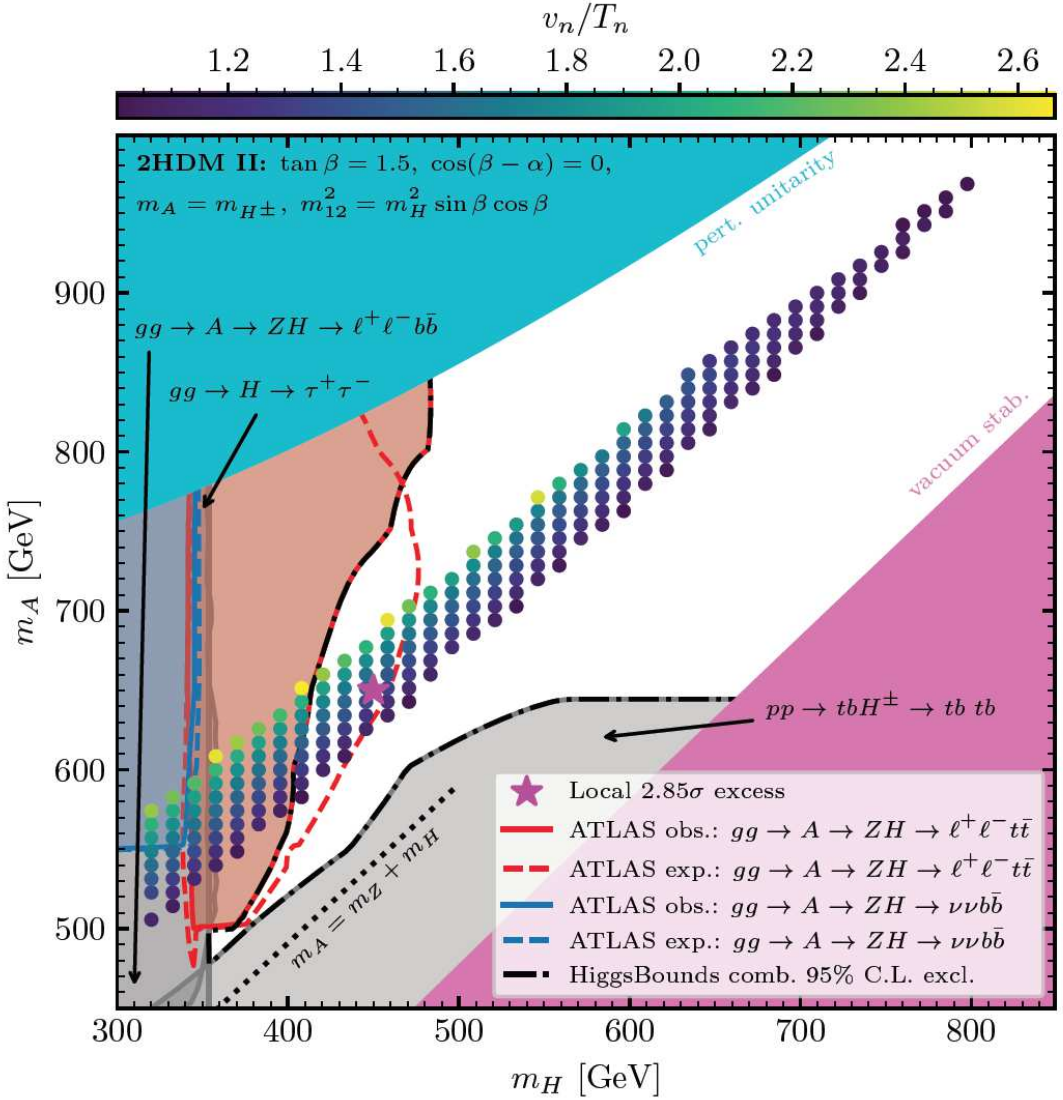
[*ATLAS '23*]



⇒ interesting excess in the "right spot" :-) ($m_H = 450$ GeV, $m_A = 650$ GeV)

Smoking gun signature: highest excess for $\tan\beta = 1.5$

[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein '23*]



$\Rightarrow$ excess in the sweet spot

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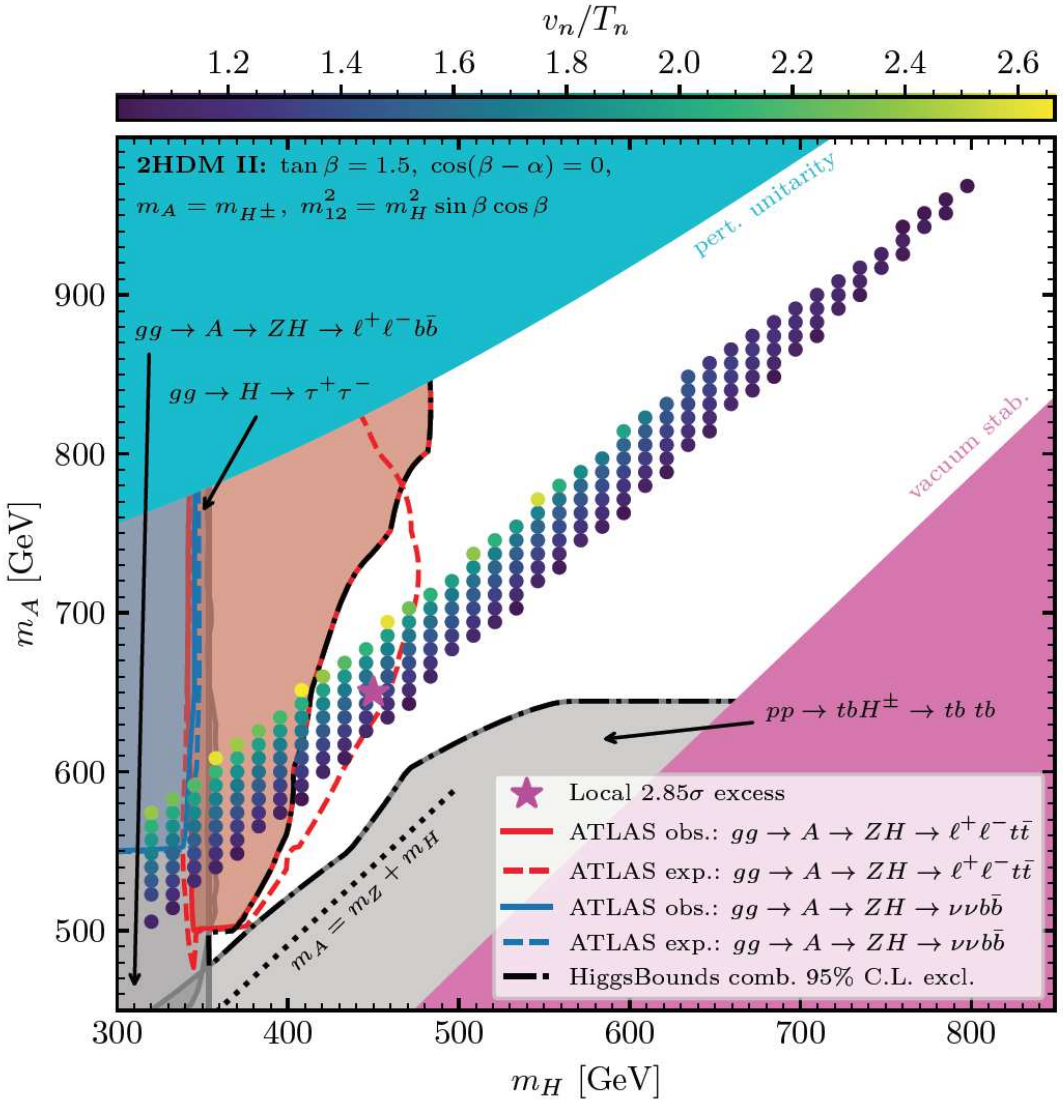
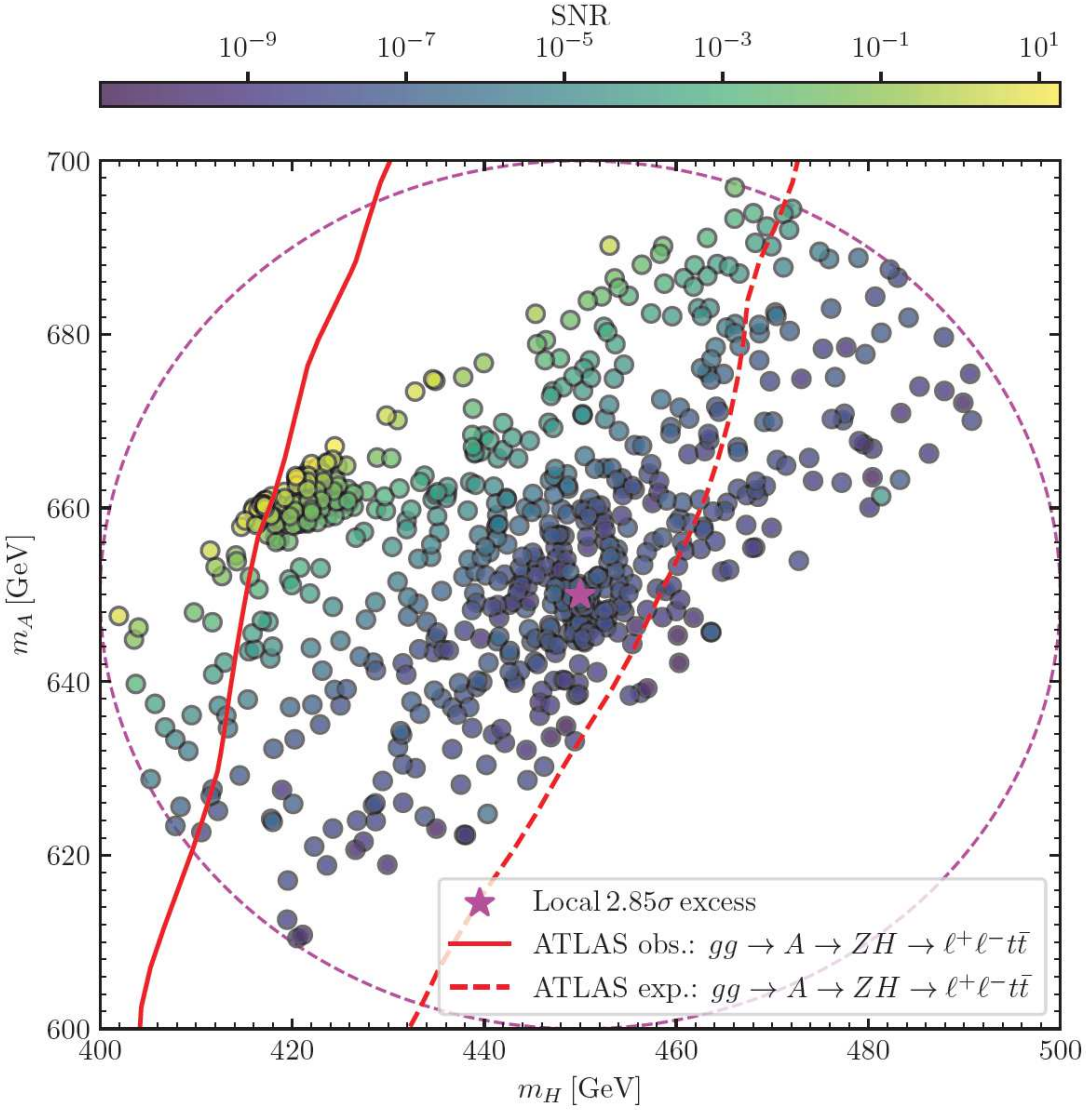
[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein '23*]



$\Rightarrow$ excess in the sweet spot $\Rightarrow$ not confirmed by CMS Run 2 analysis :-(

Smoking gun signature: GW signal at LISA?

[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein '23*]



$\Rightarrow$ Again Georg demonstrated that a GW signal is very difficult!

Intermezzo II: Life in Karlsruhe & our Phys. Rep.

PhD party in Karlsruhe, Georg opens the beer barrel:

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PhD party in Karlsruhe, Georg opens the beer barrel: or not . . .

Intermezzo II: Life in Karlsruhe & our Phys. Rep.

PhD party in Karlsruhe, Georg opens the beer barrel: or not . . .

Intermezzo II: Life in Karlsruhe & our Phys. Rep.

At the ITP everybody worked super hard, until the very end:

Intermezzo II: Life in Karlsruhe & our Phys. Rep.: EWPO in the MSSM

deadline: 12/99. Hand in: 12/04. Party: 05/06 (Santander, Spain) *[400+ cit.]*

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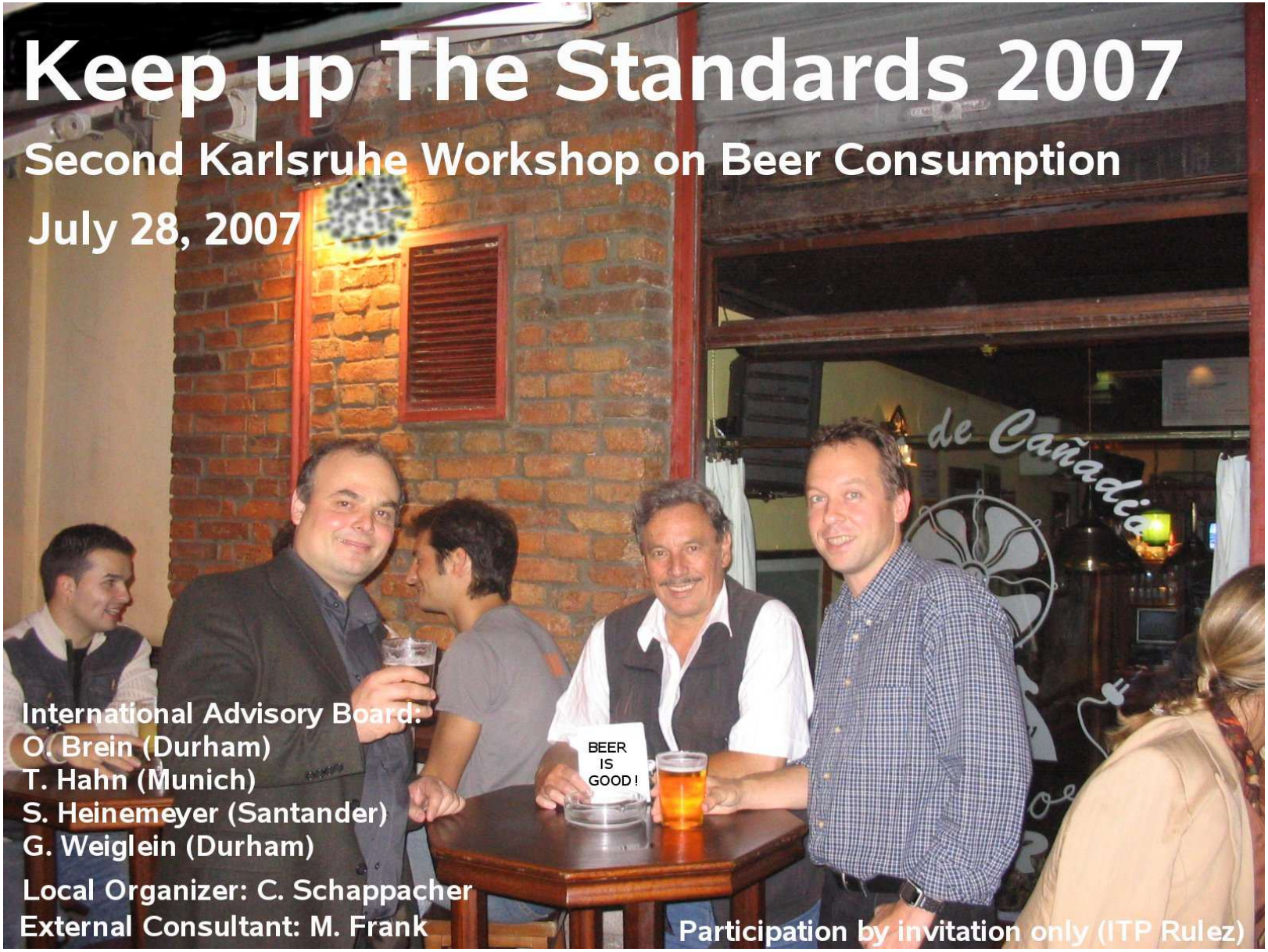

BSM Higgs physics and GW III:

Georg's (only?) chance to win the Nobel Prize?

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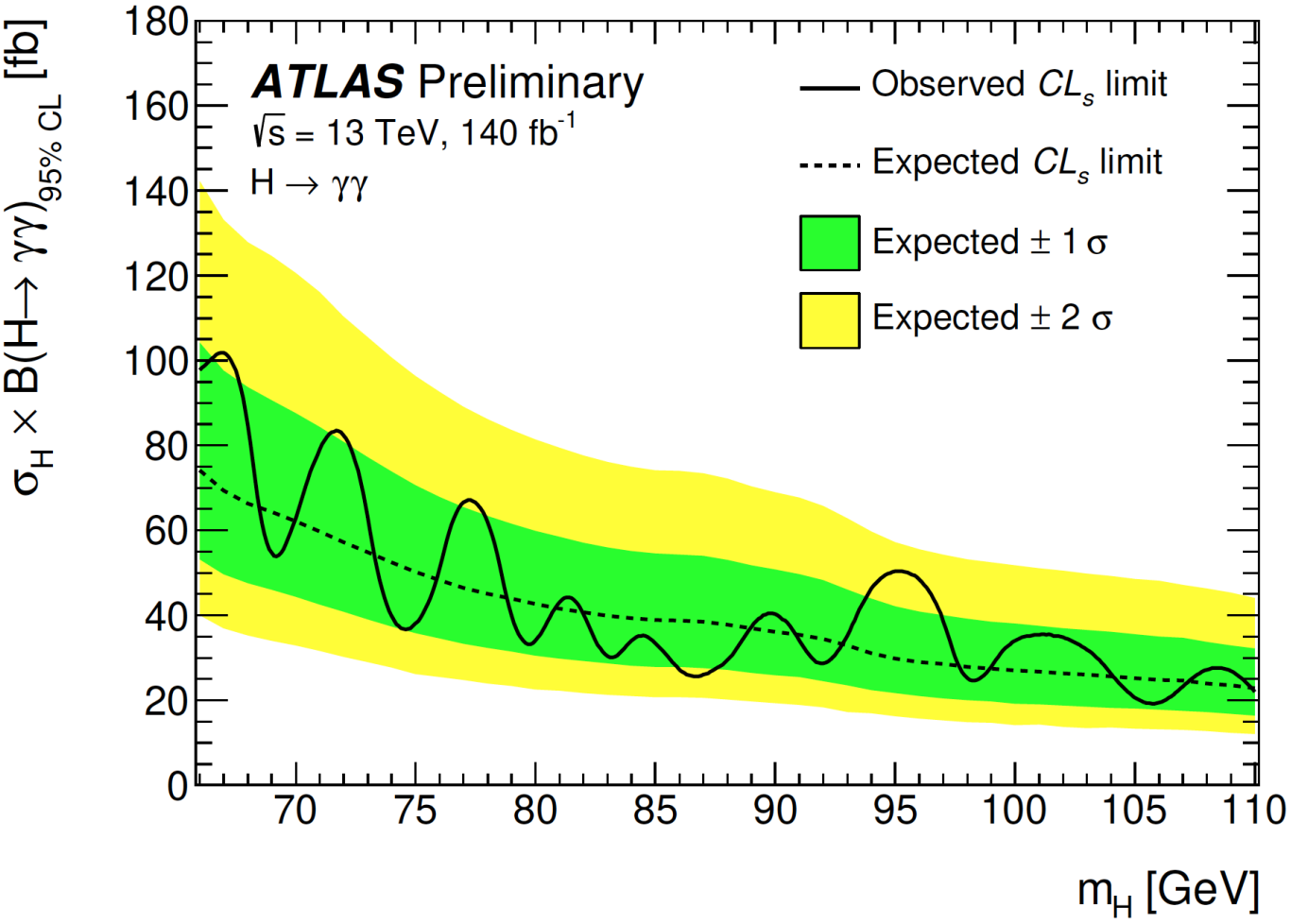
Georg's (only?) chance to win the Nobel Prize?

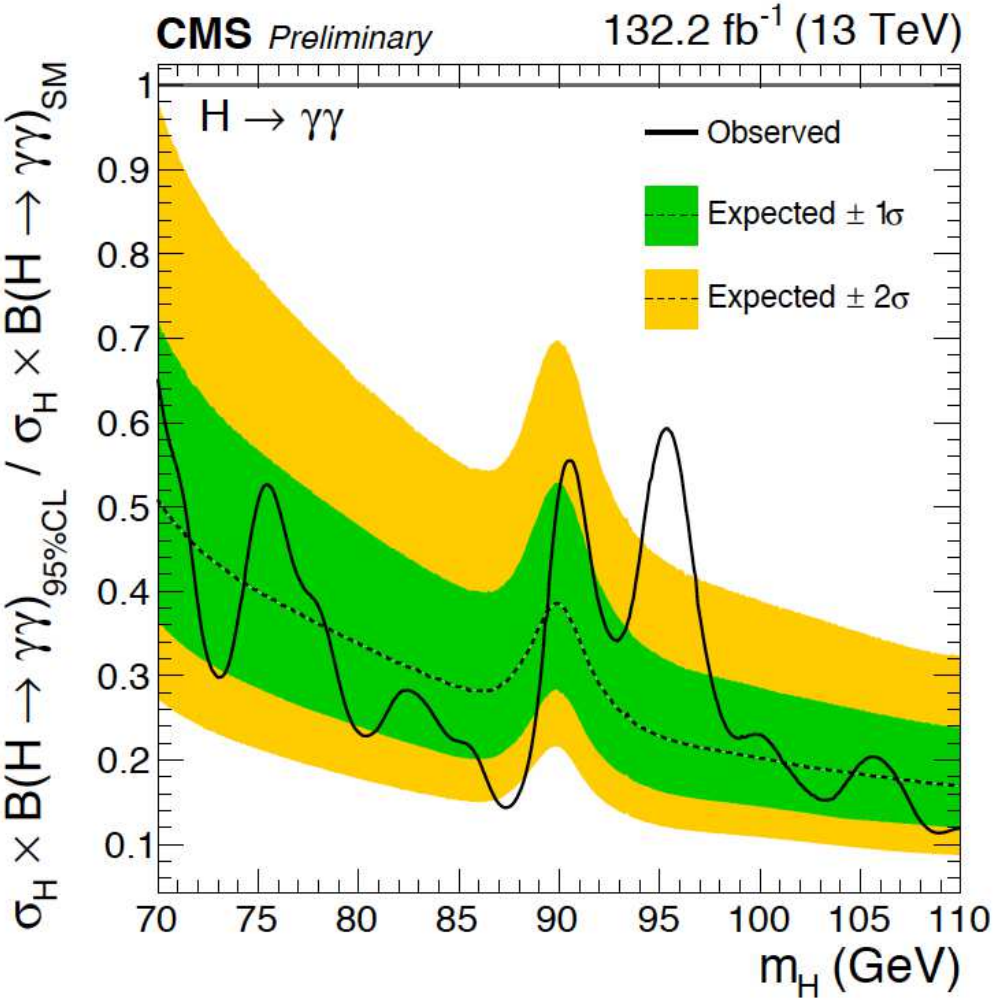
ATLAS results for low-mass search in $pp \to \phi \to \gamma\gamma$:

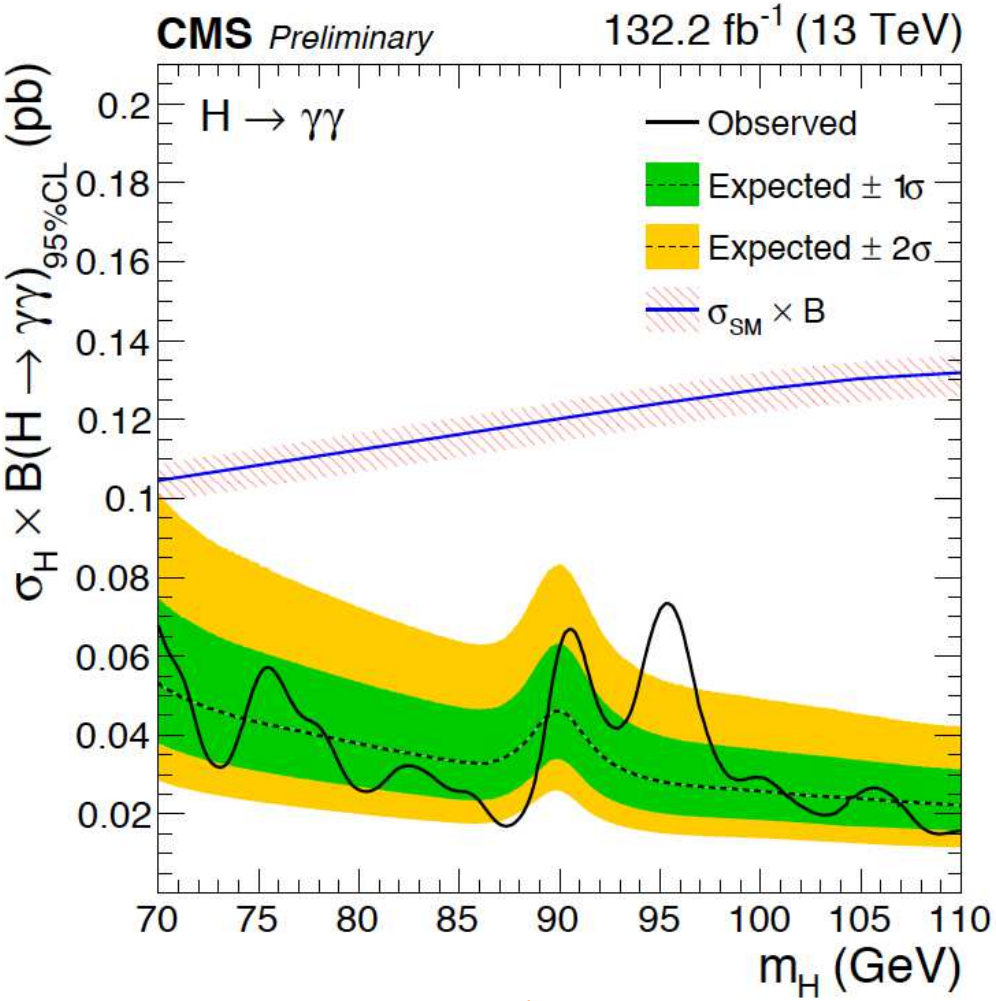


$\Rightarrow$ higest "excess" at 95.4 GeV

Full Run 2 results from CMS: excess at 95.4 GeV

[*CMS '23*]



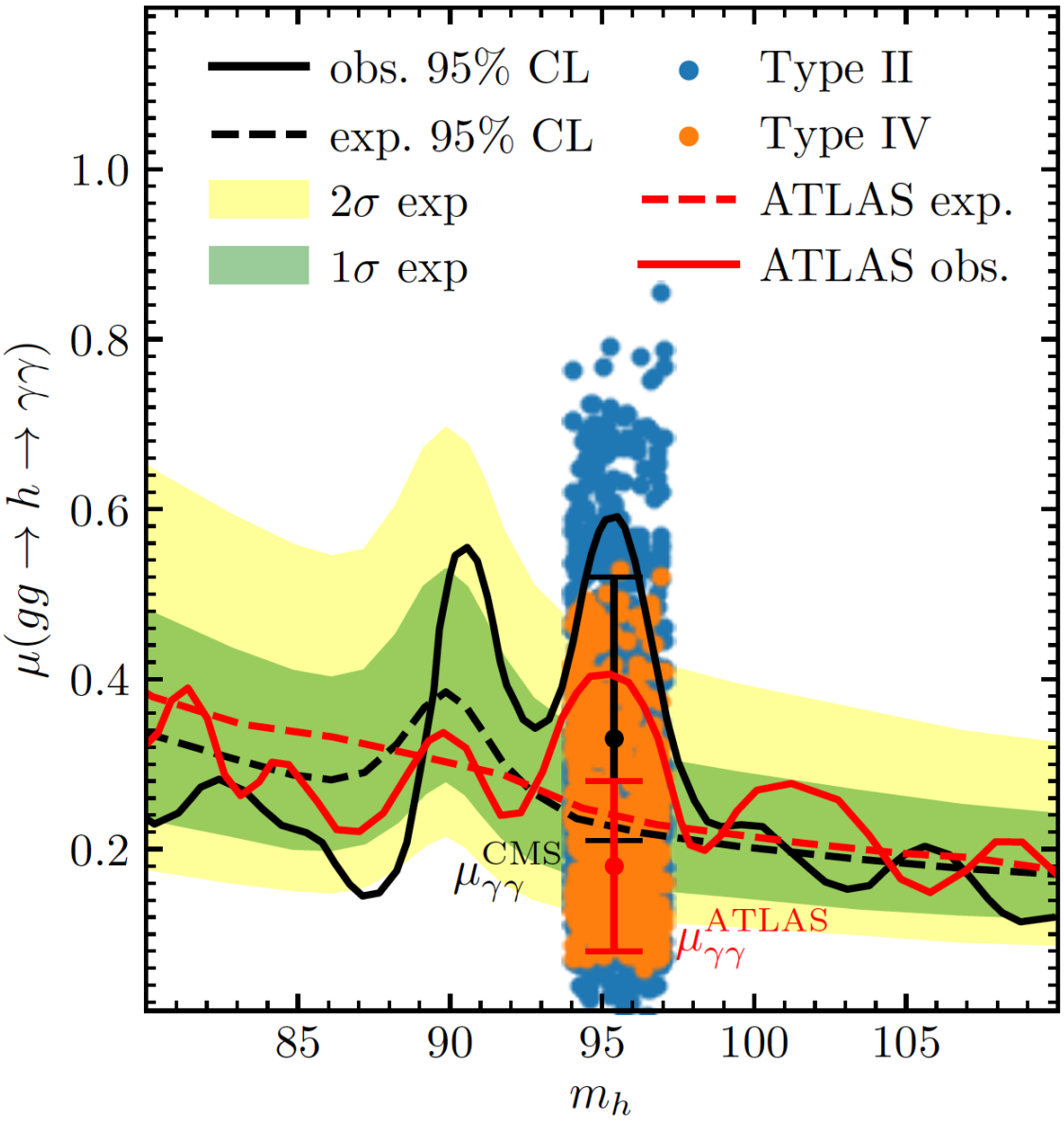


$$\mu_{\gamma\gamma}^{\text{CMS}} = [\sigma(gg \to h_{95}) \times \text{BR}(h_{95} \to \gamma\gamma)]_{\text{exp/SM}} = 0.33^{+0.19}_{-0.12}\ (2.9\,\sigma)$$

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

New CMS/ATLAS comparison:

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



⇒ agreement between ATLAS and CMS!

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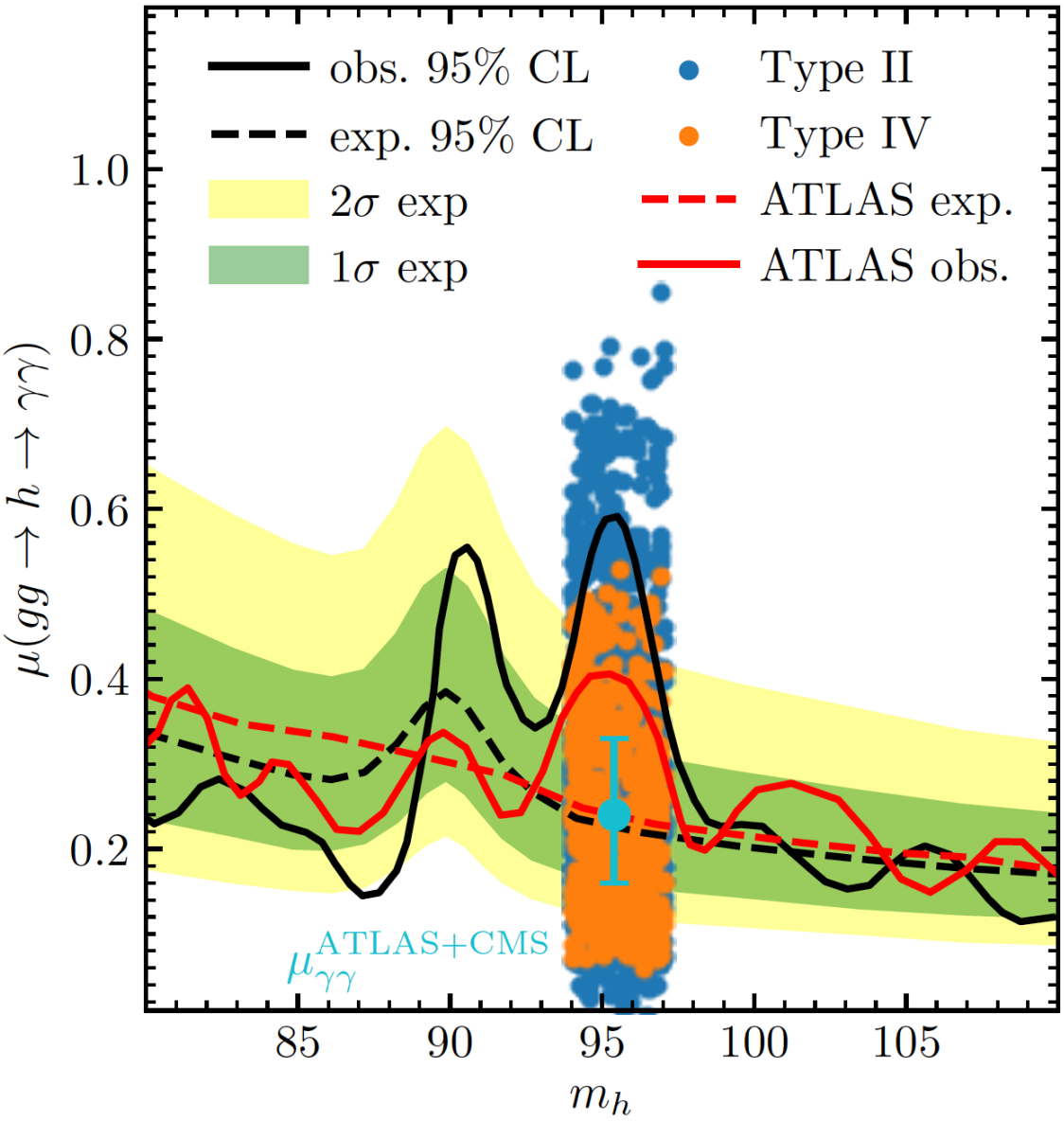
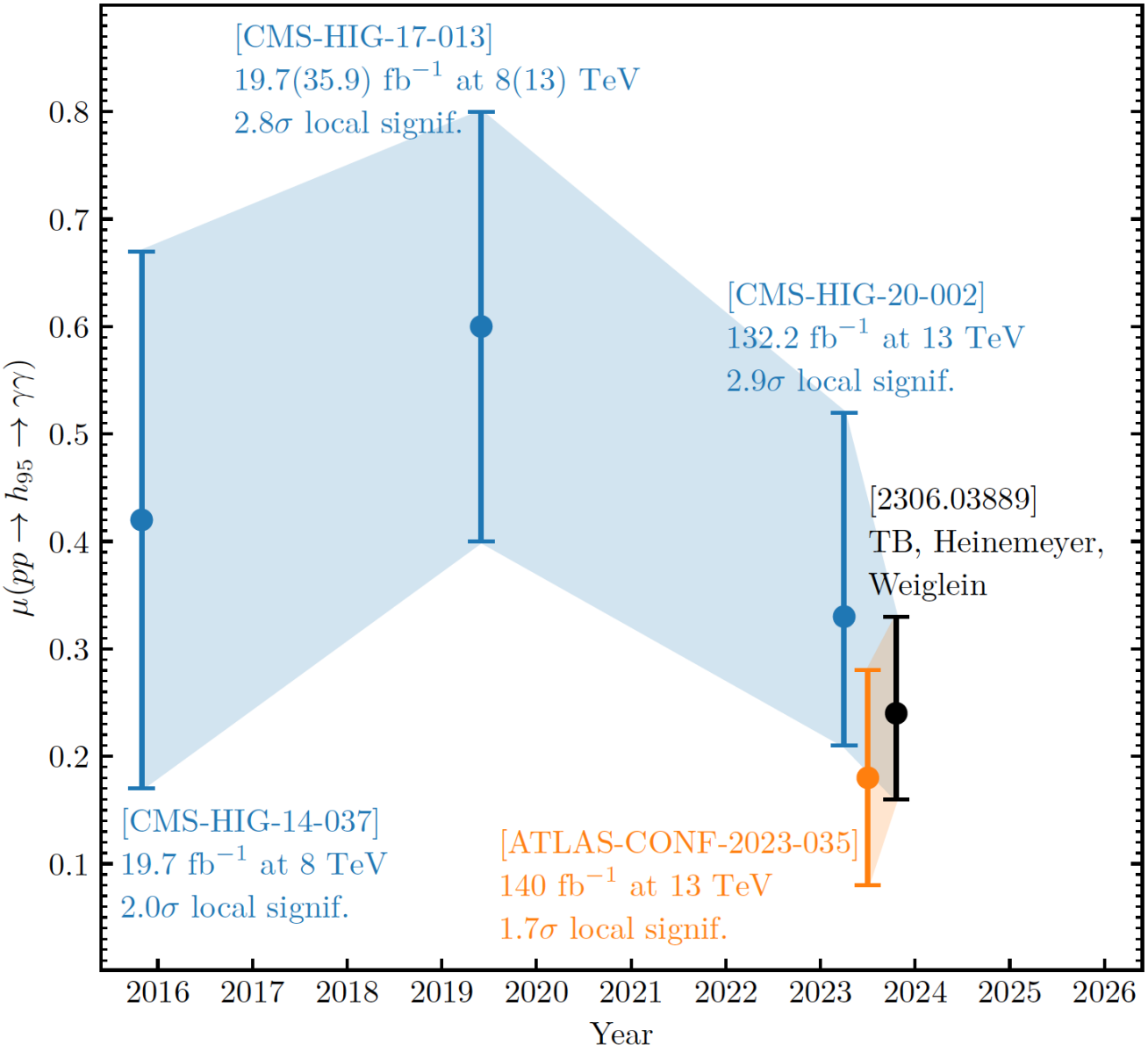


⇒ agreement between ATLAS and CMS!

$\mu_{\gamma\gamma} = 0.24^{+0.09}_{-0.08}$ $(3.1\,\sigma)$

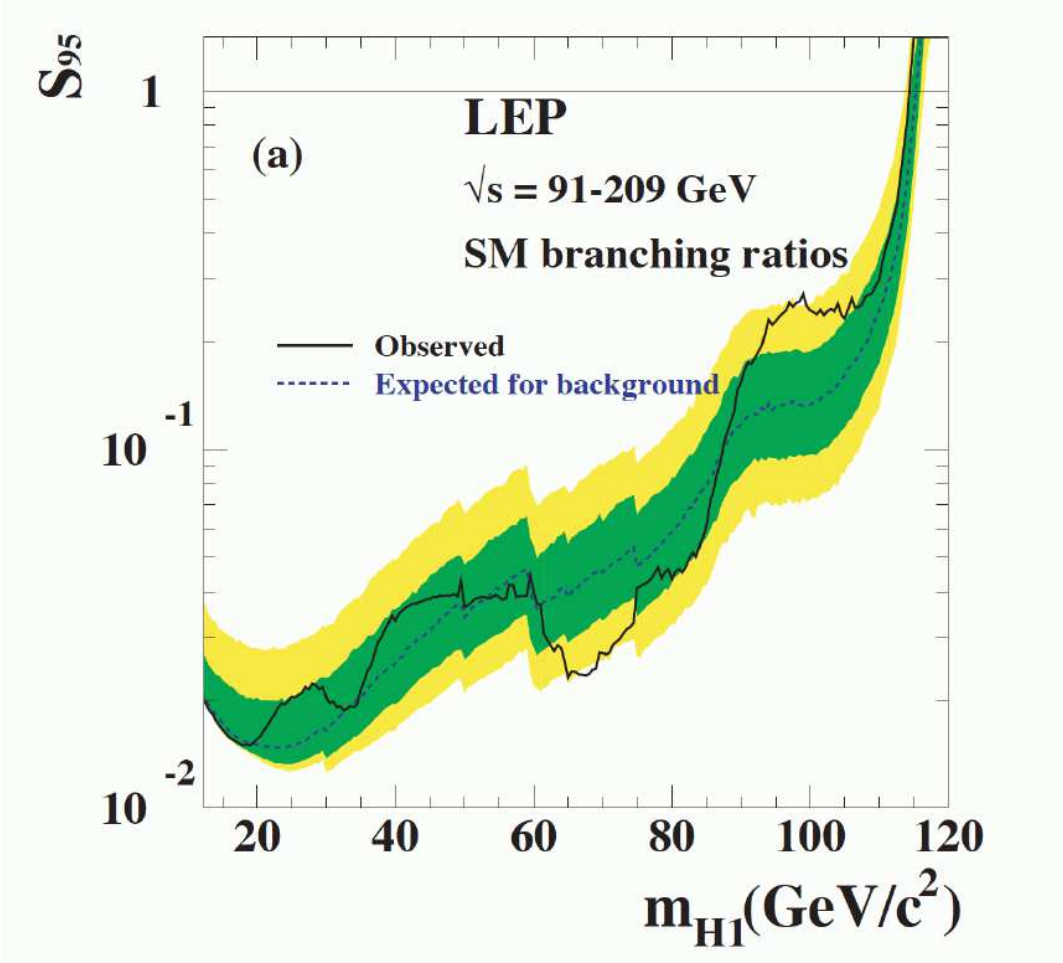
Road to discovery:

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



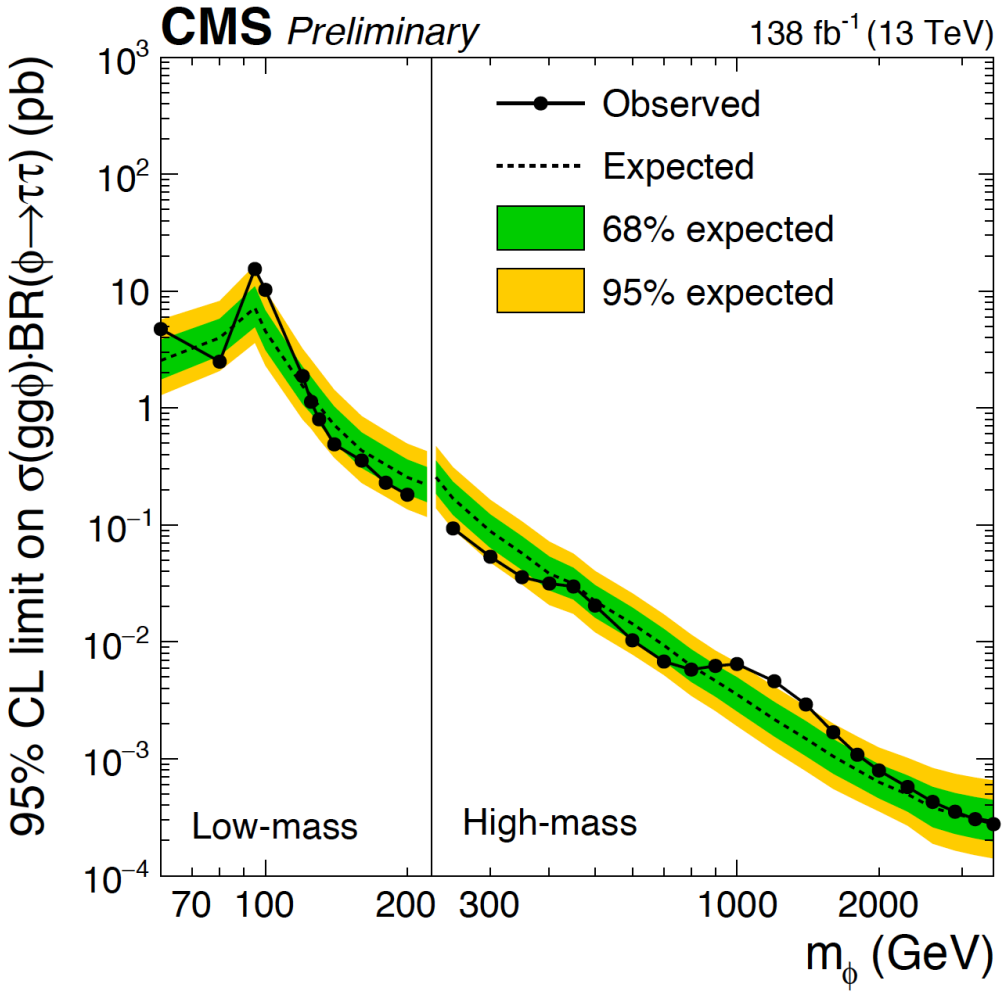
$\Rightarrow$ note the reduction of $\mu_{\gamma\gamma}$ over time!

LEP: $e^+e^- \to Z\phi \to Zb\bar{b}$ $(2\,\sigma)$



$$\mu_{bb}^{\rm exp} = 0.117 \pm 0.057,$$

CMS: $pp \to \phi \to \tau^+\tau^-$ $(2.4\,\sigma)$



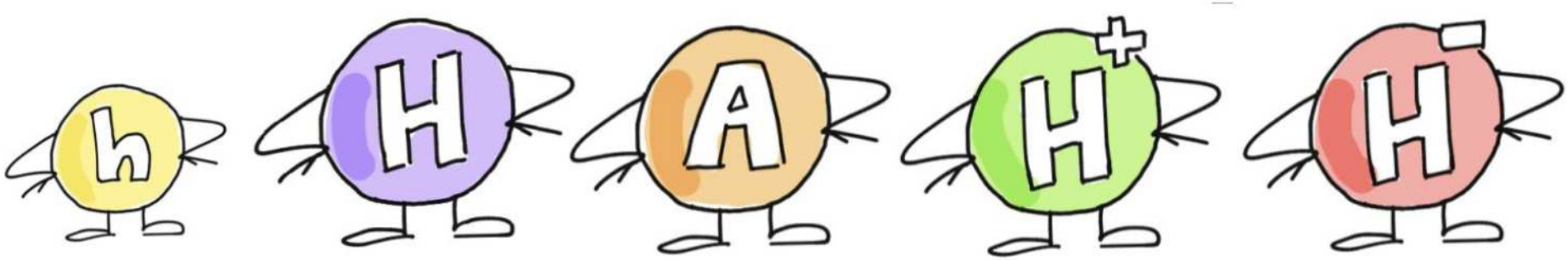
$$\mu_{\tau\tau}^{\rm exp} = 1.2 \pm 0.5$$

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

$\Rightarrow$ note: $tt\phi, Z\phi$ with $\phi \to \tau\tau$

$\Rightarrow \sim 3.7\,(4.6)\,\sigma$

Possible model interpretation



[*K. Radchenko*]

Georg (plus various groups of collaborators) showed
that the h_{95} can be naturally/easily described by:

- N2HDM (type II/IV)
- S2HDM (type II/IV)
- Georgi-Machacek (GM) Model
- minimally extended Georgi-Machacek (meGM) Model
- what about SUSY?

The Happy Higgs Family:

Intermezzo III: Xmas party in Karlsruhe with a special ritual

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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

$\Rightarrow$ leave $\tau\tau$ excess out for a moment . . .

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- NMSSM
- $\mu\nu$SSM
- . . .

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$\Rightarrow$ models with an additional singlet??

– NMSSM
– $\mu\nu$SSM
– . . .

Q: Can the models fit the excesses despite the additional SUSY constraints on the Higgs sector **???**

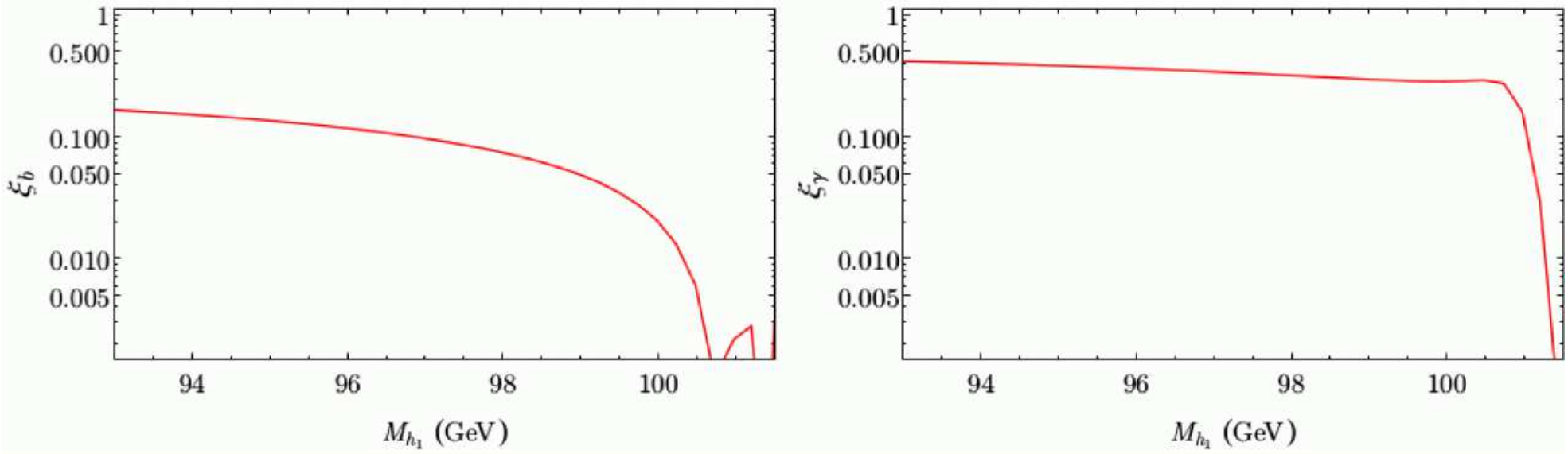
What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

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

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

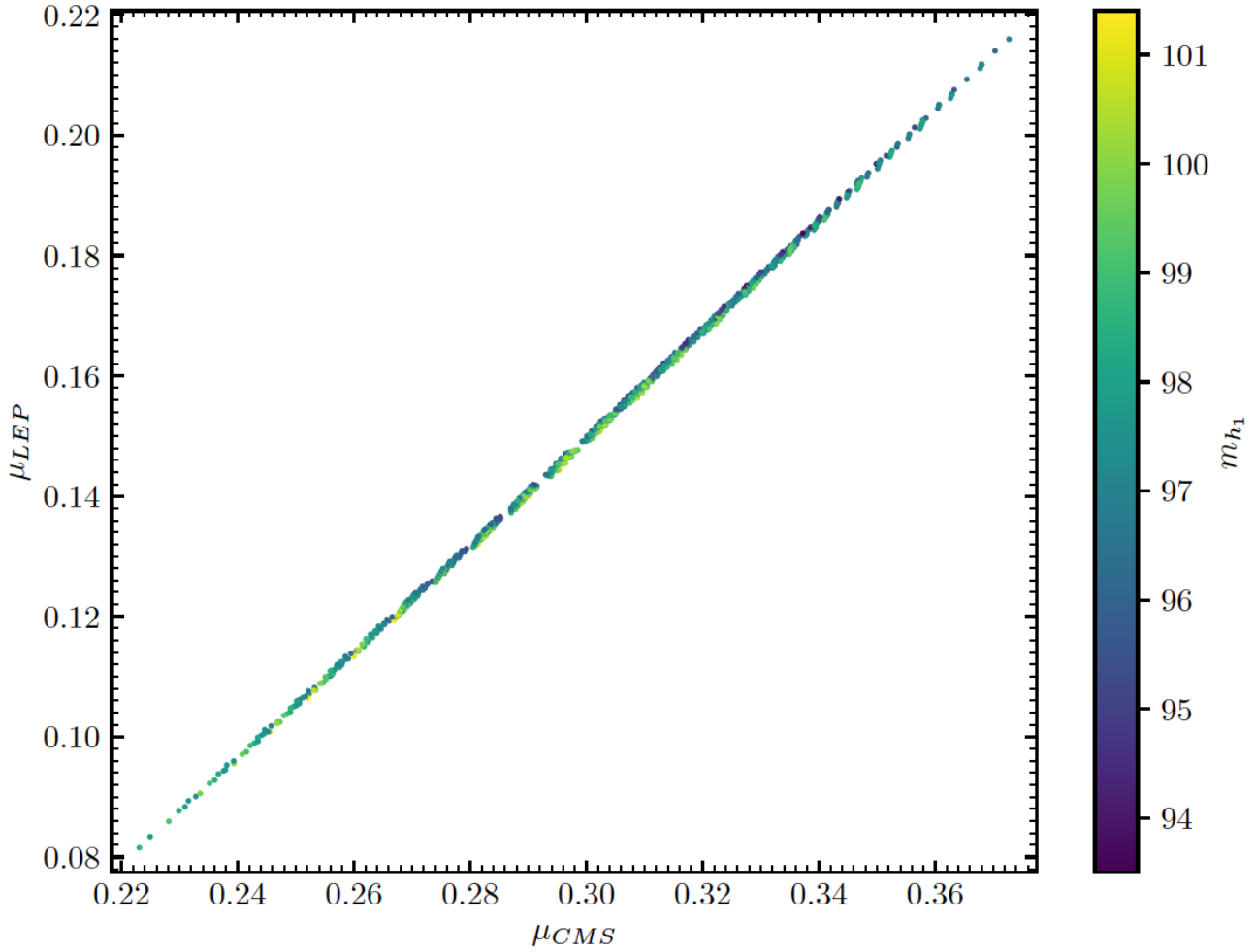
$$\xi_\gamma \equiv \frac{\Gamma[h_1 \to gg] \cdot \text{BR}[h_1 \to \gamma\gamma]}{\Gamma[H_{\text{SM}}(M_{h_1}) \to gg] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \to \gamma\gamma]} \sim \frac{\sigma[gg \to h_1 \to \gamma\gamma]}{\sigma[gg \to H_{\text{SM}}(M_{h_1}) \to \gamma\gamma]}\,.$$



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

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

[T. Biekötter, S.H., C. Muñoz '19]



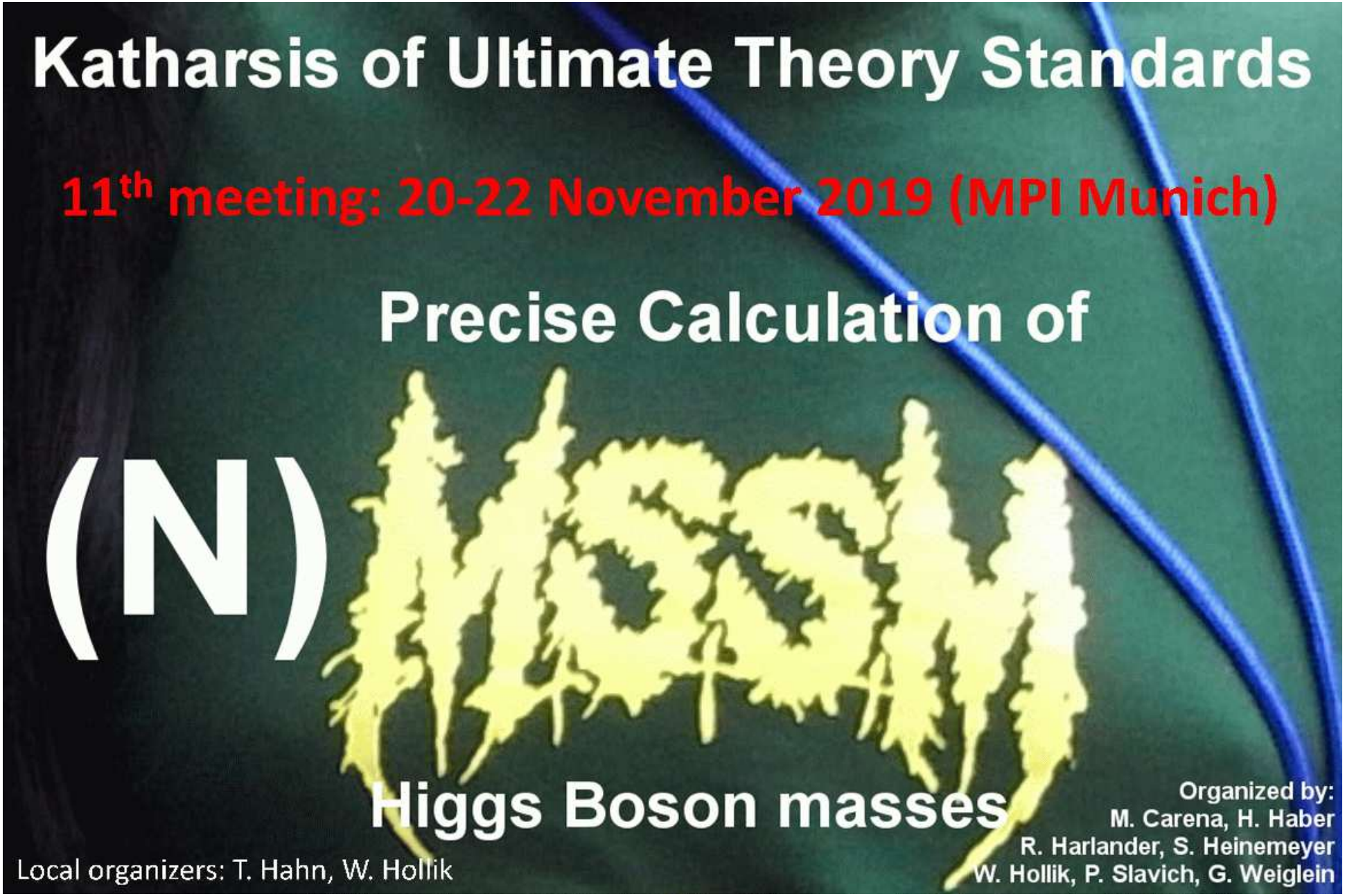
$\Rightarrow$ SUSY enforces strong correlation!

$\Rightarrow$ LEP excess enforces $\mu_{\gamma\gamma} \lesssim 0.35$ – as found in the data now :-)

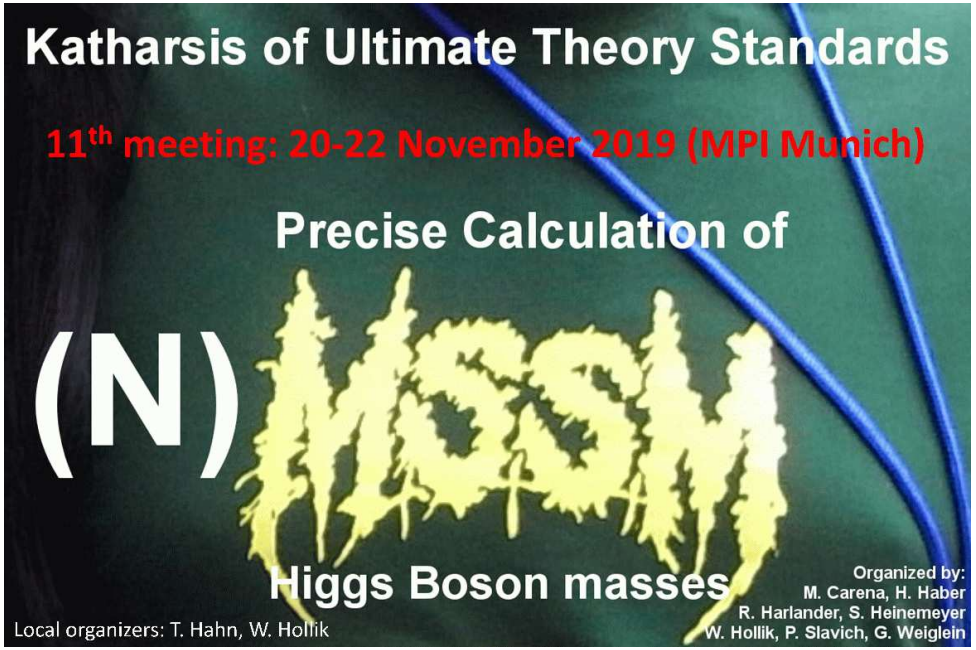
And very finally: a photo from SUSY'09 with two previous speakers . . .

. . . that introduces the second paper

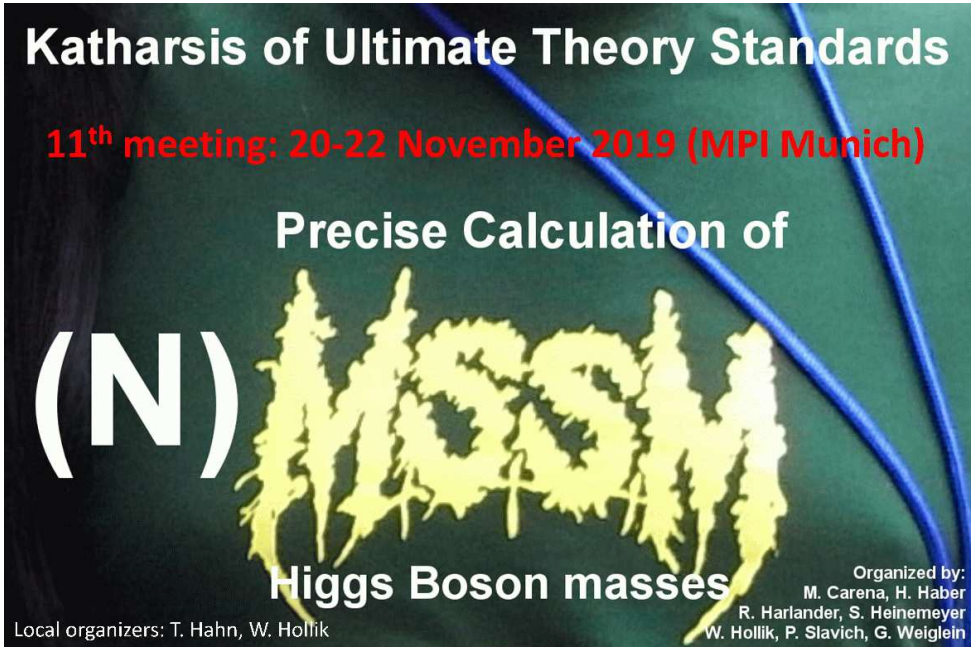
Howie and Marcela as a model for the poster of the KUTS workshop series:

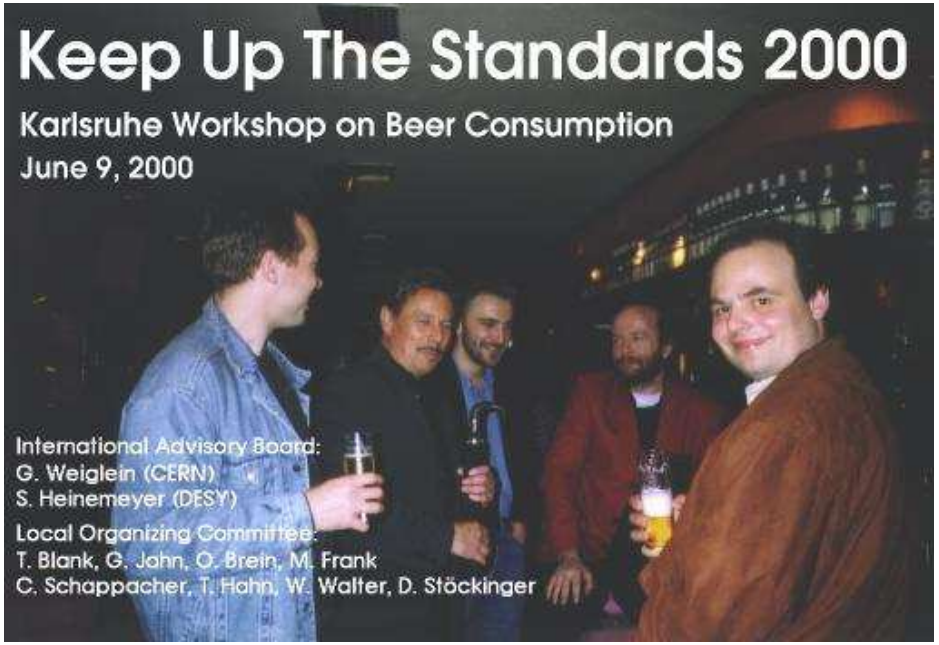


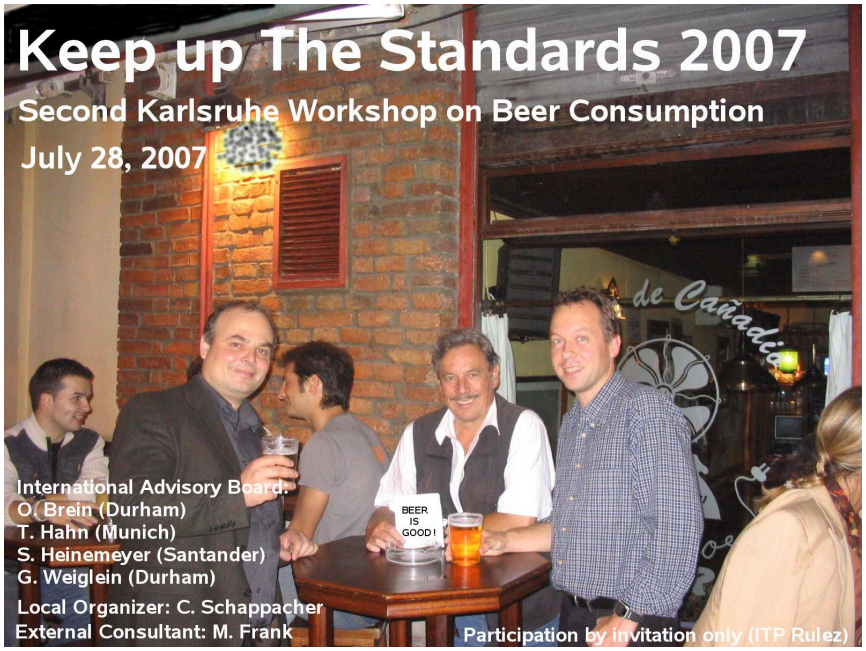
The KUTS workshop series: Georg's idea for the title! :-)



KUTS: Georg's idea for the title! ⇒ based on the ITP motto!







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

Higgs-mass predictions in the MSSM and beyond

P. Slavich[a] and S. Heinemeyer[b,c,d] (eds.),

E. Bagnaschi[e], H. Bahl[f], M. Goodsell[a], H.E. Haber[g], T. Hahn[h], R. Harlander[i], W. Hollik[h], G. Lee[j,k,l], M. Mühlleitner[m], S. Paßehr[i], H. Rzehak[n], D. Stöckinger[o], A. Voigt[p], C.E.M. Wagner[q,r,s] and G. Weiglein[f],

B.C. Allanach[t], T. Biekötter[f], S. Borowka[u‡], J. Braathen[f], M. Carena[r,s,v], T.N. Dao[w], G. Degrassi[x], F. Domingo[y], P. Drechsel[f‡], U. Ellwanger[z], M. Gabelmann[m], R. Gröber[aa], J. Klappert[i], T. Kwasnitza[o], D. Meuser[f], L. Mihaila[bb‡], N. Murphy[cc‡], K. Nickel[y‡], W. Porod[dd], E.A. Reyes Rojas[ee], I. Sobolev[f] and F. Staub[m‡]

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

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 29th Birthday, Georg!!

One down, five to go!

Happy 29th Birthday, Georg!! (for the 32nd time!)

One down, five to go!

As promised: a little quiz: spot Georg! (It is possible . . .)