FeynHiggs - da weiß man, was man hat. Guten Abend!

Impact of Improved SUSY Higgs-boson mass predictions

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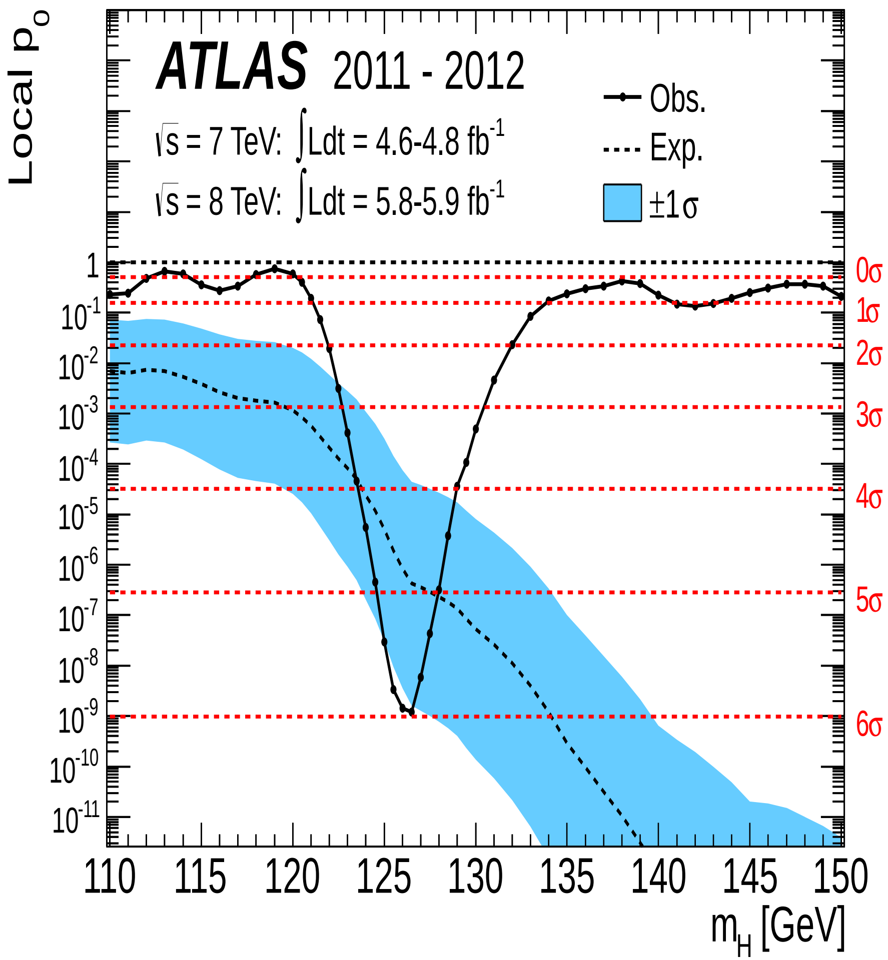
Corpus Cristi, 05/2019

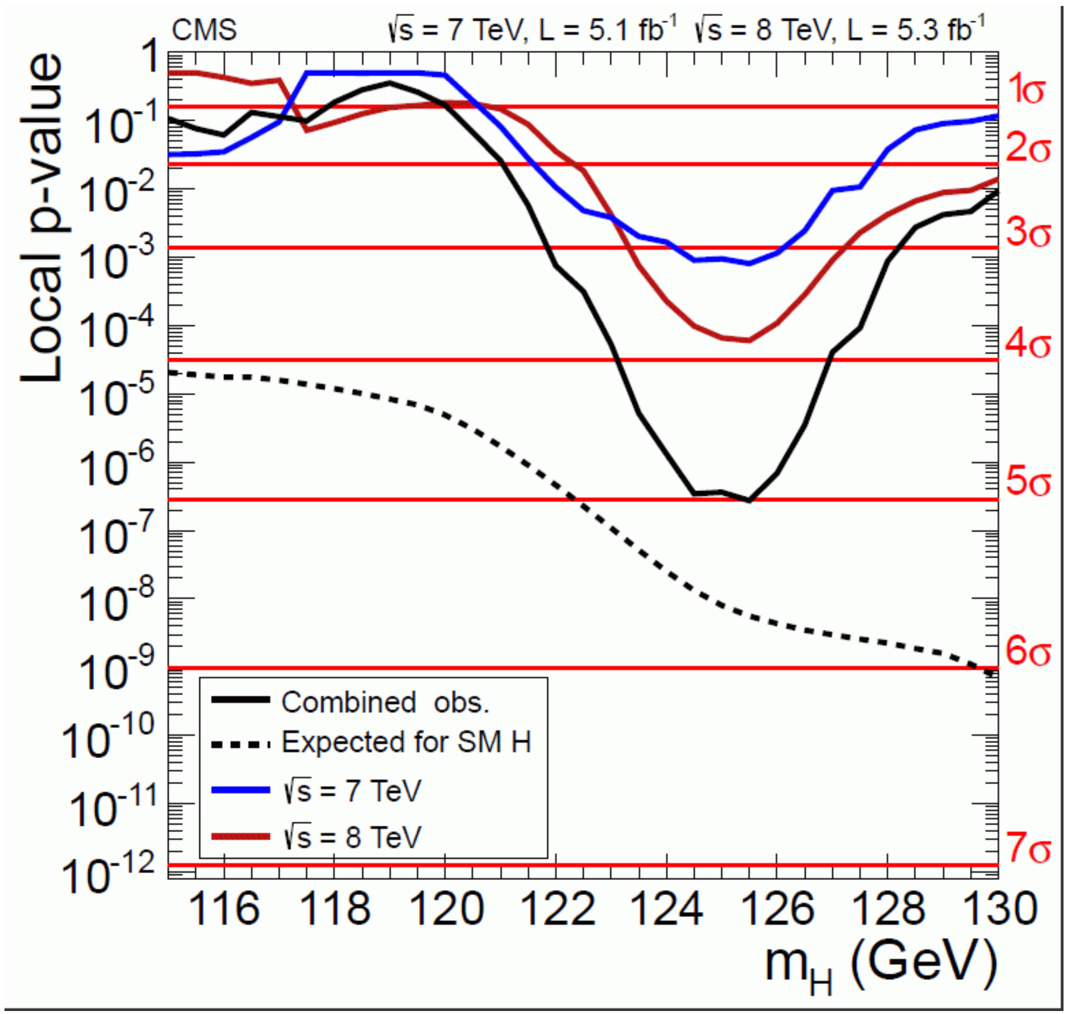
FeynHiggs team: *H. Bahl, T. Hahn, S.H., W. Hollik, S. Paßehr, H. Rzehak and G. Weiglein*

with *E. Bagnaschi, J. Ellis, J. Evans, K. Olive, I. Sobolev, J. Zheng*

- The Quest for Precision
- MSSM Higgs mass calculations
- Improved predictions for MSSM scenarios
- Conclusions

1. The Quest for Precision





⇒ clear discovery at ∼ 125 GeV!

⇒ can be interpreted as the light(/heavy) $\mathcal{CP}$-even MSSM Higgs

The Higgs mass accuracy: experiment vs. theory:

Experiment:

ATLAS:	$M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV
CMS:	$M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15$ GeV
combined:	$M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11$ GeV

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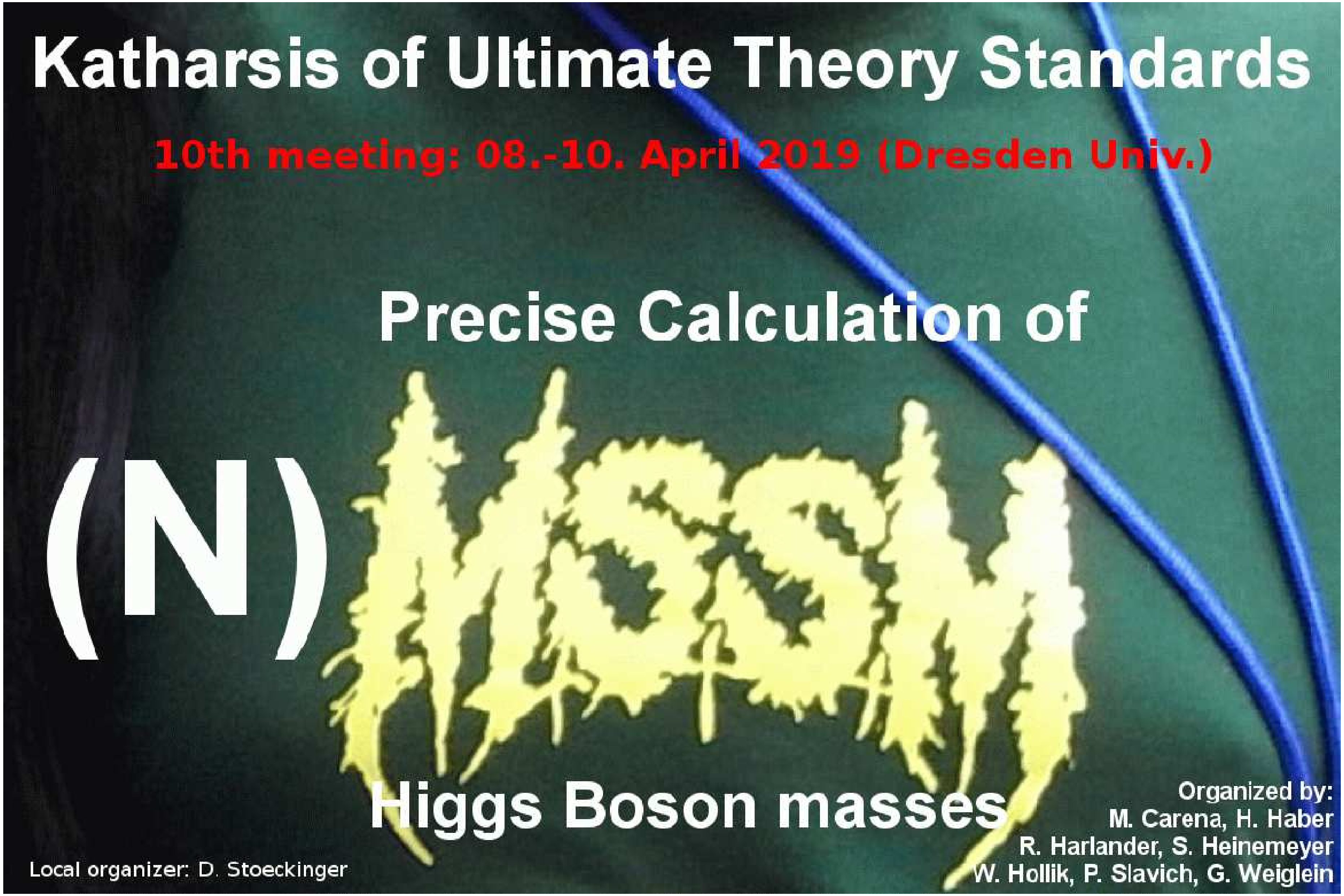
MSSM theory:

LHCHXSWG adopted FeynHiggs for the prediction of MSSM Higgs boson masses and mixings (considered to be the code containing the most complete implementation of higher-order corrections)

FeynHiggs: $\delta M_h^{\text{theo}} \sim 3$ GeV (now 2 GeV?)

$\rightarrow$ rough estimate, FeynHiggs contains algorithm to evaluate uncertainty, depending on parameter point

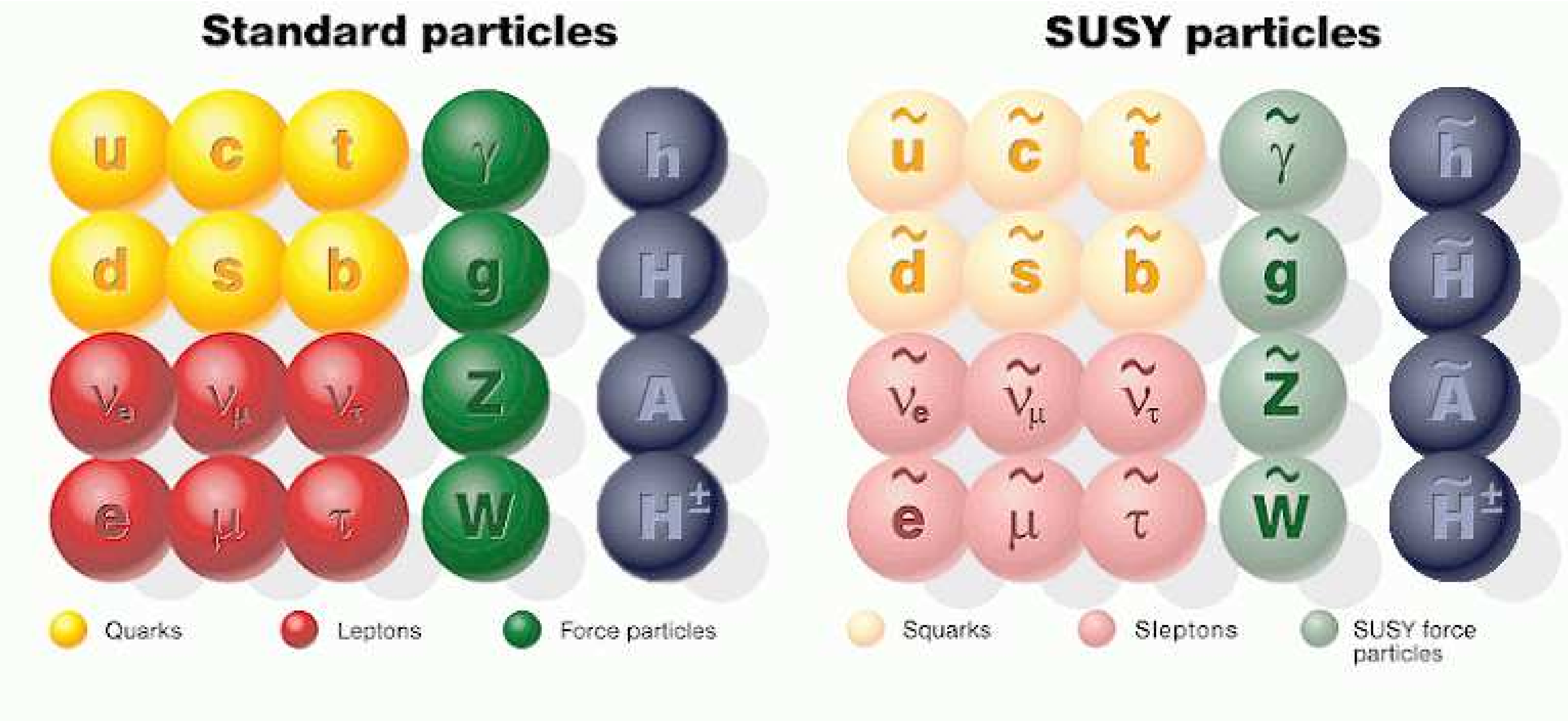
Working group on M_h predictions: sites.google.com/site/kutsmh



⇒ next meeting: 11/2019 at MPI Munich, Germany

The MSSM:

⇒ Superpartners for Standard Model particles



Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

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gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

2 $\mathcal{CP}$-violating phases: ξ, arg(m_{12}) $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

2. MSSM Higgs mass calculationss

Method I

Higher-order corrections in the Feynman diagrammatic method:

Propagator/Mass matrix at tree-level:

$$\begin{pmatrix} q^2 - m_H^2 & 0 \\ 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections
($\to$ Feynman-diagrammatic approach):

$$M_{hH}^2(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H)$: renormalized Higgs self-energies

$\mathcal{CP}$-even fields can mix

$\Rightarrow$ complex roots of det$(M_{hH}^2(q^2))$: $\mathcal{M}_{h_i}^2 (i = 1, 2)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

Structure of higher-order corrections:

One-loop: $$\Delta M_h^2 \sim m_t^2 \alpha_t \left[L + L^0 \right] \quad , \qquad L := \log\left(\frac{m_{\tilde{t}}}{m_t}\right)$$

Two-loop: $$\Delta M_h^2 \sim m_t^2 \left\{ \alpha_t \alpha_s \left[L^2 + L + L^0 \right] + \alpha_t^2 \left[L^2 + L + L^0 \right] \right\}$$

Three-loop: $$\Delta M_h^2 \sim m_t^2 \Big\{ \quad \alpha_t \alpha_s^2 \left[L^3 + L^2 + L + L^0 \right] + \alpha_t^2 \alpha_s \left[L^3 + L^2 + L + L^0 \right] + \alpha_t^3 \left[L^3 + L^2 + L + L^0 \right] \Big\}$$

Partial results: [*S. Martin '07*] [*R. Harlander, P. Kant, L. Mihaila, M. Steinhauser '08*] [*R. Harlander, J. Klappert, A. Ochoa, A. Voigt '18*] $\Rightarrow$ *H3m/Himalaya*

H3m adds $\mathcal{O}\left(\alpha_t \alpha_s^2\right)$ corrections to *FeynHiggs*
Himalaya can be linked to other codes

Large $m_{\tilde{t}}$ $\Rightarrow$ large L $\Rightarrow$ resummation of logs necessary $\Rightarrow$ Method **II**

Advantages of Feynman-diagrammatic method:

– all contributions at fixed order are captured

– trivial to include many SUSY scales

– full control over Higgs boson self-energies
$\rightarrow$ needed for other quantities (production and decay)

Problems of Feynman-diagrammatic method:

– always only fixed order

– large logs not captured beyond the calculated order

Method II: EFT approach: Log resummation via RGE's:

Excellent overview paper: [*P. Draper, G. Lee, C. Wagner, arXiv:1312.5743*]

Simple example for log resummation:

SUSY mass scale: $M_{\text{SUSY}} = M_{\text{S}} \sim m_{\tilde{t}}$

Above M_{SUSY}: MSSM
Below M_{SUSY}: SM

Relevant SM parameters:
– quartic coupling λ
– top Yukawa coupling h_t ($\alpha_t = h_t^2/(4\,\pi)$)
– strong coupling constant g_s ($\alpha_s = g_s^2/(4\,\pi)$)

1. Take: $h_t(m_t), g_s(m_t)$

   SM RGEs for h_t, g_s: $h_t, g_s(m_t) \to h_t, g_s(M_{\text{S}})$

2. Take $\lambda(M_{\text{S}}), h_t(M_{\text{S}}), g_s(M_{\text{S}})$

   SM RGEs for λ, h_t, g_s: $\lambda, h_t, g_s(M_{\text{S}}) \to \lambda, h_t, g_s(m_t)$

3. Evaluate M_h^2

$$M_h^2 \sim 2\lambda(m_t)v^2$$

Advantages of RGE log resummation:

– large logs taken into account to all orders

– calculation can easily be extended to very large scales

Problems of RGE log resummation:

– not all contributions at fixed order are captured
  → sub-leading logs more difficult
  → momentum dependence

– difficult (impossible?): include many different SUSY scales

– difficult (impossible?): control over Higgs boson self-energies
  → needed for other quantities (production and decay)

The best of both worlds:

to get the most precise prediction of M_h:

Combination of FD and RGE result!

$$\Delta M_h^2 = (\Delta M_h^2)^{\mathsf{RGE}}(X_t^{\overline{\mathsf{MS}}}, M_S^{\overline{\mathsf{MS}}}, \overline{m}_t) - (\Delta M_h^2)^{\mathsf{FD,log}}(X_t, M_S, \overline{m}_t)$$

$$M_h^2 = (M_h^2)^{\mathsf{FD}} + \Delta M_h^2$$

$\Rightarrow$ many^2 technical aspects and complications . . .

$\Rightarrow$ combination of best FD result with
resummed LL, NLL corrections for large $m_{\tilde{t}}$

$\Rightarrow$ most precise M_h prediction for large $m_{\tilde{t}}$

$\Rightarrow$ first "hybrid code": FeynHiggs 2.10.0

[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '13*]

Codes on the market:

1.) Fixed order codes: good for all scales low
- SuSpect
- SPheno/SARAH
- SoftSUSY/FlexibleSUSY
- H3m

2.) EFT codes: good for all scales high
- SusyHD
- MhEFT
- HSSUSY

3.) Hybrid codes: good always?!
- FeynHiggs
- FlexibleEFTHiggs
- SPheno/SARAH

Obviously: quality depends on the details implemented

Possible & necessary refinements of the EFT calculation:

- Inclusion of EWino mass scale in RGE's

- Inclusion of gluino mass scale in RGE's

- Inclusion of EW effects in RGE's

- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.

- "Two Higgs Doublet Model" below M_S

- Splitting in the scalar top sector

- ...

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  $\Rightarrow$ included into FeynHiggs

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- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.
  $\Rightarrow$ included into FeynHiggs

- "Two Higgs Doublet Model" below M_S
  $\Rightarrow$ private version of FeynHiggs exists, other code: MhEFT

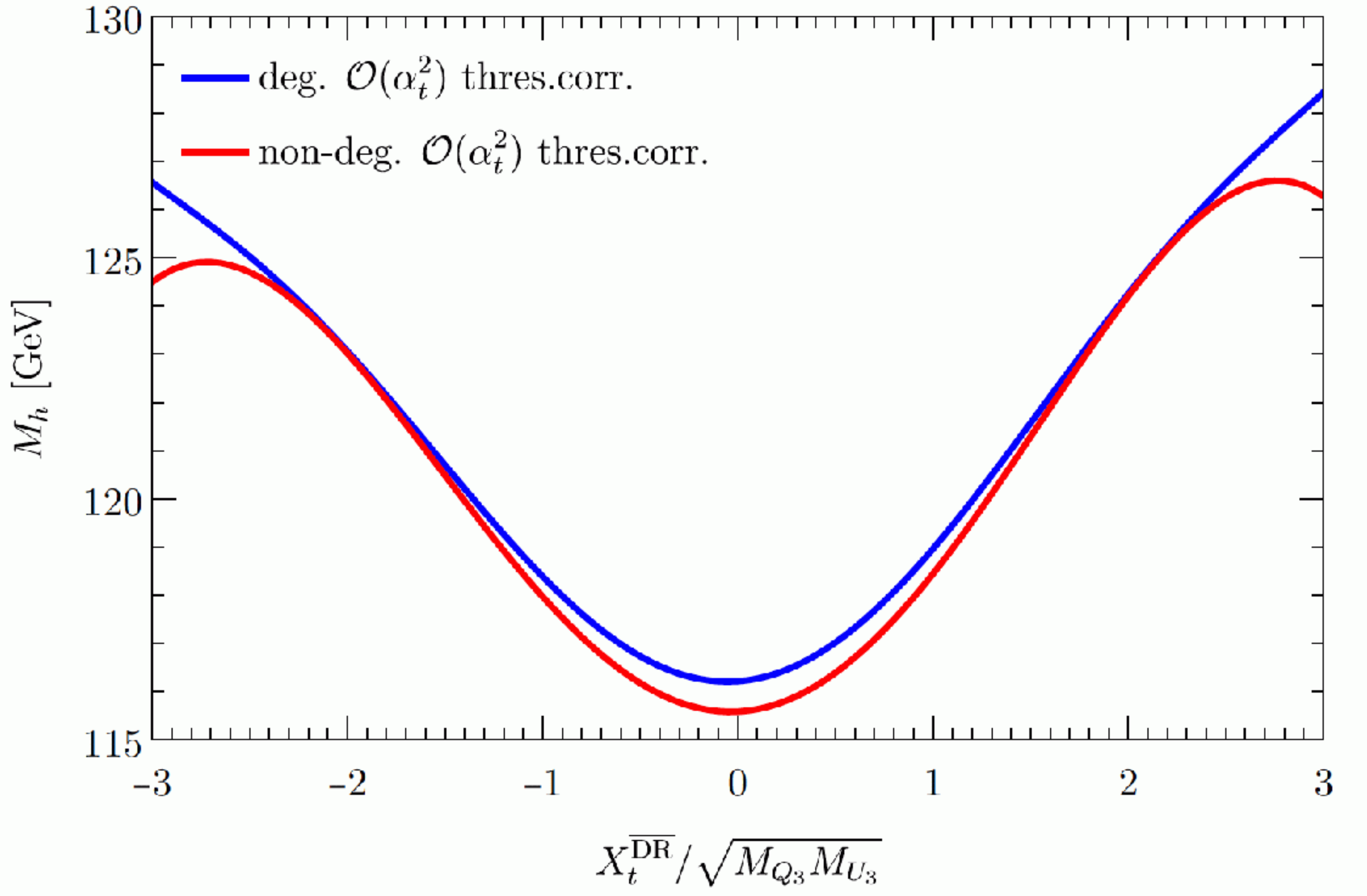
- Splitting in the scalar top sector
  $\Rightarrow$ future work

- ...

Impact of precise M_h calculation (I):

Impact of non-degenerate $\mathcal{O}\left(\alpha_t^2\right)$ threshold corr. in EFT part:

One scale $M_{\rm SUSY}$, but large stop sector splitting, $\tan\beta = 10$:



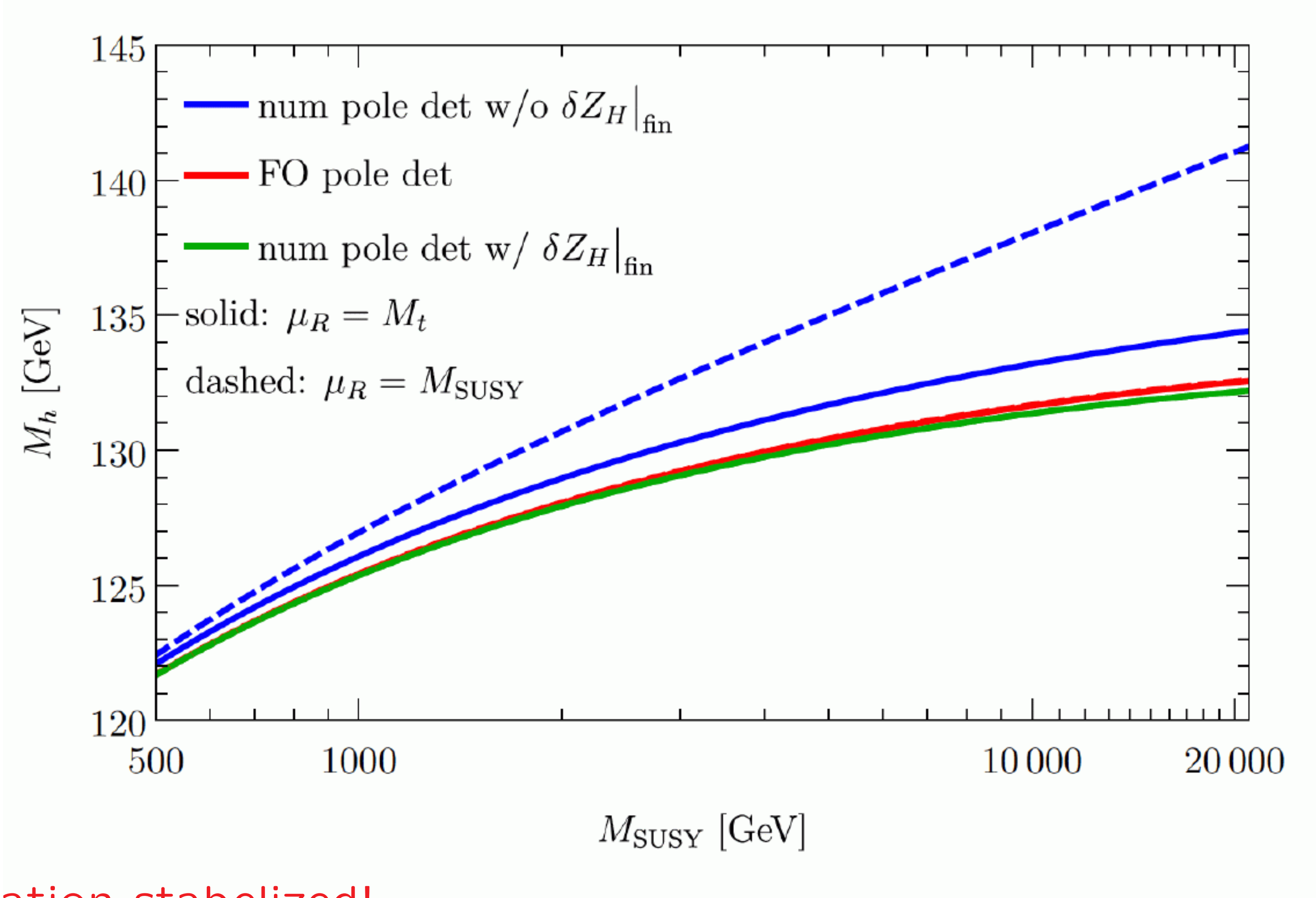
⇒ important for large X_t (more in a moment)

Impact of precise M_h calculation (II):

Impact of pole mass determination improvements:

(ask me details over coffee!)

One scale M_{SUSY}, $\tan\beta = 10$:



$\Rightarrow$ calculation stabelized!

3. Improved predictions for MSSM scenarios

Are these improved calculations relevant?
Are they relevant in any "realistic" scenario?

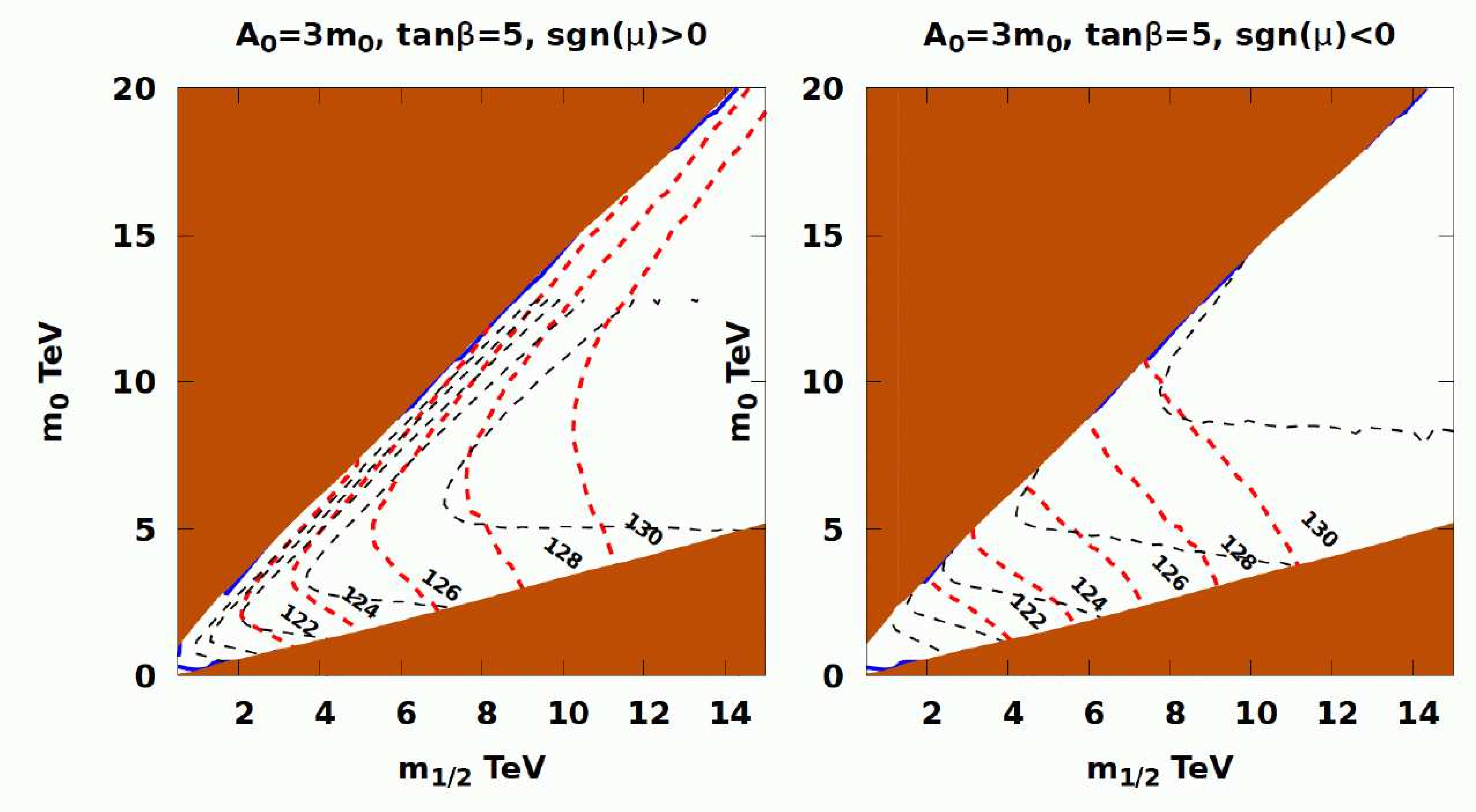
Analysis in:
- CMSSM with stop co-annihiliation
- sub-GUT models
- minimal Anomaly Mediation SUSY-breaking
- pMSSM11

Comparison of hybrid codes:

FeynHiggs 2.10.0
- log-resummation with M_S
- 2L RGEs, 1L thresholds
- $m_t^{\overline{\text{MS}}}$ at NLO

FeynHiggs 2.14.1
- log-resummation with M_S
- Inclusion of EWino mass scale in RGE's
- Inclusion of gluino mass scale in RGE's
- 3L RGEs, 2L thresholds
- $m_t^{\overline{\text{MS}}}$ at NNLO
- Inclusion of EW effects in RGE's and $m_t^{\overline{\text{MS}}}$

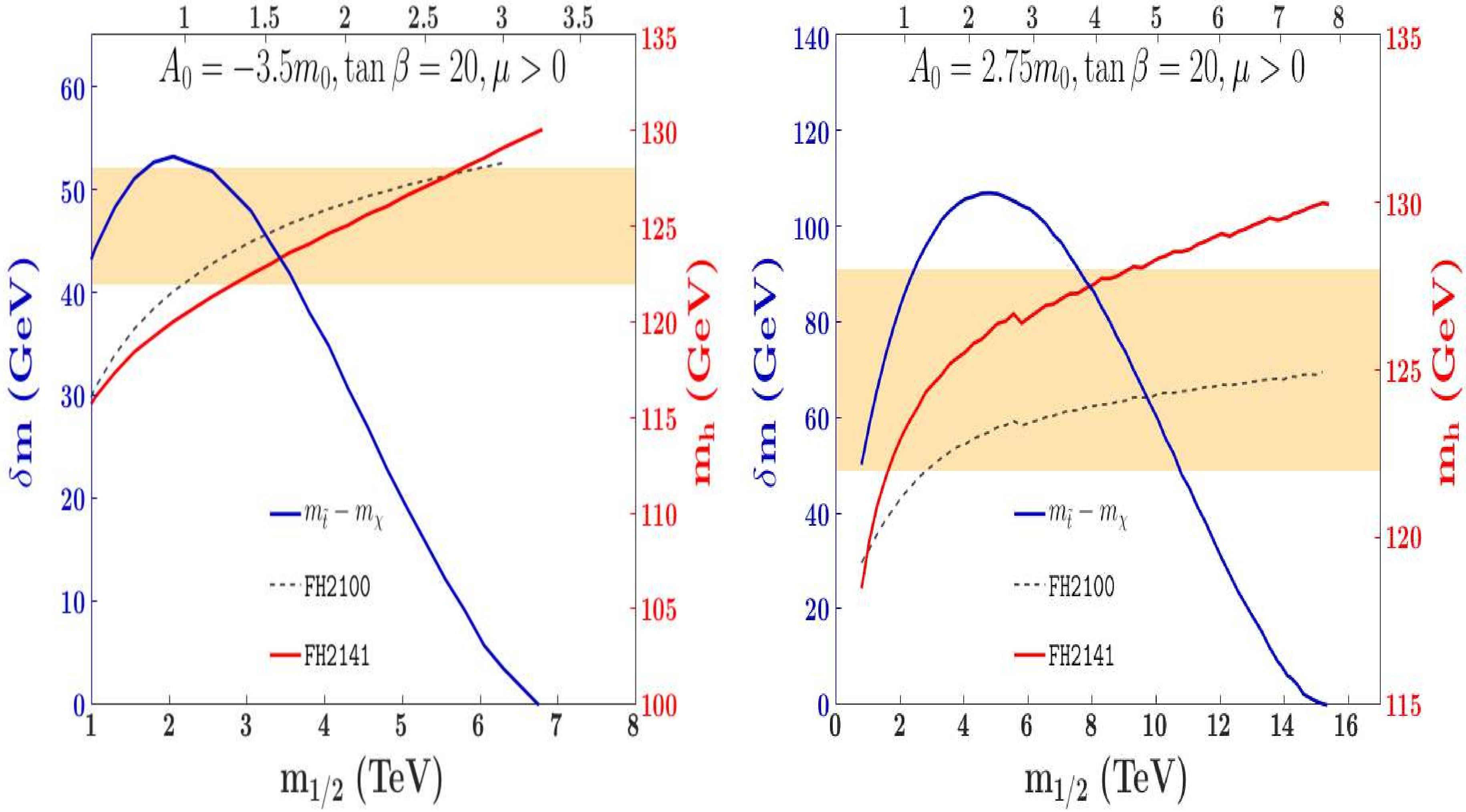
3. A) Stop-coannihilation in the CMSSM:



⇒ clear impact of improved M_h calculation

⇒ $\mathcal{O}\left(\alpha_t^2\right)$ non-degenerate threshold corr. crucial!

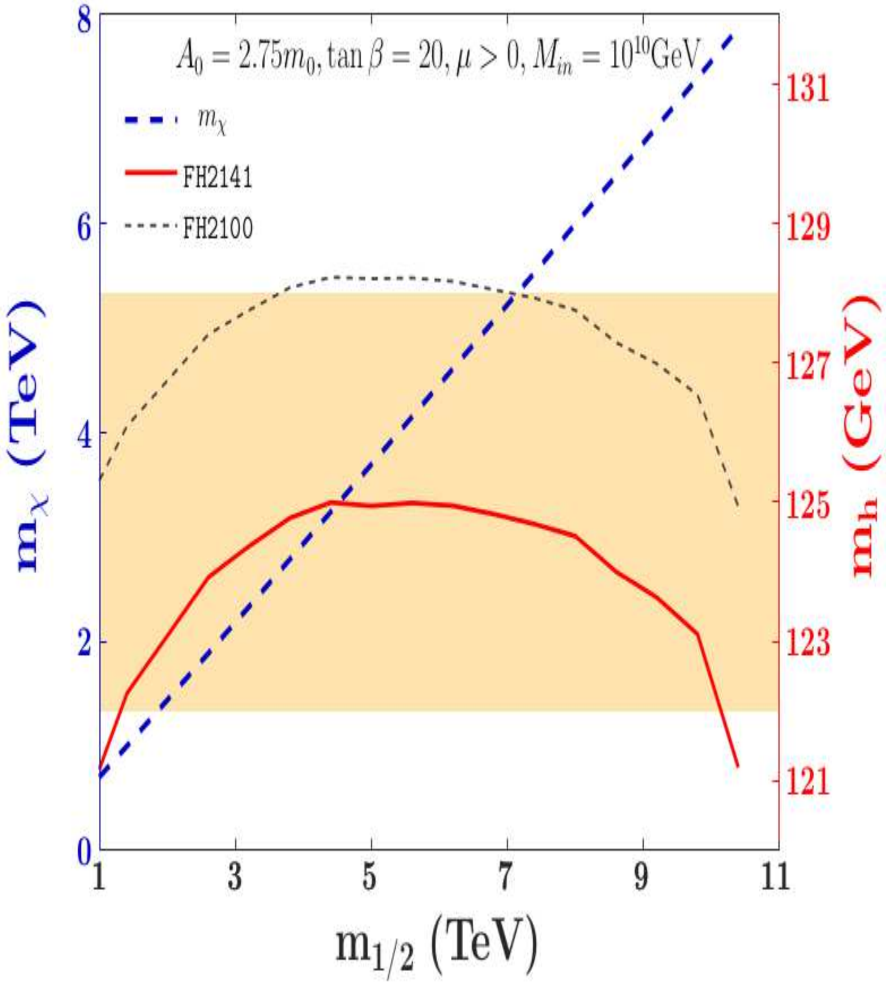
3. A) Stop-coannihilation in the CMSSM:

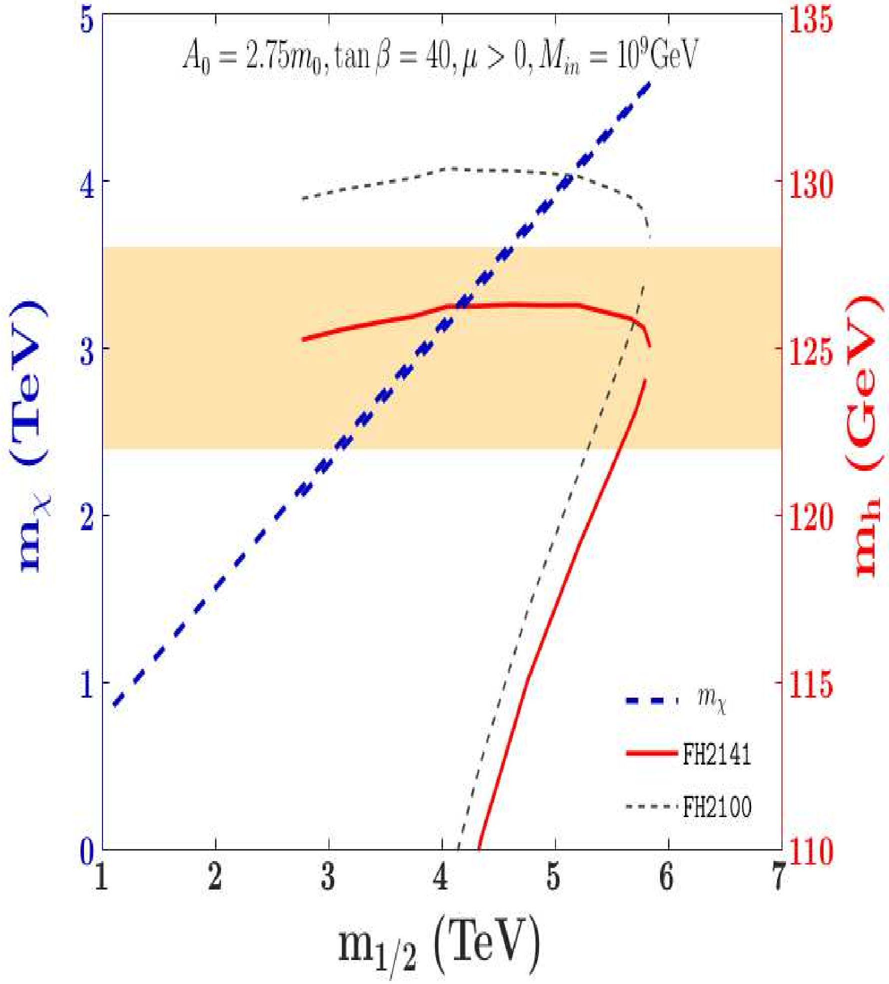


$\Rightarrow$ clear impact of improved M_h calculation

$\Rightarrow$ refined allowed regions with new M_h

3. B) Sub-GUT models:

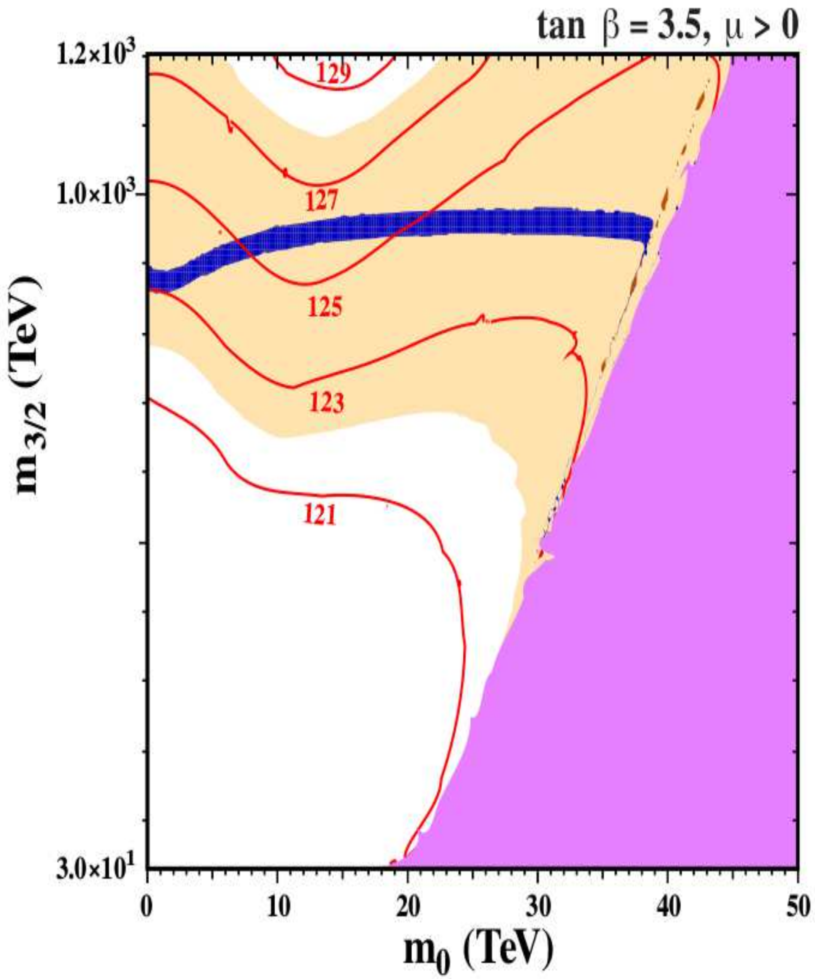


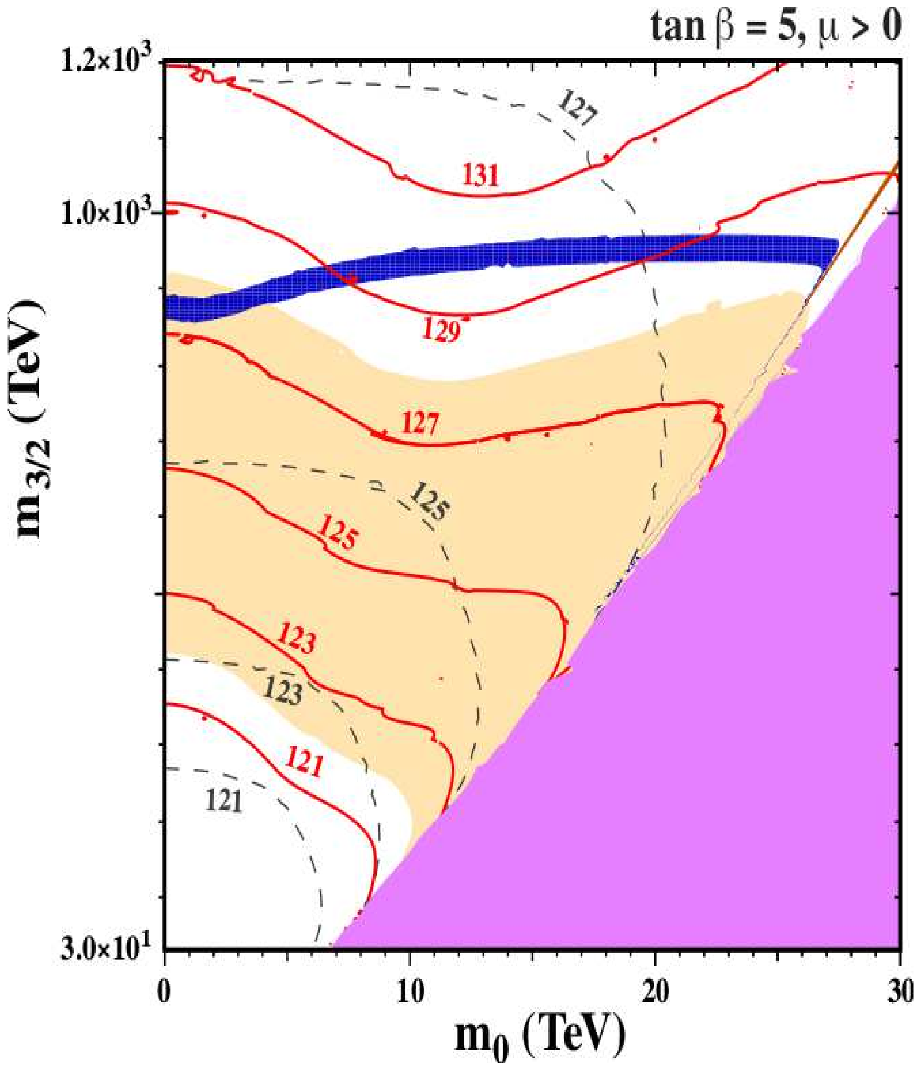


⇒ clear impact of improved M_h calculation

⇒ enlarged allowed regions, better compatibility!

3. C) mAMSB:

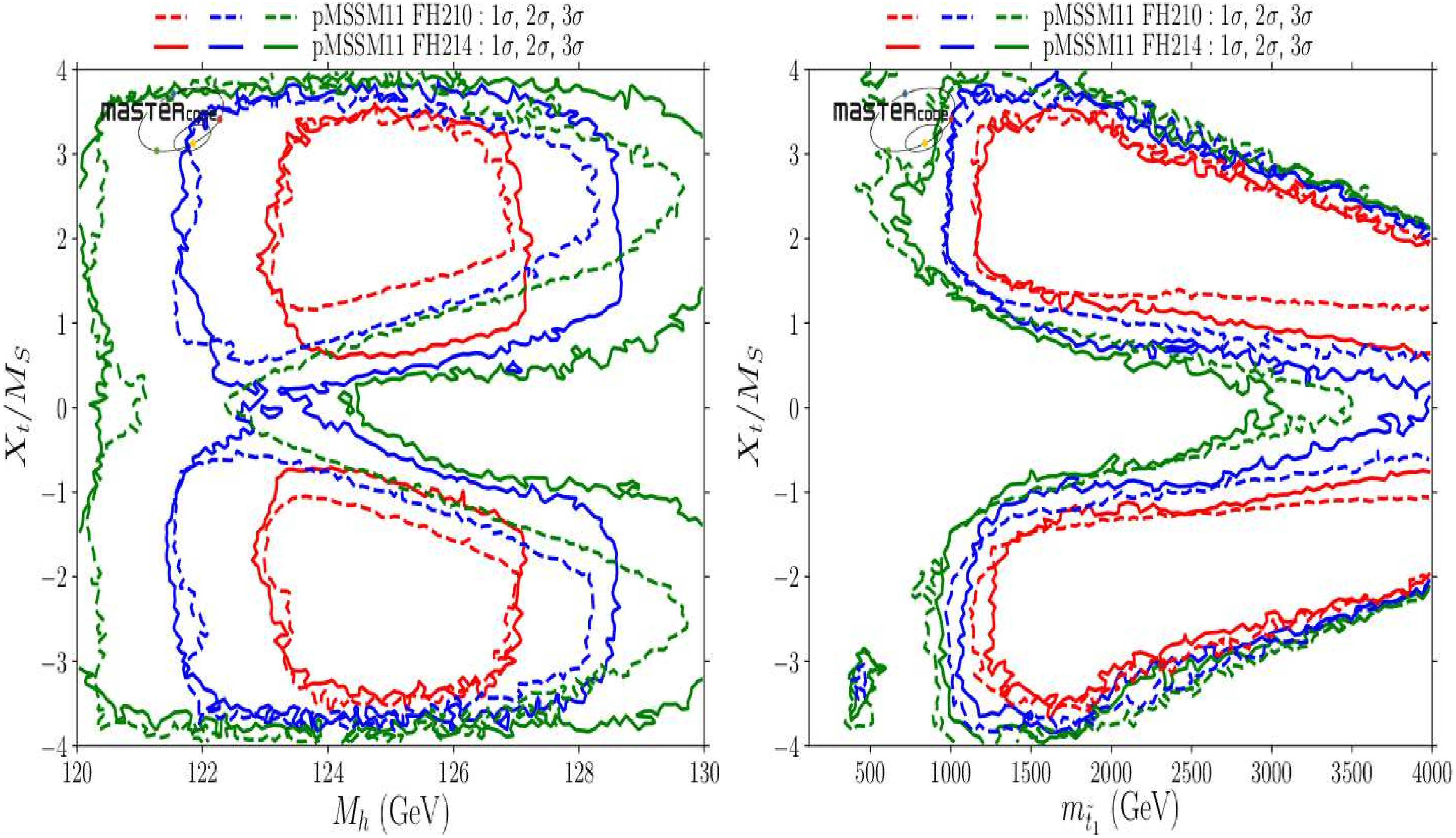




⇒ clear impact of improved M_h calculation

⇒ new allowed/disallowed regions!

3. D) pMSSM11:



⇒ clear impact of improved M_h calculation

⇒ enlarged allowed regions, better compatibility!

4. Conclusinos

- High precision predictions in BSM models for Higgs physics are needed!
  $\to$ to match experimental accuracy at the LHC and ILC/CLIC

- **FeynHiggs** provides these predictions for the MSSM (and beyond)
  ($\Rightarrow$ code adopted by the LHCHXSWG)
  $\Rightarrow$ first and most developed "hybrid code" – necessary for high precision

- CMSSM stop co-annihilation:
  $\mathcal{O}\left(\alpha_t^2\right)$ non-degenerte threshold corrections crucial
  $\Rightarrow$ refined allowed regions

- Sub-GUT models: enlarged allowed regions, better compatibility!

- mAMSB: new allowed/disallowed regions!

- pMSSM11: enlarged allowed regions, better compatibility!

- Overall better compatibility with improved M_h calculation!


Higgs Days at Santander 2019
Theory meets Experiment
16.-20. September
EXCELENCIA SEVERO OCHOA
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Further Questions?