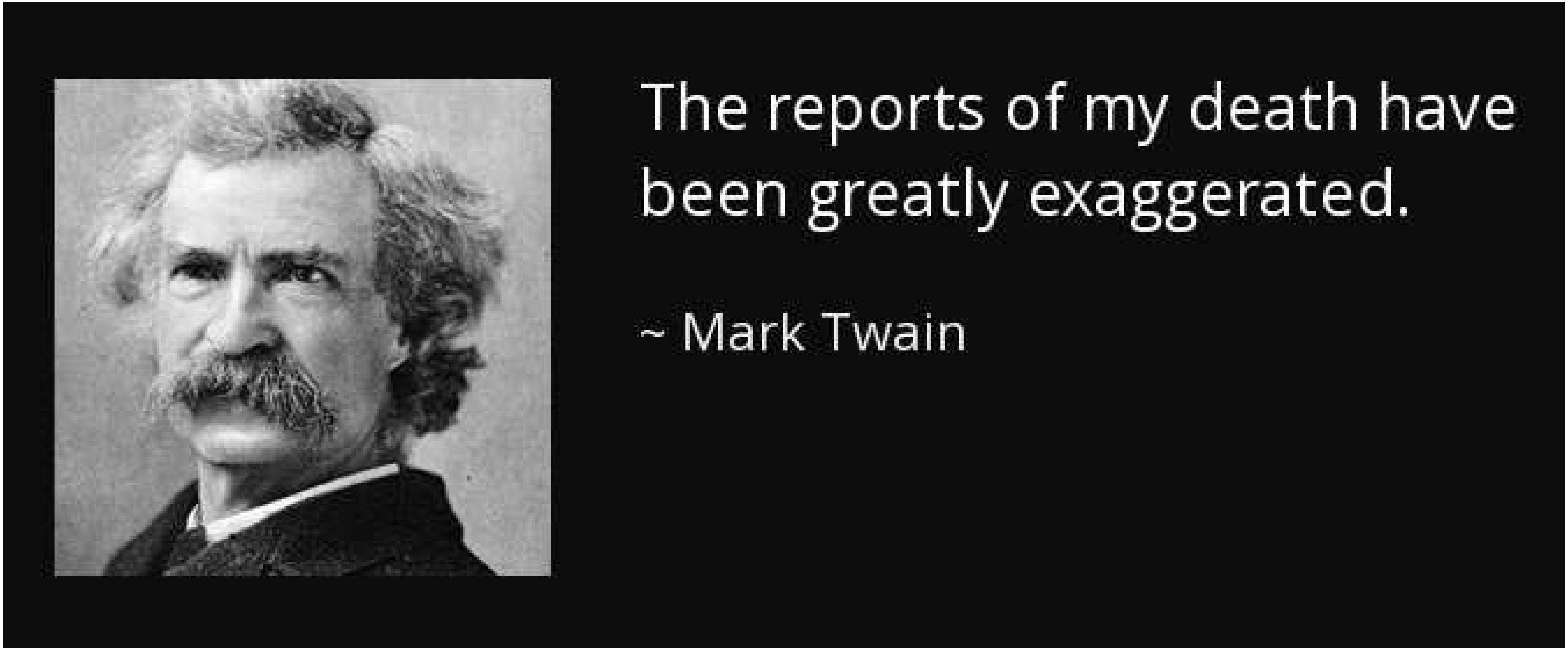
Some original SUSY literature:



pMSSM Fits:

(Theory) Problems and Solutions – Short version

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

virtual only, 11/2020

1. SUSY Higgs-boson masses
   couplings and BRs
2. LHC rate measurements
   and BSM Higgs limits
3. Example results
4. Conclusions

1. SUSY Higgs-boson masses, couplings and BRs

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

1. SUSY Higgs-boson masses, couplings and BRs

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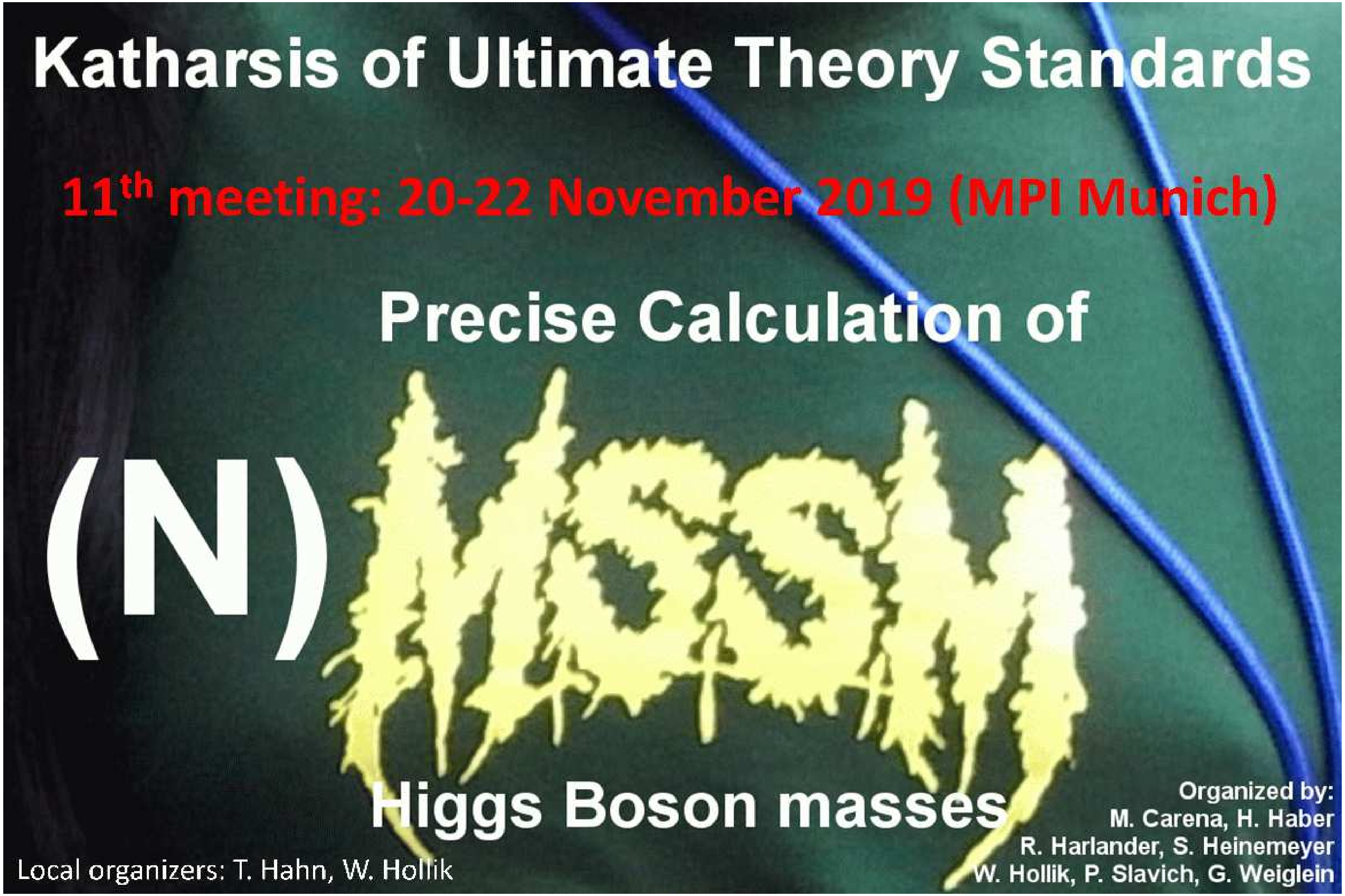
MSSM theory:

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 $1 - 2$ 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: 06/2021 at PSI, Switzerland (originally 06/2020 . . .)

Improved predictions for MSSM scenarios

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

Example for: – CMSSM with stop co-annihiliation
– pMSSM11 (later!)

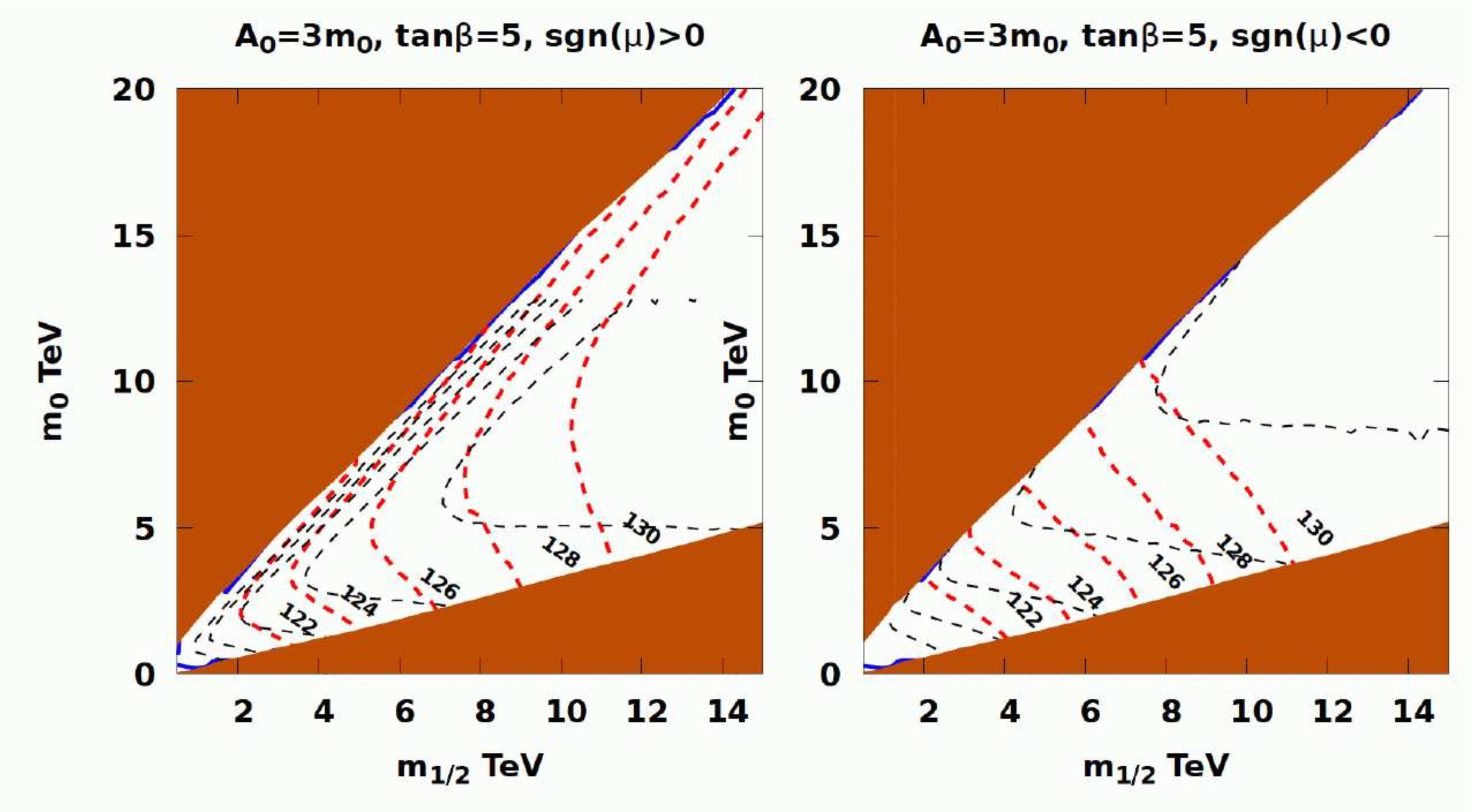
Comparison of hybrid codes:

FeynHiggs 2.10.0 (first hybrid code in 2013)
- 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 $m_t^{\overline{\text{MS}}}$

Stop-coannihilation in the CMSSM:

[*E. Bagnaschi et al. '18*]

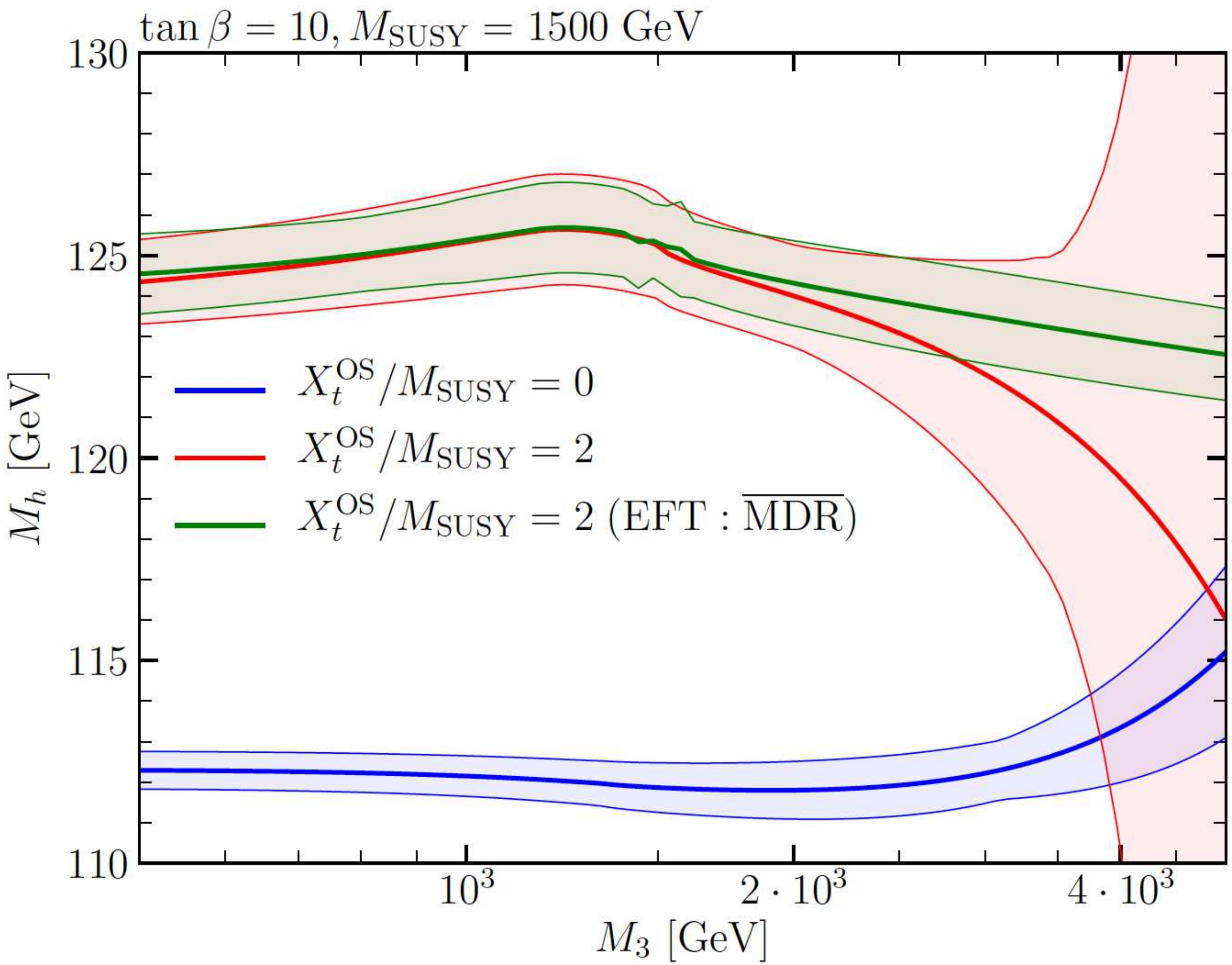


⇒ clear impact of improved M_h calculation

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

Another important example: large gluino mass:

[*H. Bahl, S.H., W. Hollik, G. Weiglein '19*]

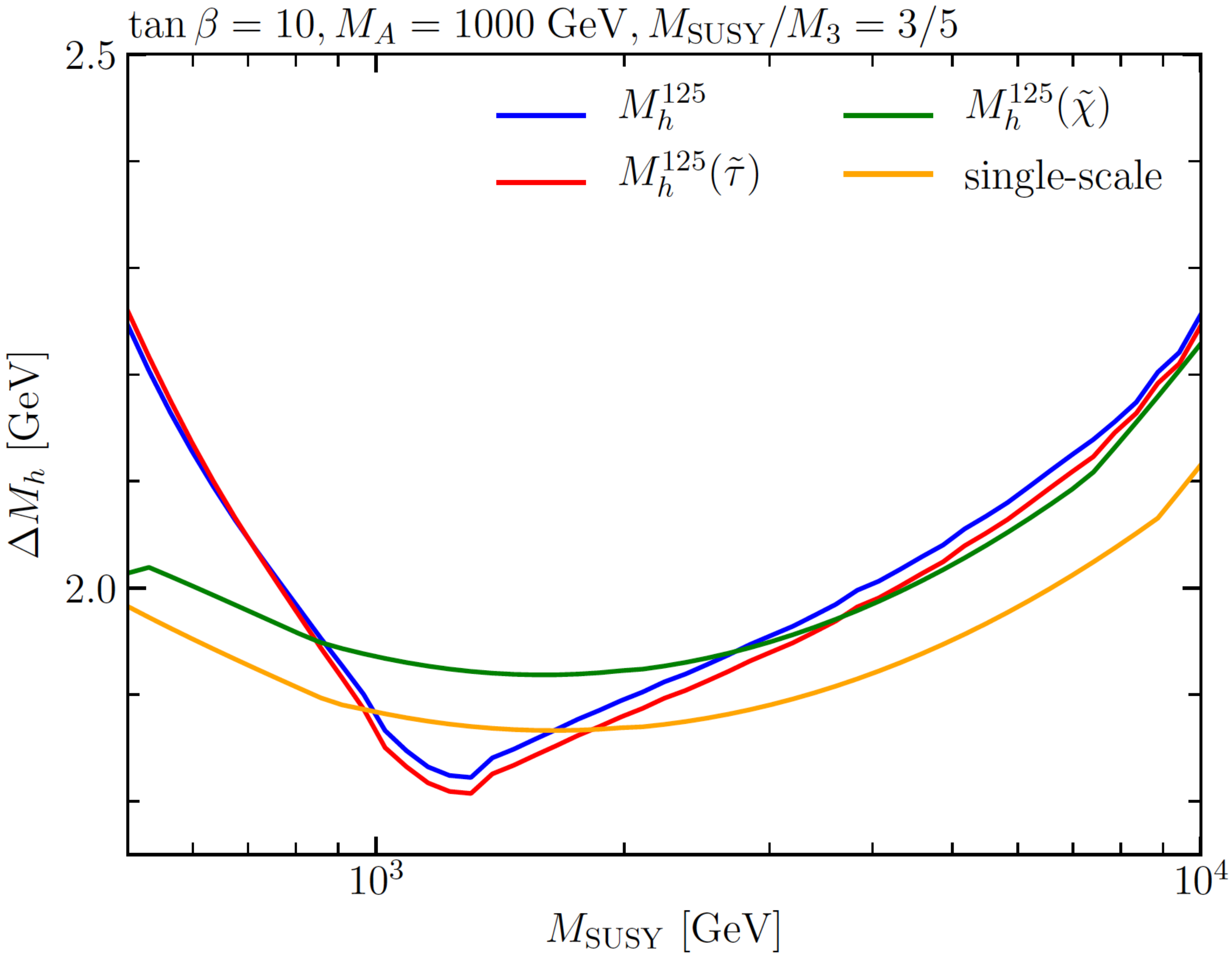


⇒ only latest FeynHiggs version gives accurate results

⇒ note the small uncertainty band (green)!

Crucial for pMSSM scans: M_h theory uncertainty [H. Bahl et al. '19]

$\Rightarrow$ estimate in several benchmark scenarios with FeynHiggs 2.16.0



$\Rightarrow$ $\Delta M_h \sim 2$ GeV – but point-by-point evaluation crucial!

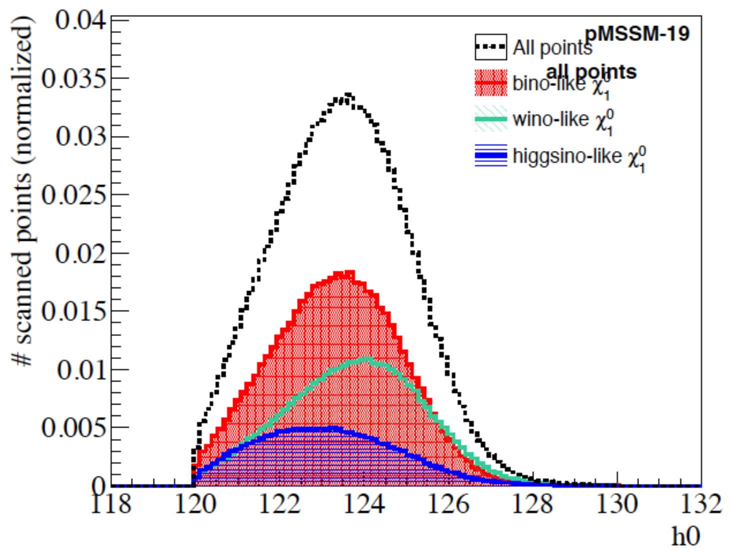
CMS example in pMSSM scan:

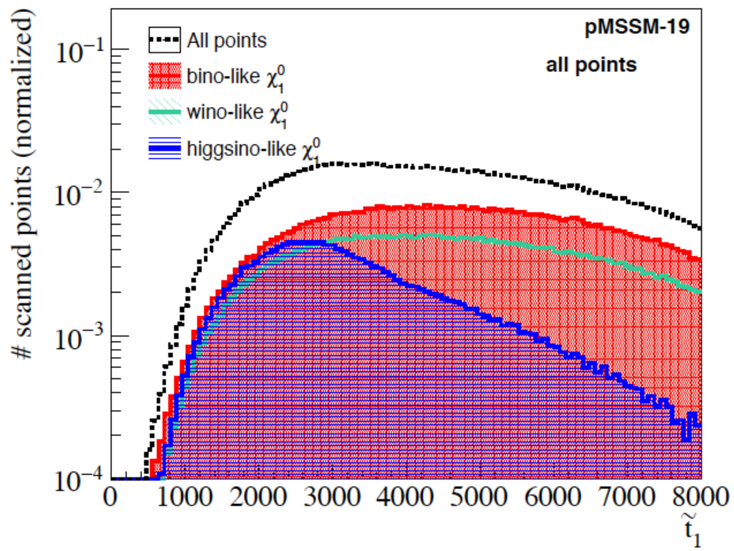
[S. Bein, Snowmass talk '20]

- m_h not a free parameter in the MSSM (or pMSSM)
- window cut placed on the Higgs mass: $m_h \in [120, 130]$ GeV

  →almost not necessary due to the natural range of values
- heaviness of Higgs boson (∼125 GeV) associated largely with heavier stops

$$m^2_{h^0} \sim m^2_Z \cos^2 2\beta + \frac{3}{\pi^2} \frac{m^4_{\tilde{t}} \sin^4\beta}{v} log(\frac{m_{\tilde{t}}}{m_t})$$



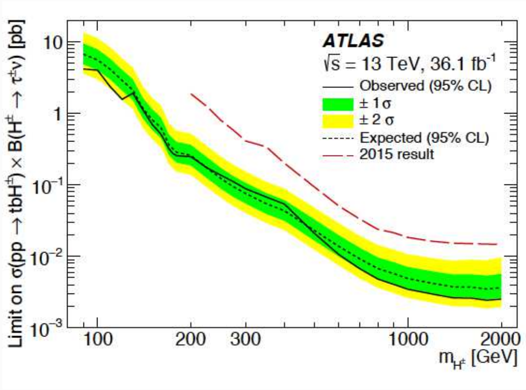


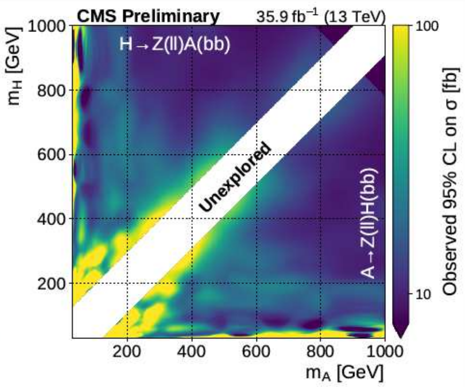
⇒ room for improvement . . .

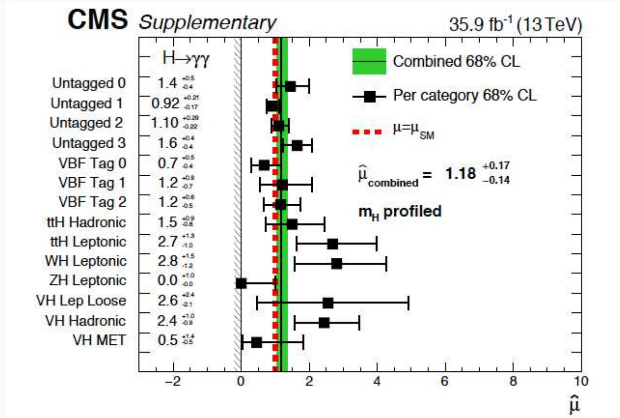
HiggsBounds and HiggsSignals

Team: P. Bechtle, SH, T. Klingl, T. Stefaniak, G. Weiglein, J. Wittbrodt

HiggsBounds	HiggsSignals
Confronts BSM Higgs sectors with **exclusion limits** from LEP, Tevatron and LHC Higgs searches.	Confronts BSM Higgs sectors with LHC Higgs **signal rate** and **mass measurements**.
$\Rightarrow$ excluded/allowed at 95% C.L. ($\chi^2_{\tau\tau}$ ...)	$\Rightarrow \chi^2$ (sep. for rates and mass)







Codes available at GitLab & hepforge.

Most important BSM Higgs searches for pMSSM scan:

$$pp \to H/A \to \tau^+\tau^-$$

ATLAS and CMS published $-2\ln\mathcal{L}$ values for 13 TeV
- ATLAS with full Run 2 data
- CMS (so far) for 36 fb^{-1}

Narrow resonance (ϕ) toy model in three dimensions: m_ϕ, $\sigma_{gg\phi}$, $\sigma_{bb\phi}$

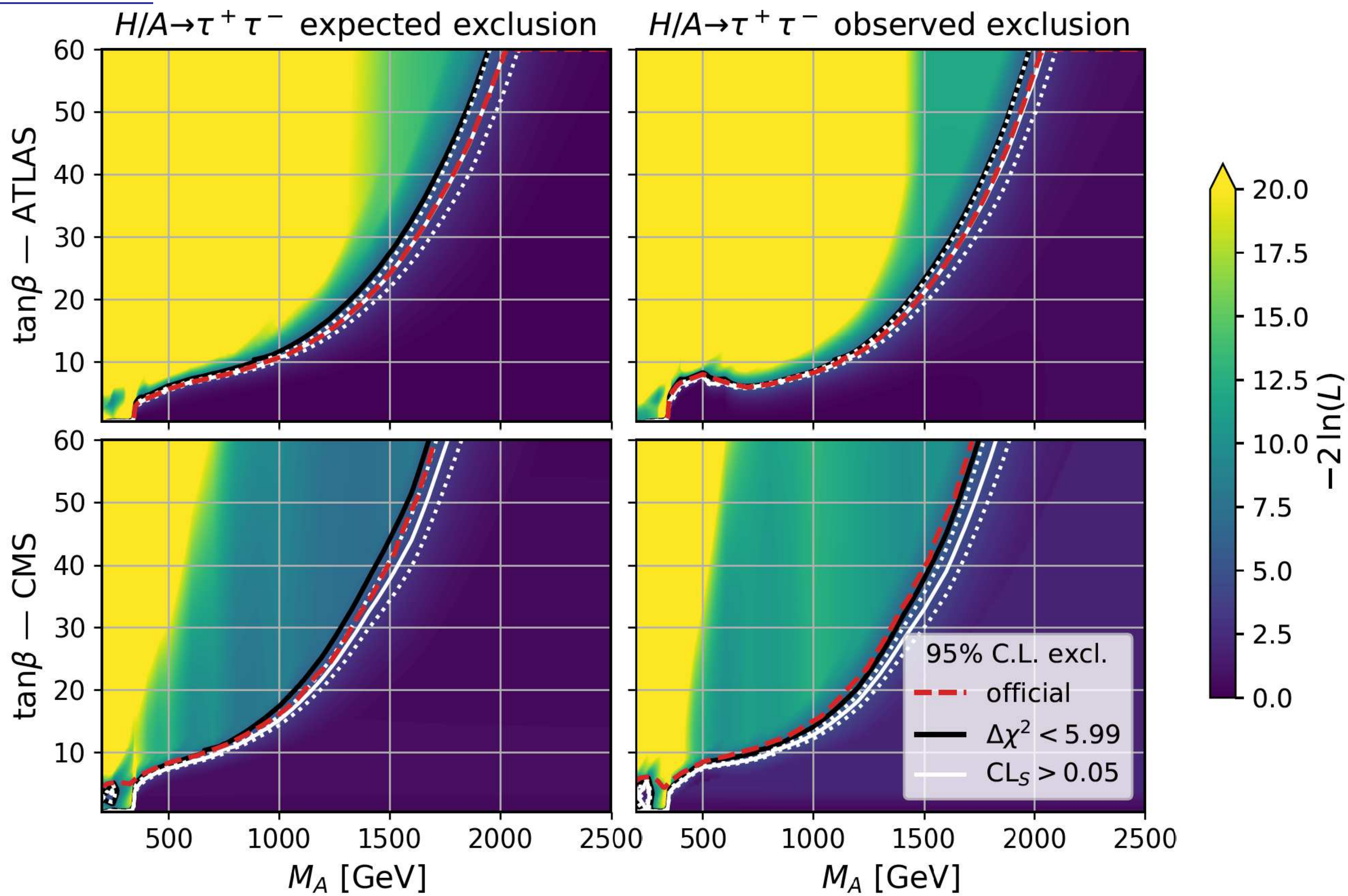
⇒ full $-2\ln\mathcal{L}$ result for many BSM models in HiggsBounds
via simple algorithm [*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '15*]

⇒ re-interpretation in the MSSM possible

⇒ preferred over just a hard cut at 95% CL

Validation:

[*HiggsBounds* 5 '20]



$\Rightarrow \chi^2(H/A \to \tau^+\tau^-)$ can reliably be used in the MSSM

HiggsSignals:

Is the h_{125} in agreement with the LHC rate measurements?

Included:

– 7, 8, 13 TeV data
– μ values
– STXS measurements
– correlations (where available)

$\Rightarrow$ overall χ^2 to all available channels

Validation:

– 1-dim (μ, STXS)
– 2-dim κ-plots or μ-plots
– effect of correlations crucial

$\Rightarrow$ $\chi^2(h_{125})$ can reliably be used in the MSSM

3. Example results: pMSSM11 predictions

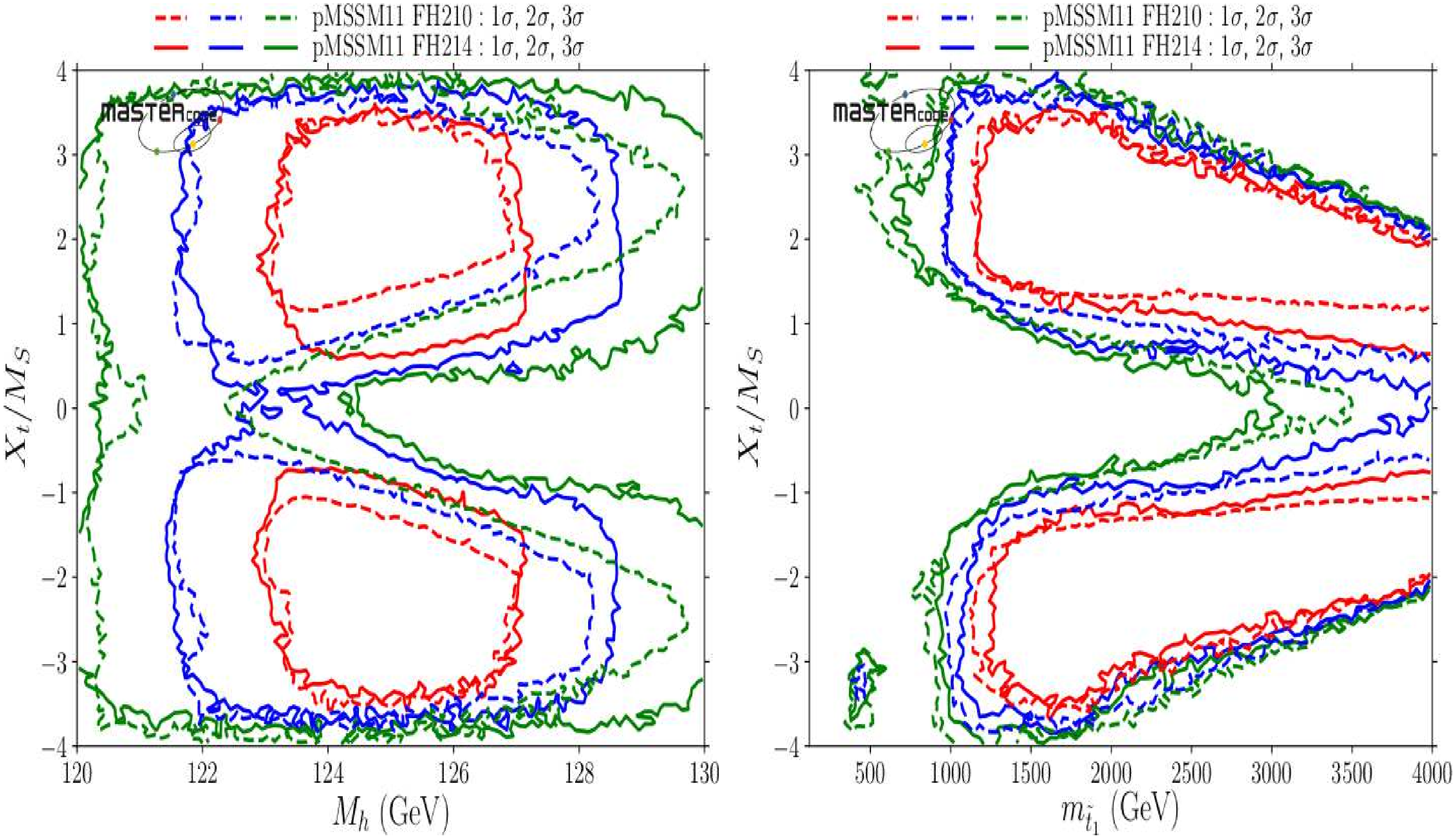
[2017]

Parameter	Range	# of segments
M_1	(-4 , 4) TeV	6
M_2	(0 , 4) TeV	2
M_3	(-4 , 4) TeV	4
$m_{\tilde{q}}$	(0 , 4) TeV	2
$m_{\tilde{q}_3}$	(0 , 4) TeV	2
$m_{\tilde{l}}$	(0 , 2) TeV	1
$m_{\tilde{\tau}}$	(0 , 2) TeV	1
M_A	(0 , 4) TeV	2
A	(-5 , 5) TeV	1
μ	(-5 , 5) TeV	1
$\tan\beta$	(1 , 60)	1

$\Rightarrow$ I doubt that (many) more dimensions can reliably(!) be sampled

pMSSM11: impact of improved M_h predictions

[*E. Bagnaschi et al. '18*]



⇒ clear impact of improved M_h calculation

⇒ enlarged allowed regions, better compatibility!

4. Conclusinos

- Needed for LHC/HL-LHC physics:
  Precise and consistent theory predictions:
  masses, mixings, couplings, XS's, BR's, . . .
  $\Rightarrow$ (partially) provided by FeynHiggs (adopted by LHCHXSWG)

- High precision in M_h crucial: huge effects for large mass splittings
  $\Delta M_h^{\text{FH}} \sim 1 - 2$ GeV $\Rightarrow$ Important: point-by-point evaluation

- Consistent compilation of BSM Higgs searches: HiggsBounds
  Crucial for pMSSM scan: $pp \to H/A \to \tau^+\tau^-$
  3-dim likelihood from ATLAS/CMS $\Rightarrow$ reinterpretation in pMSSM

- Consistent compilation of h_{125} measurements: HiggsSignals
  overall χ^2 to all available channels $\Rightarrow$ reliable use in pMSSM

- MasterCode results for the pMSSM11:
  (I doubt that (many) more dimensions can reliably be sampled)
  $\Rightarrow$ compressed spectra play a crucial role
  $\Rightarrow$ large effects of improved M_h calculations


Further Questions?

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

- ...

Possible & necessary refinements of the EFT calculation:

- Inclusion of EWino mass scale in RGE's
  $\Rightarrow$ included into FeynHiggs
- Inclusion of gluino mass scale in RGE's
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- Inclusion of EW effects in RGE's
  $\Rightarrow$ included into FeynHiggs
- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.
  $\Rightarrow$ included into FeynHiggs
- "Two Higgs Doublet Model" below M_S
  $\Rightarrow$ included into FeynHiggs, other code: MhEFT
- Splitting in the scalar top sector
  $\Rightarrow$ not available yet, but crucial for the future!
- ...

FeynHiggs provides: [*www.feynhiggs.de*]

Evaluation of all MSSM Higgs boson masses and mixing angles

- $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}$, α_{eff}, $\mathbf{Z}_{ij}$, $\mathbf{U}_{ij}$, ... $\Rightarrow$ precision disussed before

Evaluation of all neutral MSSM Higgs boson decay channels (so far)

- total decay width Γ_{tot}
- BR($h_i \to f\bar{f}$): decay to SM fermions: full 1L, running m_q at 3L, $\mathbf{Z}_{ij}$
- BR($h_i \to Z^{(*)}Z^{(*)}, W^{(*)}W^{(*)}$): decay to massive SM gauge bosons: Prophecy4f $\oplus$ coupling factors, $\mathbf{U}_{ij}$
- BR($h_i \to \gamma\gamma, gg$): decay to massless SM gauge bosons: NLO QCD, gg: NNLO, NNLL from SM, $\mathbf{U}_{ij}$
- BR($h_i \to h_j Z^{(*)}, h_j h_k$): decay to gauge and Higgs bosons: $h_j Z^{(*)}$: $\mathbf{U}_{ij}$, $h_j h_k$: full 1L, log-resum, $\mathbf{Z}_{ij}$
- BR($h_i \to \tilde{f}_i \tilde{f}_j$): decay to sfermions: $\mathbf{U}_{ij}$
- BR($h_i \to \tilde{\chi}^\pm_i \tilde{\chi}^\mp_j, \tilde{\chi}^0_i \tilde{\chi}^0_j$): decay to charginos, neutralinos: $\mathbf{U}_{ij}$

Evaluations for the charged Higgs boson

- total decay width Γ_{tot}
- $\text{BR}(H^+ \to f^{(*)}\bar{f}')$: decay to SM fermions
- $\text{BR}(H^+ \to h_i W^{+(*)})$: decay to gauge and Higgs bosons
- $\text{BR}(H^+ \to \tilde{f}_i \tilde{f}'_j)$: decay to sfermions
- $\text{BR}(H^+ \to \tilde{\chi}_i^0 \tilde{\chi}_j^+)$: decay to charginos and neutralinos
- H^+ production cross sections at the LHC
- $\text{BR}(t \to H^+ \bar{b})$ for $M_{H^\pm} \leq m_t$ ($H^\pm$ production)

Evaluation of additional couplings:

- $g(V \to V h_i, h_i h_j)$: coupling of gauge and Higgs bosons
- $g(h_i h_j h_k)$: all Higgs self couplings (including charged Higgs)

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:

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

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:

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

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
$\to$ 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: $M_{\rm SUSY} = M_{\rm S} \sim m_{\tilde{t}}$

Above $M_{\rm SUSY}$: MSSM
Below $M_{\rm SUSY}$: 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: $h_t, g_s(m_t) \to h_t, g_s(M_{\rm S})$

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

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

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

$\rightarrow$ sub-leading logs more difficult

$\rightarrow$ momentum dependence

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

– difficult (impossible?): control over Higgs boson self-energies

$\rightarrow$ 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!

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

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

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

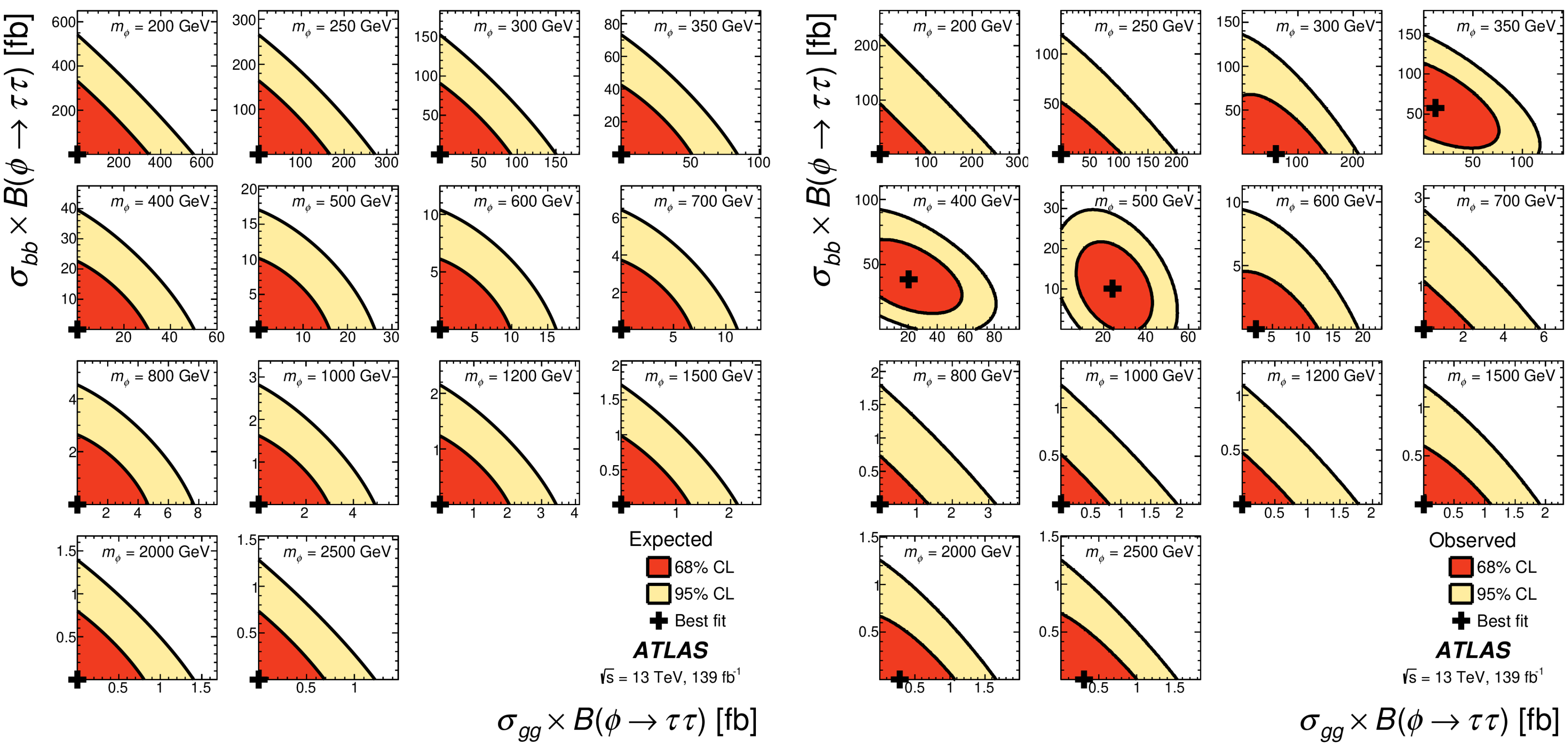
$\Rightarrow$ combination of best FD result with
resummed LL, NLL corrections for large $m_{\tilde{t}}$
$\Rightarrow$ most precise M_h prediction for large $m_{\tilde{t}}$
$\Rightarrow$ first "hybrid code": FeynHiggs 2.10.0

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

Experimental data

[*ATLAS '20*]

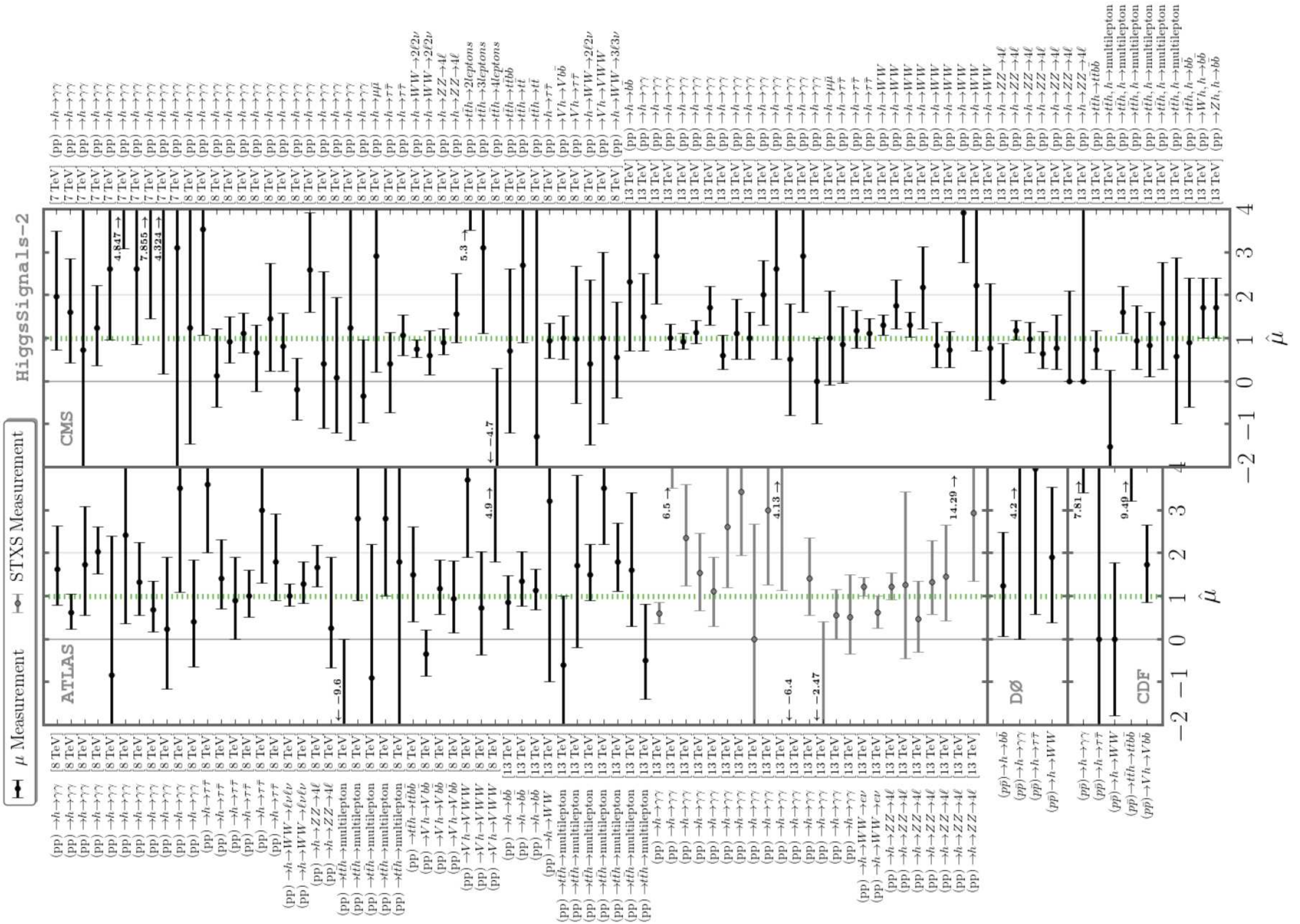
expected | observed



$\Rightarrow$ note the nice excess at $\sim$ 400 GeV :-)

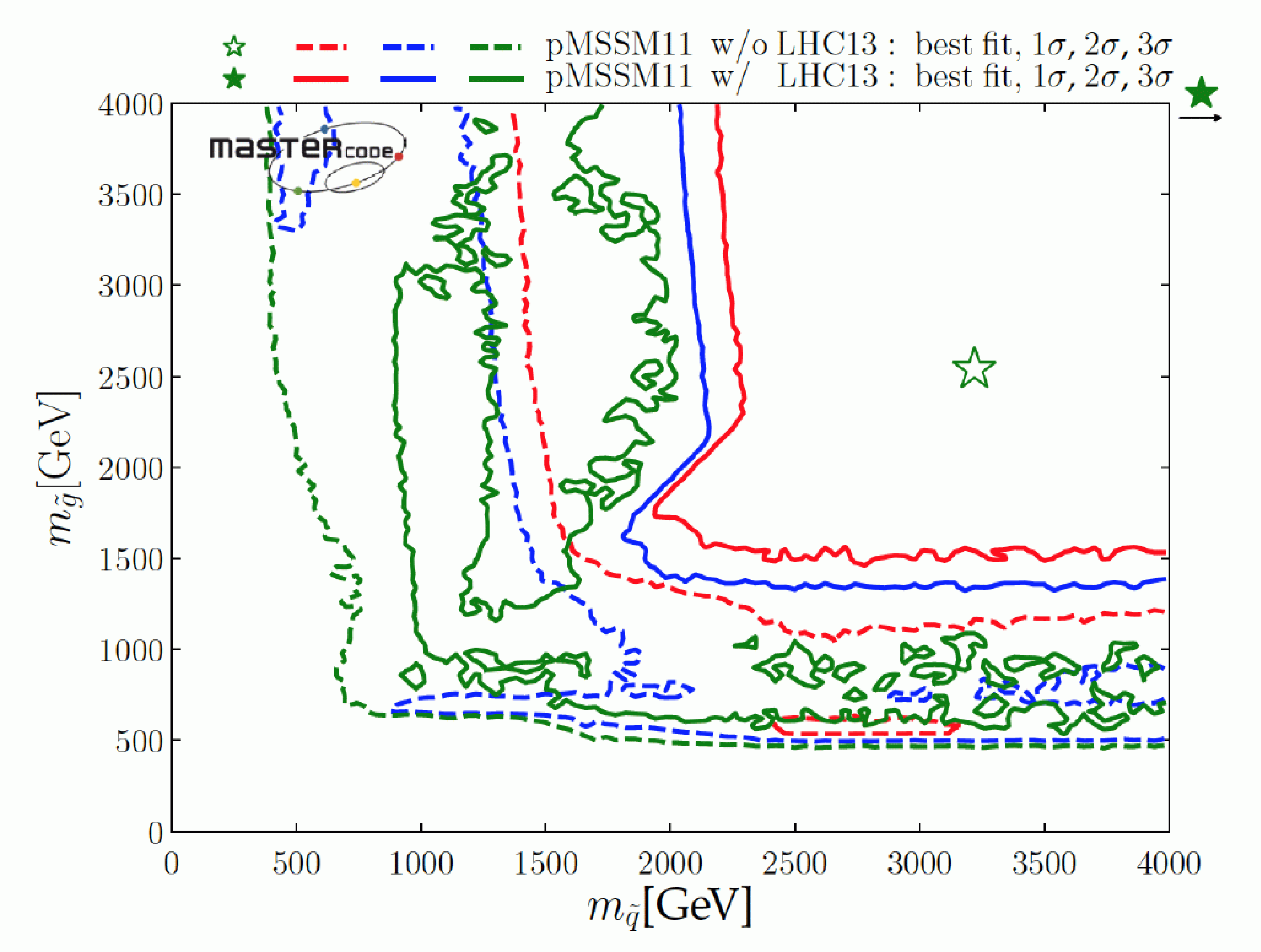
All channels and their experimental input:

[*HiggsSignals 2 '20*]



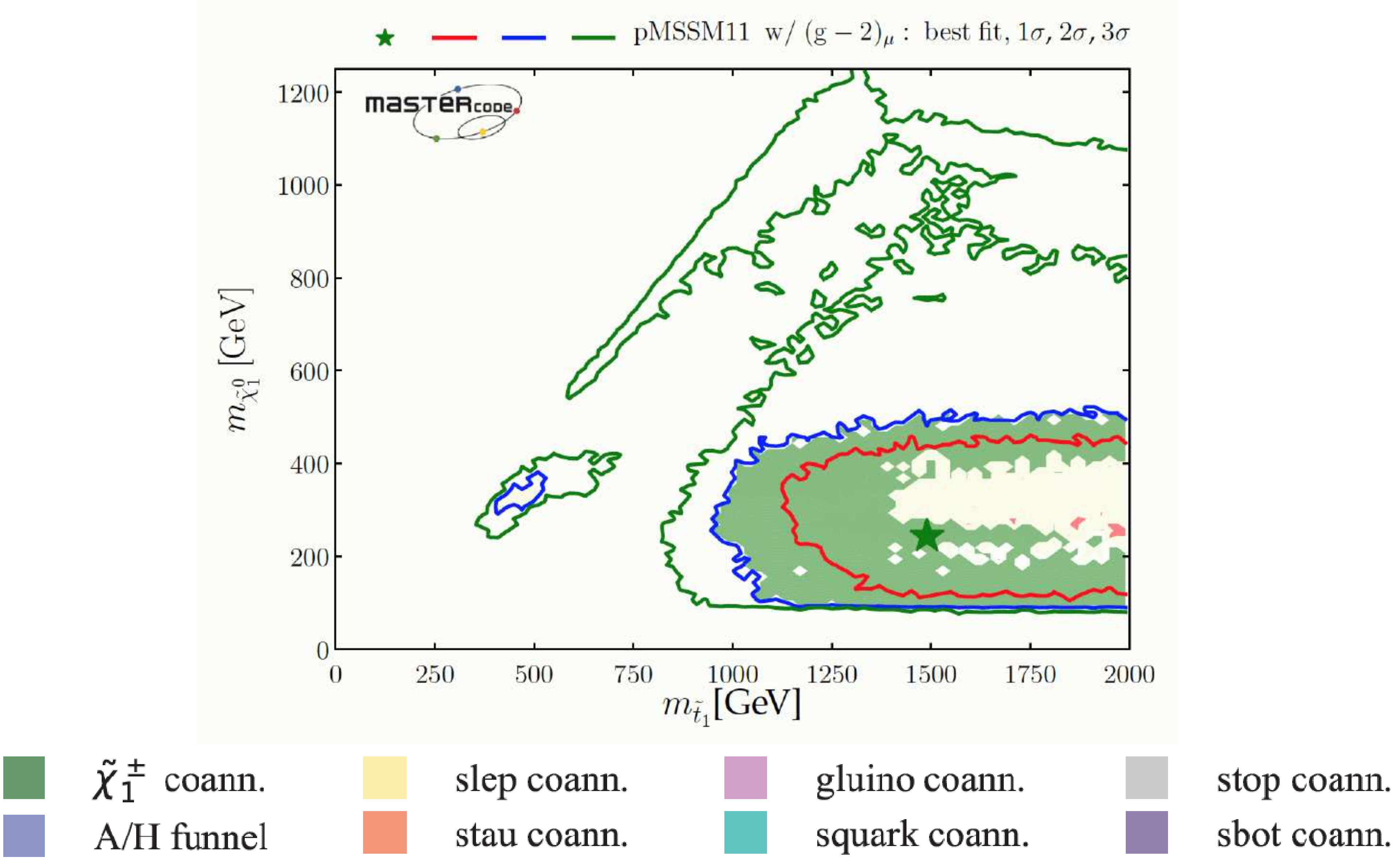
pMSSM11: Going from 8 TeV to 13 TeV (and adding latest DM limits)

[2017]

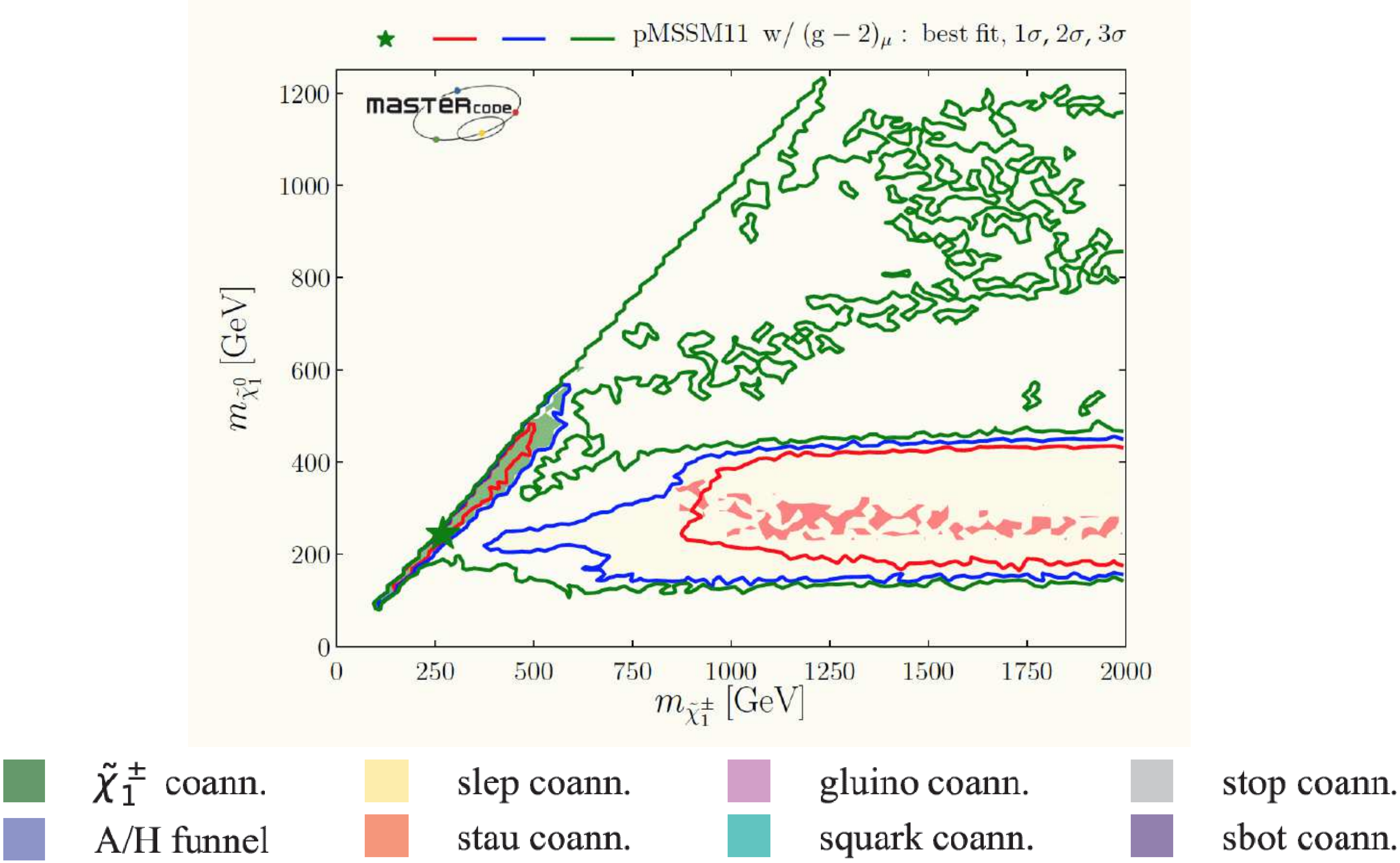


⇒ notice the "nose"! Do you have it?

pMSSM11: $m_{\tilde{t}_1}$–$m_{\tilde{\chi}^0_1}$ plane



⇒ notice the compressed region! Do you have it?



⇒ chargino co-annihilation ⇒ $M_1 \sim M_2$ Do you have it?

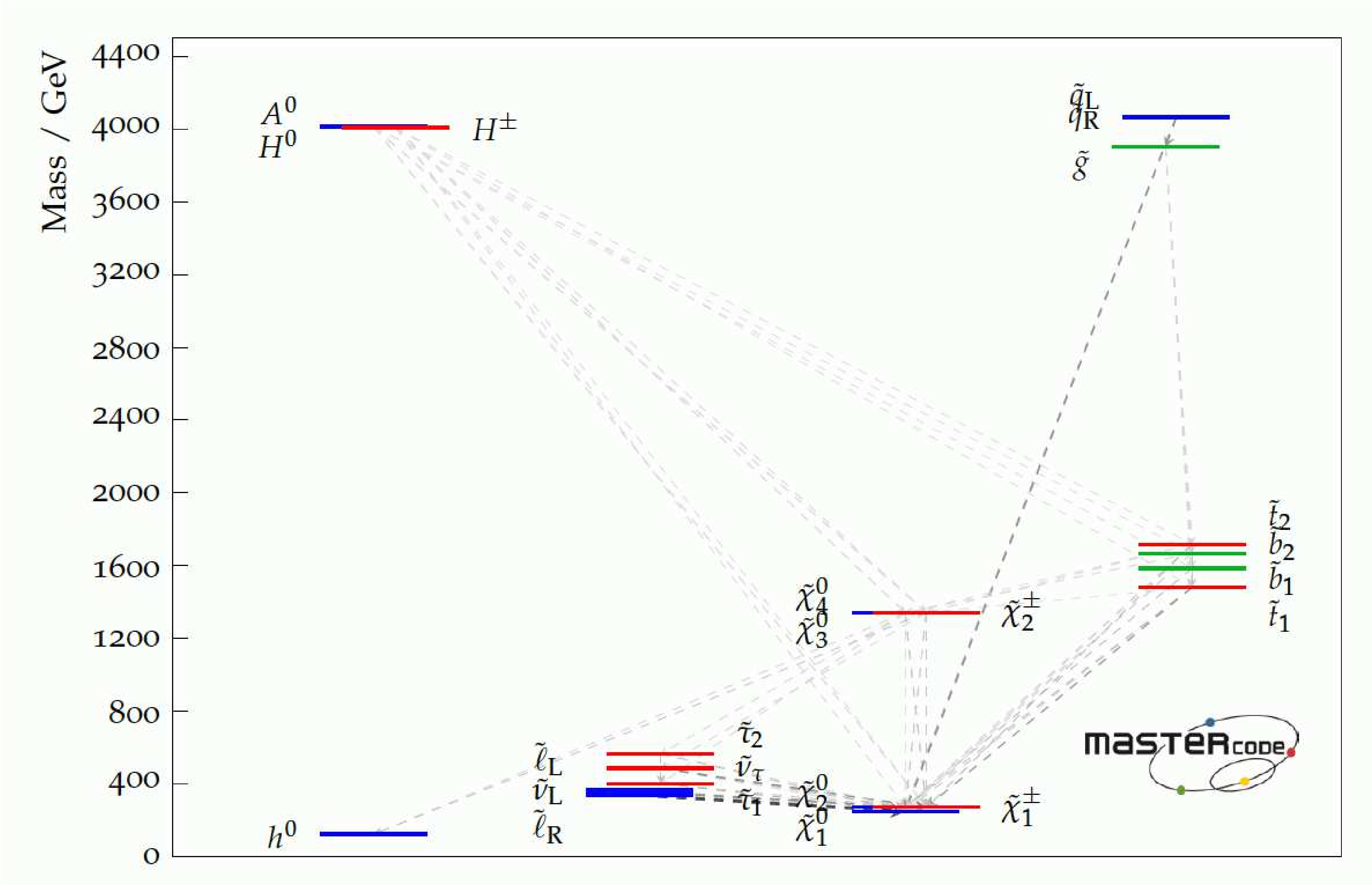
pMSSM11: best-fit point parameters

[2017]

Parameter	With LHC 13 TeV and $(g-2)_\mu$ Best fit	'Nose' region
M_1	0.25 TeV	- 0.39 TeV
M_2	0.25 TeV	1.2 TeV
M_3	- 3.86 TeV	- 1.7 TeV
$m_{\tilde{q}}$	4.0 TeV	2.00 TeV
$m_{\tilde{q}_3}$	1.7 TeV	4.1 TeV
$m_{\tilde{\ell}}$	0.35 TeV	0.36 TeV
$m_{\tilde{\tau}}$	0.46 TeV	1.4 TeV
M_A	4.0 TeV	4.2 TeV
A	2.8 TeV	5.4 TeV
μ	1.33 TeV	- 5.7 TeV
$\tan\beta$	36	19
χ^2/d.o.f.	22.1/20	24.46/20
p-value	0.33	0.22
$\chi^2(HS)$	68.01	67.97

$\Rightarrow$ excellent p value! $\Rightarrow$ Much better than in GUT based models!

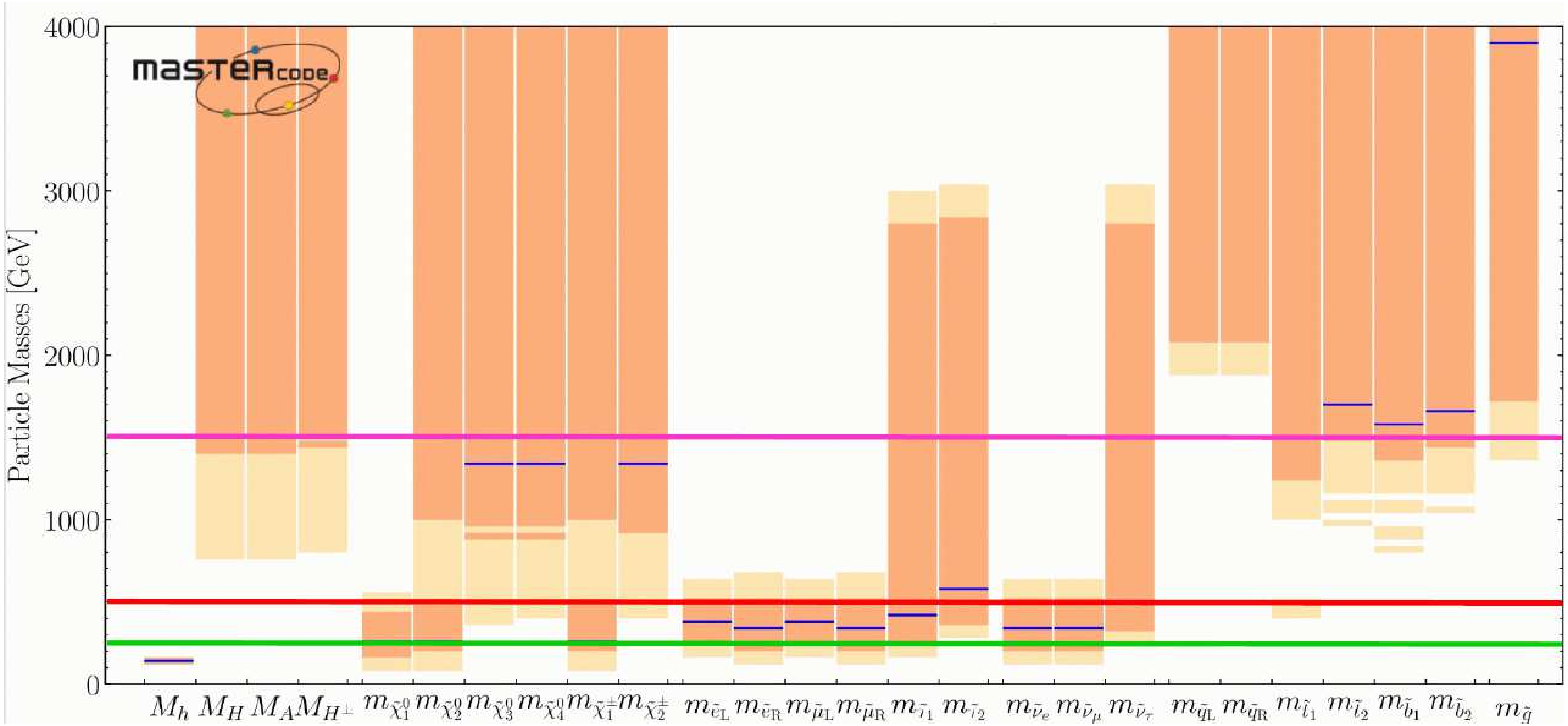
pMSSM11: best-fit point phenomenology [2017]



⇒ heavy colored, light uncolored spectrum

pMSSM11: full fit spectrum

[2017]



⇒ LHC Run 3 reach?

⇒ HL-LHC reach?