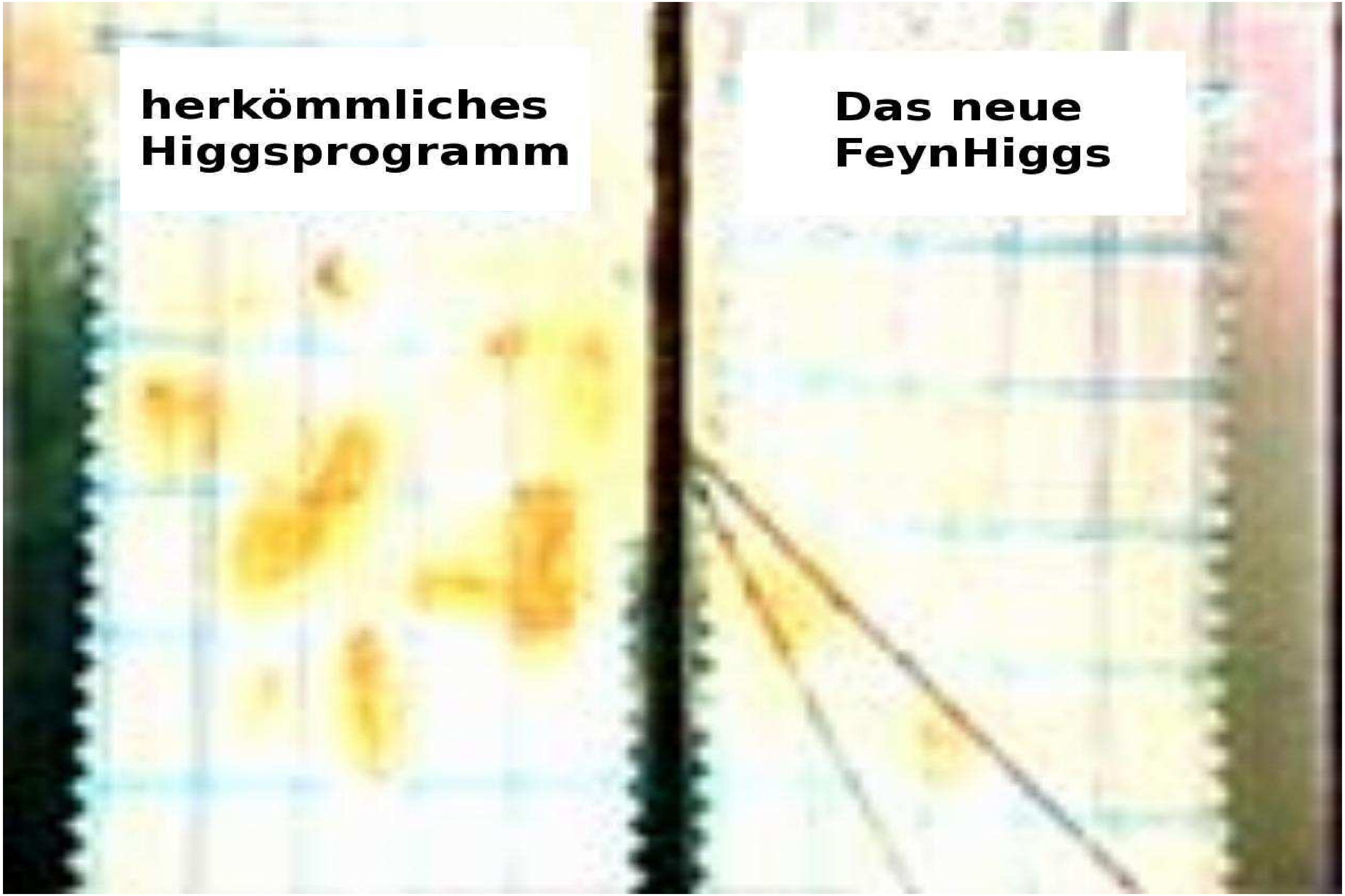

herkömmliches Higgsprogramm
Das neue FeynHiggs

SUSY Higgs-mass predictions:
MSSM vs. EFT Approach

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

Leipzig, 04/2016

- Motivation: why we need a precise M_h^{MSSM} prediction
- Feynman diagrammatic calculations vs. EFT approach
- The best of both worlds
- Applicability and uncertainties
- Conclusions

1. Motivation

The LHC up and running . . .
→ discovery of BSM physics this year?

The ILC is still coming . . .
. . . a bit later than anticipated
→ to investigate BSM physics

Worldwide Study of
the Physics and Detectors
for Future Linear
$e^+ e^-$ Colliders

⇒ New Physics is certainly around the corner

⇒ Time to get ready for BSM physics

Which model should we focus on?

Some “recent” measurements:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

Which model should we focus on?

Some "recent" measurements:

- top quark mass
- Higgs boson mass
- Higgs boson "couplings"
- Dark Matter (properties)

Simple SUSY models predicted correctly:

- top quark mass
- Higgs boson mass
- Higgs boson "couplings"
- Dark Matter (properties)

Which model should we focus on?

<u>Some “recent” measurements:</u>

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

<u>Simple SUSY models predicted correctly:</u>

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

$\Rightarrow$ **good motivation to look at SUSY! :-)**

The big question:

Which Lagrangian describes the world?

My guess:

It is a supersymmetric one

$\Rightarrow$ concentrate on the (N)MSSM from now on

other people $\Rightarrow$ other guesses $\Rightarrow$ other priorities . . .

In any case:

$\Rightarrow$ we have to measure as many observables as possible

– masses
– branching ratios
– angular distributions
– cross sections
– . . .

The big question:

Which Lagrangian describes the world?

My guess:

It is a supersymmetric one

⇒ concentrate on the (N)MSSM from now on

other people ⇒ other guesses ⇒ other priorities . . .

In any case:

⇒ we have to measure as many observables as possible

- masses
- branching ratios
- angular distributions
- cross sections
- . . .

⇒ compare with theory calculations at the same level of accuracy

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets $\Leftarrow$ focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

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)

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

$\tilde{t}$ sector of the MSSM:

Stop mass matrices

$$\mathbf{M}_{\tilde{t}}^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M_{\tilde{t}_R}^2 + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix}$$

with

$$X_t = A_t - \mu/\tan\beta$$

$\Rightarrow$ mixing important in stop sector!

Simplifying abbreviation:

$$M_{\text{SUSY}} := M_{\tilde{t}_L} = M_{\tilde{t}_R}$$

Importance of precise $M_h^{\rm MSSM}$ predictions

The Higgs mass accuracy: experiment vs. theory:

Experiment:

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

Importance of precise $M_h^{\rm MSSM}$ predictions

The Higgs mass accuracy: experiment vs. theory:

Experiment:

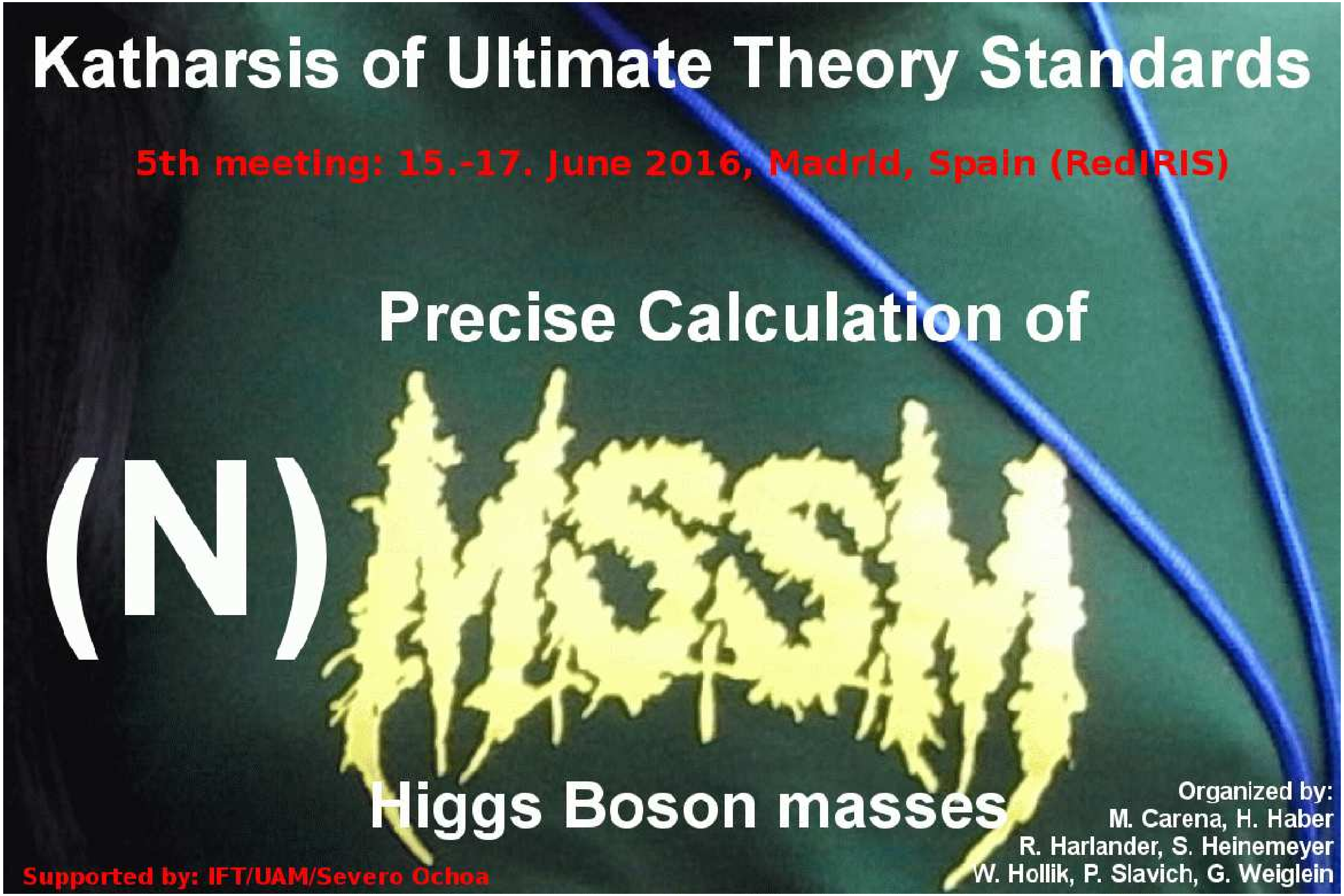
ATLAS:	$M_h^{\rm exp} = 125.36 \pm 0.37 \pm 0.18$ GeV
CMS:	$M_h^{\rm exp} = 125.03 \pm 0.27 \pm 0.15$ GeV
combined:	$M_h^{\rm exp} = 125.09 \pm 0.21 \pm 0.11$ GeV

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: $\delta M_h^{\rm theo} \sim 3$ GeV

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


Katharsis of Ultimate Theory Standards
5th meeting: 15.-17. June 2016, Madrid, Spain (RedIRIS)
Precise Calculation of
(N)MSSM
Higgs Boson masses
Supported by: IFT/UAM/Severo Ochoa
Organized by:
M. Carena, H. Haber
R. Harlander, S. Heinemeyer
W. Hollik, P. Slavich, G. Weiglein

2. Feynman diagrammatic calculation vs. EFT approach

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

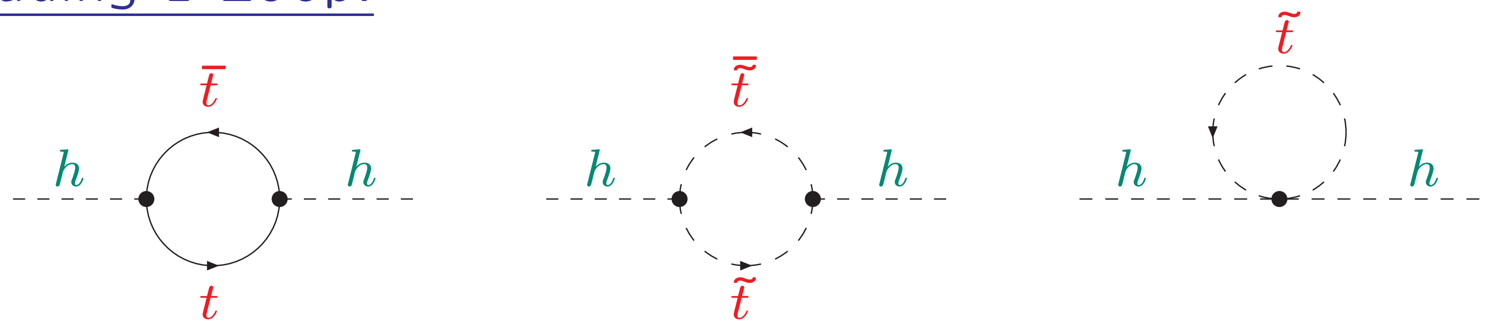
Calculation of renormalized Higgs boson self-energies:

$$\hat{\Sigma}(q^2) = \hat{\Sigma}^{(1)}(q^2) + \hat{\Sigma}^{(2)}(q^2) + \ldots$$

all MSSM particles contribute

main contribution: $t/\tilde{t}$ sector ($\tilde{t}$: scalar top, SUSY partner of the t)

Very leading 1-Loop:



2-Loop:

To avoid large corrections:

On-shell renormalization of the scalar top sector $\Rightarrow X_t^{\text{OS}}$

$$\sim m_t^4 \left[\log^2\left(\frac{m_{\tilde{t}}}{m_t}\right) + \log\left(\frac{m_{\tilde{t}}}{m_t}\right) \right]$$

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:

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

Partial results: [*S. Martin '07*]

[*R. Harlander, P. Kant, L. Mihaila, M. Steinhauser '08*] $\Rightarrow$ *H3m*

H3m adds $\mathcal{O}\left(\alpha_t \alpha_s^2\right)$ corrections to *FeynHiggs*

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 recent 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: $h_t, g_s(m_t) \to h_t, g_s(M_{\text{S}})$

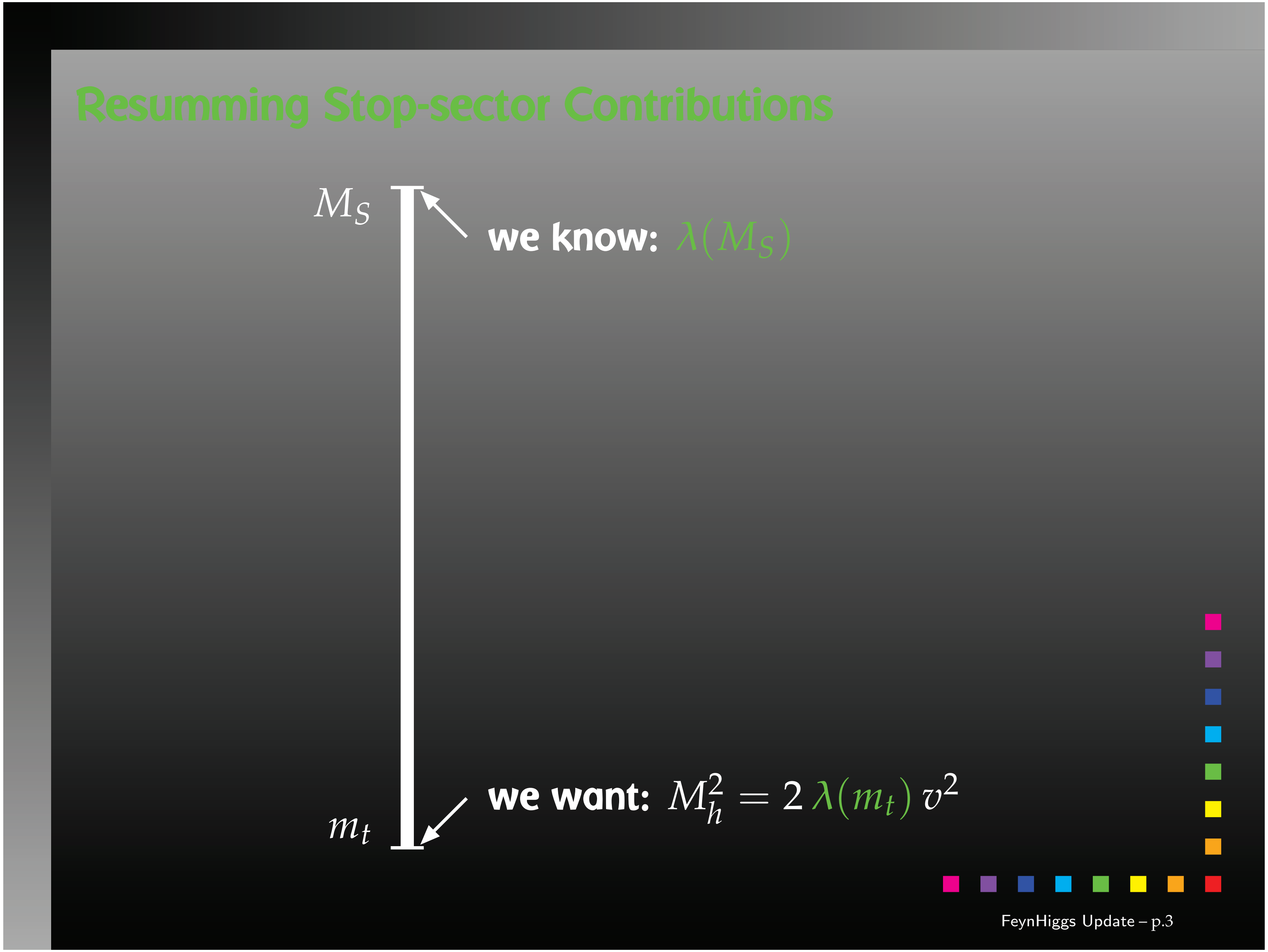
2. Take $\lambda(M_{\text{S}}), h_t(M_{\text{S}}), g_s(M_{\text{S}})$

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

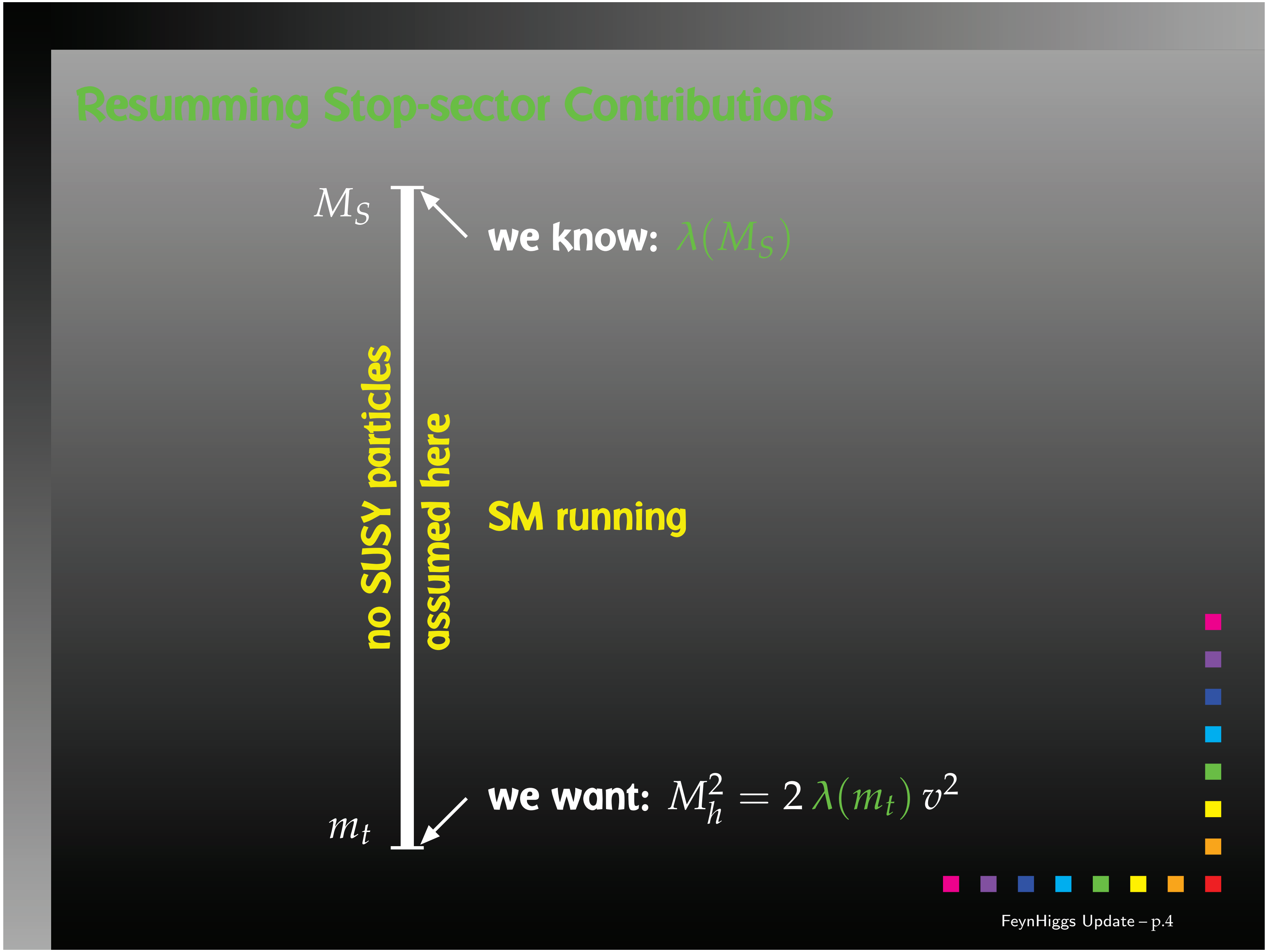
3. Evaluate M_h^2

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

[HDays14, talk by T. Hahn]



[HDays14, talk by T. Hahn]



Standard Model RGEs

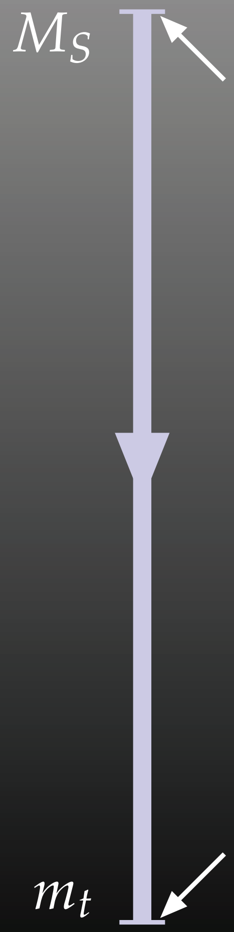
$$g_s^{2\prime} = \frac{1}{16\pi^2} g_s^4 \left(G_1 + \frac{1}{16\pi^2} G_2\right),$$
$$G_1 = \tfrac{2}{3} N_f - 11,$$
$$G_2 = \left(\tfrac{38}{3} N_f - 102\right) g_s^2 - 2h_t^2,$$

$$h_t^{2\prime} = \frac{1}{16\pi^2} h_t^2 \left(H_1 + \frac{1}{16\pi^2} H_2\right),$$
$$H_1 = \tfrac{9}{2} h_t^2 - 8 g_s^2,$$
$$H_2 = 6h_t^2(6g_s^2 - 2h_t^2 - \lambda) + \tfrac{3}{2}\lambda^2 + \left(\tfrac{40}{9} N_f - \tfrac{404}{3}\right) g_s^4,$$

$$\lambda' = \frac{1}{16\pi^2} \frac{1}{2} \left(\Lambda_1 + \frac{1}{16\pi^2} \Lambda_2\right),$$
$$\Lambda_1 = 12(\lambda^2 - h_t^4 + \lambda h_t^2),$$
$$\Lambda_2 = h_t^2(3h_t^2(20h_t^2 - \lambda) + g_s^2(80\lambda - 64h_t^2) - 72\lambda^2) - 78\lambda^3.$$

Espinosa, Quiros 1991 – Arason et al. 1992

Integrating the RGEs



start from

g_s^2, h_t^2 **from 1L RGE (analytic)**

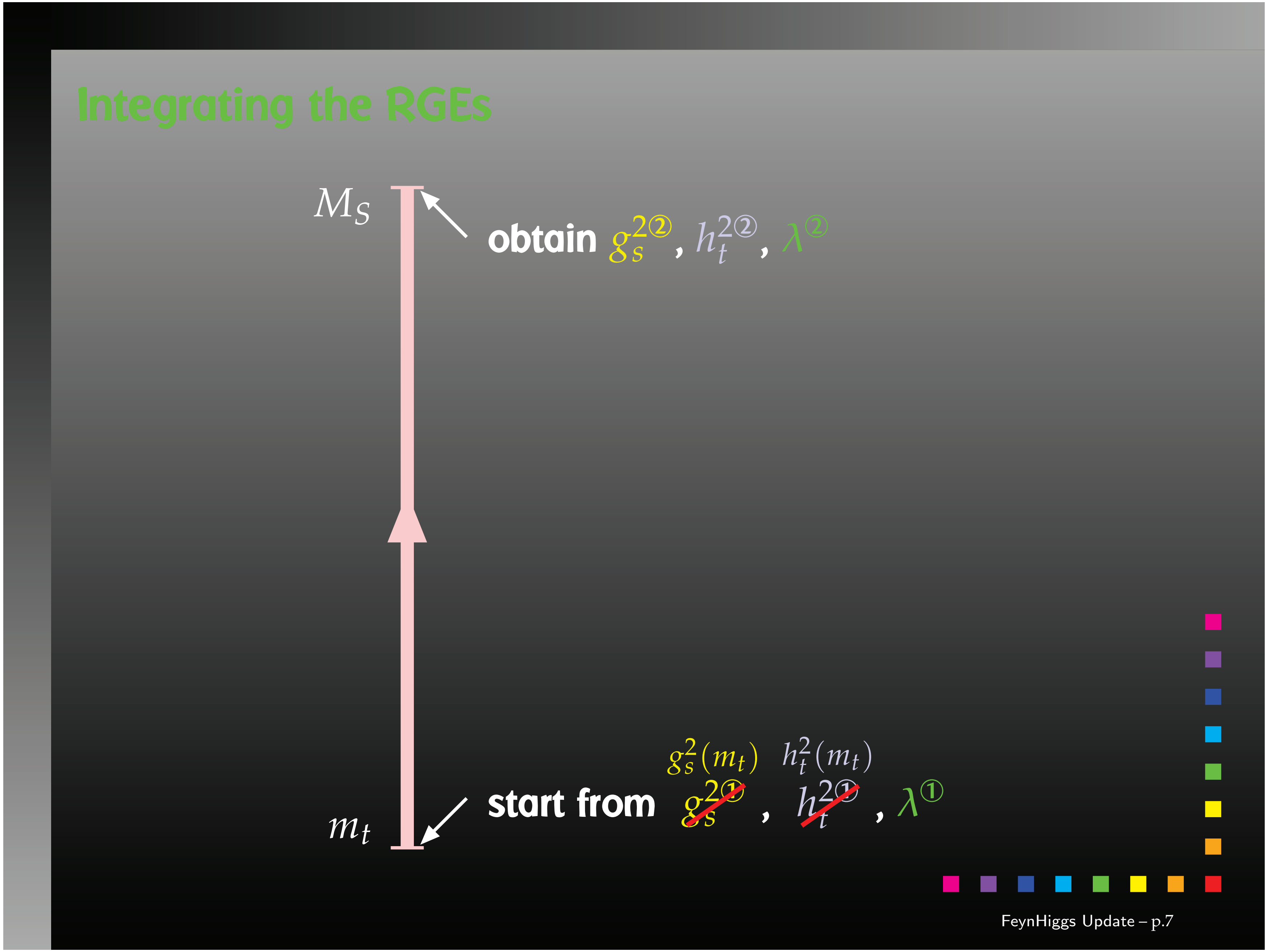
$$\lambda(M_S) = \frac{3}{8\pi^2} h_t^4 \left(\frac{X_t}{M_S}\right)^2 \left(1 - \frac{1}{12}\left(\frac{X_t}{M_S}\right)^2\right)$$

Carena et al. 2000

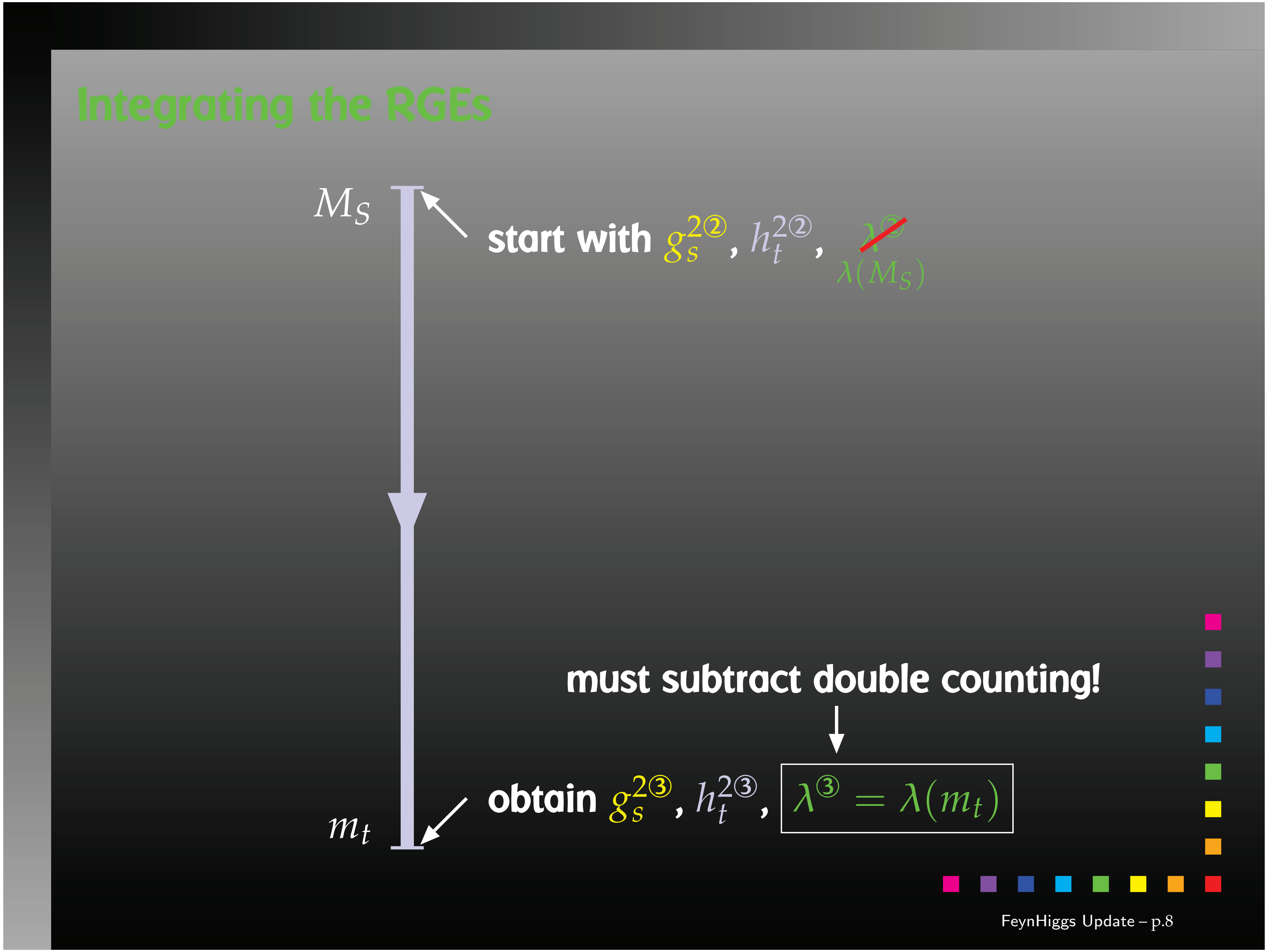
obtain $g_s^{2①}$, $h_t^{2①}$, $\lambda^{①}$

FeynHiggs Update – p.6

[HDays14, talk by T. Hahn]



[HDays14, talk by T. Hahn]



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)

3. The best of both worlds:

to get the most precise prediction of M_h:

Combination of FD and RGE result!

3. The best of both worlds:

to get the most precise prediction of M_h:

Combination of FD and RGE result!

$\Rightarrow$ example of FeynHiggs implementation

3. The best of both worlds:

to get the most precise prediction of M_h:

Combination of FD and RGE result!

⇒ example of FeynHiggs implementation

Problem:

Some terms exist in both calculations!

One-loop:

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

Two-loop:

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

Combination of FD and RGE result:

⇒ to avoid double counting:
subtract leading and subleading logs at one- and two-loop

Problem:

– FD result with $X_t^{\mathrm{OS}}, M_S^{\mathrm{OS}}, \overline{m}_t$

– RGE result with $X_t^{\overline{\mathrm{MS}}}, M_S^{\overline{\mathrm{MS}}}, \overline{m}_t$

$$\overline{m}_t = \frac{m_t^{\mathrm{pole}}}{1 + \frac{4}{3\pi}\alpha_s(m_t^{\mathrm{pole}}) - \frac{1}{2\pi}\alpha_t(m_t^{\mathrm{pole}})}$$

$$X_t^{\overline{\mathrm{MS}}} = X_t^{\mathrm{OS}}\left[1 + 2L\left(\frac{\alpha_s}{\pi} - \frac{3\,\alpha_t}{16\,\pi}\left(1 - \frac{X_t^2}{M_S^2}\right)\right)\right]$$

$$M_S^{\overline{\mathrm{MS}}} \sim M_S^{\mathrm{OS}} \quad : \quad \text{no log differences!}$$

Combination of FD and RGE result:

$$\Delta M_h^2 = (\Delta M_h^2)^{\text{RGE}}(X_t^{\overline{\text{MS}}}, M_S^{\overline{\text{MS}}}, \overline{m}_t) - (\Delta M_h^2)^{\text{FD,LL1,LL2}}(X_t^{\text{OS}}, M_S^{\text{OS}}, \overline{m}_t)$$

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

Technical aspect:

$$(\Delta M_h^2)^{\text{FD,LL1,LL2}}(X_t^{\text{OS}}, M_S^{\text{OS}}, \overline{m}_t)$$

$$:= (\Delta M_h^2)^{\text{FD,LL1,LL2}}(X_t^{\overline{\text{MS}}}, M_S^{\overline{\text{MS}}}, \overline{m}_t)\Big|_{X_t^{\overline{\text{MS}}} \to X_t^{\text{OS}}, M_S^{\overline{\text{MS}}} = M_S^{\text{OS}}}$$

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

⇒ most precise M_h prediction for large $m_{\tilde{t}}$ ⇒ FeynHiggs 2.10.0

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

Some example results

[*FeynHiggs 2.10.0*]

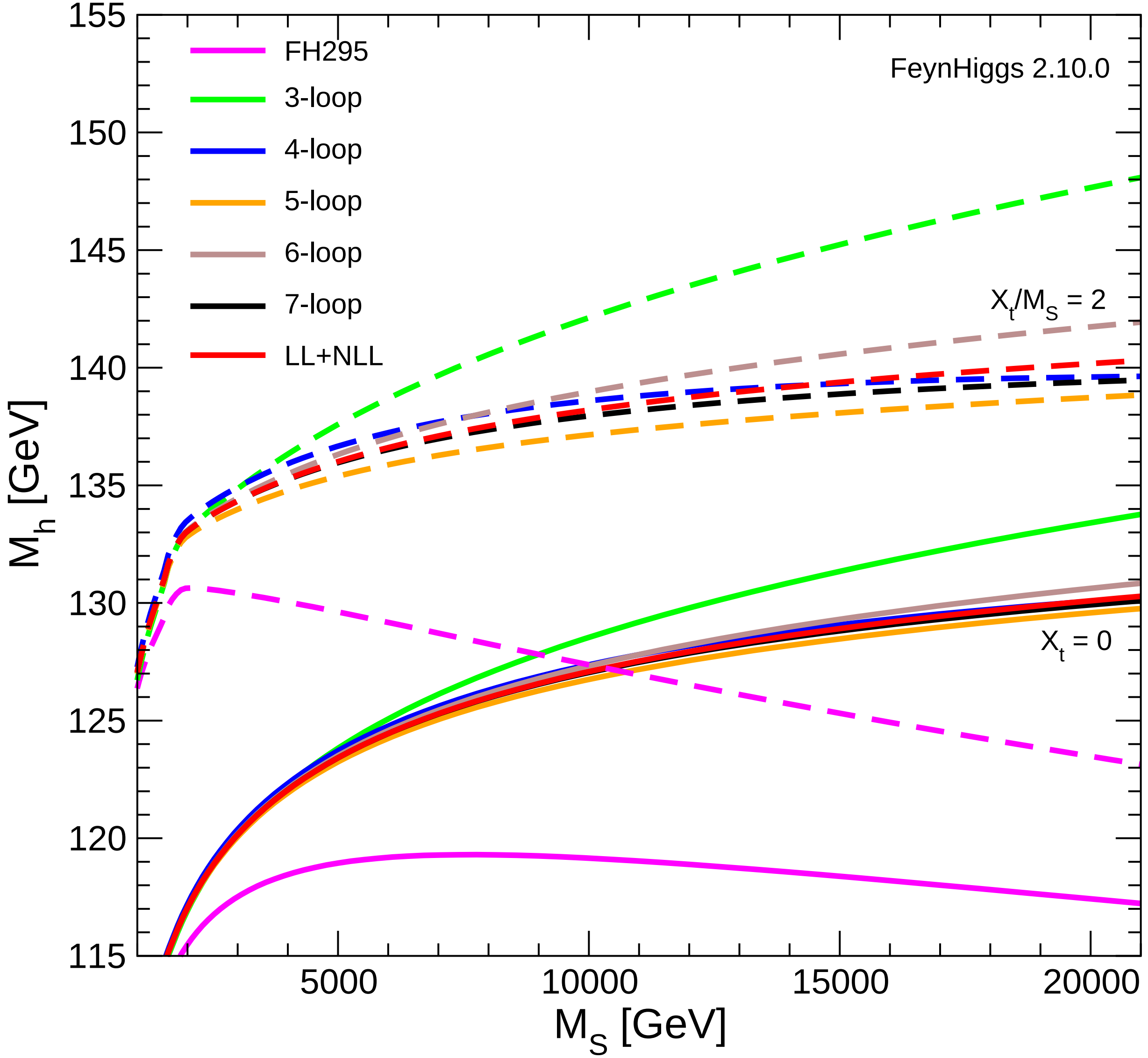
[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '13 - '15*]

Parameters:

$$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$
$$M_A = 1000 \text{ GeV}$$
$$\mu = 1000 \text{ GeV}$$
$$M_2 = 1000 \text{ GeV}$$
$$m_{\tilde{g}} = 1600 \text{ GeV}$$
$$\tan\beta = 10$$

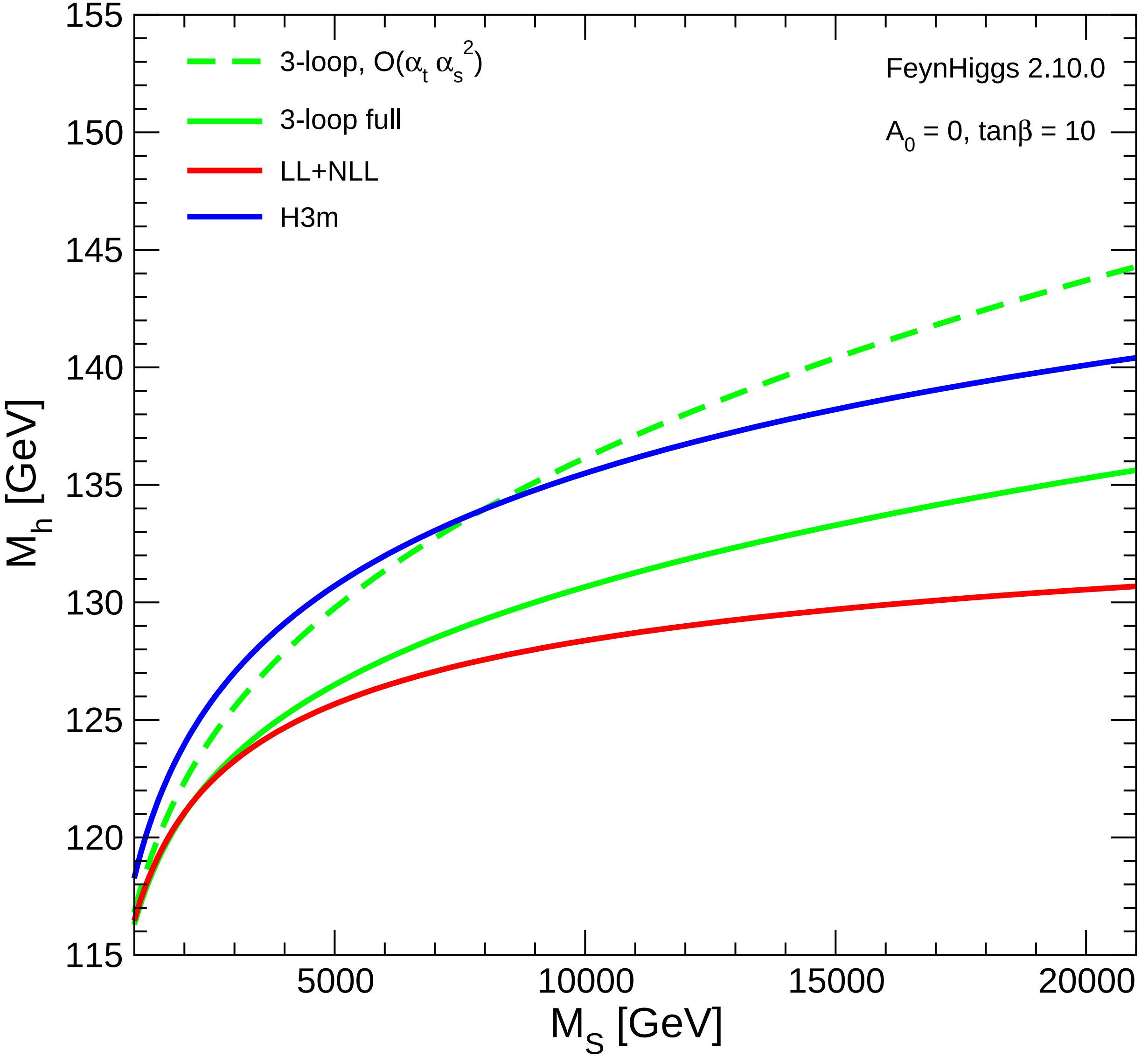
Vary M_S, X_t to analyze effects

$M_h(M_S)$ for various approximations: [*FeynHiggs 2.10.0*]



$\Rightarrow$ 3-loop good for $M_S \lesssim 2$ TeV, 7-loop: $\Delta \sim 1$ GeV for $M_S = 20$ TeV

$M_h(M_S)$ compared with H3m (2014): [*FeynHiggs 2.10.0*]

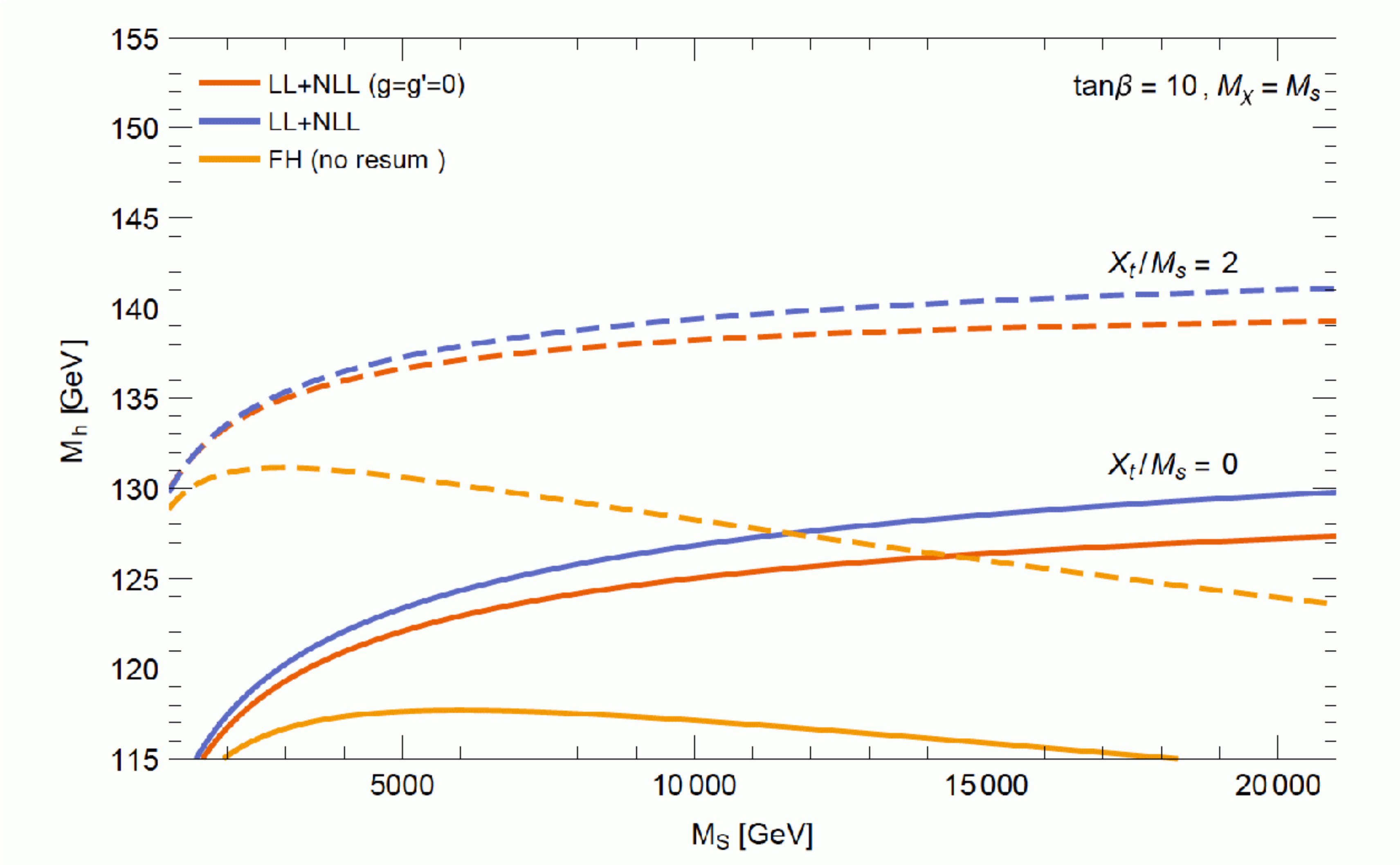


$\Rightarrow$ 3-loop $\mathcal{O}\left(\alpha_t^2\alpha_s, \alpha_t^3\right) \oplus$ beyond 3-loop important for precise M_h prediction!

Inclusion of further log-resummed results

[H. Bahl, W. Hollik '16 – PRELIMINARY]

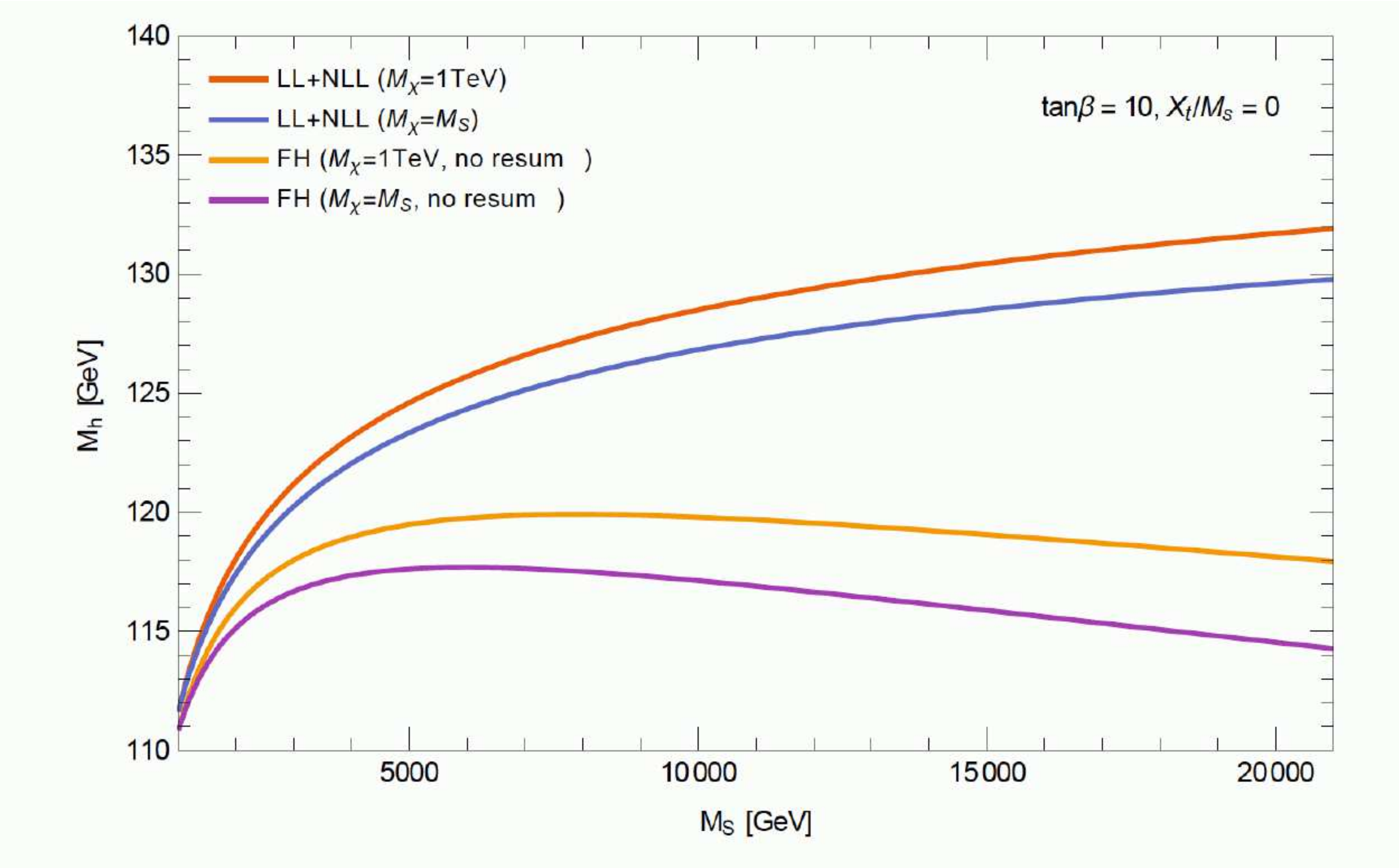
Inclusion of EW effects in RGE's:



Inclusion of further log-resummed results

[H. Bahl, W. Hollik '16 – PRELIMINARY]

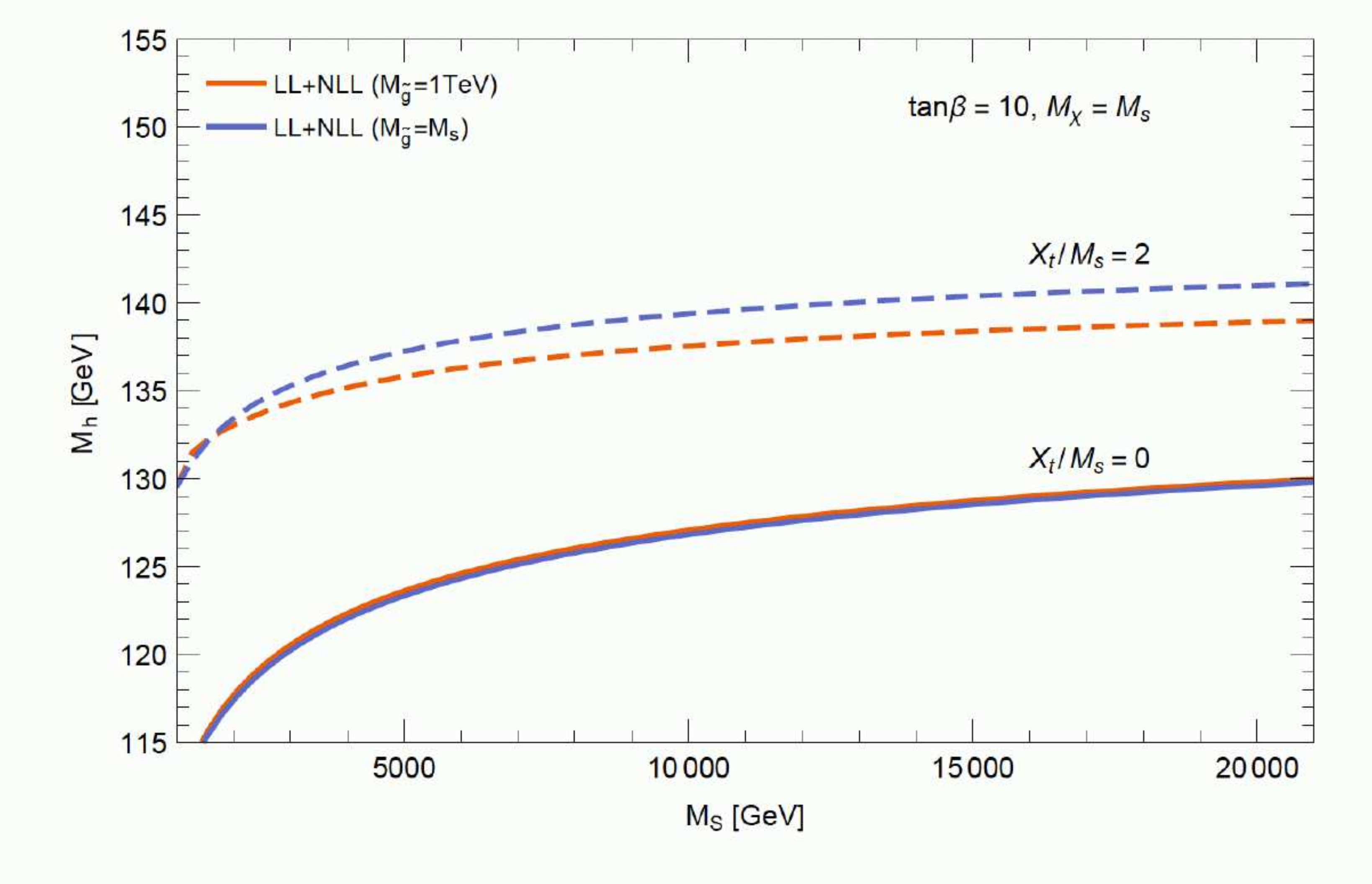
Inclusion of EWino mass scale in RGE's:



Inclusion of further log-resummed results

[H. Bahl, W. Hollik '16 – PRELIMINARY]

Inclusion of gluino mass scale in RGE's:



Future improvements/work in progress:

- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.
  $\Rightarrow$ already in, not fully tested

- "Two Higgs Doublet Model" below M_S
  $\Rightarrow$ work in progress

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

- ...

$\Rightarrow$ Loops & Legs 2018?! :-)

4. Applicability and uncertainties

1.) SUSY mass scales below ~ 1 TeV require full calculation

2.) Log resum. for $t/\tilde{t}$ (beyond 2L) at M_S

– effects at $M_S = 1$ TeV:

– at $M_S = 2$ TeV:

– at $M_S = 3$ TeV:

4. Applicability and uncertainties

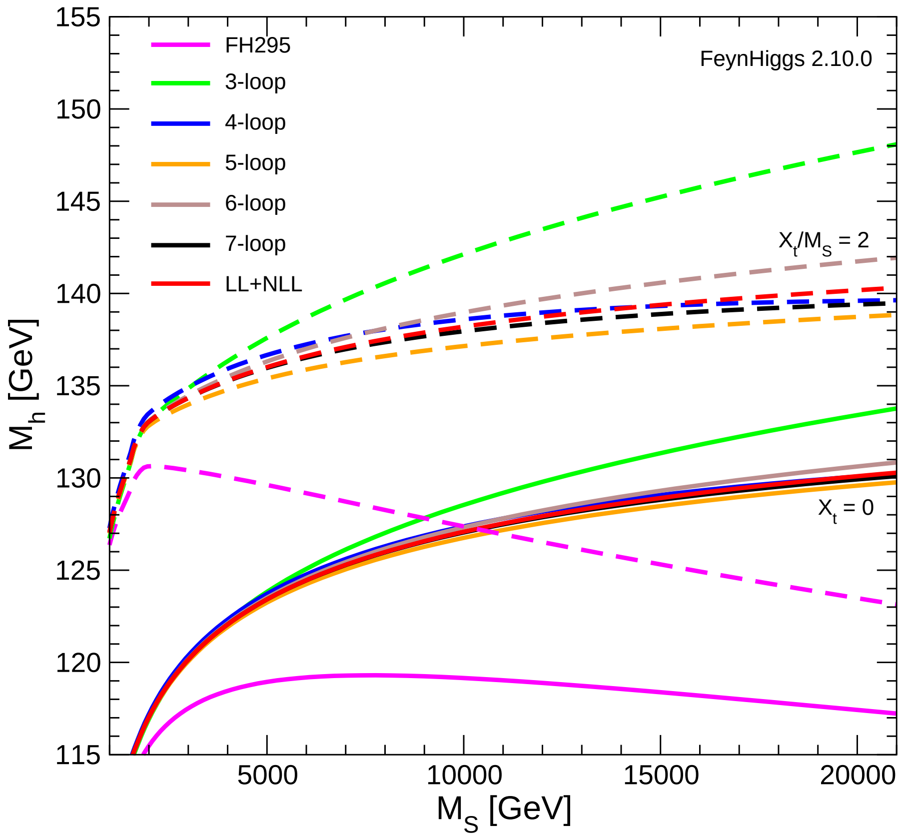
1.) SUSY mass scales below ~ 1 TeV require full calculation

2.) Log resum. for $t/\tilde{t}$ (beyond 2L) at M_S for $\Delta M_h^{\text{diagrammatic}} \sim 40$ GeV

– effects at $M_S = 1$ TeV: tiny

– at $M_S = 2$ TeV: $\Delta M_h^{\text{log-resum}} \sim 2$ GeV

– at $M_S = 3$ TeV: $\Delta M_h^{\text{log-resum}} \gtrsim 3$ GeV



$M_h(M_S)$ for various approximations:

[*FeynHiggs 2.10.0*]

magenta: no log-resum for $t/\tilde{t}$

red: log-resum at 2-loop level

($\rightarrow$ included in FH)

All other logs less relevant!

4. Applicability and uncertainties

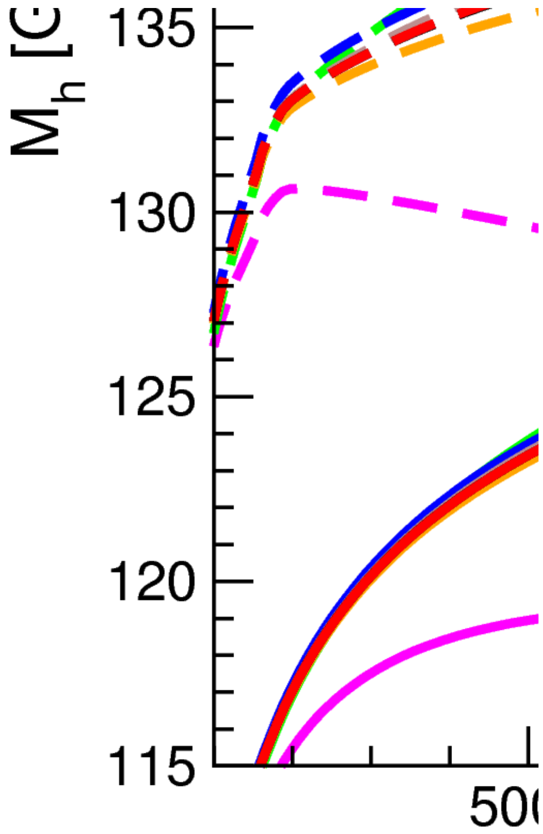
1.) SUSY mass scales below ~ 1 TeV require full calculation

2.) Log resum. for $t/\tilde{t}$ (beyond 2L) at M_S for $\Delta M_h^{\rm diagrammatic} \sim 40$ GeV

– effects at $M_S = 1$ TeV: tiny

– at $M_S = 2$ TeV: $\Delta M_h^{\rm log-resum} \sim 2$ GeV

– at $M_S = 3$ TeV: $\Delta M_h^{\rm log-resum} \gtrsim 3$ GeV



$M_h(M_S)$ for various approximations:

[*FeynHiggs 2.10.0*]

magenta: no log-resum for $t/\tilde{t}$

red: log-resum at 2-loop level

($\to$ included in FH)

All other logs less relevant!

4. Applicability and uncertainties

1.) SUSY mass scales below $\sim$ 1 TeV require full calculation

2.) Log resum. for $t/\tilde{t}$ (beyond 2L) at M_S for $\Delta M_h^{\text{diagrammatic}} \sim 40$ GeV

– effects at $M_S = 1$ TeV: tiny

– at $M_S = 2$ TeV: $\Delta M_h^{\text{log-resum}} \sim 2$ GeV

– at $M_S = 3$ TeV: $\Delta M_h^{\text{log-resum}} \gtrsim 3$ GeV

$\Rightarrow$ FeynHiggs gives most reliable predictions for SUSY mass scales below the level of $2-3$ TeV, where log contributions are not too large i.e. at the scales relevant/interesting for LHC physics (e.g. with light EW SUSY particles in the spectrum)

$\Rightarrow$ uncertainty estimate based on diagrammatic calculation reliable

$\Rightarrow$ EFT gives most reliable predictions for all SUSY mass scales in the multi-TeV range

$\Rightarrow$ intermediate region:
both types of calculations can be used for uncertainty estimate

arXiv.org > hep-ph > arXiv:1504.05200

Search or Article-id

High Energy Physics - Phenomenology

SusyHD: Higgs mass Determination in Supersymmetry

Javier Pardo Vega, Giovanni Villadoro

(Submitted on 20 Apr 2015)

We present the state-of-the-art of the effective field theory computation of the MSSM Higgs mass, improving the existing ones by including extra threshold corrections. We show that, with this approach, the theoretical uncertainty is within 1 GeV in most of the relevant parameter space. We confirm the smaller value of the Higgs mass found in the EFT computations, which implies a slightly heavier SUSY scale. We study the large tan(\beta) region, finding that sbottom thresholds might relax the upper bound on the scale of SUSY. We present SusyHD, a fast computer code that computes the Higgs mass and its uncertainty for any SUSY scale, from the TeV to the Planck scale, even in Split SUSY, both in the DRbar and in the on-shell schemes. Finally, we apply our results to derive bounds on some well motivated SUSY models, in particular we show how the value of the Higgs mass allows to determine the complete spectrum in minimal gauge mediation.

arXiv.org > hep-ph > arXiv:1504.05200

Search or Article-id

High Energy Physics - Phenomenology

SusyHD: Higgs mass Determination in Supersymmetry

Javier Pardo Vega, Giovanni Villadoro

(Submitted on 20 Apr 2015)

We present the state-of-the-art of the effective field theory computation of the MSSM Higgs mass, improving the existing ones by including extra threshold corrections. We show that, with this approach, the theoretical uncertainty is within 1 GeV in most of the relevant parameter space. We confirm the smaller value of the Higgs mass found in the EFT computations, which implies a slightly heavier SUSY scale. We study the large tan(\beta) region, finding that sbottom thresholds might relax the upper bound on the scale of SUSY. We present SusyHD, a fast computer code that computes the Higgs mass and its uncertainty for any SUSY scale, from the TeV to the Planck scale, even in Split SUSY, both in the DRbar and in the on-shell schemes. Finally, we apply our results to derive bounds on some well motivated SUSY models, in particular we show how the value of the Higgs mass allows to determine the complete spectrum in minimal gauge mediation.

arXiv.org > hep-ph > arXiv:1504.05200

Search or Article-id

High Energy Physics - Phenomenology

SusyHD: Higgs mass Determination in Supersymmetry

Javier Pardo Vega, Giovanni Villadoro

(Submitted on 20 Apr 2015)

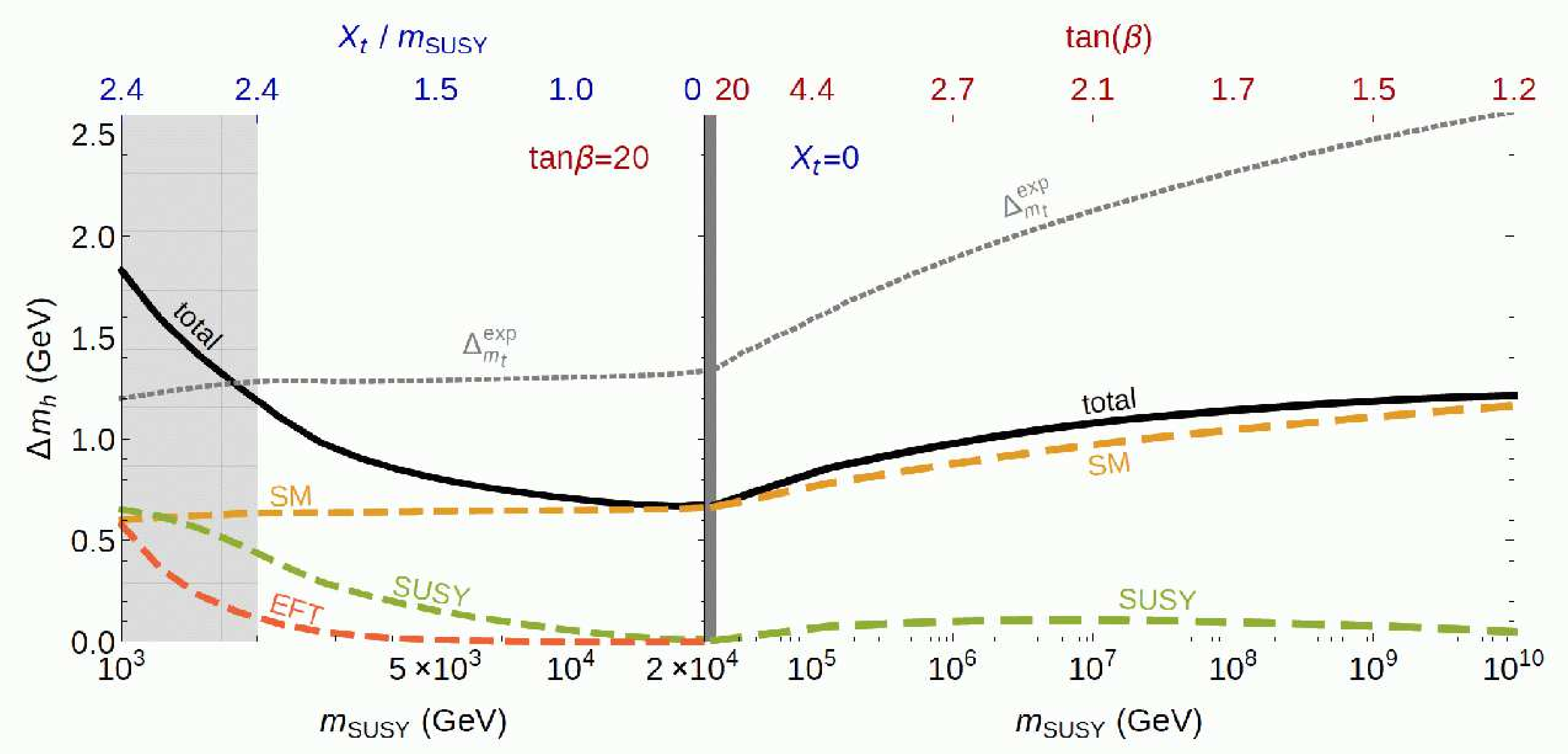
We present the state-of-the-art of the effective field theory computation of the MSSM Higgs mass, improving the existing ones by including extra threshold corrections. We show that, with this approach, the theoretical uncertainty is within 1 GeV in most of the relevant parameter space. We confirm the smaller value of the Higgs mass found in the EFT computations, which implies a slightly heavier SUSY scale. We study the large tan(\beta) region, finding that sbottom thresholds might relax the upper bound on the scale of SUSY. We present SusyHD, a fast computer code that computes the Higgs mass and its uncertainty for any SUSY scale, from the TeV to the Planck scale, even in Split SUSY, both in the DRbar and in the on-shell schemes. Finally, we apply our results to derive bounds on some well motivated SUSY models, in particular we show how the value of the Higgs mass allows to determine the complete spectrum in minimal gauge mediation.

Does this mean that now there exists a better prediction for M_h in the MSSM with substantially smaller theory uncertainty?

Claim by SusyHD authors:

[*J. Pardo Vega, G. Villadoro '15*]

$\Rightarrow$ Predictions of high-scale SUSY model valid down to ~ 1 TeV, theoretical uncertainty in prediction of SM-like Higgs: ~ 1 GeV
("the theoretical uncertainty is within 1 GeV in most of the relevant parameter space")



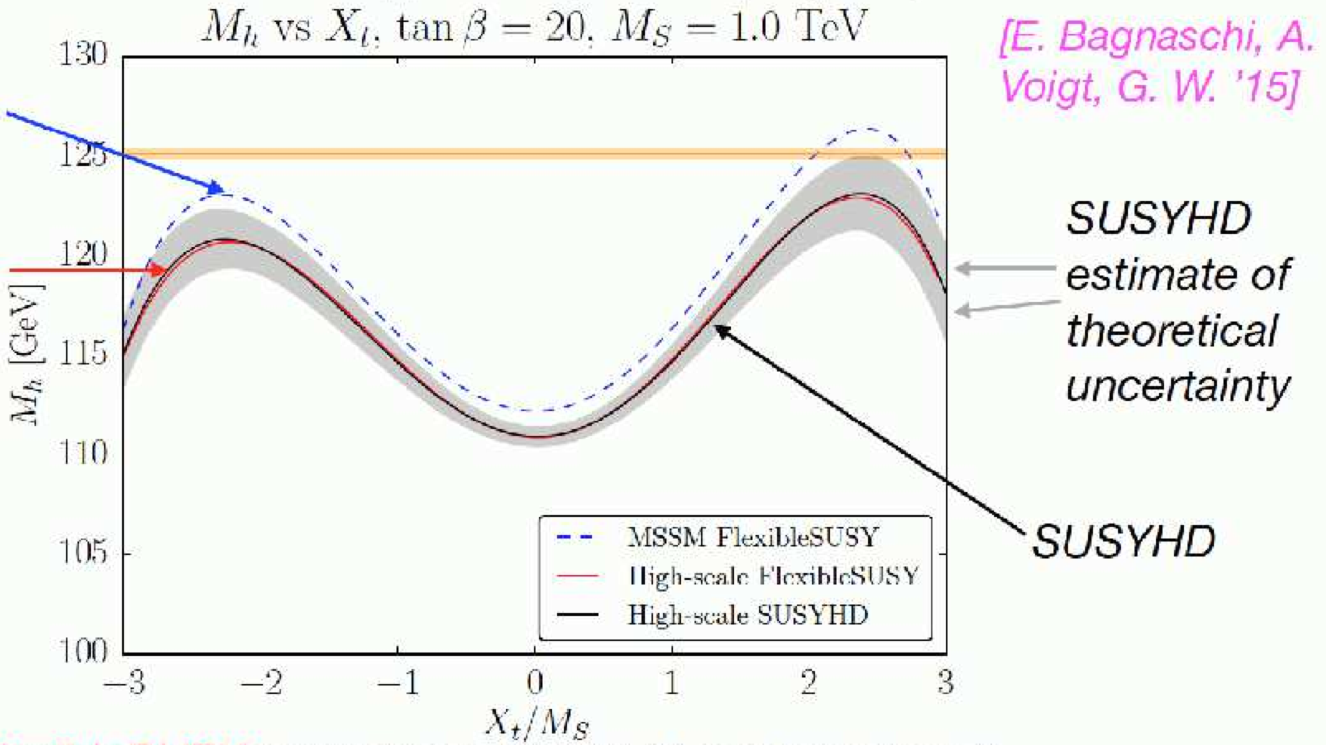
Uncertainty analysis (I)

[G. Weiglein, HDays15]

Comparison of full model and EFT result produced with the same code

MSSM *FlexibleSUSY*: full model calculation based on Pietro's 2-loop corrections in the DRbar scheme

High-scale *FlexibleSUSY*: EFT approach (work in progress)



⇒ High-scale *FlexibleSUSY* reproduces *SUSYHD* result very well
Sizable difference to full-model result (MSSM *FlexibleSUSY*), outside of estimate of theoretical uncertainty from *SUSYHD*

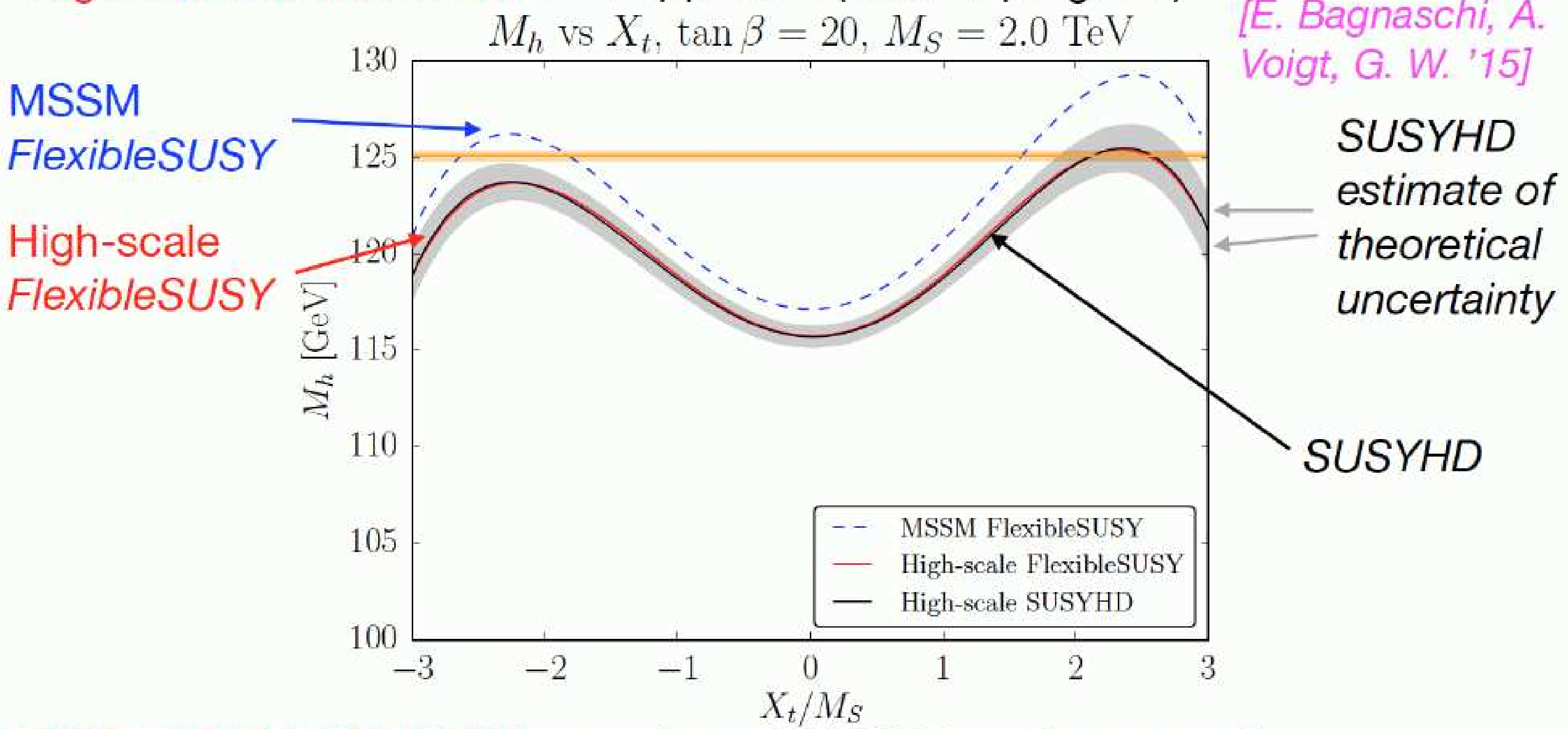
Off-shell effects, interference effects, 2HDM, MSSM and EFT, Georg Weiglein, Higgs Days at Santander 2015, Santander, 09 / 2015

Comparison of full model and EFT result produced with the same code

MSSM *FlexibleSUSY*: full model calculation based on Pietro's 2-loop corrections in the DRbar scheme

High-scale *FlexibleSUSY*: EFT approach (work in progress)

[E. Bagnaschi, A. Voigt, G. W. '15]



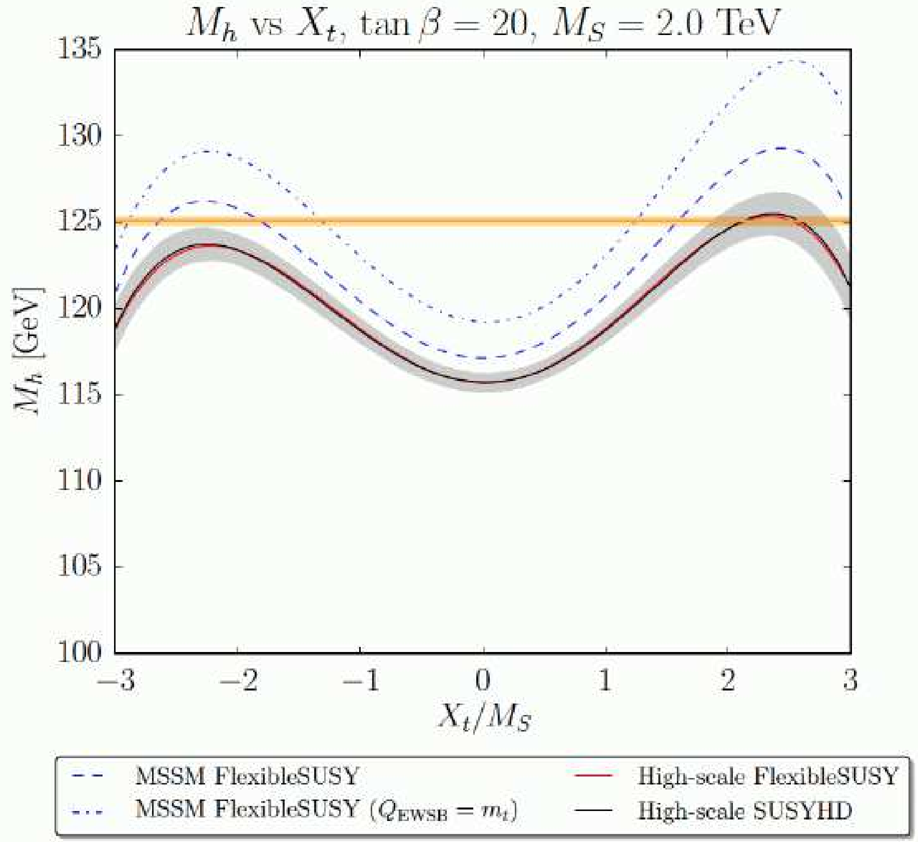
⇒ High-scale *FlexibleSUSY* reproduces *SUSYHD* result very well

Sizable difference to full-model result (MSSM *FlexibleSUSY*), outside of estimate of theoretical uncertainty from *SUSYHD*

Off-shell effects, interference effects, 2HDM, MSSM and EFT, Georg Weiglein, Higgs Days at Santander 2015, Santander, 09 / 2015

Different options for doing the full model calculation in the DRbar scheme

Option 1: Higgs mass computation at scale $Q = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
Option 2: First run parameters down to scale Q = m_t, compute Higgs mass there



FlexibleSUSY

[E. Bagnaschi, A. Voigt, G. W. '15]

⇒ Differences are of higher order, much larger than uncertainty estimated in *SUSYHD*

Off-shell effects, interference effects, 2HDM, MSSM and EFT, Georg Weiglein, Higgs Days at Santander 2015, Santander, 09 / 2015 25

Uncertainty estimates:

FeynHiggs (diagrammatic + log-resum): linear sum of

– missing 3-loop corrections in $t/\tilde{t}$ sector (change of m_t def.)
– missing 2-loop corrections in $b/\tilde{b}$ sector (Δ_b resummation)
– missing 2-loop corrections in EW sector (change of renormalizaion scale)
⇒ reliable estimate up to 2 – 3 TeV or higher

SusyHD (EFT): linear sum of

– SM unc.: missing corrections from matching at m_t and RGE evolution
– MSSM unc.: missing corrections from matching at M_S
– EFT unc.: effects not captured by EFT: $\mathcal{O}\left(v^2/M_S^2\right)$ (prefactor 1)

⇒ uncertainty estimate of ∼ 1 GeV
⇒ estimate for the multi-TeV range (no large scale diff.?!)
⇒ unclear to which low scales it can be extrapolated

Intermediate region:
⇒ both types of calculations can be used for uncertainty estimate

Conclusinos

- Prediction of M_h^{MSSM} needed at the $\mathcal{O}$ (500 MeV) level to match experimental uncertainty

- Feynman diagrammatic approach:

  Below $\sim$ 2 TeV full MSSM spectrum covered by diagrammatic calculation up to the 2-loop level

- EFT approach:

  Logarithmic contributions to M_h become larger at $M_S = 2 - 3$ TeV

  Largest logs from $t/\tilde{t}$ sector, but many scales possible

- FeynHiggs: diagrammatic (up to 2-loop)

  $\oplus$ resummed logs from $t/\tilde{t}$

  $\oplus$ more scales and EW effects!)

  $\Rightarrow$ reliable results (at least) up to $2 - 3$ TeV - and going up!

  $\Rightarrow$ reliable uncertainty estimate

- Much more work needed to reach the requiered accuracy!


Further Questions?

Some NMSSM Higgs theory (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

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

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

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

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

Some NMSSM Higgs theory (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} \\
S &= v_s + S_R + IS_I
\end{aligned}
$$

$$
\begin{aligned}
V = & (\tilde{m}_1^2 + |\not{\mu}\lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\not{\mu}\lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
& + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \\
& + |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})
\end{aligned}
$$

Free parameters:

$$\lambda,\ \kappa,\ A_\kappa,\ M_{H^\pm},\ \tan\beta,\ \mu_{\text{eff}} = \lambda v_s$$

Higgs spectrum:

$$\mathcal{CP}\text{–even} : h_1, h_2, h_3$$
$$\mathcal{CP}\text{–odd} : a_1, a_2$$
$$\text{charged} : H^+, H^-$$
$$\text{Goldstones} : G^0, G^+, G^-$$

Neutralinos:

$$\mu \to \mu_{\text{eff}}$$

compared to the MSSM: one singlino more

$$\to \tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4, \tilde{\chi}^0_5$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM} : M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM} : \text{"} M_A^2 \text{"} = \mu_{\text{eff}} B_{\text{eff}}(\tan\beta + \cot\beta)$$

with $B_{\text{eff}} = A_\lambda + \kappa\, s,\ \mu_{\text{eff}} = \lambda\, s$ $\Rightarrow$ one very light a_1

Mass of the charged Higgs:

$$\text{MSSM} : M_{H^\pm}^2 = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM} : M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2 \right)$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM}: M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM}: \text{"}M_A^2\text{"} = \mu_{\text{eff}} B_{\text{eff}}(\tan\beta + \cot\beta)$$

with $B_{\text{eff}} = A_\lambda + \kappa\, s,\ \mu_{\text{eff}} = \lambda\, s$ $\Rightarrow$ one very light a_1

Mass of the charged Higgs:

$$\text{MSSM}: M^2_{H^\pm} = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM}: M^2_{H^\pm} = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2\right)$$

$\Rightarrow M_{h_1}^{\text{MSSM,tree}} \leq M_{h_1}^{\text{NMSSM,tree}}$, one light a_1, $M_{H^\pm}^{\text{MSSM,tree}} \geq M_{H^\pm}^{\text{NMSSM,tree}}$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM}: M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM}: \text{"}M_A^2\text{"} = \mu_{\text{eff}} B_{\text{eff}}(\tan\beta + \cot\beta)$$

with $B_{\text{eff}} = A_\lambda + \kappa\, s,\ \mu_{\text{eff}} = \lambda\, s$ $\Rightarrow$ one very light a_1

Mass of the charged Higgs:

$$\text{MSSM}: M^2_{H^\pm} = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM}: M^2_{H^\pm} = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2\right)$$

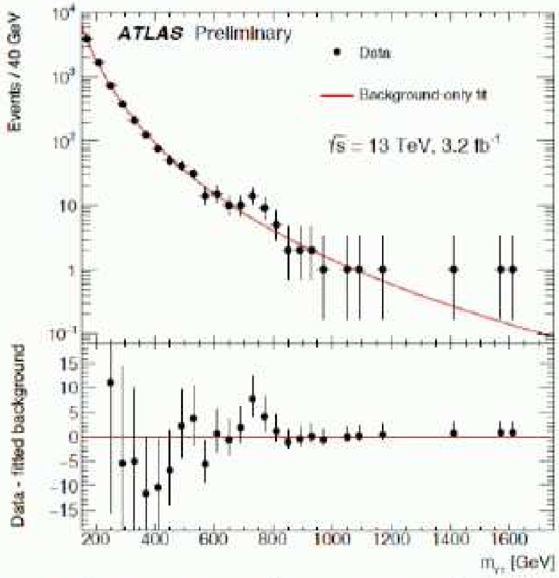
$\Rightarrow$ can accomodate $gg \to \phi_{750} \to \gamma\gamma$ *[1602.07691]*

The 750 GeV diphoton “excess” and SUSY

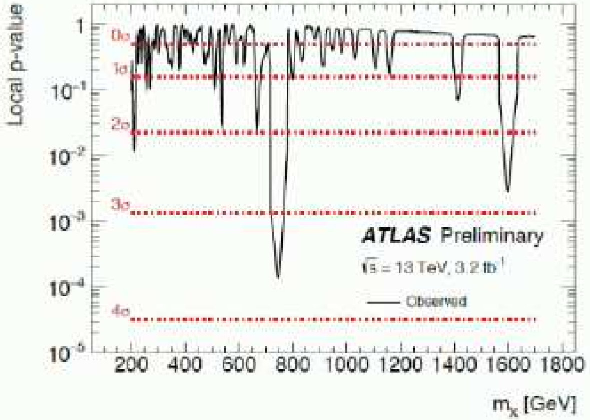
ATLAS:

Search for a **Two Photons Resonance** (II)

Results: Events with mass in excess of 200 GeV are included in **unbinned fit**



- **In the NWA search**, an excess of **3.6σ** (local) is observed at a mass hypothesis of minimal p_0 of 747 GeV
- Taking a LEE in a mass range (fixed before unblinding) **of 200 GeV to 1.8 TeV** the global significance of the excess is **1.9σ**



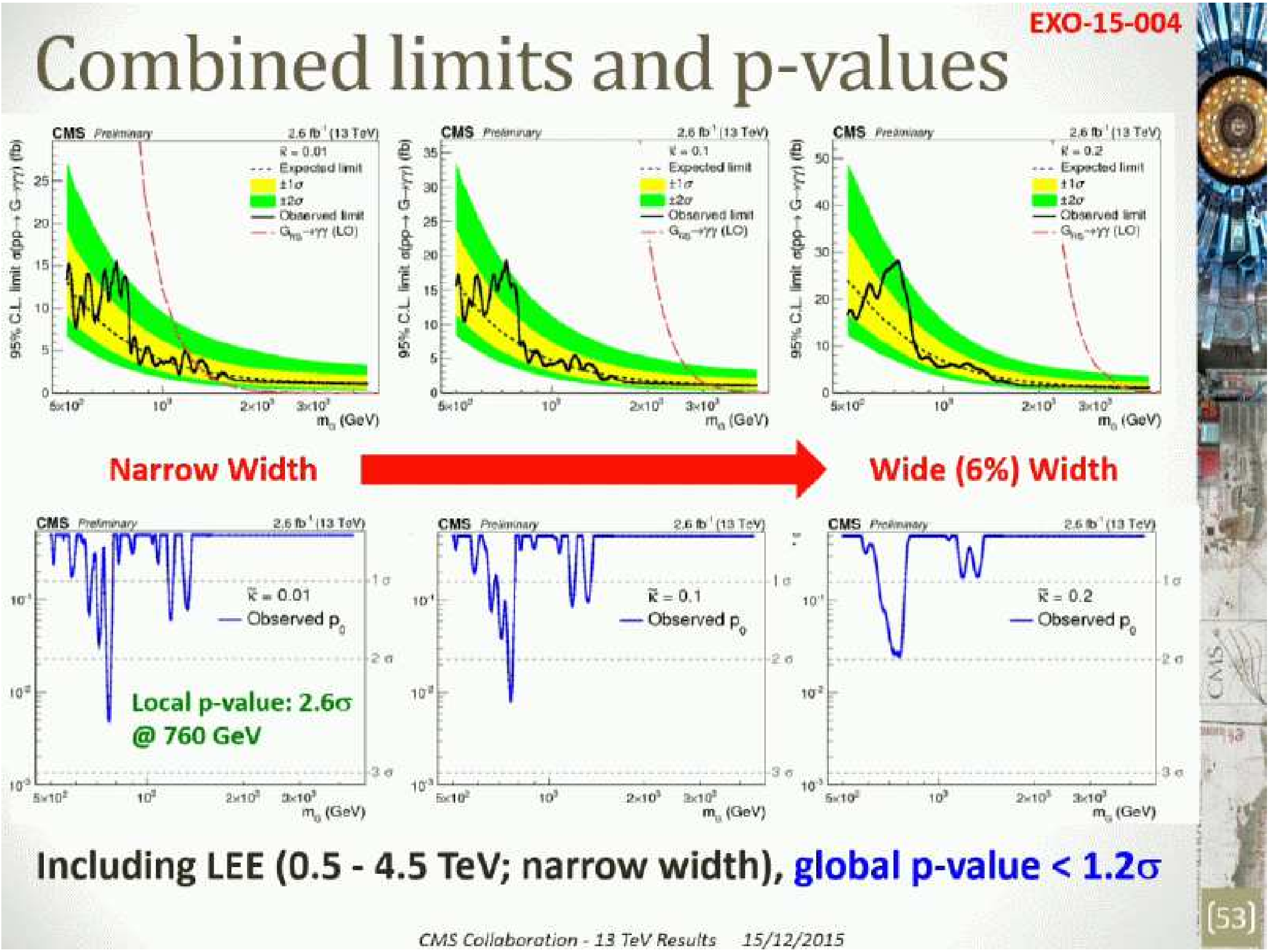
In the NWA fit the resolution uncertainty is profiled in the NWA fit and is pulled by 1.2σ

The data was then fit under a **LW hypothesis** yielding a width of approximately 45 GeV (Approx. 6% of the best fit mass of approximately 750 GeV)

- As expected the local significance increases to **3.9σ**
- Taking into account a LEE in mass and width of up to **10%** of the mass hypothesis of **2.3σ** (Note: upper range in resolution fixed after unblinding)

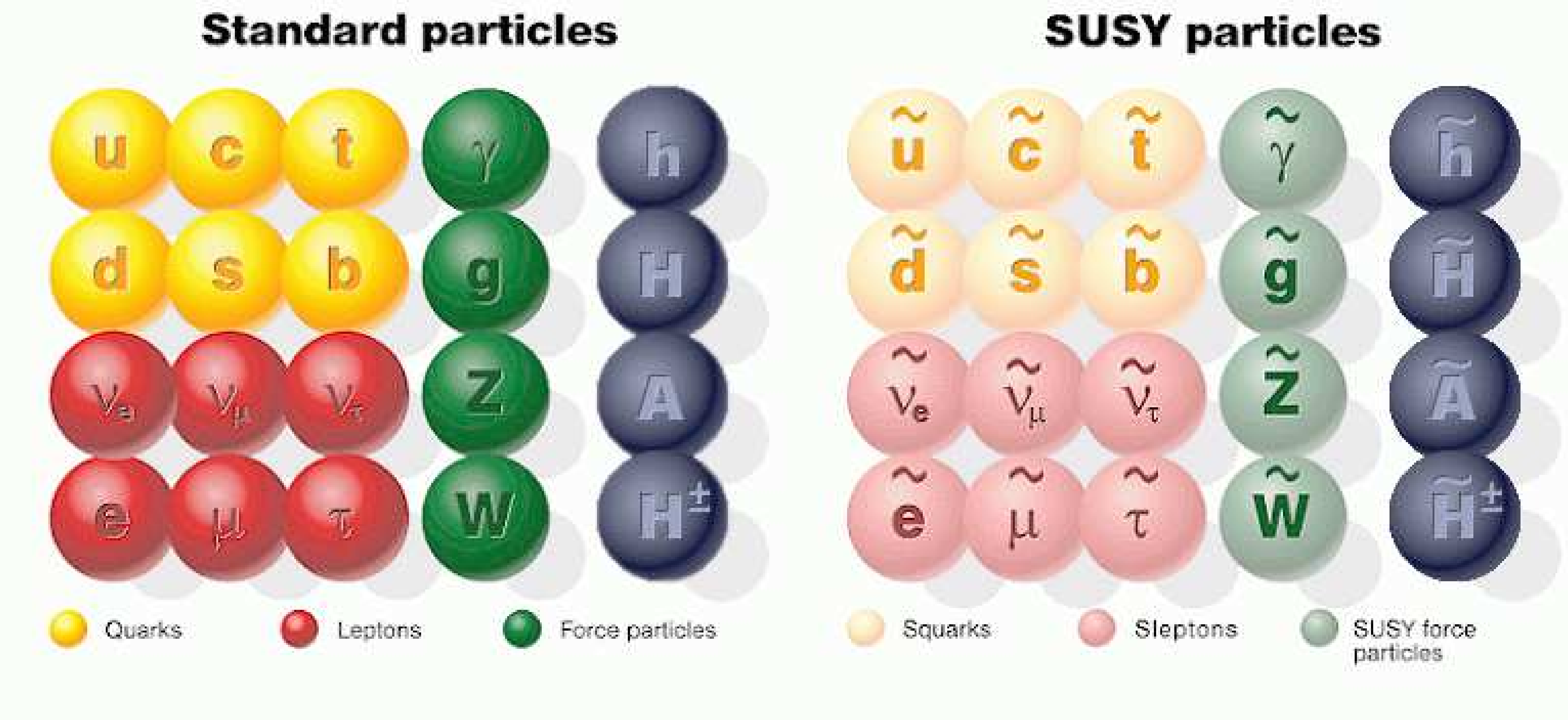
⇒ local (global) significance: 3.6(1.9)σ

CMS:

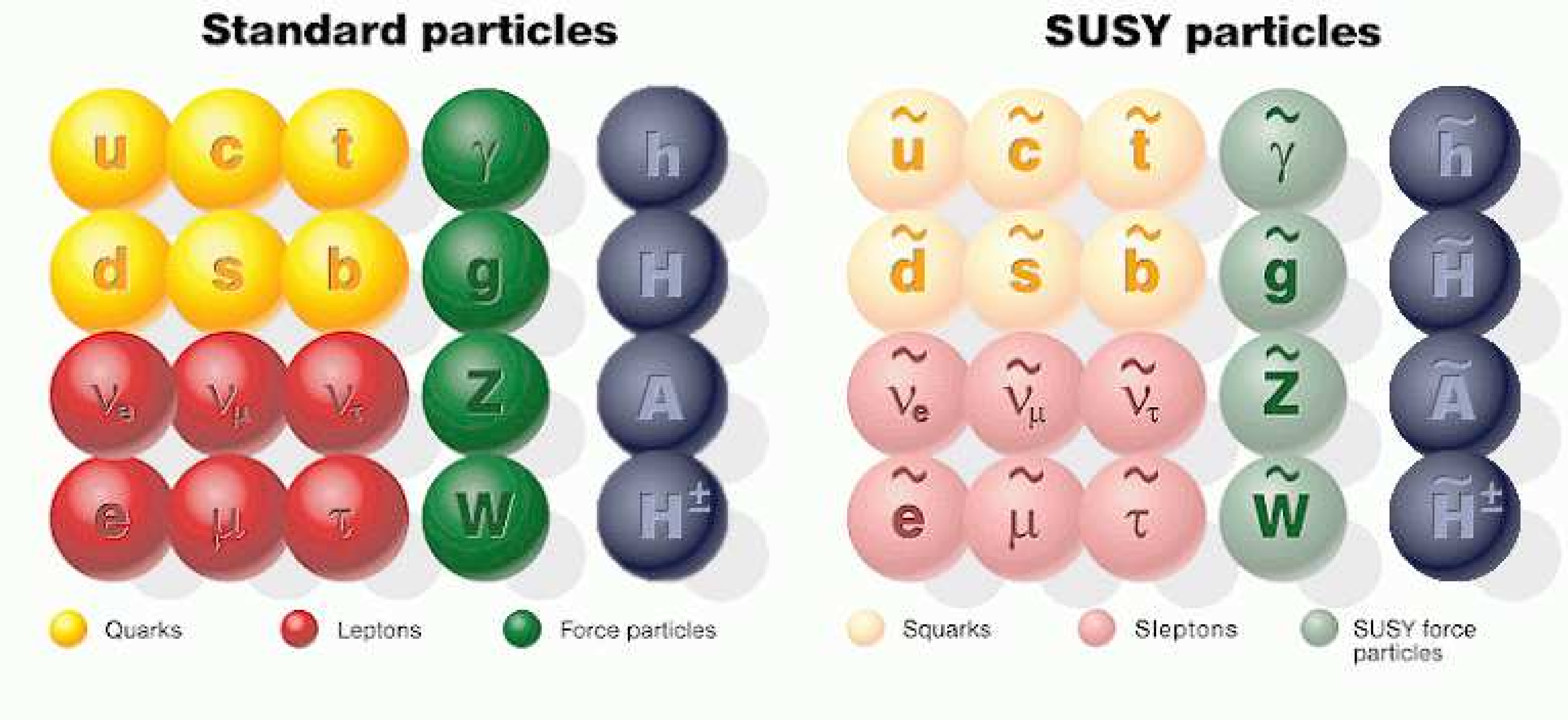


⇒ local (global) significance: 2.6(1.2)σ

What about the MSSM?

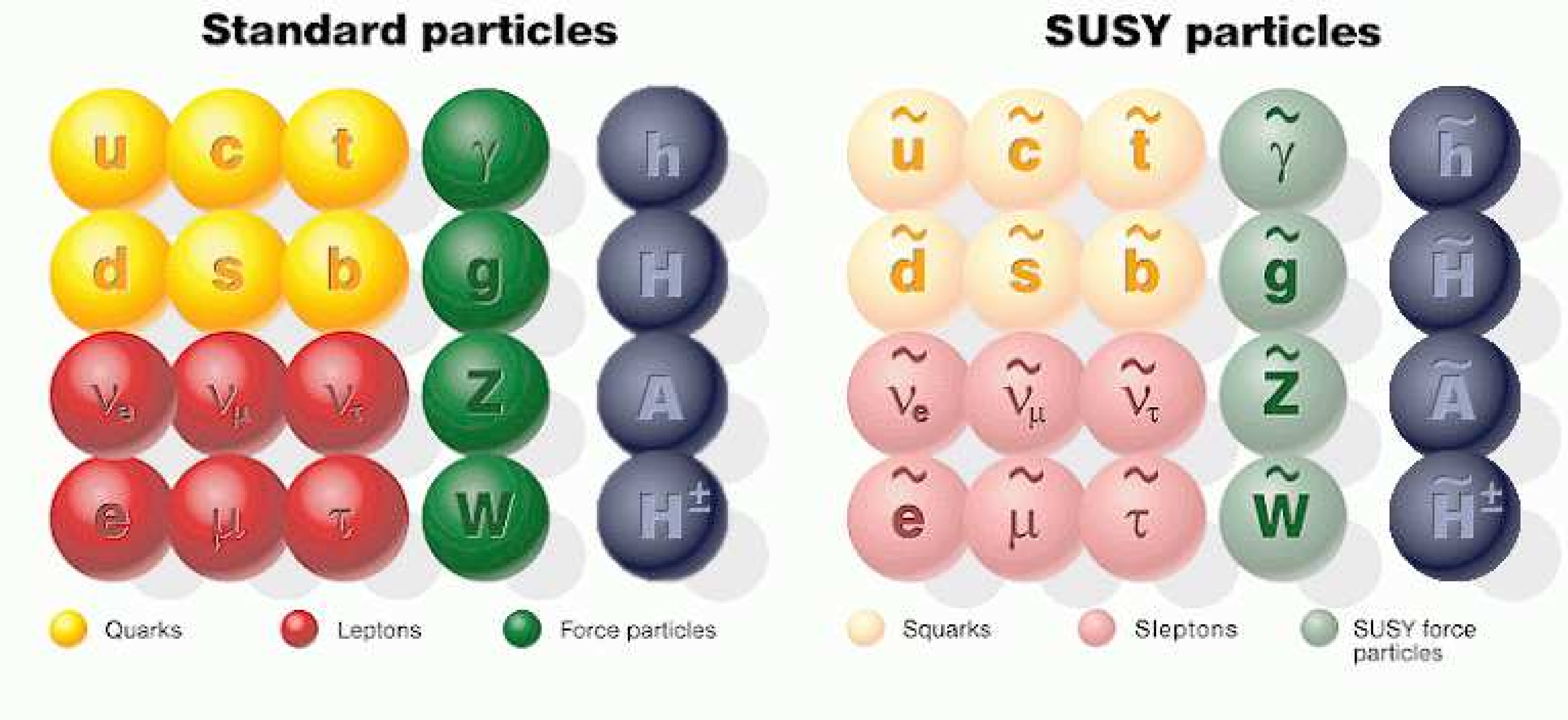


What about the MSSM?



Problem: $gg \to \phi_{750} \to \gamma\gamma$ cannot be accomodated! (Rates too low!)

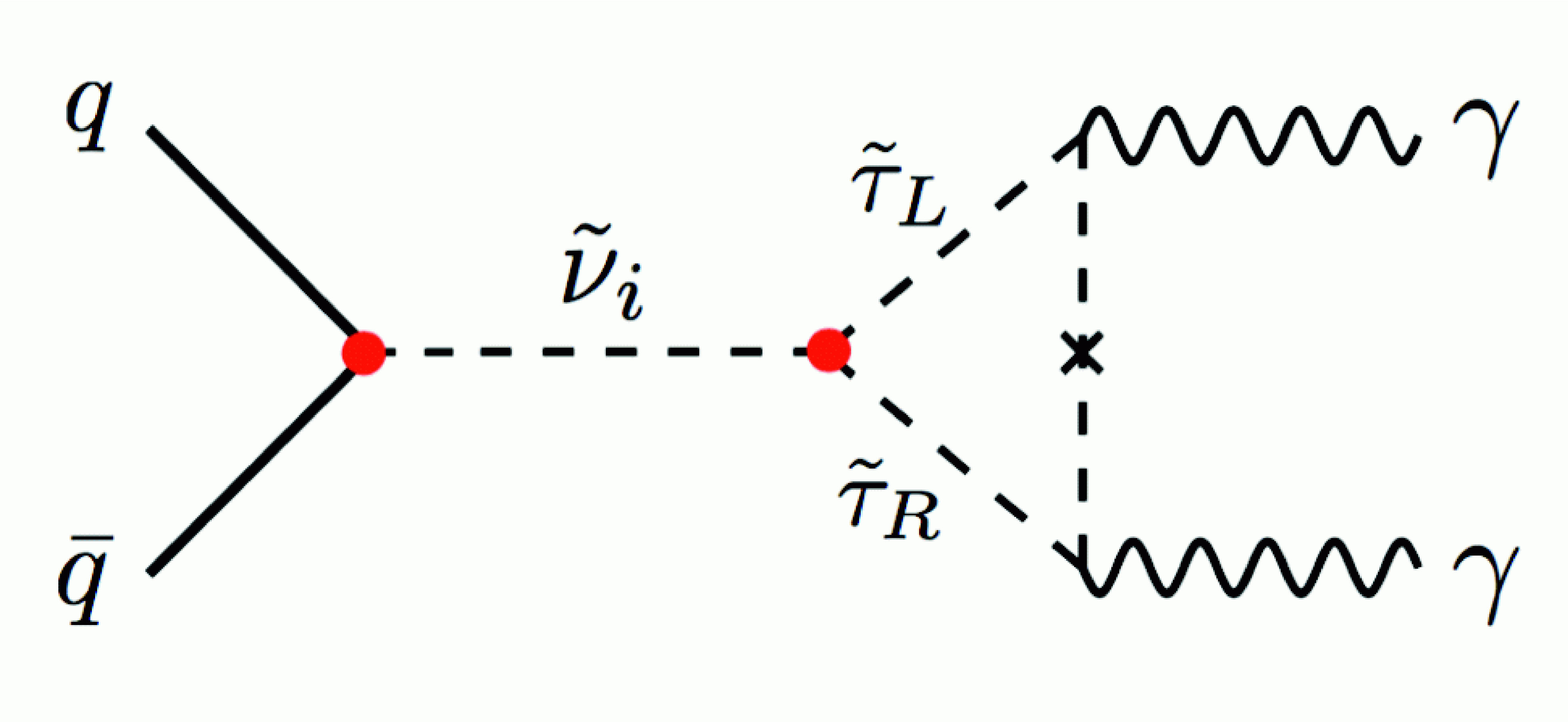
What about the MSSM?



Problem: $gg \to \phi_{750} \to \gamma\gamma$ cannot be accomodated! (Rates too low!)

$\Rightarrow$ Extensions of the MSSM can accomodate it!

Check the RPV-MSSM!



How to accomodate $gg \to \phi_{750} \to \gamma\gamma$ in SUSY II:

Check the MSSM with low SUSY-breaking scale: the Sgoldstino scenario

$\Rightarrow$ SUSY breaking at "low energies" via $\langle F \rangle$

$\to$ gives rise to a massless fermion: goldstino

$\to$ "eaten up" by the gravitino

$\to$ scalar SUSY partner: Sgoldstino with $\mathcal{CP}$-even and -odd component!
Always exist, but "normally" at high energy with no implications for phenomenology

Here: choose $m_S \sim 750$ GeV $\Rightarrow m_{3/2} < 1$ MeV (LSP)

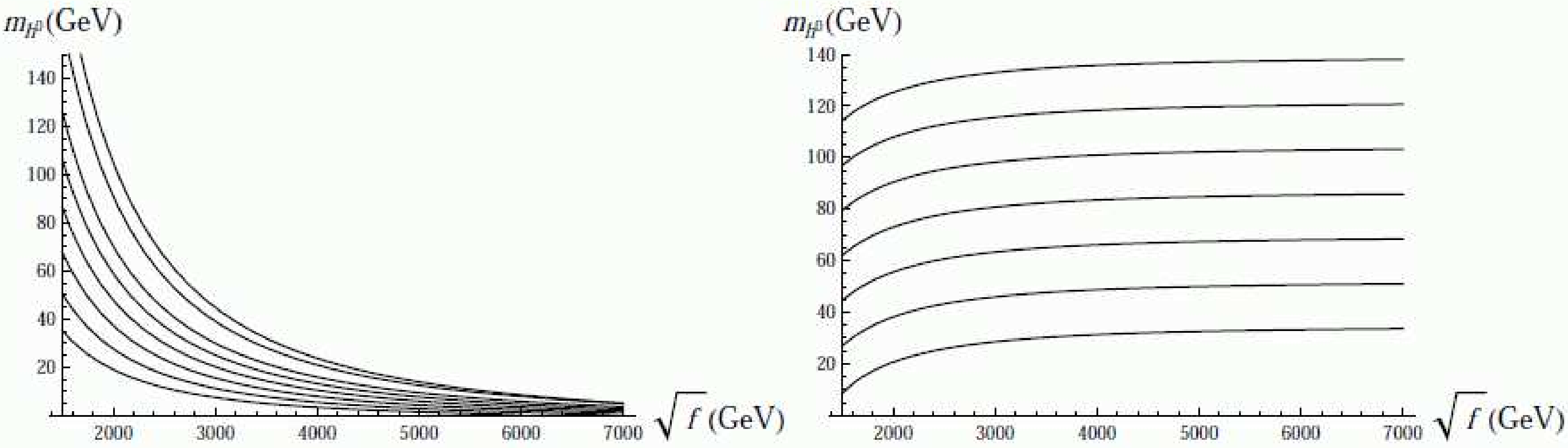
$\Rightarrow$ strong Sgoldstino couplings to all gauge bosons $\Rightarrow$ rate ok

$\Rightarrow$ "similar" to NMSSM, but "more strongly interacting"

How to accomodate $gg \to \phi_{750} \to \gamma\gamma$ in SUSY II:

Check the MSSM with low SUSY-breaking scale: the Sgoldstino scenario

Tree-level Higgs mass: [*1111.3368*]



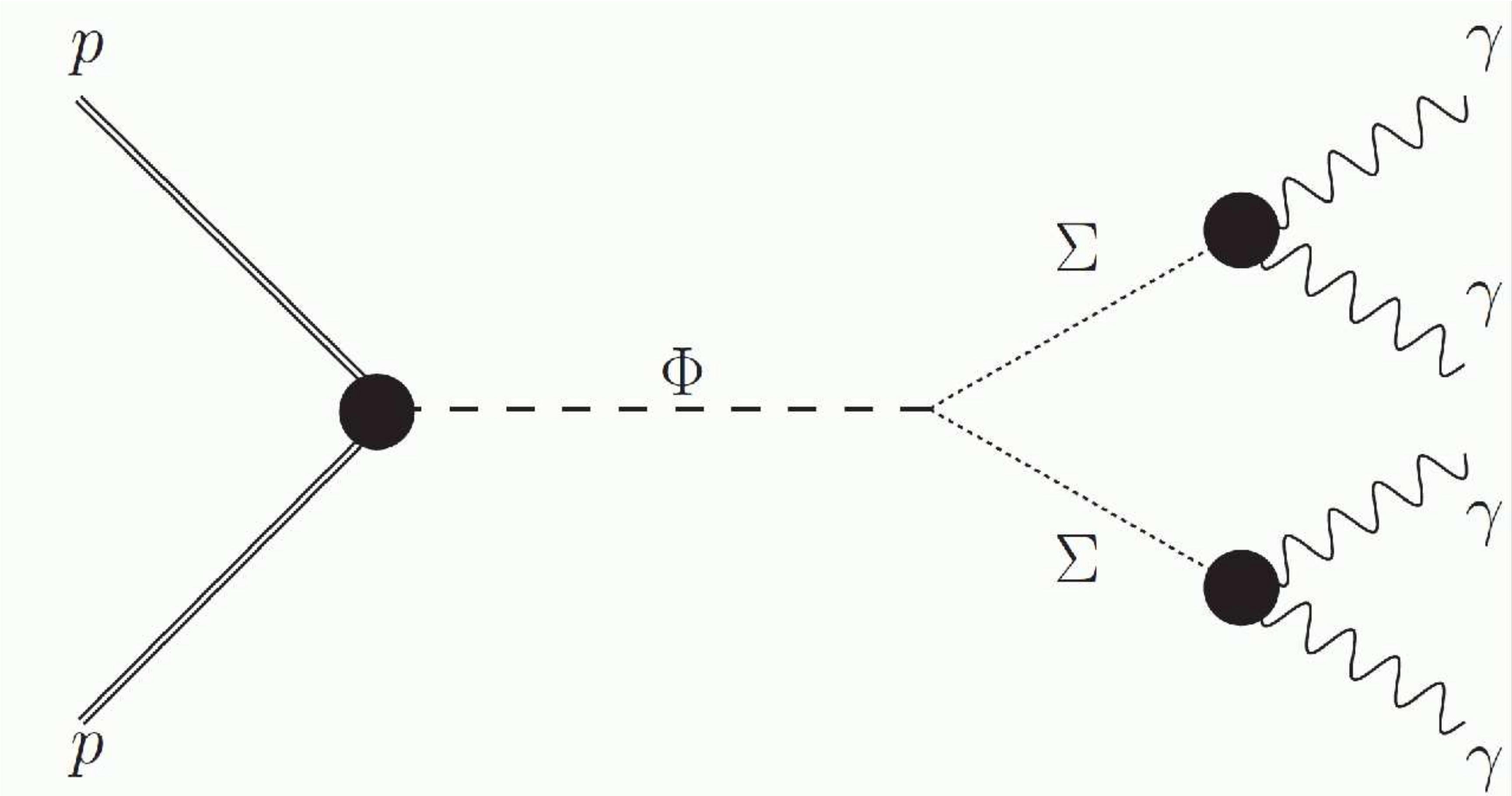
(a) m_{h^0} in function of $\sqrt{f}$, varying μ. (b) m_{h^0} in function of $\sqrt{f}$, varying c_B.

Figure 2: In these figures the tree level mass of the lightest CP-even neutral Higgs m_{h^0} is plotted as a function of $\sqrt{f}$. In both figures we have fixed $\tan\beta = 1$ and $m_x = 1.8$ TeV. In (a) $c_B = 0.01$ and μ increases upwards from 500 GeV to 1000 GeV (in steps of 100 GeV) and with 1.2 TeV and 1.5 TeV corresponding to the two upper curves. In (b) $\mu = 400$ GeV and c_B increases upwards from 0.2 to 0.8 (in steps of 0.1).

How to accomodate $gg \to \phi_{750} \to \gamma\gamma$ in SUSY III:

[*F. Domingo, S.H., J.S. Kim, K. Rolbiecki '16, 1602.07691*] similar: [*1602.03344*]

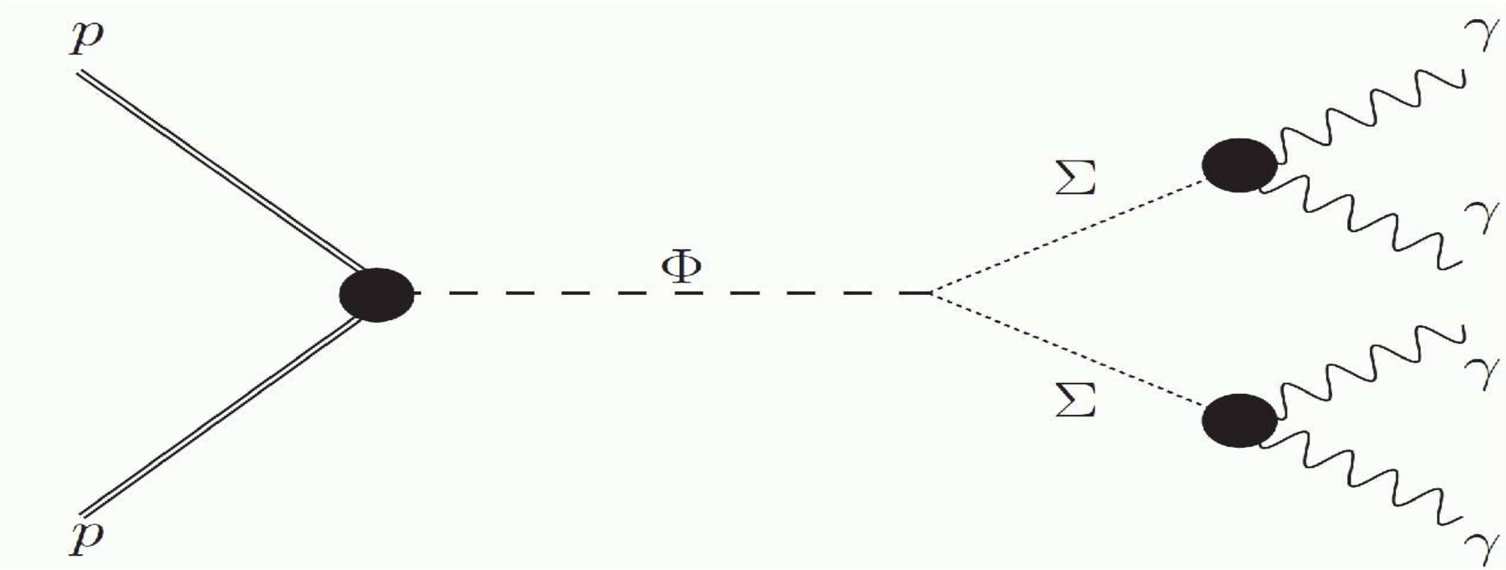
Check the NMSSM!



NMSSM: MSSM + Higgs singlet

Higgs content: 3 $\mathcal{CP}$-even: H_1, H_2, H_3, 2 $\mathcal{CP}$-odd: A_1, A_2, 2 charged: $H^\pm$

Characteristics of this NMSSM scenario:



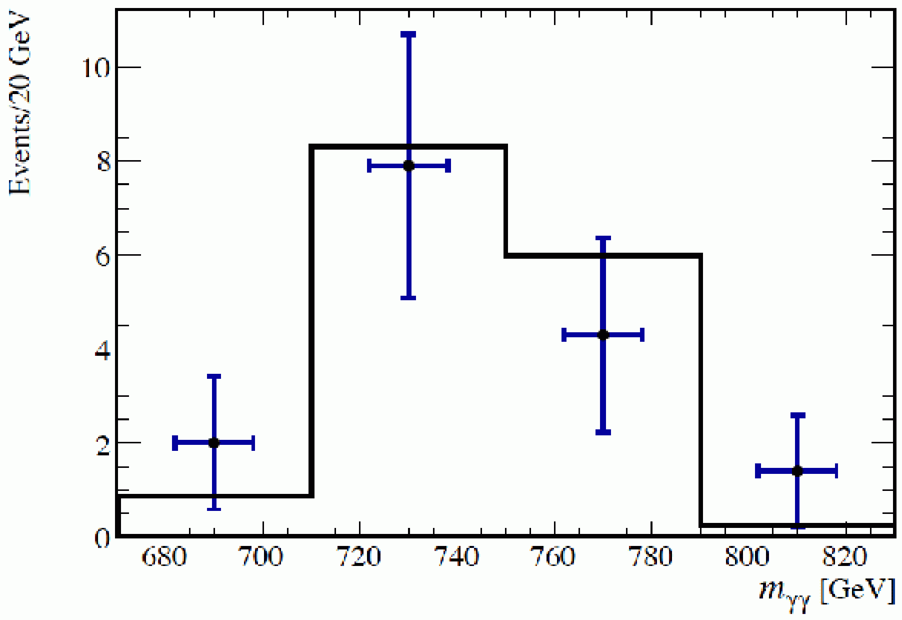
H_1: SM-like Higgs boson at $\sim$ 125 GeV

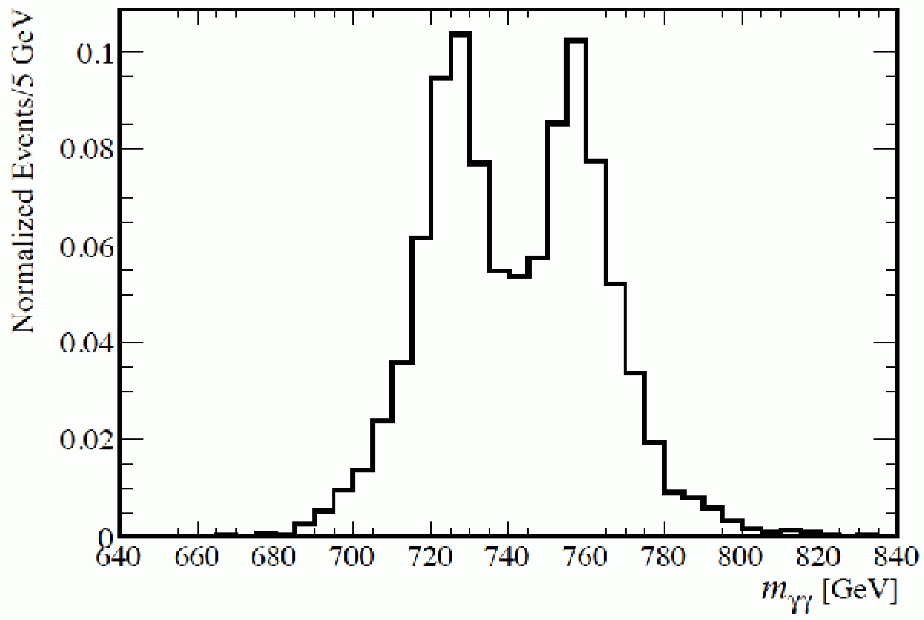
Φ: H_2 or H_3, mixed $\mathcal{CP}$-even singlet/doublet Higgses at $\sim$ 750 GeV
production via $gg \to H_{2,3}$ or $b\bar{b} \to b\bar{b}H_{2,3}$
possible mass difference of $\mathcal{O}$(20 GeV) can mimic large width

Σ : A_1 at $\sim$ 135 MeV
strong mixing with π^0 $\Rightarrow$ strong decay to $A_1 \to \gamma\gamma$
$\Rightarrow$ highly collimated $\gamma\gamma$ $\Rightarrow$ appears as one photon in the ECAL
stongly suppressed deacy $H_1 \to A_1 A_1$ to keep H_1 SM-like

A_2, H^+, H^-: masses at $\sim$ 750 GeV, but not relevant here

H_2 and H_3 appear as one resonance?





Left: our scenario as it appears in the ATLAS analysis (bin size 40 GeV)
blue crosses: ATLAS data

Right: (hypothetical) future bin size of 5 GeV
$\Rightarrow$ two peak structure! $\Rightarrow$ clear prediction for future analyses!

For the experts: the preferred NMSSM parameter space:

- $M_A = \frac{2\lambda v_s}{\sin 2\beta} \simeq 750$ GeV
- $\kappa \simeq \frac{\lambda}{2\sin 2\beta}$
- $\frac{0.4\tan\beta}{1+\tan^2\beta} \lesssim \lambda \lesssim \frac{2\sqrt{2}\tan\beta}{\sqrt{1+18\tan^2\beta+\tan^4\beta}}$
- $\mu \sim M_A \sin 2\beta$, 100 GeV $\lesssim \mu \lesssim$ 500 GeV
- $5 \lesssim \tan\beta \lesssim 15$
- $A_\kappa \lesssim \mathcal{O}(0.1)$ GeV
- $A_\lambda \ll v$
- other SUSY masses, mixings: free to avoid other constraints

Parameter "choice" places the scenario in the approximate R-symmetry limit of the NMSSM

$\Rightarrow$ A_1 thus appears as the pseudo-Goldstone boson of this R-symmetry

How to test our scenario:

- Two peak structure of H_2 and H_3 can be resolved
- Enhanced photon $\to$ electron-jet conversion due to four γ (instead of 2 γ in other explanations)
- No (relevant) decay of heavy Higgs bosons to WW or ZZ
- $H_2, H_3, A_2 \to \tau^+\tau^-$ searches at HL-LHC
- Relatively light higgsinos (μ small) $\Rightarrow$ discovery of $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm$

How to test our scenario:

- Two peak structure of H_2 and H_3 can be resolved
- Enhanced photon $\to$ electron-jet conversion due to four γ (instead of 2 γ in other explanations)
- No (relevant) decay of heavy Higgs bosons to WW or ZZ
- $H_2, H_3, A_2 \to \tau^+\tau^-$ searches at HL-LHC
- Relatively light higgsinos (μ small) $\Rightarrow$ discovery of $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm$

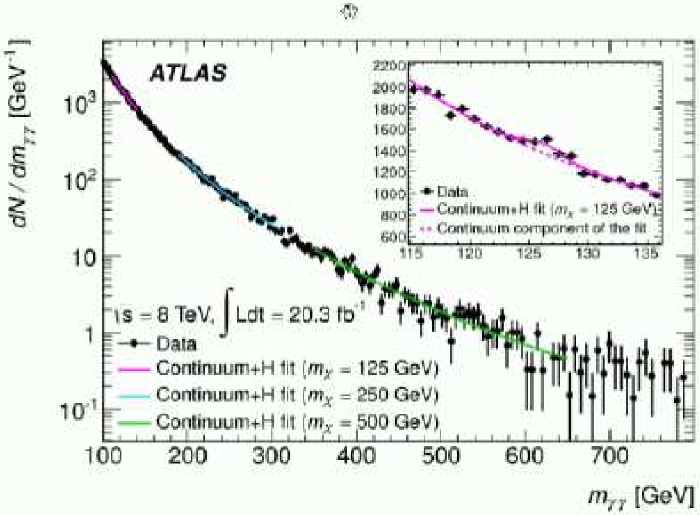
$\Rightarrow$ Our NMSSM scenario is

– in agreement with the "excess" and all other constraits
– clearly distinguishable from other explanations
– makes clear and testable predictions for future analyses

Why I am very sceptical:

ATLAS: compatible with Run I?

Search for a two Photons resonance



Run 1 Search for a high mass Higgs boson up to 600 GeV, no significant excess reported

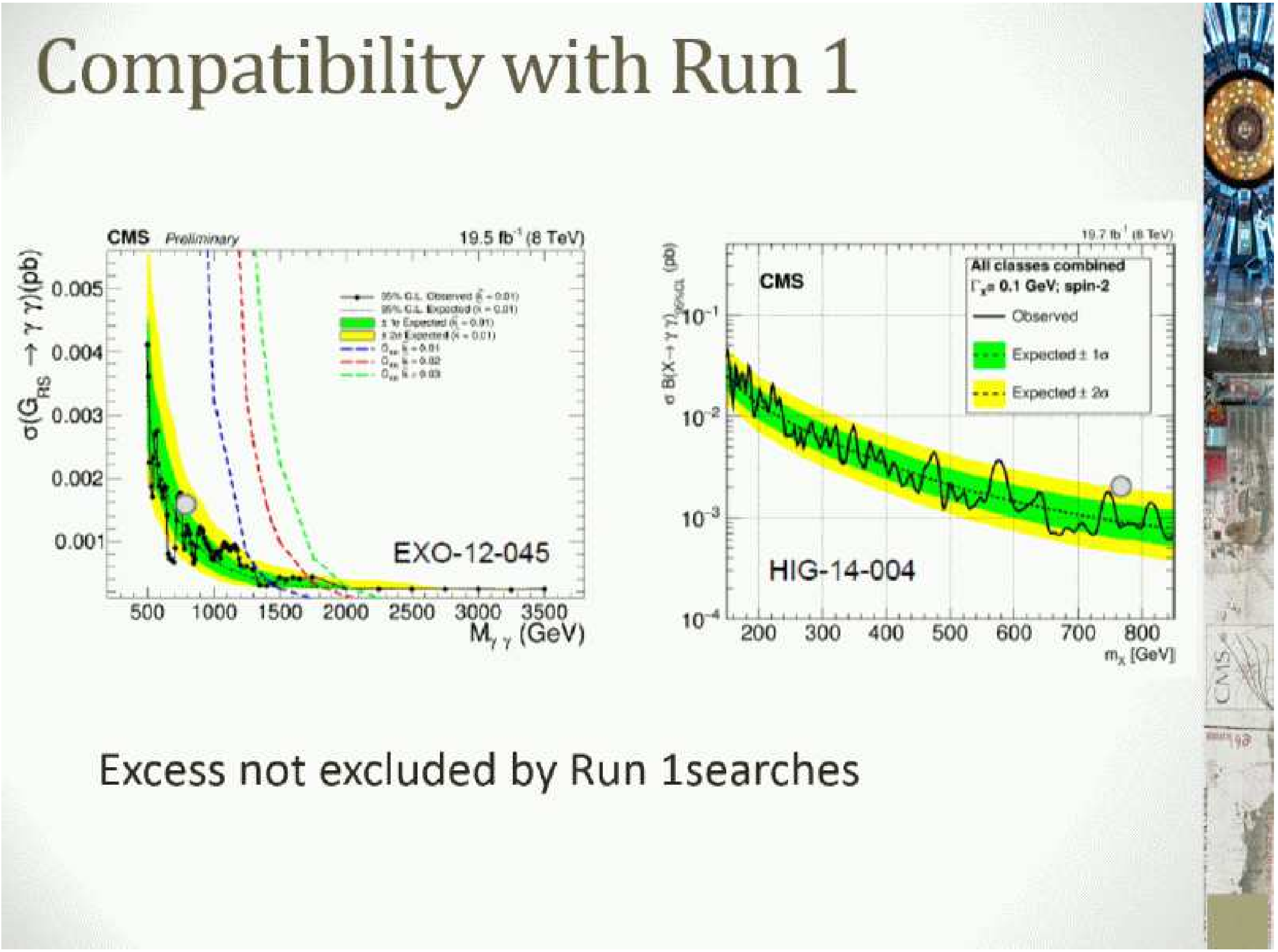
- Run 1 data was reanalyzed with the same procedure as the above analysis
- Under the LW hypotheses of 6% and for an s-channel production of a scalar particle via gluon fusion, a compatibility of the Run 2 excess with Run 1 data of 1.4s is found (the ratio of parton luminosities is 4.7 for a mass of 750 GeV)
- For a quark initiated process, the Run 1 and Run 2 observation are compatible at the 2.3s level (the ratio of parton luminosities in this case is 2.7 for a mass of 750 GeV)

1

$\Rightarrow$ they claim yes

Why I am very sceptical:

CMS: compatible with Run I?



⇒ they claim yes

Why I am very sceptical:

[1512.06797]

Spin 0 analysis:

signal region	observed	background	best fit	$\Delta\chi^2$	best fit	$\Delta\chi^2$	best fit	$\Delta\chi^2$
			ATLAS13		ATLAS13+CMS13		combined	
ATLAS13	28	11.4 ± 3	16.6	–	9.6	1.3	6.6	2.7
CMS13 EBEB	14	9.5 ± 1.9	14.4	2.1	8.3	1.1	5.8	0.7
CMS13 EBEE	16	18.5 ± 3.7	5.4	5.6	3.1	0.8	2.2	0.1
ATLAS8 HIG	34	28 ± 5	20.7	3.7	12.0	0.6	8.3	0.1
ATLAS8 EXO	99	96.4 ± 3.2	28.1	5.9	16.2	1.7	11.2	0.7
CMS8 EXO	46	48.6 ± 5.4	12.2	3.7	7.1	1.0	4.9	0.3
CMS8 HIG	53	50 ± 6	21.1	2.9	12.2	1.2	8.4	0.7

Spin 2 analysis:

signal region	observed	background	best fit	$\Delta\chi^2$	best fit	$\Delta\chi^2$	best fit	$\Delta\chi^2$
			ATLAS13		ATLAS13+CMS13		combined	
ATLAS13	28	11.4 ± 3	16.6	–	9.6	1.3	6.6	2.7
CMS13 EBEB	14	9.5 ± 1.9	14.4	2.1	8.3	1.1	5.8	0.7
CMS13 EBEE	16	18.5 ± 3.7	5.4	5.6	3.1	0.8	2.2	0.1
ATLAS8 HIG	34	28 ± 5	20.7	3.7	12.0	0.6	8.3	0.1
ATLAS8 EXO	99	96.4 ± 3.2	28.1	5.9	16.2	1.7	11.2	0.7
CMS8 EXO	46	48.6 ± 5.4	12.2	3.7	7.1	1.0	4.9	0.3
CMS8 HIG	53	50 ± 6	21.1	2.9	12.2	1.2	8.4	0.7