Physics at the Terascale: On the Verge of the LHC

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DESY

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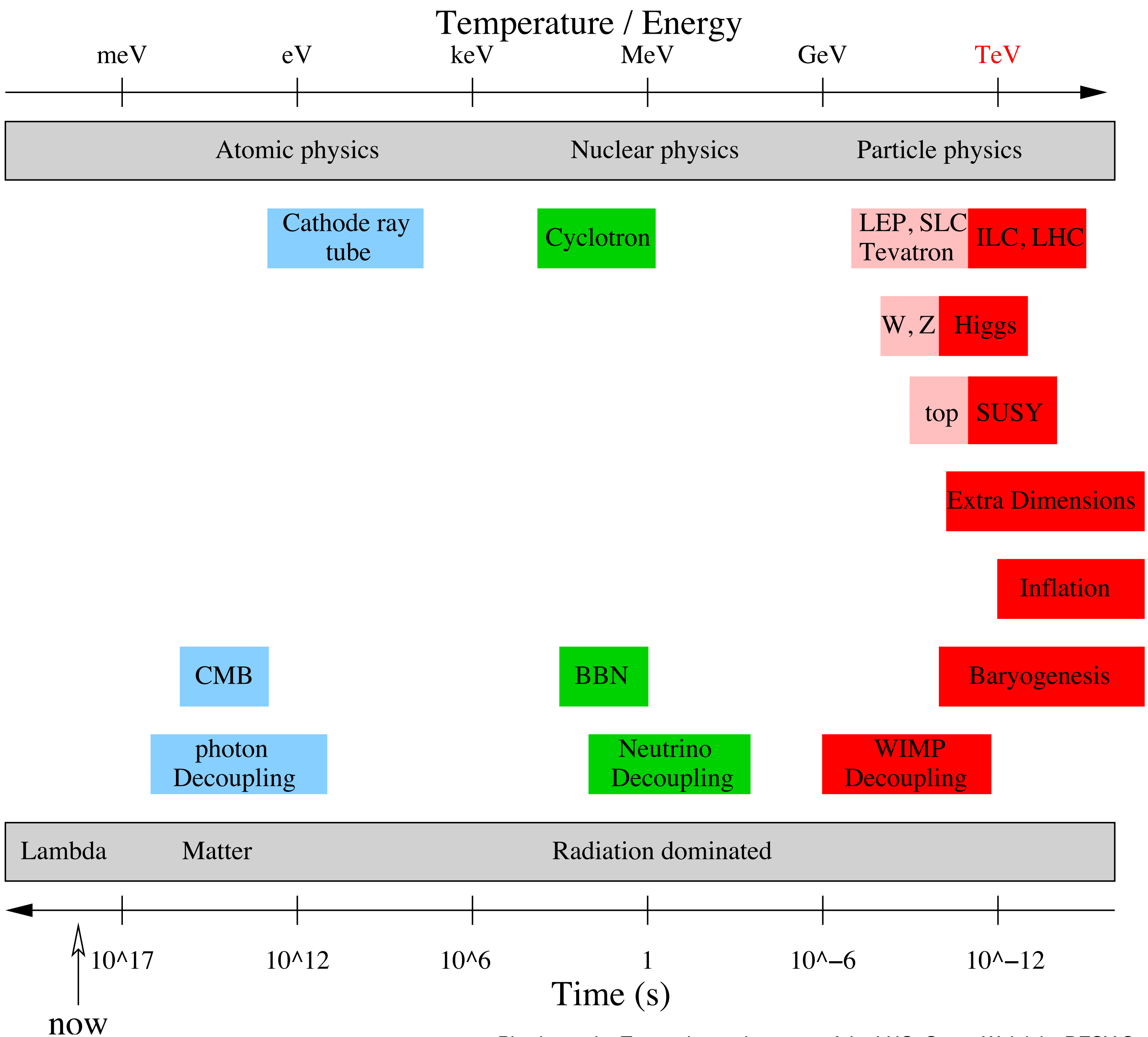
- Introduction: on the way to the TeV scale
- What is the scale of new physics?
- Physics of electroweak symmetry breaking
- Conclusions

Introduction: on the way to the TeV scale

$$1\ \mathrm{TeV} \approx 1000 \times m_{\mathrm{proton}} \Leftrightarrow 2 \times 10^{-19}\ \mathrm{m}$$



What can we learn from exploring the new territory of TeV-scale physics?

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- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking?

- Do all the forces of nature arise from a single fundamental interaction?

- Are there more than three dimensions of space?

- Are space and time embedded into a “superspace”?

- What is dark matter? Can it be produced in the laboratory?

- . . .

Probing the electroweak symmetry breaking mechanism at the TeV scale

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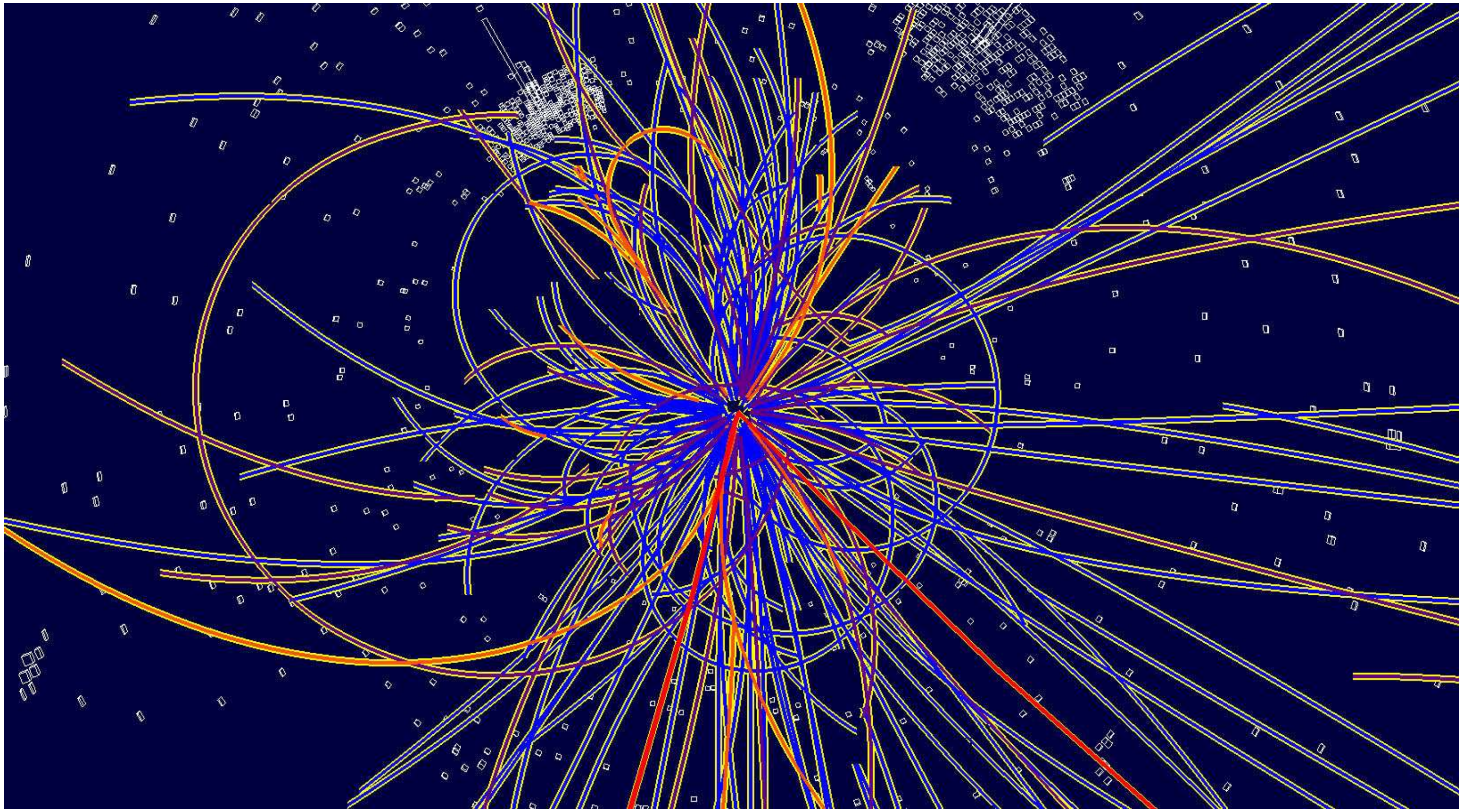
⇒ The mechanism of electroweak symmetry breaking will manifest itself at the TeV scale



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- Higgsless models in extra dimensions: boundary conditions for SM gauge bosons and fermions on Planck and TeV branes in higher-dimensional space

$\Rightarrow$ New phenomena required at the TeV scale

Electroweak symmetry breaking in the SM

Electroweak Standard Model (SM): Higgs is last missing ingredient

Higgs mechanism, spontaneous electroweak symmetry breaking:

Scalar field with non-vanishing v.e.v. postulated, gauge-invariant mass terms from coupling to Higgs field

3 components of Higgs doublet $\longrightarrow$ longitudinal components of $W^\pm$, Z; H: elementary scalar field, Higgs boson

Fermion masses, gauge-boson masses from coupling to Higgs field

$\Rightarrow$ Higgs couplings proportional to masses of the particles

Mass of the Higgs boson: free parameter

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- Nature has found a way to prevent this
  The Standard Model provides no explanation

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Extra dimensions of space:

Fundamental Planck scale is $\sim \mathrm{TeV}$ (large extra dimensions),

hierarchy of scales is related to a “warp factor”
(“Randall–Sundrum” scenarios)

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

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

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

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

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

General parametrisation of possible SUSY-breaking terms
$\Rightarrow$ free parameters, no prediction for SUSY mass scale

Hierarchy problem $\Rightarrow$ expect observable effects at TeV scale

How does SUSY breaking work?

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Strong phenomenological constraints on flavour off-diagonal and $\mathcal{CP}$-violating SUSY-breaking terms

$\Rightarrow$ Good phenomenological description for universal SUSY-breaking terms ($\approx$ diagonal in flavour space)

Simplest ansatz: the Constrained MSSM (CMSSM)

Assume universality at high energy scale (M_{GUT}, M_{Pl}, $\ldots$)
renormalisation group running down to weak scale
require correct value of M_{Z}

$\Rightarrow$ CMSSM characterised by

$$m_0^2,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

CMSSM is in agreement with all experimental constraints:
Electroweak precision observables (EWPO) $+$ flavour physics $+$ cold dark matter density $+$ $\ldots$

The Non-Universal Higgs Model (NUHM)

Universality of soft SUSY-breaking contributions to the Higgs scalar masses is less motivated than universality between squarks and sleptons

$\Rightarrow$ NUHM:

two additional parameters (can be traded for M_A and μ after imposing the electroweak vacuum conditions)

Simplest realisation:

$$m^2_{H_1} = m^2_{H_2} \equiv m^2_H$$

Common soft SUSY-breaking contribution to Higgs scalar masses squared: "NUHM1"

SUSY-breaking scenarios

“Hidden sector”: $\longrightarrow$ Visible sector:

SUSY breaking MSSM

“Gravity-mediated”: SUGRA
“Gauge-mediated”: GMSB
“Anomaly-mediated”: AMSB
“Gaugino-mediated”
...

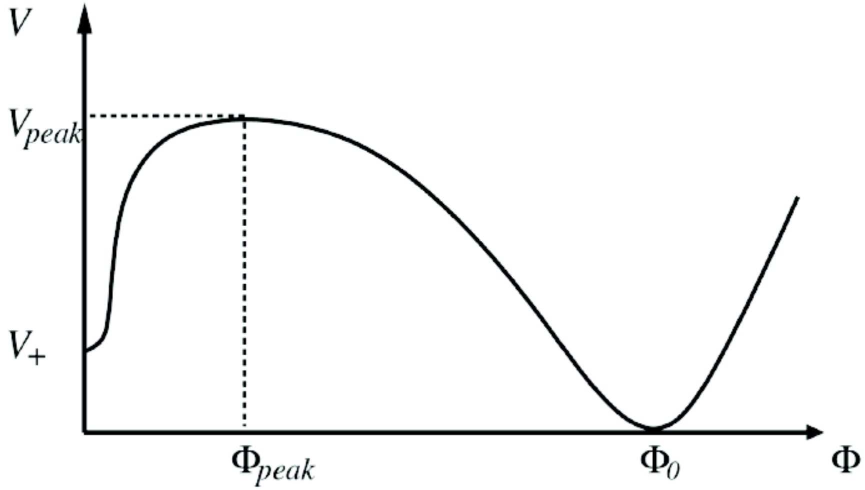
SUGRA: mediating interactions are gravitational

GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions

AMSB, Gaugino-mediation: SUSY breaking happens on a different brane in a higher-dimensional theory

Do we live in a meta-stable vacuum?

Suppose we live in a SUSY-breaking meta-stable vacuum, while the global minimum has exact SUSY

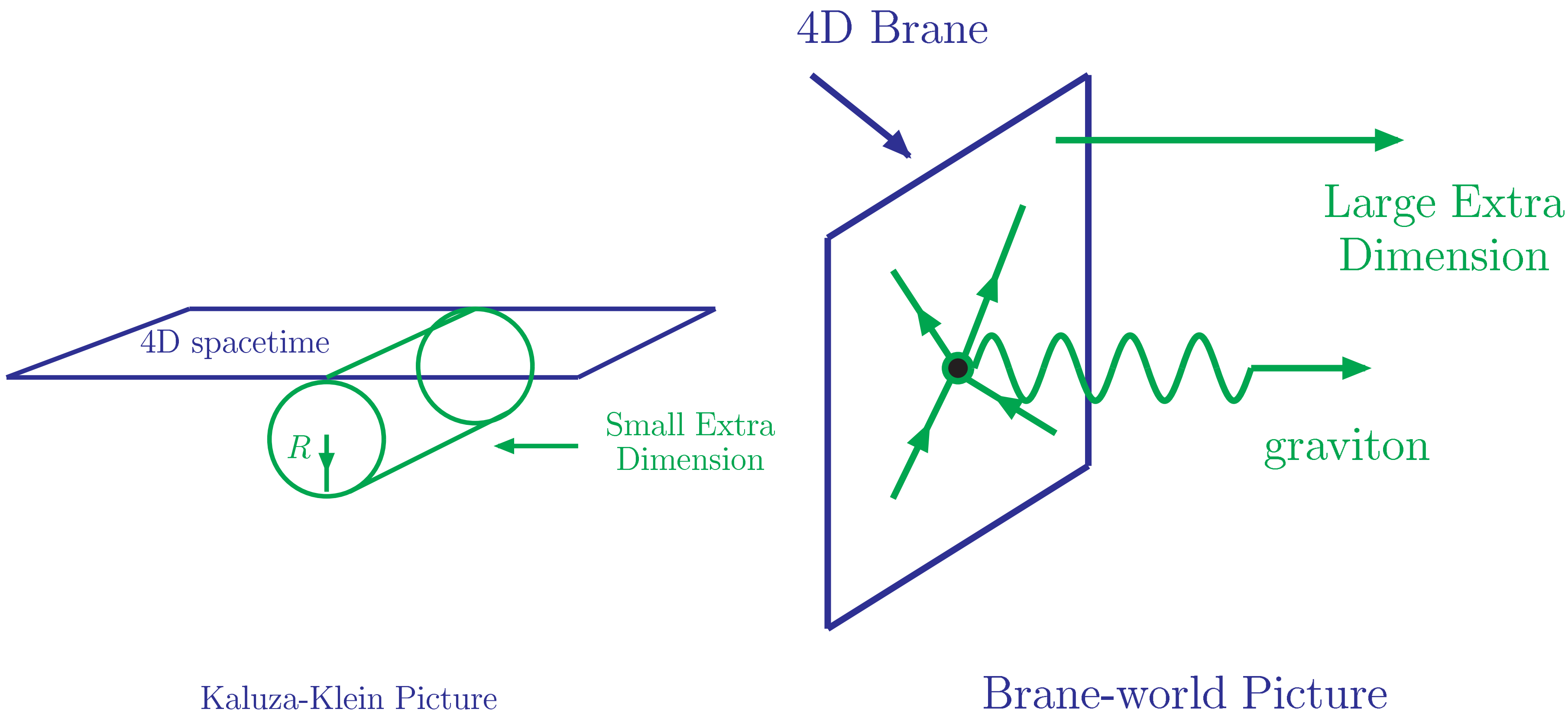


Recent developments: meta-stable vacua arise as generic feature of SUSY QCD with massive flavours

Meta-stable SUSY-breaking vacua are “generic” in local SUSY / string theory, can have cosmologically long life times [*K. Intriligator, N. Seiberg, D. Shih ’06*], . . .

⇒ Many new ideas — hope for experimental input!

Models with extra dimensions of space

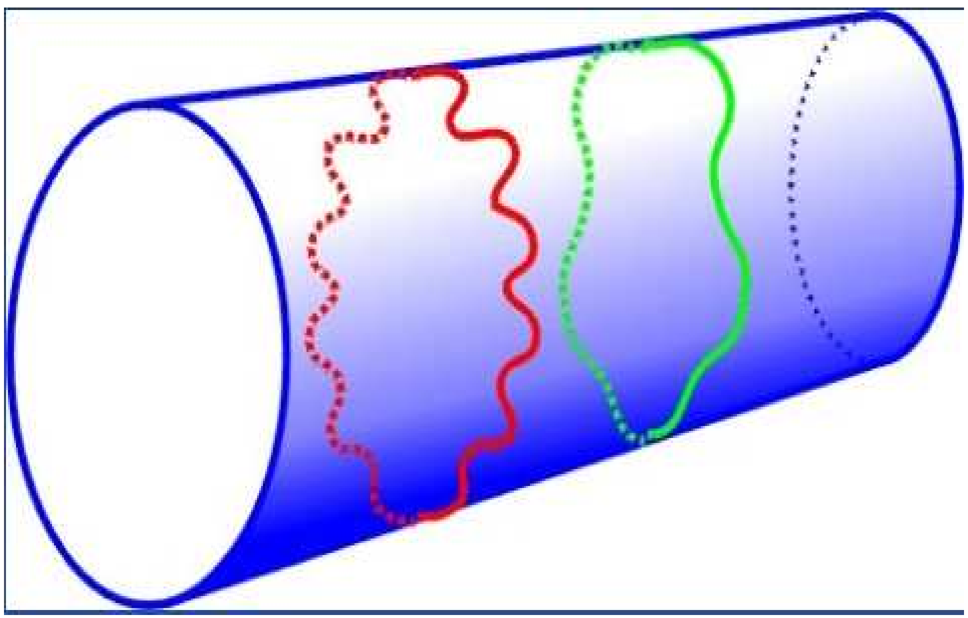


Hierarchy between M_{Planck} and M_{weak} is related to the volume or the geometrical structure of additional dimensions of space

$\Rightarrow$ observable effects at the TeV scale

Phenomenological consequences of extra dimensions

The wave function of a free particle must be $2\pi R$ periodic



$$e^{ip.x_5} = e^{ip.(x_5+2\pi R)}$$

$$p = \frac{n}{R}$$

⇒ momentum is quantised

⇒ Looks in 4-dim like a series of new, more massive partners associated with each known particle: “Kaluza–Klein tower”

Phenomenological consequences of extra dimensions

We may be trapped on a $(3+1)$-dimensional brane in a higher-dimensional space-time, while gravity can enter the extra dimensions

Extra dimensions could be large, even infinite

⇒ Could explain the apparent weakness of gravity in our 4-dimensional world

⇒ At the LHC, gravitons could be emitted into the extra dimensions

⇒ “missing energy” signals

If gravity is strong at the TeV scale, particle collisions at the LHC may form “mini black holes”

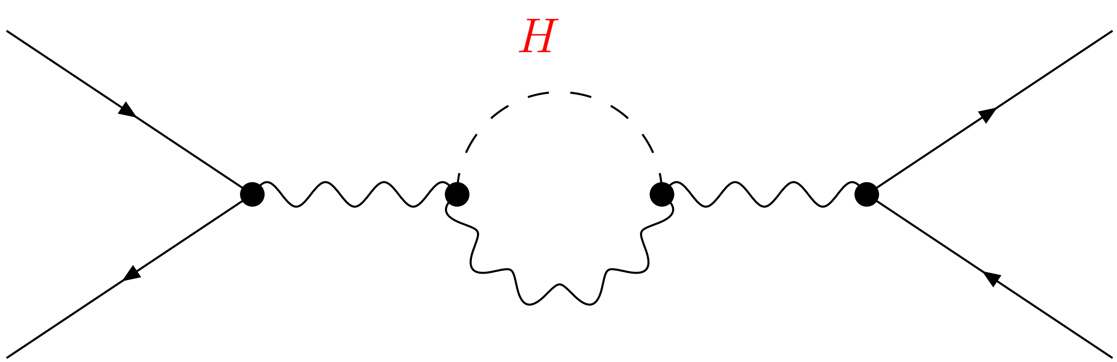
What is the scale of new physics?

EW precision data:
$M_Z, M_W, \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}, \ldots$

Theory:
SM, MSSM, . . .

$\Downarrow$

Test of theory at quantum level: loop corrections



$\Downarrow$

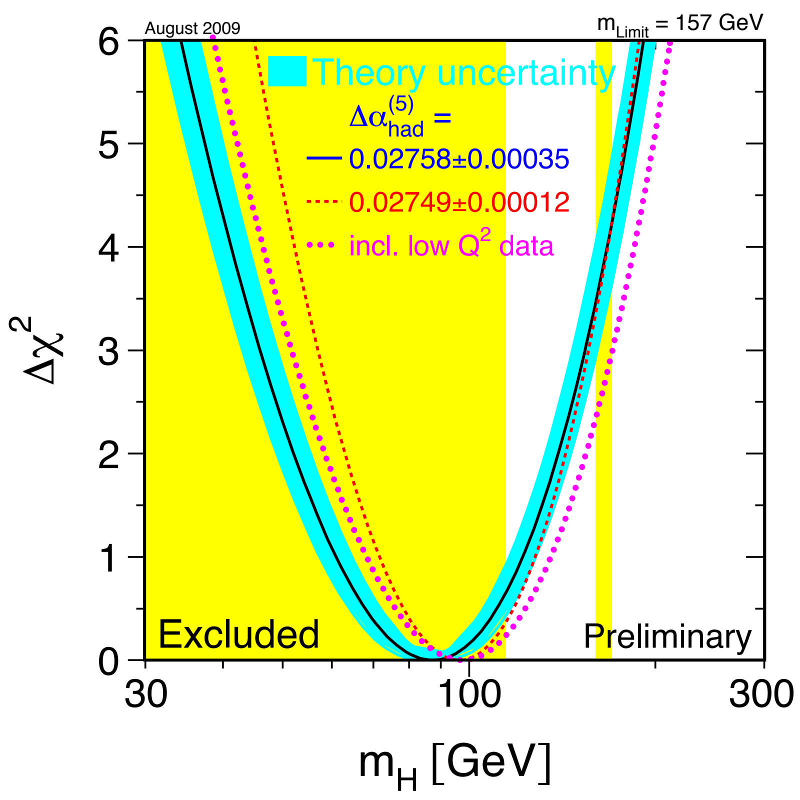
Sensitivity to effects from unknown parameters: M_H, $M_{\tilde{t}}$, . . .

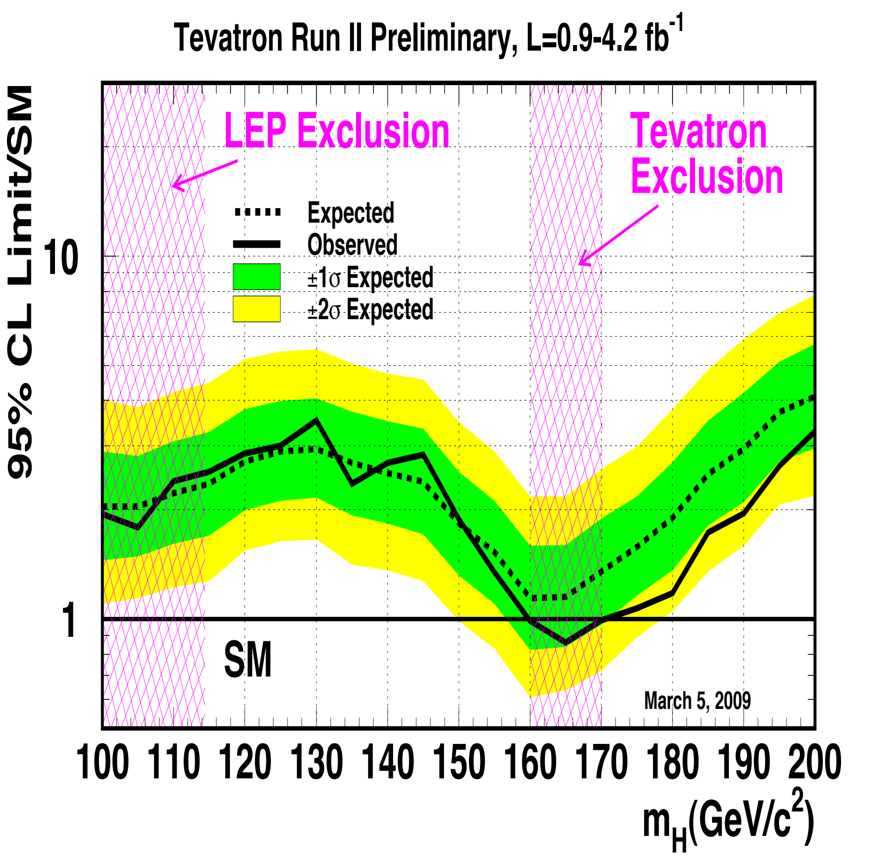
Window to “new physics”

Constraints on the SM Higgs from electroweak precision data and direct searches

SM Higgs: ew. prec. data + direct search at LEP & Tevatron

[*LEPEWWG '09*] [*TEVNPH Working Group '09*]

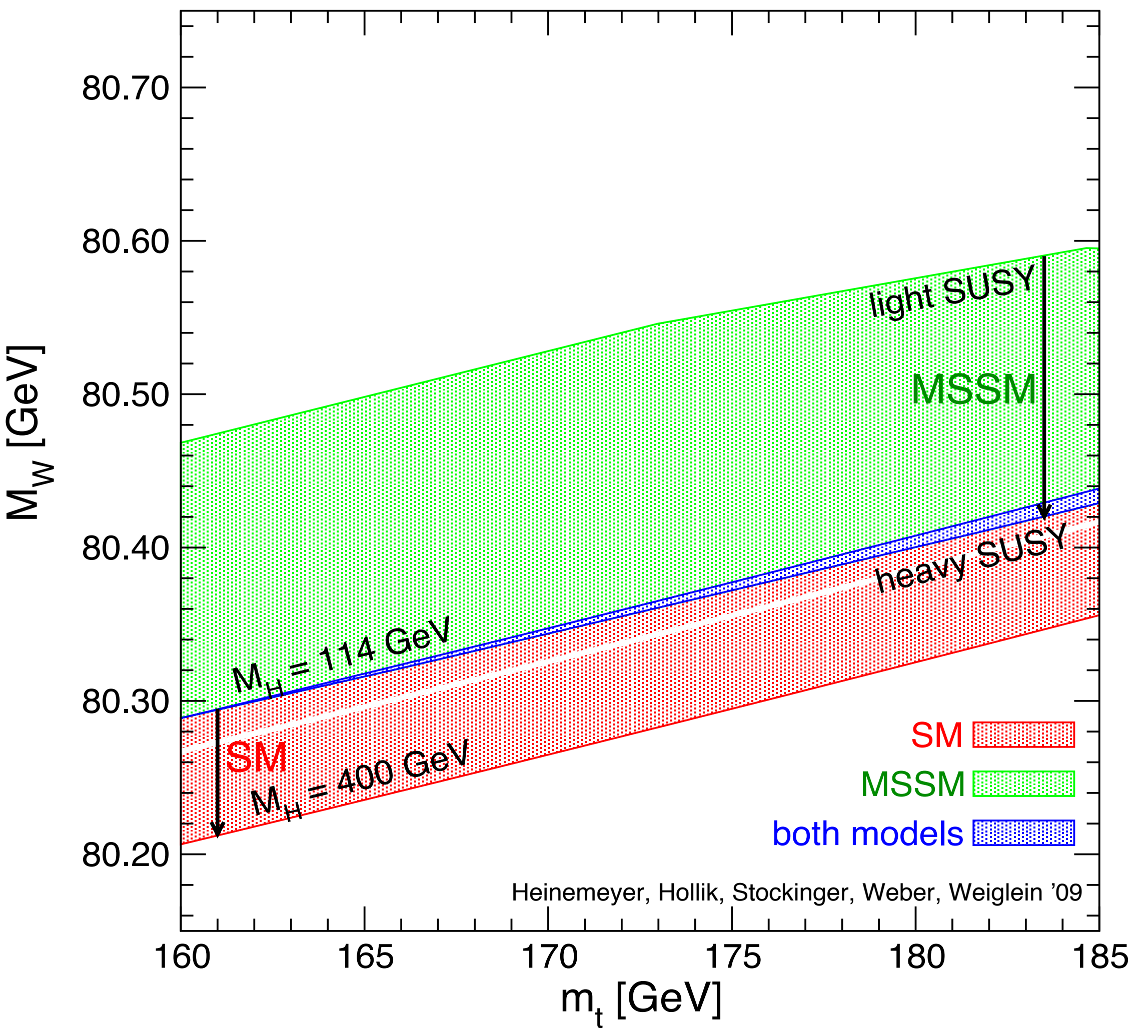




⇒ Preference for a light Higgs

Prediction for M_{W} (parameter scan): SM vs. MSSM

Prediction for M_{W} in the SM and the MSSM:



[*S. Heinemeyer, W. Hollik, D. Stöckinger, A.M. Weber, G. W. '09*]

MSSM: SUSY parameters varied

SM: M_{H} varied

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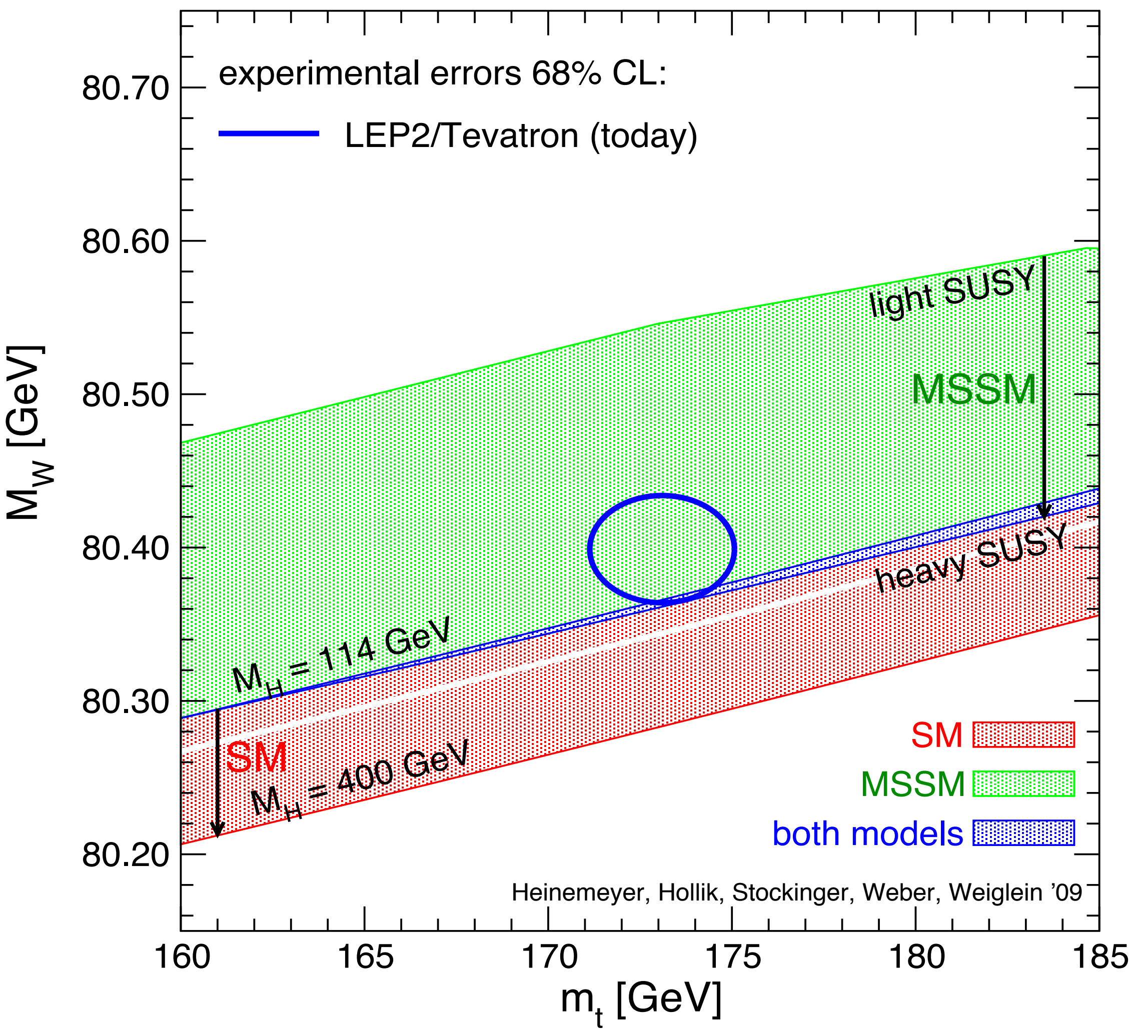

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⇒ Slight preference for MSSM over SM

Global CMSSM and NUHM1 fits using indirect experimental and cosmological constraints

Global χ^2 fit in the CMSSM ($m_{1/2}$, m_0, A_0 (GUT scale), $\tan\beta$, $\mathrm{sign}(\mu)$ (weak scale)) and the NUHM1 (m_H^2 as add. param.)

Fit includes (*MasterCode*, Markov-chain Monte Carlo sampling):
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]

- All observables used in the SM fit of the LEPEWWG
- $+$ Cold dark matter (CDM) density (WMAP, . . .), $\Omega_{\rm CDM}\, h^2 = 0.1099 \pm 0.0062$
- $+ \, (g-2)_\mu$
- $+$ BPO: $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$, $\mathrm{BR}(B \to \tau\nu)$, . . .
- $+$ Kaon decay data: $\mathrm{BR}(K \to \mu\nu)$, . . .

MasterCode: ***predictions***

- *MasterCode:* Consistent set of predictions
  - RGE running and spectrum calculators:
    SoftSUSY, *SuSpect*
  - SUSY observables:
    Higgs sector: *FeynHiggs* (soon: *HiggsBounds*)
    Electroweak physics: *FeynHiggs*, *FeynWZ*
    Flavour physics: *SuFla*, *SuperIso*
    CDM: *MicrOMEGAs, DarkSUSY*
  - Interface: SLHA

$\Rightarrow$ State-of-the art predictions, well tested, modular structure

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Global fits at DESY: strong activity, long tradition

Fittino, *Gfitter*, *MasterCode*, *ZFITTER*, . . .

The anomalous magnetic moment of the muon:

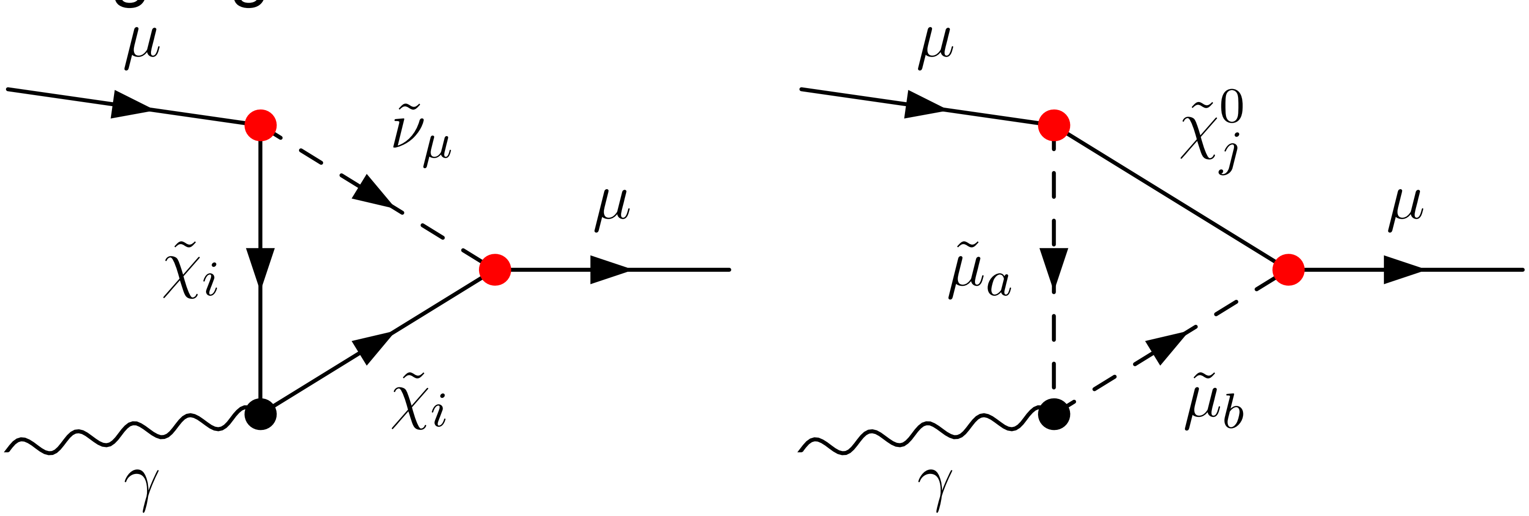
$$(g-2)_\mu \equiv 2a_\mu$$

Experimental result for a_μ vs. SM prediction (using e^+e^- data for hadronic vacuum polarisation):

$$a_\mu^{\rm exp} - a_\mu^{\rm theo} = (30.2 \pm 8.8) \times 10^{-10} \;:\; 3.4\,\sigma\ .$$

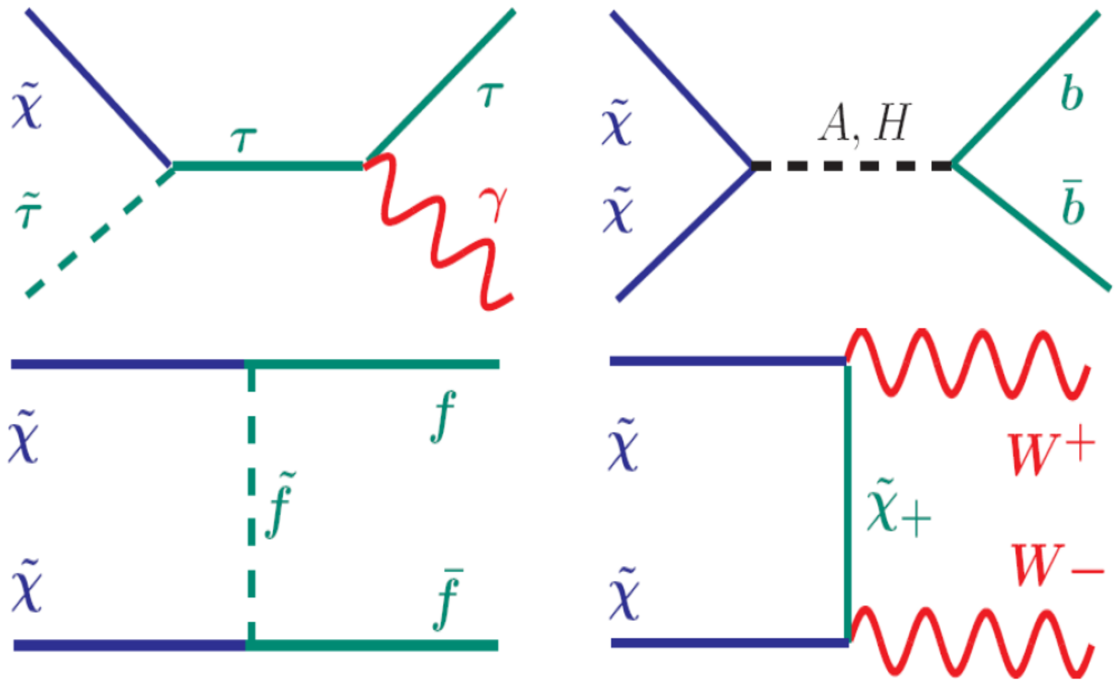
Better agreement between theory and experiment possible in models of physics beyond the SM

Example: one-loop contributions of superpartners of fermions and gauge bosons



Prediction for the density of cold dark matter (CDM) in the Universe

Cross sections for annihilation and co-annihilation processes



Cold Dark Matter density (WMAP, . . .):

$$\Omega_{\rm CDM}\, h^2 = 0.1099 \pm 0.0062$$

⇒ Comparison yields constraints on new physics

Global SUSY fits: statistics and parameter space sampling

- Frequentist statistical method: global χ^2 likelihood function

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \chi^2(M_\mathrm{h}) + \chi^2(\mathrm{BR}(\mathrm{B_s} \to \mu\mu))$$

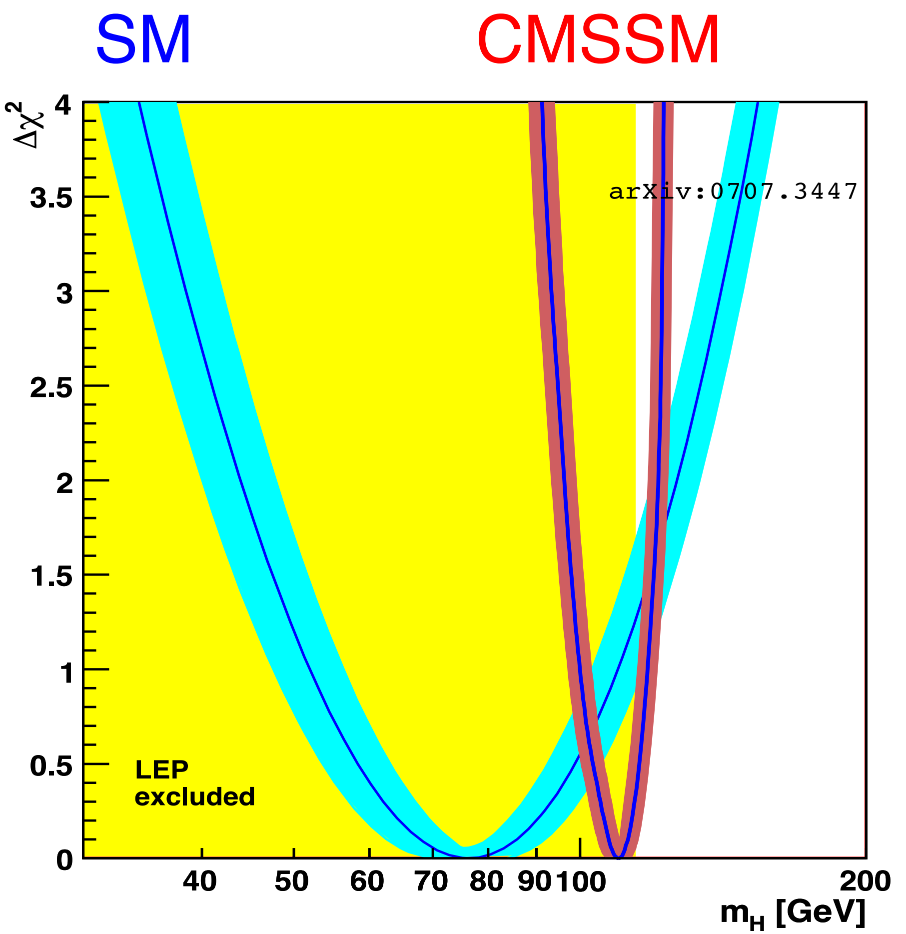
$$+ \chi^2(\text{SUSY search limits}) + \sum_i^M \frac{(f^{\mathrm{obs}}_{\mathrm{SM}_i} - f^{\mathrm{fit}}_{\mathrm{SM}_i})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

  Fit parameters: SUSY parameters $m_{1/2}$, m_0, A_0, $\tan\beta$, m_H^2
  $+$ SM parameters $\Delta\alpha_\mathrm{had}$, m_t, M_Z (simultaneous fit)
  $\Rightarrow$ χ^2 distribution is quantitative measure of goodness-of-fit

- Markov-chain Monte Carlo (MCMC) sampling
  $\Rightarrow$ Thorough sampling of multi-dim. parameter space
  25 million points

Indirect prediction for the Higgs mass in the SM and the constrained MSSM (CMSSM) from precision data

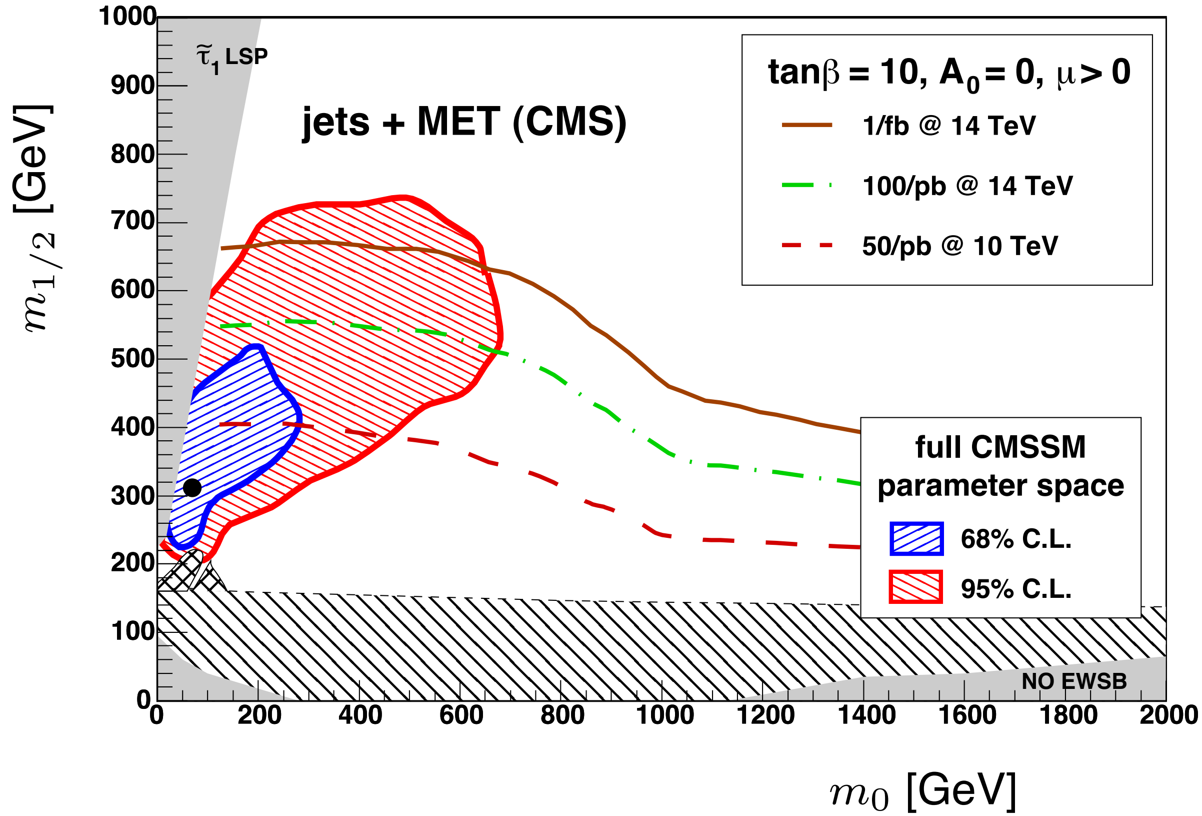
χ^2 fit for M_h, without imposing direct search limit [*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]



⇒ Accurate indirect prediction; Higgs "just around the corner"?

Predictions for the SUSY scale from precision data

Comparison: preferred region for the SUSY mass scale vs. LHC discovery reach for $1, 0.1, 0.05~\mathrm{fb}^{-1}$ of understood data
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]



⇒ Preferred region would lead to early discovery

Preferred region in the m_0–$m_{1/2}$ plane of the NUHM1 vs. LHC discovery reach

68% and 95% C.L. contours from the fit vs. LHC discovery reach for $1, 0.1, 0.05\ \mathrm{fb}^{-1}$ of understood data

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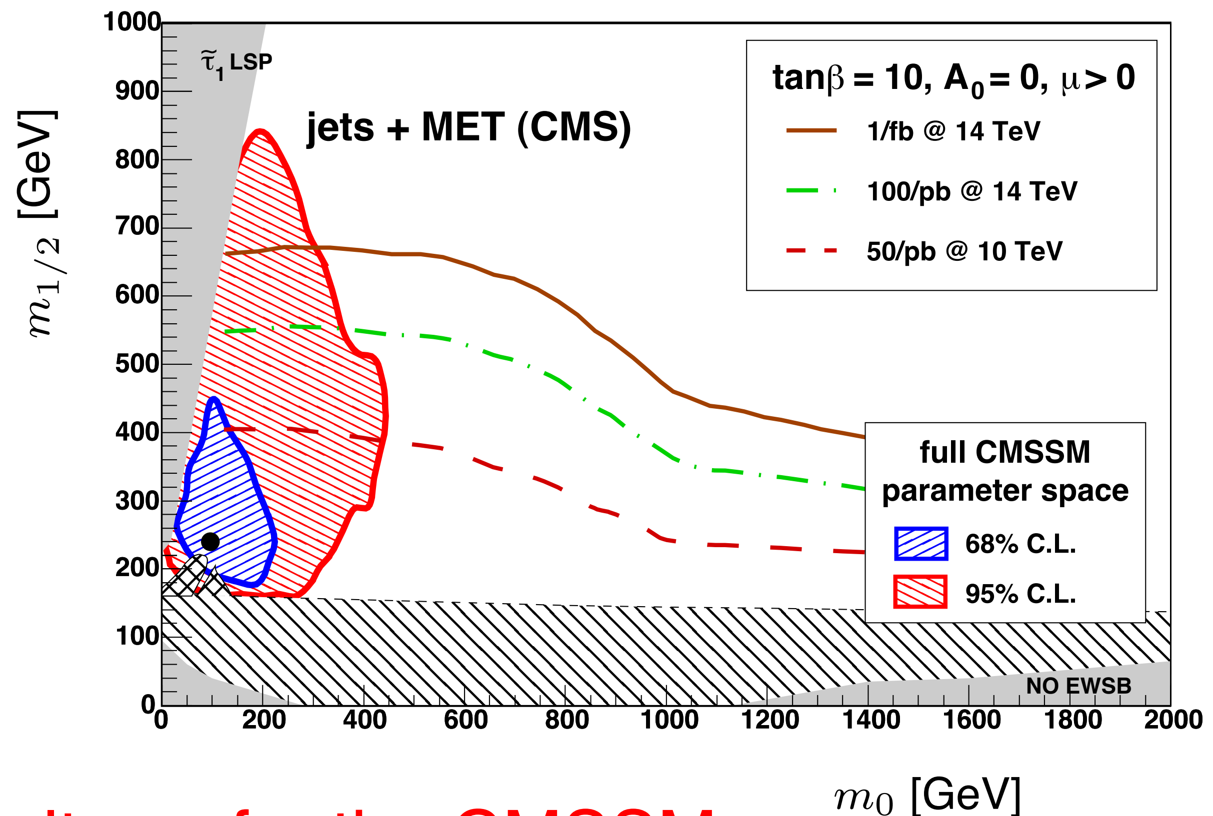
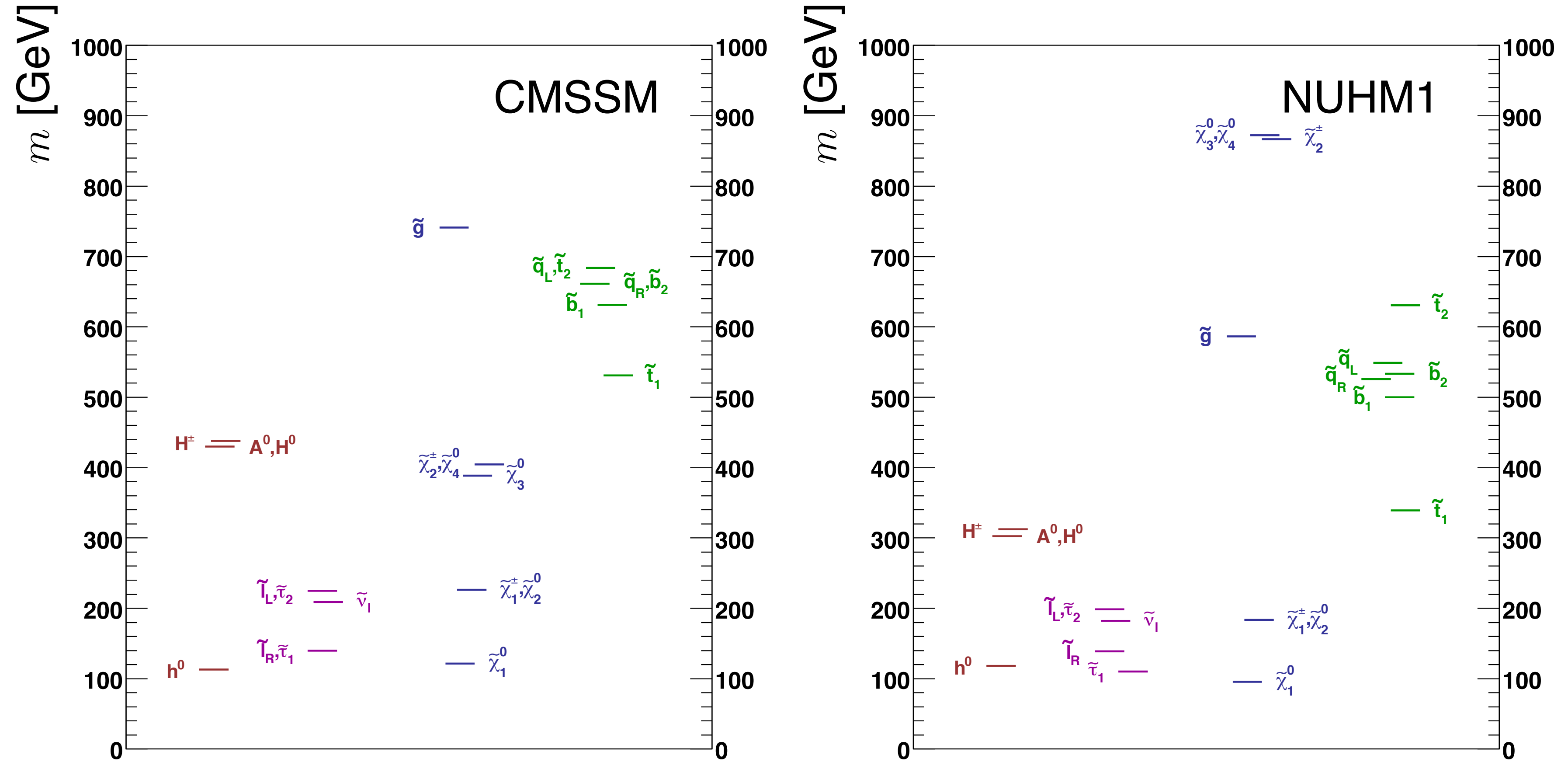


⇒ Similar results as for the CMSSM

Spectra of the best-fit points in the CMSSM and the NUHM1



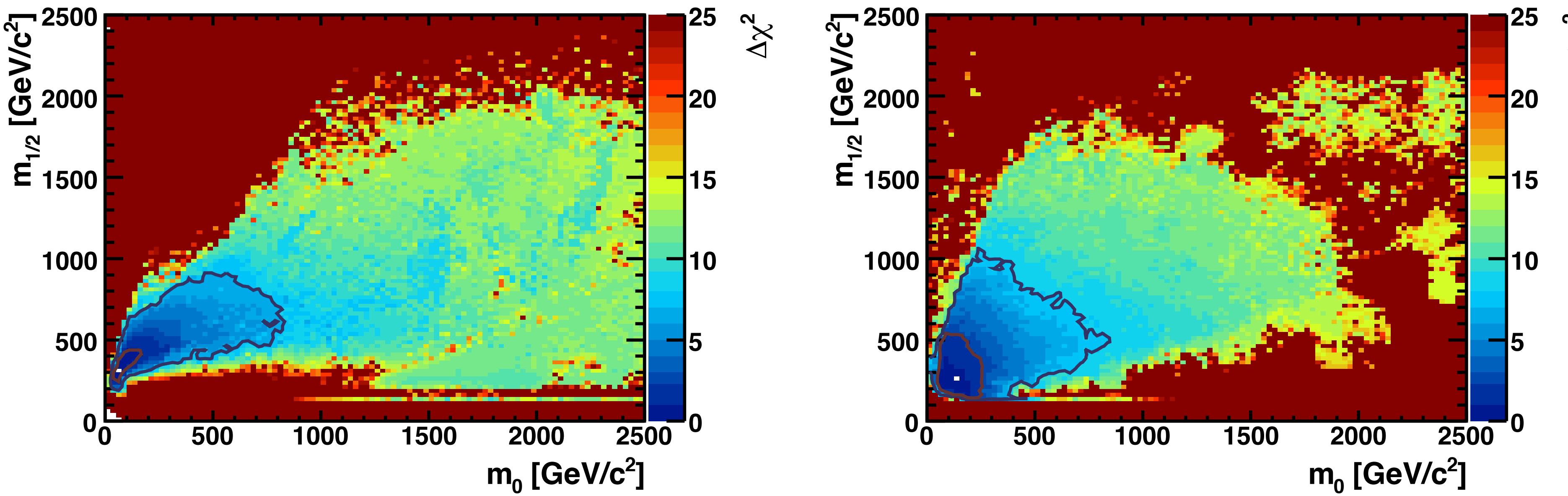
⇒ Similar spectra, close to SPS1a benchmark point

Similar fit probabilities for the two models

Good prospects for LHC and ILC

$\Delta\chi^2$ *distributions: CMSSM and NUHM1*

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '09*]



⇒ Preference for light SUSY scale

Focus point (FP) region is disfavoured at the 3σ level

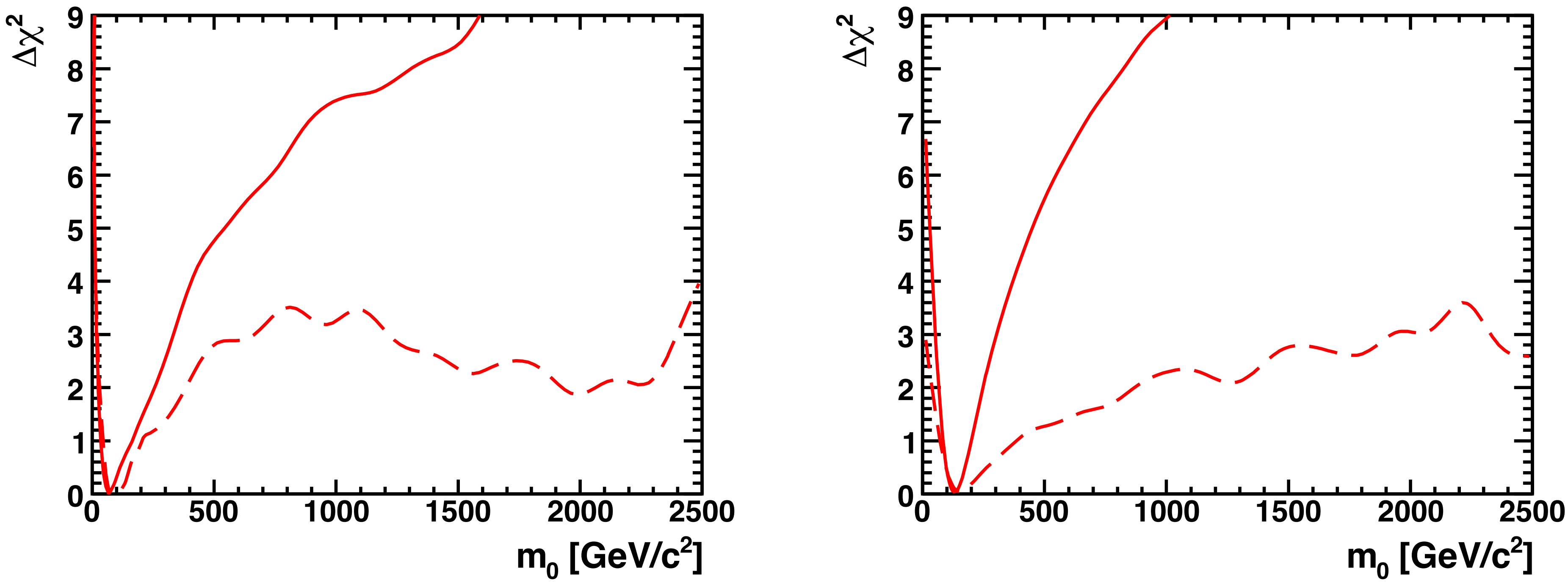
χ^2 *contributions for best fit points*
Comparison with best fit in FP region

Observable	Best CMSSM fit	Best NUHM1 fit	Best CMSSM FP fit
$(g_\mu - 2)$	0.44	0.002	8.4
$\mathrm{BR}(B \to \tau\nu)$	0.20	0.41	0.85
M_W	0.53	0.08	1.5
$A_\ell(\mathrm{SLD})$	2.84	3.22	3.56
$A_\mathrm{fb}(b)$(LEP)	7.61	7.08	6.74
R_ℓ	0.96	1.01	1.05
$\mathrm{BR}^{\mathrm{SUSY}}_{\mathrm{b}\to\mathrm{s}\gamma}/\mathrm{BR}^{\mathrm{SM}}_{\mathrm{b}\to\mathrm{s}\gamma}$	1.16	0.001	0.95
M_h	0.17	0	0
χ^2_tot	20.6	18.5	29.8

$\Rightarrow$ Clear preference for light SUSY;
Strongest contribution from $(g_\mu - 2)$

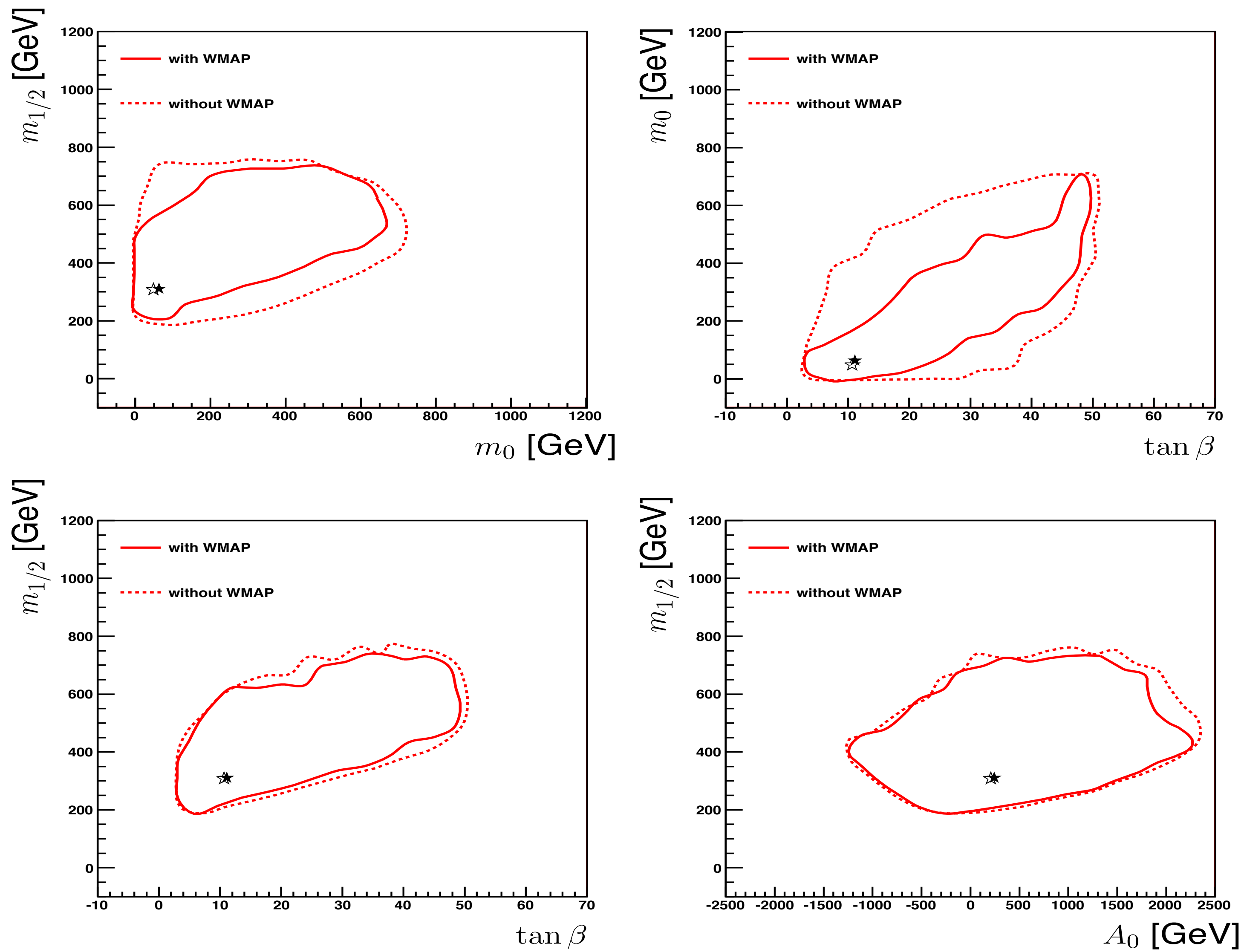
$\Delta\chi^2$ *for CMSSM and NUHM1 with (solid) and without (dashed)* $(g_\mu - 2)$ *constraint*

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '09*]



$\Rightarrow$ Slight Preference for light SUSY scale even if $(g_\mu - 2)$ is excluded from the fit

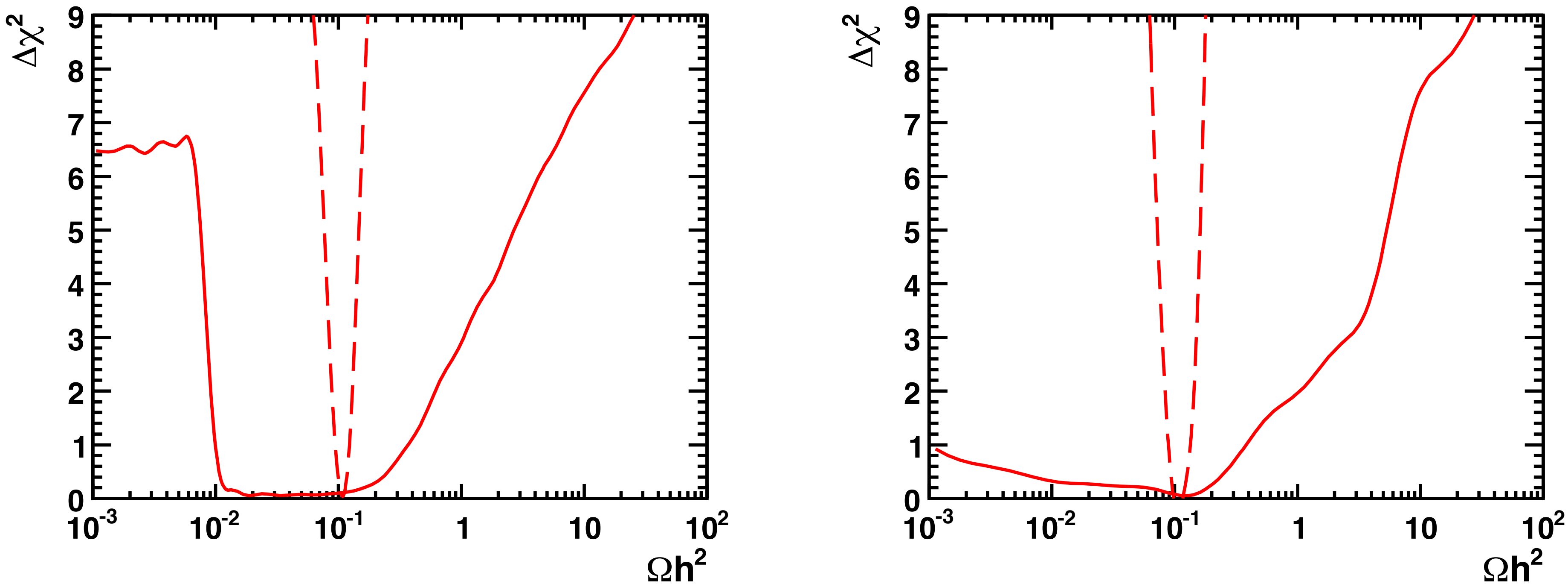
Impact of CDM constraint, CMSSM results



$\Rightarrow$ Fit results are robust w.r.t. in-/exclusion of Ω_{CDM} constraint

χ^2 functions for the relic density in the CMSSM and NUHM1 without (solid) and with (dashed) the $\Omega_{\rm CDM}$ constraint

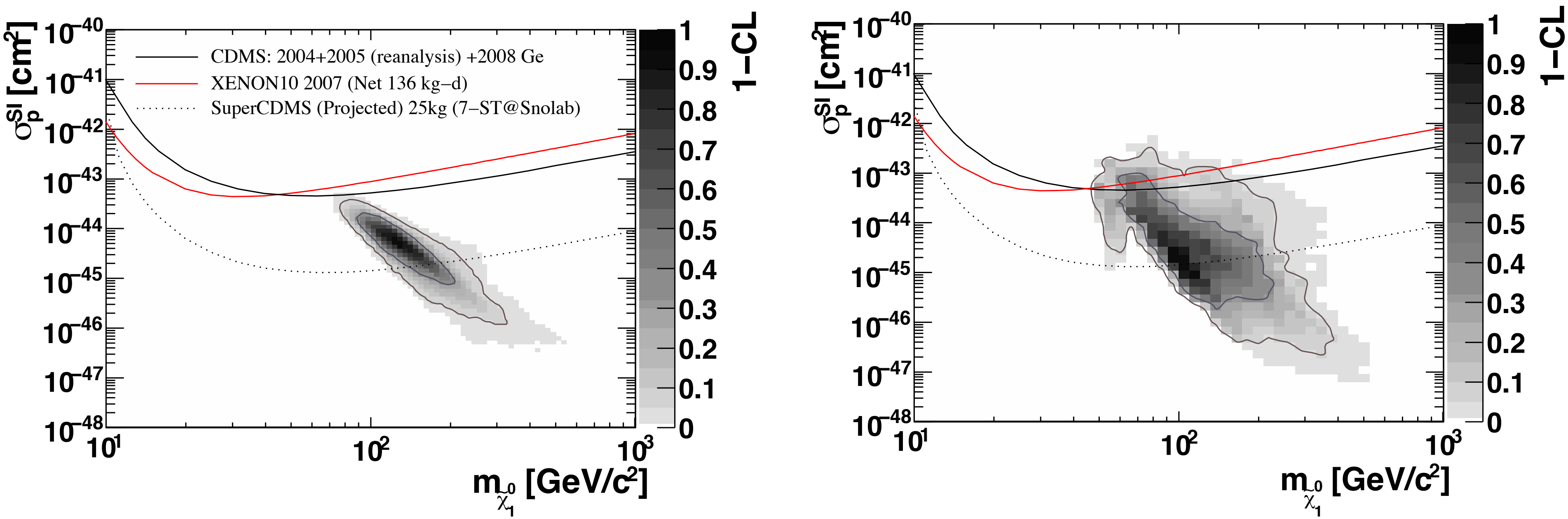
[O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '09]



⇒ Indirect CDM prediction is in agreement with the measured value of the CDM relic density

Preferred regions for the spin-independent dark matter cross sections vs. present limit and future sensitivity

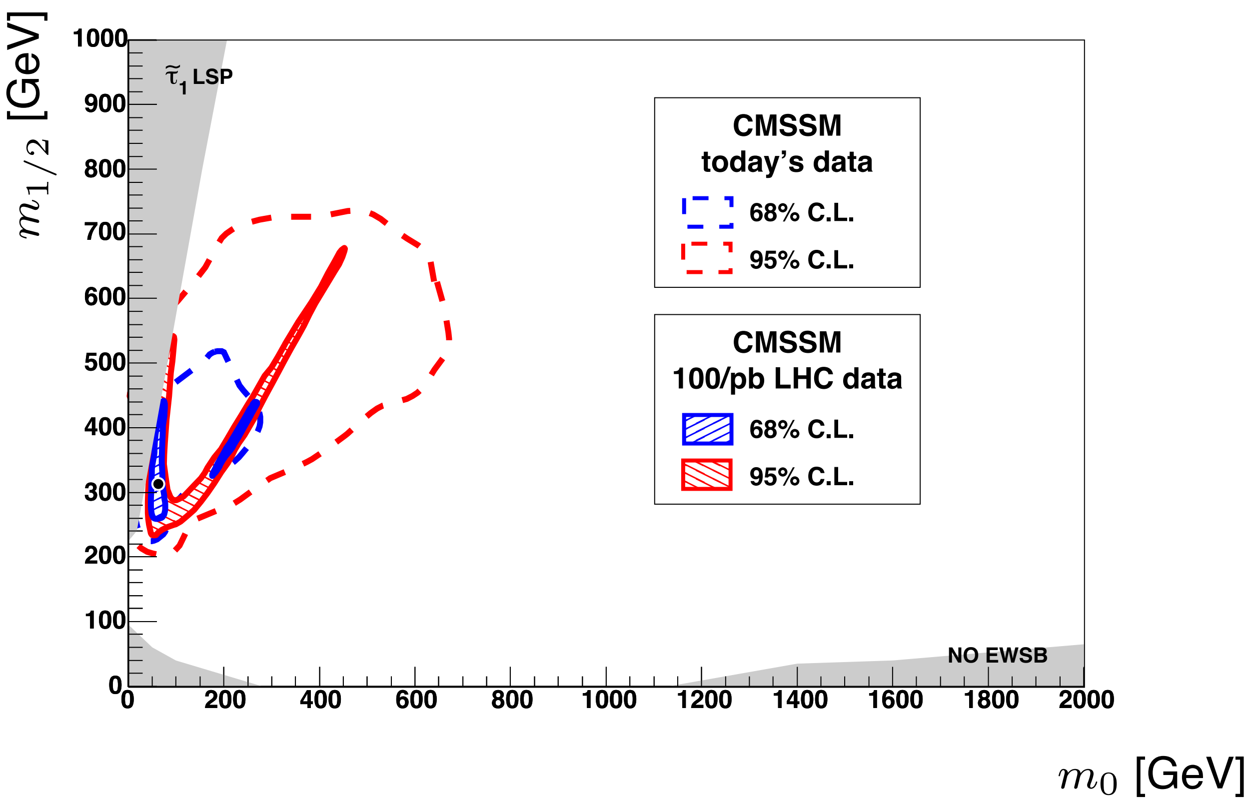
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '09*]



$\Rightarrow$ Projected sensitivity of the *SuperCDMS* direct detection experiment will probe a sizable part of the preferred region

Improvements from measuring a dilepton edge

CMSSM fit with additional information from measuring the opposite-sign dilepton edge in $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ ($\ell = e, \mu$) with $1\ \mathrm{fb}^{-1}$: [*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]

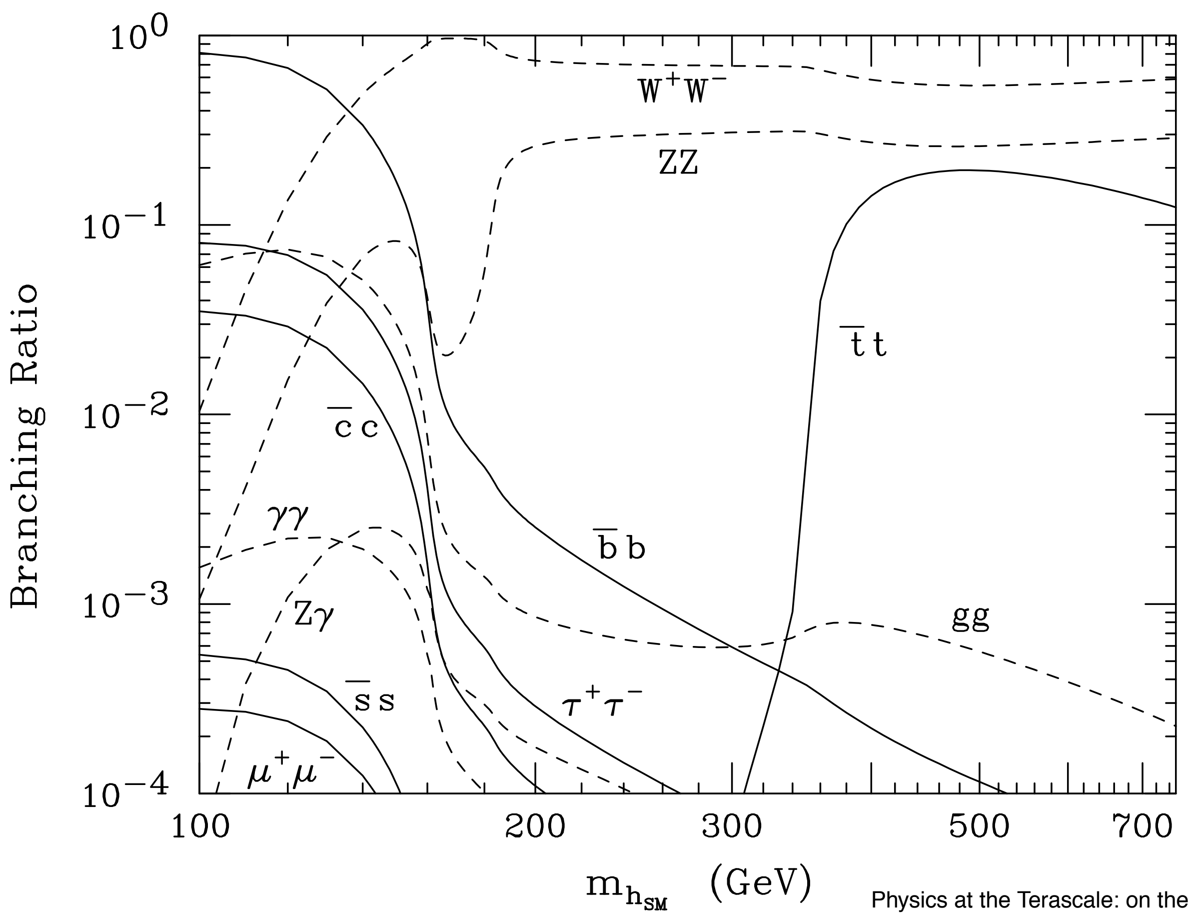


$\Rightarrow$ Big improvement in determination of m_0, $m_{1/2}$

Physics of electroweak symmetry breaking

Standard Model: a single parameter determines the whole Higgs phenomenology: M_{H}

Branching ratios of the SM Higgs:



$\Rightarrow$ dominant BRs:

$M_{\mathrm{H}} \lesssim 140$ GeV:
$H \to b\bar{b}$

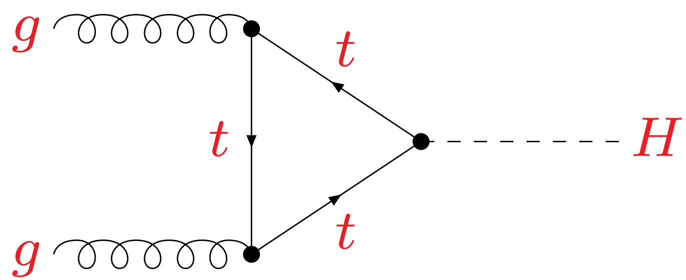
$M_{\mathrm{H}} \gtrsim 140$ GeV:
$H \to W^+W^-, ZZ$

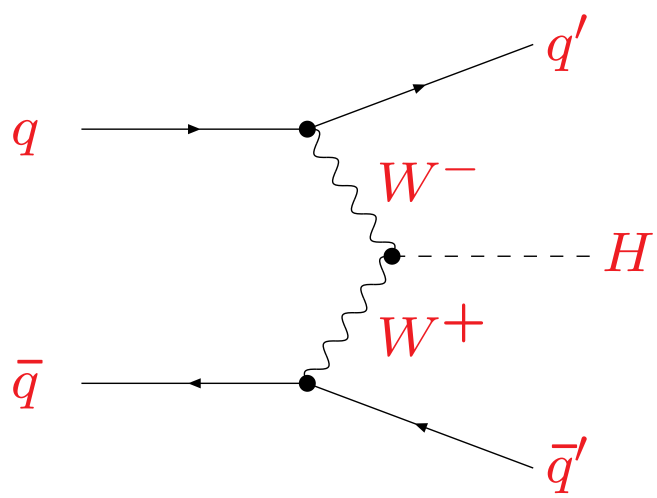
Production of a SM-like Higgs at the LHC

SM Higgs production at the LHC:

Dominant production processes:

gluon fusion: $gg \to H$, weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$





Other possibility: Central exclusive diffractive (CED) Higgs production, $pp \to p + H + p$

Higgs physics beyond the SM

In the SM the same Higgs doublet is used “twice” to give masses both to up-type and down-type fermions

$\Rightarrow$ extensions of the Higgs sector having (at least) two doublets are quite “natural”

$\Rightarrow$ Would result in several Higgs states

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Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”

Higgs physics beyond the SM

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⇒ Would result in several Higgs states

Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

Example: SUSY in the "decoupling limit"

But there is also the possibility that none of the Higgs bosons is SM-like

Higgs physics in Supersymmetry

"Simplest" extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters

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⇒ Two parameters instead of one: $\tan\beta \equiv \frac{v_u}{v_d}$, M_A (or $M_{\mathrm{H}^\pm}$)

⇒ Upper bound on lightest Higgs mass, M_h (*FeynHiggs*):
[*S. Heinemeyer, W. Hollik, G. W. '99*], [*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

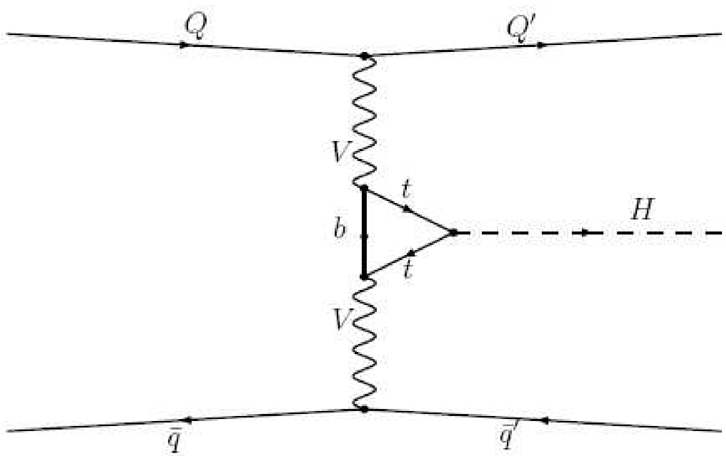
$$M_\mathrm{h} \lesssim 130\,\mathrm{GeV}$$

Very rich phenomenology

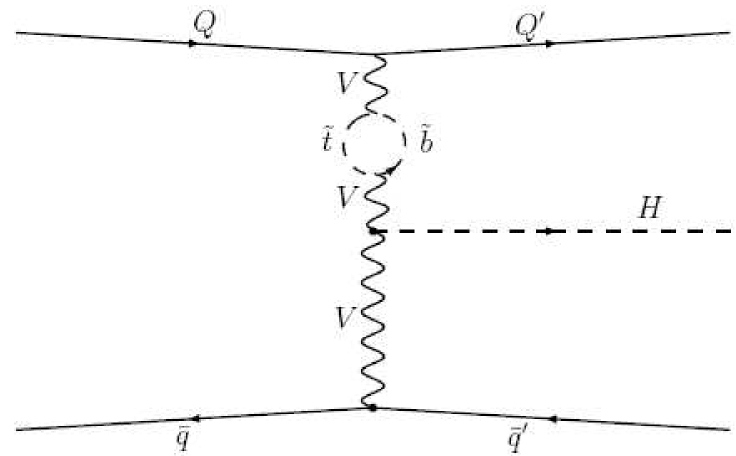
Higgs production in weak-boson fusion:

full SM-type one-loop + dominant SUSY loop corrections

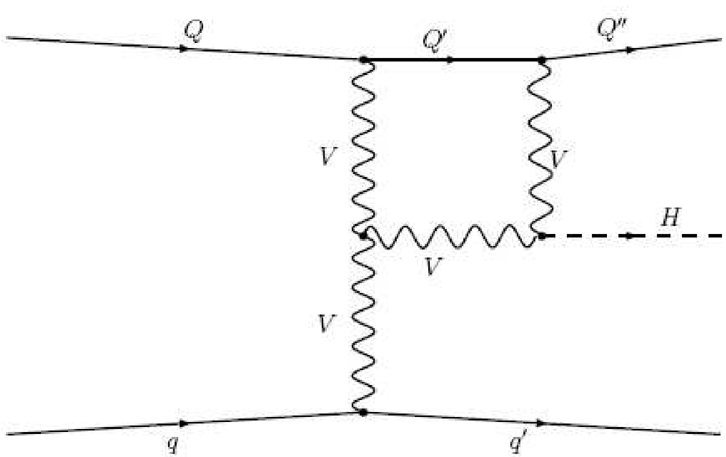
[*T. Figy, S. Palmer, G. W. ’09*]



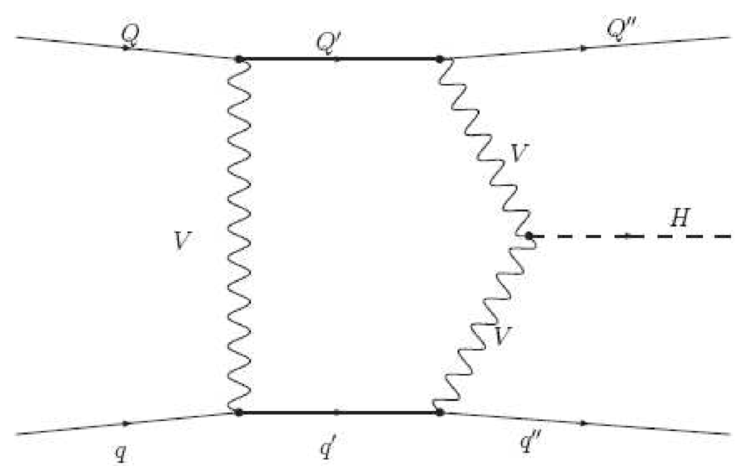
(a) Corrections to the VVH vertex



(b) Corrections to the VV self energy



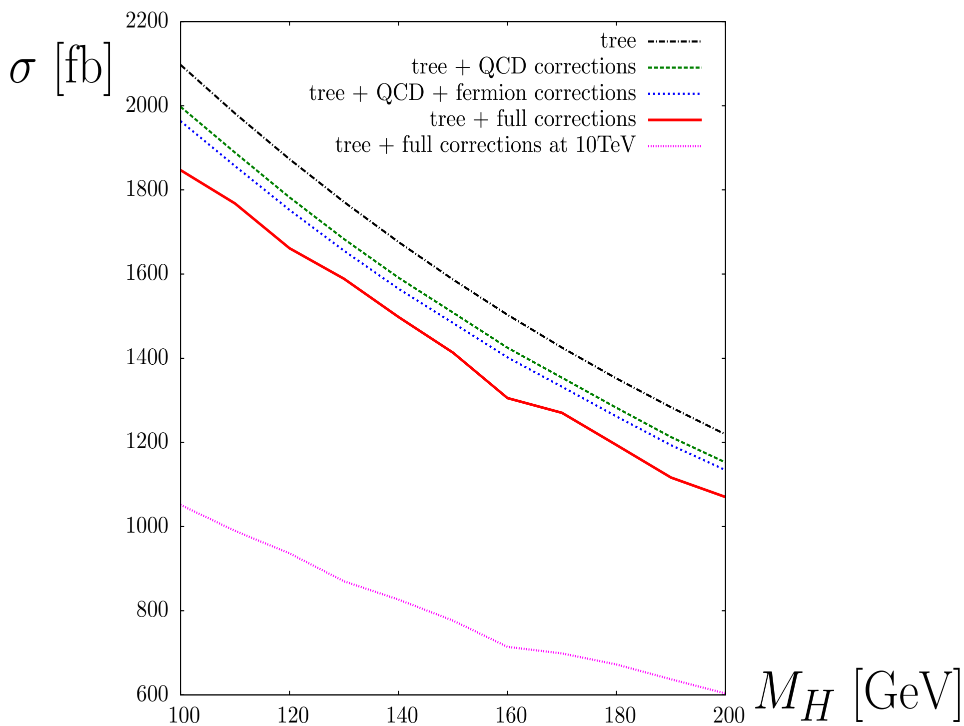
(c) Box diagrams

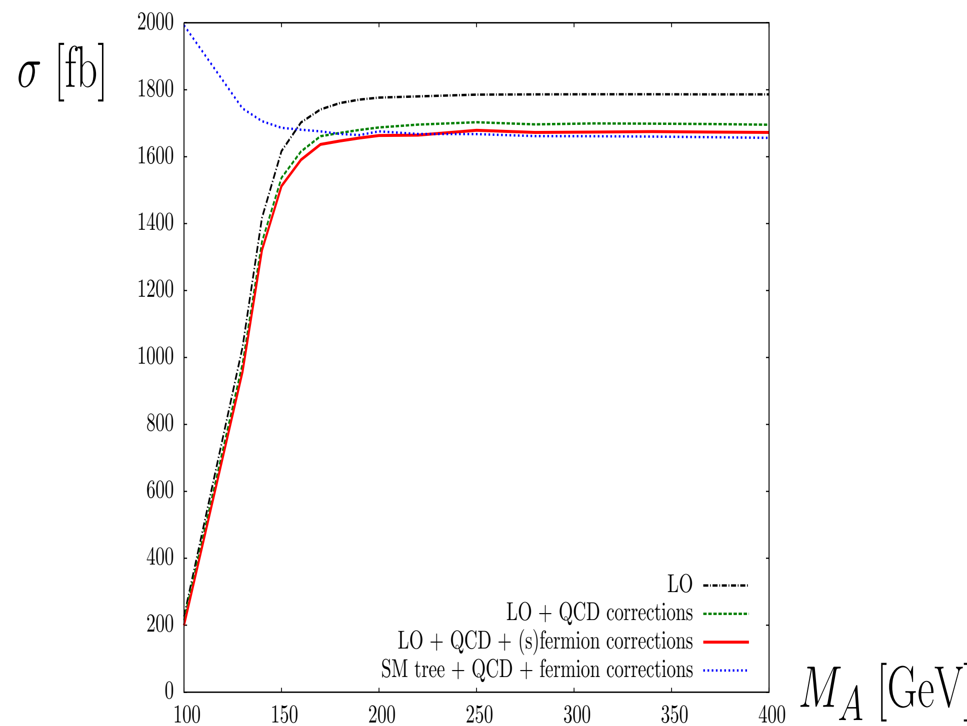


(d) Pentagon diagrams

Results for total cross section in the SM and the MSSM with WBF cuts

[*T. Figy, S. Palmer, G. W. '09*]





$\Rightarrow$ Electroweak corrections are as big as the QCD corrections

Results have been implemented into the public *VBFNLO* Monte Carlo program

Higgs potential of the MSSM

MSSM Higgs potential contains two Higgs doublets:

$$V_H = m_1^2 H_{1i}^* H_{1i} + m_2^2 H_{2i}^* H_{2i} - \epsilon^{ij} (m_{12}^2 H_{1i} H_{2j} + {m_{12}^2}^* H_{1i}^* H_{2j}^*)$$

$$+ \frac{1}{8}(g_1^2 + g_2^2)(H_{1i}^* H_{1i} - H_{2i}^* H_{2i})^2 + \frac{1}{2} g_2^2 |H_{1i}^* H_{2i}|^2$$

$$\begin{pmatrix} H_{11} \\ H_{12} \end{pmatrix} = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}$$

$$\begin{pmatrix} H_{21} \\ H_{22} \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

Complex phases $\arg(m_{12}^2)$, ξ can be rotated away

$\Rightarrow$ Higgs sector is $\mathcal{CP}$-conserving at tree level

Higher-order corrections in the MSSM Higgs sector

- Quartic couplings in the Higgs sector are given by the gauge couplings, g_1, g_2 (SM: free parameter)

  $\Leftrightarrow$ Upper bound on the lightest Higgs mass

- Large higher-order corrections from Yukawa sector:

  $\Rightarrow$ Leading corr.: $\Delta m_{\mathrm{h}}^2 \sim G_\mu m_{\mathrm{t}}^4$

  Can be of $\mathcal{O}(100\%)$

$\Rightarrow$ Higher-order corrections are phenomenologically very important (constraints on parameter space from search limits / possible future measurements)

Can induce $\mathcal{CP}$-violating effects

Higgs physics in the MSSM with complex parameters

Five physical states; tree level: $h^0, H^0, A^0, H^{\pm}$

Complex parameters enter via (often large) loop corrections:

– μ: Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– M_3: gluino mass $m_{\tilde{g}}$ + complex phase

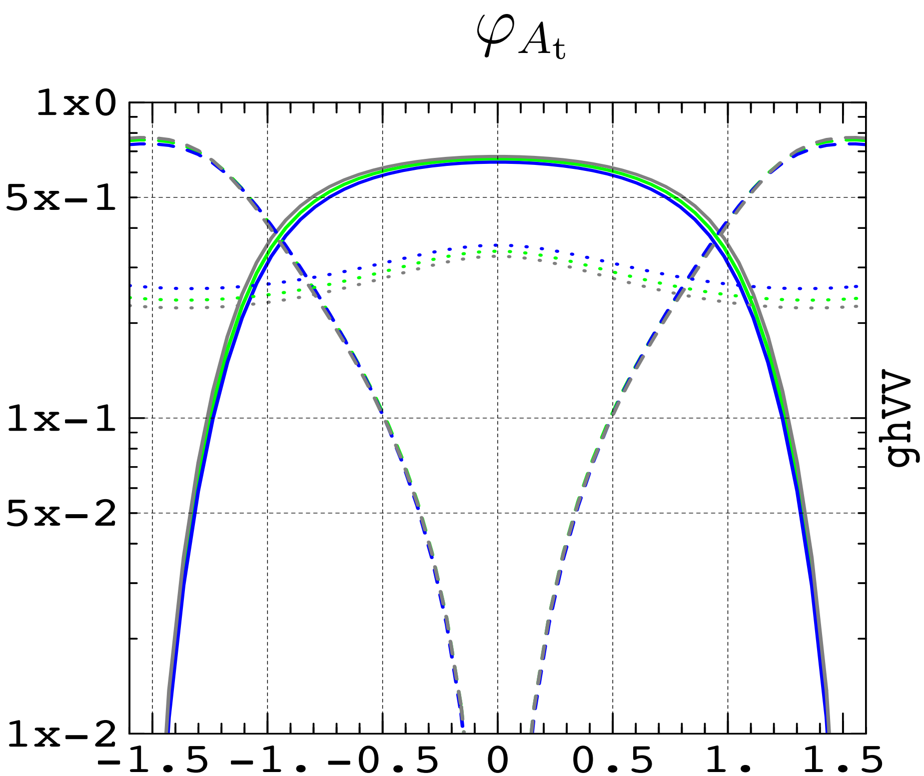
$\Rightarrow$ $\mathcal{CP}$-violating mixing between neutral Higgs bosons h_1, h_2, h_3

Lowest-order Higgs sector has two free parameters

$\Rightarrow$ choose $\tan\beta \equiv \frac{v_2}{v_1}$, $M_{\mathrm{H}^{\pm}}$ as input parameters

Impact of complex phases

Example: g^2_{hVV} for h_1, h_2, h_3: [*M. Frank, S. Heinemeyer, W. Hollik, G. W. '03*]



full: h_1, dashed: h_2, dotted: h_3

Parameters:

$M_{\rm SUSY} = 500$ GeV,

$M_2 = 500$ GeV,

$\mu = 2000$ GeV,

$|A_t| = 1000$ GeV,

$M_{H^\pm} = 150$ GeV, $\tan\beta = 5$

$\Rightarrow$ Complex phases can have large effects on Higgs couplings

Example: how light can the Higgs be?

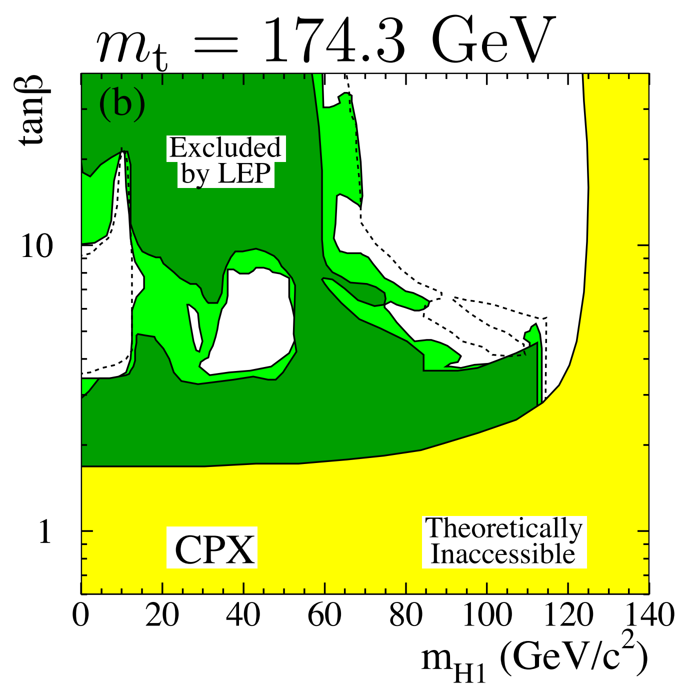
MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

Light Higgs, h_1: strongly suppressed h_1VV couplings

Second-lightest Higgs, h_2, possibly within LEP reach (with reduced VVh_2 coupling), h_3 beyond LEP reach

Large $\mathrm{BR}(h_2 \to h_1 h_1)$ $\Rightarrow$ difficult final state

[*LEP Higgs WG '06*]



$\Rightarrow$ Light SUSY Higgs not ruled out!

Some motivation for a very light non SM-like Higgs

"Little hierarchy problem:"

Prediction for $M_{\rm h}$:

$$M_{\rm h}^2 \approx M_{\rm Z}^2 \cos^2 2\beta + \frac{3G_\mu}{\sqrt{2}\pi^2} m_{\rm t}^4 \ln(M_{\tilde{\rm t}}^2/m_{\rm t}^2) + \ldots$$

⇒ Need $M_{\tilde{\rm t}} \gtrsim 500$ GeV to satisfy exclusion bound on SM-like Higgs, $M_{\rm h} > 114.4$ GeV

RG running from $M_{\rm GUT}$:

$$M_{\rm Z}^2 \approx 1.6\, M_{\tilde{\rm t}}^2 - 1.8\, \mu^2 + 5.9\, M_3^2 - 0.4\, M_2^2 - 1.2\, m_{H_u}^2 + \ldots$$

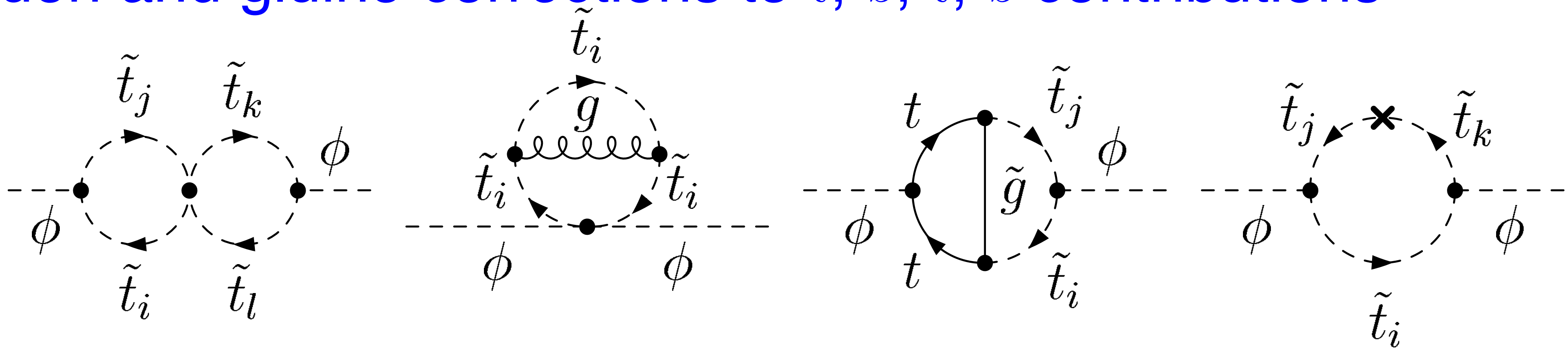
⇒ Need cancellations between soft SUSY-breaking parameters

⇒ (Slight) tension can be relaxed if Higgs is light

$\mathcal{CP}$-violating loop effects on Higgs-boson masses, Higgs decays and production processes

Leading two-loop QCD corrections in the Higgs sector:

Gluon and gluino corrections to t, b, $\tilde{\mathrm{t}}$, $\tilde{\mathrm{b}}$ contributions



Leading $\mathcal{O}(\alpha_{\mathrm{t}}\alpha_s)$ corrections: 2-loop contrib. evaluated in limit of vanishing gauge couplings, external momentum: $p^2 \to 0$

Renormalisation:

- 2-loop renormalisation in the Higgs sector, independent parameters: $M_{\mathrm{H}^\pm}$, $\tan\beta$
- 1-loop renormalisation in the $\tilde{\mathrm{t}}$, $\tilde{\mathrm{b}}$ sector, need also renormalisation of complex phase $\varphi_{A_{\mathrm{t}}}$

Higher-order corrections to the Higgs masses

Mixing between h, H, A

$\Rightarrow$ loop-corrected masses obtained from propagator matrix

$$\Delta_{hHA}(p^2) = -\left(\hat{\Gamma}_{hHA}(p^2)\right)^{-1}, \quad \hat{\Gamma}_{hHA}(p^2) = i\left[p^2 \mathbb{1} - \mathrm{M_n}(p^2)\right]$$

where (up to sub-leading two-loop corrections)

$$\mathrm{M_n}(p^2) = \begin{pmatrix} m_\mathrm{h}^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_\mathrm{H}^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & -\hat{\Sigma}_{HA}(p^2) & m_\mathrm{A}^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

$\Rightarrow$ Higgs propagators: $\Delta_{ii}(p^2) = \dfrac{i}{p^2 - m_i^2 + \hat{\Sigma}_{ii}^{\mathrm{eff}}(p^2)}$

Higher-order corrections to the Higgs masses

$$\hat{\Sigma}_{ii}^{\text{eff}}(p^2) = \hat{\Sigma}_{ii}(p^2) - i\frac{2\hat{\Gamma}_{ij}(p^2)\hat{\Gamma}_{jk}(p^2)\hat{\Gamma}_{ki}(p^2) - \hat{\Gamma}_{ki}^2(p^2)\hat{\Gamma}_{jj}(p^2) - \hat{\Gamma}_{ij}^2(p^2)\hat{\Gamma}_{kk}(p^2)}{\hat{\Gamma}_{jj}(p^2)\hat{\Gamma}_{kk}(p^2) - \hat{\Gamma}_{jk}^2(p^2)}$$

Complex pole $\mathcal{M}^2$ of each propagator is determined from

$$\mathcal{M}_i^2 - m_i^2 + \hat{\Sigma}_{ii}^{\text{eff}}(\mathcal{M}_i^2) = 0,$$

where

$$\mathcal{M}^2 = M^2 - iM\Gamma,$$

Expansion around the real part of the complex pole:

$$\hat{\Sigma}_{jk}(\mathcal{M}_{h_a}^2) \approx \hat{\Sigma}_{jk}(M_{h_a}^2) + i\,\mathrm{Im}\left[\mathcal{M}_{h_a}^2\right]\hat{\Sigma}'_{jk}(M_{h_a}^2)$$

$j, k = h, H, A,\ a = 1, 2, 3$

Impact of complex phases at the two-loop level

$\mathcal{O}(\alpha_t \alpha_s)$ corrections depend only on the phase combinations

$$\mu\, A_t\, \left(m_{12}^2\right)^* \quad \text{and} \quad A_t\, M_3^*$$

Phase of m_{12}^2 has been rotated away (see above)

$\Rightarrow$ Analyse the dependence on the phases of A_t (X_t) and M_3

Variation of φ_{A_t} for fixed μ, $\tan\beta$

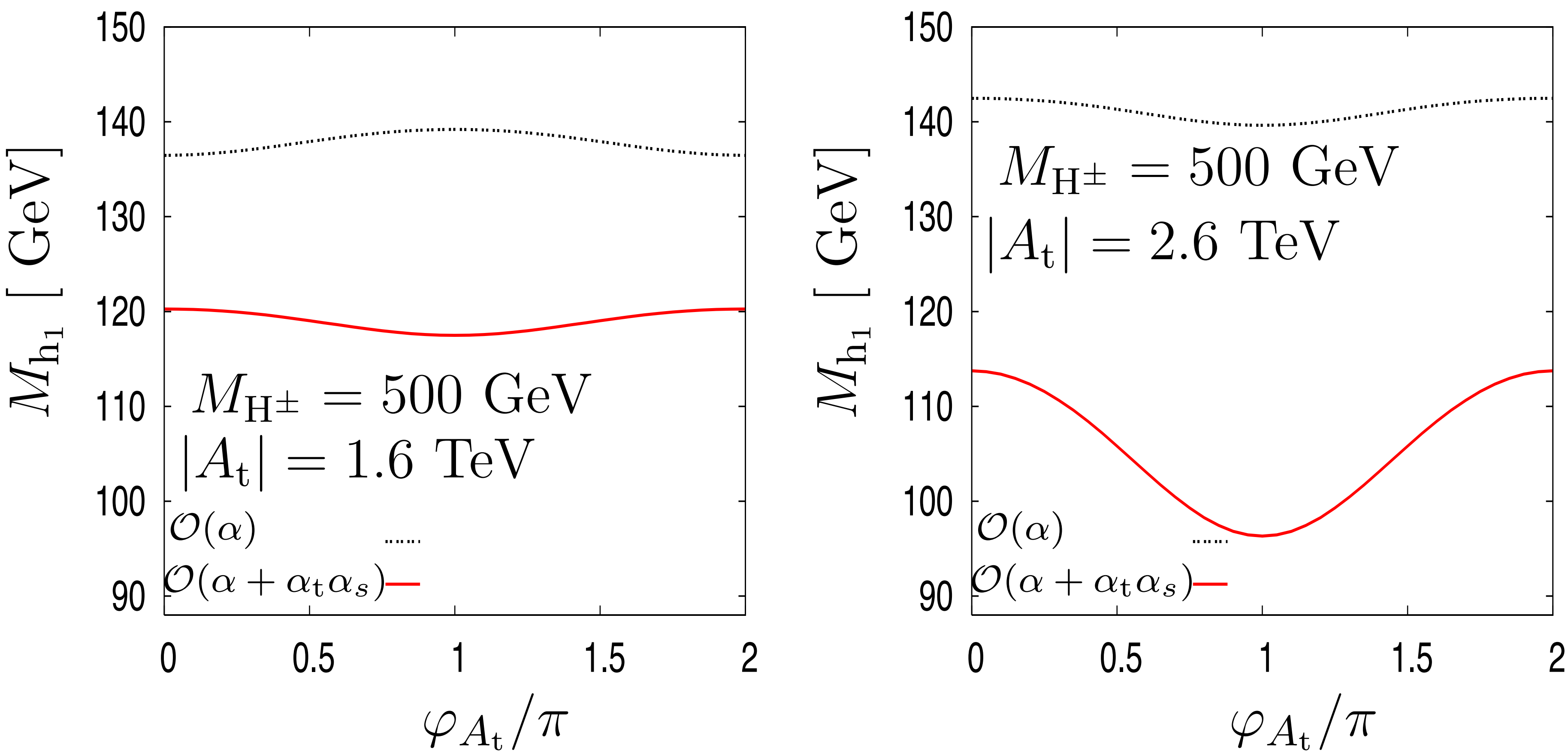
$\Rightarrow$ change of $|X_t| \equiv |A_t - \mu^*/\tan\beta|$ $\Rightarrow$ change of stop masses

Variation of φ_{X_t}

$\Rightarrow$ change of A_t, stop masses stay the same

Dependence of prediction for M_{h_1} on φ_{A_t}: one-loop vs. two-loop

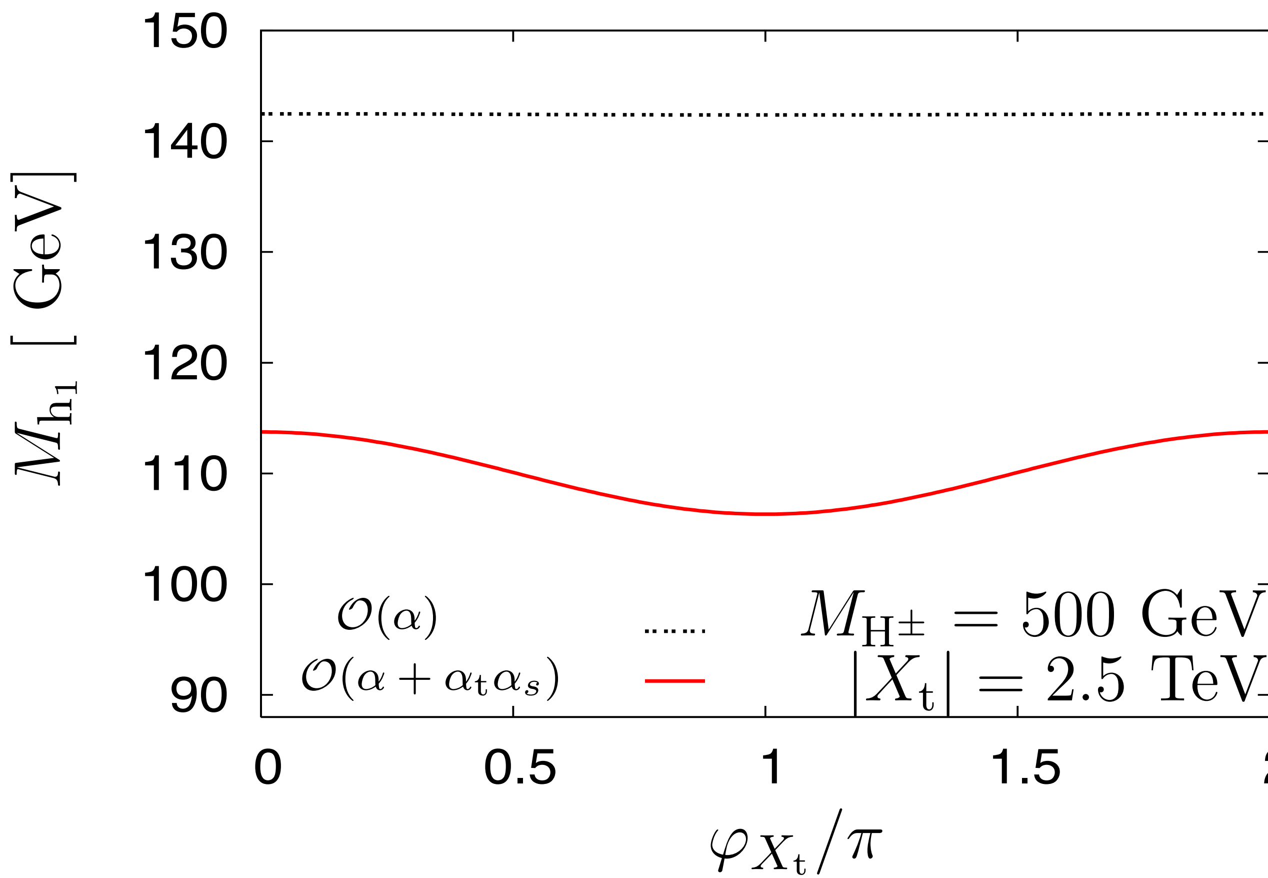
[*S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '07*] $\mu = 1$ TeV, $\tan\beta = 10$



$\Rightarrow$ Two-loop corrections significantly enhance the effects of the complex phase φ_{A_t}, sizable effects for large $|A_t|$

Dependence of prediction for M_{h_1} on φ_{X_t}: one-loop vs. two-loop

[S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '07] $\mu = 1$ TeV, $\tan\beta = 10$



$\Rightarrow$ One-loop: very weak dependence on φ_{X_t}

Two-loop: large change in phase dependence

Reason for the large impact of the phase in the two-loop contribution

Leading one-loop result in the limit $M_{\mathrm{H}^\pm} \gg M_{\mathrm{Z}}$ depends only on the absolute value $|X_{\mathrm{t}}| \equiv |A_{\mathrm{t}} - \mu^* / \tan\beta|$

$\Leftrightarrow$ only combination $\varphi_{A_{\mathrm{t}}} + \varphi_\mu$ enters

$\Rightarrow$ weak dependence of one-loop result on $\varphi_{X_{\mathrm{t}}}$
dependence on $\varphi_{A_{\mathrm{t}}}$ mainly through $|X_{\mathrm{t}}|$

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Two-loop level:

$\Rightarrow$ Gluino contributions introduce dependence on phase combination $A_{\mathrm{t}}\, M_3^*$

$\Rightarrow$ Large modification of phase dependence

Higgs mixing

- Need to establish the correct on-shell properties of processes with external Higgs bosons

  $\Rightarrow$ finite wave function normalisation factors Z_i introduced

- Unstable particles $\Rightarrow$ finite-width effects important

- h_2, h_3 are almost mass-degenerate over a large part of the parameter space

  $M_{h_3} - M_{h_2} \sim \Gamma_{h_2}, \Gamma_{h_3}$

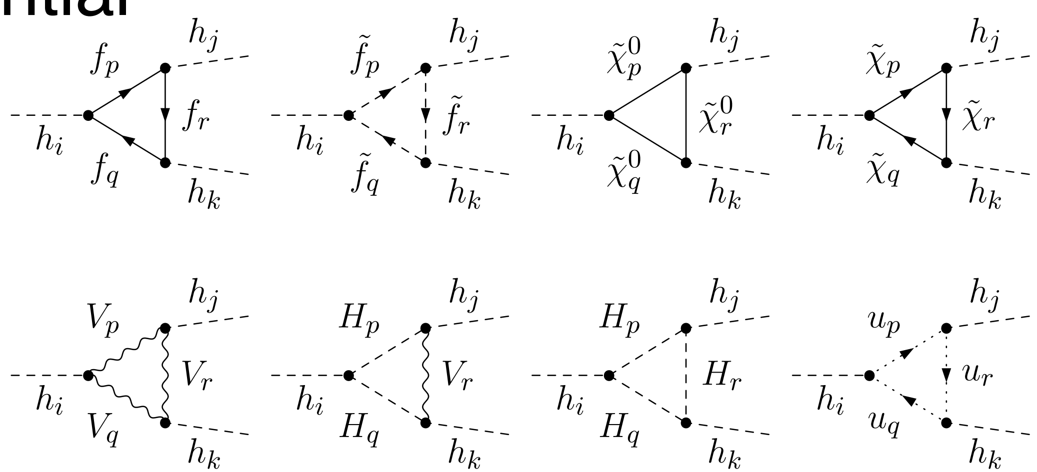
  $\Rightarrow$ resonance-type effects possible

Higgs cascade decays: $h_2 \to h_1 h_1$***, . . .***

Higgs cascade decays:

- Important for Higgs searches: $h_2 \to h_1 h_1$ is in general the dominant channel where it is kinematically allowed

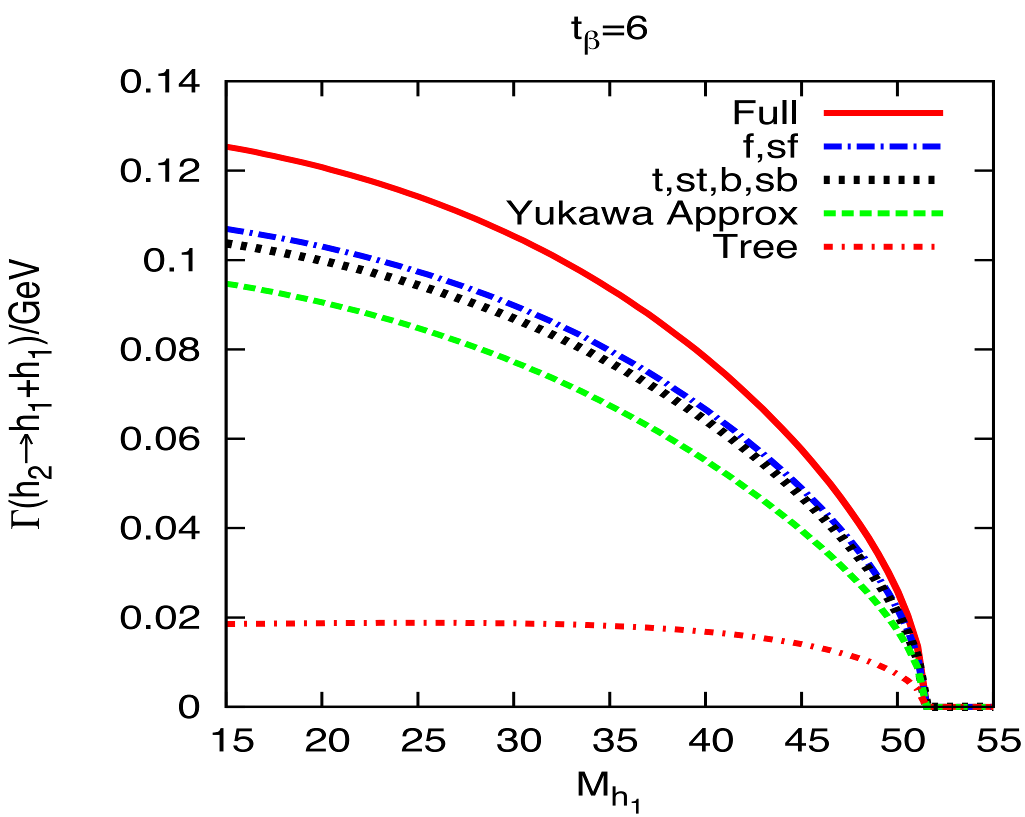
- Access to Higgs self-coupling $\Rightarrow$ reconstruction of the Higgs potential



Complete one-loop results in the MSSM with complex parameters $+$ two-loop propagator-type corrections
[*K. Williams, G. W. ’07*]

Impact of higher-order corrections on prediction for $\Gamma(h_2 \to h_1 h_1)$

Complete 1-loop result for $(h_2 h_1 h_1)$ vertex contribution in the MSSM with complex parameters [*K. Williams, G. W. '07*]
$+$ 2-loop propagator corrections; CPX benchmark scenario
[*S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '07*]

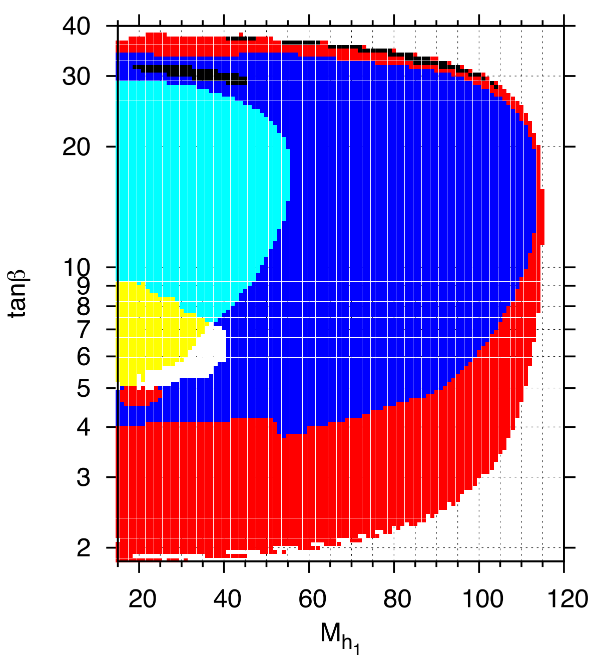


$\Rightarrow$ Huge effect from corrections to genuine $(h_2 h_1 h_1)$ vertex

Analysis of LEP coverage with improved theoretical prediction

HiggsBounds [P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08]

Use cross section limits (expected and observed) from LEP and the Tevatron; determine for every parameter point the search channel with the highest statistical sensitivity for setting an exclusion; comparison of prediction for this channel with observed limit yields 95% C.L. exclusion contour



Channels:

(■ red) $= (h_1 Z) \to (b\bar{b}Z)$

(■ blue) $= (h_2 Z) \to (b\bar{b}Z)$

(□) $= (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$

(■ cyan) $= (h_2 h_1) \to (b\bar{b}b\bar{b})$

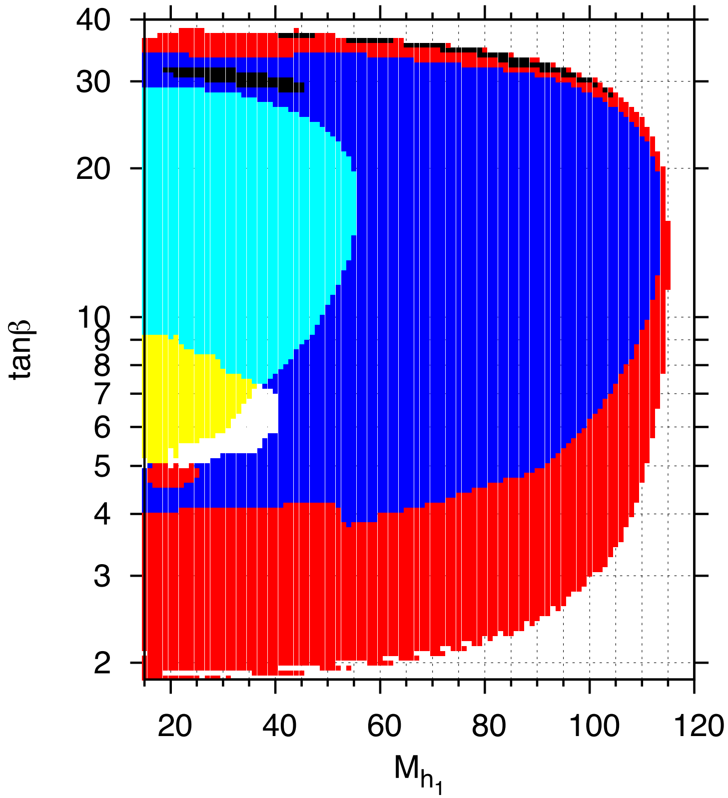
(■ yellow) $= (h_2 h_1) \to (h_1 h_1 h_1) \to (b\bar{b}b\bar{b}b\bar{b})$

(■ black) $=$ other channels

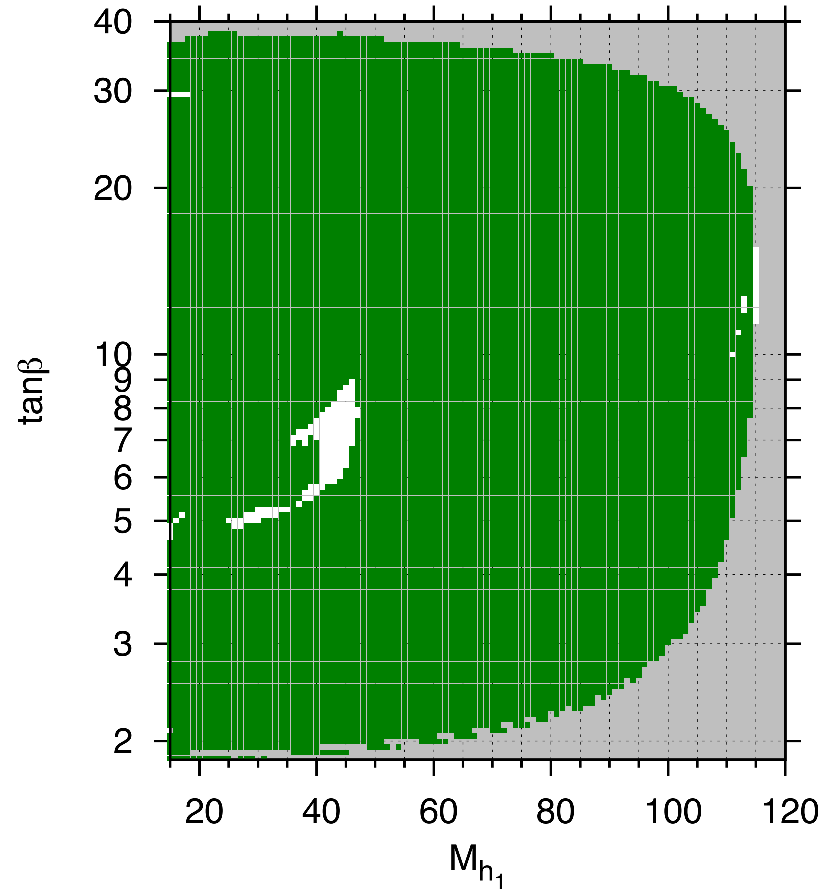
Impact on exclusion bounds from the LEP Higgs searches, CPX scenario, $m_{\rm t} = 170.9~\mathrm{GeV}$

Channels (*HiggsBounds*)

$(\square) : (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$



Excluded region from LEP, 95% C.L. [*K. Williams, G. W. '07*]



⇒ Confirmation of the “hole” in the LEP coverage

⇒ Very light Higgs boson is not excluded

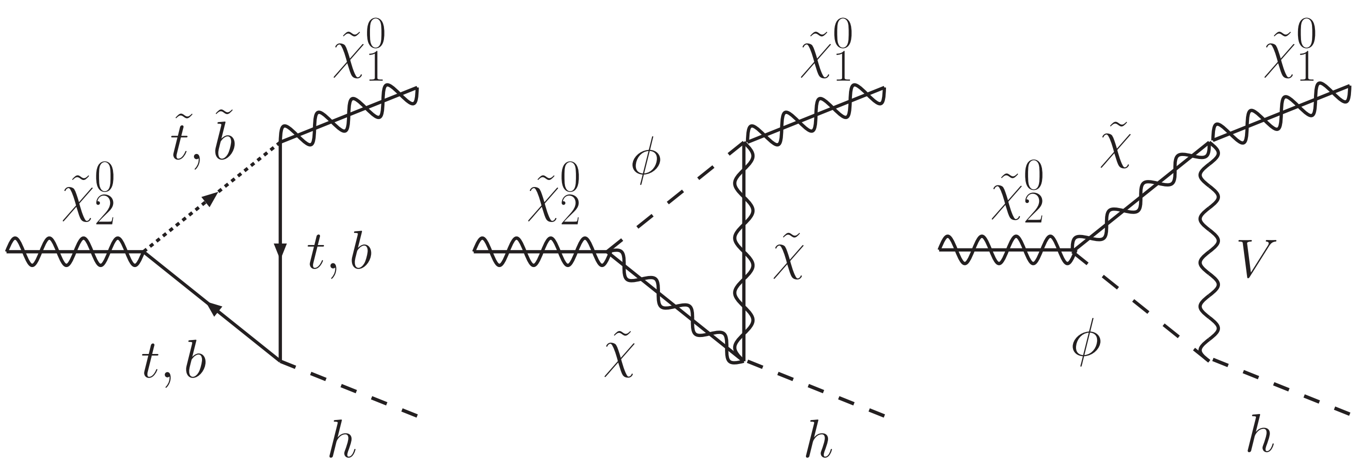
Higgs production in SUSY cascade decays

SUSY cascade decays could be a promising Higgs source

E.g. $\mathcal{CP}$-violating scenario: very light Higgs, $M_{\mathrm{h}_1} \approx 40\ \mathrm{GeV}$ not excluded by LEP, difficult to cover with standard search channels at the LHC

$\Rightarrow \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ can dominate over $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l \bar{l}$

[*A. Fowler, G. W. '09*]



$\Rightarrow$ CPX scenario: 13% of the gluinos decay into h_1

If a Higgs candidate has been detected: experimental questions

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- Is it a Higgs boson?
- What are its mass, spin and $\mathcal{CP}$ properties?
- What are its couplings to fermions and gauge bosons? Are they really proportional to the masses of the particles?
- What are its self-couplings?
- Are its properties compatible with the SM, the MSSM, the NMSSM, . . . ?
- Are there indications that there are more than one Higgs bosons or other new states that influence Higgs physics?

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$\Rightarrow$ Comprehensive set of precision measurements needed
LHC / LC complementarity

Conclusions

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  ⇒ Expect manifestations of mechanism(s) responsible for EWSB and for stabilising hierarchy M_{weak} / M_{Planck}

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- Figuring out the nature of TeV-scale physics will be challenging and exciting
  Interaction between experiment and theory will be crucial

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- MSSM with complex parameters has rich phenomenology
  Improved prediction for Higgs cascade decays $h_j \to h_i h_i$
  ⇒ A very light MSSM Higgs boson is not excluded
  ⇒ Could be produced at LHC in SUSY cascade decays
- Figuring out the nature of TeV-scale physics will be challenging and exciting
  Interaction between experiment and theory will be crucial

Looking forward to very exciting times ahead of us!