LHC Physics on Day 1 after the Discovery

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DESY

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- Introduction
- How to interpret the observed signal?
- Where are the SUSY particles?
- What next?
- Conclusions

Introduction

[*R.-D. Heuer, 04.07.2012*]

Highest significance: $\gamma\gamma$ channel

ATLAS: 4.5σ observed, 2.4σ expected for SM Higgs
Signal strength: $\mu = 1.9 \pm 0.5$

CMS: 4.1σ observed, $\sim 2.6\sigma$ expected for SM Higgs
Signal strength: $\mu = 1.56 \pm 0.43$

$\Rightarrow$ Observed signal strength of $\gamma\gamma$ rate is above the expectation for a SM Higgs in ATLAS and CMS

Statistically not sufficiently significant to draw firm conclusions

Will be interesting to watch . . .

What's so special about a Higgs?

- The fundamental interactions of elementary particles are described very successfully by quantum field theories that follow an underlying symmetry principle:
  "gauge invariance"
- This fundamental symmetry principle requires that all the elementary particles and force carriers should be massless
- However: W, Z, top, bottom, . . . , electron are massive, have widely differing masses

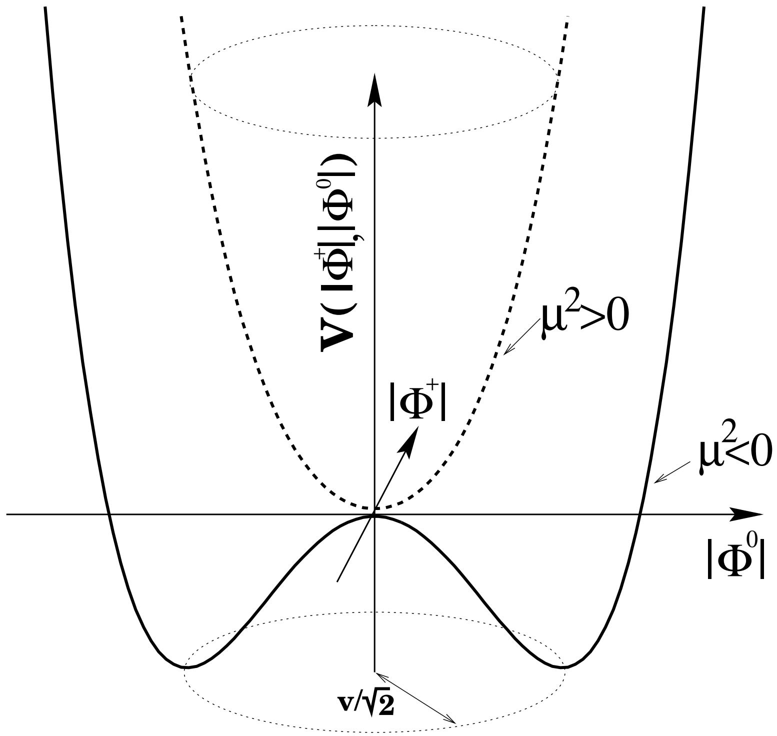
How can elementary particles acquire mass without spoiling the fundamental symmetries of nature?

The Higgs mechanism

Spontaneous symmetry breaking: the interaction obeys the symmetry principle, but not the state of lowest energy

New field postulated that fills all of the space: the Higgs field

The state of the lowest energy of the Higgs field (vacuum state) does not obey the underlying symmetry principle (gauge invariance)



$\Rightarrow$ Spontaneous breaking of the gauge symmetry

The Higgs field and the Higgs boson

Higgs mechanism: fundamental particles obtain their masses from interacting with the Higgs field

Higgs boson(s): field quantum of the Higgs field
(like the photon is the quantum of the electromagnetic field)

Higgs coupling to other particles is proportional to their masses

The postulated Higgs boson is a scalar particle (spin 0)

Up to now no fundamental scalar particle has been observed in nature

The Higgs mechanism sounds like a rather bold assumption to cure a theoretical / aesthetical problem

But: we know that there has to be new physics that is responsible for electroweak symmetry breaking

Our current description breaks down at the TeV scale

$\Rightarrow$ The physics of electroweak symmetry breaking must manifest itself at the TeV scale

Possible alternatives to the Higgs mechanism:

- A new fundamental strong interaction (“strong electroweak symmetry breaking”)
- New dimensions of space (electroweak symmetry breaking via boundary conditions for SM gauge bosons and fermions on “branes” in a higher-dimensional space)

Higgs: last missing ingredient of the "Standard Model"

But: the Standard Model cannot be the ultimate theory

- The Standard Model does not include gravity

  $\Rightarrow$ breaks down at the latest at $M_{\rm Planck} \approx 10^{19}$ GeV

- "Hierarchy problem": $M_{\rm Planck}/M_{\rm weak} \approx 10^{17}$

  How can two so different scales coexist in nature?

  Via quantum effects: physics at $M_{\rm weak}$ is affected by physics at $M_{\rm Planck}$

  $\Rightarrow$ Instability of $M_{\rm weak}$

  $\Rightarrow$ Would expect that all physics is driven up to the Planck scale

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

Hierarchy problem: how can the Planck scale be so much larger than the weak scale?

$\Rightarrow$ Expect new physics at the TeV scale to stabilise the hierarchy

Supersymmetry:

Large quantum corrections cancel out because of symmetry fermions $\Leftrightarrow$ bosons

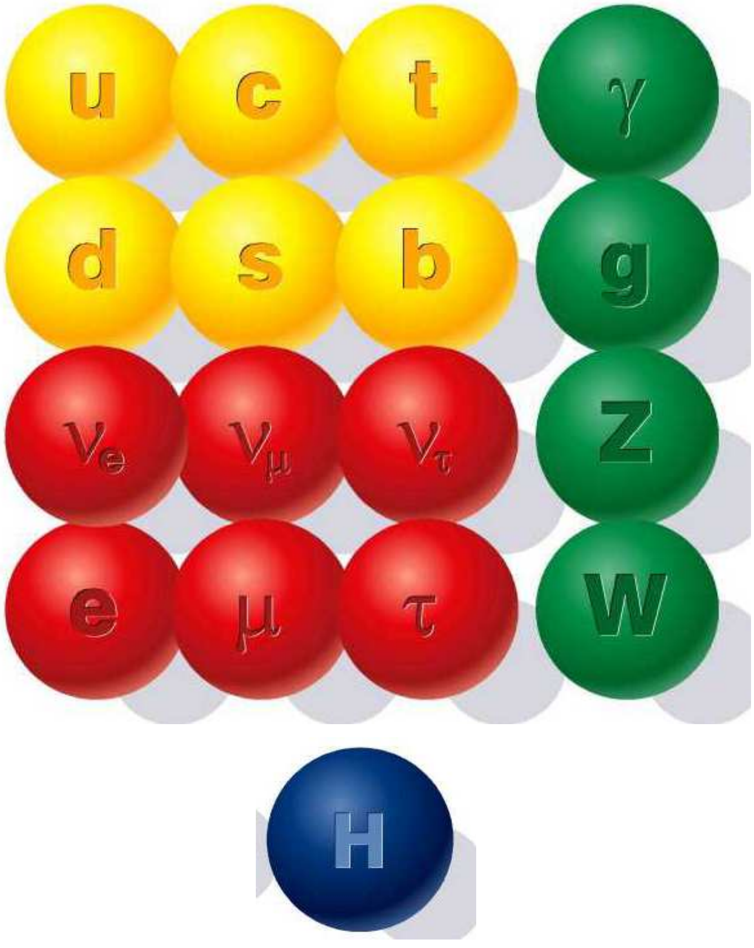
Extra dimensions of space:

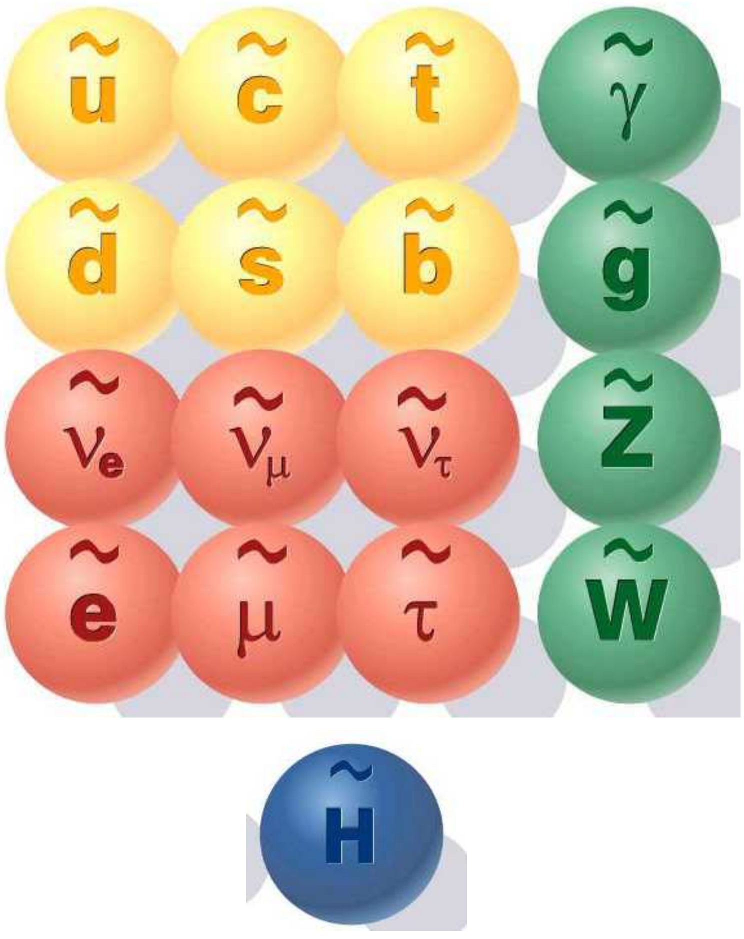
Fundamental Planck scale is $\sim \mathrm{TeV}$ (large extra dimensions),

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

Supersymmetry (SUSY)

Supersymmetry: fermion $\longleftrightarrow$ boson symmetry,
leads to compensation of large quantum corrections





The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

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

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

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

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

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?

Exact SUSY $\Leftrightarrow m_{\mathrm{e}} = m_{\tilde{\mathrm{e}}}, \ldots$

$\Rightarrow$ SUSY can only be realised as a broken symmetry

MSSM: no particular SUSY breaking mechanism assumed, parameterisation of possible soft SUSY-breaking terms

$\Rightarrow$ relations between dimensionless couplings unchanged

$\Rightarrow$ cancellation of large quantum corrections preserved

Most general case: 105 new parameters

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}, ...)
renormalisation group running down to weak scale
require correct value of M_{Z}

$\Rightarrow$ CMSSM characterised by

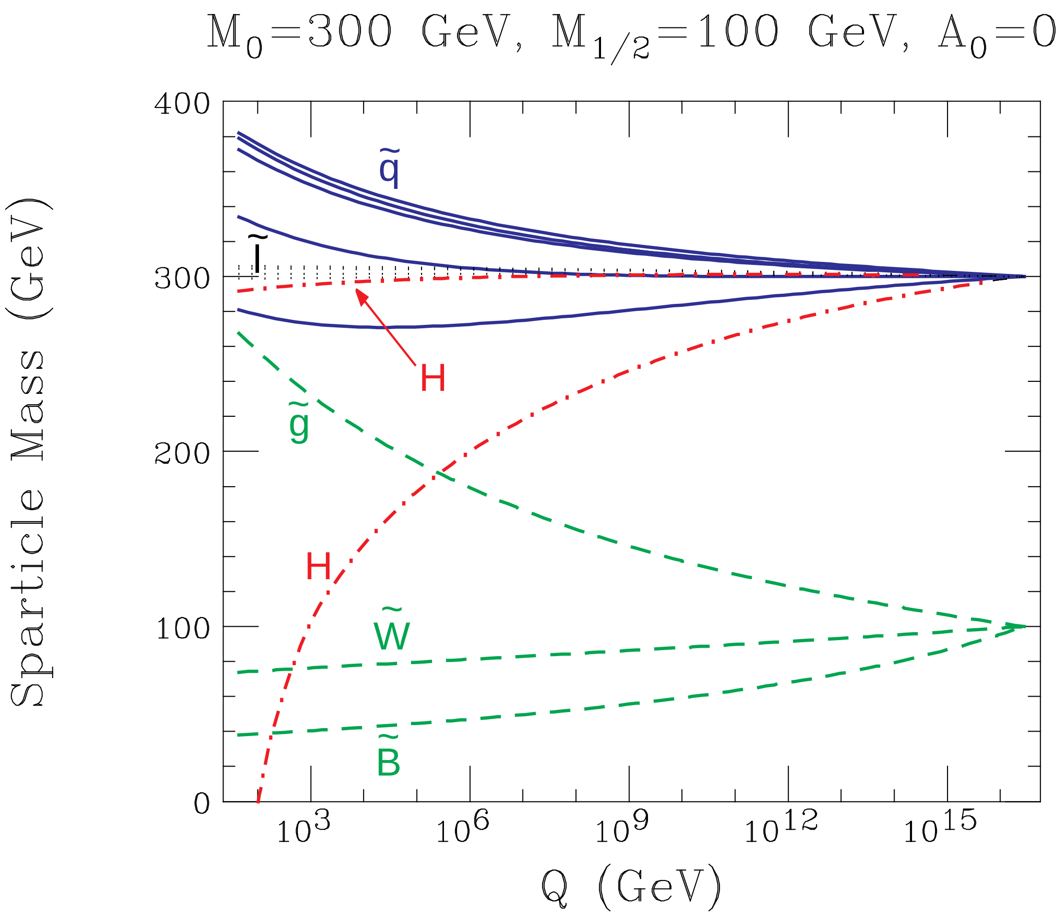
$$m_0^2,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

CMSSM has been the “favourite toy” for both theorists and experimentalists so far

CMSSM is in agreement with the experimental constraints from electroweak precision observables (EWPO)
$+$ flavour physics $+$ cold dark matter density $+$ ...

Radiative electroweak symmetry breaking

Universal boundary conditions at GUT scale,
renormalisation group running down to weak scale



large corrections from top-quark Yukawa coupling

$\Rightarrow$ $m^2_{H_u}$ driven to negative values

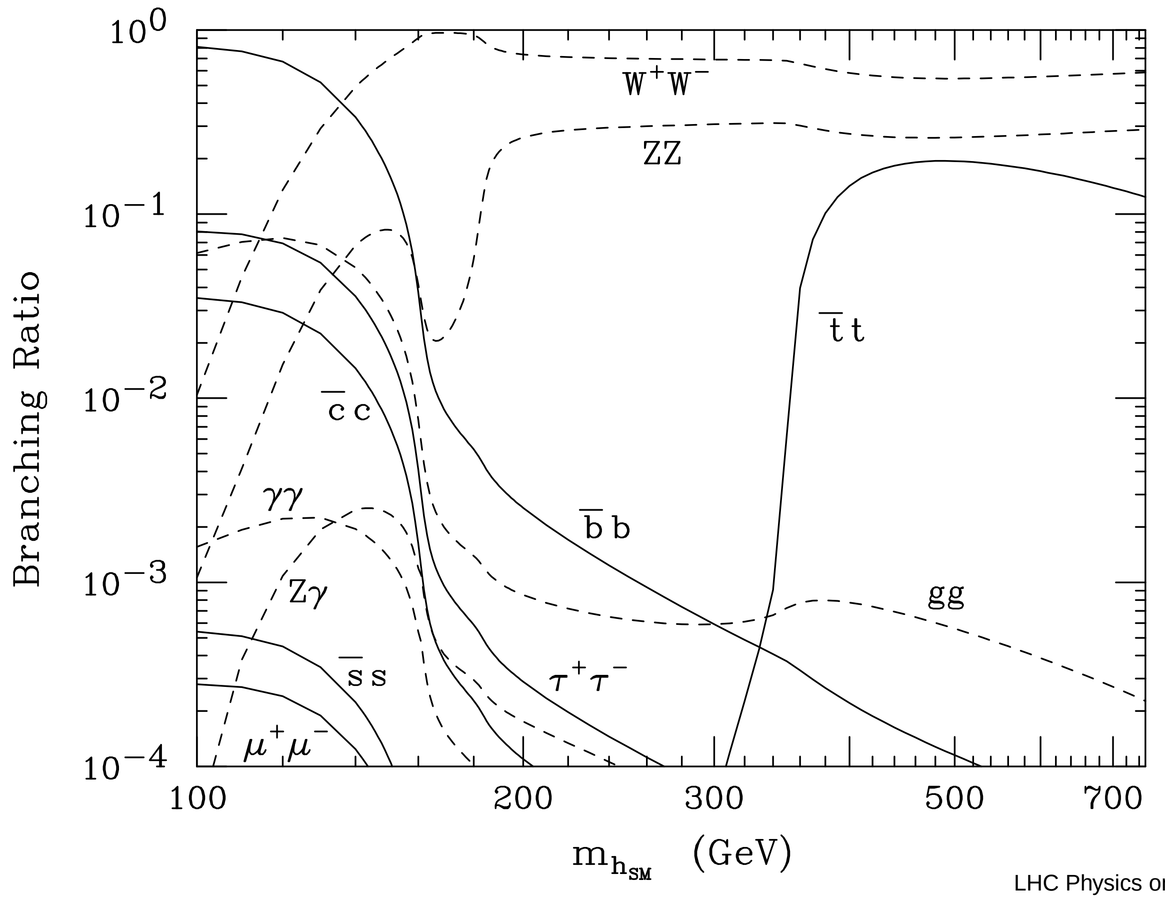
$\Rightarrow$ ew symmetry breaking

emerges naturally at scale $\sim 10^2$ GeV for $100\ \text{GeV} \lesssim m_\text{t} \lesssim 200\ \text{GeV}$

Higgs phenomenology: SM and beyond

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:
$H \to W^+W^-, ZZ$

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

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 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

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

$\Rightarrow$ 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*]

$$M_\mathrm{h} \lesssim 135\,\mathrm{GeV}$$

Very rich phenomenology

NMSSM Higgs sector: additional singlet

Motivated by "μ problem":

MSSM contains term $\mu H_d H_u$ in superpotential

μ: dimensionful parameter

For EW symmetry breaking required: $\mu \sim$ electroweak scale

But: no a priori reason for $\mu \neq 0$, $\mu \ll M_{\mathrm{Pl}}$

NMSSM: μ related to v.e.v. of additional field

$\Rightarrow$ Introduction of extra singlet field S, v.e.v. s

Superpotential: $\mathcal{V} = \lambda H_d H_u S + \frac{1}{3}\kappa S^3 + \dots$

Physical states in NMSSM Higgs-sector:

S_1, S_2, S_3 (CP-even), P_1, P_2 (CP-odd), $H^\pm$

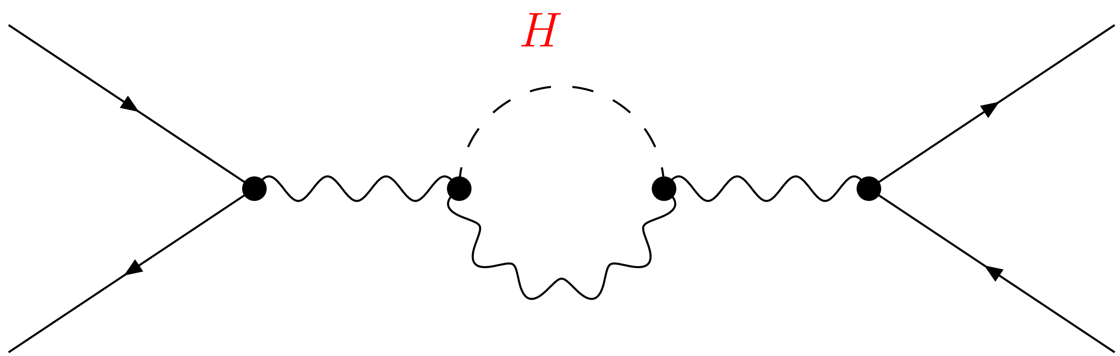
Indirect constraints

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

Theory:
SM, MSSM, ...

$\Downarrow$

Test of theory at quantum level: loop corrections



$\Downarrow$

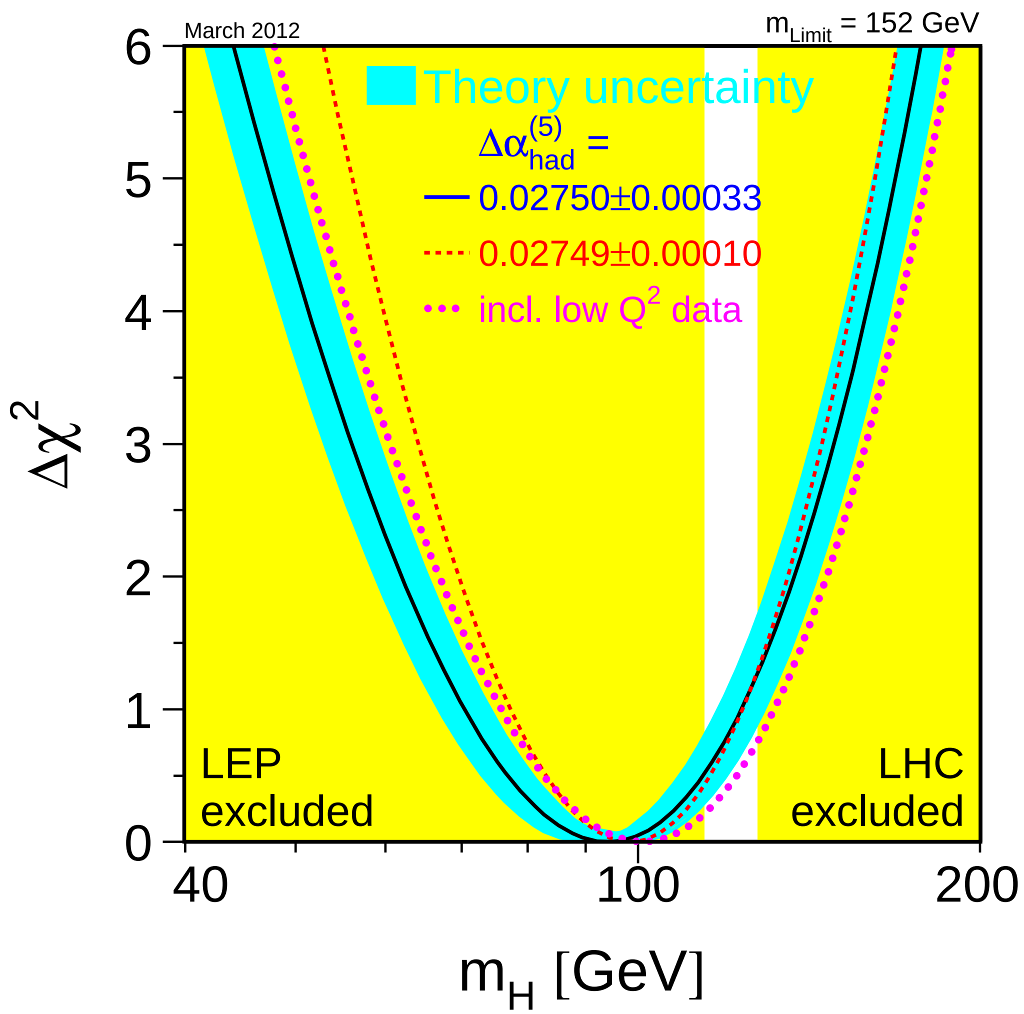
Sensitivity to effects from unknown parameters: M_H, $M_{\tilde{t}}$, ...

Window to “new physics”

Constraints on the SM Higgs from electroweak precision data

Indirect constraint on $M_{\mathrm{H_{SM}}}$, no direct search limits included in the fit

[*LEPEWWG '12*]

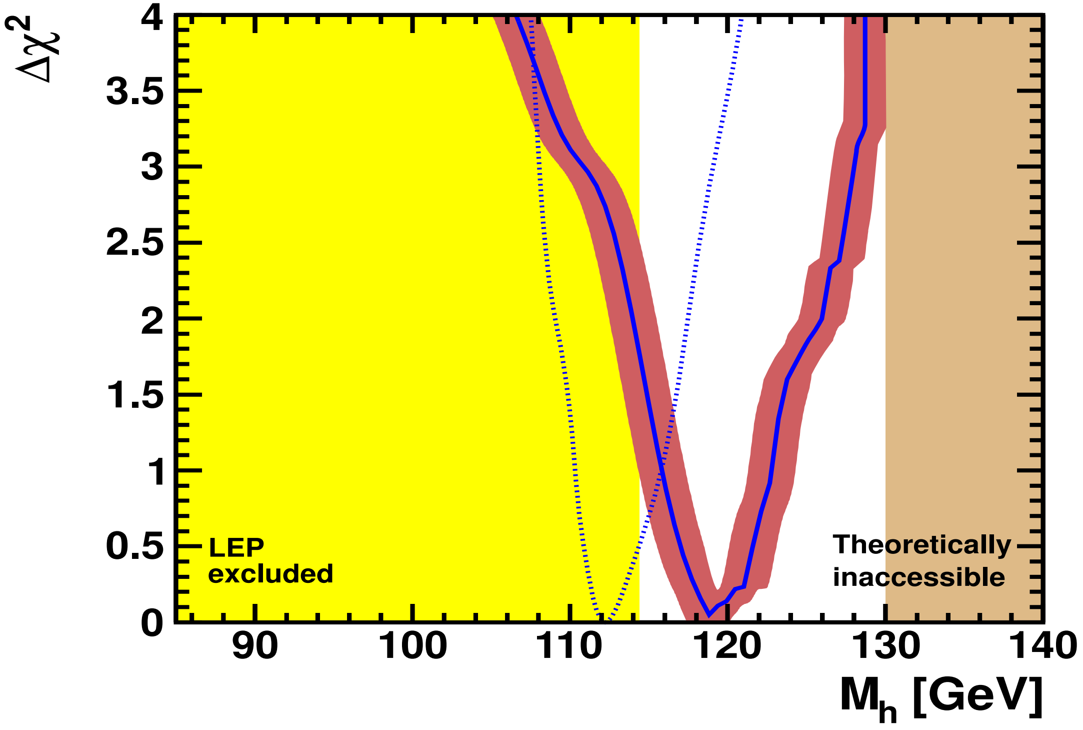


⇒ Preference for a light Higgs, $M_{\mathrm{H_{SM}}} < 152\ \mathrm{GeV}$, 95% C.L.

Indirect prediction for the Higgs mass in constrained SUSY model: pre-LHC vs. LHC2011

χ^2 fit for M_h, without imposing direct search limit

CMSSM:



$\Rightarrow$ Accurate indirect prediction

Fit without $(g-2)_\mu$, best fit value for M_h:

CMSSM: $M_\mathrm{h} \sim 125$ GeV, NUHM1: $M_\mathrm{h} \sim 127$ GeV

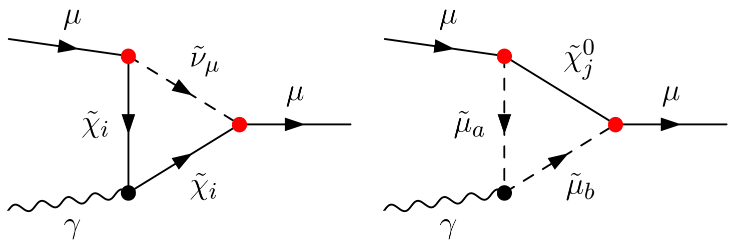
The anomalous magnetic moment of the muon:

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

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 extensions of the SM $\Leftrightarrow$ additional loop contributions

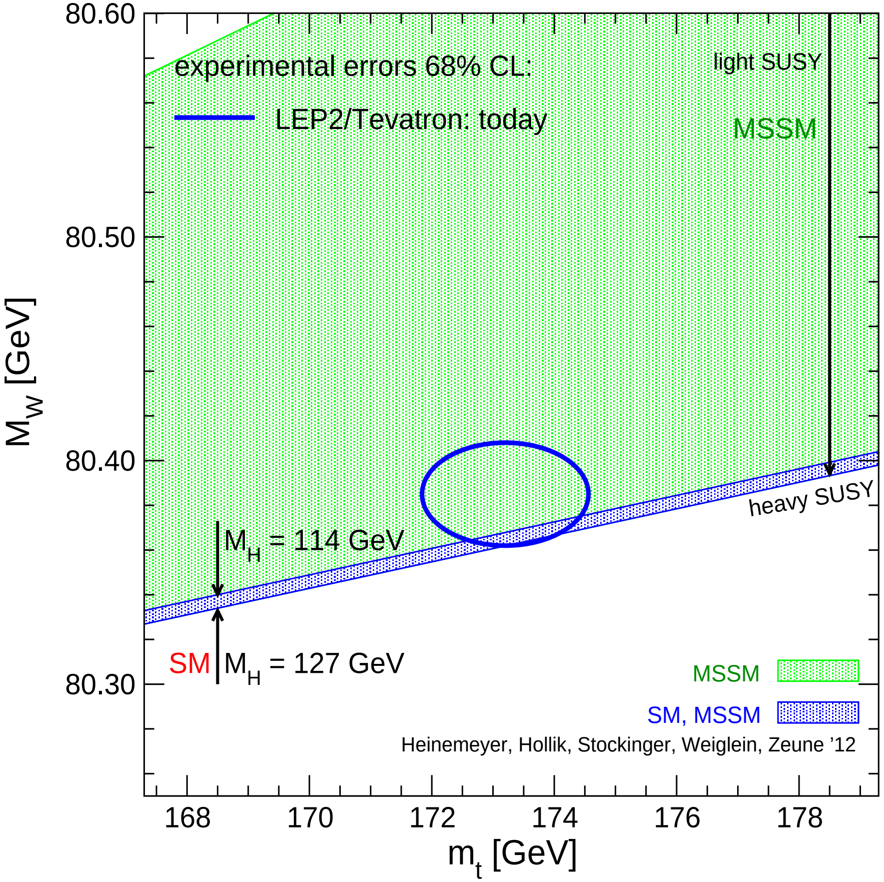


$(g-2)_\mu$: preference for light new physics contributions has further solidified (convergence of SM predictions using low-energy e^+e^- and τ decay data as input)

[*F. Jegerlehner, R. Szafron '11*]

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, G. W., L. Zeune '12*]

MSSM: SUSY parameters varied

SM: M_H varied

Formerly: MSSM only,
SM / MSSM overlap, SM only

Tevatron result for m_t interpreted (perturbatively) as pole mass

$\Rightarrow$ Parameter region that could only be realised in the SM but not in the MSSM has disappeared because of Higgs limits

Slight pref. for SUSY spectrum where some states are light

How to interpret the observed signal?

Limits $+$ observation are good news for SUSY!

The SUSY relations imply an upper bound on the mass of the light $\mathcal{CP}$-even Higgs, M_h

$\Rightarrow$ In the MSSM: $M_\mathrm{h} \lesssim 135\ \mathrm{GeV}$

- The detection of a SM-like Higgs with $M_\mathrm{H} \gtrsim 135\ \mathrm{GeV}$ would have unambiguously ruled out the MSSM

  Region above the upper bound of the MSSM has been ruled out for a SM-like Higgs

- Observed state at $\sim 125\ \mathrm{GeV}$ fits well into the mass range predicted for the light $\mathcal{CP}$-even Higgs of the MSSM

Interpretation of the observed state within the MSSM and the NMSSM

- Limits from the SM Higgs searches have constrained the allowed region for a light SM-like Higgs to about $123~\mathrm{GeV} \lesssim M_{\mathrm{H_{SM}}} \lesssim 127~\mathrm{GeV}$
- State observed by ATLAS and CMS with a mass of about $125~\mathrm{GeV}$, detected rate in the $\gamma\gamma$ channel is somewhat higher than the expectation for a SM Higgs

  Excess of about 3σ observed at the Tevatron

  Statistical significance of possible deviation from the expectation for a SM Higgs is not yet conclusive

$\Rightarrow$ Investigate MSSM and NMSSM interpretation of observed signal at $\approx 125~\mathrm{GeV}$

Here: use $125 \pm 1~\mathrm{GeV}$ for mass of observed state, theo. uncertainties from unknown higher-order corr., $\Delta M_{\mathrm{h}}^{\mathrm{intr}} \sim 2~\mathrm{GeV}$, and parametric uncertaintes (m_{t} varied by $\pm 1\sigma$) taken into account

Interpretation of the observed signal at ~ 125 GeV ***in terms of the light MSSM CP-even Higgs*** h

Observed signal at ~ 125 GeV implies lower bound on M_h

$\Rightarrow$ Set parameters entering via higher-order corrections such that M_h is maximised ($m_\mathrm{h}^\mathrm{max}$ benchmark scenario)

$\Rightarrow$ Lower bounds on M_A, $\tan\beta$

Search limits from LEP and from LHC (2011 data) taken into account:

HiggsBounds

[*P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., K. Williams '08, '12*]

HiggsBounds: *determination of 95% C.L. exclusion region from given cross section limits*

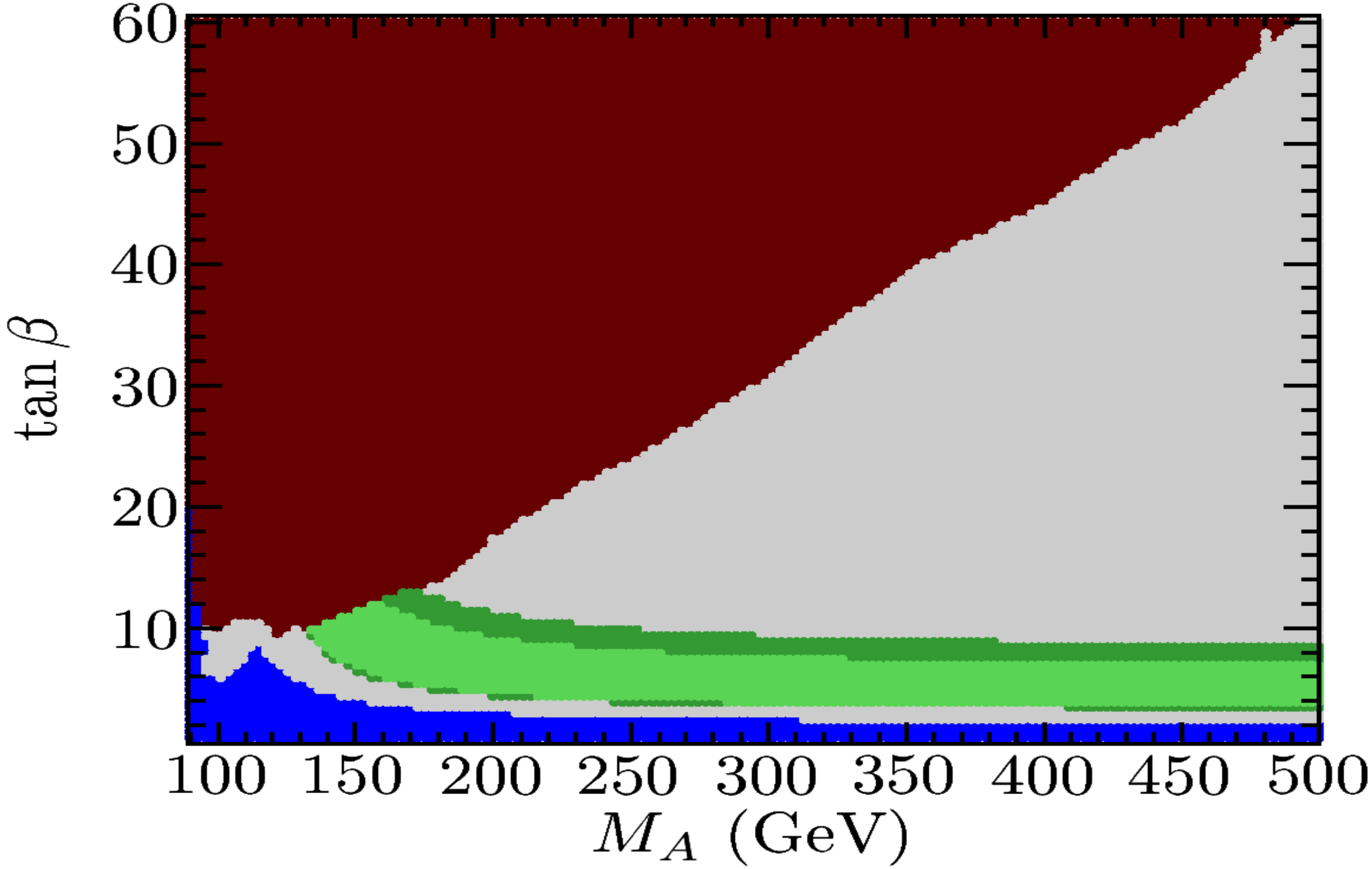
In order to obtain an exclusion limit having the correct statistical interpretation as a 95% C.L.:

- On the basis of the expected search limits for different channels in a given model one needs to determine for every parameter point the search channel having the highest statistical sensitivity for setting an exclusion limit

- For this single channel only one needs to compare the observed limit with the theory prediction for the Higgs production cross section times decay branching ratio to determine whether or not the considered parameter point of the model is excluded at 95% C.L.

Lower bounds on M_A *and* $\tan\beta$ *from assumed Higgs signal at* ~ 125 GeV

Green region: compatible with assumed Higgs signal with / without m_t variation [*S. Heinemeyer, O. Stål, G. W. '11*]

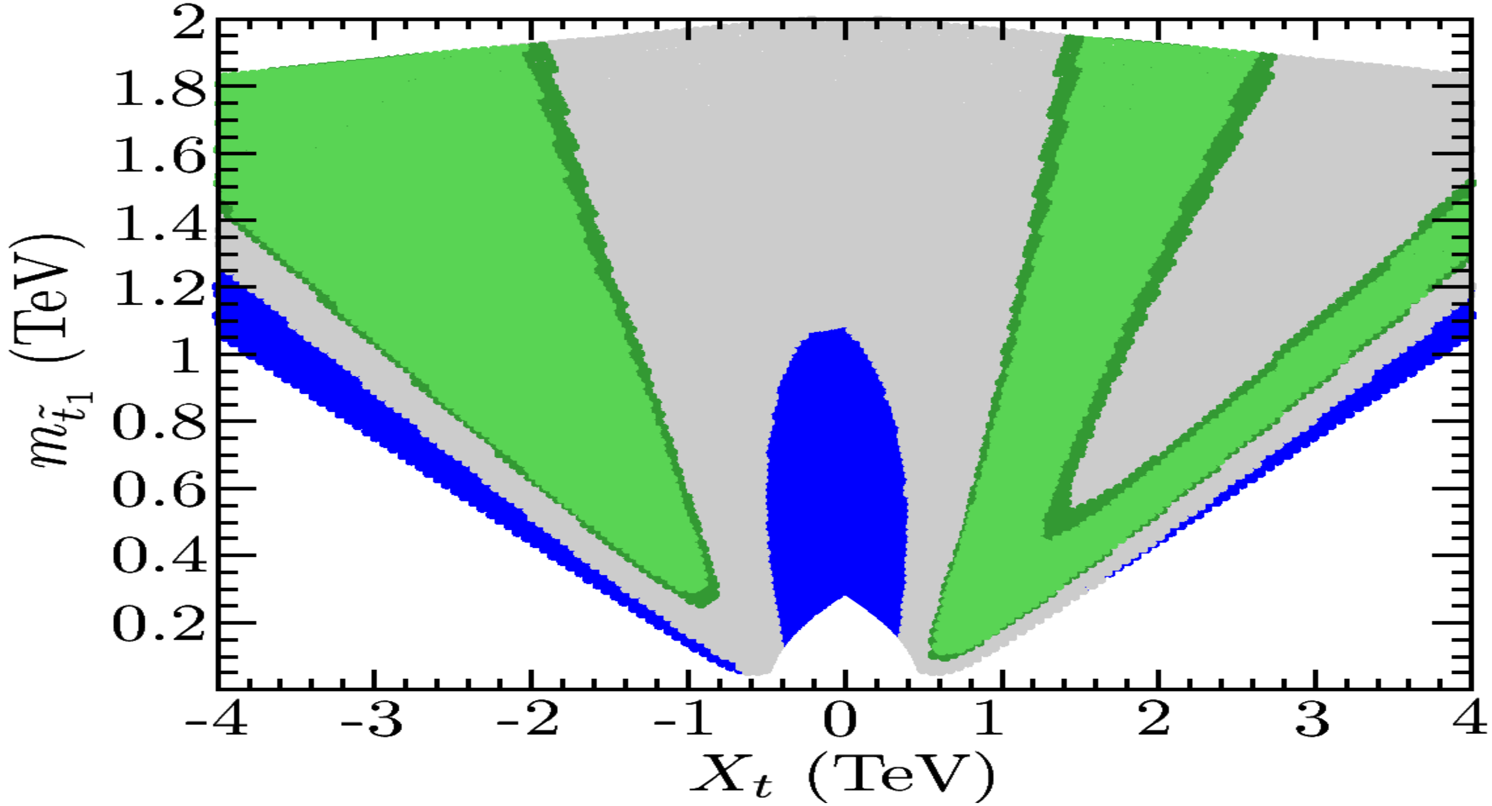


$\Rightarrow \tan\beta \gtrsim 3,\ M_\mathrm{A} \gtrsim 130$ GeV, $M_{\mathrm{H}^\pm} \gtrsim 152$ GeV

Lower bound on the lightest stop mass from assumed Higgs signal at ~ 125 GeV

M_A, $\tan\beta$ chosen in decoupling region: $M_A = 1$ TeV, $\tan\beta = 20$

[S. Heinemeyer, O. Stål, G. W. '11]



$\Rightarrow m_{\tilde{t}_1} > 100\ (250)$ GeV for positive (negative) X_t

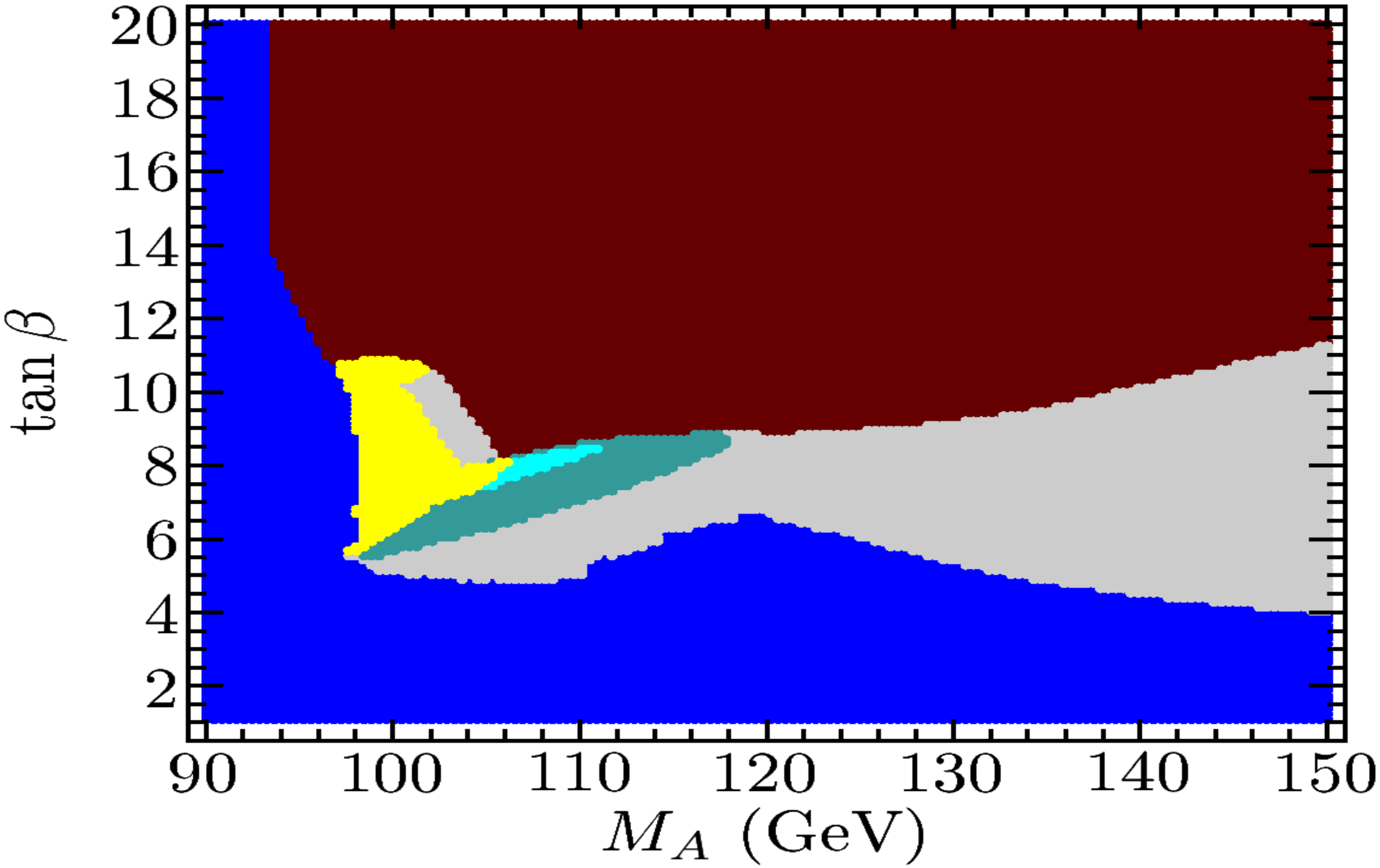
Compatibility with assumed signal would be difficult in constrained models: mGMSB, mAMSB, . . .

Interpretation of the observed signal at ~ 125 GeV

in terms of the heavy MSSM CP-even Higgs H

Scan over M_A, $\tan\beta$, M_{SUSY}, X_t

[*S. Heinemeyer, O. Stål, G. W. '11*]



$\Rightarrow$ possible for low M_A, moderate $\tan\beta$
(in yellow region: $\gamma\gamma$ rate compatible with LHC results)

Can an enhanced rate in the $\gamma\gamma$ channel be accomodated for a 125 GeV Higgs in SUSY: MSSM and NMSSM?

[*R. Benbrik, M. Gomez Bock, S. Heinemeyer,O. Stål, G. W., L. Zeune '12*]

Investigate MSSM and NMSSM predictions for the $\gamma\gamma$ rate, normalised to the SM prediction

$$R^{h_i}_{\gamma\gamma} = \frac{\sigma(pp \to h_i) \times \mathrm{BR}(h_i \to \gamma\gamma)}{\sigma(pp \to H_{\mathrm{SM}}) \times \mathrm{BR}(H_{\mathrm{SM}} \to \gamma\gamma)}$$

$$\approx \frac{\Gamma(h_i \to gg) \times \mathrm{BR}(h_i \to \gamma\gamma)}{\Gamma(H_{\mathrm{SM}} \to gg) \times \mathrm{BR}(H_{\mathrm{SM}} \to \gamma\gamma)}$$

$\Rightarrow$ Parameter scans in both models

MSSM results from *FeynHiggs*

NMSSM results obtained using *FeynArts* (new NMSSM model file generated), *FormCalc* and *LoopTools*

Applied constraints

- Direct search limits for SUSY particles $+$ theo. constraints (perturbativity up to $M_{\rm GUT}$, no charge / colour breaking minima, . . .)

  $\longrightarrow$ grey points

- Higgs searches at LEP, Tevatron and the LHC (2011): HiggsBounds

  $\longrightarrow$ blue points

- $(g-2)_\mu$, flavour physics observables ($\mathrm{BR}(b \to s\gamma)$, . . .)

  $\longrightarrow$ black points

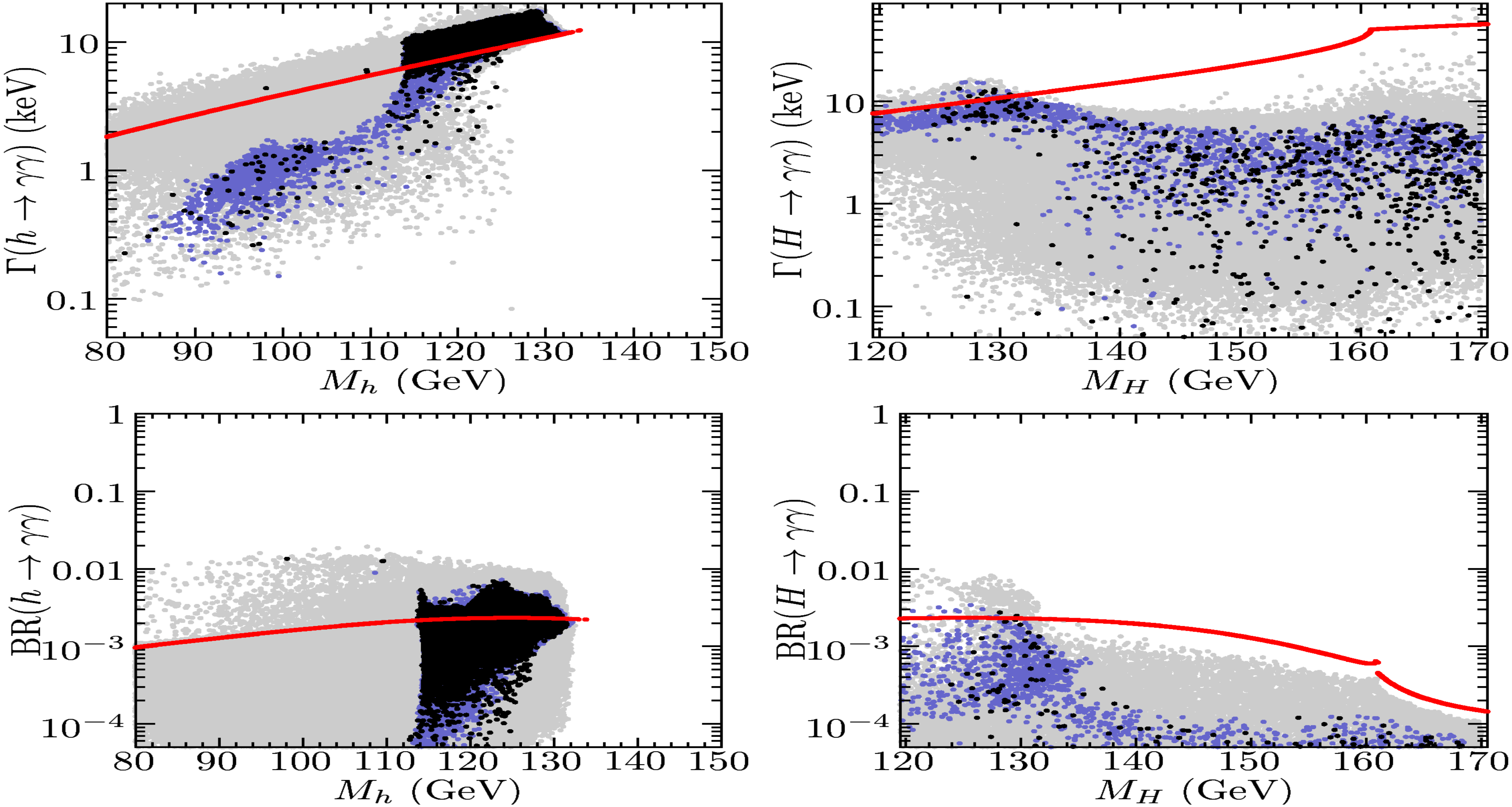
Parameter scan in the MSSM

Parameter	Minimum	Maximum
M_{SUSY}	750	1500
$M_2 \simeq 2M_1$	200	500
$A_t = A_b = A_\tau$	-2400	2400
μ	200	3000
M_{A}	100	600
$\tan\beta$	1	60

$$M_{\mathrm{SUSY}} = M_{\tilde{q}_L} = M_{\tilde{q}_R},\ M_{\tilde{l}_L} = M_{\tilde{l}_R} = 250\ \mathrm{GeV},\ m_{\tilde{\mathrm{g}}} = 1200\ \mathrm{GeV}$$

MSSM (scan) vs. SM (red):
Results for $\Gamma(h, H \to \gamma\gamma)$ *and* $\mathrm{BR}(h, H \to \gamma\gamma)$

[R. Benbrik, M. Gomez Bock, S. Heinemeyer, O. Stål, G. W., L. Zeune '12]

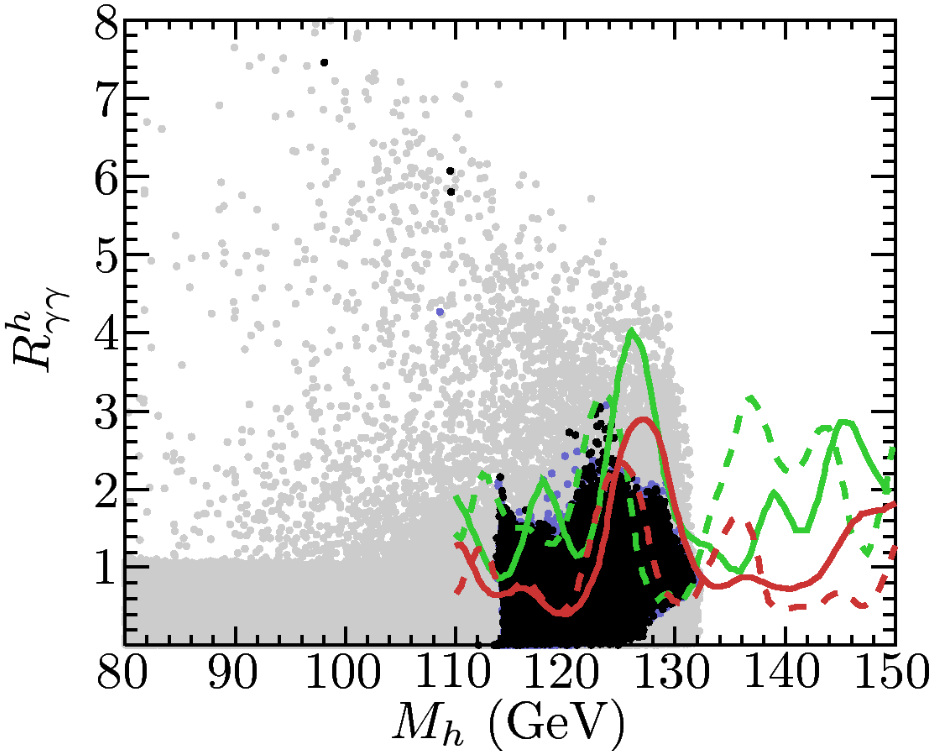


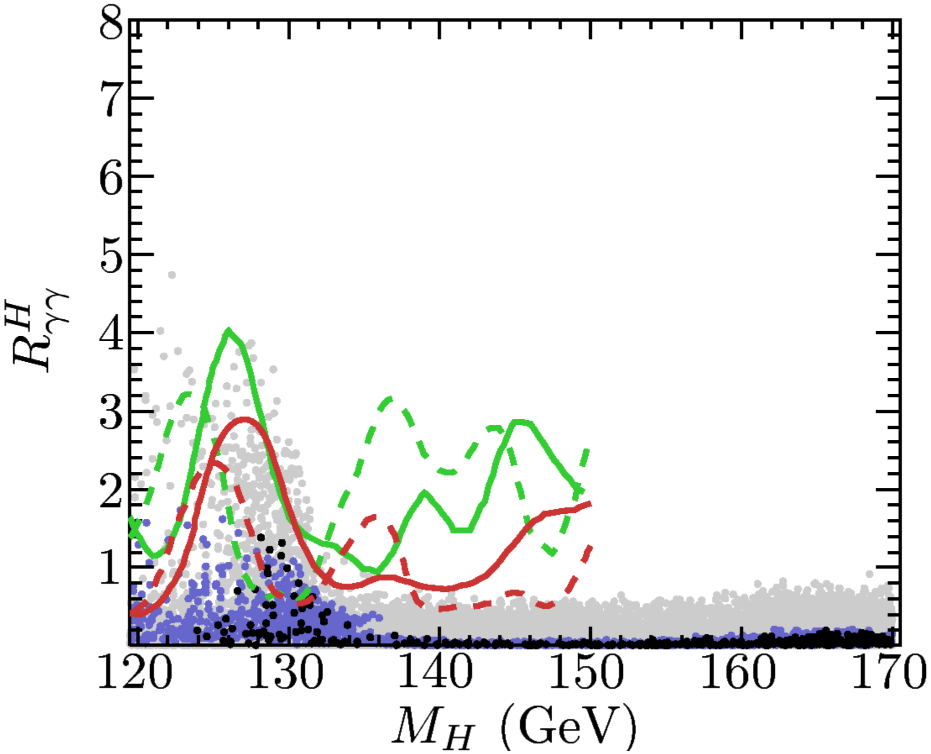
$\Rightarrow$ Sizable enhancement possible around 125 GeV for h and H

MSSM predictions for the $\gamma\gamma$ rate of h and H normalised to the SM prediction

Comparison with search limits from ATLAS (solid) and CMS (dashed) from 2011 data (green) and from latest results (yesterday)

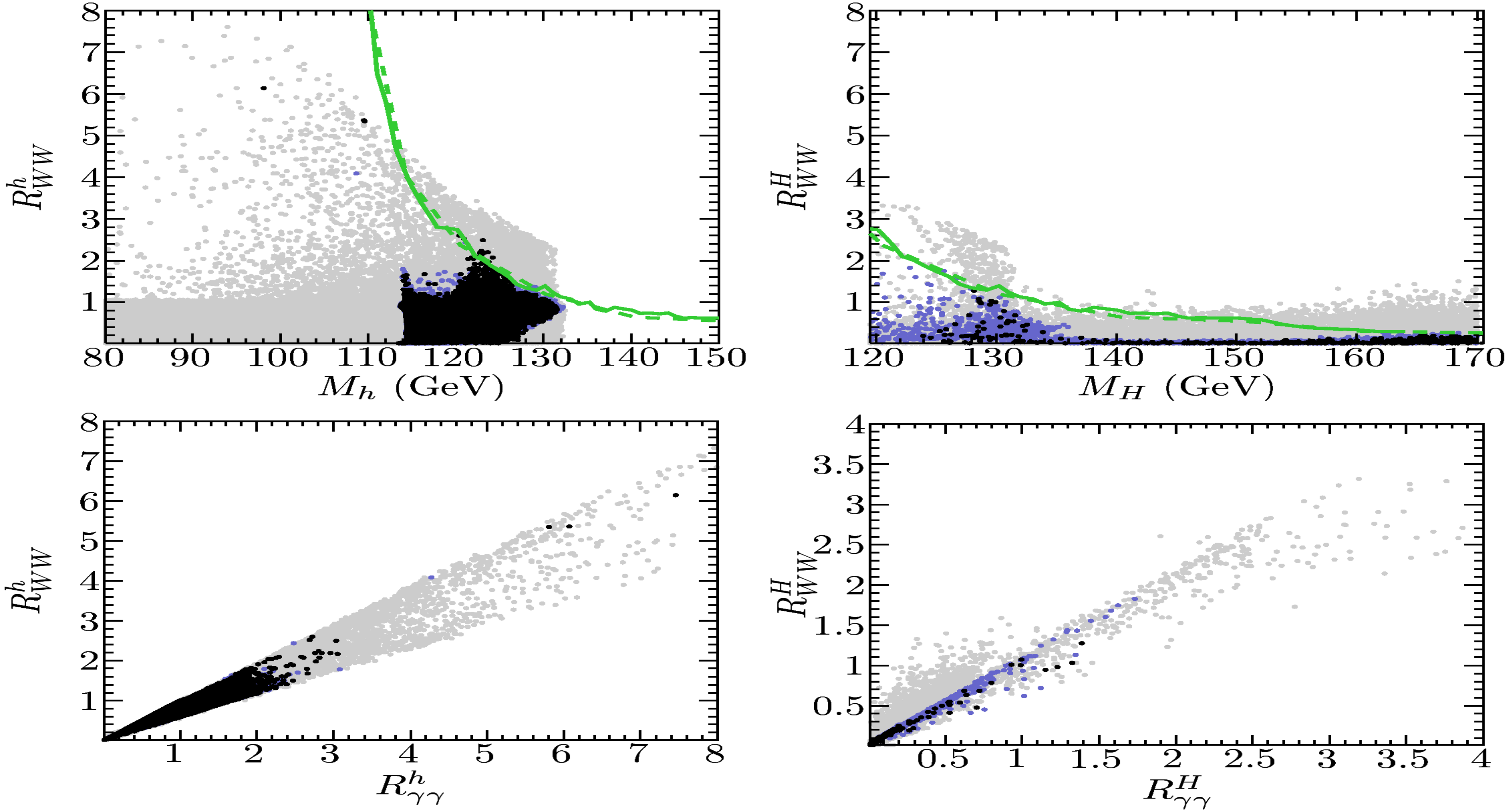
[*R. Benbrik, M. Gomez Bock, S. Heinemeyer,O. Stål, G. W., L. Zeune ’12*]





$\Rightarrow$ Sizable enhancement possible around 125 GeV for h and H

Comparison with WW^* channel



$\Rightarrow$ Strong correlation, but enhanced $\gamma\gamma$ rate possible for SM-like (or even slightly suppressed) WW^* rate

Possible mechanisms for enhancing the $\gamma\gamma$ rate in the MSSM

- Enhancement of $\Gamma(h, H \to \gamma\gamma)$:
  loop contributions from light staus

- Suppression of Higgs (h, H) coupling to $b\bar{b}$:
  $\Rightarrow$ Enhancement of $\mathrm{BR}(h, H \to \gamma\gamma)$

$$\frac{g_{hb\bar{b}}}{g_{H_{\mathrm{SM}}b\bar{b}}} = \frac{1}{1+\Delta_b}\left(-\frac{\sin\alpha_{\mathrm{eff}}}{\cos\beta} + \Delta_b \frac{\cos\alpha_{\mathrm{eff}}}{\sin\beta}\right)$$

Suppression of $g_{hb\bar{b}}$ because of large Higgs propagator-type corrections ($\to$ small α_{eff}) or large correction to the relation between m_{b} and the bottom Yukawa coupling (Δ_b) [similar for H]

Experimental situation for $\tau^+\tau^-$ and $b\bar{b}$ channels still inconclusive

Parameter scan in the NMSSM

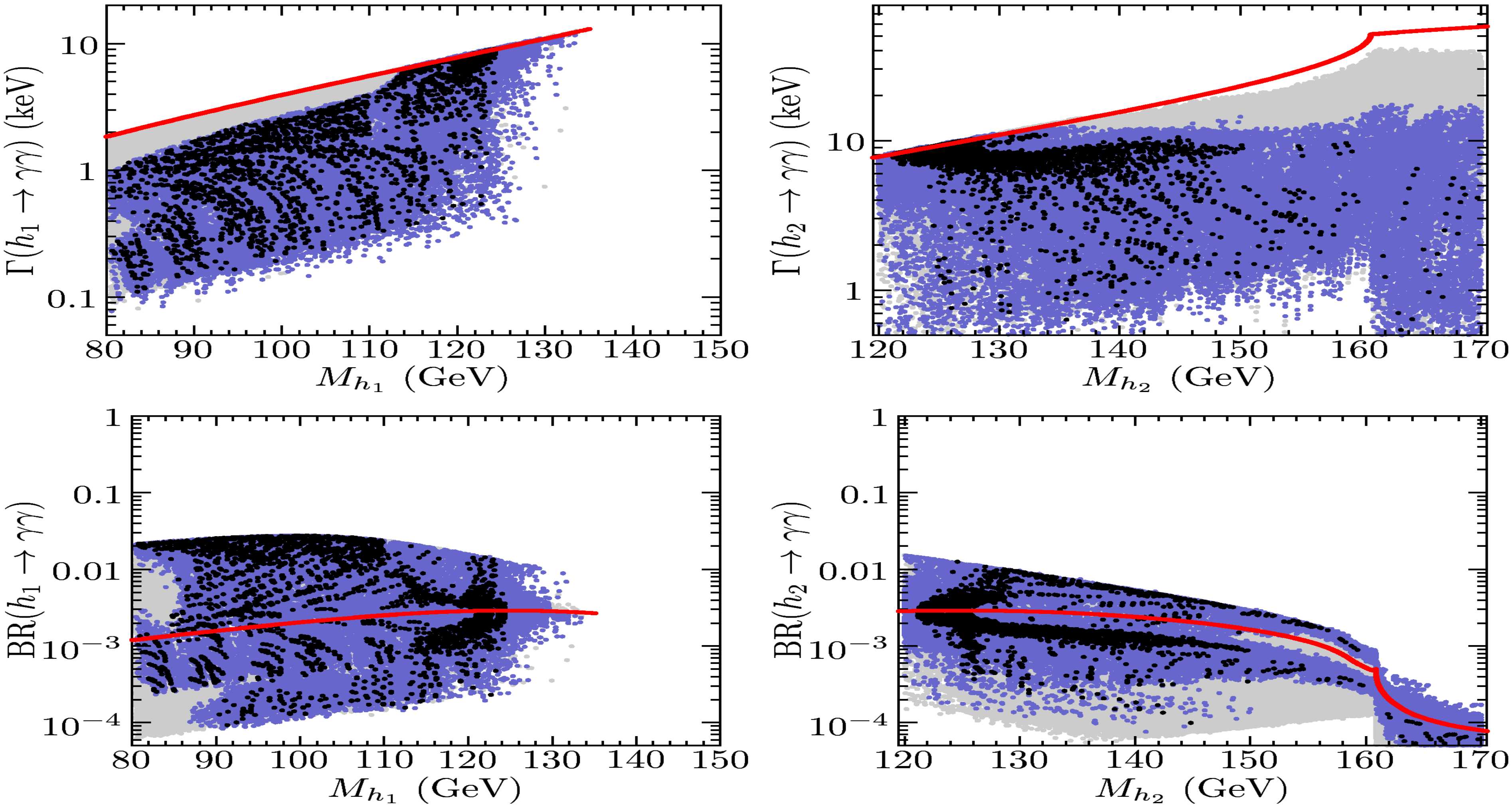
Additional mechanism for suppression of Higgs coupling to $b\bar{b}$ in the NMSSM: Mixing of Higgs singlet to doublet fields can result in small H_d component $\Rightarrow$ coupling to down-type fermions suppressed

Scan ranges chosen such that enhancements of the $\gamma\gamma$ rate already discussed for the MSSM do not occur (also: heavy staus):

Parameter	Minimum	Maximum	
$A_t = A_b = A_\tau$	$-2\,400$	$2\,400$	GeV
μ_{eff}	150	250	GeV
$M_{\text{H}^\pm}$	500	$1\,000$	GeV
$\tan\beta$	2.6	6	
λ	0.5	0.7	
K	0.3	0.5	
A_κ	-100	-5	GeV

NMSSM (scan) vs. SM (red):
Results for $\Gamma(h_1, h_2 \to \gamma\gamma)$ *and* $\mathrm{BR}(h_1, h_2 \to \gamma\gamma)$

[*R. Benbrik, M. Gomez Bock, S. Heinemeyer,O. Stål, G. W., L. Zeune '12*]



$\Rightarrow$ Enhancement of BR possible for ~ 125 GeV for h_1 and h_2

MSSM predictions for the $\gamma\gamma$ rate of h and H normalised to the SM prediction

Comparison with search limits from ATLAS (solid) and CMS (dashed) from 2011 data (green) and from latest results (yesterday)

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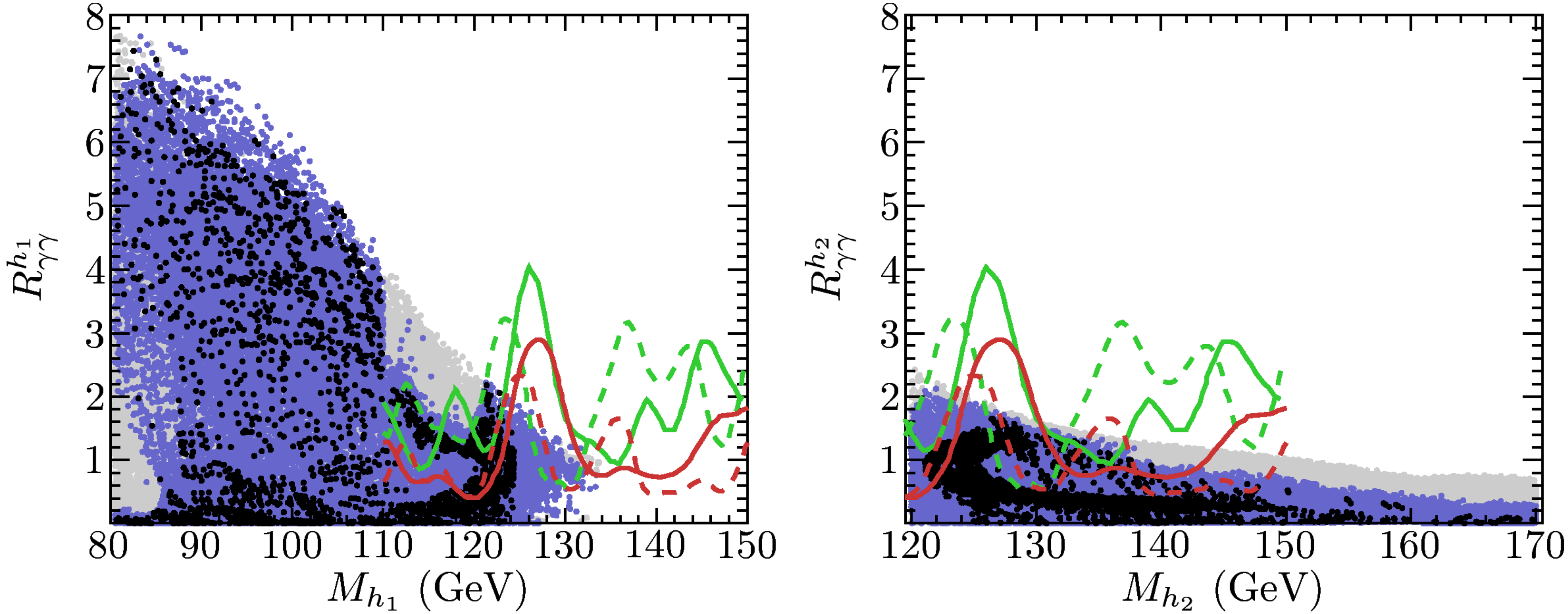
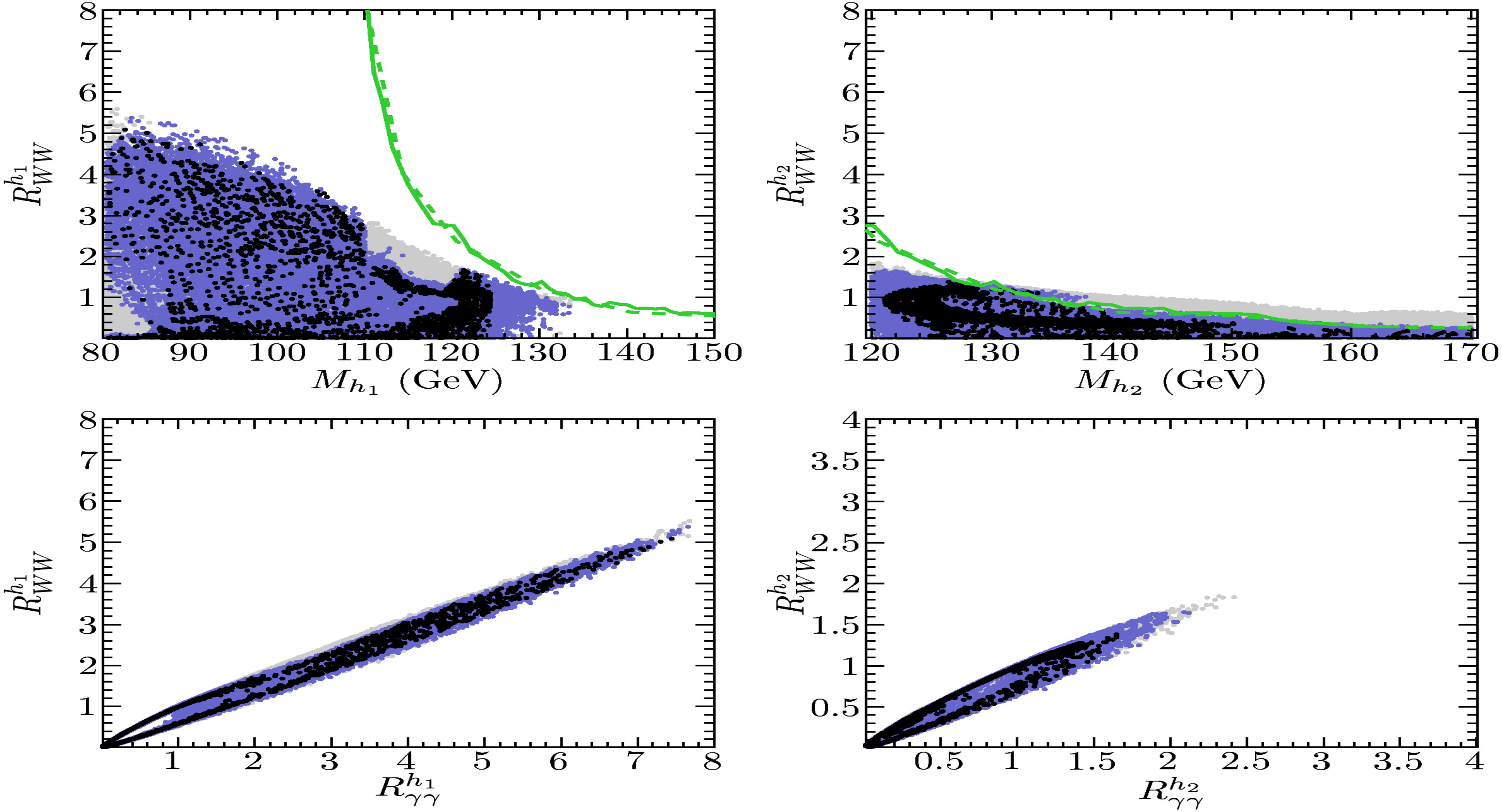


$\Rightarrow$ Sizable enhancement possible for ~ 125 GeV for h_1 and h_2

Comparison with WW^* channel



$\Rightarrow$ Strong correlation, but enhanced $\gamma\gamma$ rate possible for SM-like (or even slightly suppressed) WW^* rate

Interpretation of the observed signal at ~ 125 GeV in terms of the second-lightest Higgs of the MSSM and the NMSSM

The light Higgs h in this scenario has a mass that is often below the LEP limit of $M_{H_{SM}} > 114.4$ GeV (with reduced couplings to gauge bosons, in agreement with LEP bounds)

Could have, for instance, $M_H \sim 125$ GeV, $M_h \sim 98$ GeV (slight excess observed at LEP at $M_h \sim 98$ GeV)

$\Rightarrow$ It is important to extend the LHC Higgs searches to the region below 114 GeV!

The best way of experimentally proving that the observed state is not the SM Higgs is to find in addition (at least one) non-SM like Higgs!

A light Higgs in SUSY cascades?

Example: NMSSM scenario, light $\mathcal{CP}$-even Higgs, $20\ \mathrm{GeV} < M_{\mathrm{h}_1} < 110\ \mathrm{GeV}$, in agreement with all search limits (large singlet component)

$\mu_{\mathrm{eff}} = -200\ \mathrm{GeV}$, $M_1 = 300\ \mathrm{GeV}$, $M_2 = 600\ \mathrm{GeV}$

$M_{\mathrm{SUSY}} = 750\ \mathrm{GeV}$, $m_{\tilde{\mathrm{g}}} = 1\ \mathrm{TeV}$

$\Rightarrow$ Higgs production in chargino and neutralino decays in SUSY cascades

$$\tilde{q} \to q\tilde{\chi}_i^0 \to q\tilde{\chi}_1^0 h_k \to q\tilde{\chi}_1^0 b\bar{b}$$

$$\tilde{g} \to g\tilde{q} \to gq\tilde{\chi}_i^0 \to gq\tilde{\chi}_1^0 h_k \to gq\tilde{\chi}_1^0 b\bar{b}$$

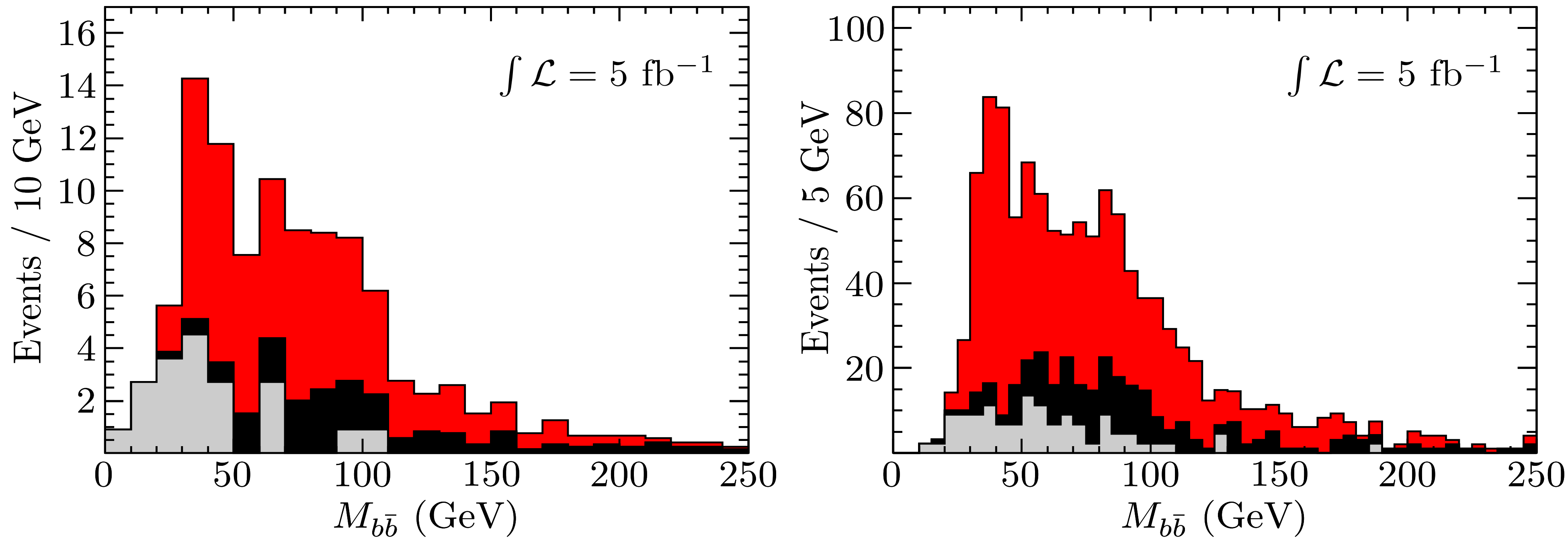
$\ldots$

Results for $b\bar{b}$ jet invariant mass distribution:

SUSY signal, SUSY background, SM $t\bar{t}$ background (grey)

$\int \mathcal{L} = 5\ \mathrm{fb}^{-1}$, $M_{\mathrm{h}_1} \approx 40$ GeV [O. Stål, G. W. '11]

$\sqrt{s} = 7$ TeV $\sqrt{s} = 14$ TeV

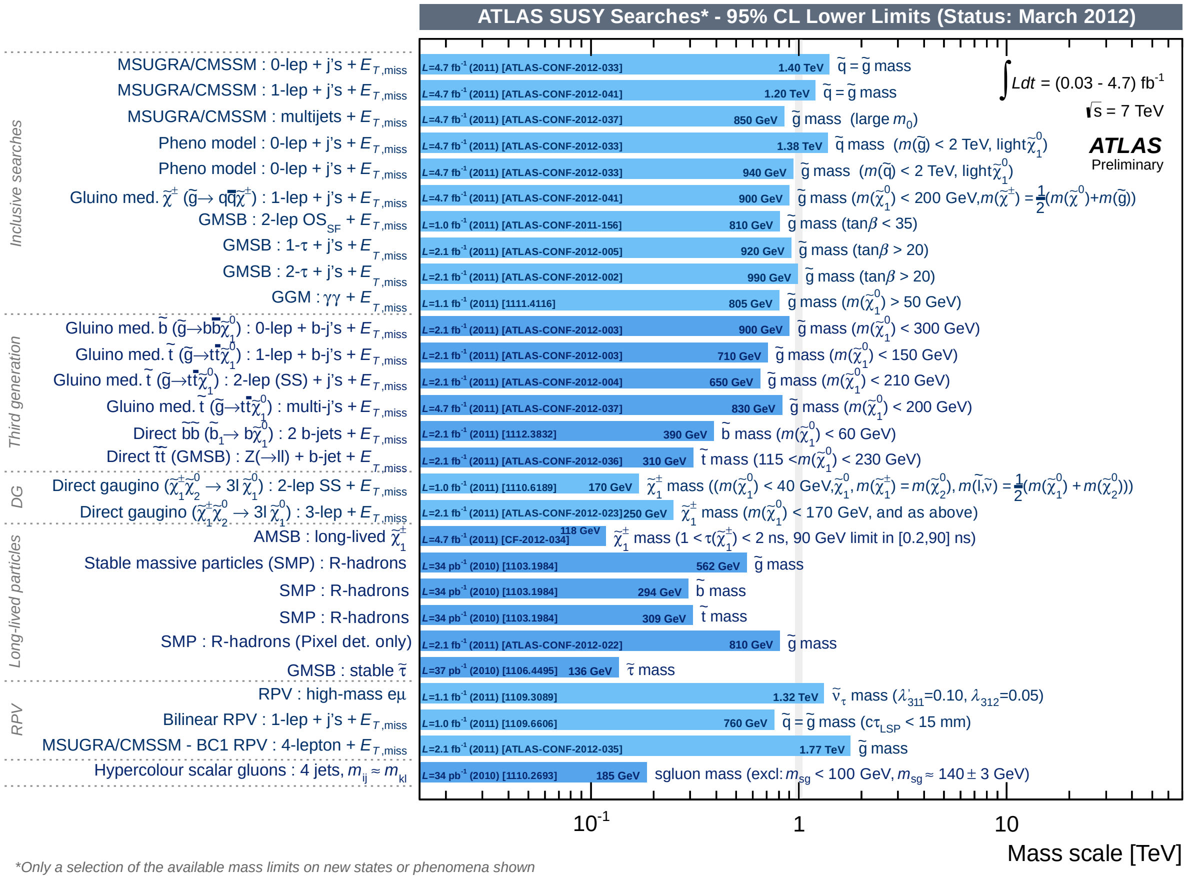


$\Rightarrow$ Signal over background ratio looks encouraging
h_1 peak and Z peak visible

$\Rightarrow$ We could get a signal for SUSY $+$ Higgs at once

Where are the SUSY particles?

Large number of searches, many limits, . . . *[ATLAS Collaboration '12]*



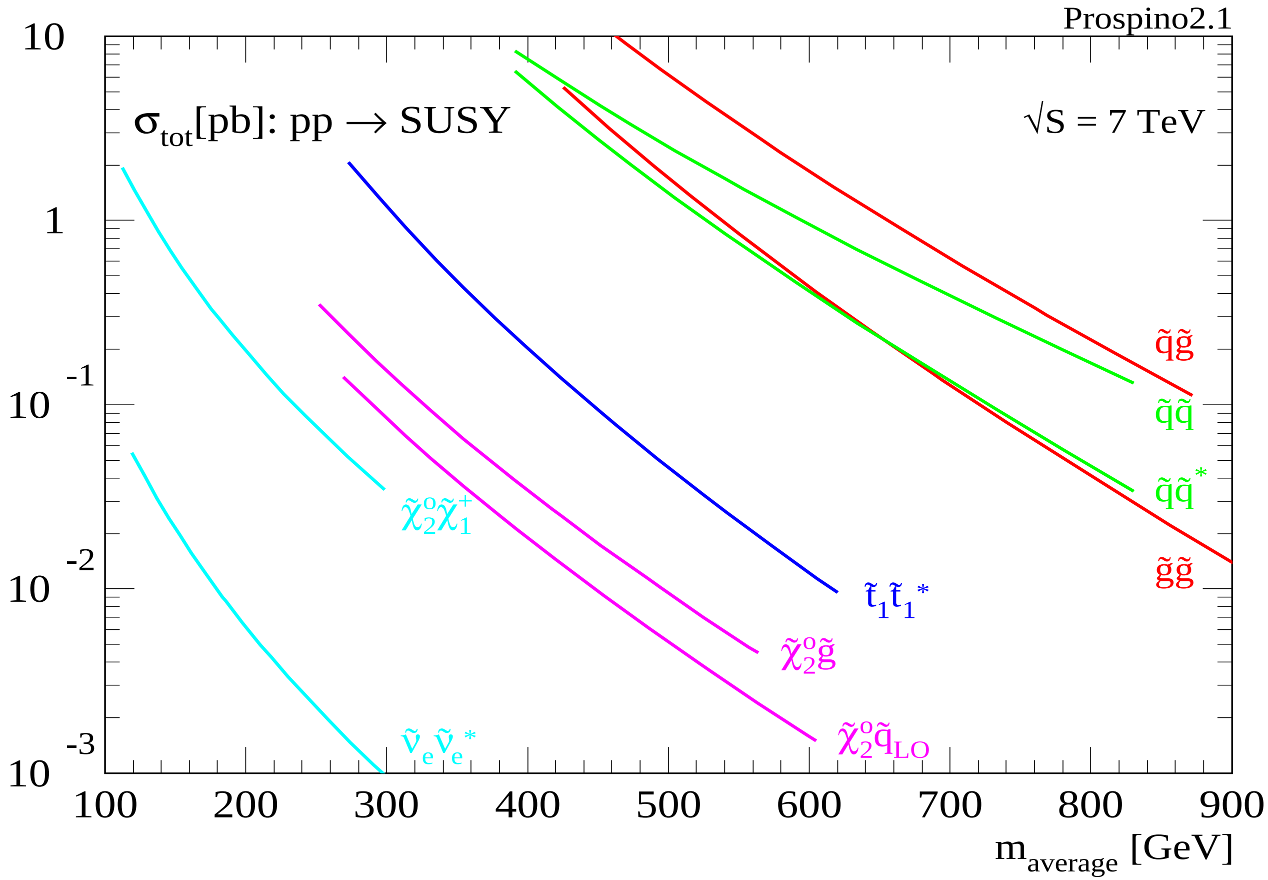
Interpretation in specific scenarios, e.g. CMSSM, and in "simplified models"

Widespread interpretation of SUSY search results

“If SUSY is realised at all, the SUSY particles must be very heavy”

That’s a vast over-simplification and over-interpretation (politely expressed)!

SUSY production cross sections at the LHC with $7\ \mathrm{TeV}$



⇒ Highest cross section for squarks of the first two generations and gluino

Squark and gluino couplings $\sim \alpha_s$; cross sections mainly determined by $m_{\tilde{q},\tilde{g}}$, small residual model dependence

SUSY searches at the LHC

Dominated by production of coloured particles:

gluino, squarks (mainly first two generations)

Very large mass reach in the searches for
jets $+$ missing energy

$\Rightarrow$ gluino, squarks accessible up to 2–3 TeV at LHC ($14\ \mathrm{TeV}$)

Coloured particles are usually heavier than the colour-neutral ones $\Rightarrow$ long decay chains possible; complicated final states

e.g.: $\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}_1^0$

Many states could be produced at once, difficult to disentangle

Global fits in constrained SUSY models

Take into account information from

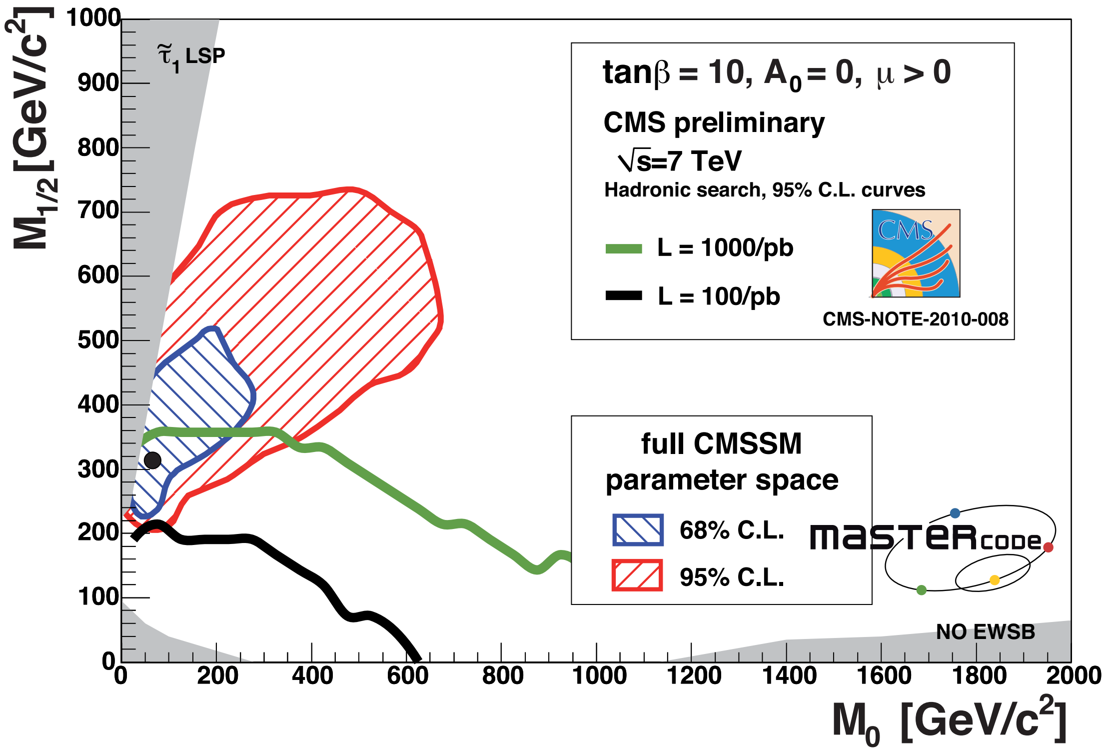
- Electroweak precision observables: $M_{\rm W}$, $\sin^2\theta_{\rm eff}$, $\Gamma_{\rm Z}$, ...
- $+ \, (g-2)_\mu$
- $+$ Cold dark matter (CDM) density (WMAP, ...)
- $+$ B-physics observables:
  $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_{\rm s} \to \mu^+\mu^-)$, $\mathrm{BR}(B \to \tau\nu)$, ...

$\Rightarrow$ Fits using frequentist or Bayesian statistical methods

Pre–LHC: *Fit results for the CMSSM from precision data*

Comparison: preferred region in the m_0–$m_{1/2}$ plane vs. prospective CMS 95% C.L. reach for $0.1, 1\ \mathrm{fb}^{-1}$ at $7\ \mathrm{TeV}$

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10*]



$\Rightarrow$ Best fit point was within the 95% C.L. reach with $1\ \mathrm{fb}^{-1}$

Pre–LHC fit result: a closer look

The preference for a light SUSY scale (best fit value in the CMSSM close to the SPS 1a benchmark point) was mainly driven by $(g-2)_\mu$ ($+\, M_\mathrm{W}$, CDM constraint, ...)
$\Rightarrow$ colour–neutral part of the SUSY spectrum

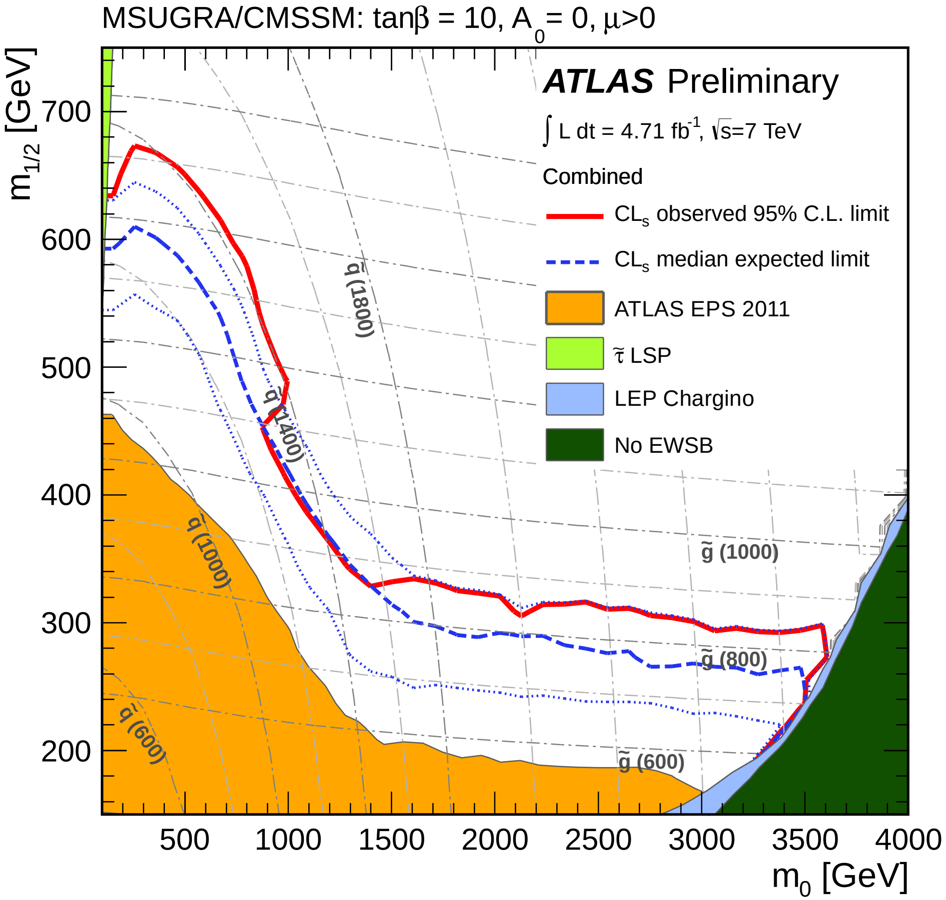
The SUSY searches at the LHC up to now set limits mainly on the coloured SUSY particles

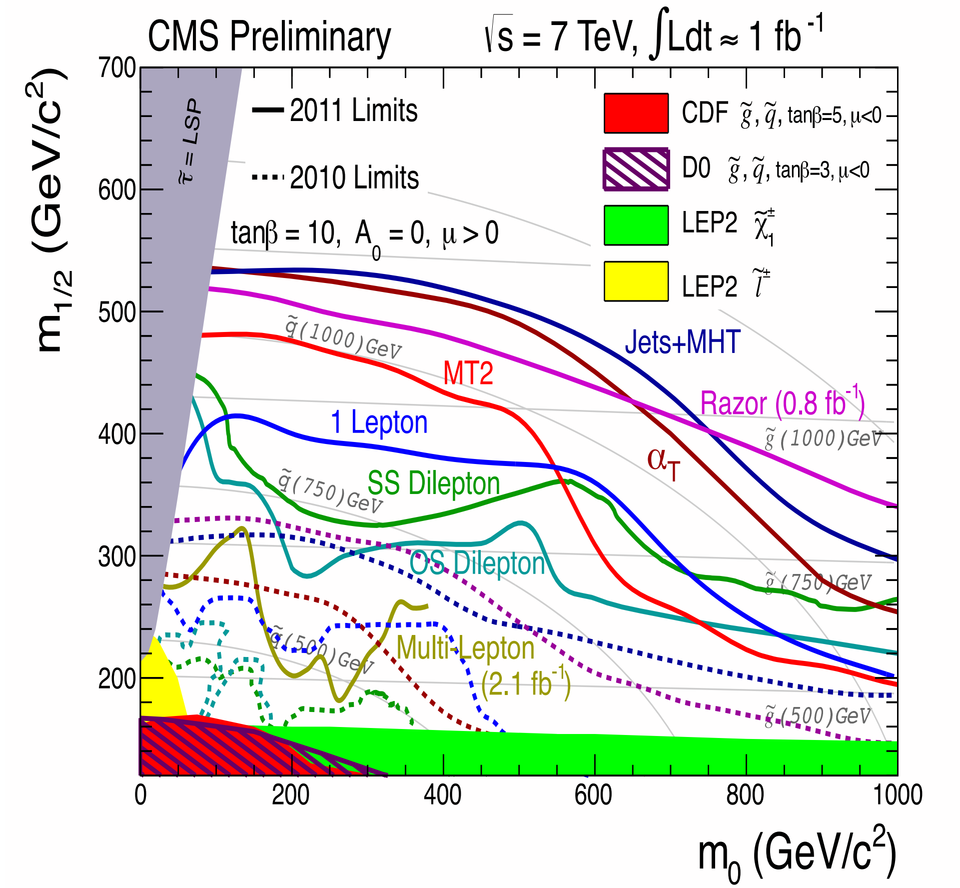
$\Rightarrow$ The constraints from electroweak precision observables, which prefer relatively light SUSY particles, and the limits from the direct SUSY searches at the LHC, which are mainly sensitive to coloured SUSY particles, apply to different sectors of the SUSY model

There is only a tension between indirect constraints and direct search limits if one assumes a specific connection between coloured and colour–neutral sector, like in the CMSSM

LHC: *SUSY search results for the CMSSM*

[*ATLAS Collaboration ’12*] [*CMS Collaboration ’12*]





⇒ High sensitivity from search for jets + missing energy

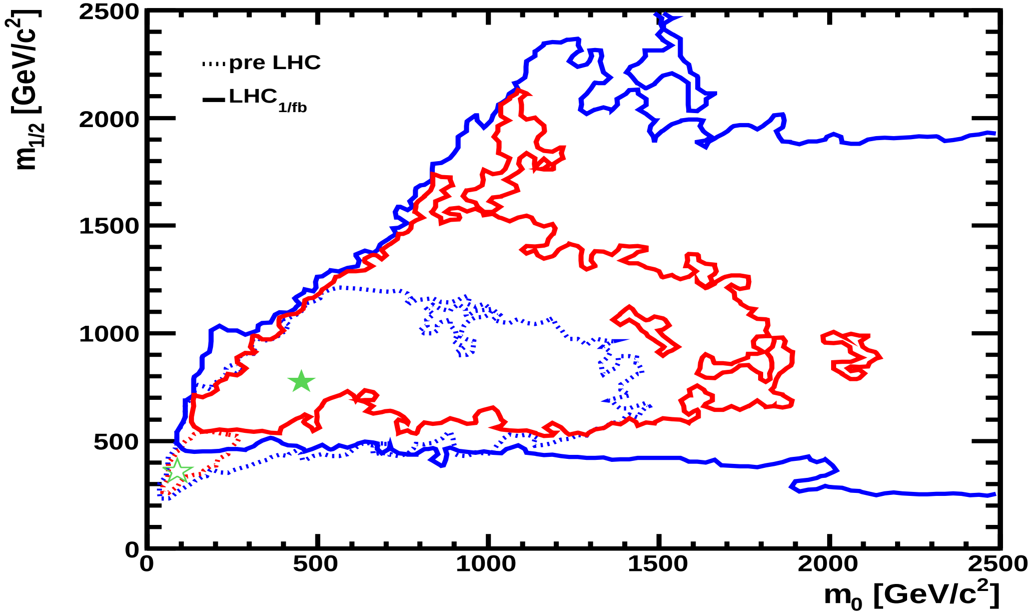
Previous best-fit point is excluded

CMSSM is under some pressure

Global fit in the CMSSM including 2011 LHC data ($1\ \mathrm{fb}^{-1}$) and XENON100 results

68% and 95% CL contours, pre- and post-LHC

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, D. Martínez Santos, K. Olive, S. Rogerson, F. Ronga, G. W. '11*]

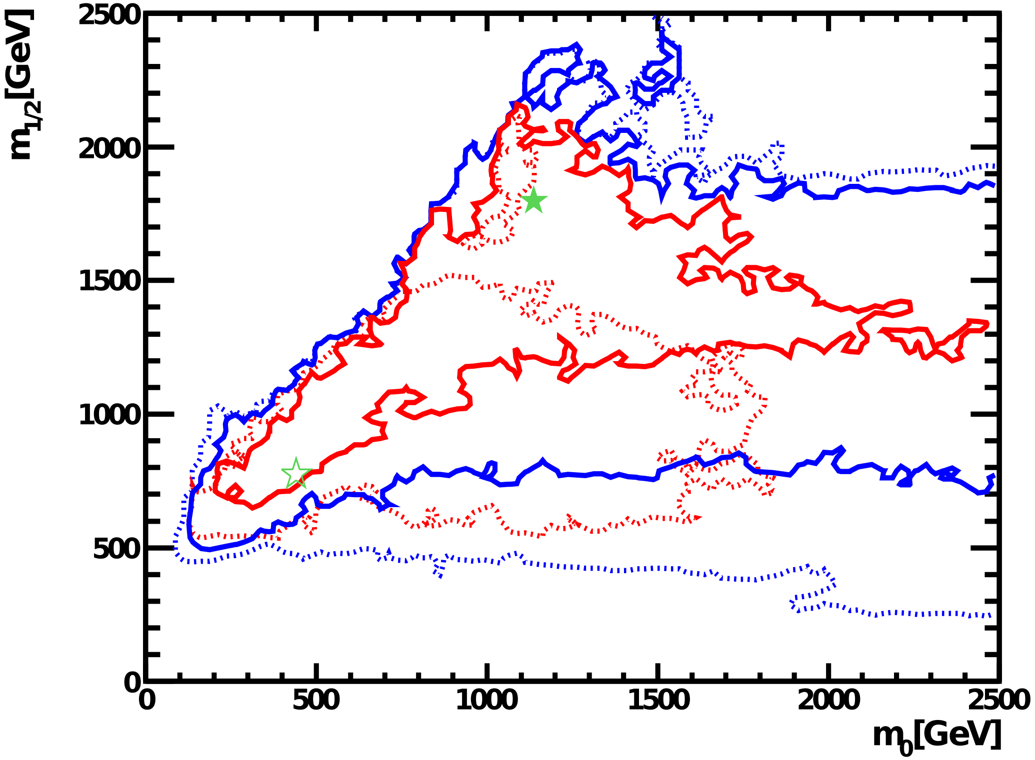


$\Rightarrow$ Preferred region "opens up", overall χ^2 worsened
Shift towards higher mass scales, higher values of $\tan\beta$

Comparison: GMSB yields much larger splitting between coloured and colour-neutral part of the spectrum

Implications of an assumed Higgs signal at ~ 125 GeV *in the CMSSM*

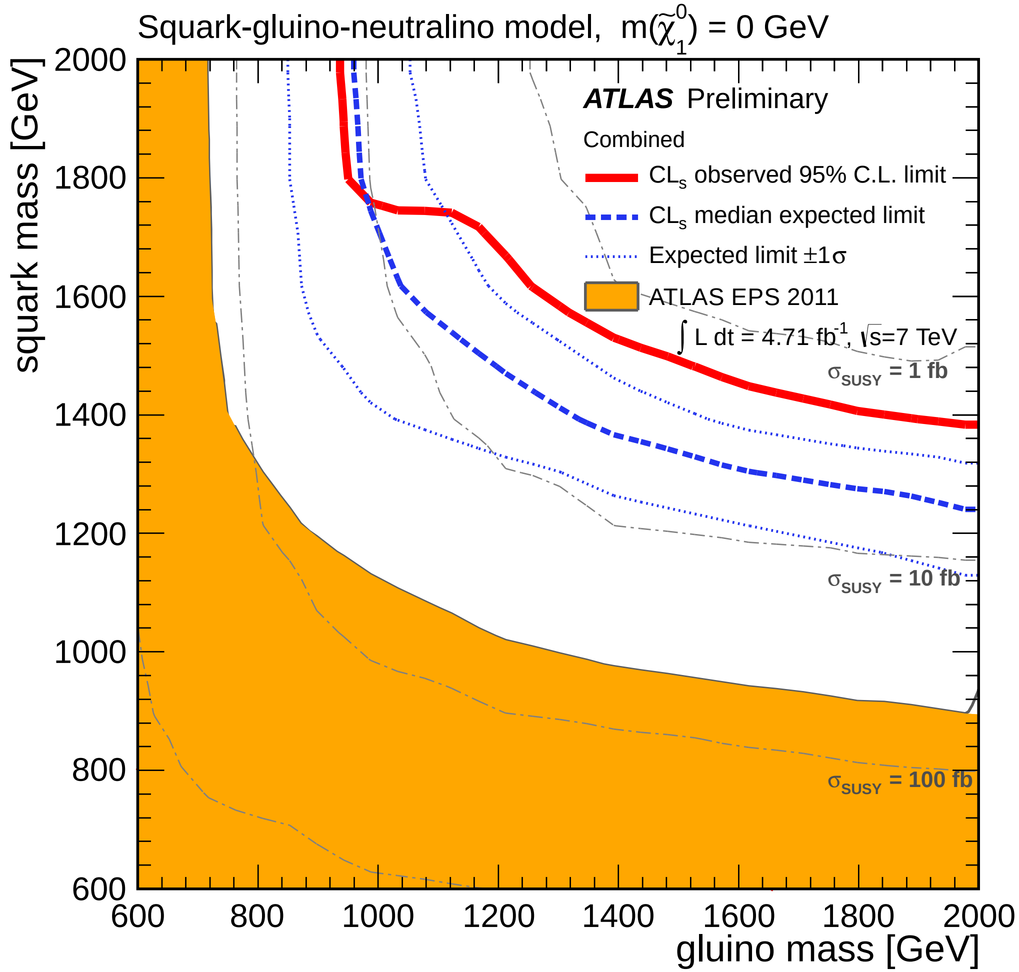
[O. Buchmueller, R. Cavanaugh, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, J. Marrouche, D. Martínez Santos, K. Olive, S. Rogerson, F. Ronga, K. de Vries, G. W. '11]



$\Rightarrow$ Shift to higher mass scales, reduced fit probability

Interpretation of SUSY search result in "simplified model"

"Simplified model": squarks of first two generations, gluino + massless neutralino (LSP), all other SUSY particles heavy
⇒ "Best case" scenario [*ATLAS Collaboration '12*]



Implications of SUSY search results

For the interpretation of the search results of the LHC in the context of SUSY models it is useful to classify the limits according to the production channels to which they apply:

(a) First and second generation squarks and gluino

(b) Direct production of stops / sbottoms

(c) Direct production of electroweak SUSY particles

Most limits so far refer to (a): strong production of first and second generation squarks / gluino

Which constraints remain if the gluino and the squarks of the first two generations are heavy?

Direct production of colour–neutral SUSY particles

Is it possible to exclude the pre-LHC best fit point
($\approx$ SPS 1a benchmark point)?

$\Rightarrow$ Interpret m_0 as slepton (and Higgs) mass scale,
$m_{1/2}$ as scale of electroweak inos

(Remember: it was the preference for light electroweak SUSY particles that drove the pre-LHC CMSSM fit to low values of the SUSY scale)

$\Rightarrow$ Searches for direct production of electroweak SUSY particles and of third generation squarks should have high priority!

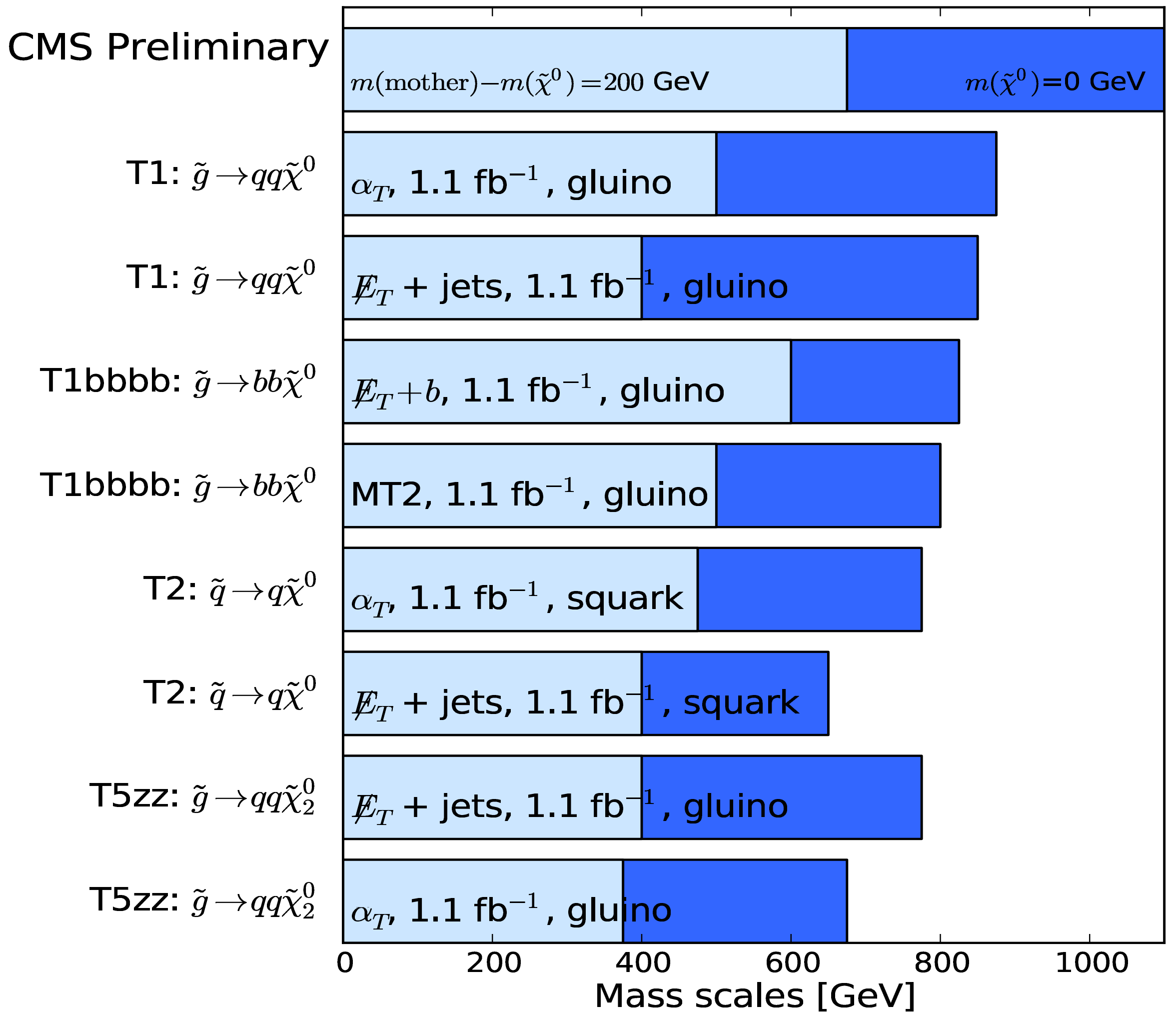
Better-informed interpretation of SUSY search results

"Stringent bounds on squarks of the first two generations and the gluino, much weaker limits for all other parts of the SUSY spectrum"

How robust are the bounds on the squarks of the first two generations and the gluino?

Limits for gluinos and squarks in simplified models, LSP mass varied from 0 to $m_{\tilde{g}} - 200$ GeV

[*CMS Collaboration '12*]

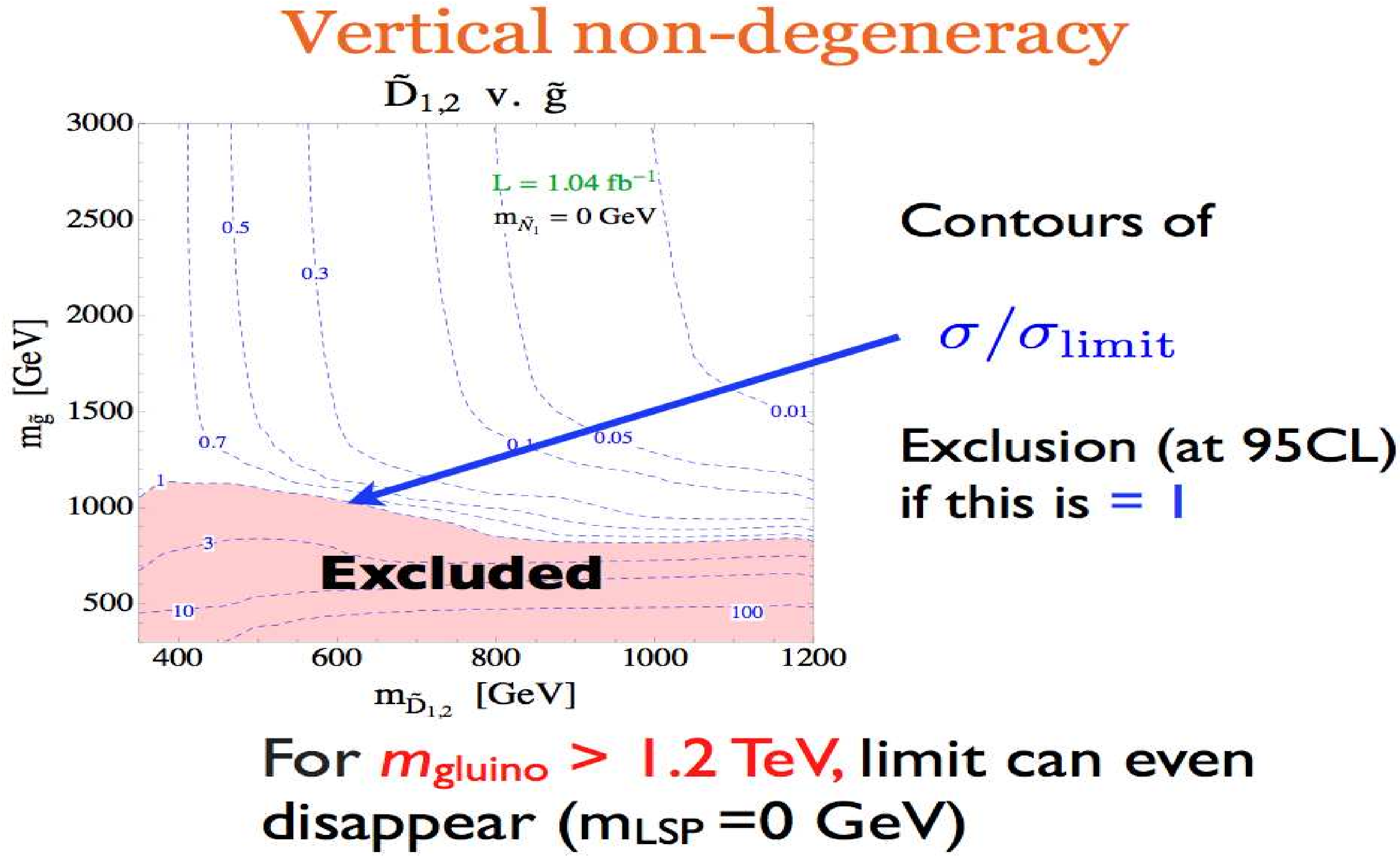


$\Rightarrow$ Large dependence on LSP mass
Reduced sensitivity to compressed spectra

Reinterpretation of the ATLAS and CMS search results

($1\ \mathrm{fb}^{-1}$) for case of non-degenerate squarks (1st, 2nd gen)

[*R. Mahbubani, M. Papucci, G. Perez, J. Ruderman, A. Weiler ’12*]



$\Rightarrow$ Squark limits are drastically weakened compared to the degenerate case

What next?

Comprehensive set of precision measurements and accurate theory predictions will be needed to establish the Higgs mechanism and to determine the Higgs properties

$\Rightarrow$ One of the main goals for physics at the LHC and a future Linear Collider

LHC Higgs XS WG: properties of a light Higgs

- Mass: finite width effects assumed to be negligible
- Couplings:

  What is actually meant by a Higgs coupling measurement?

  - Use tree-level relations

    $\Rightarrow$ Misses large higher-order corrections

    Compatibility of the results with the SM?

  - Full SM predictions $+$ anomalous couplings

    $\Rightarrow$ Appropriate tools needed

    Anomalous couplings would in general change kinematic distributions

    $\Rightarrow$ no simple rescaling of MC predictions possible

Determination of the properties of a light Higgs-like state

- - Scaling of couplings + free parameters for additional (loop) contributions
    Note: scaling of couplings is in general not possible if higher-order electroweak corrections are included
  - Coupling ratios vs. absolute coupling determination: assumption on total width needed
- Higgs spin an $\mathcal{CP}$ properties [M. Schumacher '12]

Production in gluon fusion:

H→γγ: discriminate spin 0 and 2 from Gottfried Jackson angle

H→VV→4l: discriminate spin 0,1,2 and CP structures from invariant di-lepton mass and up to 5 decay angles

H→ττ discriminate CP (and spin) from decay angle correlations

Production in association with two jets / vector boson fusion, decays H→γγ,VV,ττ

discriminate spin and CP structure from azimuthal angle difference of two jets, event shapes (thrust, ...) + other observables

other possibilities:

- ttH, H→γγ or bb: angular angle correlations
- H produced in central exclusive diffration
- ...

Advertisement: ***Workshop "Implications of LHC results for TeV-scale physics"***

Plenary meetings (CERN): 29/08/2011–02/09/2011, 26/03/2012–30/03/2012, 13/07/2012–17/07/2012

$\Rightarrow$ Discuss impact of experimental results on future strategy for particle physics

Results will be summarised in a document to be submitted as input for the 2012 update of the European Strategy for Particle Physics (as input for Open Symposium at Krakow)

Main organisers:

O. Buchmueller, P. De Jong, A. De Roeck, J. Ellis, C. Grojean, S. Heinemeyer, J. Hewett, K. Jakobs, M. Mangano, F. Teubert, G. W.

Workshop "Implications of LHC results for TeV-scale physics"

Three working groups:

- WG1: Signals of electroweak symmetry breaking
  Conv.: *S. Heinemeyer, M. Kado, C. Mariotti, G. W., A. Weiler*
- WG2: Signatures with missing energy
  Conv.: *R. Cavanaugh, J. Hewett, S. Kraml, G. Polesello*
- WG3: Other signatures of possible BSM physics
  Conv.: *C. Grojean, D. Martinez, J. Santiago Perez, P. Savard, S. Worm*

$\Rightarrow$ If you haven't done so already, you can still join this activity!

Conclusions

- Day 1 after the discovery: we are now entering the phase of probing the properties of the new particle
- Observed $\gamma\gamma$ rate is somewhat higher than expected for the SM Higgs: could this be a first hint of BSM physics?
- The observed signal could easily be accommodated within the MSSM and the NMSSM
- Interpretation is possible both in terms of the lightest and the lightest SUSY Higgs $\Rightarrow$ second possibility would imply an additional non-SM like light Higgs
- LHC SUSY searches so far: mainly sensitive to processes involving production of $\tilde{g}$ and $\tilde{q}$ of first two generations
  There are good reasons suggesting that at least part of the colour-neutral states $+ \tilde{\mathrm{t}}$ should be relatively light

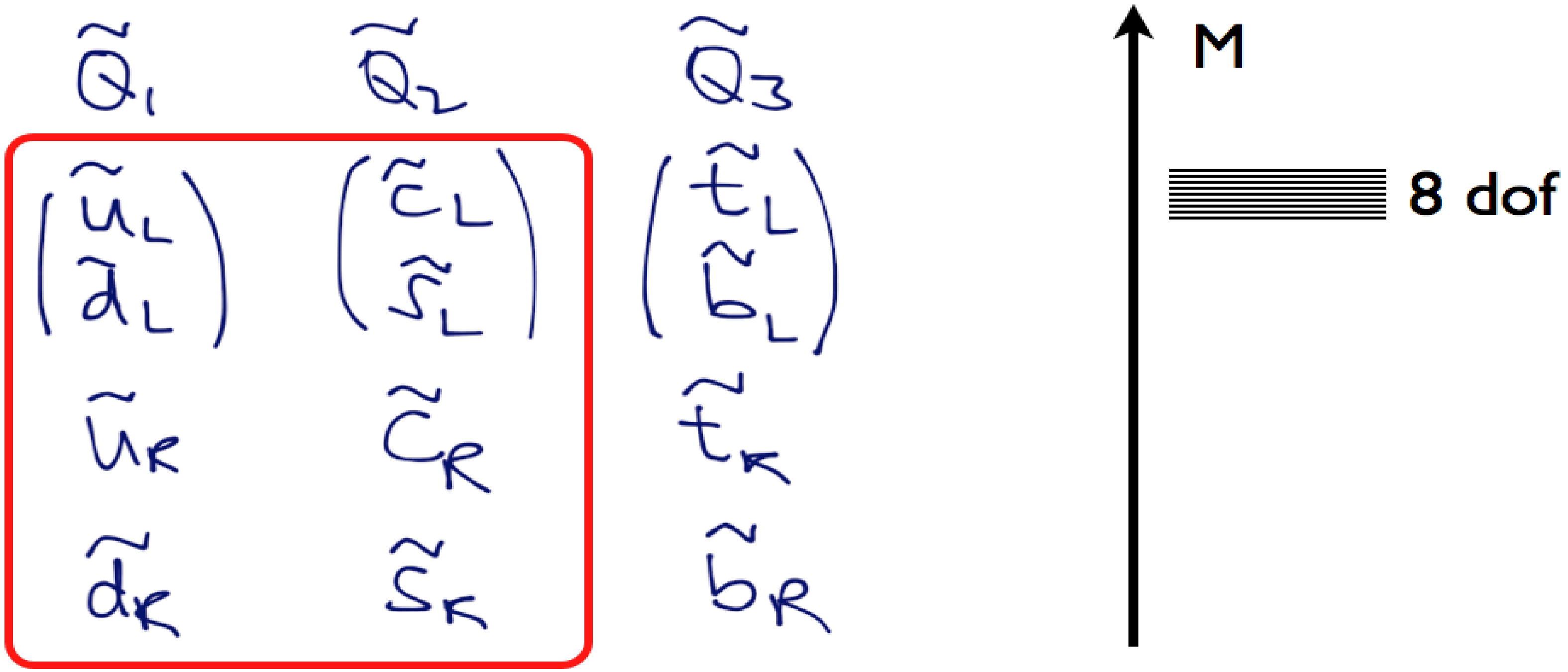
$\Rightarrow$ Bright prospects for the LHC and a future Linear Collider

Backup

What if the squarks of the first two generations are non-degenerate?

[R. Mahbubani, M. Papucci, G. Perez, J. Ruderman, A. Weiler '12]

Known case: 1st & 2nd gen' squarks degenerate

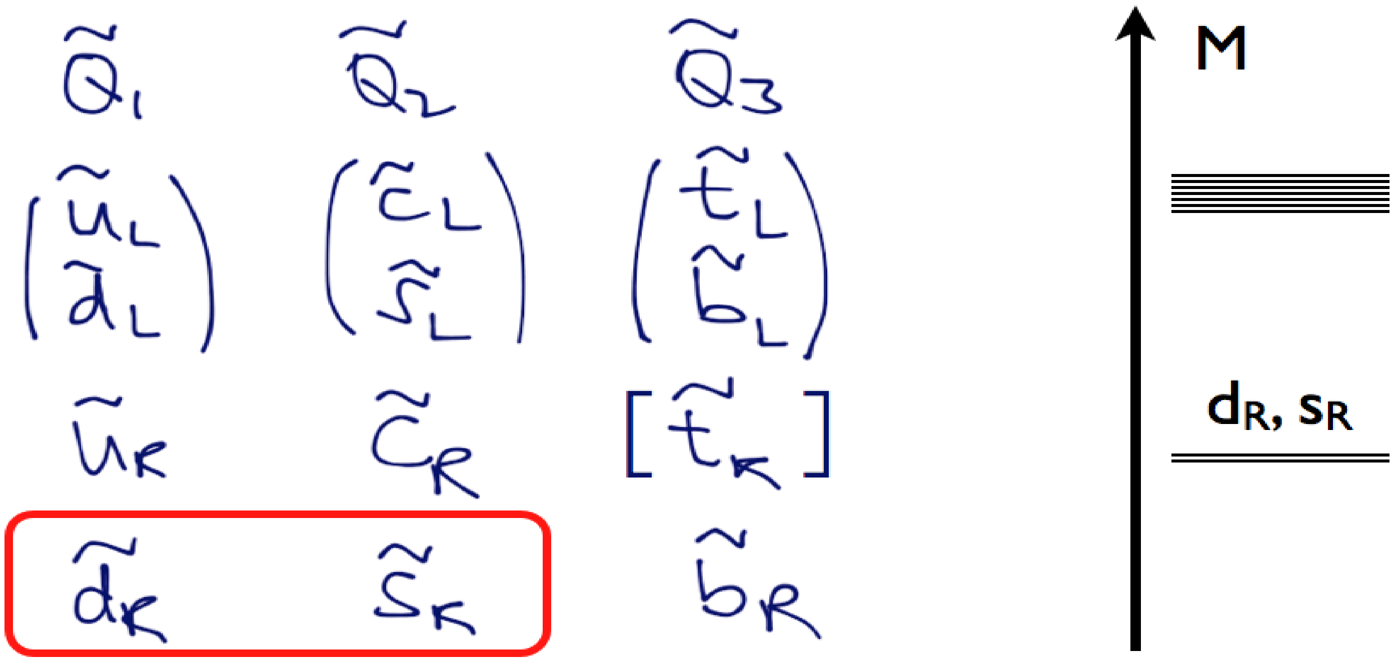


assumption in ATLAS/CMS plots

What if the squarks of the first two generations are non-degenerate?

[R. Mahbubani, M. Papucci, G. Perez, J. Ruderman, A. Weiler ’12]

Split squarks w/ different quantum numbers (vertical)

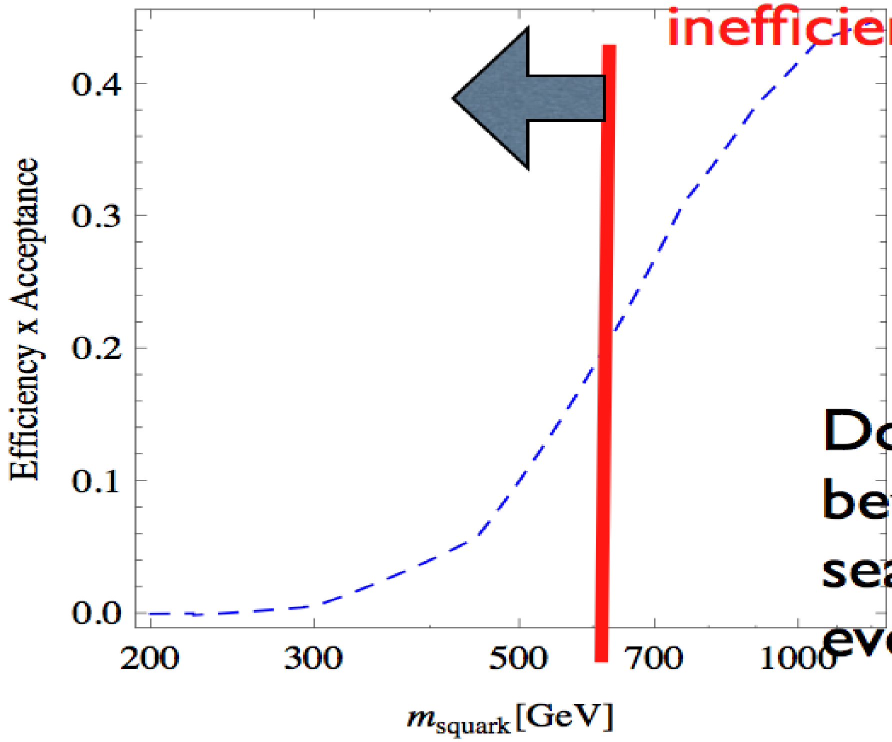


Could there be* $400\ \mathrm{GeV}$ *squarks of the first two generations in the data?

[*R. Mahbubani, M. Papucci, G. Perez, J. Ruderman, A. Weiler ’12*]

Efficiencies

Searches have hard thresholds, inefficient for light squarks



Example: ATLAS 1/fb
2jet, Meff > 1 TeV,
m_{LSP} = 0GeV

Do no expect it to be much better for higher luminosity searches (> 5 /fb) b/c even harder cuts used

$\Rightarrow$ Searches are optimised for the highest squark masses