SUSY & Higgs

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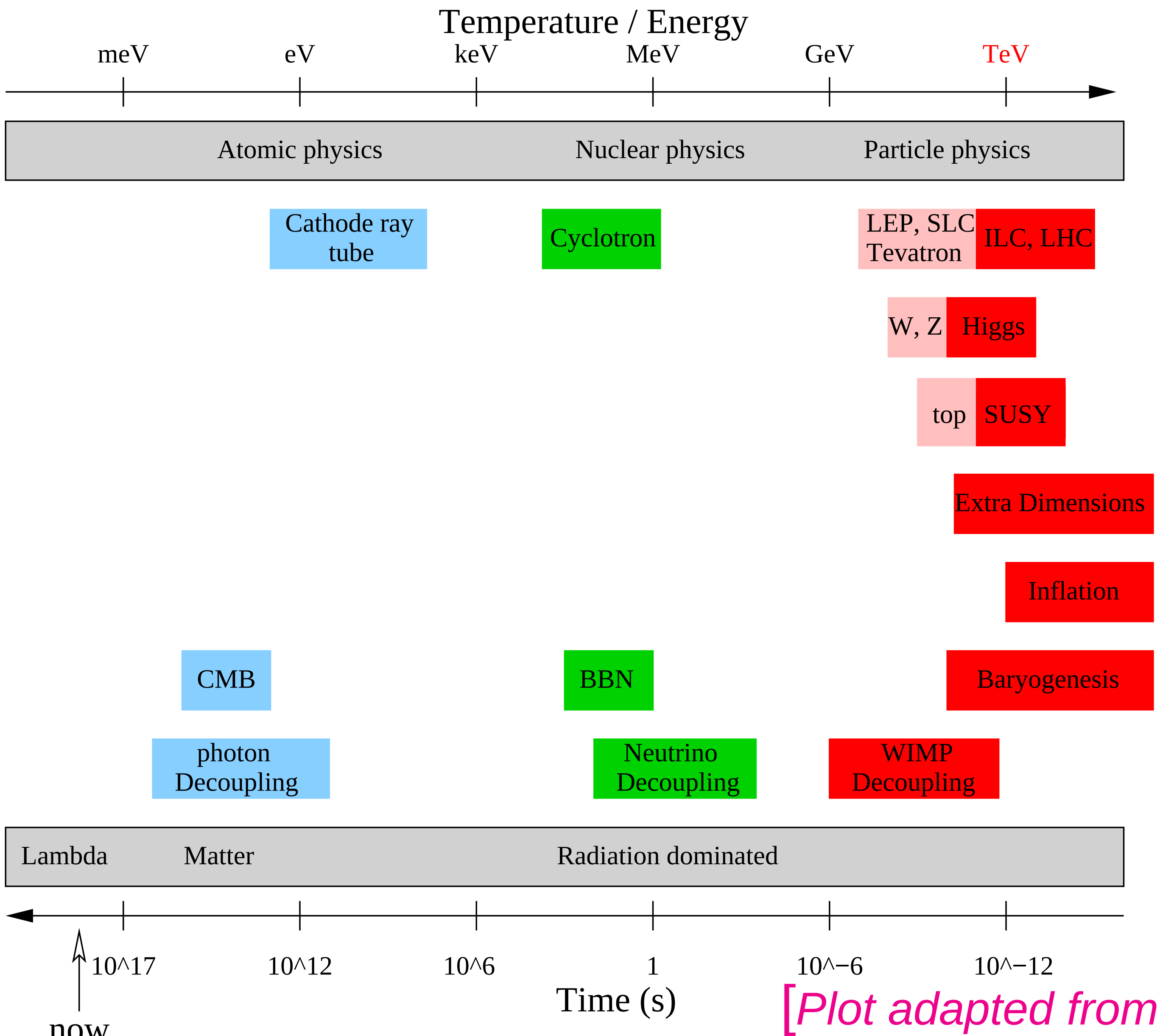
DESY

Durham, 12 / 2011

- Introduction
- Confronting SUSY with experiment: present status
- Conclusions and outlook

Introduction: exploring the Terascale

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



[Plot adapted from J. Feng '05]

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

- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking? Is there a Higgs boson (or more than one)?
- 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?
- Are there new sources of $\mathcal{CP}$-violation?
  Can they explain the asymmetry between matter and anti-matter in the Universe?
- . . .

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 $M_{\mathrm{Planck}} \approx 10^{19}$ GeV

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

  How can two so different scales coexist in nature?

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

  $\Rightarrow$ Instability of M_{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 to stabilise the hierarchy

Supersymmetry:

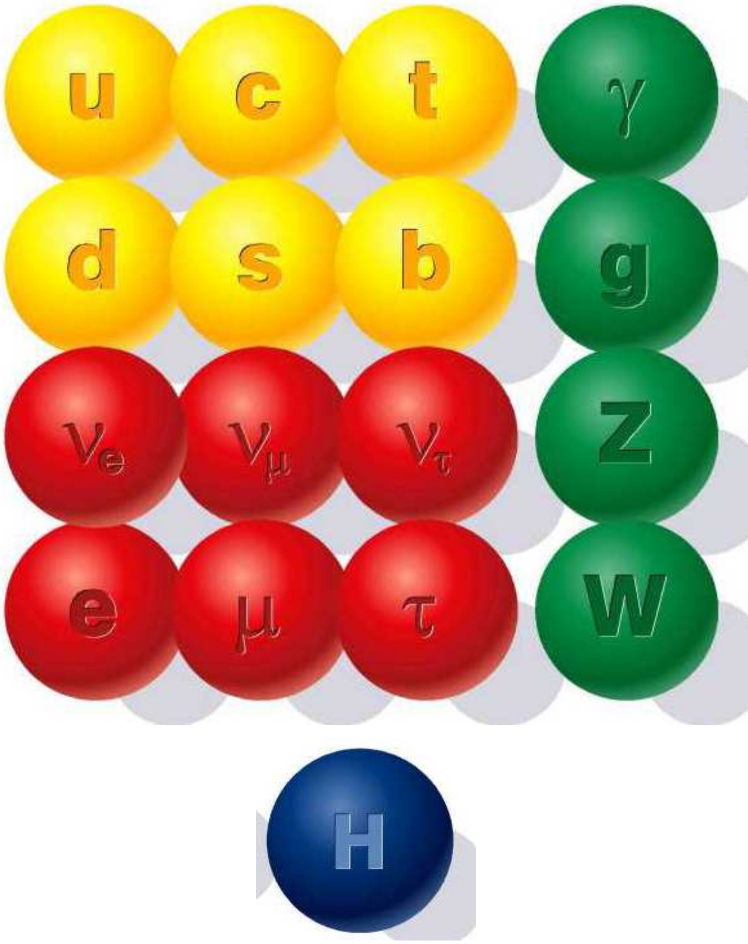
Large corrections cancel out because of symmetry
fermions $\Leftrightarrow$ bosons

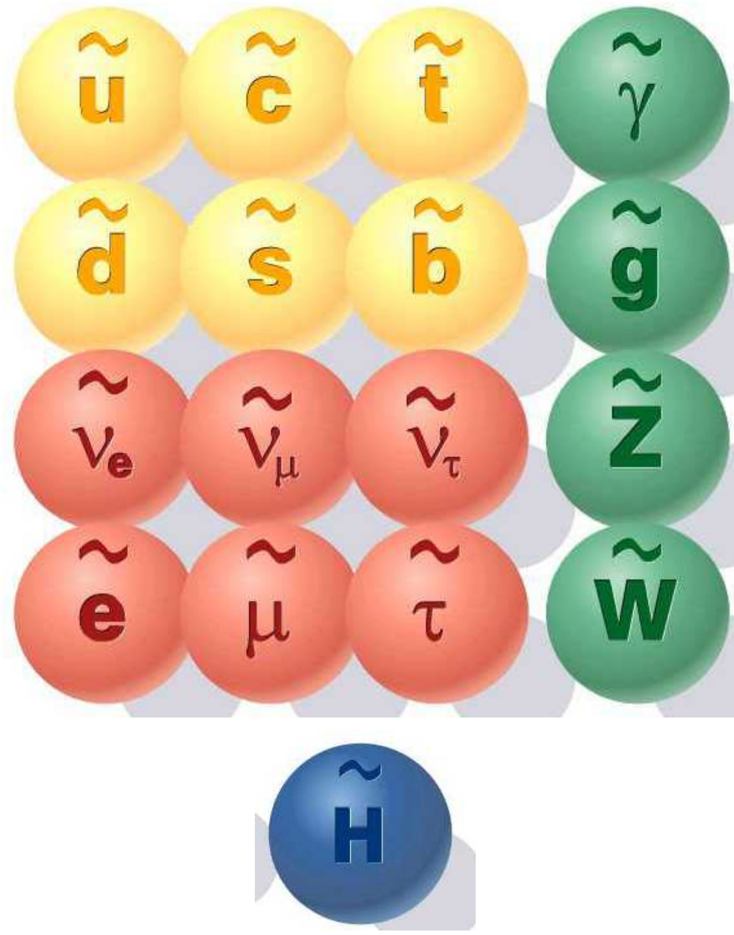
Extra dimensions of space:

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:

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

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

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

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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?

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

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

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

$\Rightarrow$ CMSSM characterised by

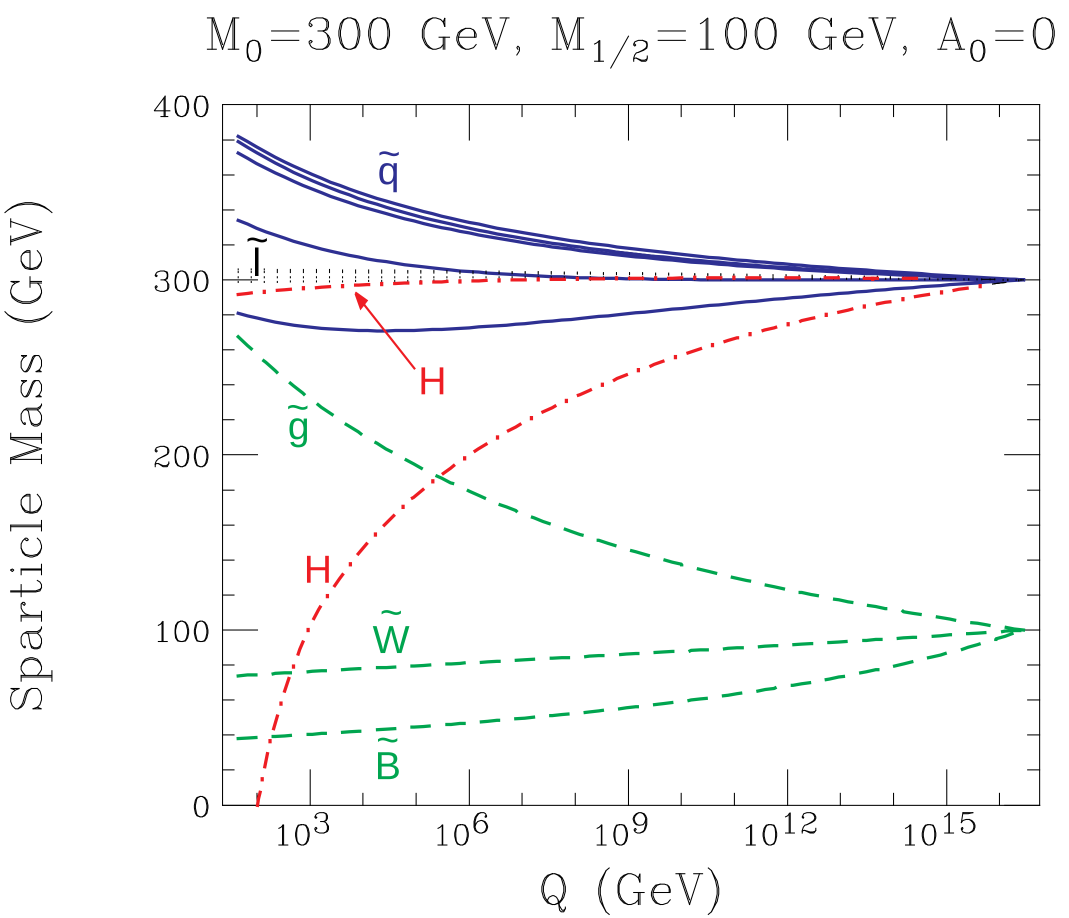
$$m_0^2,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

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 $100\ \text{GeV} \lesssim m_{\rm t} \lesssim 200\ \text{GeV}$

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”

...

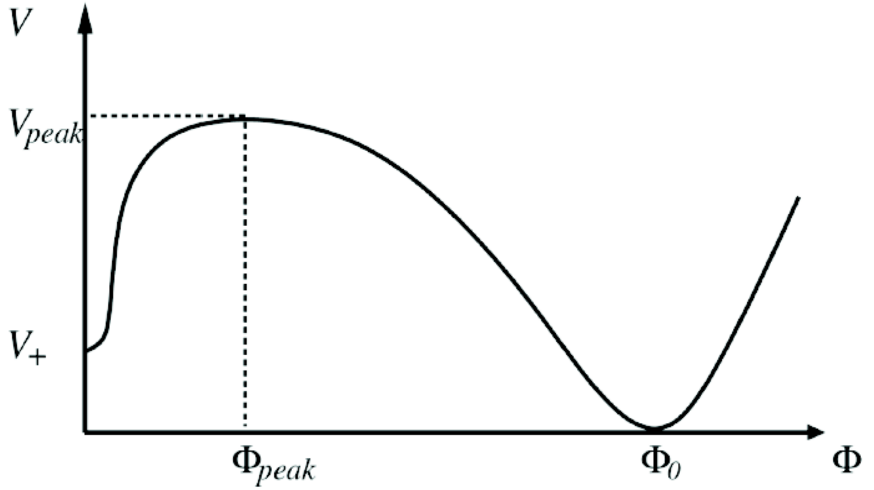
SUGRA: mediating interactions are gravitational

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

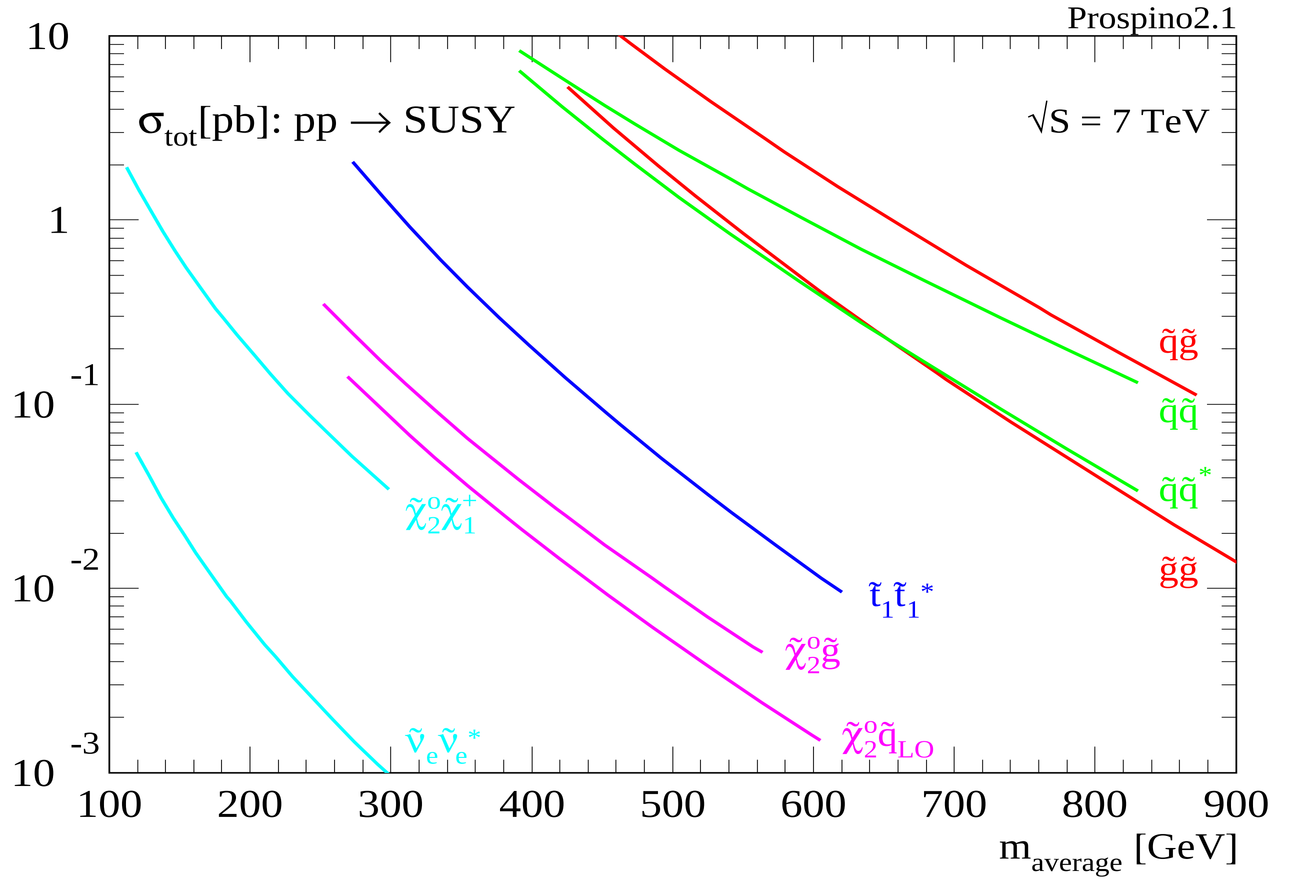


Recent developments: meta-stable vacua arise as generic feature of SUSY QCD with massive flavours

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*], . . .

$\Rightarrow$ Many new ideas — hope for experimental input!

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



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

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

Confronting SUSY with experiment

Requires big efforts on experimental and theoretical side

On the theory side within the last year: many improved predictions for signal and background processes: higher-order predictions for many-particle final states, threshold resummations, higher-order corrections in the MSSM with complex parameters, . . .

Theorists have made numerous proposals for improved experimental methods:

Momentum reconstruction, spin determination, . . .

Proposal of an "LHC SUSY/BSM cross section working group"
[*M. Krämer, M. Mangano '11*]

Proposal for the formation of a SUSY/BSM cross-section working group

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LHC SUSY/BSM cross-section working group

Aim of the WG: provide state-of-the-art cross section and branching ratio predictions for SUSY and other new physics models at the LHC.

[cf. the LHC Higgs Cross Section Working Group]

Specific tasks:

- collect SUSY/BSM cross section and branching ratio predictions, including the most advanced theory calculations (NLO, NLL resummation, electroweak corrections, bound state effects...), up-to-date SM inputs like pdf's *and a proper error estimate*;
- compare dedicated theory calculations, including higher-order corrections, with Monte Carlo predictions;
- compile a list of existing SUSY/BSM LHC tools with contact persons and test these tools for a wide region of parameter space;
- provide a common forum for discussion among the LHC experiments and the theory community.

We are starting now, please join in...

Theoretical uncertainties

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- Parametric uncertainties from the experimental errors of the input parameters: m_{t}, α_s, ..., SUSY parameters

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How about pdf fits including electroweak corrections?

Experiment and theory still haven't found the best place to meet

So far: experimental results are either interpreted in specific models, e.g. CMSSM, or in "simplified models", e.g. MSSM with just squarks of first two generations, gluino and massless LSP

In the past (LEP, . . .), the interface between experiment and theory was often established in terms of "pseudo-observables" – it will be difficult to do something similar for new physics searches at the LHC

Goal: publish results that are as much as possible model-independent (cross section limits, . . .), so that a variety of theoretical models could be probed without having to perform a new experimental analysis each time

Several proposals on the market, no satisfactory solution yet

Theorists doing “experimental” studies

More and more theorists are starting to do their own “experimental-type” analyses:

$\Rightarrow$ Reinterpretation of results published by ATLAS and CMS, . . .

The level of sophistication of this procedure is limited by the fact that theorists (who are not collaboration members) can at best use an emulation of an ATLAS or CMS fast-detector simulation (*Delphes*, . . .), but no official ATLAS or CMS software

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

Kick-off meeting:

29/08/2011–02/09/2011, CERN, $\gtrsim 200$ participants

$\Rightarrow$ 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 (in time for “Orsay-type” meeting of strategy update, 09/2012)

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*

$\Rightarrow$ It is now the right time to join in to this activity!

Confronting SUSY with experiment: present status

- Direct searches:
  LEP, Tevatron, LHC

- Indirect constraints:
  Electroweak precision observables, flavour physics, dark matter relic density

- Dark matter searches:
  Direct detection experiments, indirect detection (+ dark matter production at colliders)

Results from SUSY searches at LEP

- LEP2: limits on charged SUSY particles of $\mathcal{O}(100\ \mathrm{GeV})$

- LEP1: Stringent limits on invisible Z width

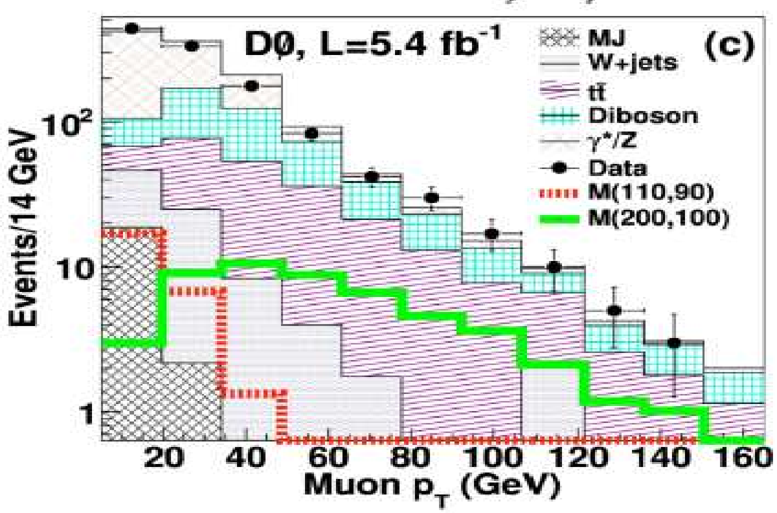
Results from SUSY searches at the Tevatron

Example: Limits from D0 stop search [*A. Annovi, LP11*]

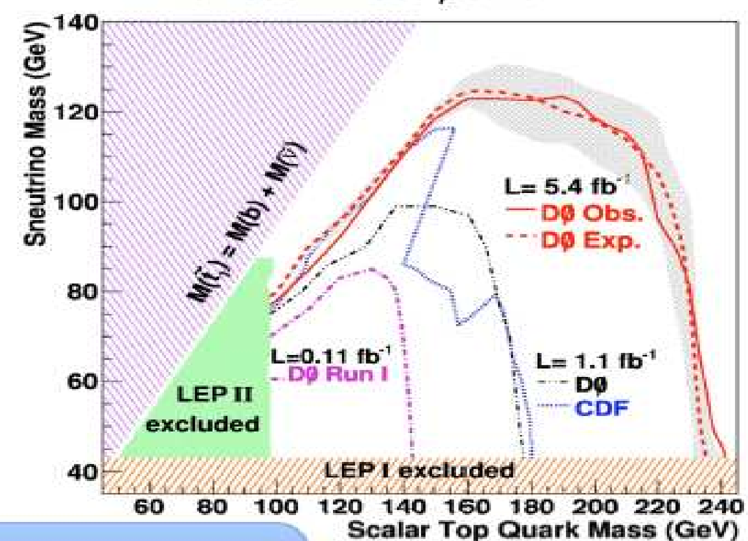
Search for scalar top

$$\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow b\bar{b}e^{\pm}\mu^{\mp}\tilde{\nu}\bar{\tilde{\nu}}$$

arXiv:1009.5950 acc. by Phys. Lett. B



2D discriminant optimized for each mass point



Exclude if
stop<210 GeV, sv<110 GeV
and ΔM>30 GeV

$\Rightarrow$ Sensitivity up to ≈ 200 GeV, depending on decay kinematics

Higgs searches at the Tevatron and the LHC

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

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

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- 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 is meanwhile ruled out for a SM-like Higgs

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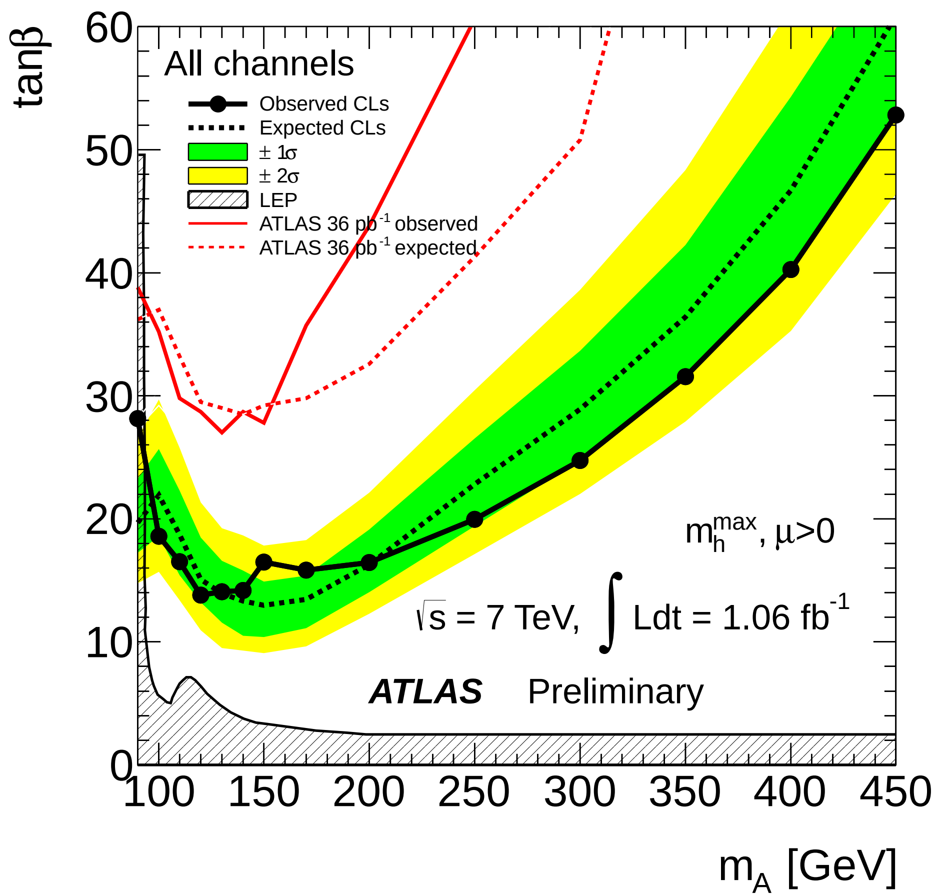
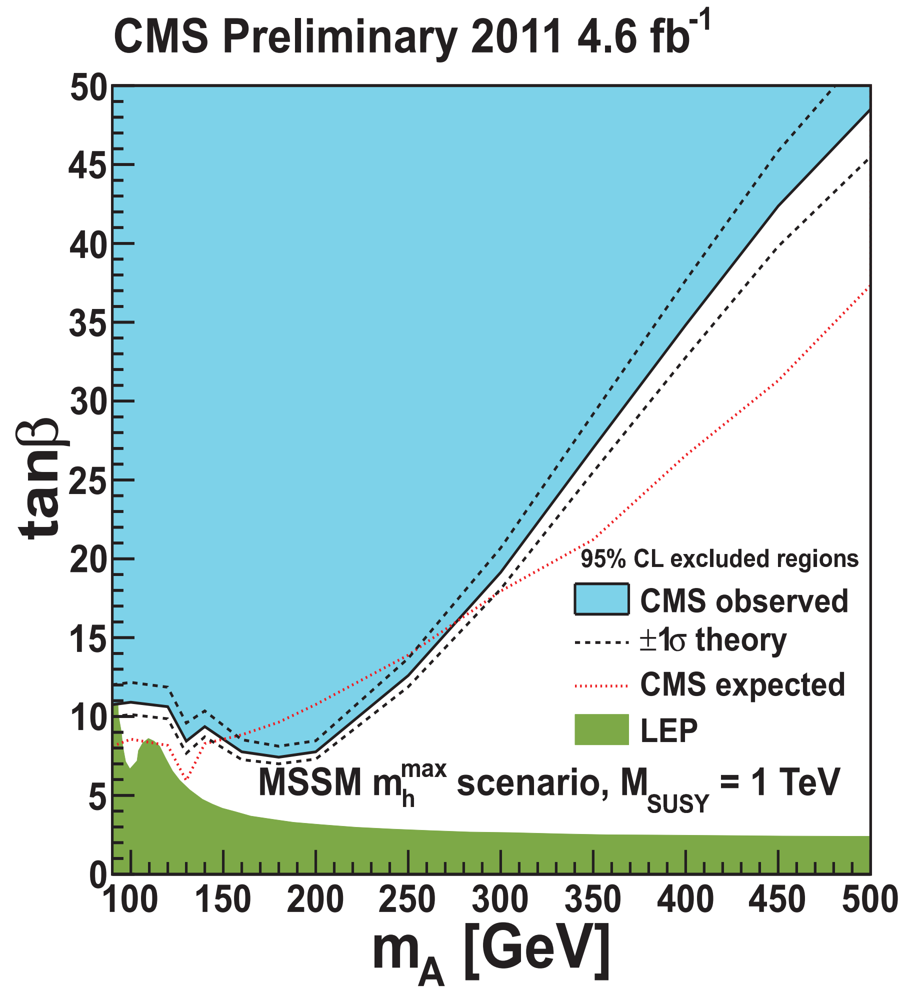
- Unexcluded low-mass region corresponds to the mass range predicted for the light $\mathcal{CP}$-even Higgs of the MSSM

Search for the heavy SUSY Higgs bosons H, A: limits in the M_{A}–$\tan\beta$ plane

[*ATLAS Collaboration '11*]



[*CMS Collaboration '11*]



⇒ Large coverage in M_{A}–$\tan\beta$ plane

LHC + LEP start to narrow down the region of very low M_{A}

MSSM interpretation of new Higgs search results from ATLAS and CMS

Excess reported by ATLAS and CMS in SM-like Higgs searches near $M_{\mathrm{H_{SM}}} \approx 125\ \mathrm{GeV}$, supported by several channels (in particular $\gamma\gamma$, ZZ^*)

Statistical significance not yet conclusive

Statistical interpretation:

LEE works in favour of the MSSM as compared to the SM

Investigate MSSM interpretation of assumed Higgs signal at $125 \pm 1\ \mathrm{GeV}$

Intrinsic theoretical uncertainties from unknown higher-order corrections, $\Delta M_{\mathrm{h}}^{\mathrm{intr}} \sim 2\ \mathrm{GeV}$, and parametric uncertaintes (variations of m_{t} by $\pm 1\sigma$) taken into account

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

Assumed signal would imply a lower bound on $M_{\rm h}$

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

$\Rightarrow$ Lower bounds on $M_{\rm A}$, $\tan\beta$

Search limits from LEP and from LHC $H, A \to \tau^+\tau^-$ search taken into account:

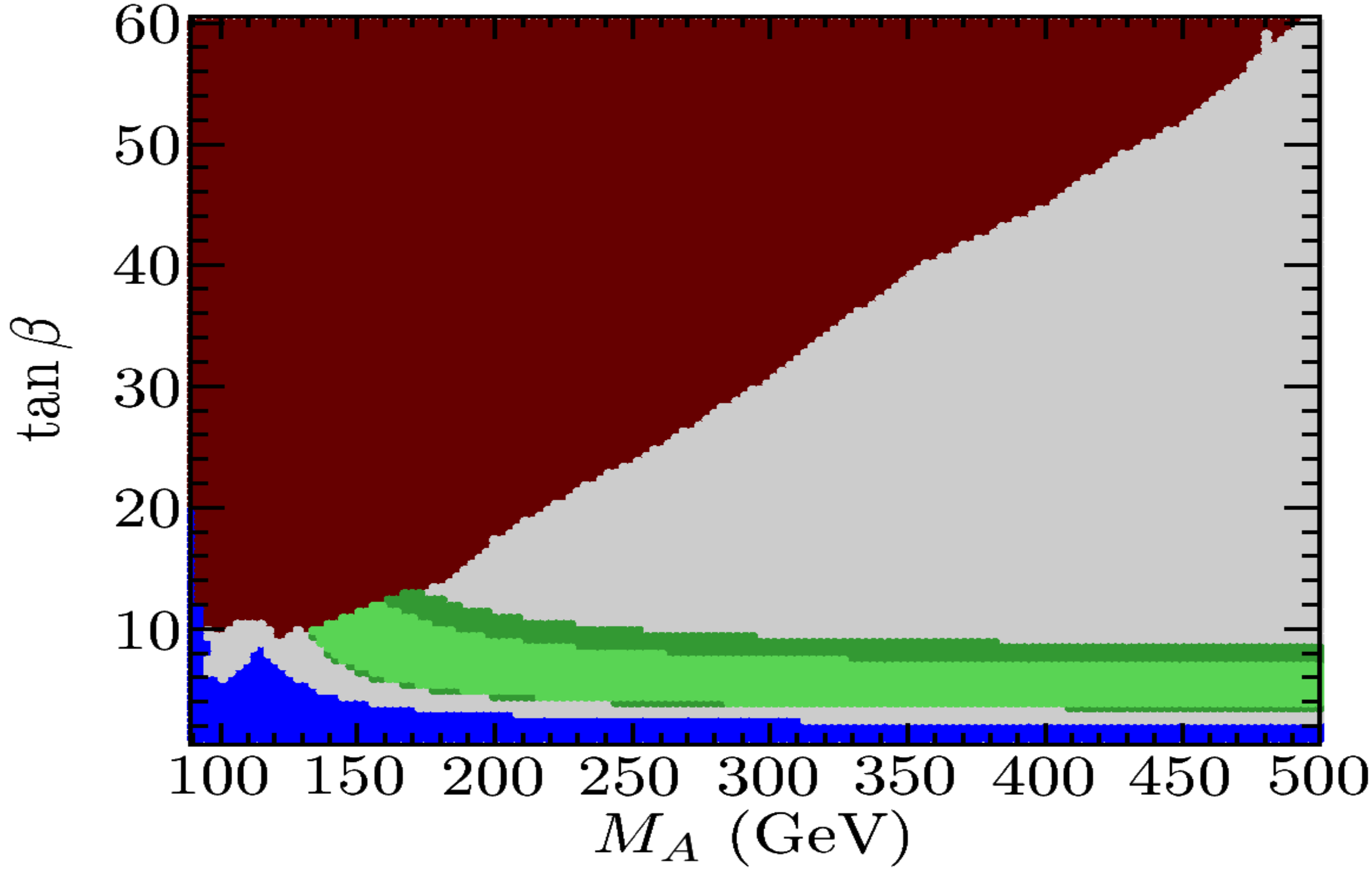
HiggsBounds

[*P. Bechtle, O. Brein, S. Heinemeyer, G. W., T. Stefaniak, K. Williams '08, '11*]

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*]

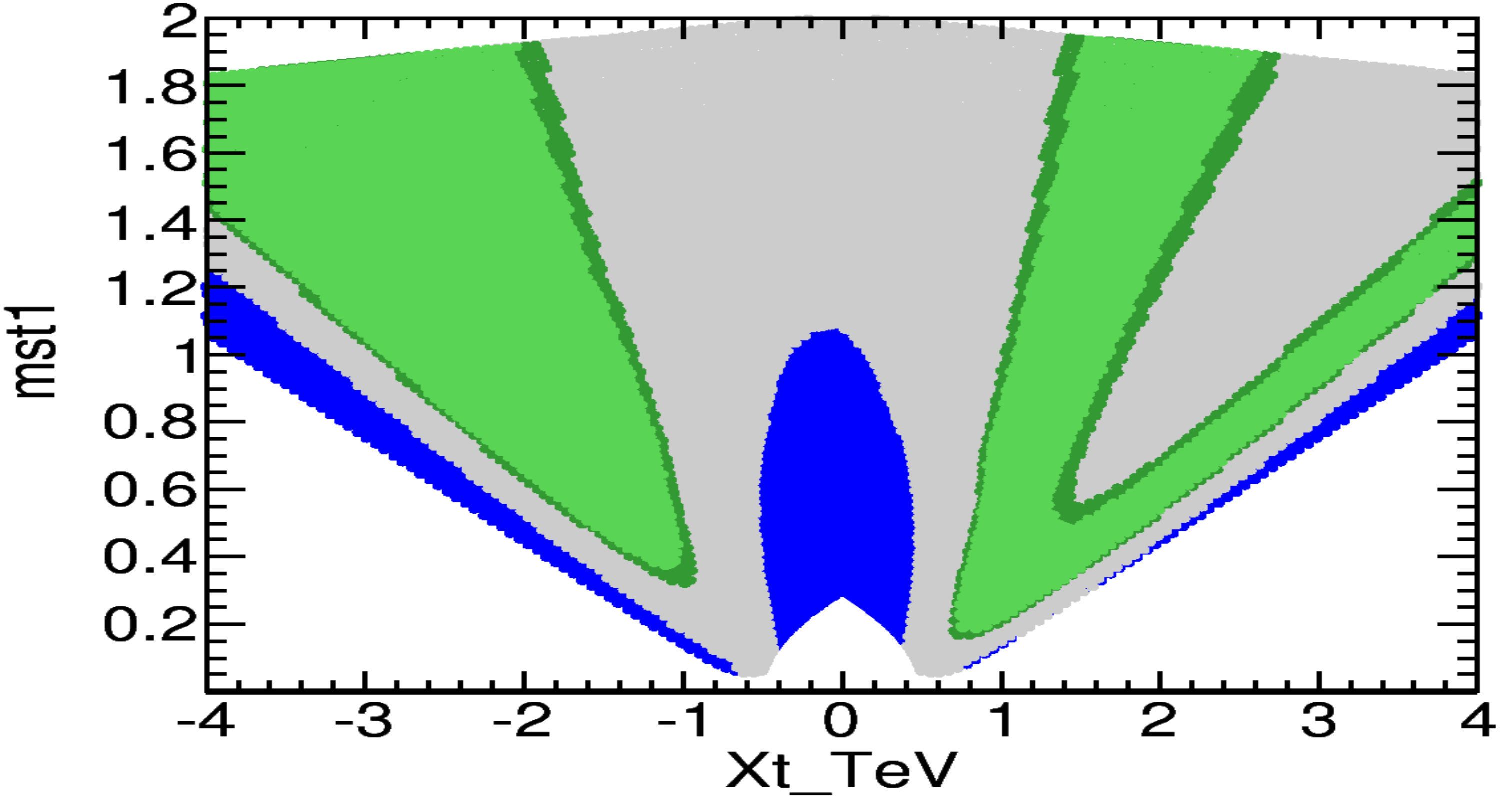


$\Rightarrow \tan\beta \gtrsim 3$, $M_\mathrm{A} \gtrsim 130$ GeV, $M_{\mathrm{H}^\pm} \gtrsim 152$ GeV

Lower bound on the lightest stop mass from assumed Higgs signal at $\sim 125\ \mathrm{GeV}$

M_A, $\tan\beta$ chosen in decoupling region: $M_\mathrm{A} = 1\ \mathrm{TeV}$, $\tan\beta = 20$

[*S. Heinemeyer, O. Stål, G. W. '11*]



$\Rightarrow m_{\tilde{t}_1} > 170\ (320)\ \mathrm{GeV}$ for positive (negative) X_t

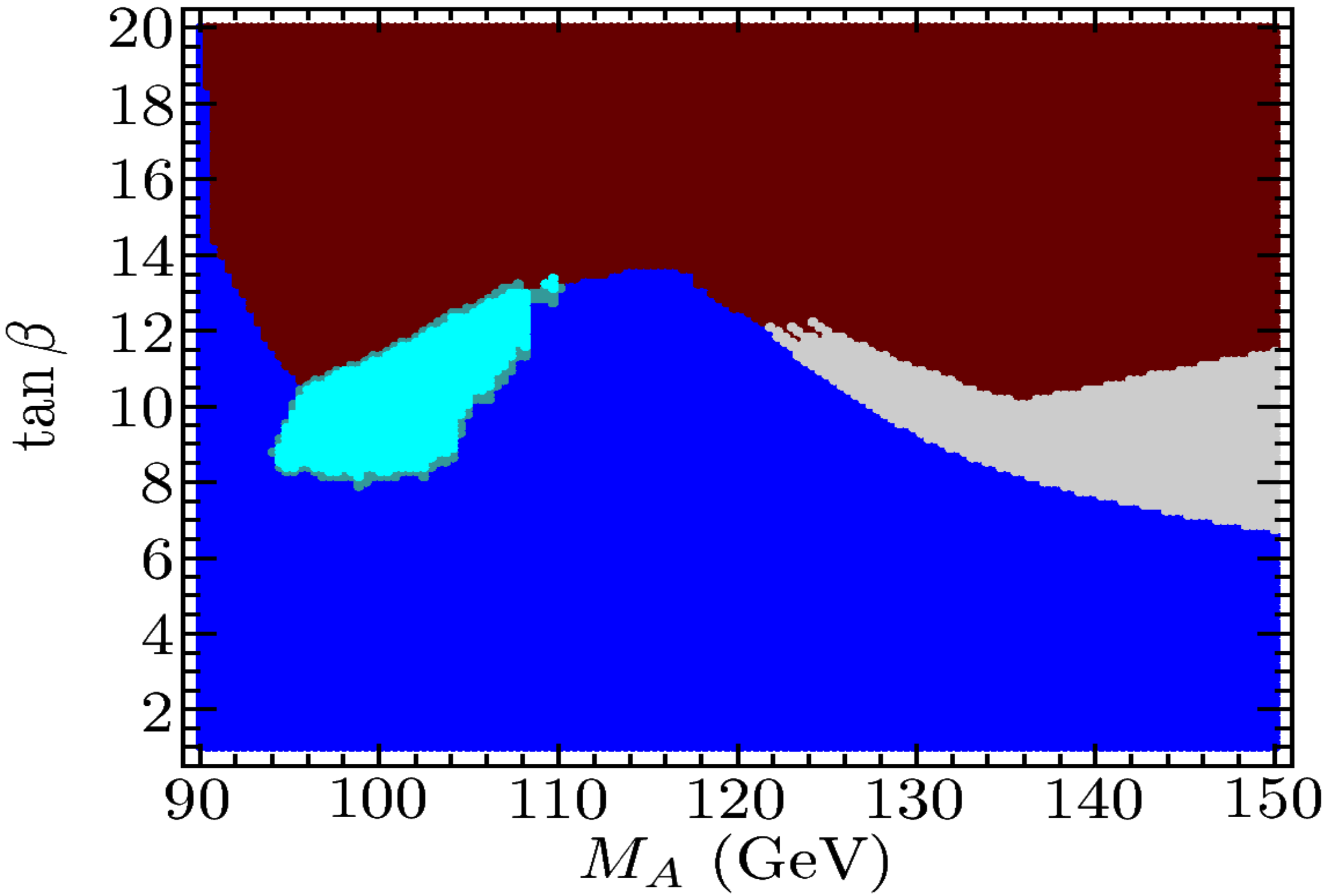
Compatibility with assumed signal would be difficult in constrained models: mGMSB, mAMSB, ...

Interpretation of an assumed Higgs 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 $\tan\beta$

Interpretation of an assumed Higgs signal at $\sim 125\ \mathrm{GeV}$ in terms of the heavy MSSM CP-even Higgs H

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

Could have, for instance, $M_{\mathrm{H}} \sim 125\ \mathrm{GeV}$, $M_{\mathrm{h}} \sim 98\ \mathrm{GeV}$ (slight excess observed at LEP at $M_{\mathrm{h}} \sim 98\ \mathrm{GeV}$)

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

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

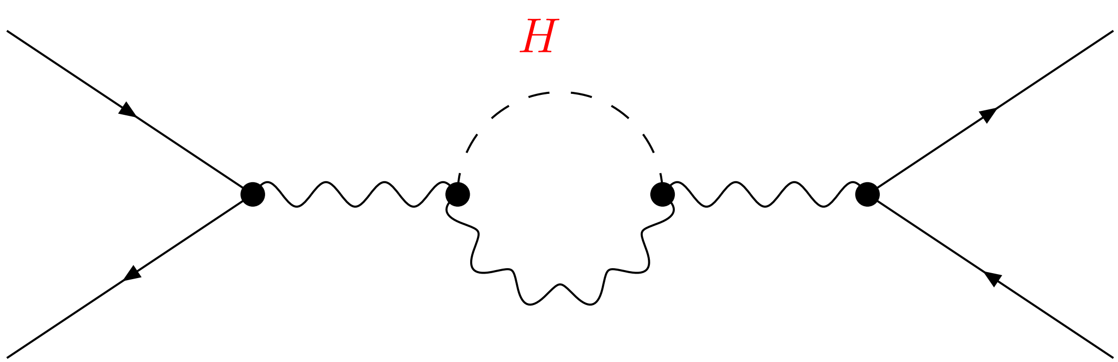
Indirect constraints

EW precision data:
$M_{\rm Z}, M_{\rm W}, \sin^2\theta_{\rm eff}^{\rm lept}, \ldots$

Theory:
SM, MSSM, . . .

$\Downarrow$

Test of theory at quantum level: loop corrections



$\Downarrow$

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

Window to “new physics”

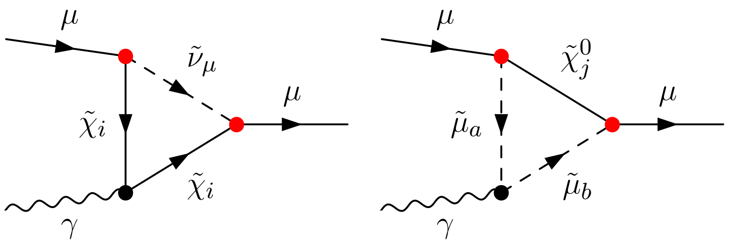
The anomalous magnetic moment of the muon:

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

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



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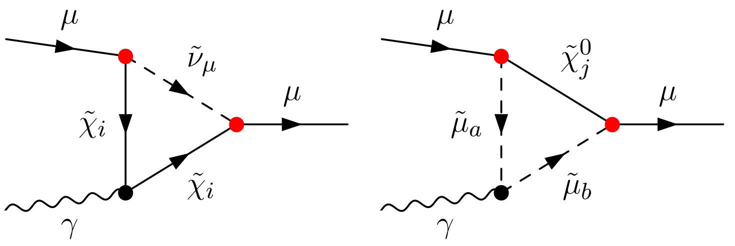
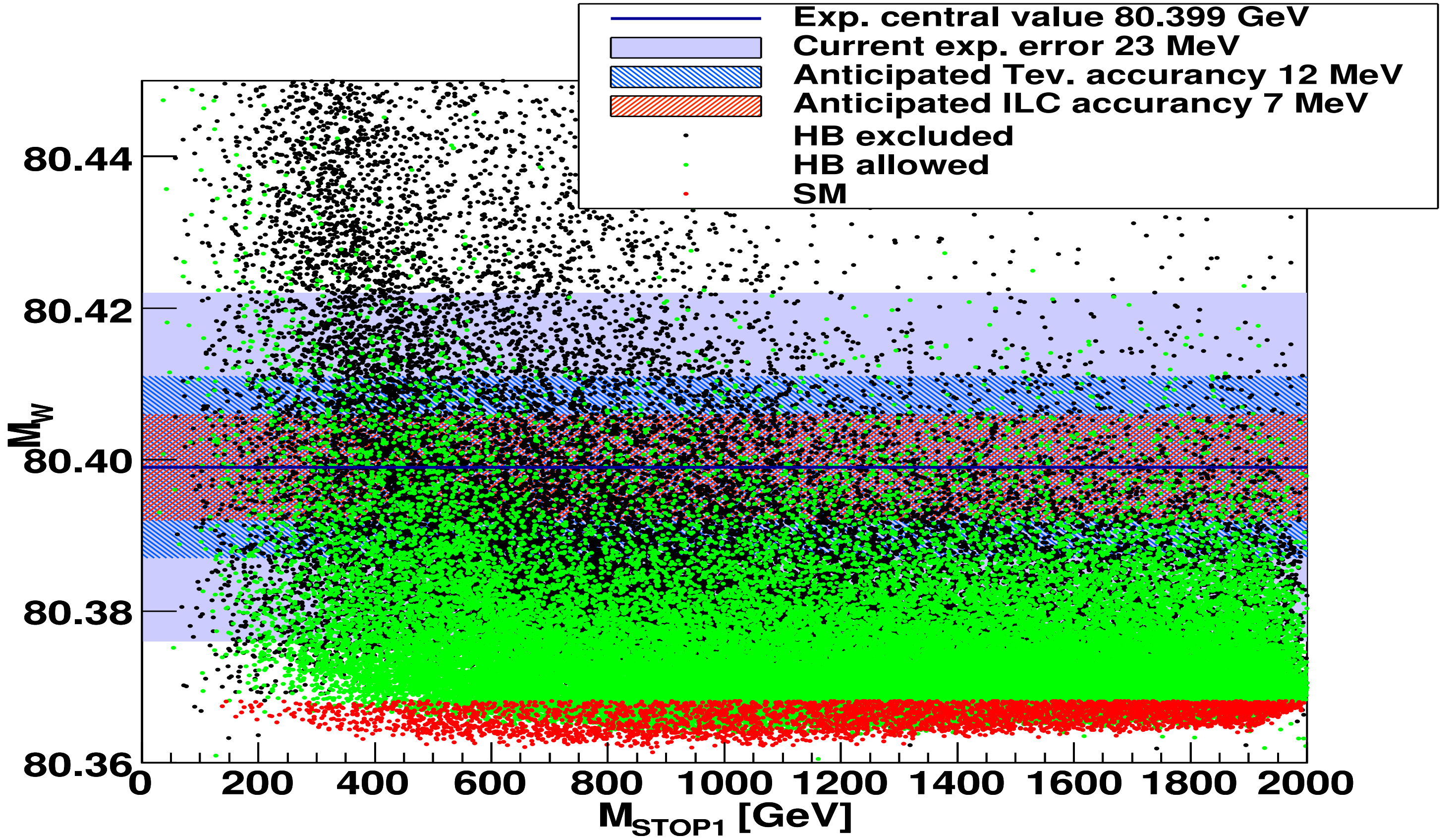


$(g-2)_\mu$: preference for light new physics contributions has further solidified (convergence of SM predictions using low-energy e^+e^- and τ decay data as input)

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

Current experimental result for $M_{\rm W}$ and future projections vs. predictions in the MSSM and the SM ($M_{\rm H_{SM}} \lesssim 130$ GeV)

[*L. Zeune, G. W. '11*]

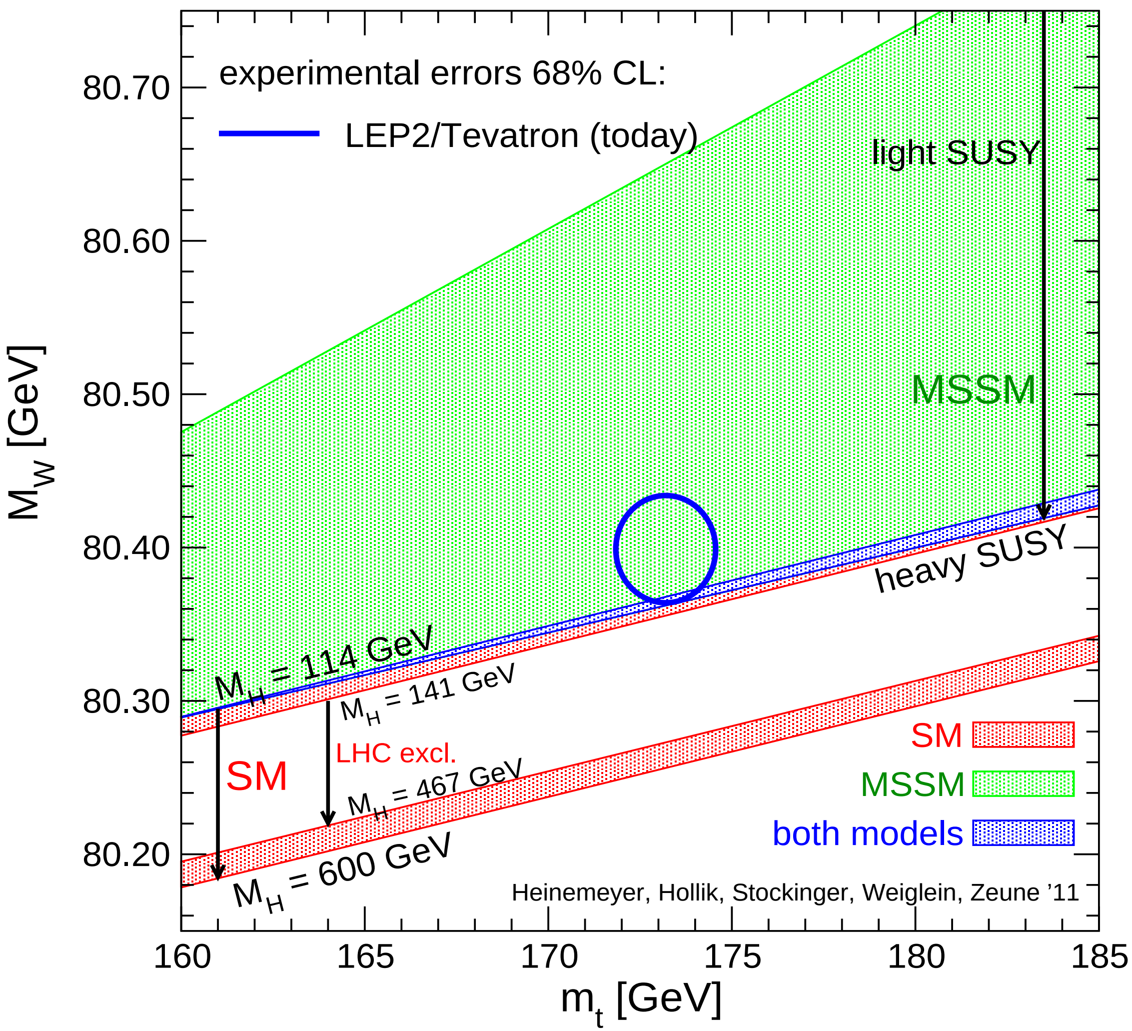


⇒ High sensitivity for discriminating SM / new physics

NB: The density of points has no physical significance

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 '11*]

MSSM: SUSY parameters varied

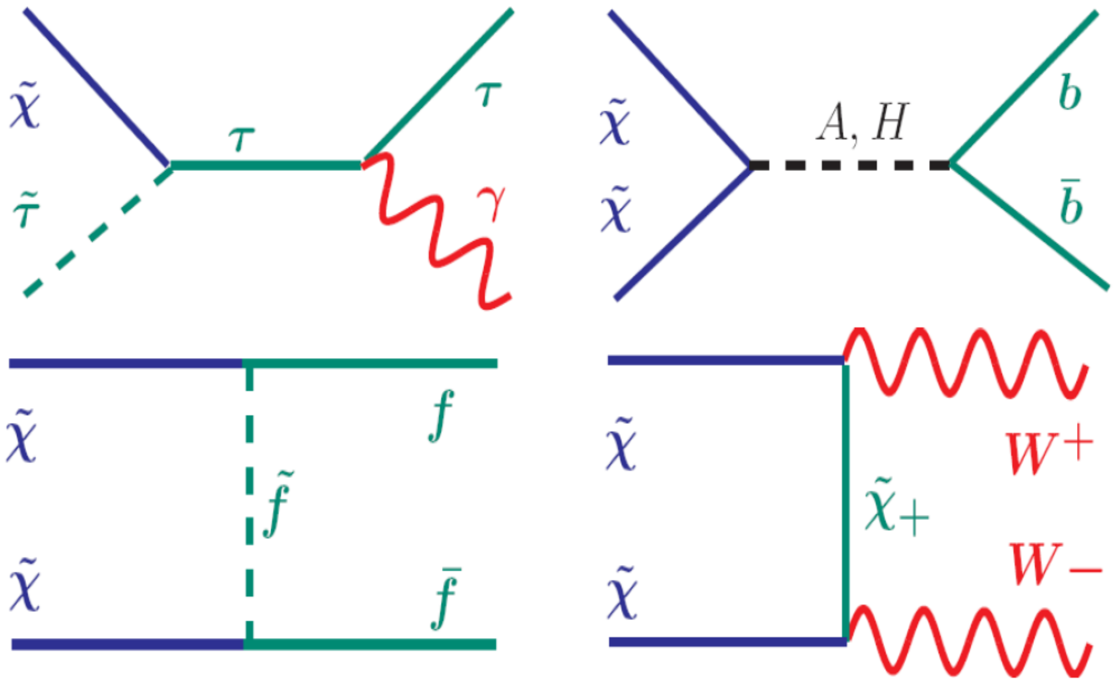
SM: M_H varied

Tevatron result for m_t interpreted (perturb.) as pole mass

$\Rightarrow$ Slight preference for MSSM over SM

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, . . .):

$$\Omega_{\rm CDM}\, h^2 = 0.1120 \pm 0.0056$$

$\Rightarrow$ Points to relatively low mass scale if interpreted as weakly interacting massive particle

A possible hint for CP-violation in the charm sector?

Recent excitement: LHCb reported first evidence for CP violation in charm decays: $\Delta A_{\rm CP}$, significance 3.5σ

Sizable hadronic uncertainties

BSM interpretations still somewhat premature

Global fits in constrained SUSY models

Take into account information from

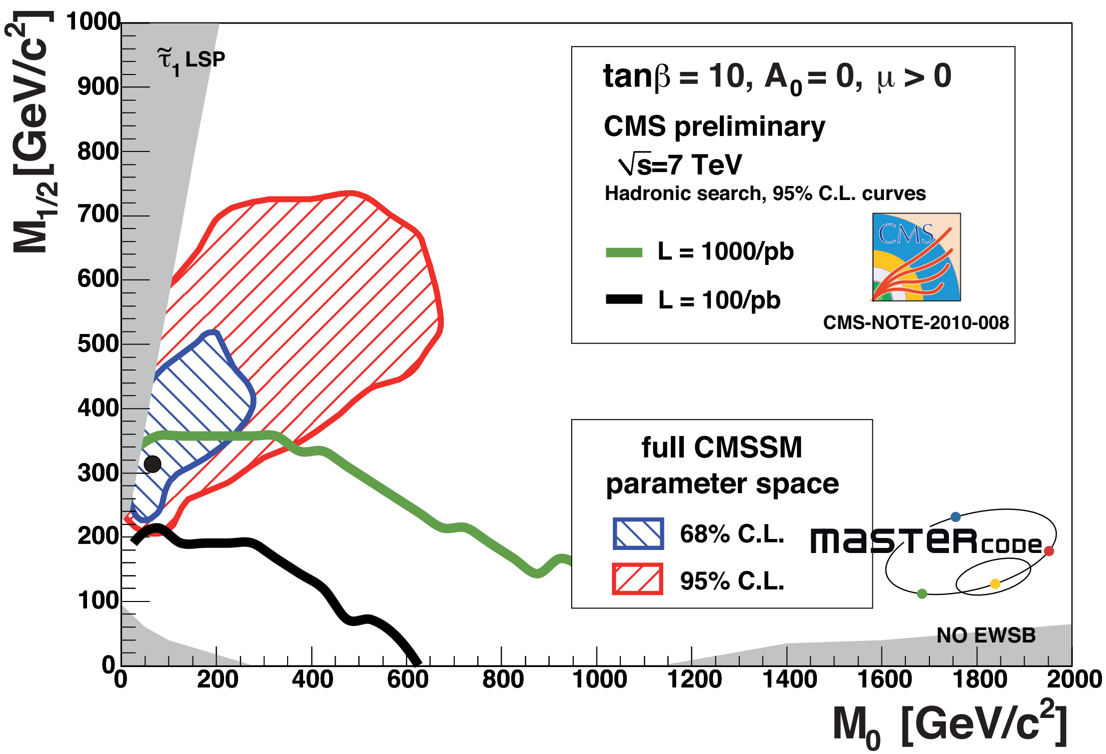
- Electroweak precision observables: $M_{\mathrm{W}}, \sin^2\theta_{\mathrm{eff}}, \Gamma_{\mathrm{Z}}, \ldots$
- $+ (g-2)_\mu$
- $+$ Cold dark matter (CDM) density (WMAP, . . .)
- $+$ B-physics observables:
  $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_{\mathrm{s}} \to \mu^+\mu^-)$, $\mathrm{BR}(B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

$\Rightarrow$ 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 $7\ \mathrm{TeV}$

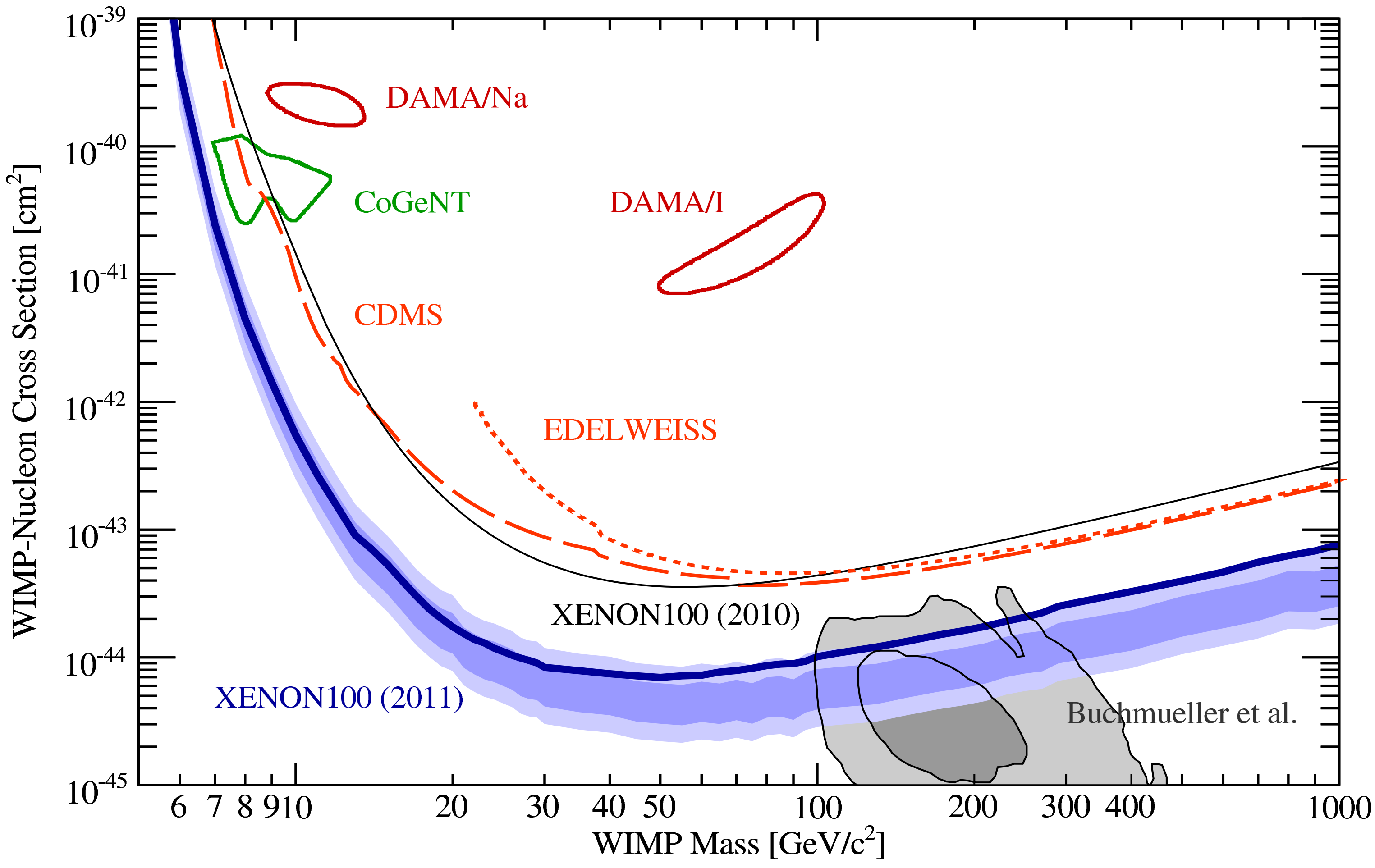
[O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10]



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

Comparison of direct dark matter search reach (XENON100) with preferred region from CMSSM fit

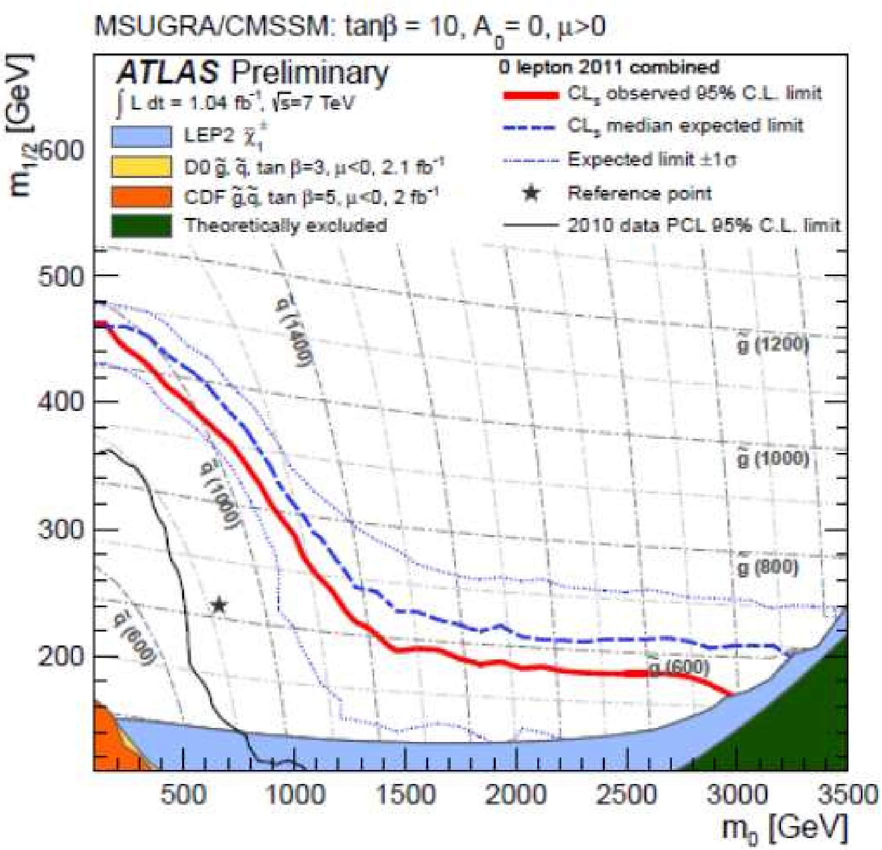
[*XENON100 Collaboration '11*]



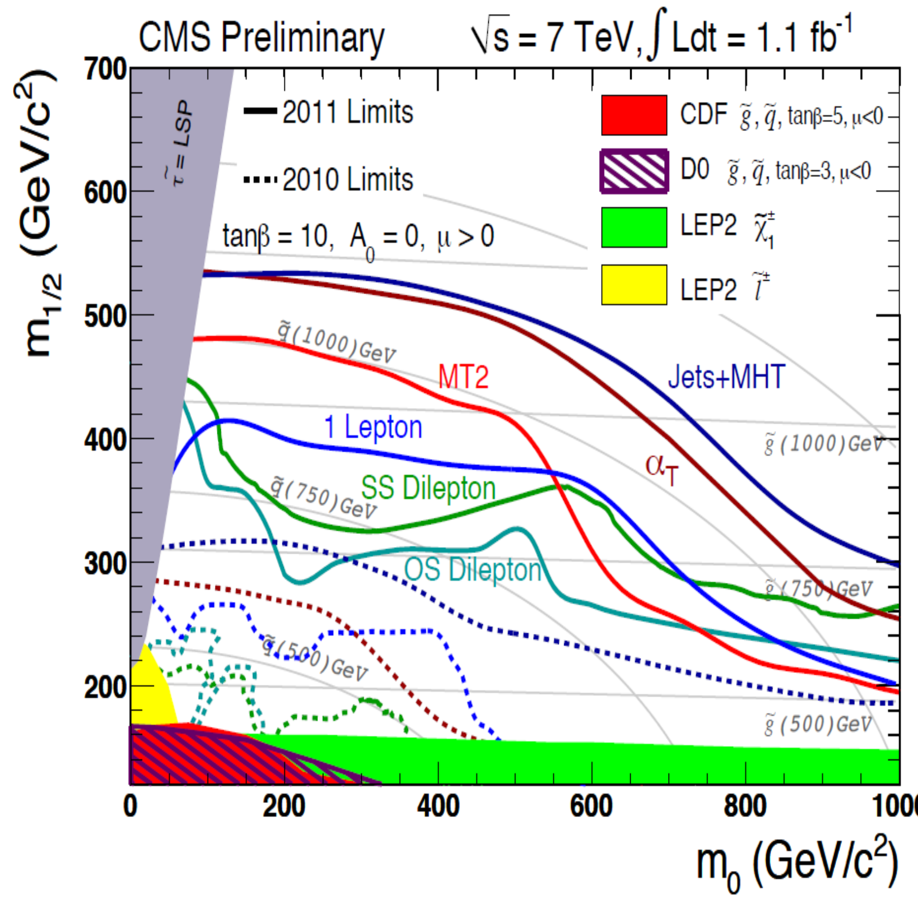
$\Rightarrow$ Direct detection experiments have started to probe preferred region in CMSSM (fit based on 2010 LHC data)

LHC: ***SUSY search results for the CMSSM***

[*ATLAS Collaboration '11*]



[*CMS Collaboration '11*]



⇒ High sensitivity from search for jets + missing energy

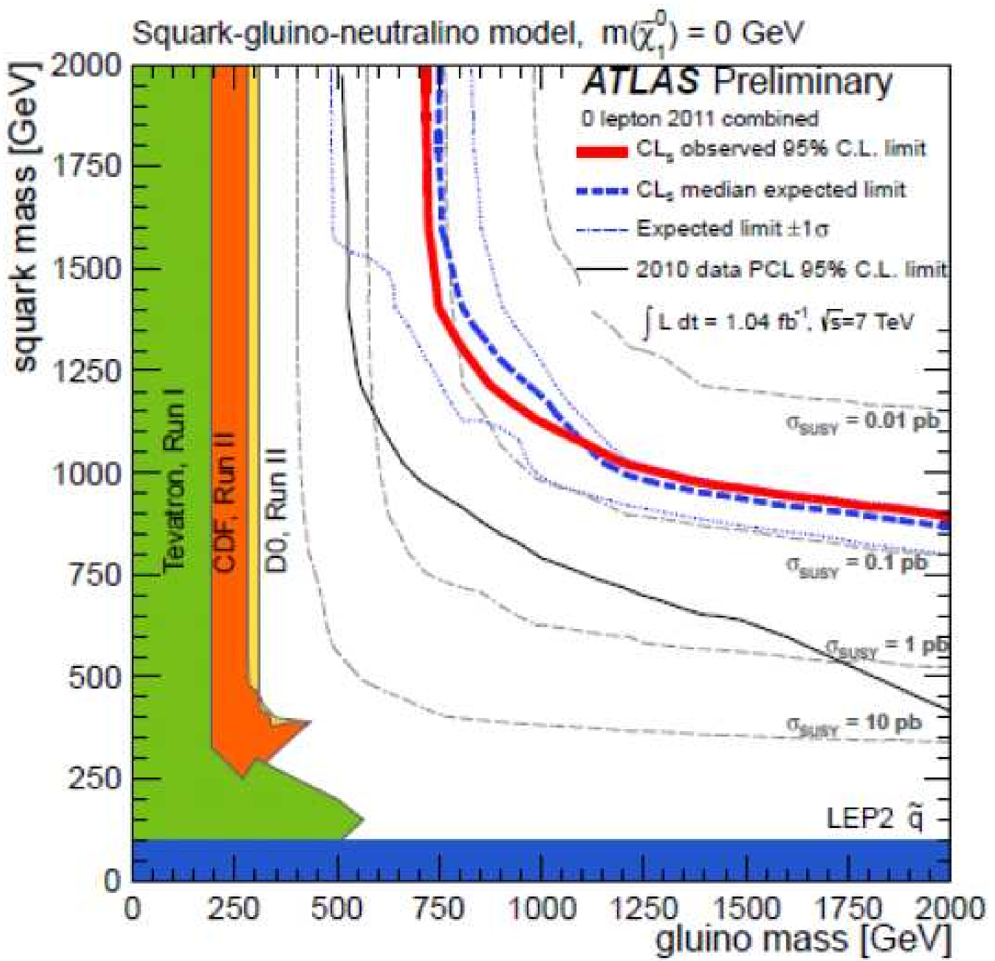
Previous best-fit point is excluded

CMSSM starts to get under pressure

Interpretation of SUSY search result in "simplified model"

"Simplified model": squarks of first two generations, gluino + massless neutralino (LSP), all other SUSY particles heavy

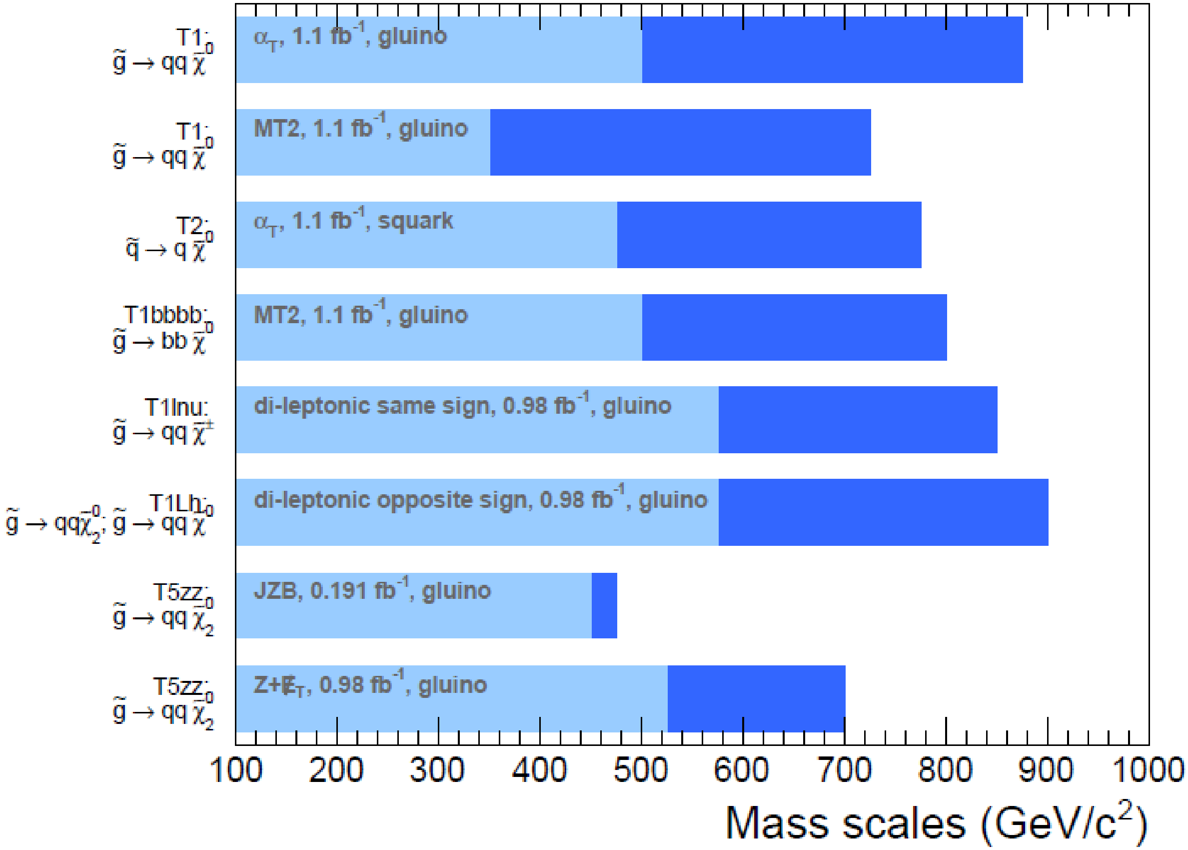
[*ATLAS Collaboration '11*]



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

[*CMS Collaboration '11*]

Ranges of exclusion limits for gluinos and squarks, varying $m(\tilde{\chi}^0)$
CMS preliminary



For limits on $m(\tilde{g})$, $m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{prod} = \sigma^{NLO\text{-}QCD}$.

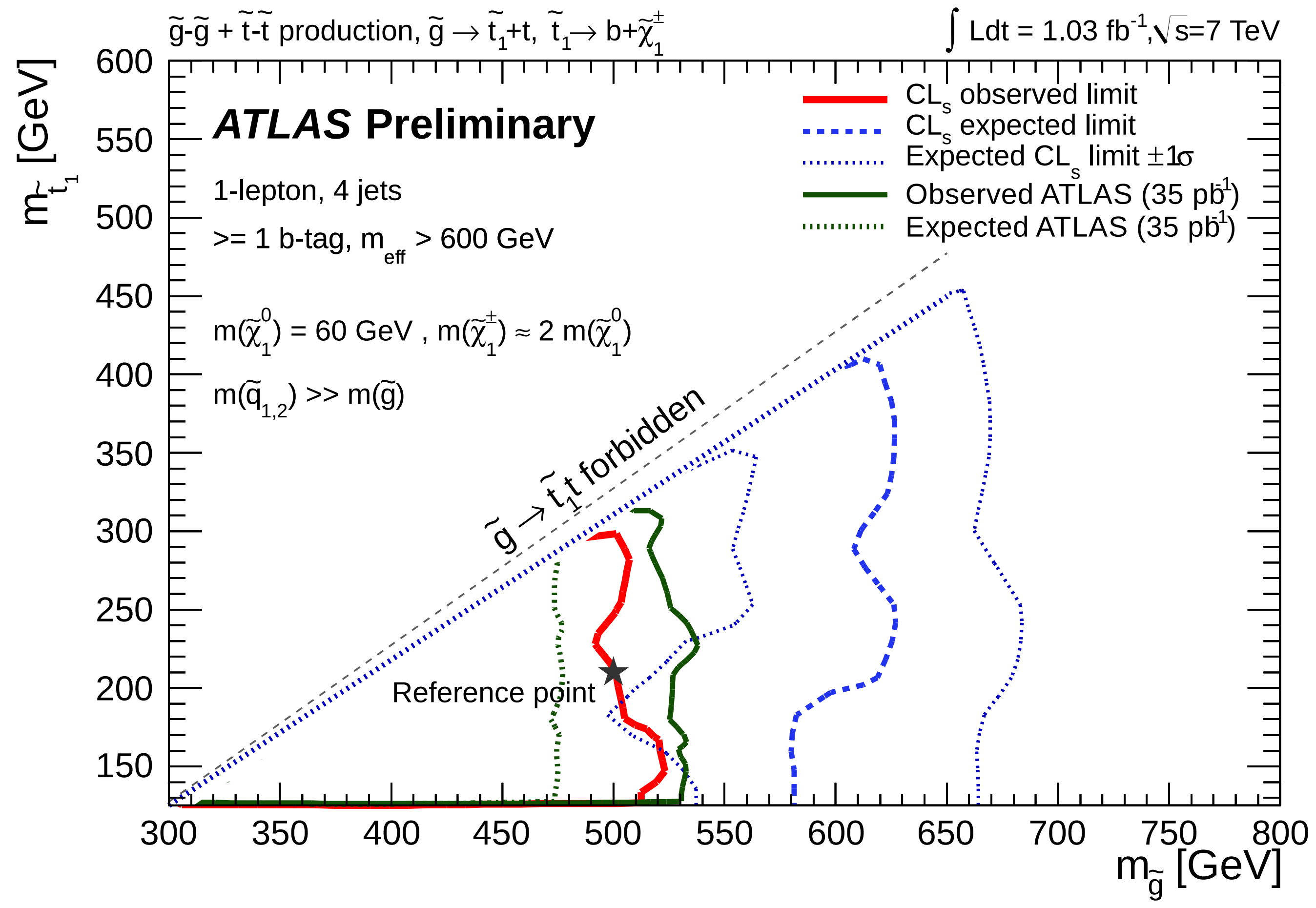
$m(\tilde{\chi}^\pm), m(\tilde{\chi}^0_2) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$.

$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g})$-200 GeV/c^2 (light blue).

$\Rightarrow$ Large dependence on LSP mass

Search for stop production in gluino decays

[ATLAS Collaboration '11]



⇒ Observed limit decreased with 30 × more luminosity

1.2 σ excess in both electron and muon channels

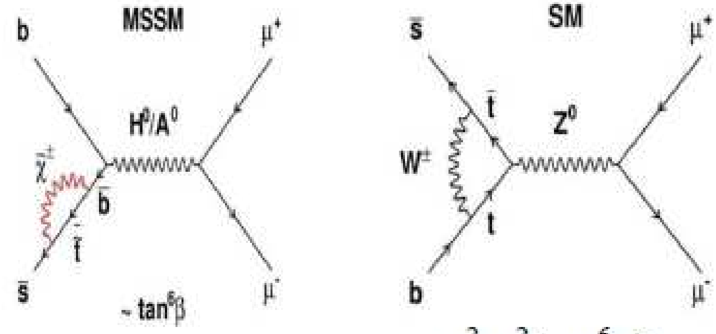
Search for the rare decay $B_s \to \mu^+\mu^-$

B physics rare decay par excellence:

$BR(B_s \to \mu\mu)_{SM} = (3.2 \pm 0.2) \times 10^{-9}$

[A.J.Buras, arXiv:1012.1447]

Precise prediction (which will improve) !

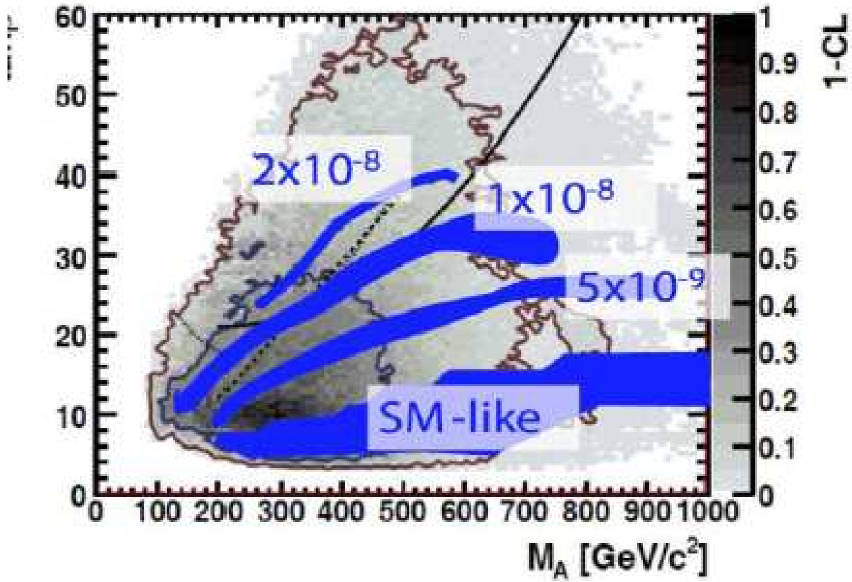


Very high sensitivity to NP, eg. MSSM:

$$Br^{MSSM}(Bq \to l^+l^-) \propto \frac{m_b^2 m_l^2 \tan^6\beta}{M_{A0}^4}$$

One example [O. Buchmuller et al, arXiv:0907.5568] : NUHM (= generalised version of CMSSM)

$BR(B_s \to \mu\mu)$ - highly discriminatory



BR UL 95% CL as of Spring 2011:

CDF (3.7 fb^{-1}): $< 4.3 \times 10^{-8}$

D0 (6.1 fb^{-1}): $< 5.1 \times 10^{-8}$

LHCb (37 pb^{-1}): $< 5.6 \times 10^{-8}$

Recent exciting hint from CDF (7 fb^{-1}):

$BR = 1.8^{+1.1}_{-0.9} \times 10^{-8}$!?!

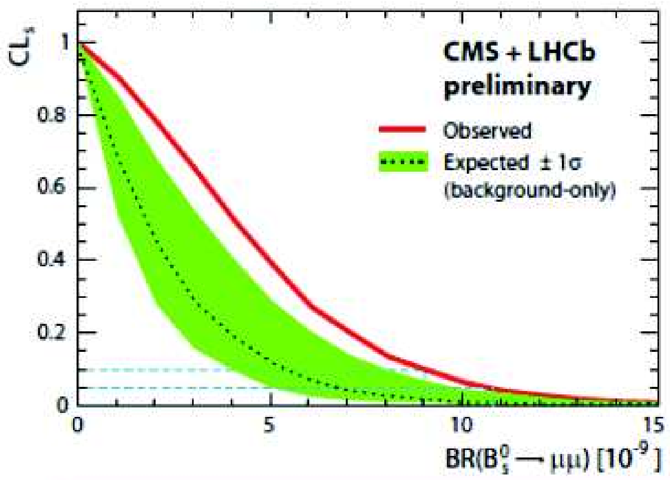
[arXiv:1107.2304]

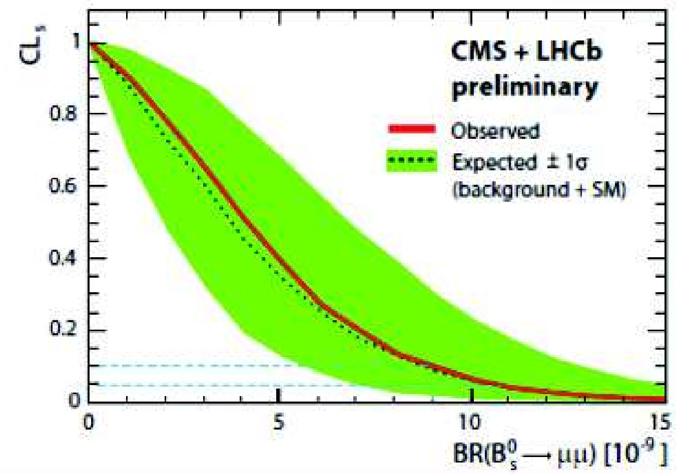
30

$\mathrm{BR}(B_s \to \mu^+\mu^-)$: *combined result from LHCb and CMS*

$B_s \to \mu^+\mu^-$: combination with CMS

- LHCb and CMS have performed a preliminary combined limit [LHCb-CONF-2011-043, CMS PAS BPH-11-019]
  - LHCb $\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.5\ (1.2) \times 10^{-8}$ at 95%(90%) c.l.
  - CMS: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.9\ (1.6) \times 10^{-8}$ at 95%(90%) c.l





LHCb+CMS limit: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.1\ (0.9) \times 10^{-8}$ at 95%(90%) c.l.

This is ~ 3 times the SM BR

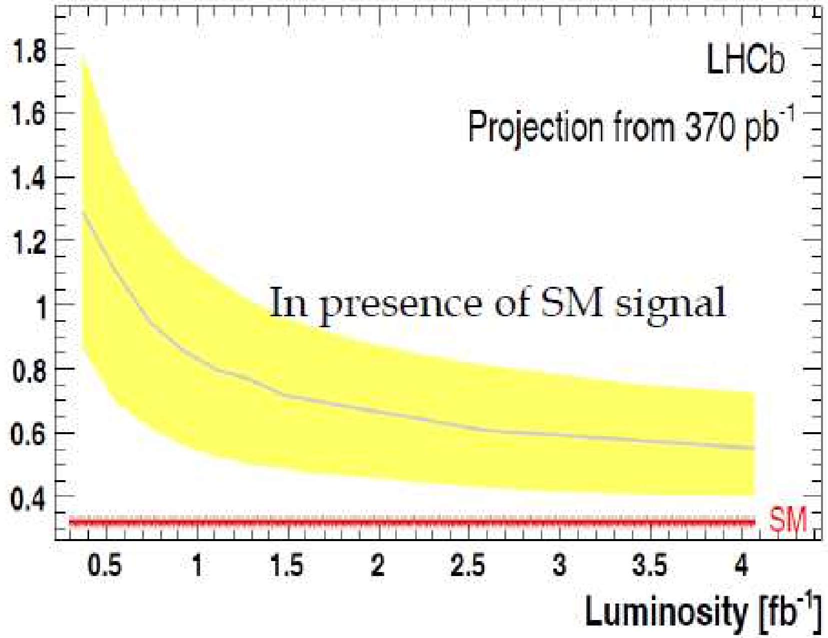
40

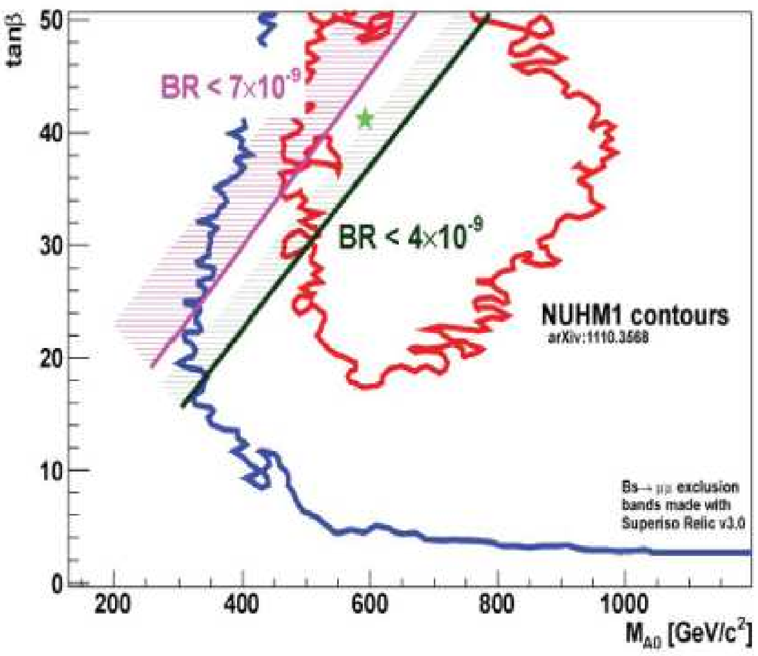
$\Rightarrow$ Very good agreement with SM expectation (so far)

LHCb prospects for 2012

[*D. Martínez Santos HCP '11*]

Extrapolated sensitivity



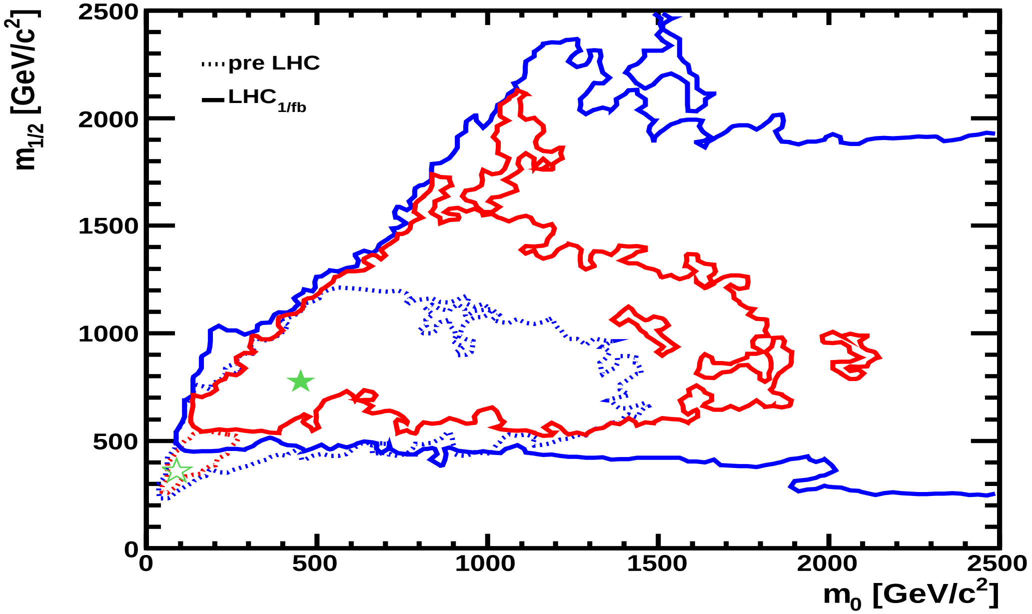


$B_s \to \mu\mu$ will continue to constrain NP scenarios.
A 3σ evidence is possible between winter conferences and end of 7 TeV run

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*]



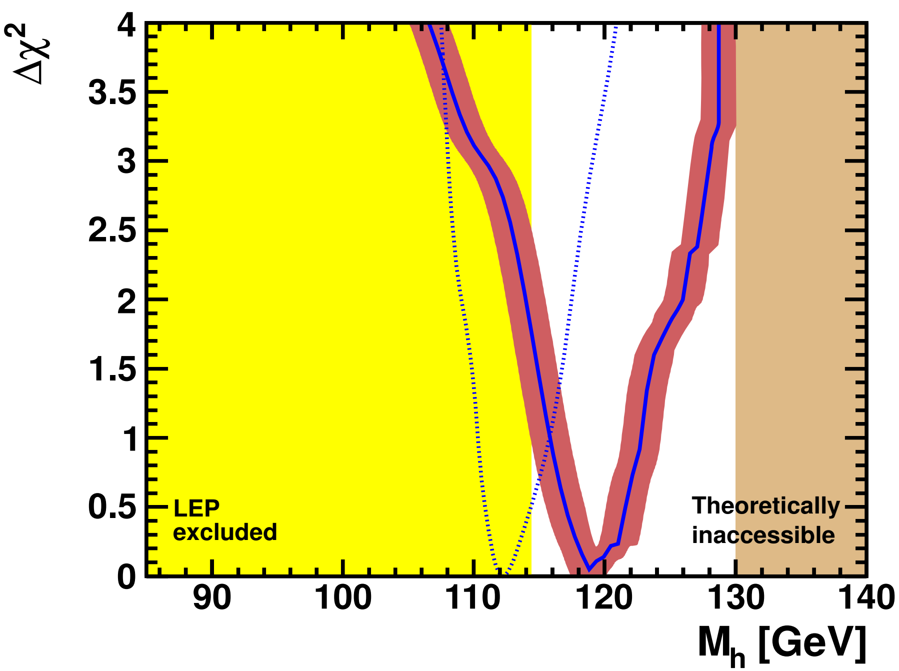
$\Rightarrow$ Preferred region "opens up", overall χ^2 worsened
Shift towards higher mass scales, higher values of $\tan\beta$

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

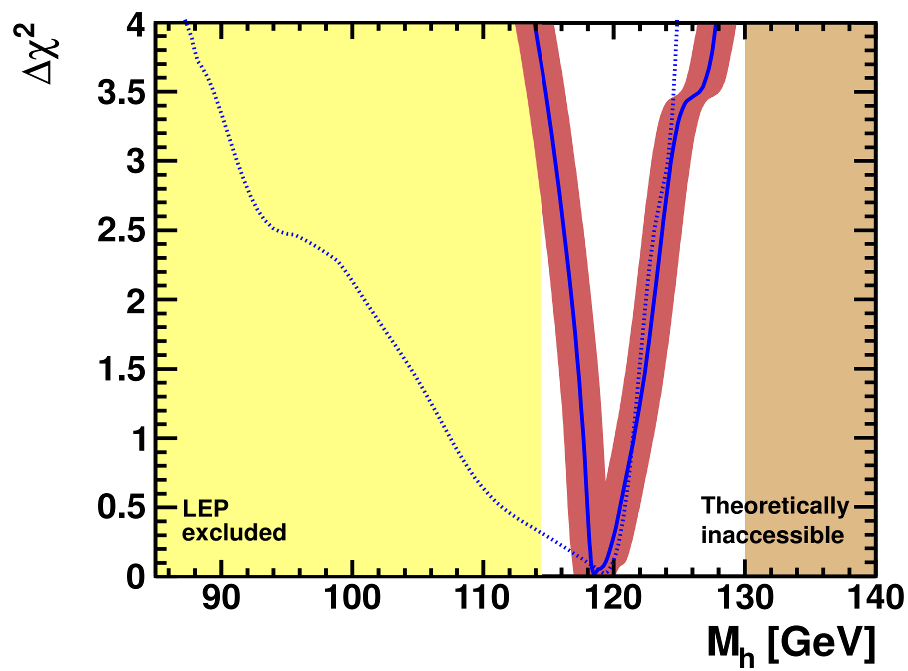
Indirect prediction for the Higgs mass in CMSSM, NUHM1: pre-LHC vs. LHC2011

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

CMSSM:



NUHM1:



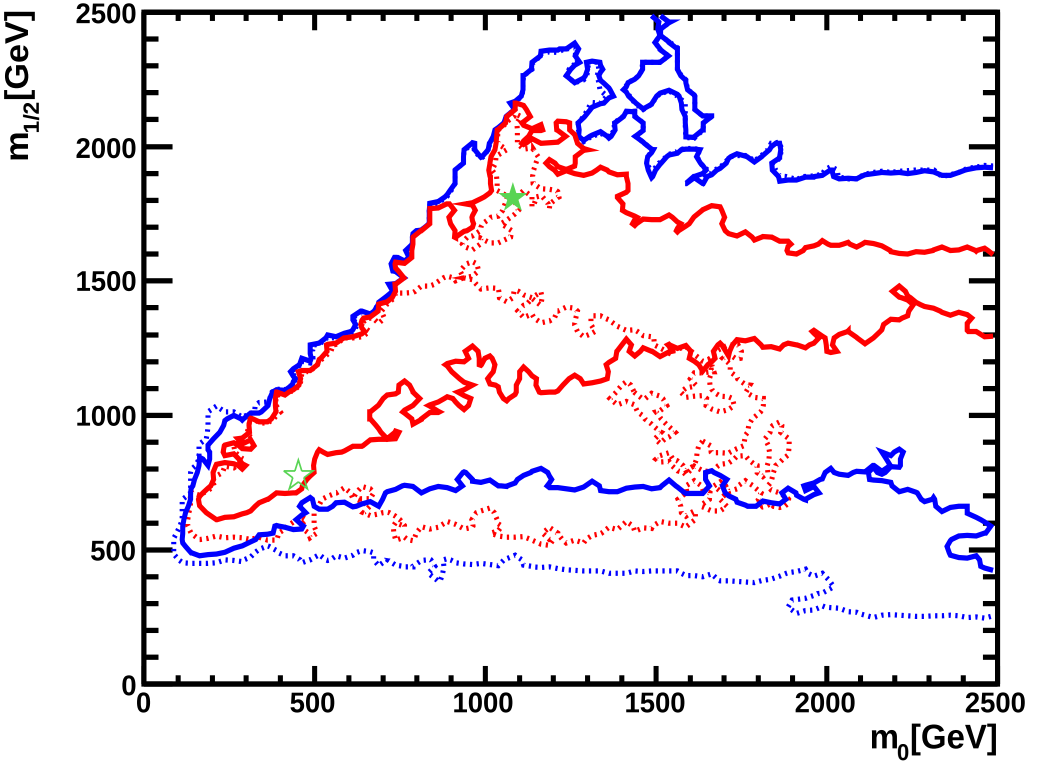
⇒ Compatibility with LEP limit improves with the inclusion of LHC SUSY search limits

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

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*]



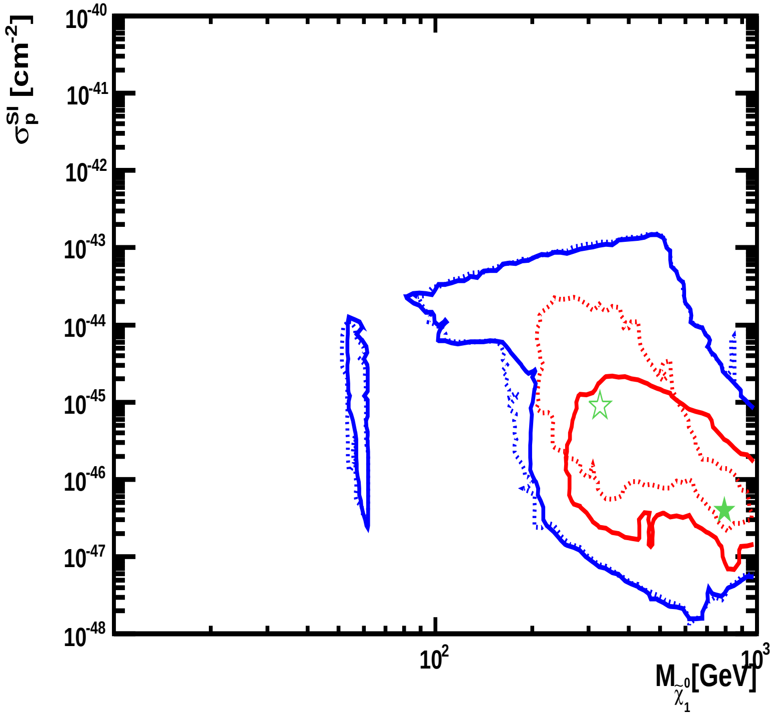
$\Rightarrow$ Shift to higher mass scales, reduced fit probability

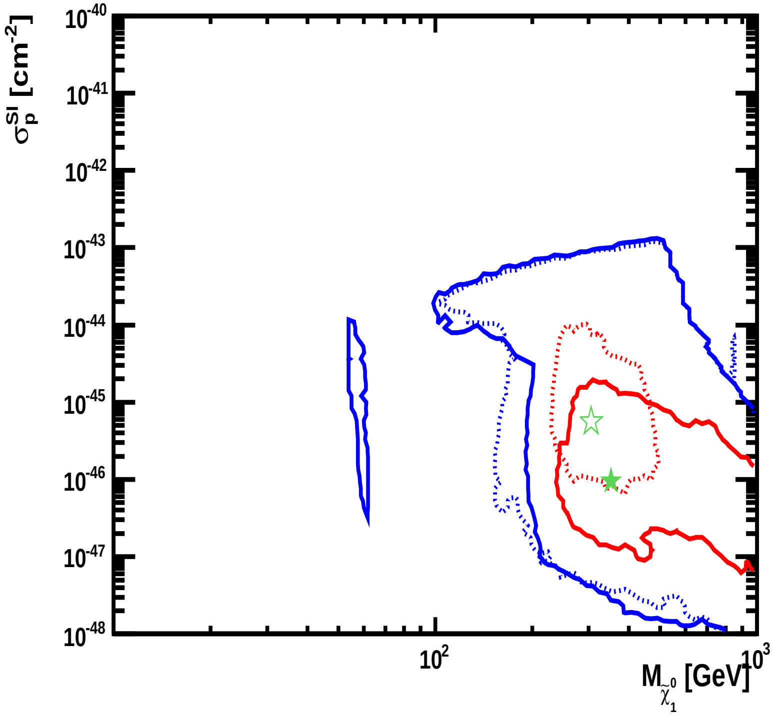
Impact of assumed Higgs signal at $\sim 125\ \mathrm{GeV}$ *on preferred region for direct dark matter searches*

[*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*]

CMSSM:

NUHM1:





$\Rightarrow$ Preferred range for cross section shifted to lower values

Status of SUSY searches at the LHC at the summer conferences: LP11, SUSY11 / LHC2TSP

- Search for jets ($+$ leptons) $+$ missing energy
  $\Rightarrow$ Bounds on gluino and squarks of first two generations of $\mathcal{O}(\text{ TeV})$

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- Reduced sensitivity to compressed spectra

- Limited sensitivity to 3rd generation squarks

  Hardly any direct constraints from the LHC on colour neutral SUSY particles

SUSY searches: what next?

[S. Padhi (CMS), LHC2TSP Workshop '11]

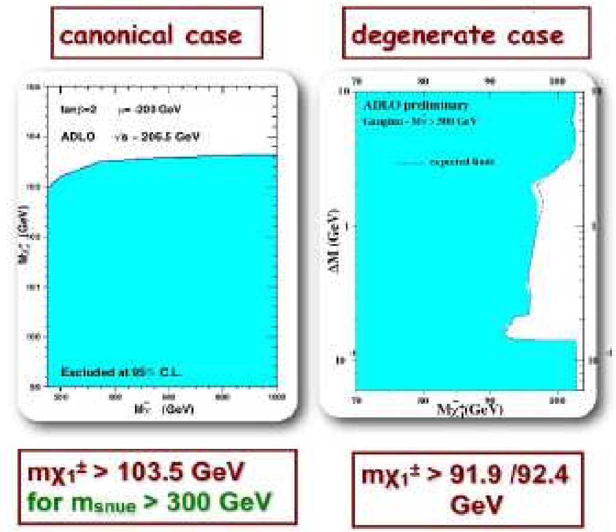
Assuming colored particles (1st and 2nd generation squarks and gluinos) are beyond the LHC range:

a) Need dedicated exclusive studies to constrain stops and sbottoms

- With and without the cross section help from the colored particles
- See also M. Papucci's EPS-2011 talk
- http://indico.in2p3.fr/contributionDisplay.py?contribId=904&sessionId=6&confId=5116

b) Need dedicated activity on EWK inos

- Current limits on Chargino/neutralinos are low
- Explore LHC reach for the electroweak sector (See also Shufang Su SUSY-11 talk)



ATLAS search for direct sbottom production

[*P. de Jong HCP ’11*]

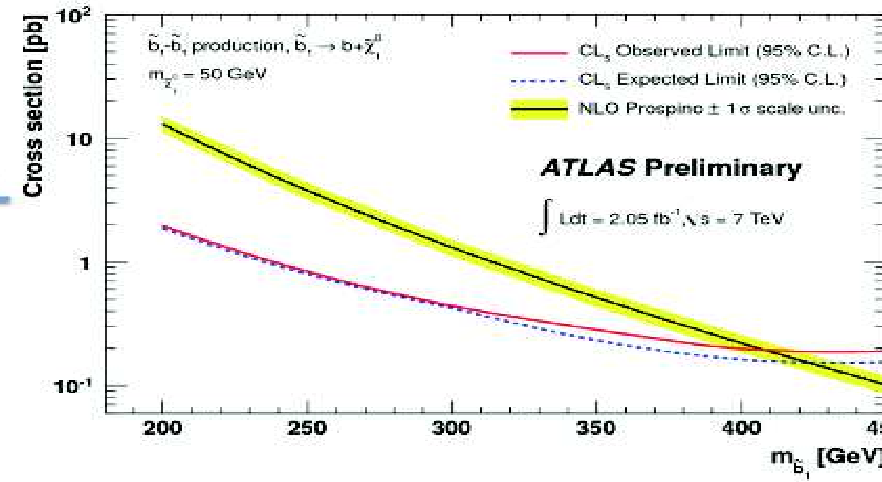
paper in preparation

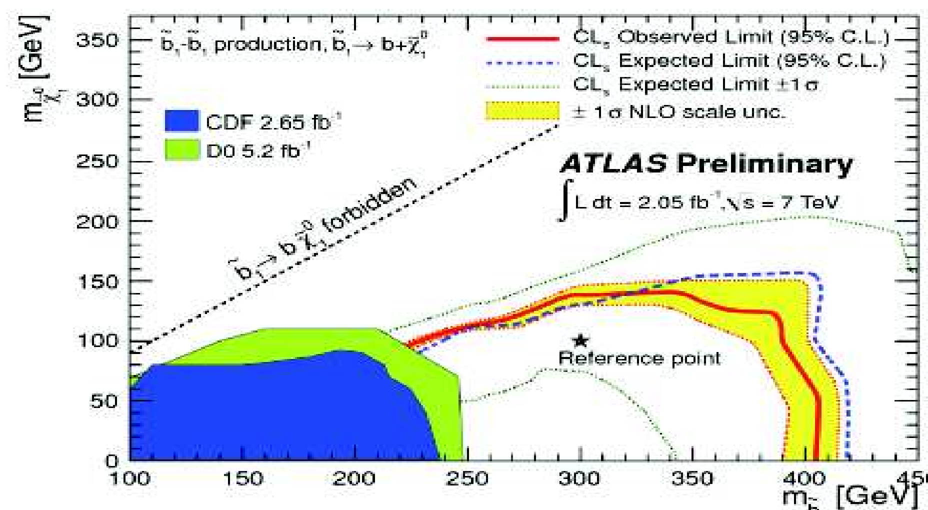
Direct sbottom pair production

NEW!

$\tilde{b}_1$-$\tilde{b}_1$ production, $\tilde{b}_1 \rightarrow b+\tilde{\chi}_1^0$

M_{CT} cut (GeV)	SM	Data	σ_{eff} limits (fb)
0	94±16	96	
100	62±13	56	13.4
150	27±8	28	9.6
200	8±4	10	5.6





Assuming 100% BR, sbottoms are excluded up to 385 GeV (for LSP < 60 GeV)

ATLAS search for direct weak gaugino production

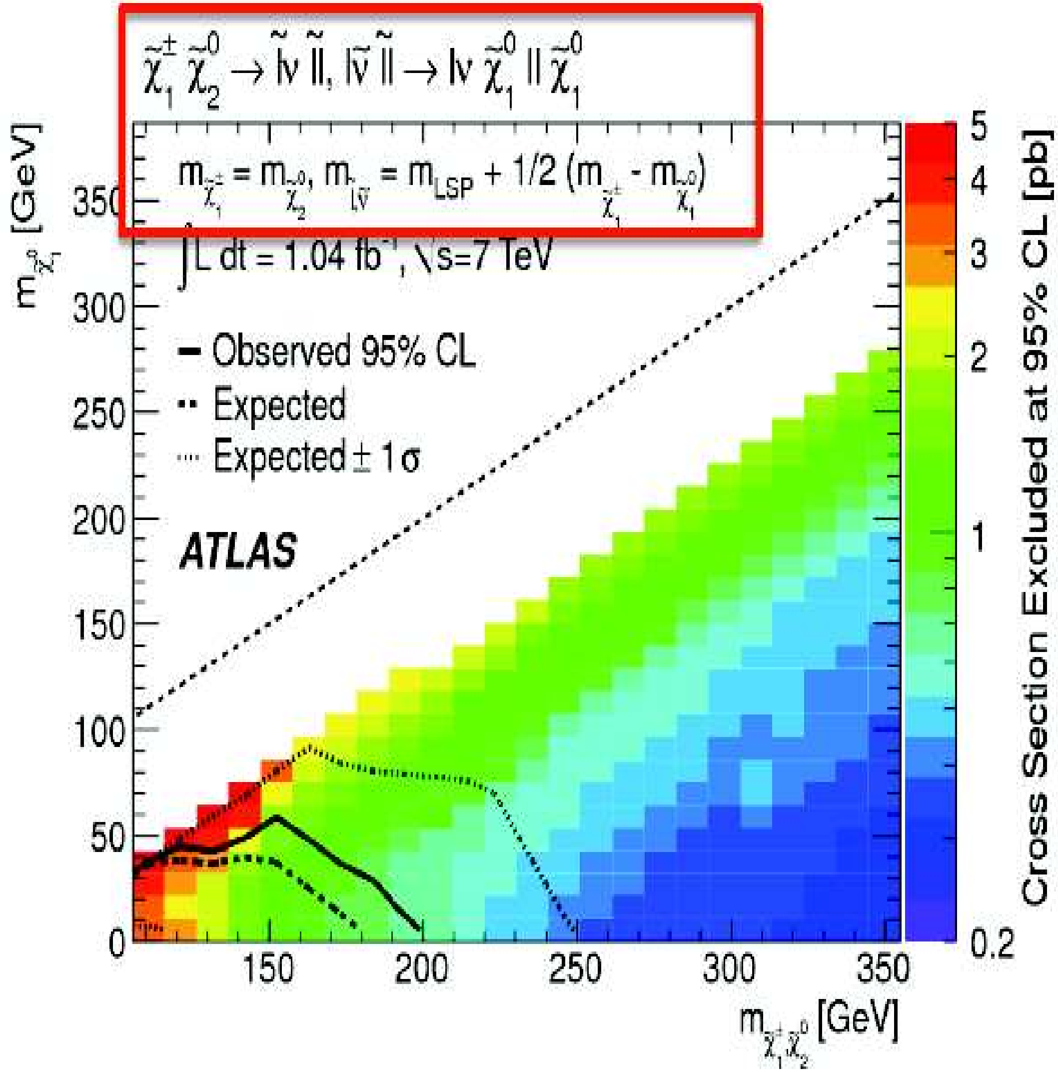
[*P. de Jong HCP '11*]

Dileptons: interpretation

Same sign dilepton interpretation in simplified model of weak gaugino production: $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$

Cornell University Library

arXiv.org 1110.6189



GMSR: M ... =250TeV N =3 sign(μ) = + C ... =1

Prospects for SUSY searches in 2012

LHC will run at 7 or $8\ \mathrm{TeV}$, higher integrated luminosity

$\Rightarrow$ Further increase in sensitivity, particular focus on results for third generation squarks and direct production of colour-neutral states

Results will be interpreted in different SUSY scenarios

Proposal for new benchmark scenarios: [*S. AbdusSalam et al. '11*]

CMSSM, NUHM, GMSB, AMSB, MM-AMSB, p19MSSM, R-parity violating MSSM, NMSSM

Some scenarios would get under pressure if $M_\mathrm{h} \approx 125\ \mathrm{GeV}$ were confirmed

Conclusions and outlook

- SUSY searches: no discoveries yet

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$\Rightarrow$ Great prospects for further exploration of the Terascale at LHC and beyond

Backup

Prospects for possible future facilities: HE–LHC, LHeC

- HE–LHC: Significant increase of LHC search reach

  But requires new magnets $\Leftrightarrow$ new machine

  $\Rightarrow$ Very good physics justification from future data needed

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- LHeC: Search for leptoquark production, . . .

  $\Rightarrow$ Some sensitivity to R-parity violating SUSY

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  ($\sim A_{\rm t}\, m_{\rm t}, m_{\rm b}\, \tan\beta$)
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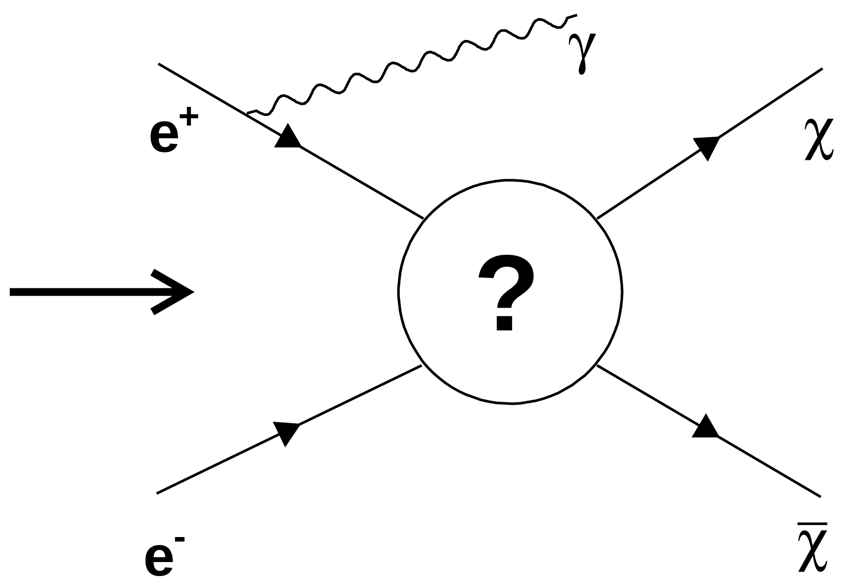
  $+$ Naturalness arguments, baryogenesis, ...
- SUSY breaking scenarios $\Rightarrow$ expect colour-neutral states to be lighter than coloured ones

  $+$ $(g-2)_\mu$, dark matter, ...

LC: model-independent reconstruction of weakly interacting massive particle

Weakly interacting massive particle (WIMP) $\Leftrightarrow$ dark matter candidate

Use WIMP production process where a photon is emitted in the initial state:



$\Rightarrow$ Reconstruct WIMP signal from the recoil mass distribution:
$M^2_{\mathrm{recoil}} = s - 2\sqrt{s}E_\gamma$

LC prospects

$\Rightarrow$ LC has good prospects in search for colour-neutral states and third generation squarks

$+$ Large indirect reach via high-precision measurements

$\Rightarrow$ Identification of underlying physics

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- Exclusion of a SM-like Higgs (at least at 90% C.L.) in the range $127 \text{ GeV} \lesssim M_{\mathrm{H_{SM}}} \lesssim 600 \text{ GeV}$
- Excess in the low mass region ($\sim 125 \text{ GeV}$) observed by ATLAS and CMS

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$\Rightarrow$ Agrees with constraints from electroweak precision data

$\Rightarrow$ Perfectly compatible with expectation in SUSY (or SM with a light Higgs)

Summary on LC physics case in light of the current experimental situation

Higgs search results from the LHC and the Tevatron

$\Rightarrow$ Strengthened LC case for “Higgs factory” ($\sqrt{s} \lesssim 250\ \mathrm{GeV}$)

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Clarification whether something has been missed at LHC

"Golden" production channel: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

As long as Higgs has a sizable coupling to gauge bosons it is guaranteed to be accessible in this channel

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$+$ Running at WW threshold and Z resonance

LC with $\sqrt{s} \lesssim 350$ GeV: “Higgs $+$ top factory”

Higher energy: further reach for SUSY states, heavy SUSY Higgs bosons, . . .

Muon collider

A $\mu^+\mu^-$ collider in the energy range of 100 GeV to several TeV could emerge as a (major) upgrade of a neutrino factory

Higgs production in the s-channel

Physics potential of a multi-TeV muon collider is in principle similar to a multi-TeV e^+e^- collider

Can the same luminosity be achieved?

Small ISR, beamstrahlung,
but huge backgrounds from μ decay