Supersymmetry

Georg Weiglein

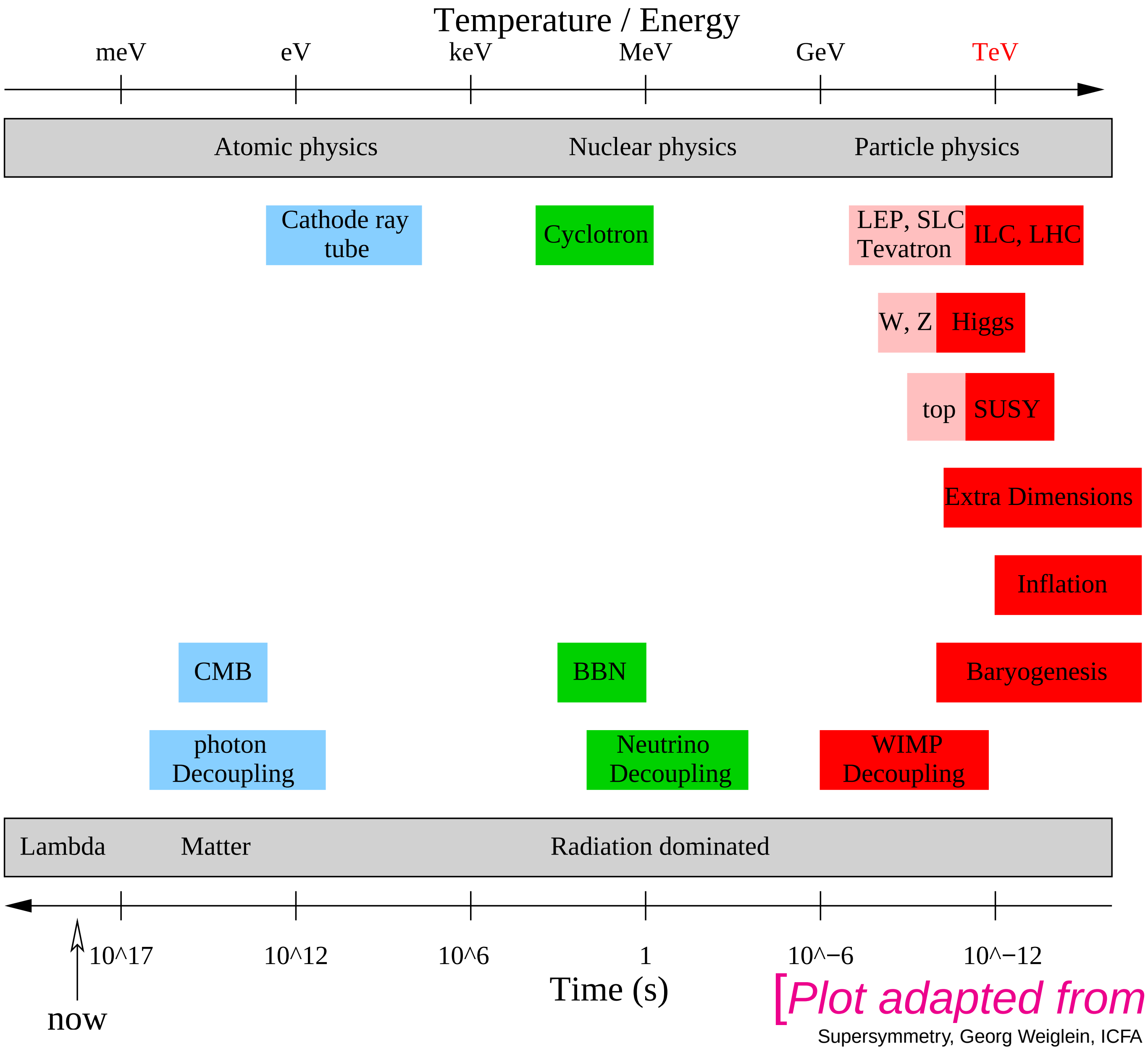
DESY

CERN, 10 / 2011

- Introduction
- Confronting SUSY with experiment: present status
- Future prospects
- 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 $M_{\rm Planck} \approx 10^{19}$ 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 to stabilise the hierarchy

Supersymmetry:

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

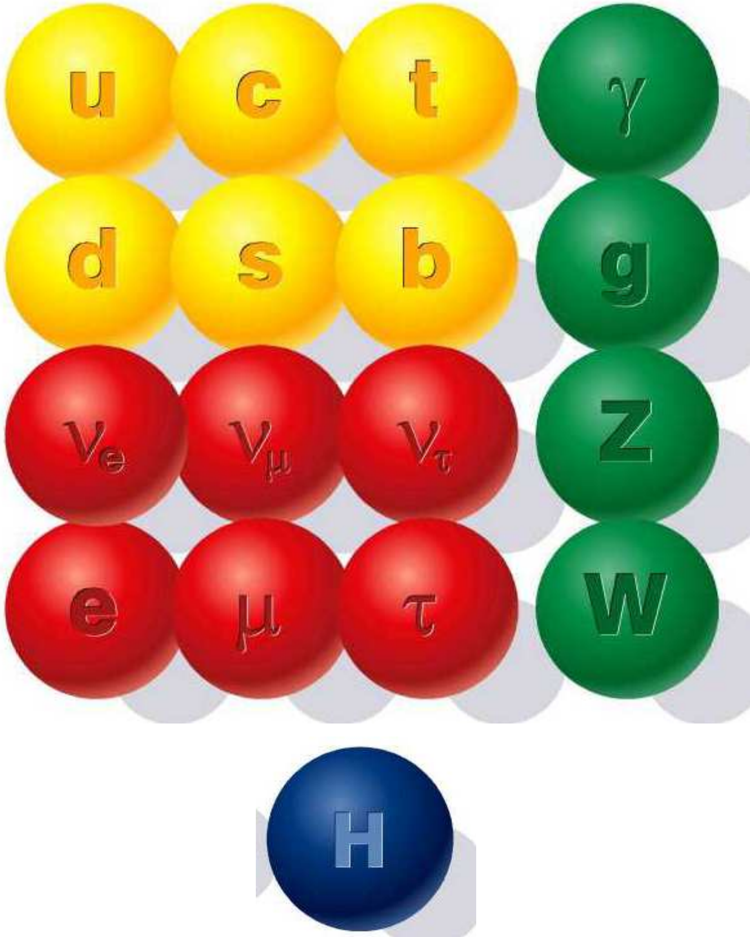
Extra dimensions of space:

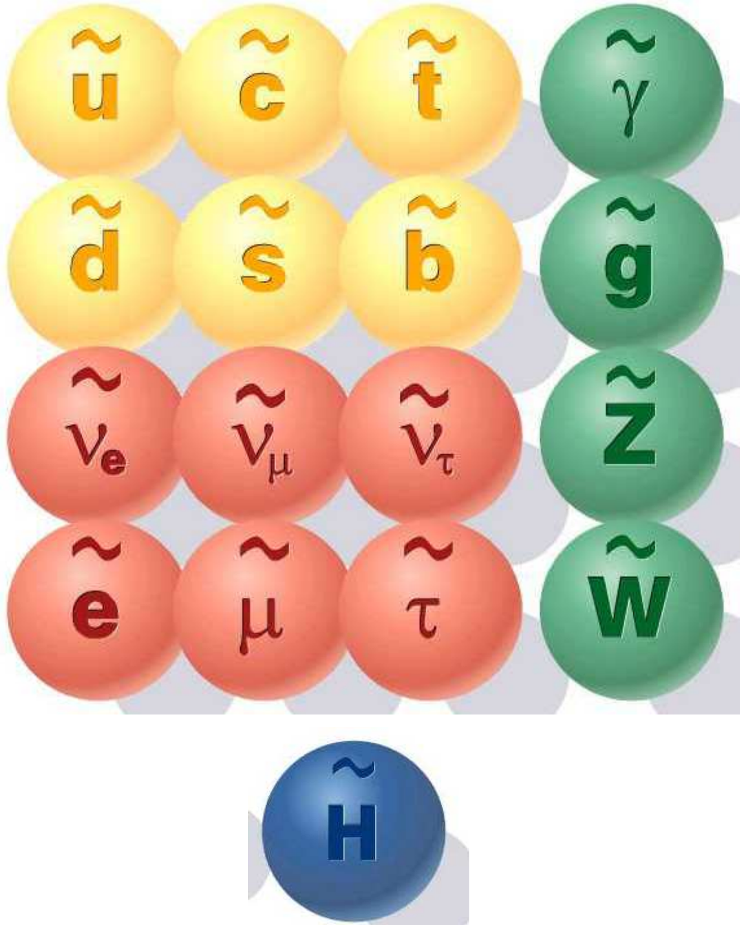
Fundamental Planck scale is $\sim \mathrm{TeV}$ (large extra dimensions),

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:

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

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

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

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

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 $+$ . . .

SUSY-breaking scenarios

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

SUSY breaking MSSM

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

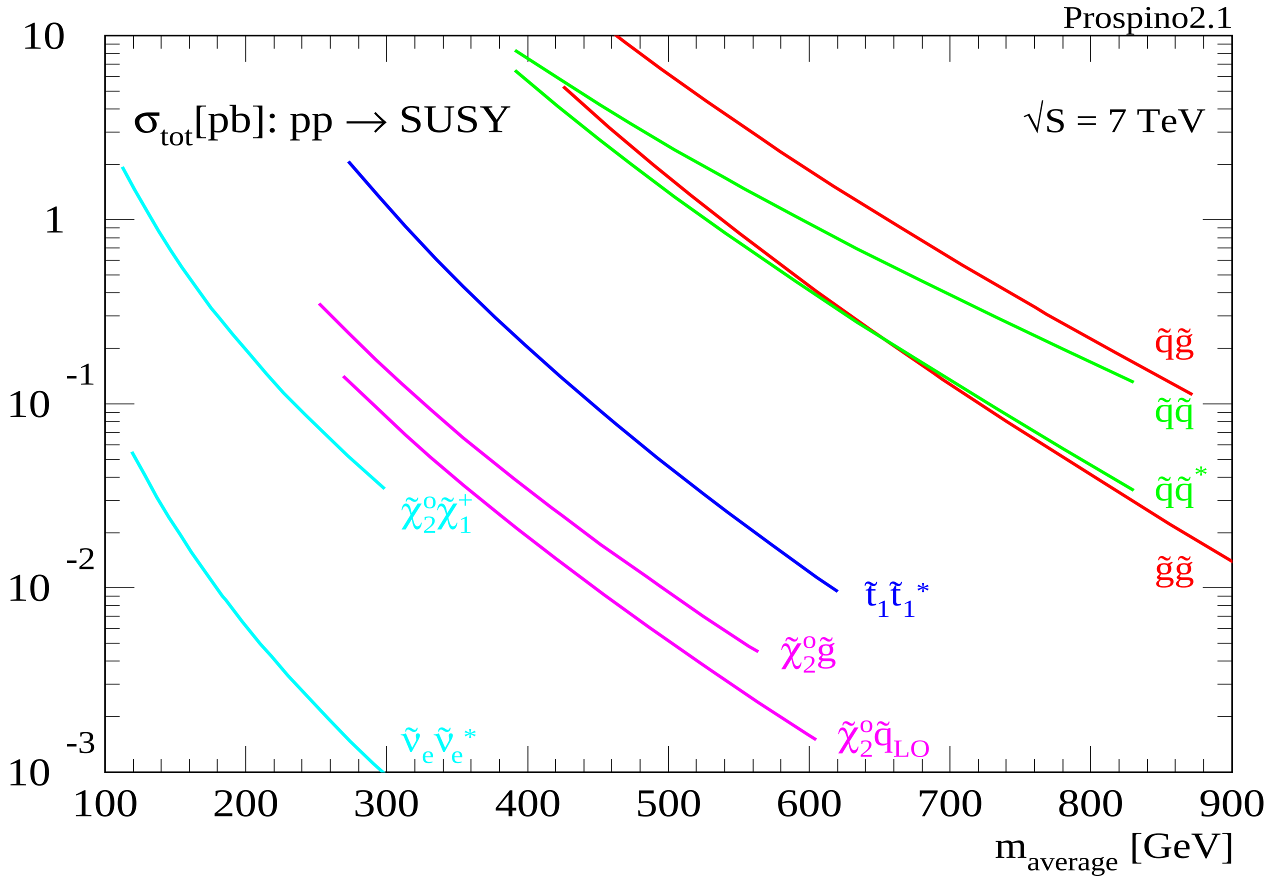
...

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

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

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.

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

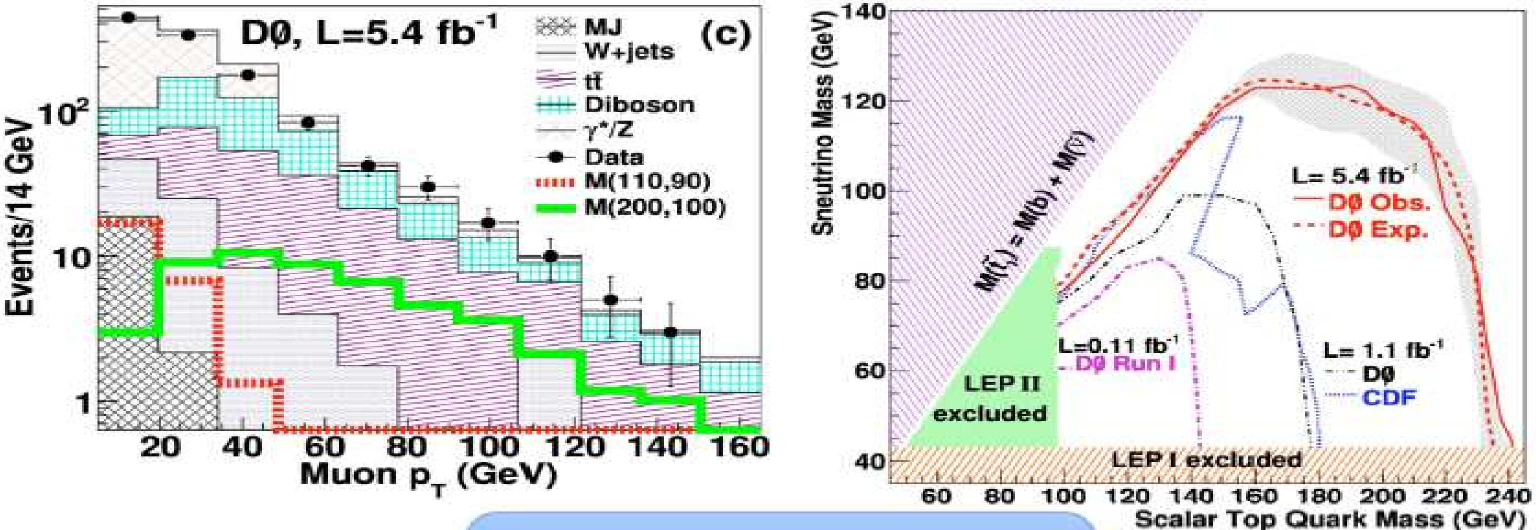
Example: Limits from D0 stop search [*A. Annovi, LP11*]

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, sν<110 GeV
and ΔM>30 GeV

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

Higgs searches at the Tevatron and the LHC

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

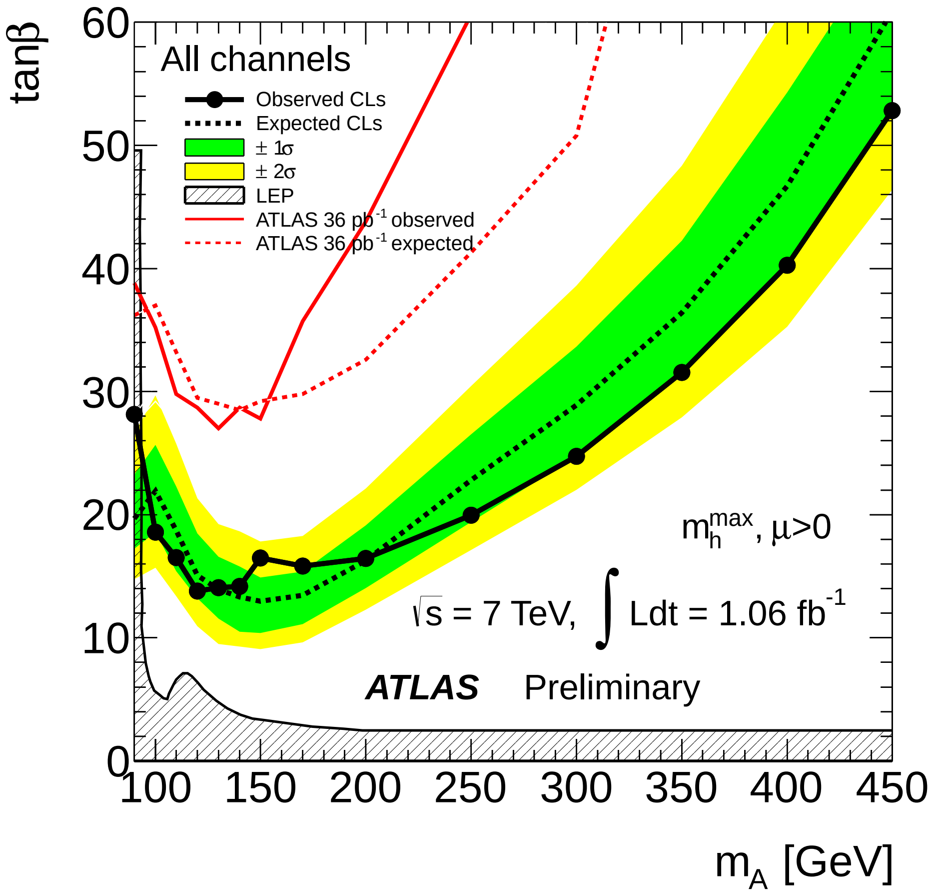
$\Rightarrow$ In the MSSM: $M_\mathrm{h} \lesssim 130 \text{ GeV}$

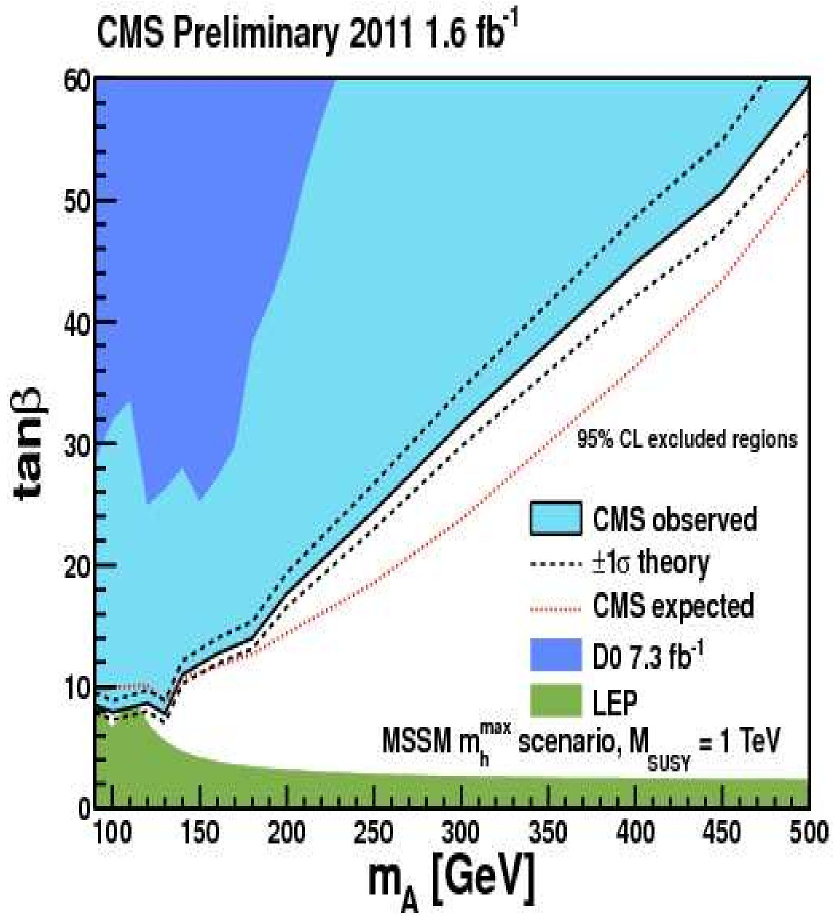
- The detection of a SM-like Higgs with $M_\mathrm{H} \gtrsim 135 \text{ GeV}$ would have unambiguously ruled out the MSSM

- 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 close the region of very low M_A

Indirect constraints

EW precision data:

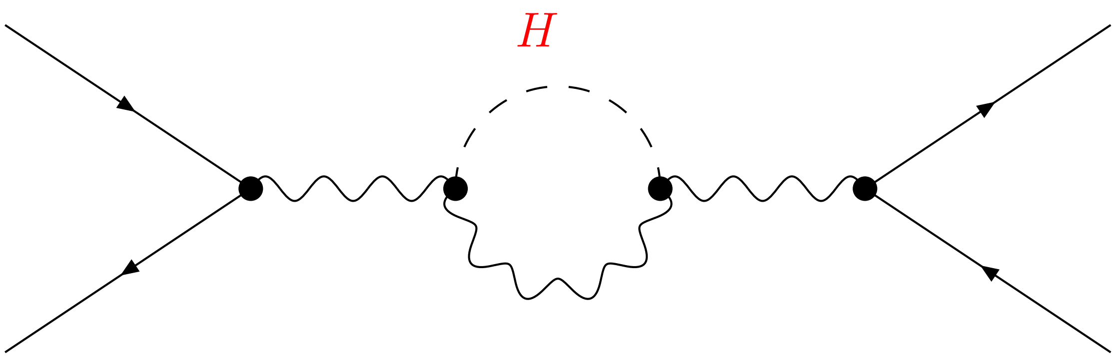
$M_Z, M_W, \sin^2\theta_{\rm eff}^{\rm lept}, \ldots$

Theory:

SM, MSSM, ...

$\Downarrow$

Test of theory at quantum level: loop corrections



$\Downarrow$

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

Window to “new physics”

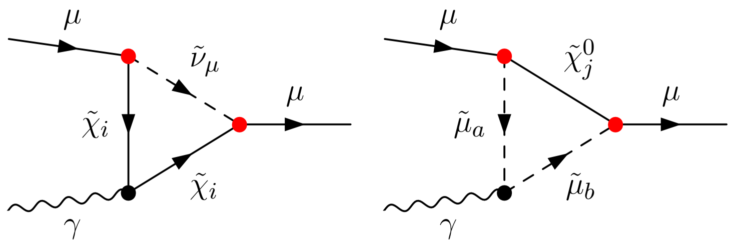
The anomalous magnetic moment of the muon:

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

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

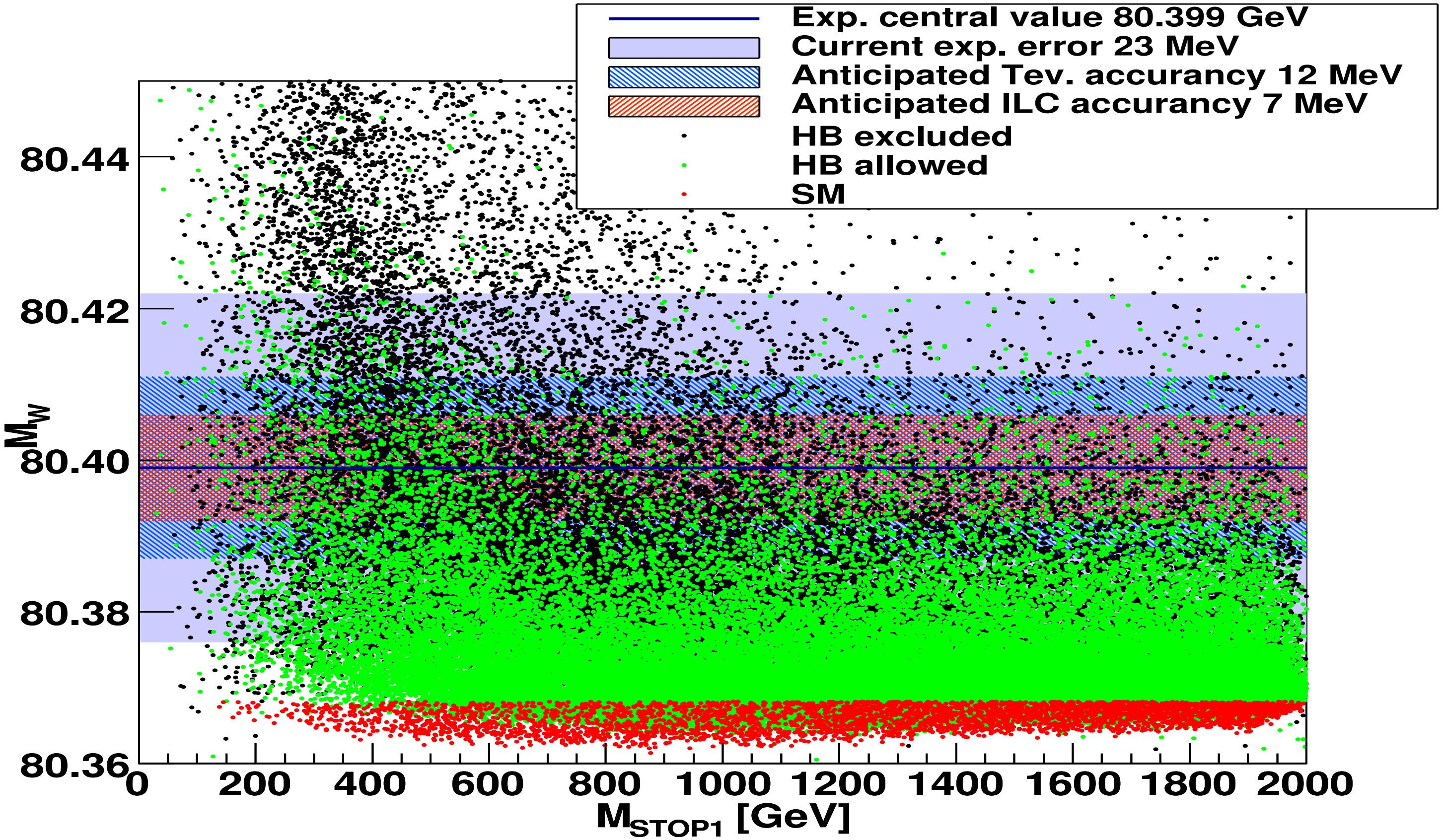


$(g-2)_\mu$: preference for light new physics contributions has further solidified (convergence of SM predictions using low-energy e^+e^- and τ decay data as input)

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

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

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

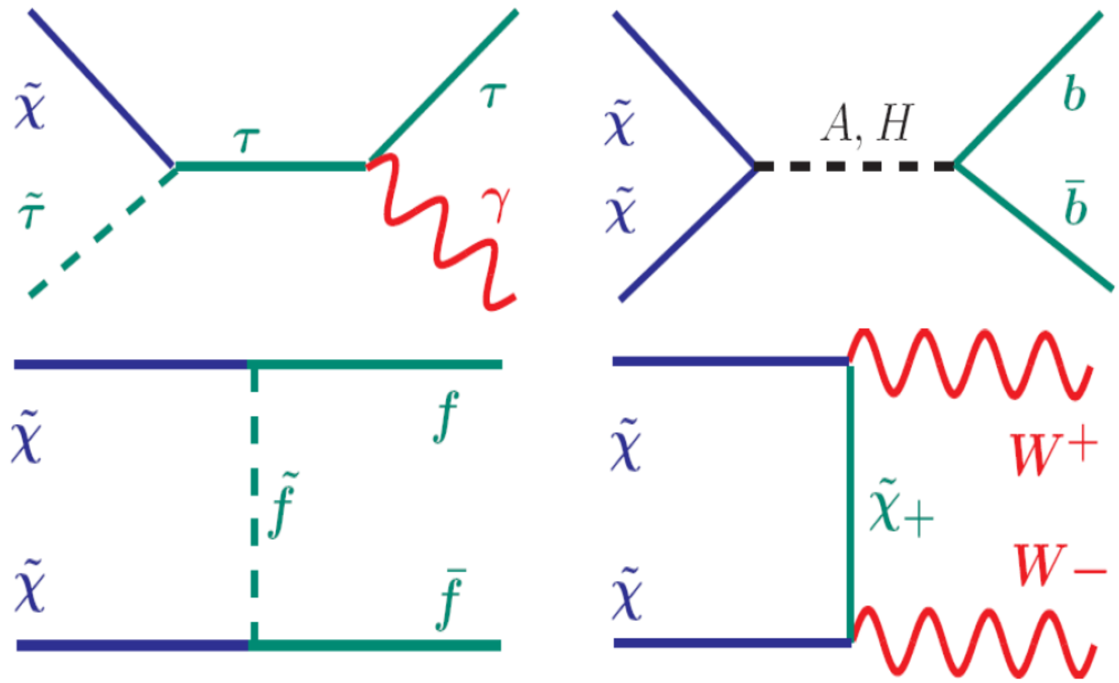


⇒ High sensitivity for discriminating SM / new physics

NB: The density of points has no physical significance

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

Cross sections for annihilation and co-annihilation processes



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

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

⇒ Points to relatively low mass scale if interpreted as weakly interacting massive particle

Global fits in constrained SUSY models

Take into account information from

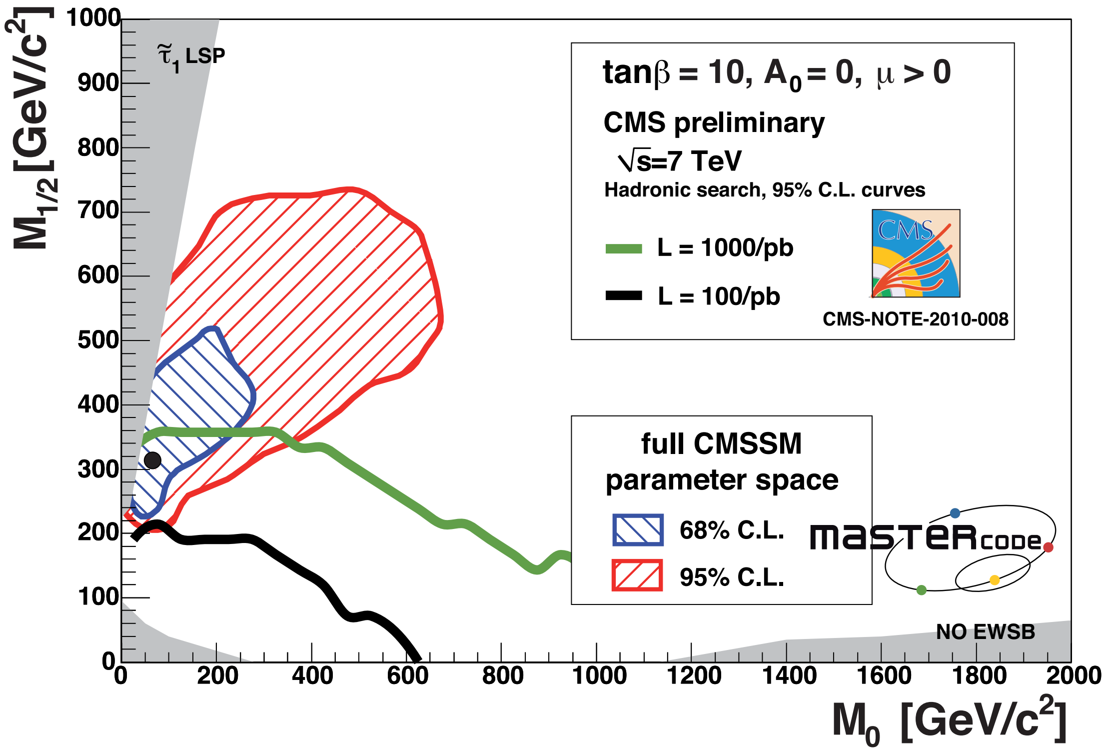
- Electroweak precision observables: $M_{\mathrm{W}}, \sin^2\theta_{\mathrm{eff}}, \Gamma_{\mathrm{Z}}, \ldots$
- $+\ (g-2)_\mu$
- $+$ Cold dark matter (CDM) density (WMAP, . . .)
- $+$ B-physics observables:
  $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_{\mathrm{s}} \to \mu^+\mu^-)$, $\mathrm{BR}(B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

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

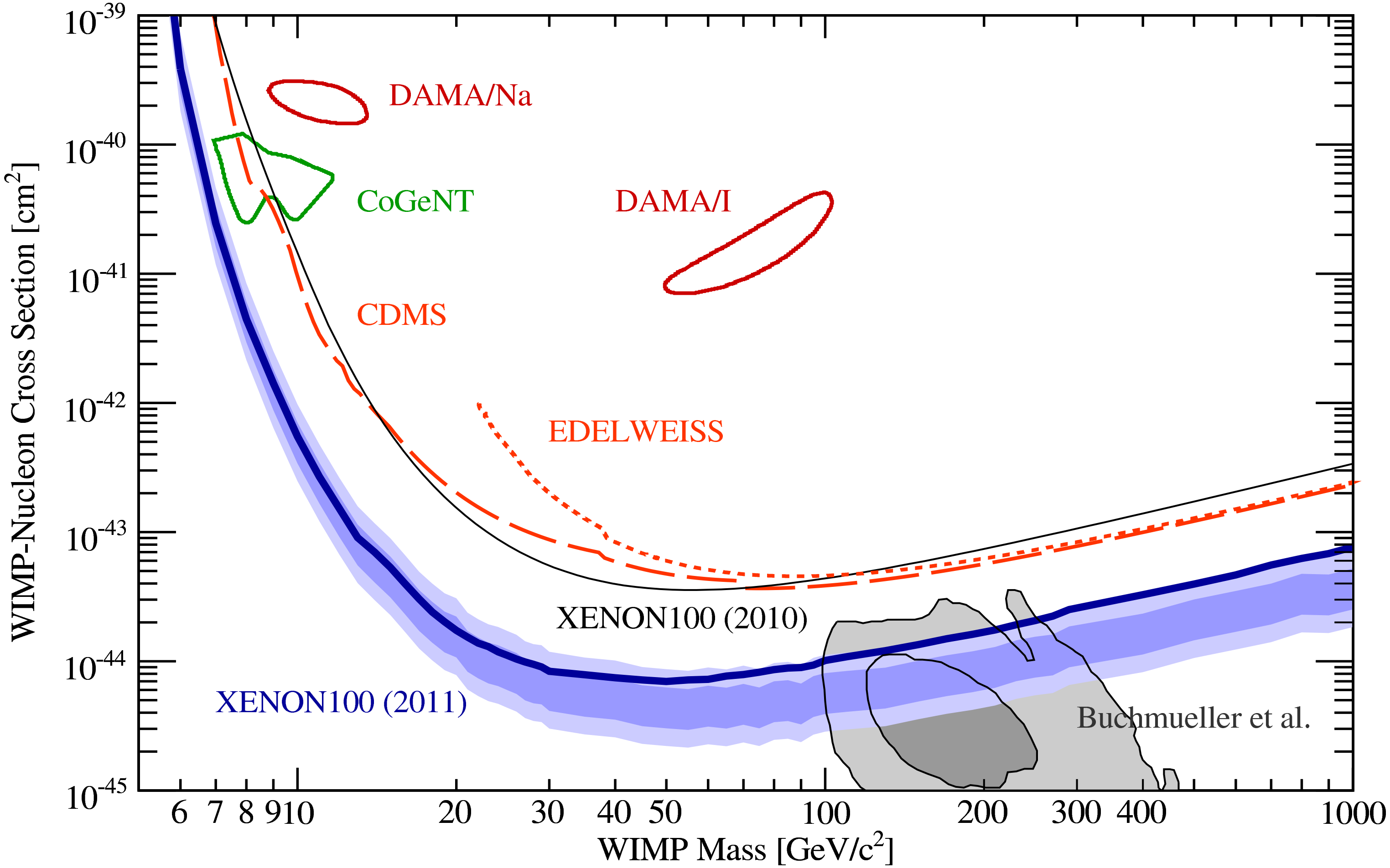
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10*]



⇒ 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

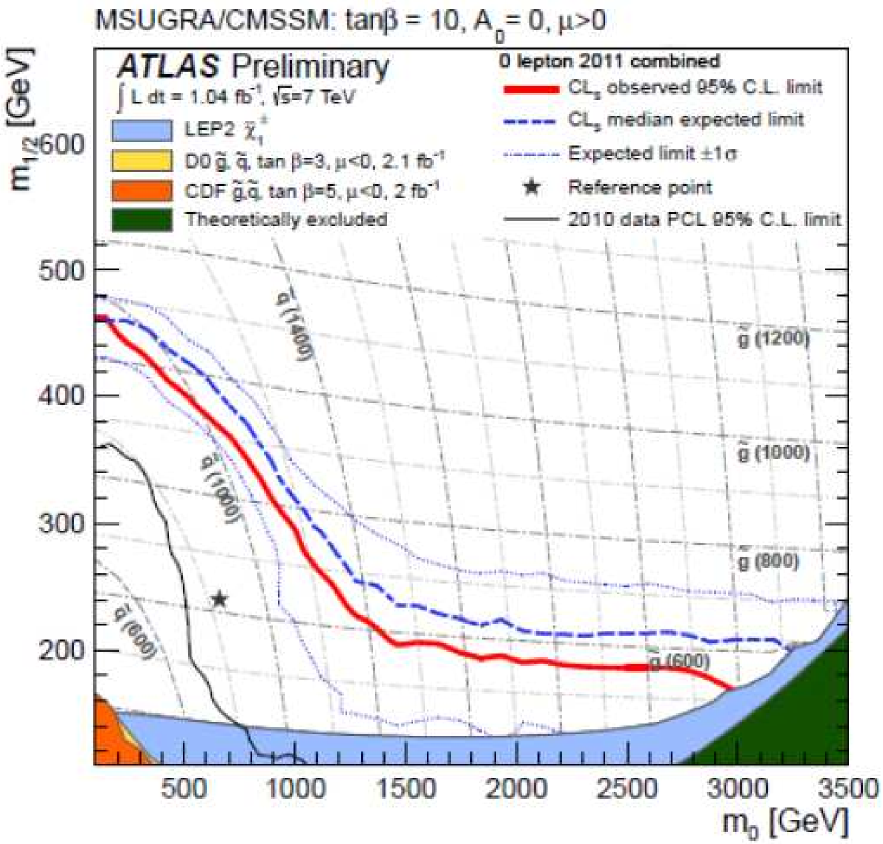
[XENON100 Collaboration '11]



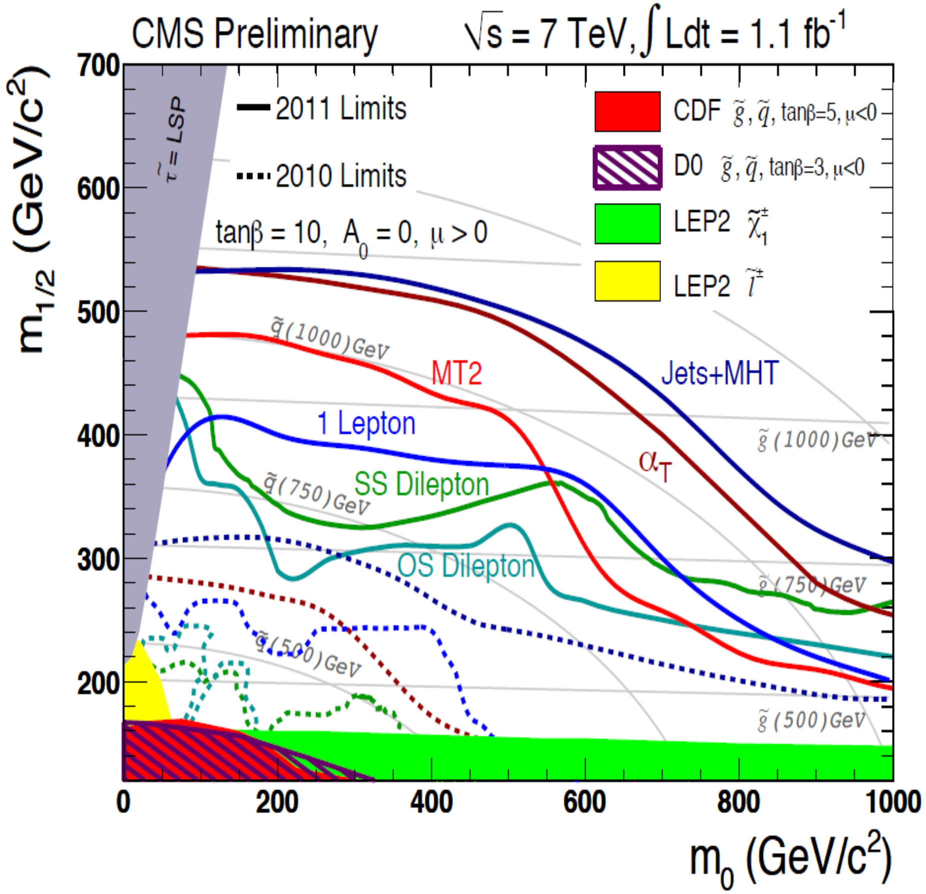
⇒ Direct detection experiments have started to probe the preferred region in the CMSSM

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

[*ATLAS Collaboration '11*]



[*CMS Collaboration '11*]

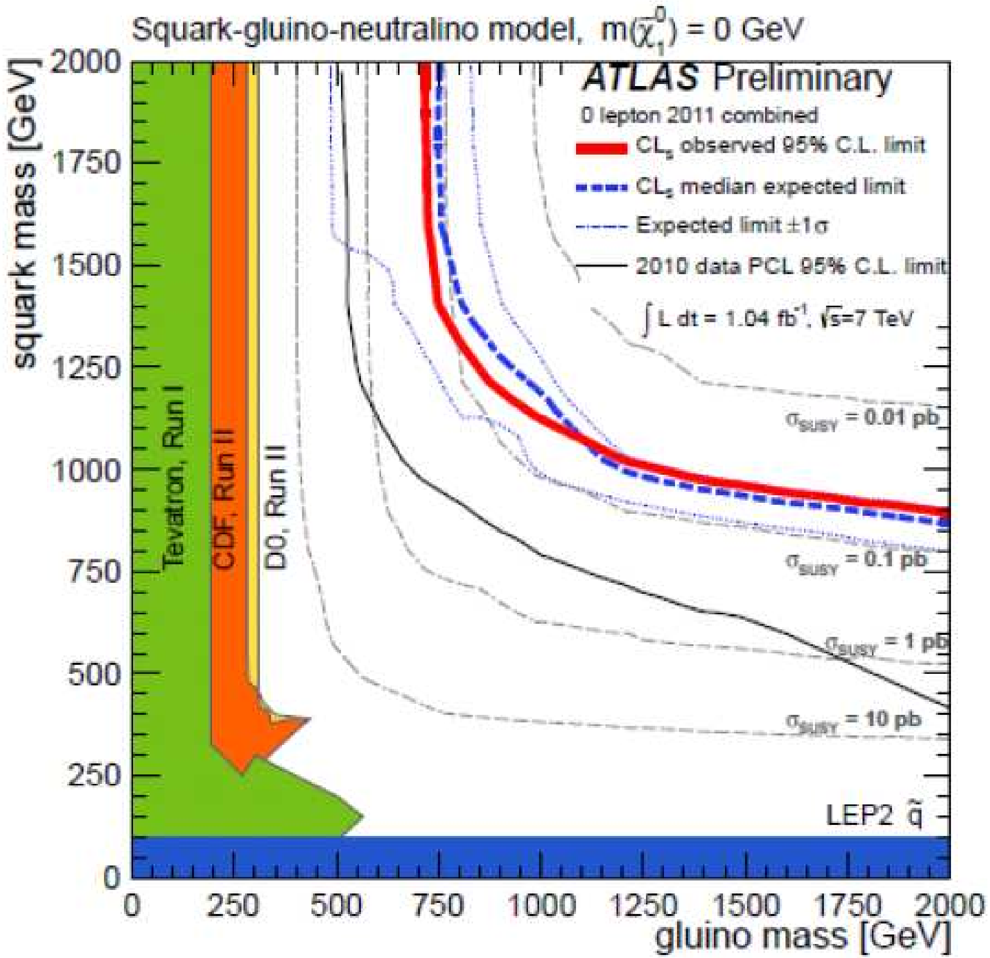


$\Rightarrow$ High sensitivity from search for jets $+$ missing energy
Previous best-fit point is excluded
CMSSM starts to get under pressure

Interpretation of SUSY search result in "simplified model"

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

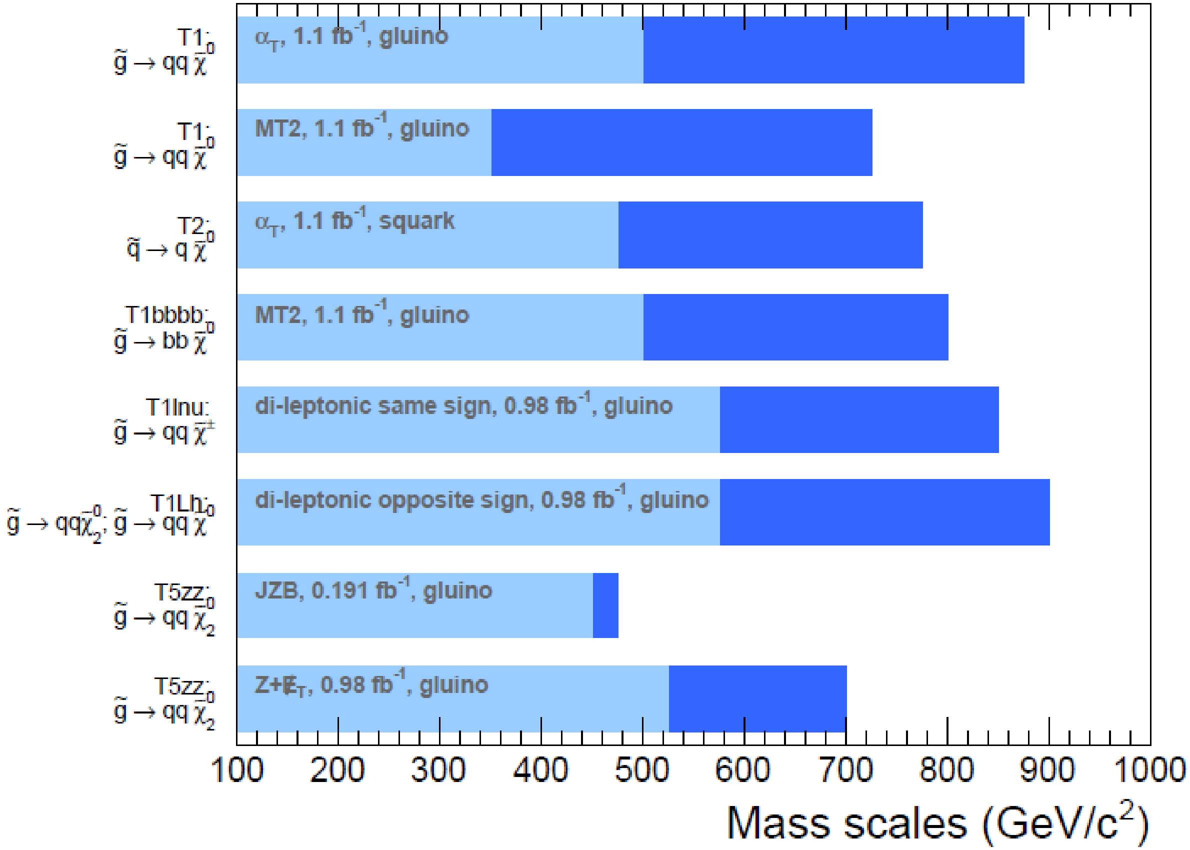
[*ATLAS Collaboration '11*]



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

[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). $\sigma^{prod} = \sigma^{NLO\text{-}QCD}$.

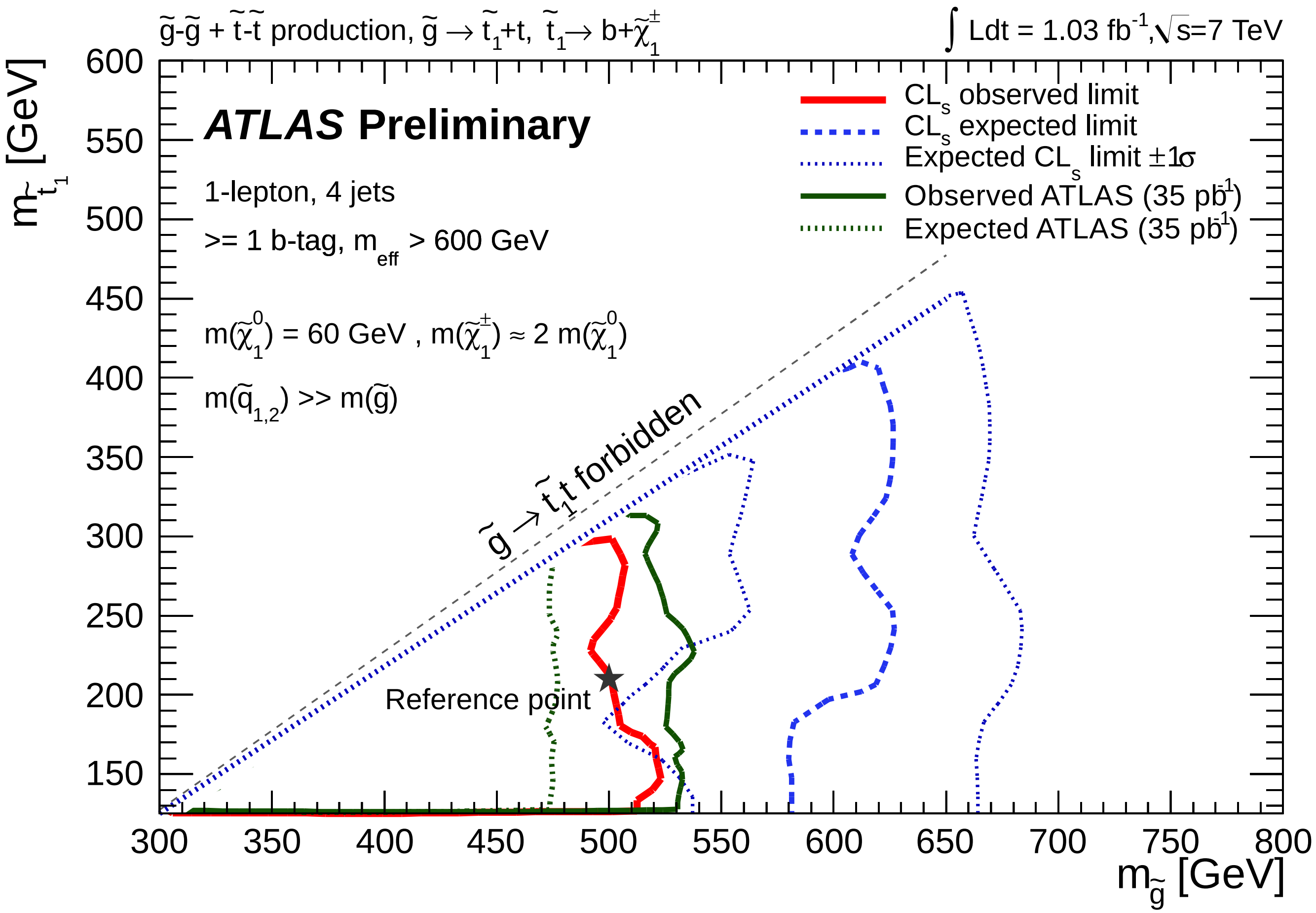
$m(\tilde{\chi}^{\pm})$, $m(\tilde{\chi}_2^0) \equiv \dfrac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$.

$m(\tilde{\chi}^0)$ 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*]



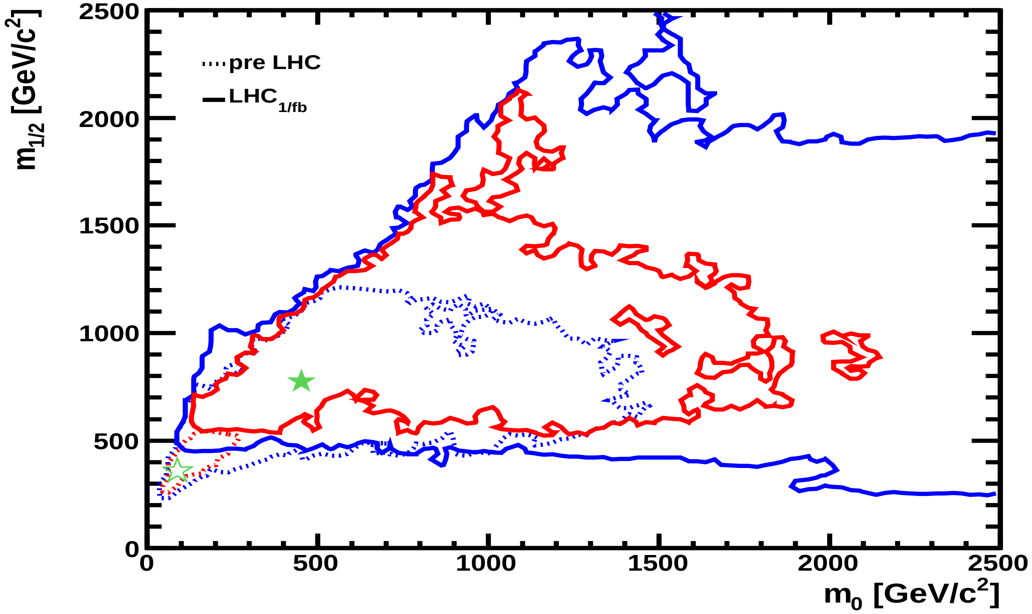
$\Rightarrow$ Observed limit decreased with 30 $\times$ more luminosity

1.2 σ excess in both electron and muon channels

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*]

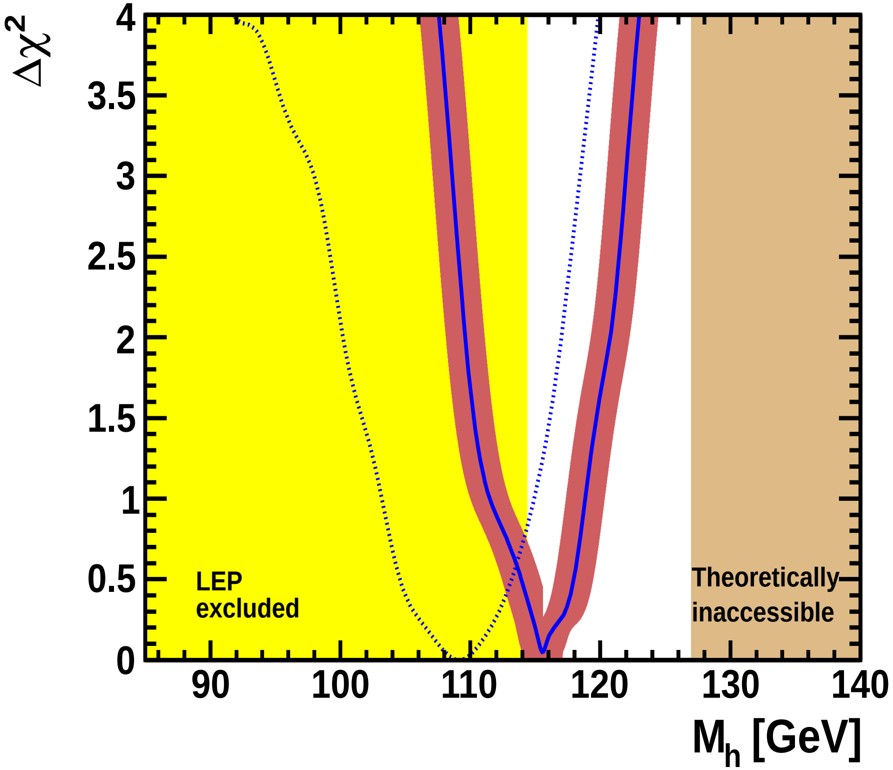


$\Rightarrow$ Preferred region "opens up", overall χ^2 worsened
Shift towards higher mass scales, higher values of $\tan\beta$

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

Indirect prediction for the Higgs mass in the CMSSM: pre-LHC vs. LHC2010

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



⇒ Inclusion of limits from LHC SUSY searches leads to upward shift in indirect orediction for M_h

⇒ Best fit value for M_h above the LEP limit, tension released

Status of SUSY searches at the LHC

- Search for jets ($+$ leptons) $+$ missing energy

  $\Rightarrow$ Bounds on gluino and squarks of first two generations of $\mathcal{O}(\text{ TeV})$

  $\Rightarrow$ The constrained scenario CMSSM starts to get under some tension: direct search limits vs. $(g-2)_\mu$

- Reduced sensitivity to compressed spectra

- Limited sensitivity to 3rd generation squarks

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

SUSY searches: what next?

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

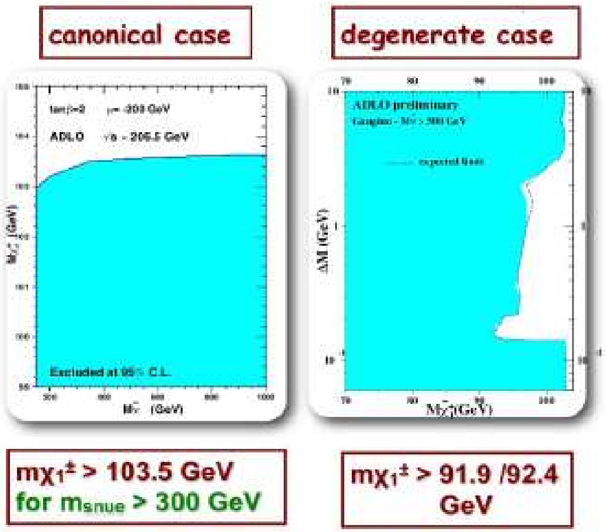
Assuming colored particles (1^{st} and 2^{nd} generation squarks and gluinos) are beyond the LHC range:

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)



Future prospects

LHC: running at $7\ \mathrm{TeV}$ (2011 / 12) and $\approx 14\ \mathrm{TeV}$ ($\gtrsim$ 2014)

$\Rightarrow$ 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

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

- LHeC: Search for leptoquark production, ...

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

Prospects for possible future facilities: Linear Collider (ILC / CLIC)

- LHC searches so far have set limits on the masses of the gluino and the squarks of the first two generations

- Third generation squarks are expected to be lighter:

  Mixing proportional to mass of partner quark ($\sim A_{\rm t}\, m_{\rm t}, m_{\rm b}\, \tan\beta$)

  $+$ Naturalness arguments, baryogenesis, . . .

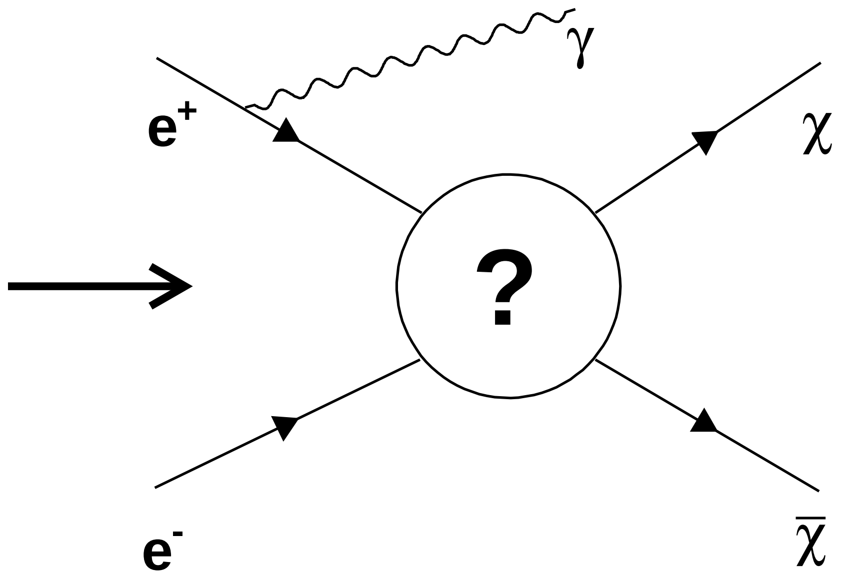
- SUSY breaking scenarios $\Rightarrow$ expect colour-neutral states to be lighter than coloured ones

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

LC: model-independent reconstruction of weakly interacting massive particle

Weakly interacting massive particle (WIMP) ⇔ dark matter candidate

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



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

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

Higgs search results from the LHC and the Tevatron

- Exclusion of a SM-like Higgs (at least at 90% C.L.) in the range $140 \text{ GeV} \lesssim M_{\mathrm{H_{SM}}} \lesssim 460 \text{ GeV}$
- Slight excess in the low mass region

$\Rightarrow$ 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” ($\sqrt{s} \lesssim 250$ GeV)

$\Rightarrow$ Determination of the physics of possible Higgs candidates

and / or

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

$+$ 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

Conclusions and outlook

- SUSY searches: no discoveries yet
- LHC searches have only been sensitive so far to those parts of the SUSY spectrum — gluino, squarks of first two generations — for which we have the least reasons to believe that they should be light
- Electroweak precision physics, dark matter, naturalness arguments, . . . seem to indicate that at least part of colour-neutral states $+ \tilde{t}$ should be relatively light
- Results from Higgs searches at LHC and Tevatron are good news for SUSY!

$\Rightarrow$ Good prospects for further exploration of the Terascale at LHC and LC