Vorlesung 11:

Search for

Supersymmetry

- Standard Model : success and problems
- Grand Unified Theories (GUT)
- Supersymmetrie (SUSY)
  - – theory
  - – direct search (pre-LHC)
  - – indirect search
  - – LHC results

The Standard Model of particle physics...

- fundamental fermions: 3 pairs of quarks plus 3 pairs of leptons
- fundamental interactions: through gauge fields, manifested in
  – $W^{\pm}$, Z^0 and γ (electroweak: SU(2)xU(1)),
  – gluons (g) (strong: SU(3))

... successfully describes all experiments and observations!

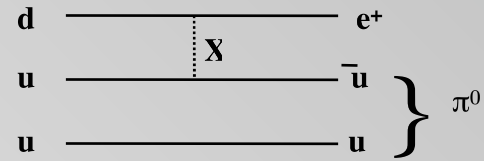
... however ...

the standard model is incomplete and unsatisfactory:

- too many free parameters (~18 masses, couplings, mixing angles)
- no unification of elektroweak and strong interaction –> **GUT** ; E~10^{16} GeV
- gravitation not covered (quantum theory of gravitation ?) –> **TOE** ; E~10^{19} GeV
- SM: neutrinos are massless and exist in only 1 helicity state
- hierarchy problem: need for precise cancellation of radiation corrections –> **SUSY** ; E~10^3 GeV
- why <u>only</u> 1/3-fractional electric quark charges? –> **GUT**

Grand Unified Theory (GUT):

- simplest symmetry which contains U(1), SU(2) und SU(3): SU(5) (Georgi, Glashow 1974)
- multiplets of (known) leptons and quarks which can transform between each other by exchange of heavy "leptoquark" bosons, *X* und *Y*, with -1/3 und -4/3 charges, as well as through $W^{\pm}$, Z^0 und γ.
- direct consequence: proton decay $p \to \pi^0 e^+$



- proton lifetime: $$\tau_p \sim \frac{M_X^4}{\alpha_{GUT}^2 M_p^5} \sim 10^{30\pm1}\ \text{yr} \quad \text{for } M_X \sim 10^{15}\ \text{GeV}$$

  experiment: $\tau_p > 5 \times 10^{32}$ yr ($p \to \pi^0 e^+$; Super-Kamiokande; 50 kT H_2O)
  –> standard-SU(5)-GUT excluded!

- electric charge is one of the generators of SU(5) group
  –> quantization follows from exchange rules of charges!
  –> $\Sigma Q_i = 0$ for each multiplet (each familie of quarks and leptons, e.g. [ν_e, e, 3(u, d)])
  –> explains exact 1/3-fractional quark charges by their 3 states of colour!
- further consequences of GUT: – small, but finite neutrino masses $M_\nu \sim M_\mu^2 / M_X$
  – existence of magnetic monopoles with mass ~10^{17} GeV
  – $\sin^2\theta_w(M_X) = 3/8$

Grand Unified Theory (GUT):

- unification of "running" U(1), SU(2) und SU(3) coupling constants :

$$\alpha_1(M_X) = \alpha_2(M_X) = \alpha_3(M_X) \quad \text{with:} \quad \alpha_1 = 8\,\alpha_{em}/3 = 8(e^2/4\pi)/3\,;$$
$$\alpha_2 = g^2/4\pi; \quad (g = e / \sin\theta_w)$$
$$\alpha_3 = \alpha_s$$

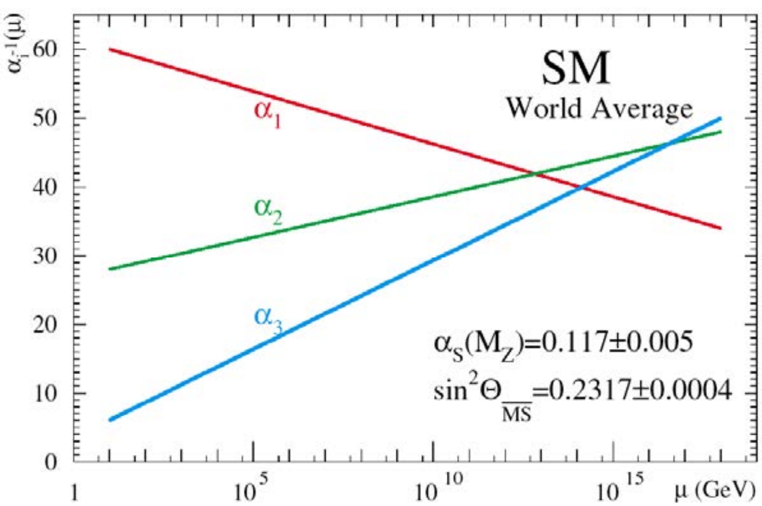
- general energy dependence:

$$\alpha\left(q^2\right) = \frac{\alpha(\mu^2)}{1-\beta_0\alpha(\mu^2)\ln(q^2/\mu^2)}\;;\;\text{mit}\quad -\beta_0 = \frac{11N_c - 4N_f}{12\pi}$$

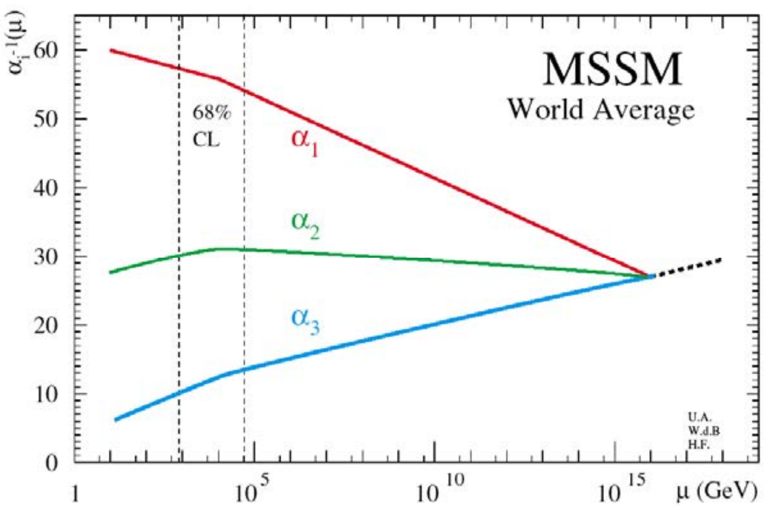
$N_c = 0, 2, 3$ for U(1), SU(2), SU(3),

$N_f = 3$ (number of generations of fermions)

- extrapolation of measured α_i:



- possible cure: Supersymmetry



the Hierarchy Problem in SM

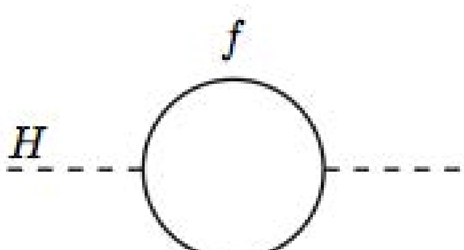
- why is gravitation 10^{32} times weaker than the weak interaction?

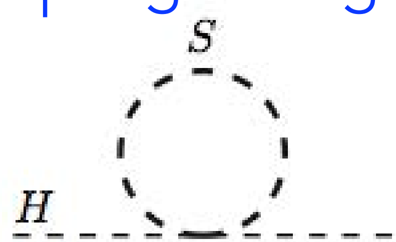
or equivalently:

- why is the typical mass scale of gravitation, $M_{Planck} \sim 10^{19}$ GeV, so much higher than the weak interaction scale, $M_{W,Z} \sim 100$ GeV ?

–> „delicate“ cancellation of large quantum corrections on bare couplings; extreme „fine tuning“ needed

- quantum corrections of heavy particles generate (too) large Higgs masses (coupling strength ~ mass).





Supersymmetry

- generates cancellation of divergent radiation corrections –> solves Hierarchy Problem
- postulates Symmetry between fermions and bosons: there is a new fermion- (Boson-) partner for all known fundamental bosons (fermions)

Teilchen	Spin	S-Teilchen	Spin
Quark Q	1/2	Squark $\tilde{Q}$	0
Lepton l	1/2	Slepton $\tilde{l}$	0
Photon γ	1	Photino $\tilde{\gamma}$	1/2
Gluon g	1	Gluino $\tilde{g}$	1/2
$W^{\pm}$	1	Wino $\tilde{W}^{\pm}$	1/.2
Z^0	1	Zino $\tilde{Z}^0$	1/2

- Higgs structure in minimal supersymmetric standard modell (MSSM):
  2 complex Higgs-doublets (8 free scalar parameters) –> 5 physical Higgs fields:
  $H^{\pm}$, H_1^0, H_2^0, A^0 . consistency requirement: $M_{H_1^0} \leq 130$ GeV
- gauginos ($\tilde{\gamma}, \tilde{W}^{\pm}, \tilde{Z}$) mix with higgsinos and form as eigenstates:
  4 *charginos* ($\chi^{\pm}_{1,2}$) und 4 *neutralions* ($\chi^0_{1,2,3,4}$)

Supersymmetry

- 124 free parameters (!!) to describe masses and couplings of SUSY particles; thereof, angle β, with $\tan(\beta) = v_1/v_2$. only known condition: $(v_1^2 + v_2^2) = 246\ \text{GeV}^2$
- new conserved quantity: "R-parity": $R = (-1)^{3(B-L)+2S}$ (B, L: baryon-/lepton number; S: Spin); R = +1 for normal matter, R = –1 for supersymmetric particles (*)
- if R-parity conserved :
  - Susy particles are produced pair wise (associated)
  - Susy particles all decay into "lightest Susy Particle", LSP, which itself is stable. –> Dark Matter
  - cosmological arguments: LSP is charge-neutral und does not carry color charge –> only weak interaction! –> leads to signature of missing energy (like neutrinos).
- Supersymmetry with masses of O(1 - 10 TeV) change energy dependence of coupling constants, so that "unification" happens at E ~ 10^{16} GeV (see figure on page 4) –> proton lifetime increases to >> 10^{32} years within SUSY-GUT.

n.b.: since ~ 2001 there is an alternative Ansatz to generate cancellation of quantum corrections also through particles with equal spin: „little Higgs models".

(*) note that R-parity is a *multiplicative* quantity - similar to *Parity* or *CP*, unlike additive quantities as e.g. charge

It all began with....

>2100 citations

Nuclear Physics B
Volume 70, Issue 1 , 18 February 1974, Pages 39-50

doi:10.1016/0550-3213(74)90355-1 Cite or Link Using DOI

Supergauge transformations in four dimensions

J. Wess

B. Zumino

Karlsruhe University, Germany
CERN, Geneva, Switzerland

Received 5 October 1973. Available online 28 October 2002.

Abstract

Supergauge transformations are defined in four space-time dimensions. Their commutators are shown to generate γ_5 transformations and conformal transformations. Various kinds of multiplets are described and examples of their combinations to new representations are given. The relevance of supergauge transformations for Lagrangian field theory is explained. Finally, the abstract group theoretic structure is discussed.

Prof. Dr. Julius Wess
MPP and LMU
+ 2007

Specific SUSY Models

MSSM: minimal supersymmetric standard model; minimal particle content; R-parity conservation; symmetry broken 'by hand' (adding to *L* all 'soft' terms consistent with SU(3) *x* SU(2) *x* U(1) gauge invariance)

SUGRA: Supergravity; spontaneous symmetry breaking (SB) in 'hidden sector'; gravity is messenger of SB to MSSM sector; gravitino irrelevant for physics in TeV region

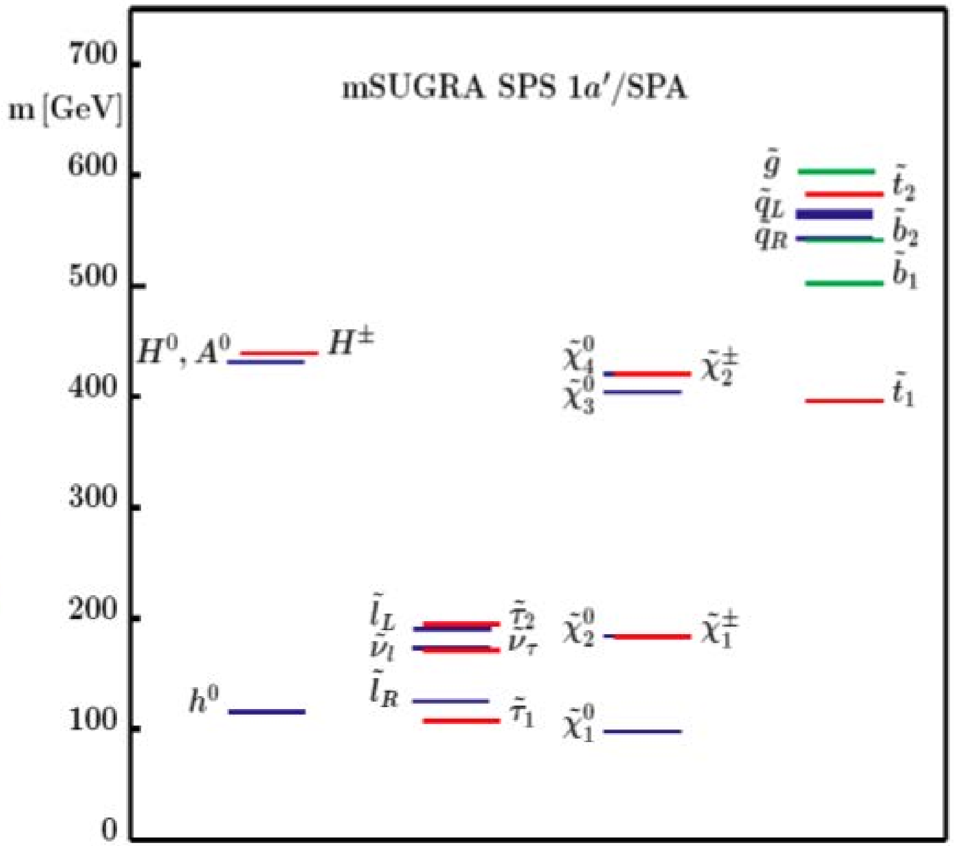
mSUGRA: minimal Supergravity; all squarks and sleptons have common mass at GUT scale: $m_{\tilde{q}}(M_{GUT}) = m_{\tilde{\ell}}(M_{GUT}) = m_0$ and all gauginos have same mass $m_{1/2}$ at GUT scale

GMSB: gauge mediated SUSY breaking; gravitino is (usually) the LSP; phenomenology depends on NLSP

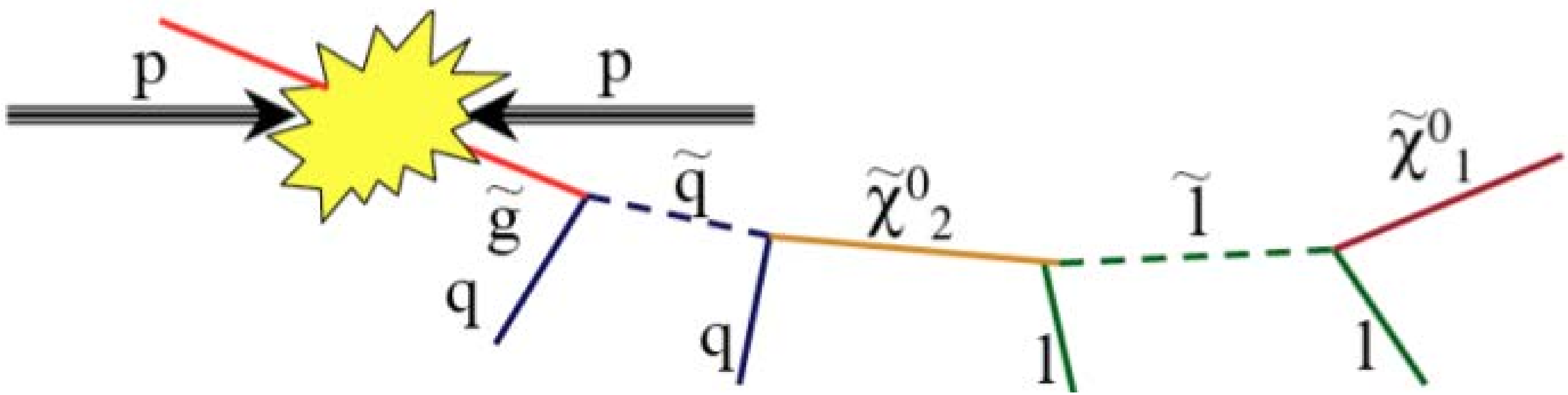
R-parity violating: violate <u>either</u> lepton- <u>or</u> baryon number conservation

Example of SUSY mass spectrum:

- m_0 = 100 GeV
- $m_{\frac{1}{2}}$ = 250 GeV
- A_0 = -100 GeV
- $\tan\beta$ = 10
- $\mathrm{sgn}(\mu)$ = +1



Supersymmetry: direct searches



exp. signatures :

- several high energy leptons, **plus**
- several high energy hadronic jets, **plus**
- missing (transverse) energy / momentum (χ_0)

backgrounds:

← *W, Z , b, c decays*

← *QCD*

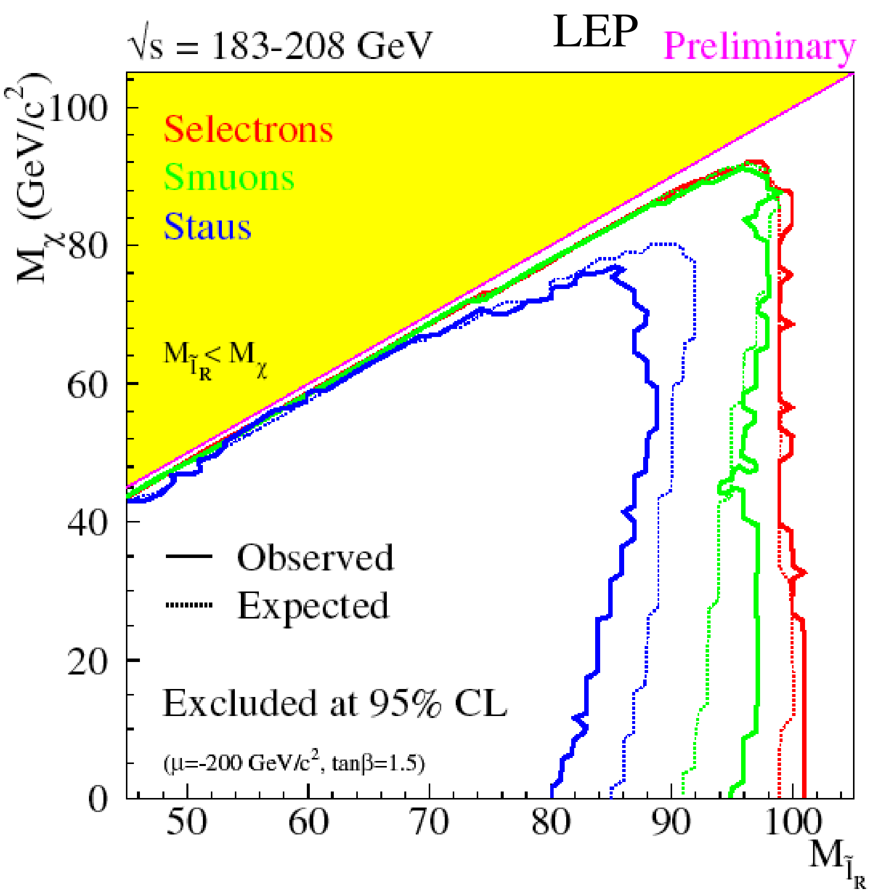
← ν *from b, c decays*

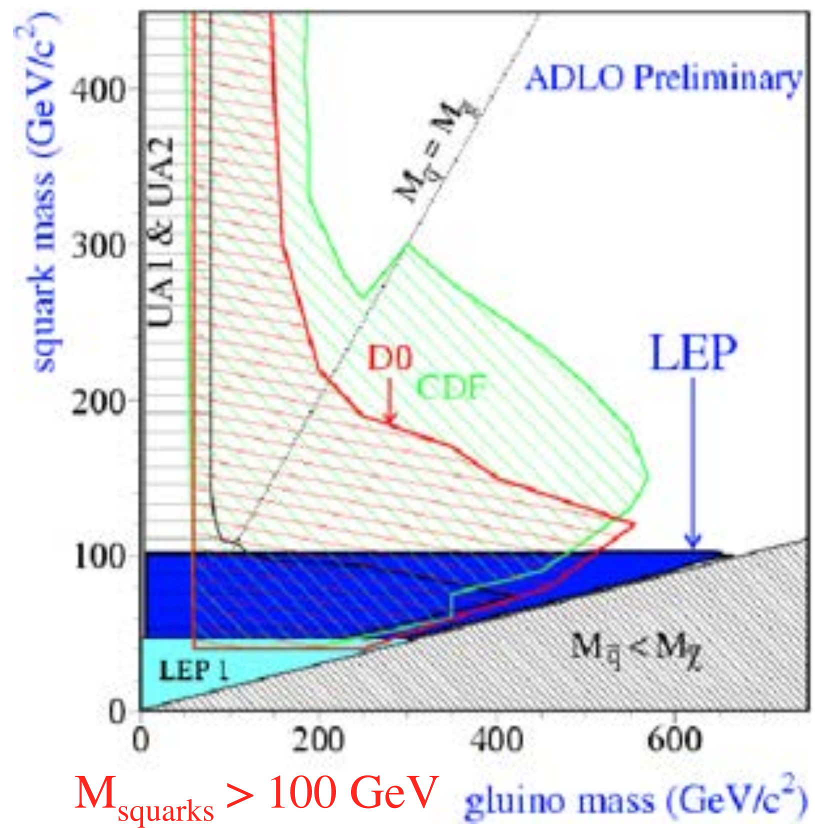
exp. signatures *if R-parity not conserved*:

- end points of mass spectra ← *combinatorics*
- mass differences of decay products in decay chains ← *combinatorics*

Supersymmetry: direct searches (pre-LHC)

- canonical analyses: search for missing energy (LSP) in high energy particle reactions
- significant exclusion limits from Tevatron and LEP.
- limits significantly depend on assumptions of SUSY parameters (model dependent)





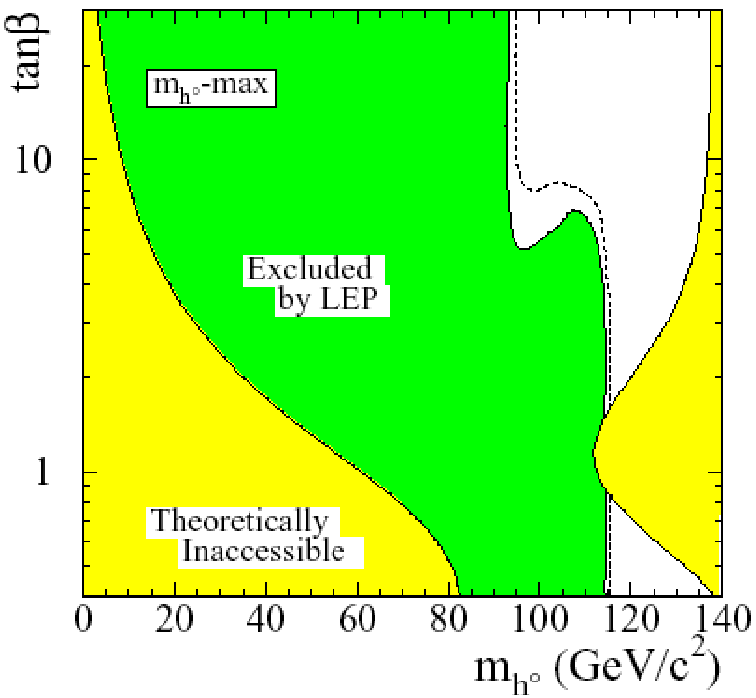
$M_{squarks} > 100$ GeV

$M_{gluino} > 190$ GeV

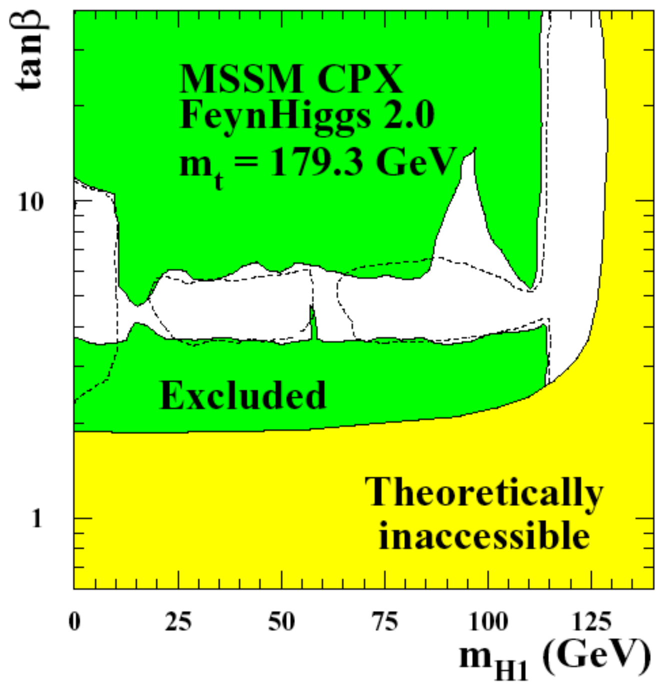
SUSY: exp. limits for tanβ and m_{h0}

- strongly depend on details of SUSY model (symmetry breaking scenario, CP violation, mixing parameters,...) !

CP-conserving MSSMwith max. upper bound on m_{h0}



CP-violating MSSM



$93 \text{ GeV} < M_{h0} < 140 \text{ GeV}$ ($\tan\beta \geq 5$)

$114 \text{ GeV} < M_{h0} < 140 \text{ GeV}$ ($\tan\beta < 5$)

$2 < \tan\beta < 11$

$M_{H1} < 126 \text{ GeV}$

SM: 114.4 GeV < M_H (95% c.l.)

LHWG-Note 2004-01

Supersymmetry: limits from direct searches (pre-LHC)

particle		Condition	Lower limit (GeV/c^2)	Source
$\widetilde{\chi}_1^\pm$	gaugino	$M_{\widetilde{\nu}} > 200$ GeV/c^2	103	LEP 2
		$M_{\widetilde{\nu}} > M_{\widetilde{\chi}^\pm}$	85	LEP 2
		any $M_{\widetilde{\nu}}$	45	Z width
	Higgsino	$M_2 < 1$ TeV/c^2	99	LEP 2
	GMSB		150	DØ isolated photons
	RPV	$LL\overline{E}$ worst case	87	LEP 2
		$LQ\overline{D}$ $m_0 > 500$ GeV/c^2	88	LEP 2
$\widetilde{\chi}_1^0$	indirect	any $\tan\beta$, $M_{\widetilde{\nu}} > 500$ GeV/c^2	39	LEP 2
		any $\tan\beta$, any m_0	36	LEP 2
		any $\tan\beta$, any m_0, SUGRA Higgs	59	LEP 2 combined
	GMSB		93	LEP 2 combined
	RPV	$LL\overline{E}$ worst case	23	LEP 2
$\widetilde{e}_R$	$e\widetilde{\chi}_1^0$	$\Delta M > 10$ GeV/c^2	99	LEP 2 combined
$\widetilde{\mu}_R$	$\mu\widetilde{\chi}_1^0$	$\Delta M > 10$ GeV/c^2	95	LEP 2 combined
$\widetilde{\tau}_R$	$\tau\widetilde{\chi}_1^0$	$M_{\widetilde{\chi}_1^0} < 20$ GeV/c^2	80	LEP 2 combined
$\widetilde{\nu}$			43	Z width
$\widetilde{\mu}_R$, $\widetilde{\tau}_R$		stable	86	LEP 2 combined
$\widetilde{t}_1$	$c\widetilde{\chi}_1^0$	any θ_{mix}, $\Delta M > 10$ GeV/c^2	95	LEP 2 combined
		any θ_{mix}, $M_{\widetilde{\chi}_1^0} \sim \frac{1}{2} M_{\widetilde{t}}$	115	CDF
		any θ_{mix} and any ΔM	59	ALEPH
	$b\ell\widetilde{\nu}$	any θ_{mix}, $\Delta M > 7$ GeV/c^2	96	LEP 2 combined
$\widetilde{g}$	any $M_{\widetilde{q}}$		195	CDF jets+$\not{E}_T$
$\widetilde{q}$	$M_{\widetilde{q}} = M_{\widetilde{g}}$		300	CDF jets+$\not{E}_T$

Quelle: review of particle properties:

http://pdg.lbl.gov

The New York Times

SCIENCE DESK | February 5, 2002, Tuesday

Years of Research Yield Nothing, And That's Good News for Physicists

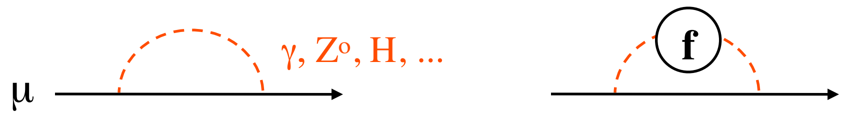
By GEORGE JOHNSON (NYT) 1868 words
Late Edition - Final , Section F , Page 1 , Column 1

ABSTRACT - Scientists at Fermilab, after slamming matter and antimatter together in Tevatron particle accelerator, publish report in January 28 issue of Physical Review Letters revealing that they did not find any supersymmetric particles--SUSY's for short; experiment reportedly establishes new lower limit on mass of hypothetical particle, member of SUSY family called gluino; diagram; photo (M)

Supersymmetry: indirect searches

example: the anomalous muon magnetic dipole moment (g–2)

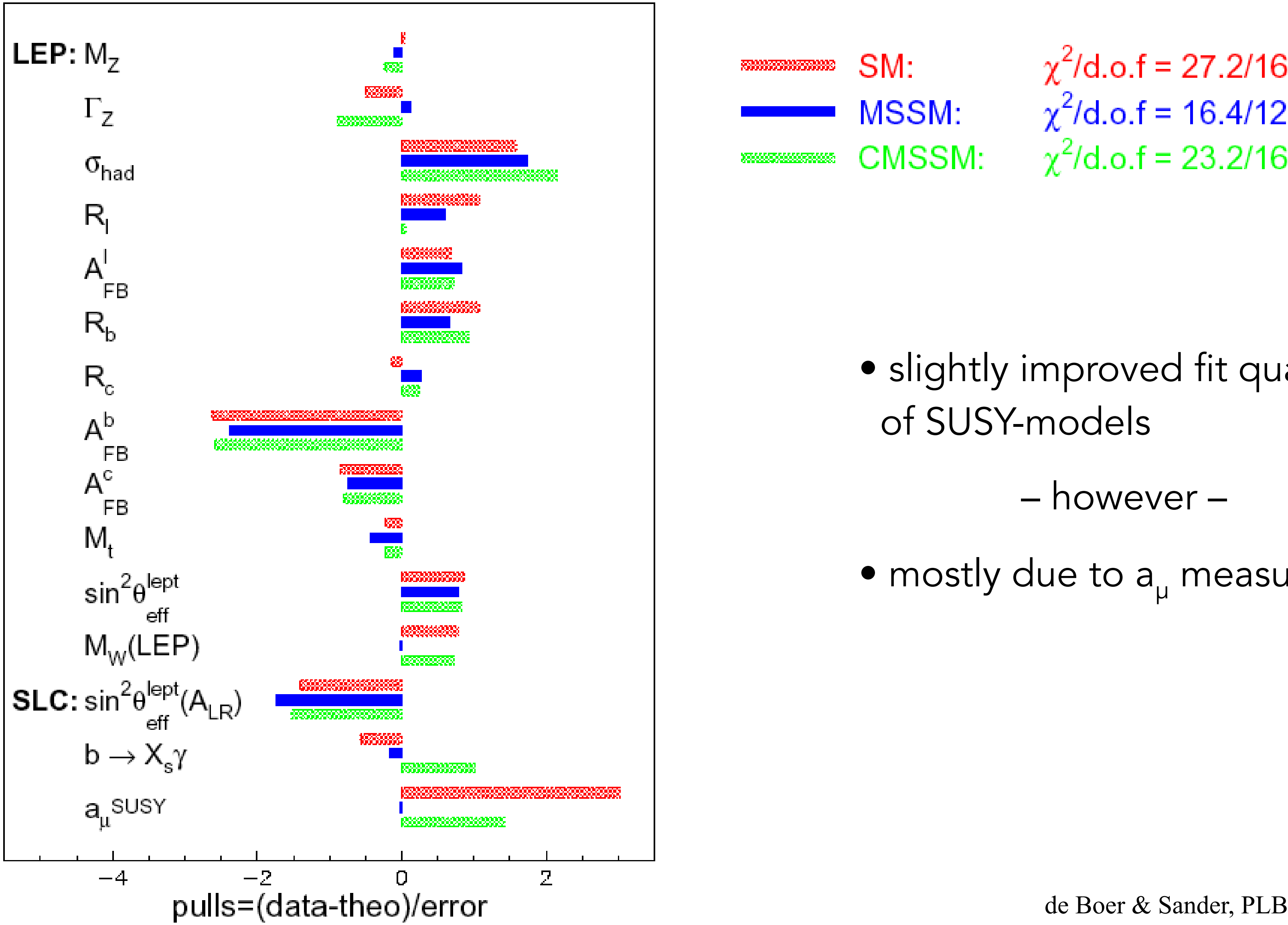
- Dirac theory: magnetic moment $\mu = g\,\mu_B\, s$, with $\mu_B = \frac{e\hbar}{2mc}$, g =2 and s = 1/2.
- radiative corrections in SM: give corrections on *g*: $$\frac{g-2}{2} = 0.5\left(\frac{\alpha}{\pi}\right) - 0.32848\left(\frac{\alpha}{\pi}\right)^2 + \ldots$$ $$= (11\ 659\ 159.6 \pm 6.7)\ 10^{-10}$$



- precise measurements resulted in: $$\frac{g-2}{2} = (11\ 659\ 203 \pm 15)\ 10^{-10}$$
- difference: $a_\mu(\exp) - a_\mu(SM) = (43 \pm 16)\ 10^{-10}$ $\left(a_\mu \equiv \frac{g-2}{2}\right)$
- Supersymmetry: contributions to a_μ, mainly through smuon-neutralino and sneutrino-chargino loops: $$\Delta a_\mu(SUSY) \approx 140 \cdot 10^{-11} \left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^2 \tan\beta$$
- –> $\tilde{m} \approx 120\ \ldots\ 400$ GeV für tanβ = 4 … 40.

Supersymmetry: indirect search

Global fits to world precision ew data



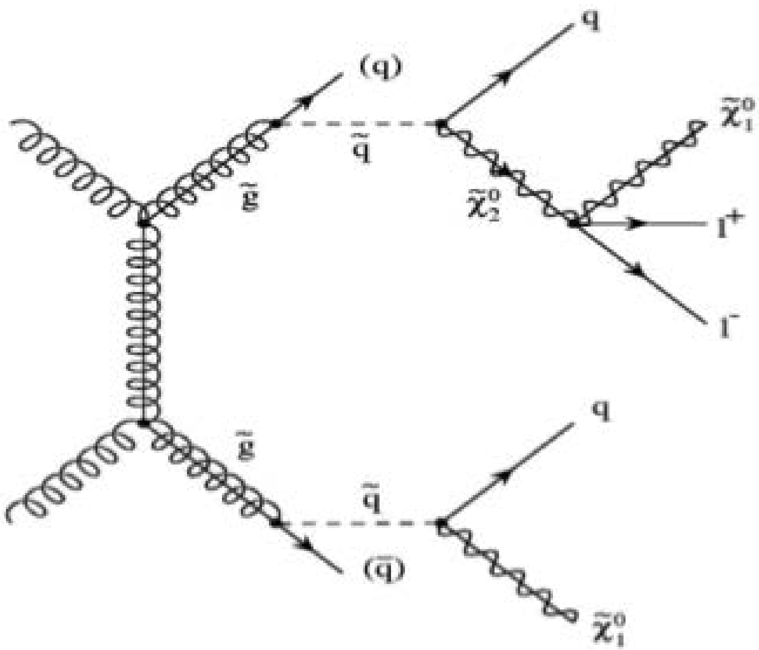
- slightly improved fit quality of SUSY-models

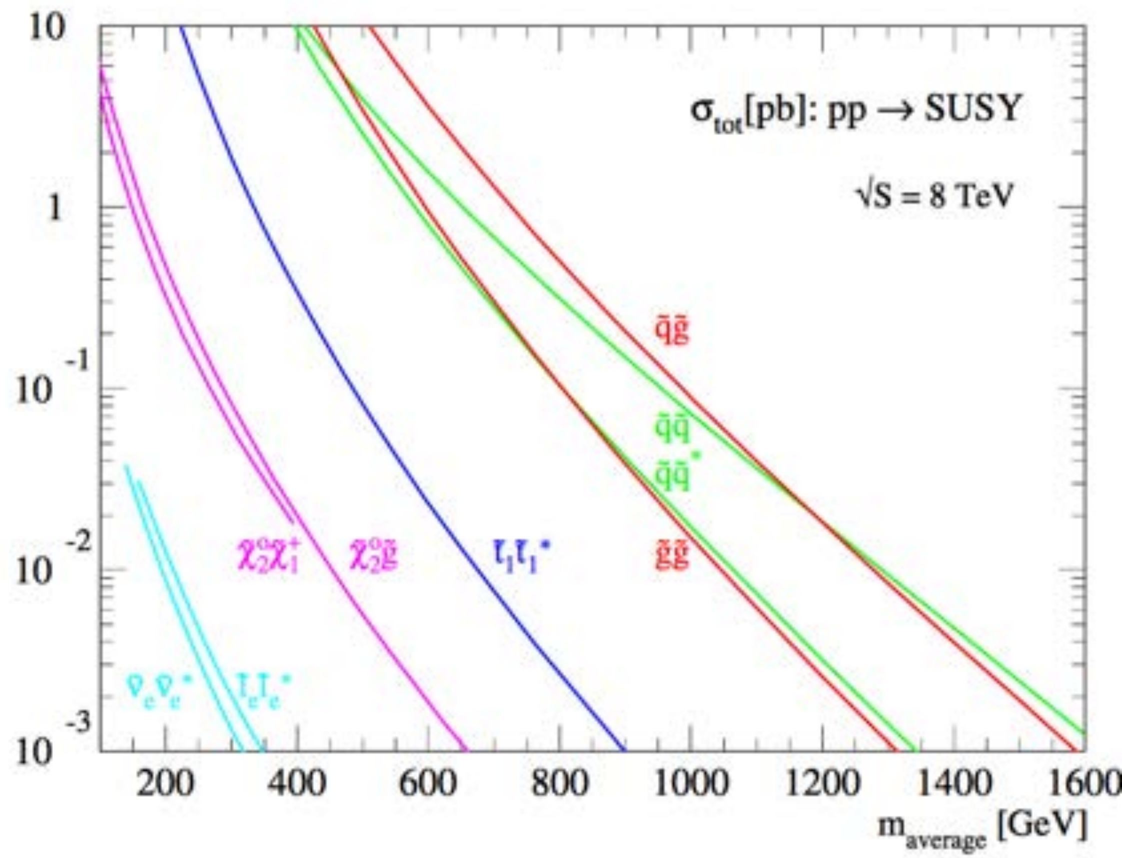
– however –

- mostly due to a_μ measurement

de Boer & Sander, PLB585 (2004) 276

SUSY: Production at Hadron Collider (LHC)





- production dominated by color-charged particles
- cross sections determined by squark/gluino masses

SUSY: exp. searches and uncertainties

search for: signatures of multi-lepton, multi-jets, missing energy

theoretical uncertainties:

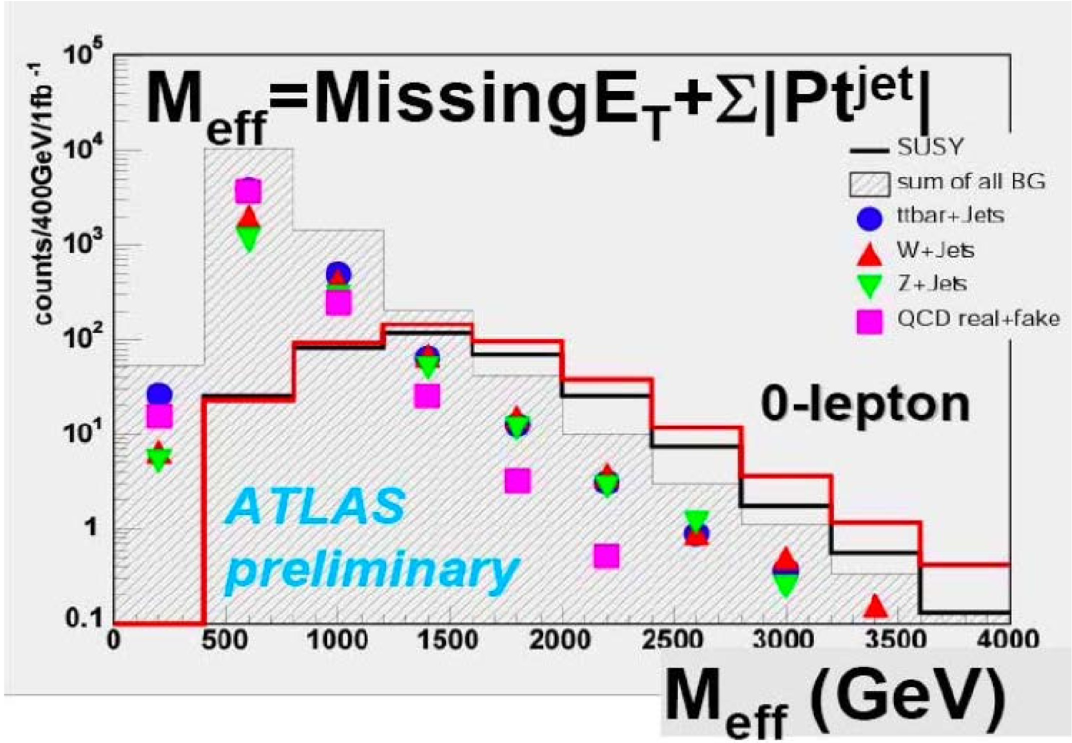
- cross sections
- contributions of higher orders of perturbation theory
- initial and final state radiation effects
- underlying event (proton remnants)

experimental uncertainties:

- jet reconstruction (E-calibration, resolution)
- pile-up at high luminosities
- reconstruction and resolution of missing energy
- lepton identification

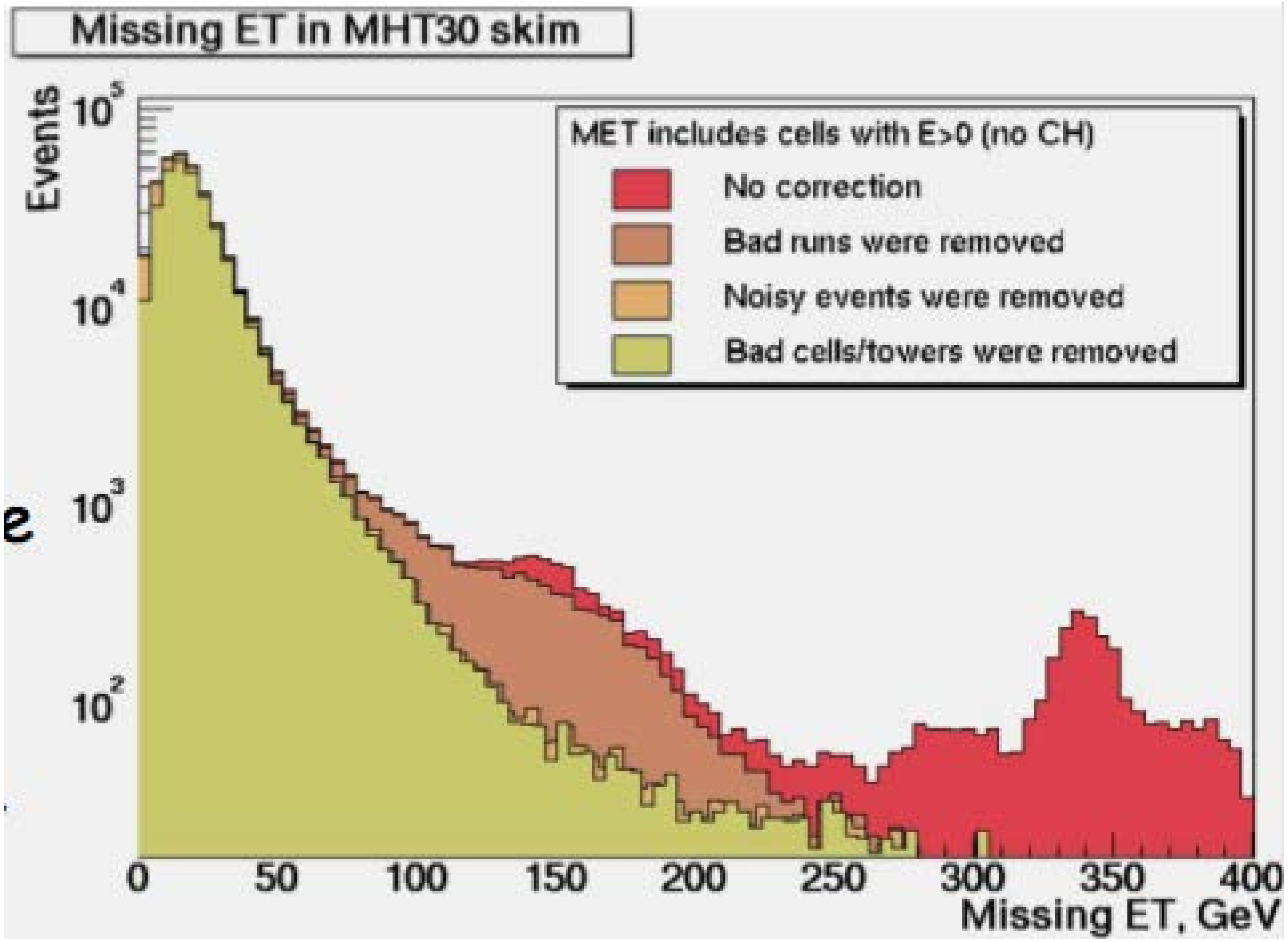
–> should possibly be calibrated with data (not MC!)!

SUSY: background



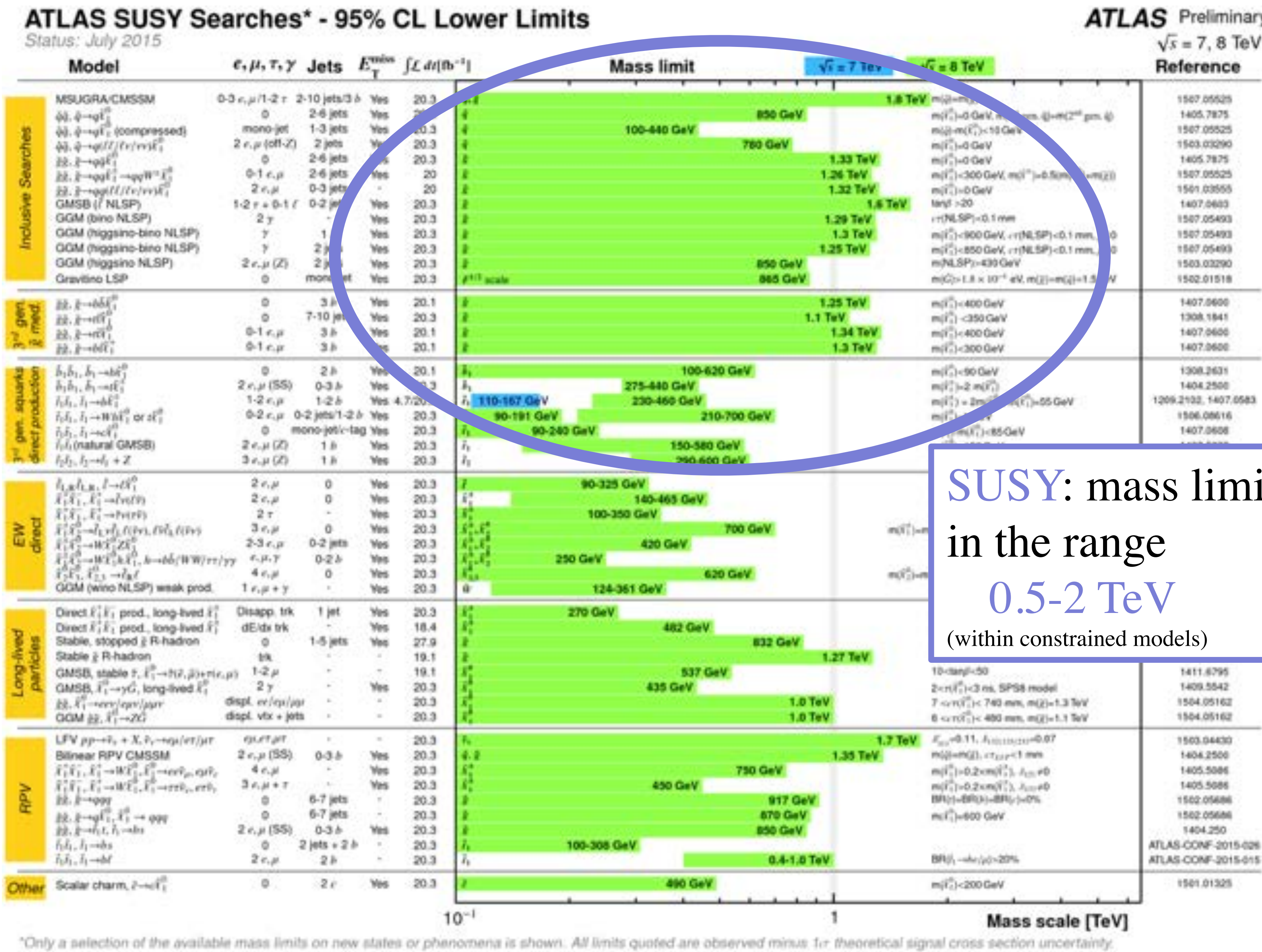
- real E_T^{miss} e.g. from W/Z + Jets, tt + Jets (neutrinos)
- „fake“ E_T^{miss} from detector effects and QCD events

SUSY: experimental background



through:
- accelerator
- beam-gas events
- „hot" calorimeter cells
- and many others

Results of main SUSY searches



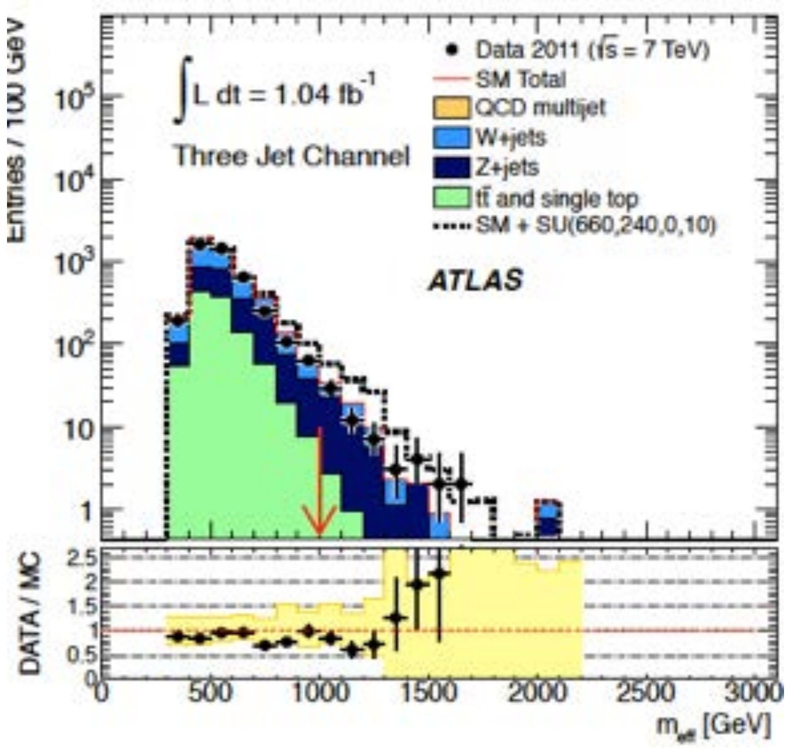
SUSY: mass limits in the range

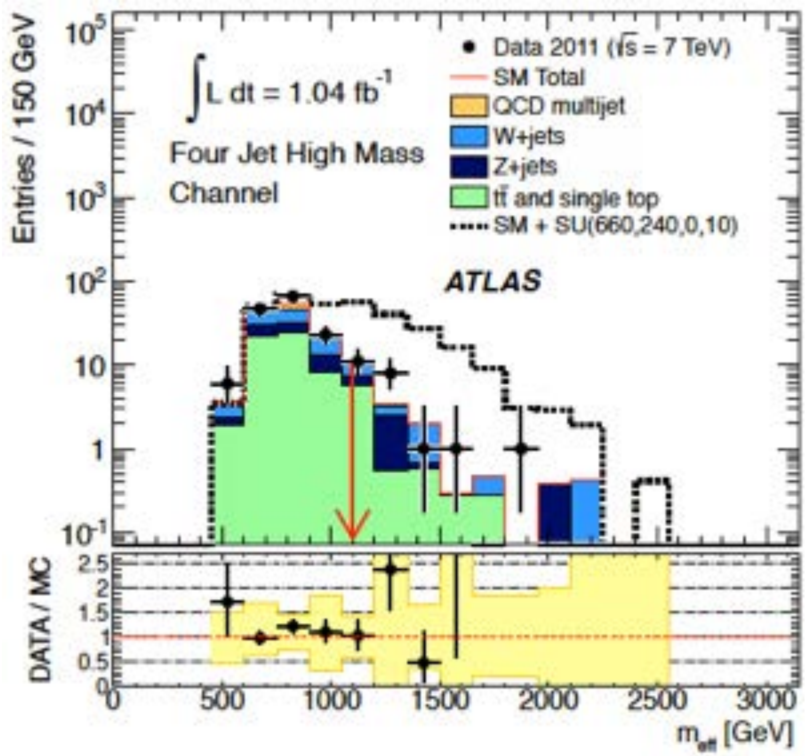
0.5-2 TeV

(within constrained models)

Example 1: search for squarks and gluinos

using final states with high p_T jets and large E_T (and NO leptons)





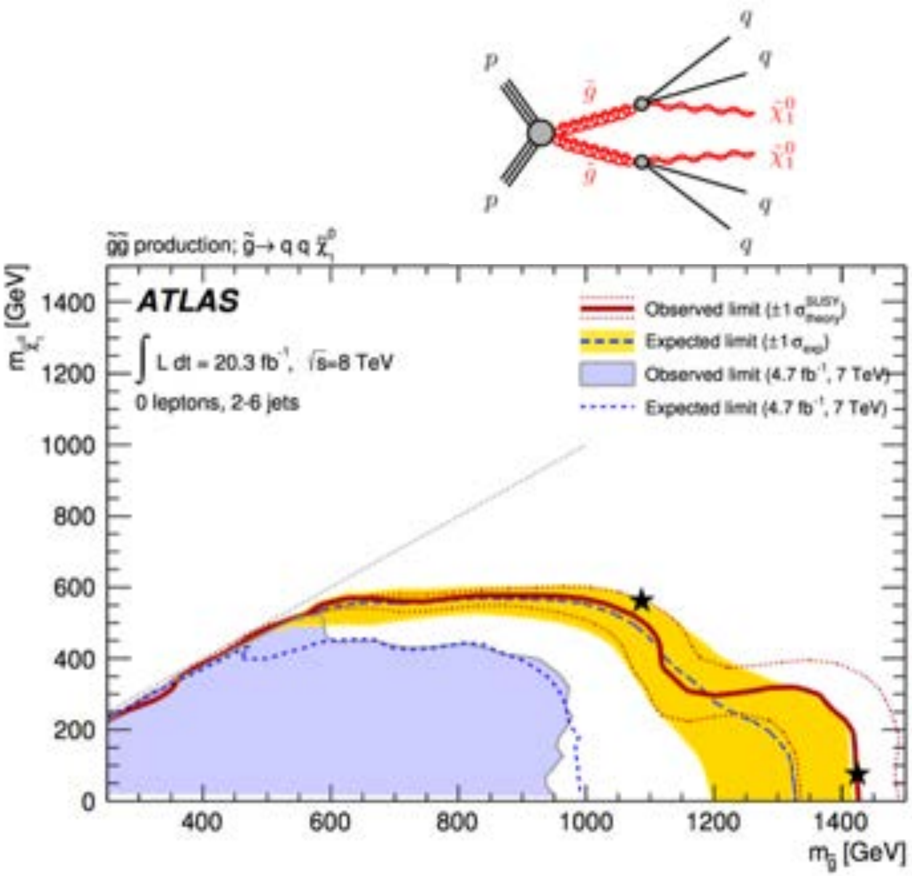
$$M_{eff} = E_T^{miss} + \Sigma \, |p_{T}\mathrm{jet}|$$

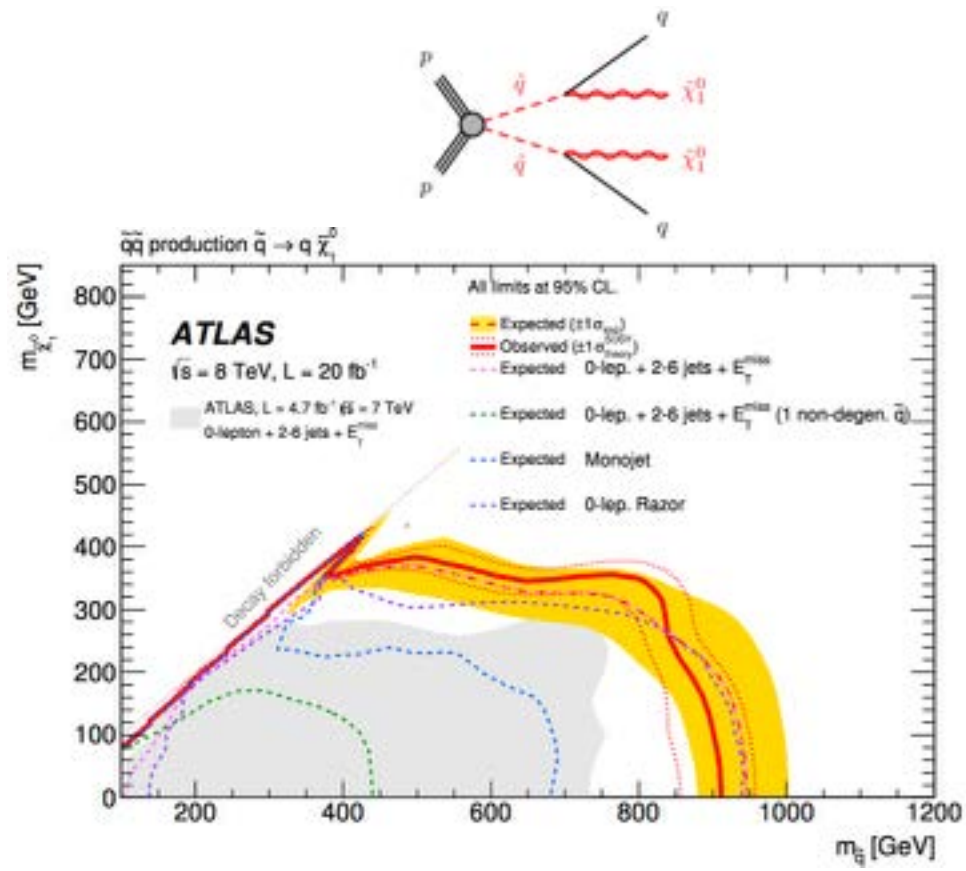
arXiv:1109.6572v1 [hep-ex]

Example 1: search for squarks and gluinos

(strong production)

using final states with high p_T jets and large E_T (and NO leptons)





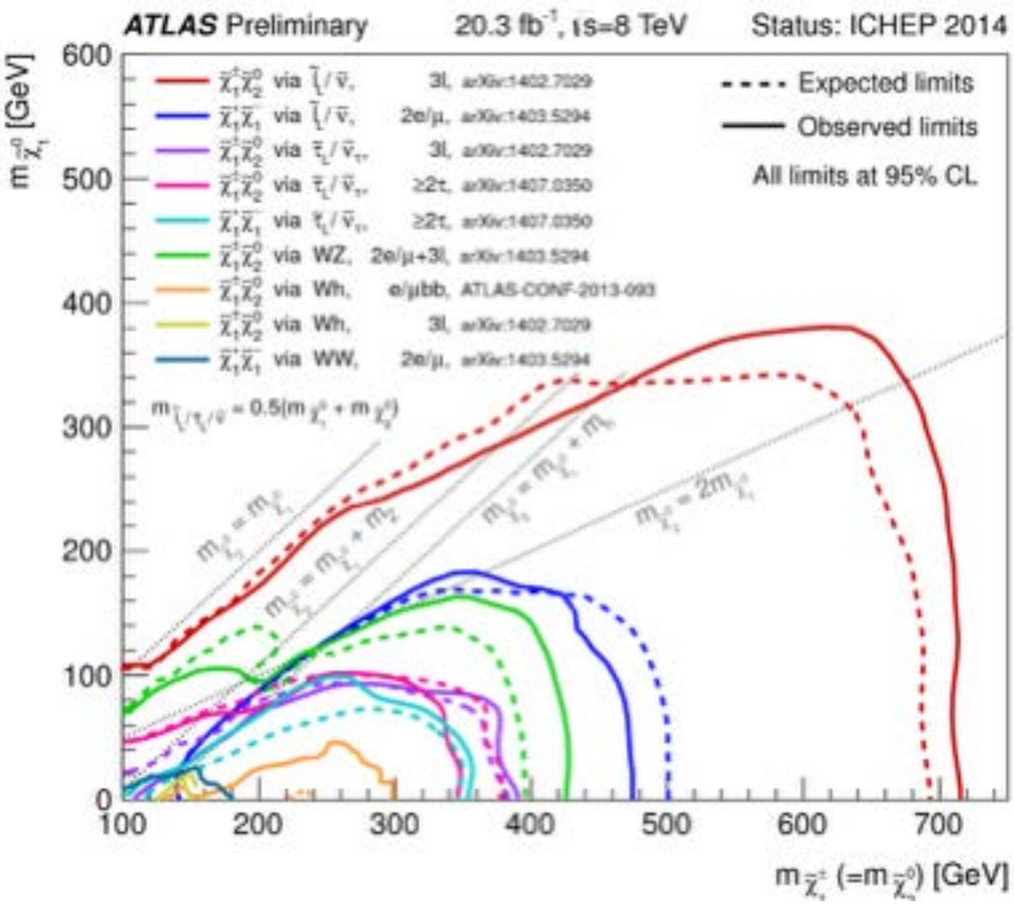
exclusion of gluino masses up to 1400 GeV

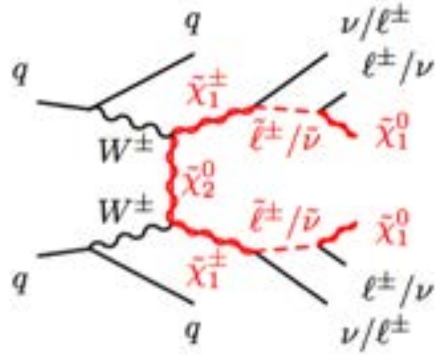
exclusion of squark masses up to 900 GeV

Example 2: search for neutralino-chargino production

(weak production)

using final states with high p_T leptons and large E_T





verifying SUSY:

- if indications or evidence for SUSY found, one should

  –> find the super partners of all SM particles

  –> verify that their spins are different by 1/2

  –> verify quantum numbers and couplings

  –> verify correct predictions of masses

- excess of events - also compatible with other (exotic) models?

  –> extra dimensions, ...

- needs: (precision-) measurements of

  –> masses

  –> production cross sections

  –> branching ratios

  –> decay angular distributions ....

Summary:

- so far, SM still describes data (LHC at 7 and 8 TeV)
- large part of phase space still open for SUSY
- SUSY is (still) main candidate for physics beyond SM
- large phase space due to many free parameters
- „standard SUSY models: MSSM, (m)SUGRA, CSSM...

- LHC still has large discovery potential for SUSY (14 TeV; hL)
- exp. signatures: multi-jets plus multi-leptons plus E_T^{miss}
- so far: exclusion of squarks, gluinos with masses < O(1 TeV)
- "guaranteed" discovery for SUSY masses of several TeV
- specifying SUSY model (if found) will be difficult at LHC

=> he-LHC; ILC

Literature:

- **Supersymmetry in Elementary Particle Physics.** Michael E. Peskin, SLAC-PUB-13079, 72pp. e-Print: **arXiv:0801.1928** [hep-ph]

- **Supersymmetry and cosmology.** Jonathan L. Feng, 66 pp., e-Print: **hep-ph/0405215**

- **A Supersymmetry primer.** Stephen P. Martin (Michigan U.) . Sep 1997. 88pp. e-Print: **hep-ph/9709356**

- **Supersymmetry and supergravity.** J. Wess (Munich U.) , J. Bagger (Johns Hopkins U.) . 1992. 259pp. Princeton, USA: Univ. Pr. (1992) 259 p.

- **SUSY searches with the ATLAS Detector.** L.S. Ancu, arXiv:1412.2784 [hep-ex].

- **SUSY searches at CMS.** A. Gaz, arXiv:1411.1886 [hep-ex].

next lectures (18.1.16): top quark physics
(25.1.16): Future accelerator projects
(1.2.16): Exotics (BSM); newest results at $\sqrt{s}$= 13 TeV