The Standard Model and beyond (5)
SM limits and some extensions

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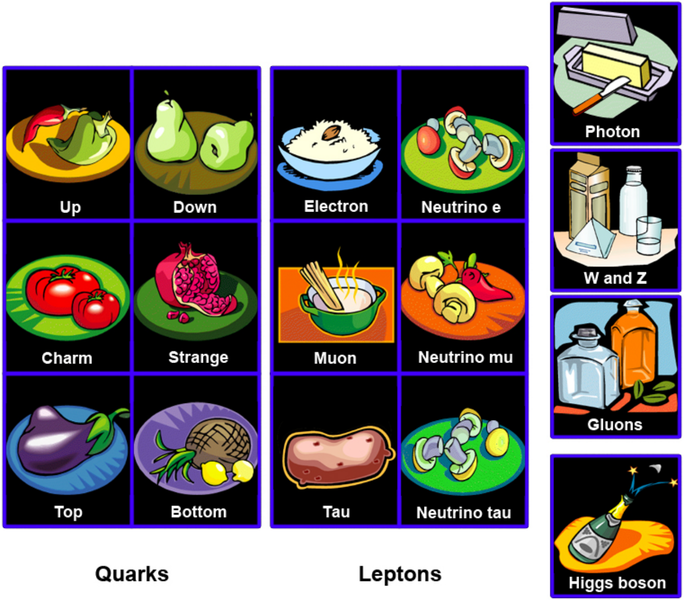
LPT Orsay



Quarks **Leptons**

Fermions **Bosons**

Fourth lecture

Spontaneous symmetry breaking

- Interactions obey a symmetry which is not visible in the spectrum
- Ground state does not respect the symmetry
- Must expand the theory around this ground state
- For global symmetry, masless scalar particles (Goldstone bosons)

Electroweak symmetry breaking

- Triggered by addition complex scalar doublet, the Higgs field
- For gauge symmetry, yields 3 massive gauge bosons
- Symmetry breaking chosen to preserve $U(1)_{em}$ and keep massless photons
- A dof not used to give masses to W, Z: the Higgs boson H
- Couplings of H to gauge bosons and to fermions
- Experimental tests: Higgs couplings, electroweak precision observables, CKM matrix

The splendors and miseries of the Standard Model

Too successful a theory ?

SM a real success story

- Description of three fundamental interactions
- Gauge symmetry yields dynamics inambiguously
- Very good agreement with experimental data

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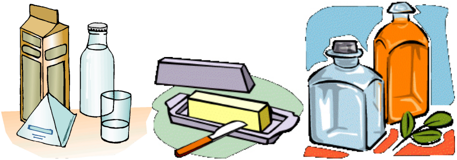
So, is the dinner too good and should we go to sleep ?

SM limits (1)



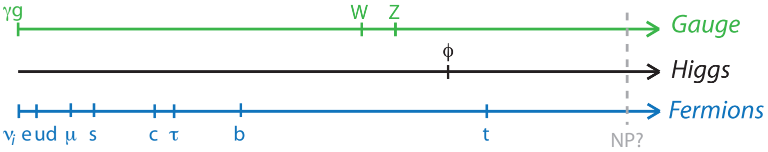
- QCD gauge sector : α_s, θ_{QCD} 2
- Electroweak gauge/scalar sector : g, g', μ, λ 4

- Yukawa sector 13

$$m_e, m_\mu, m_\tau, m_d, m_s, m_b, m_u, m_c, m_t + 4 \text{ param in } V_{CKM}$$

19 free parameters
(+ neutrinos: masses/lepton mixing depending on Dirac vs Majorana)

SM limits (2)



- Parameters, e.g., masses, completely arbitrary

$$m_e = 0.51 \text{ MeV} \to m_t = 170 \text{ GeV}$$

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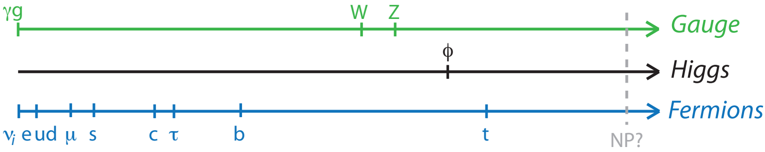

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- Origin of electroweak symmetry breaking

most simple ϕ^4 model enough for Higgs ?

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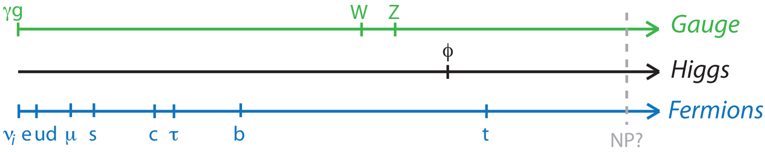

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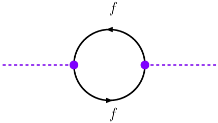


- Hierarchy "problem" with $m_H = 125$ GeV

$$\Delta m_H^2 = \frac{N_f m_f^2}{4\pi^2 v^2}\left[\Lambda_{NP}^2 + 6 m_f^2 \log\frac{\Lambda_{NP}}{m_f} - 2m_f^2\right] + O\left[\frac{1}{\Lambda_{NP}^2}\right]$$

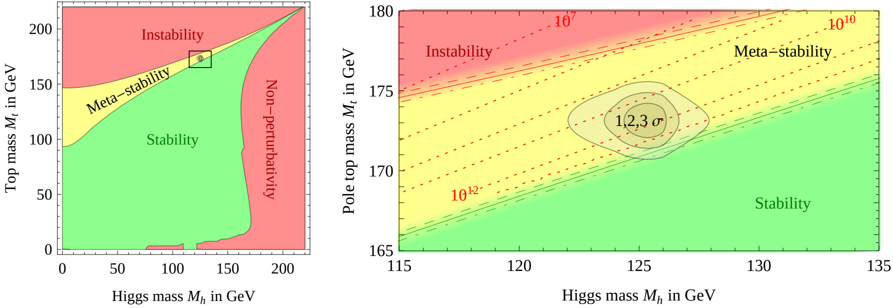
Λ_{NP} scale of new physics: fine tuning needed if no particle up to unification scale ($10^{16...19}$ GeV ?)

SM limits (3)

Analysis of NNLO analysis of SM Higgs potential

$$M_H > 129.4 + 1.4\left(\frac{m_t - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0 \quad M_H > 129.4 \pm 1.8\,\mathrm{GeV}$$

for vacuum absolutely stable up to Planck scale



M_t and M_H (if SM Higgs) favour metastability of the vacuum

as well as almost vanishing of $\lambda(M_{Planck})$

SM limits (4)

- No gravitation included
- Cosmological obs: dark matter, matter-antimatter asym...
- No explanations for gauge group, only partial unification
- Value of the charges ? Three families ? Neutrinos ?
- Why $L \neq R$? Structure of Yukawa ? Amount of CP-violation ?
- Strong CP-problem: $\theta_{QCD}\epsilon_{\mu\nu\rho\sigma}G^{\mu\nu}G^{\rho\sigma}$ alowed, but $\theta_{QCD} \leq 10^{-10}$

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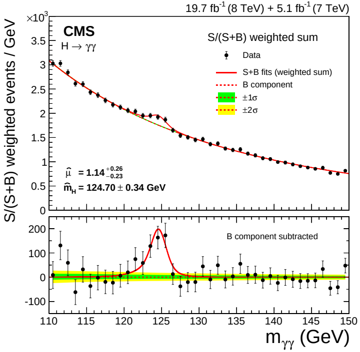
Theorists have plenty of ideas to spice up the SM

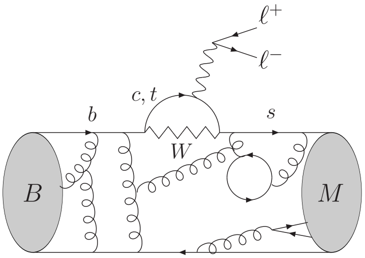
Complementary ways of observing New Physics

Relativistic path: $E = mc^2$



Collisions with enough energy
to produce directly particles
beyond the SM
Higher energy/lower intensity
"Direct" proof

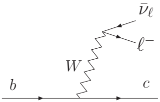
Quantum path: $\Delta E \Delta t \geq \hbar/2$

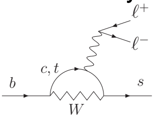


Small deviations from
intermediate states
with heavy particles
Lower energy/higher intensity
"Indirect" proof

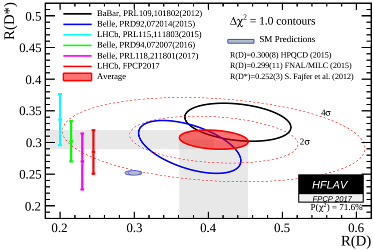
A few signs ?

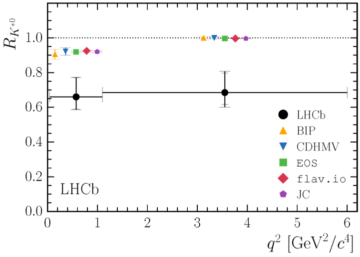
- No signal using the relativistic path at LHC
- But a few hints using the quantum path
  - anomalous magnetic moment of the muon $(g-2)_\mu$
  - CP-violation in kaon decays (ϵ'/ϵ)
  - violation of lepton flavour universality in some b decays





$$R_{D(*)} = \frac{Br(B \to D(*)\tau\nu)}{Br(B \to D(*)\ell\bar\nu_\ell)} \qquad R_{K(*)} = \frac{Br(B \to K(*)\mu\mu)}{Br(B \to K(*)ee)}$$

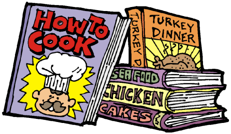




New directions to extend the SM ?

Many different directions

- Fermion content (more “matter”)
- Gauge boson content (more “interactions”)
- Scalar sector (different symmetry breakings)
- Additional symmetries
- Additional dimensions



Main constraints

- Reproduce data within experimental and theoretical uncertainties
  $\Longrightarrow$Be close to SM up to currently tested energies
- Most new phenomena should occur only in untested processes
  $\Longrightarrow$Modify structure of the theory to push NP in these corners
- Built as decoupling theories: recover SM when $\Lambda_{NP} \to \infty$
  $\Longrightarrow$SM seen as effective theory, with NP corrections $O(\Lambda_{EW}/\Lambda_{NP})$

Supersymmetry

Basic idea

Let us take seriously the hierarchy problem, can we solve it ?

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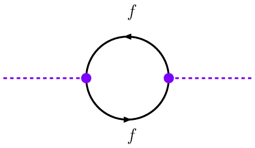

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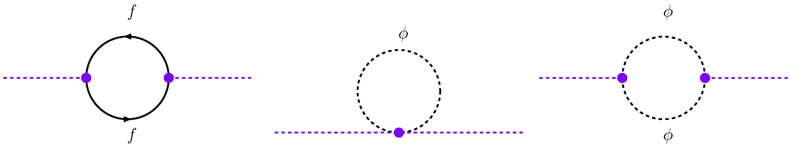

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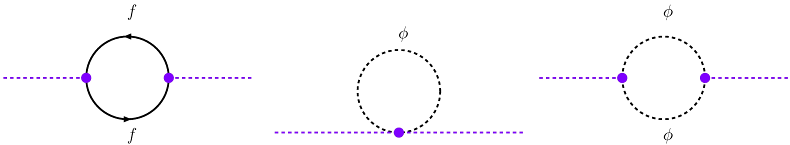

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- If $N_s = 2N_f$ and $\lambda_f = 2m_f^2/v^2 = -\lambda_s$ (particle content, symmetry), cancellation of quadratic divergences, no fine tuning needed

$$\Delta m_H^2 = \frac{N_f \lambda_f^2}{4\pi^2}\left[(m_f^2 - m_s^2)\log\frac{\Lambda}{m_f} + 3m_f^2 \log\frac{m_s}{m_f}\right] + O\left[\frac{1}{\Lambda^2}\right]$$

Supersymmetry

Such a symmetry exists, it is supersymmetry : boson $\leftrightarrow$ fermion

$$Q|\mathrm{Spin}\ S\rangle = |\mathrm{Spin}\ S + 1/2\rangle \qquad \{Q, Q^\dagger\} = P^\mu$$

$\Longrightarrow$connects different spins : extension of Lorentz-Poincaré symmetry
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- Quadratic terms in Λ cancel in m_H

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(even log. terms do cancel if $m_f = m_s$) $\Longrightarrow$ no fine-tuning !

- If supersymmetry not broken,
spectrum of bosons and fermions should be degenerate

MSSM

Minimal Supersymmetric Standard Model: minimal extension of SM

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- Doubling of the spectrum

Spin	SM particle	Susy partner	Spin
1/2	lepton $\ell_{R,L}$	slepton $\tilde{\ell}_{R,L}$	0
1/2	neutrino $\nu_{\ell,L}$	sneutrino $\tilde{\nu}_{\ell,L}$	0
1/2	quark $q_{R,L}$	squark $\tilde{q}_{R,L}$	0
1	bosons $Z^0, W^\pm$	zino, wino $\tilde{Z}, \tilde{W}^\pm$	1/2
1	gluons g	gluinos $\tilde{g}$	1/2

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- Two Higgs doublets H_1, H_2 (and higgsinos $\tilde{H}_1, \tilde{H}_2$)

$$H_u = \begin{pmatrix} H_u^+ \\ H_d^0 \end{pmatrix} \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

[different couplings to u and d-type quarks]

MSSM : electroweak symmetry breaking

Electroweak symmetry breaking triggered by

$\langle 0|H_u^0|0\rangle \neq 0$ and $\langle 0|H_d^0|0\rangle \neq 0$, with $m_W, m_Z \ldots$ depending on

- $\tan\beta = \langle H_u^0\rangle / \langle H_d^0\rangle$
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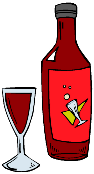
8 real scalars $-$ 3 for the Higgs mechanism
= 5 observable spin-0 particles



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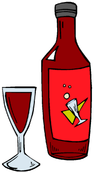

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$$m_{H^\pm} \geq m_W \qquad m_h \leq m_A, m_Z \leq m_H$$

at leading order, implying large one-loop corrections to have $m_h \geq M_Z$

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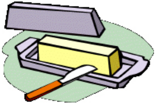

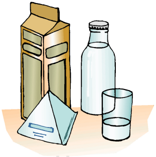

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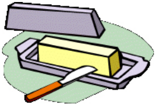

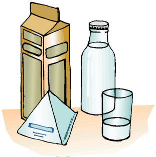

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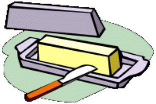

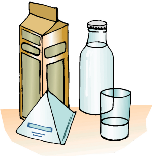

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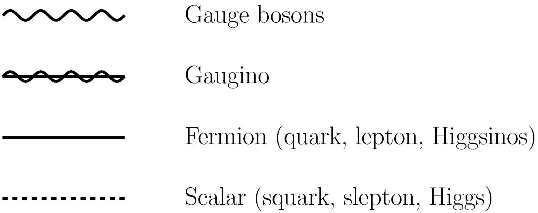
- Susy to be broken: spectrum non-degenerate with SM particles

Interactions and decays

R-parity : even number of susy particles at each vertex

- no creation/decay of a single susy particle
- lightest susy particle (LSP) is stable (dark matter candidate)

Many more particles, and thus many more interactions



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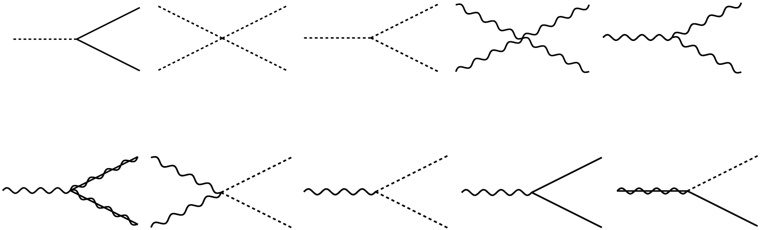

governed by the same coupling constants as their SM counterparts

Supersymmetry and its “soft” breaking

Supersymmetry not a symmetry of the spectrum
$\Longrightarrow$mechanism to break susy and
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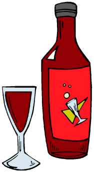

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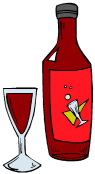

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- $\mathcal{L}_{soft}$ must not affect the couplings involved in the cancellation of quadratic divergences $\mathcal{L}_{susy}$
- $\mathcal{L}_{soft}$: typical scale $m_{soft} = O(1 \text{ TeV})$ parametrising susy breaking
- Contribution to Δm_H^2 should vanish as $m_{soft} \to 0$

$$\Delta m_H^2 = m_{soft}^2 \left[\frac{\lambda}{16\pi^2} \log \frac{\Lambda}{m_{soft}} + \ldots \right]$$

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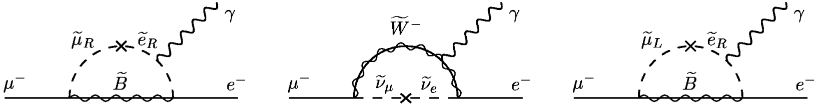

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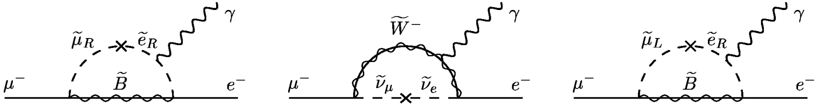
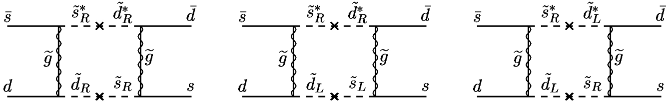


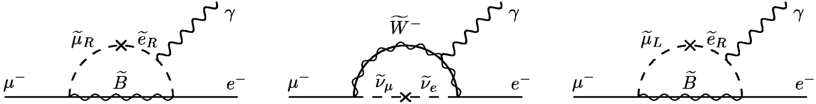
- Neutral meson mixing : $K_0 \leftrightarrow \bar{K}_0$ (i.e., $\bar{s}d \leftrightarrow s\bar{d}$)



Constraints on the parameters

$\mathcal{L}_{susy}$ fixed by SM, but $\mathcal{L}_{soft}$ contains 105 unkown parameters,
constrained by quantum loops in lower-energy processes

- Lepton-flavour violating processes : $\mu \to e\gamma$



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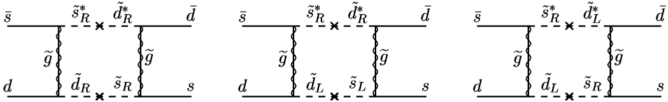

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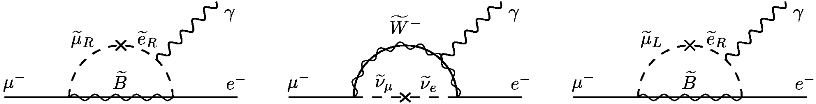

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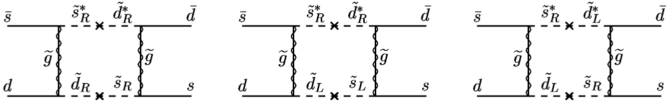


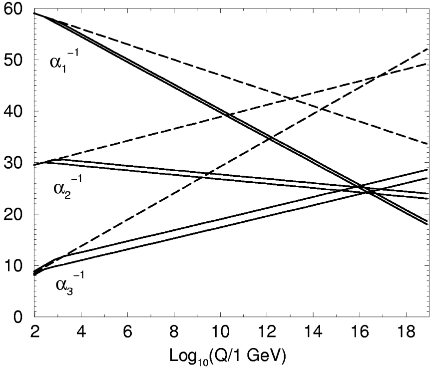
- CP-violation should remain in agreement with CKM matrix

$\Longrightarrow$Susy-breaking terms $\simeq$ almost flavour diagonal and blind,
identical for 3 generations and with small sources of CP-violation

(implemented through additional, hidden, sector
communicating susy breaking to SM via interactions)

Susy : pros

- No hierarchy “problem”: desert possible from TeV to Planck scale
- Gauge unification more satisfactory



- Lightest susy particle (if neutralino) good candidate for dark matter
- All perturbative and computable once input parameters fixed

Susy : cons

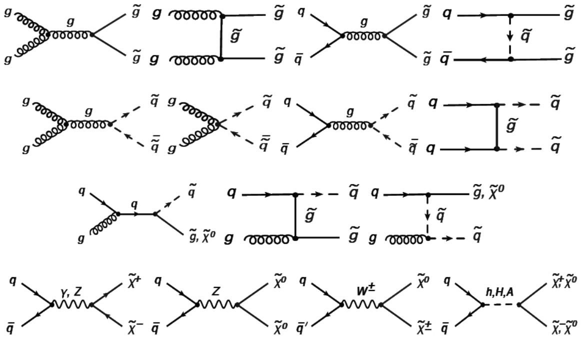
- Doubling of the spectrum, not yet observed
- Many new parameters related to susy-breaking,
  requiring modelling to fix them and be predictive
- No explanation for mass matrix, CP-violation…
- No satisfying mechanism to break susy (hidden sector ?)
- Is the desert from TeV to Planck scale such a good idea ?
- Direct searches at LHC have seen nothing up to now…

Susy is more framework than definite theory, with many extensions

- NMSSM, CNMSSM…with more scalars
- Grand unified versions with more gauge bosons
- R-parity violation with even more parameters
- split susy with different scales for the breakings
- …

Susy useful as a benchmark for discovery machines
but its "plausibility" is sometimes overstated…

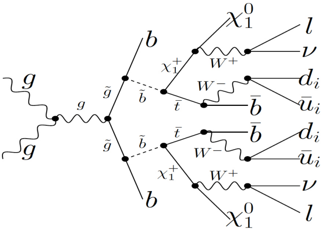
Searching for supersymmetry



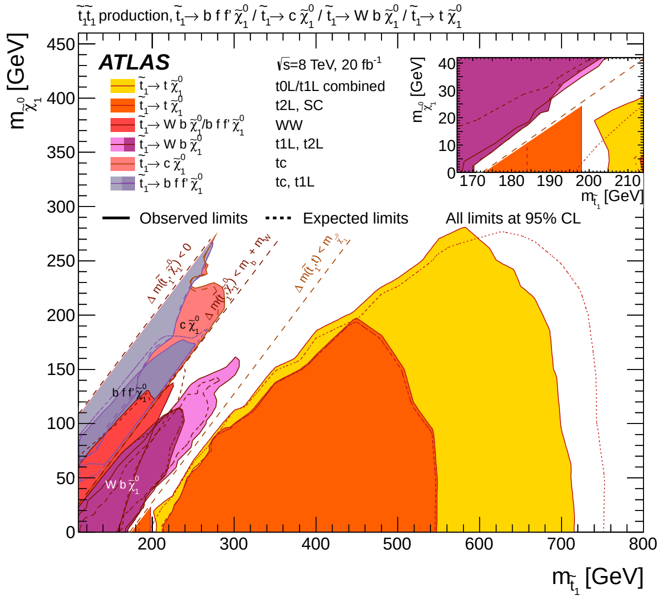
Many different productions channels

If R parity, decay chain producing

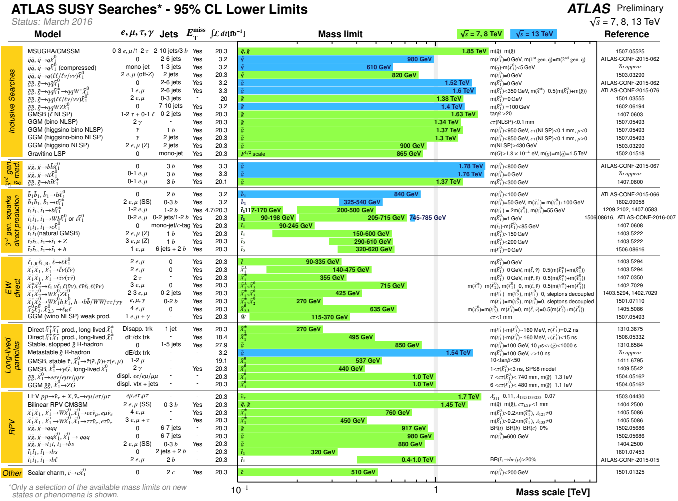
- different SM particles: jets or highly energetic leptons
- LSP χ_1^0: missing energy and missing transverse momentum



Searching for the stop (for instance)



Searches so far



- Direct searches, assuming specific decay chains
- Simplifying assumptions about susy couplings and masses

End of part V