LHC Physics (SUSY/BSM I)

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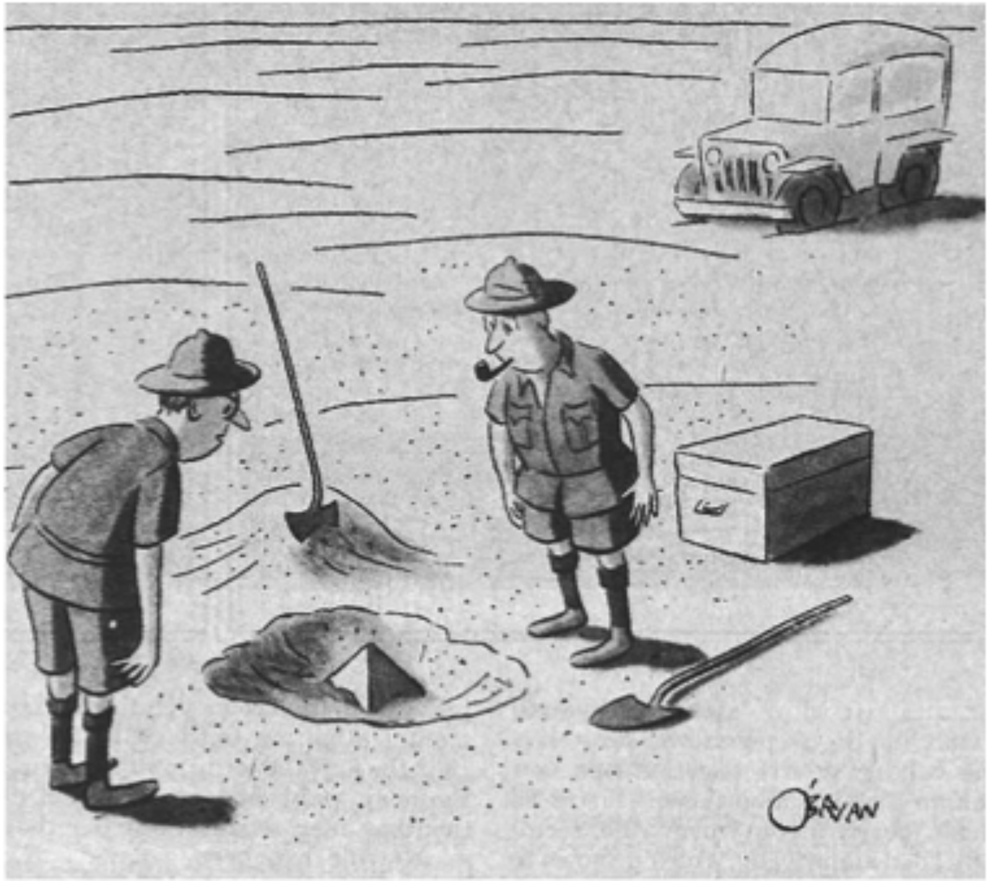
Outline for Part III

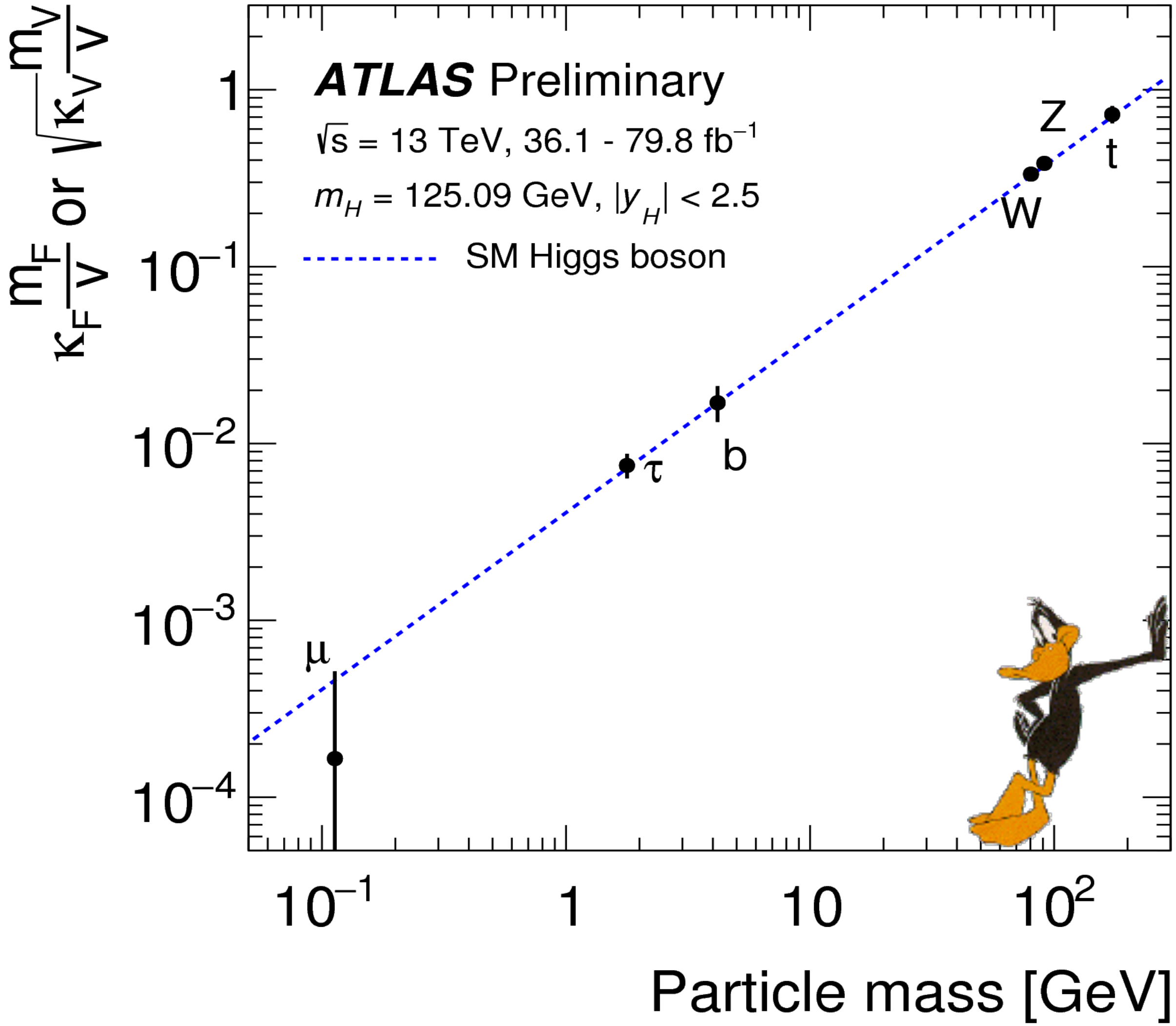
- Why SUSY ?
  - Hierarchy Problem
- SUSY primer
  - Basic Concepts
  - SUSY Breaking
  - MSSM
  - Mixing
  - SUSY spectrum
- Experimental Approach
- Selected SUSY Searches
- Future Prospects



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Higgs Couplings vs mass

If it looks like a duck, swims like a duck, and quacks like a duck…

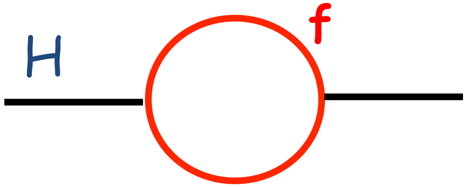


The hierarchy Problem

Hierarchy Problem

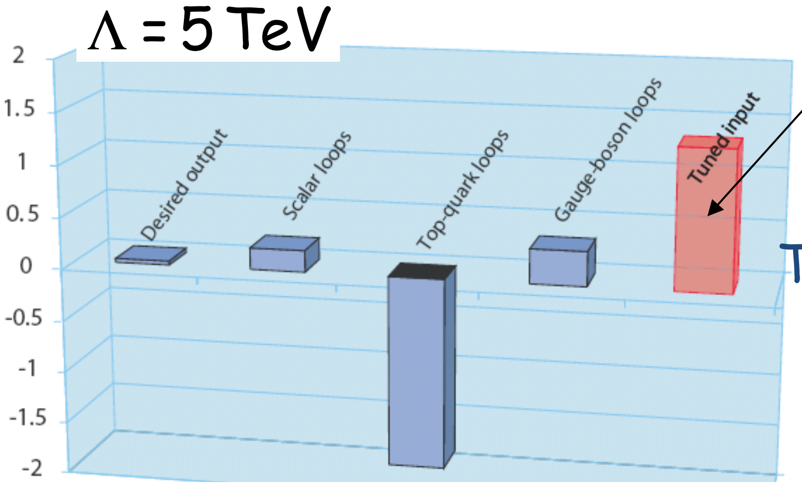

From EWK to Planck scale ?

$$< H > \;=\; 172\ \mathrm{GeV} \rightarrow m_H^2 \approx O(-100\ GeV^2)$$



$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots]$$

$$\text{if } \Lambda_{UV} \approx M_{planck} \rightarrow \text{fine tuning in } 10^{30}\ !!$$


$\Lambda = 5\ \mathrm{TeV}$

relative contributions to ΔM_H^2

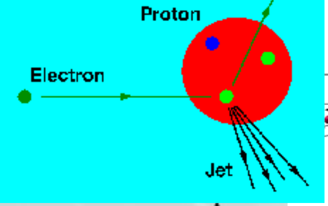
(taken from C. Quigg, hep-ph/0704.2232)

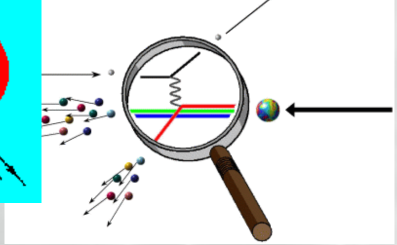
Already a serious problem at 5 TeV scale (cancellation among top, gauge and Higgs loops)

This kind of conspiracy has name in Physics…

SuperSymmetry ?

Unification of Forces ?

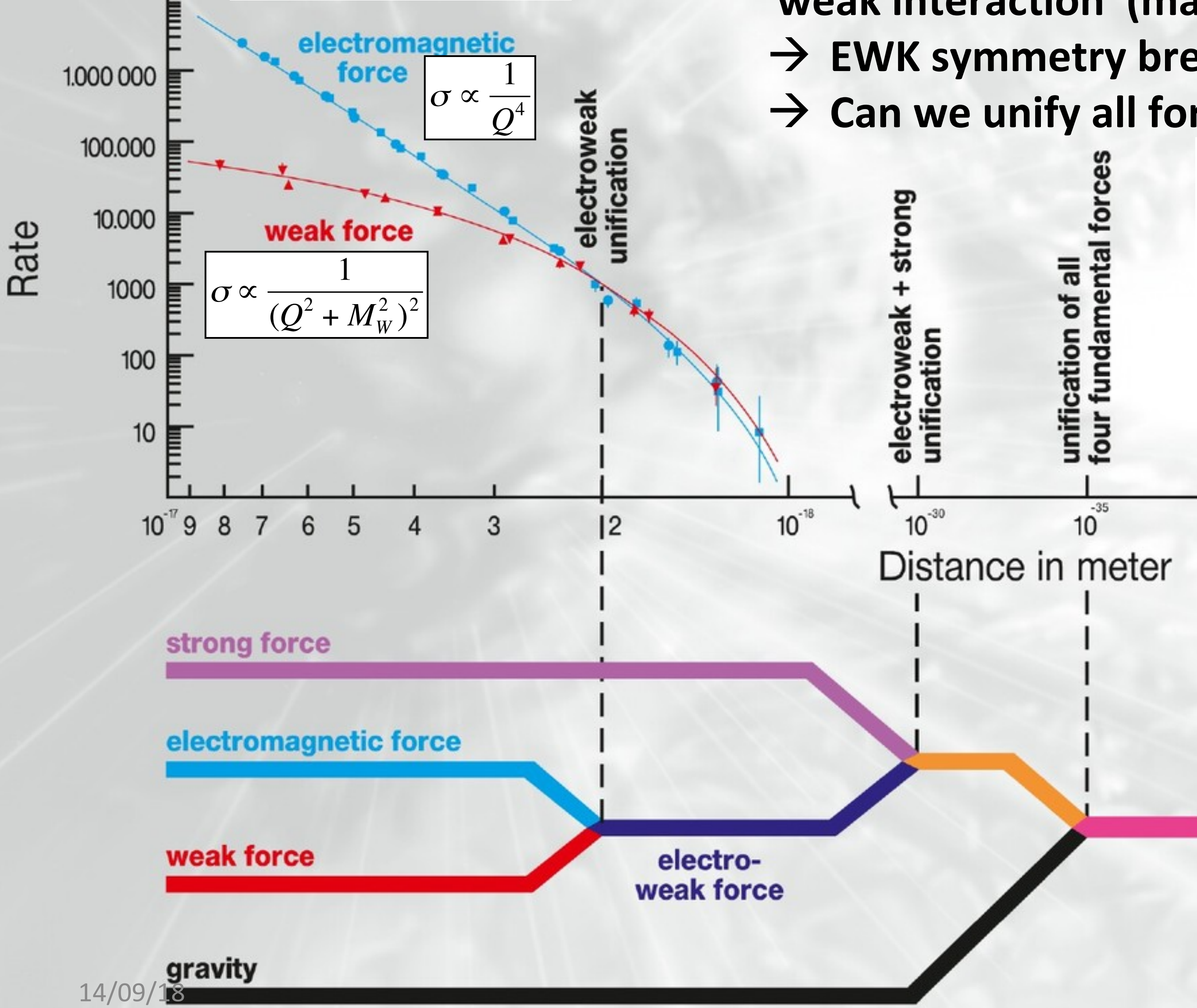


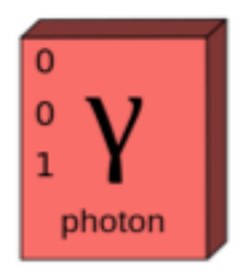


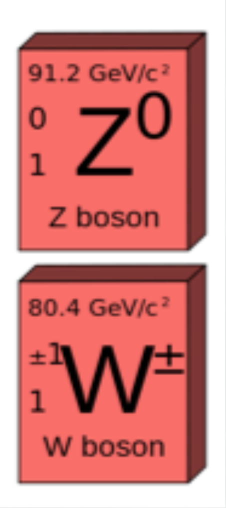
BHE mechanism makes the small range and weak interaction (massive Ws and Z)

→ **EWK symmetry breaking….**

→ **Can we unify all forces ?**

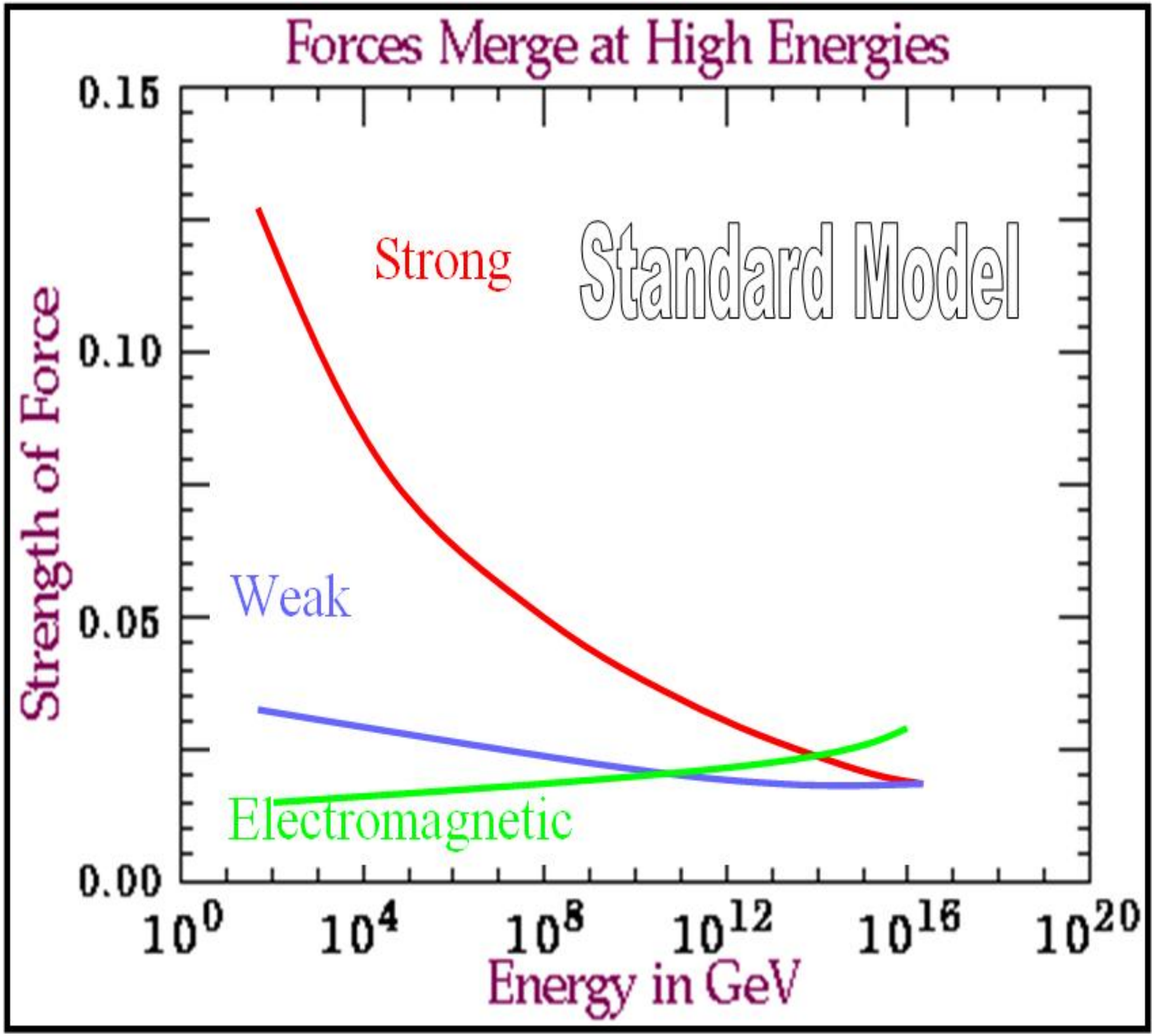






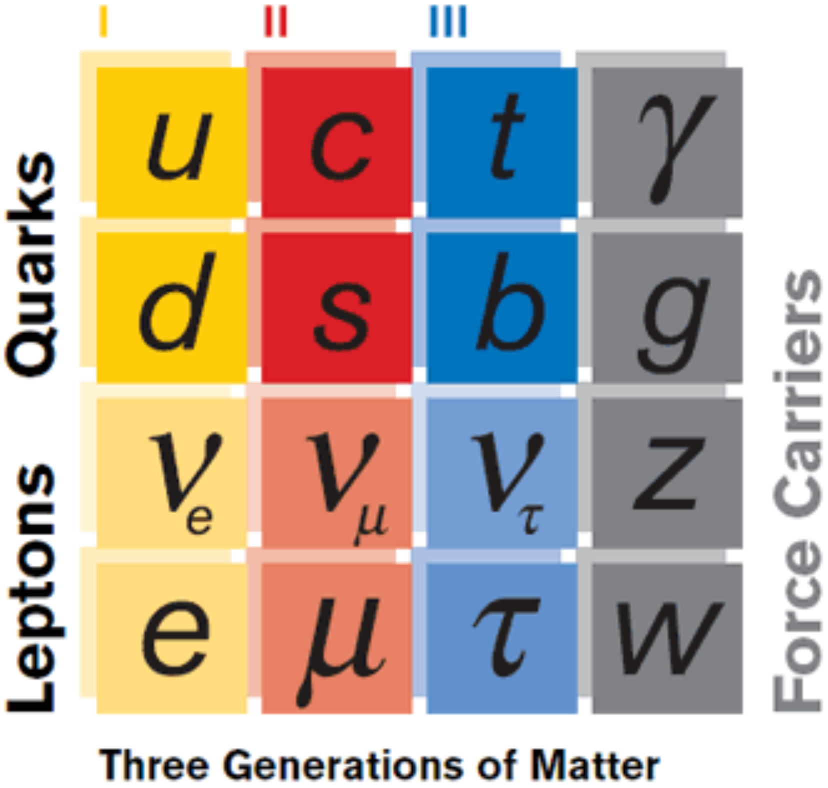
big bang

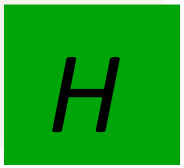
Unification of Forces…



Some of the open questions

(i.e., the need for new physics)





- Who ordered 3 generations?
- Matter/Anti-Matter ?
- ……..
- Hierarchy Problem …
- Unification at Large Scale?
- Dark Matter in the Cosmos?
- ……….
- What about Gravity ?
- ……….

New Physics (!)

O(TeV) scale phenomenology

SUSY Primer

- *SUSY version of a QM harmonic oscillator*
- *Super-Symmetry*

* Thanks to M. Kraemer

QM raising/lowering operators

Recall raising and lowering operators in quantum mechanics

$$\begin{aligned} b^+|n_B\rangle &= \sqrt{n_B+1}\,|n_B+1\rangle \\ b^-|n_B\rangle &= \sqrt{n_B}\,|n_B-1\rangle \end{aligned}$$

where $b^-|0\rangle = 0$ and $[b^-, b^+] = 1; [b^-, b^-] = [b^+, b^+] = 0$

→ b^+/b^- creates/annihilates bosons

Analogously for fermions

$$\begin{aligned} f^+|n_F\rangle &= \sqrt{n_F+1}|n_F+1\rangle \\ f^-|n_F\rangle &= \sqrt{n_F}|n_F-1\rangle \end{aligned}$$

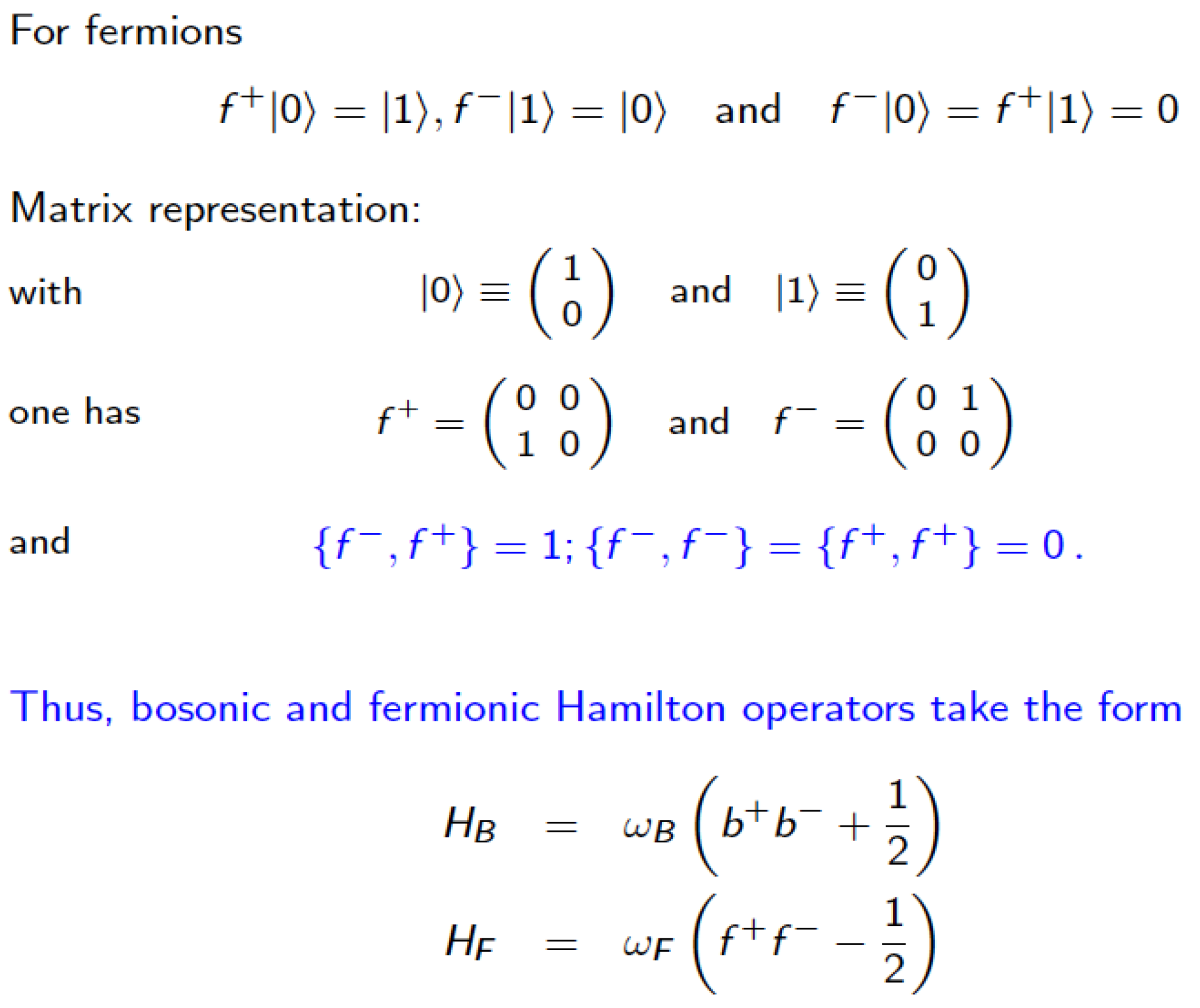
But fermions obey Pauli exclusion principle

→ only two states $|0\rangle$ and $f^+|0\rangle = |1\rangle$

So for fermions

$$f^+|0\rangle = |1\rangle, f^-|1\rangle = |0\rangle \quad \text{and} \quad f^-|0\rangle = f^+|1\rangle = 0$$

For fermions...



For fermions

$$f^+|0\rangle = |1\rangle, f^-|1\rangle = |0\rangle \quad \text{and} \quad f^-|0\rangle = f^+|1\rangle = 0$$

Matrix representation:

with $$|0\rangle \equiv \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \text{and} \quad |1\rangle \equiv \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

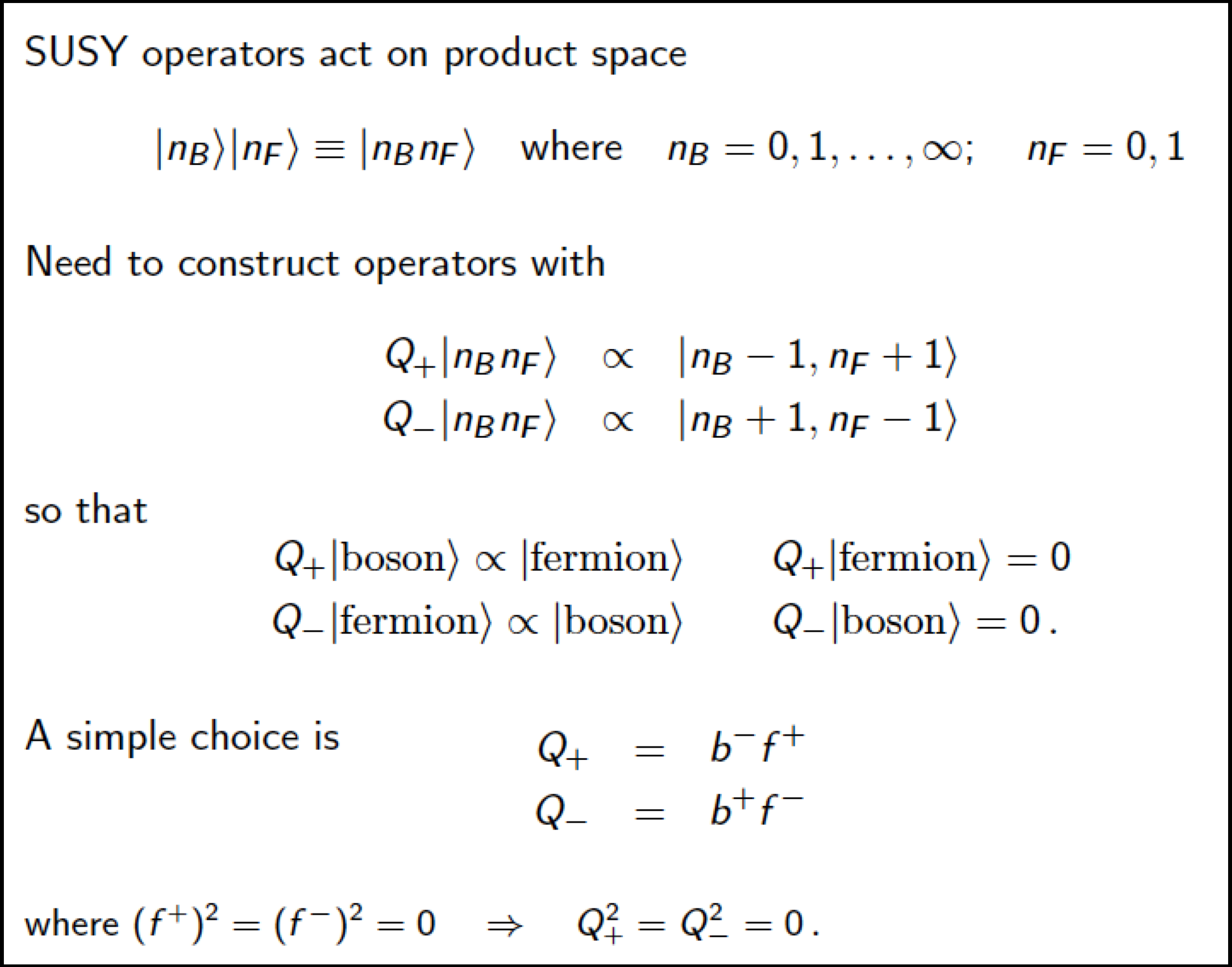
one has $$f^+ = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \quad \text{and} \quad f^- = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

and $$\{f^-, f^+\} = 1; \{f^-, f^-\} = \{f^+, f^+\} = 0\,.$$

Thus, bosonic and fermionic Hamilton operators take the form

$$\begin{aligned} H_B &= \omega_B \left(b^+ b^- + \frac{1}{2} \right) \\ H_F &= \omega_F \left(f^+ f^- - \frac{1}{2} \right) \end{aligned}$$

SUSY transformations



SUSY operators act on product space

$$|n_B\rangle|n_F\rangle \equiv |n_B n_F\rangle \quad \text{where} \quad n_B = 0, 1, \ldots, \infty; \quad n_F = 0, 1$$

Need to construct operators with

$$\begin{aligned} Q_+|n_B n_F\rangle &\propto |n_B - 1, n_F + 1\rangle \\ Q_-|n_B n_F\rangle &\propto |n_B + 1, n_F - 1\rangle \end{aligned}$$

so that

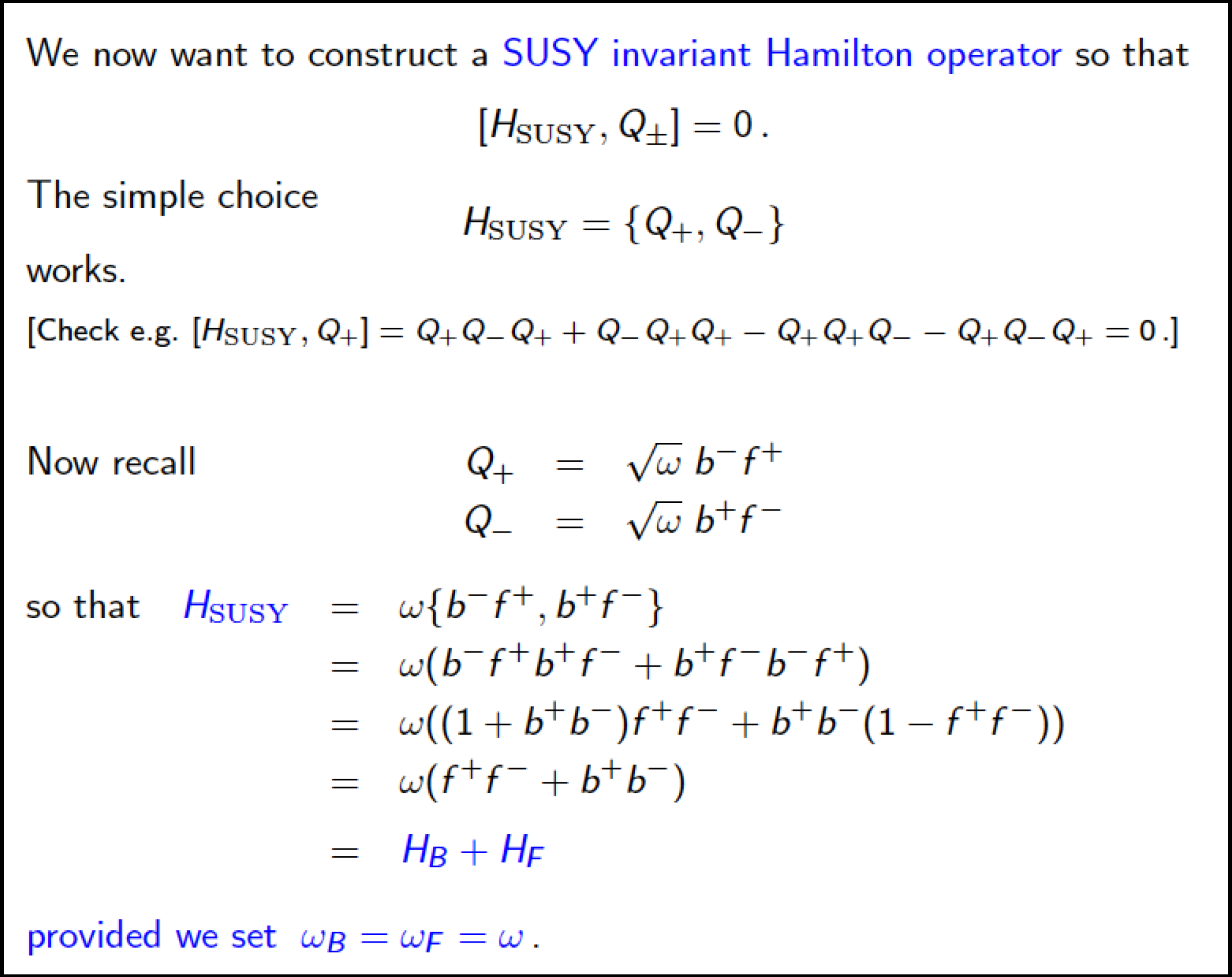
$$\begin{aligned} Q_+|\text{boson}\rangle \propto |\text{fermion}\rangle \qquad & Q_+|\text{fermion}\rangle = 0 \\ Q_-|\text{fermion}\rangle \propto |\text{boson}\rangle \qquad & Q_-|\text{boson}\rangle = 0\,. \end{aligned}$$

A simple choice is

$$\begin{aligned} Q_+ &= b^- f^+ \\ Q_- &= b^+ f^- \end{aligned}$$

where $(f^+)^2 = (f^-)^2 = 0 \quad \Rightarrow \quad Q_+^2 = Q_-^2 = 0\,.$

SUSY Hamiltonian



We now want to construct a SUSY invariant Hamilton operator so that

$$[H_{\mathrm{SUSY}}, Q_{\pm}] = 0\,.$$

The simple choice

$$H_{\mathrm{SUSY}} = \{Q_+, Q_-\}$$

works.

[Check e.g. $[H_{\mathrm{SUSY}}, Q_+] = Q_+Q_-Q_+ + Q_-Q_+Q_+ - Q_+Q_+Q_- - Q_+Q_-Q_+ = 0\,.$]

Now recall

$$\begin{aligned} Q_+ &= \sqrt{\omega}\, b^- f^+ \\ Q_- &= \sqrt{\omega}\, b^+ f^- \end{aligned}$$

so that

$$\begin{aligned} H_{\mathrm{SUSY}} &= \omega\{b^- f^+, b^+ f^-\} \\ &= \omega(b^- f^+ b^+ f^- + b^+ f^- b^- f^+) \\ &= \omega((1 + b^+ b^-) f^+ f^- + b^+ b^-(1 - f^+ f^-)) \\ &= \omega(f^+ f^- + b^+ b^-) \\ &= H_B + H_F \end{aligned}$$

provided we set $\omega_B = \omega_F = \omega\,.$

Energy Spectrum

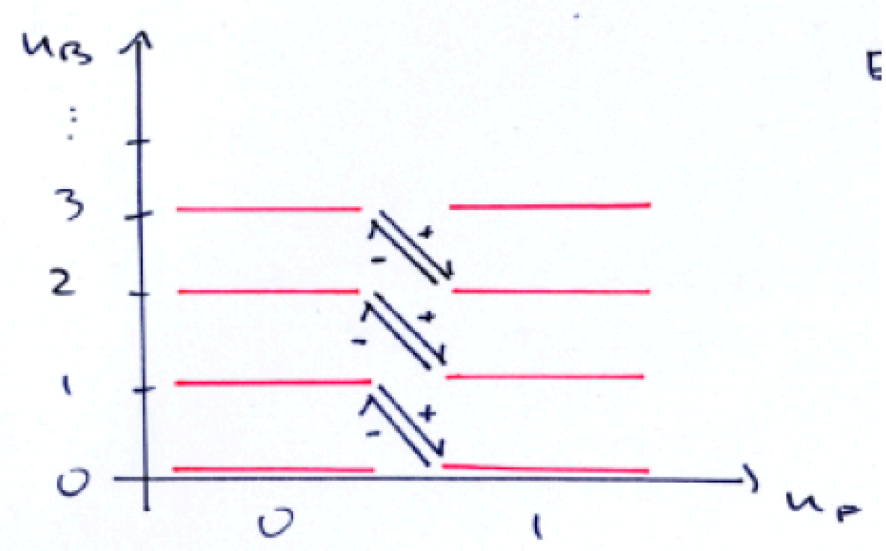
The energy spectrum of the SUSY oscillator has remarkable features

$$H_{\mathrm{SUSY}}|n_B n_F\rangle = \omega(N_B + N_F)|n_B n_F\rangle$$

$\rightarrow E = \omega(n_B + n_F)$

$\rightarrow$ the energy of the ground state is zero

The spectrum of the SUSY oscillator:



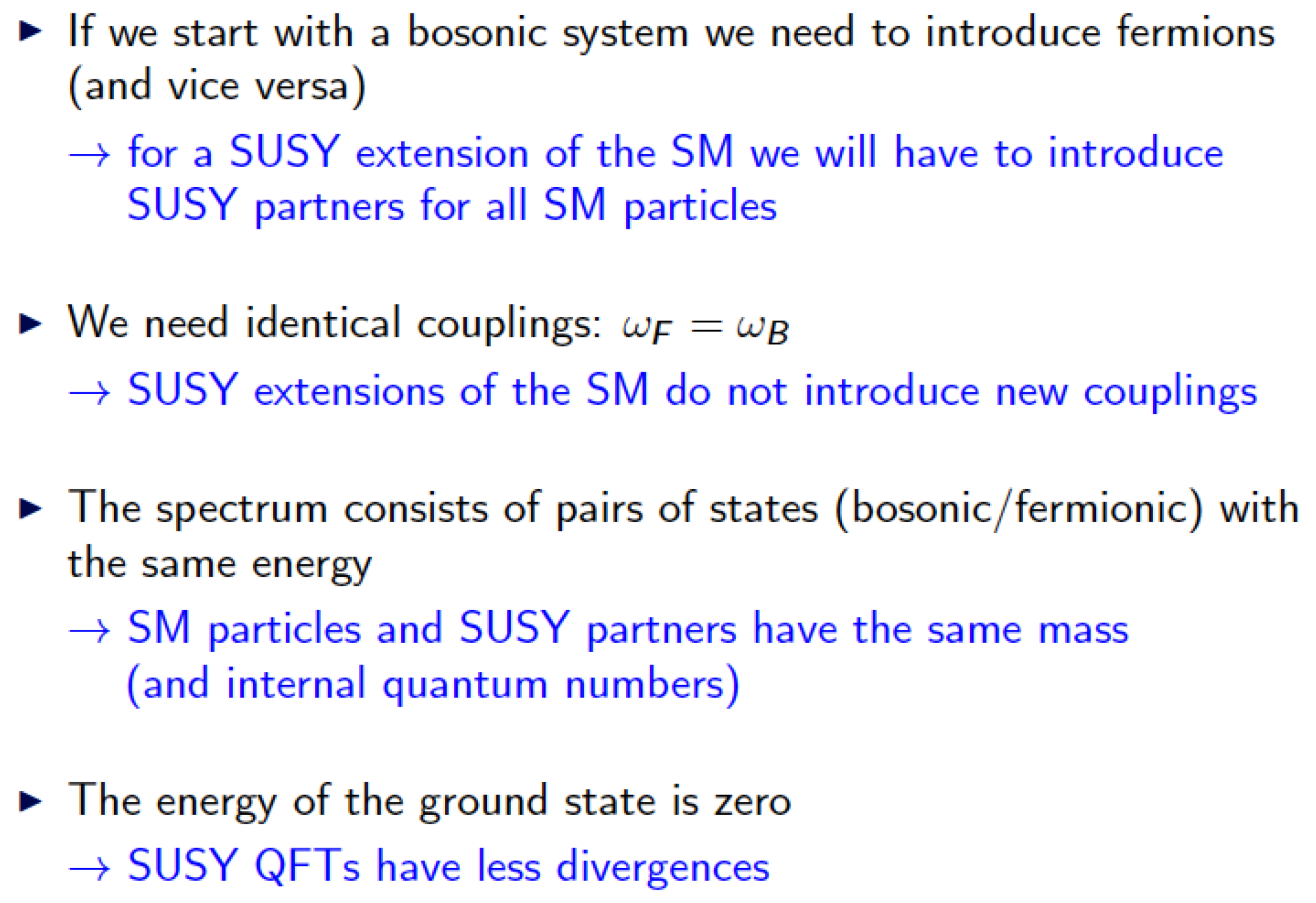
Energies

$$E_{20} = E_{11} = 2\omega$$

$$E_{10} = E_{01} = \omega$$

$$E_{00} = 0$$

Lessons from SUSY oscillator



- If we start with a bosonic system we need to introduce fermions (and vice versa)

  → for a SUSY extension of the SM we will have to introduce SUSY partners for all SM particles

- We need identical couplings: $\omega_F = \omega_B$

  → SUSY extensions of the SM do not introduce new couplings

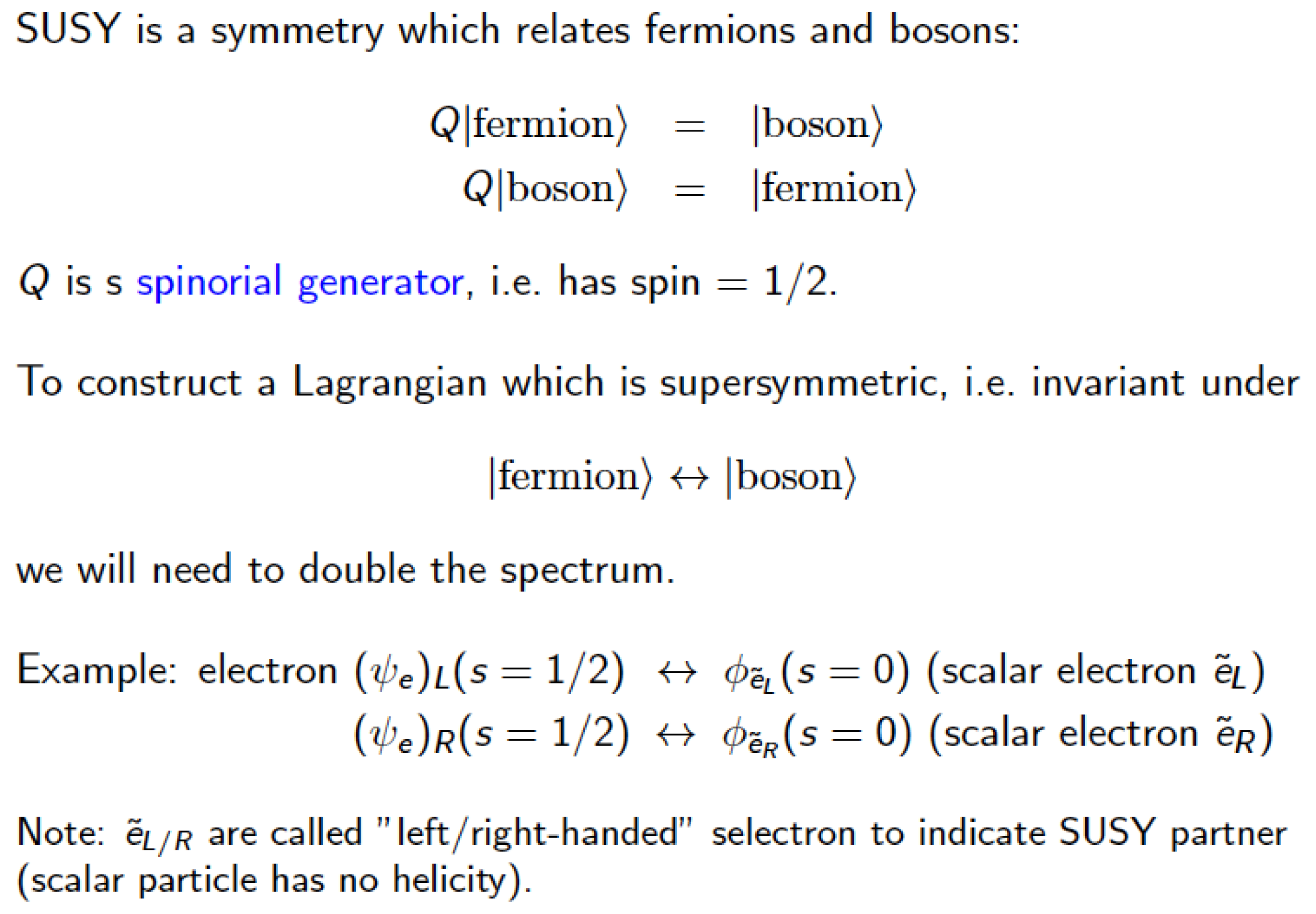
- The spectrum consists of pairs of states (bosonic/fermionic) with the same energy

  → SM particles and SUSY partners have the same mass (and internal quantum numbers)

- The energy of the ground state is zero

  → SUSY QFTs have less divergences

Super-Symmetry



SUSY is a symmetry which relates fermions and bosons:

$$\begin{aligned} Q|\mathrm{fermion}\rangle &= |\mathrm{boson}\rangle \\ Q|\mathrm{boson}\rangle &= |\mathrm{fermion}\rangle \end{aligned}$$

Q is s spinorial generator, i.e. has spin $= 1/2$.

To construct a Lagrangian which is supersymmetric, i.e. invariant under

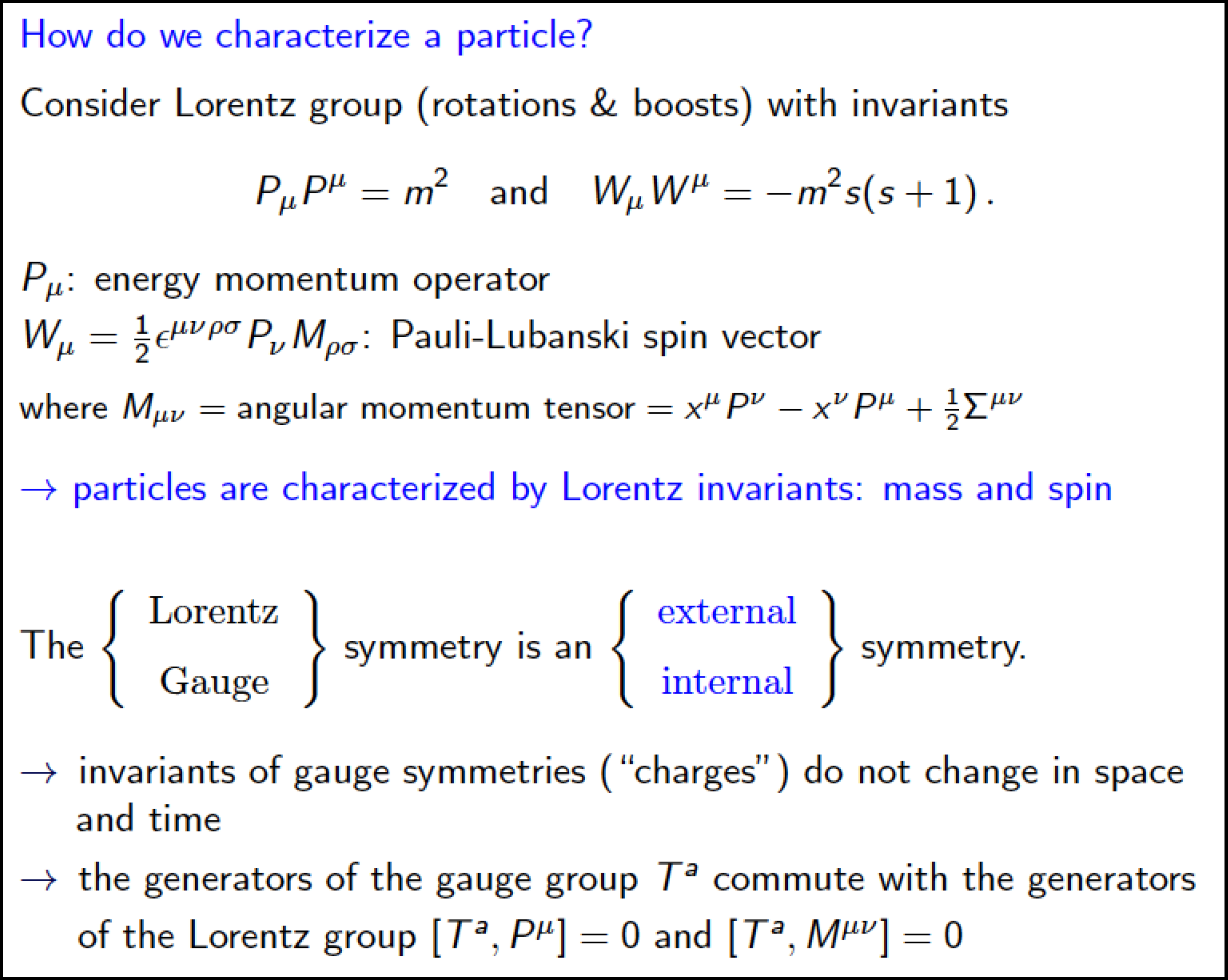
$$|\mathrm{fermion}\rangle \leftrightarrow |\mathrm{boson}\rangle$$

we will need to double the spectrum.

Example: electron $(\psi_e)_L(s = 1/2) \;\leftrightarrow\; \phi_{\tilde{e}_L}(s = 0)$ (scalar electron $\tilde{e}_L$)
$(\psi_e)_R(s = 1/2) \;\leftrightarrow\; \phi_{\tilde{e}_R}(s = 0)$ (scalar electron $\tilde{e}_R$)

Note: $\tilde{e}_{L/R}$ are called "left/right-handed" selectron to indicate SUSY partner (scalar particle has no helicity).

Super-Symmetry



How do we characterize a particle?

Consider Lorentz group (rotations & boosts) with invariants

$$P_\mu P^\mu = m^2 \quad \text{and} \quad W_\mu W^\mu = -m^2 s(s+1)\,.$$

P_μ: energy momentum operator

$W_\mu = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} P_\nu M_{\rho\sigma}$: Pauli-Lubanski spin vector

where $M_{\mu\nu}$ = angular momentum tensor $= x^\mu P^\nu - x^\nu P^\mu + \frac{1}{2}\Sigma^{\mu\nu}$

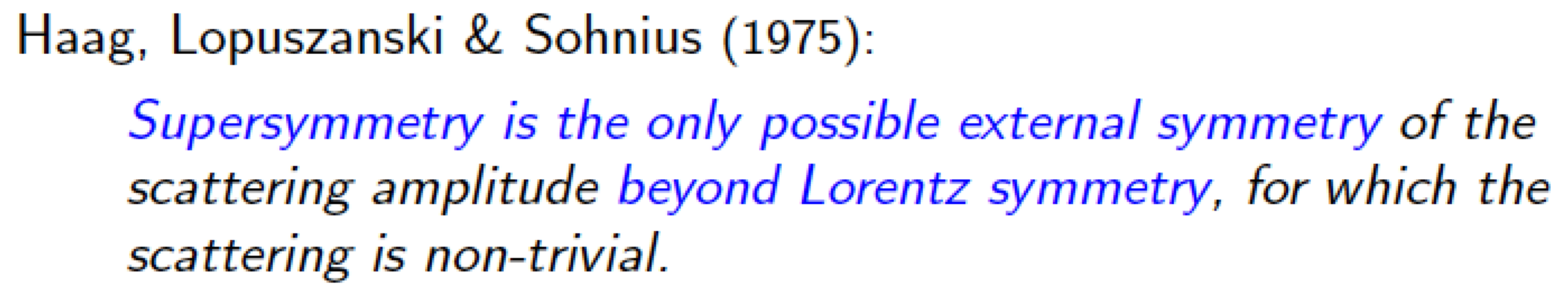
→ particles are characterized by Lorentz invariants: mass and spin

$$\text{The} \left\{ \begin{array}{c} \text{Lorentz} \\ \\ \text{Gauge} \end{array} \right\} \text{symmetry is an} \left\{ \begin{array}{c} \text{external} \\ \\ \text{internal} \end{array} \right\} \text{symmetry.}$$

→ invariants of gauge symmetries ("charges") do not change in space and time

→ the generators of the gauge group T^a commute with the generators of the Lorentz group $[T^a, P^\mu] = 0$ and $[T^a, M^{\mu\nu}] = 0$

“The” Theorem

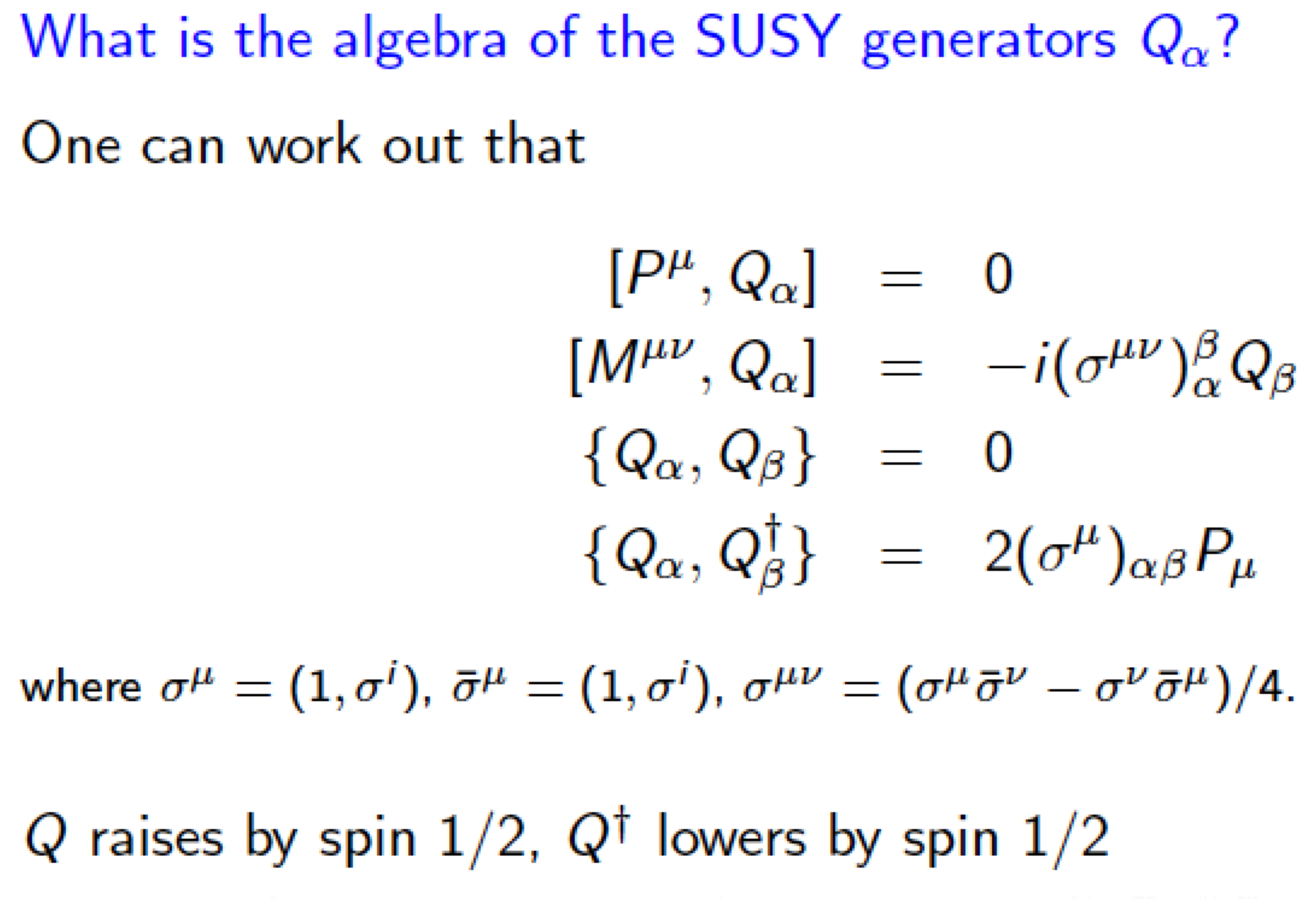


Haag, Lopuszanski & Sohnius (1975):

Supersymmetry is the only possible external symmetry of the scattering amplitude beyond Lorentz symmetry, for which the scattering is non-trivial.

→ *Pure mathematical argument… but invites to consider Nature could not ignore it..*

SUSY Algebra



What is the algebra of the SUSY generators Q_α?

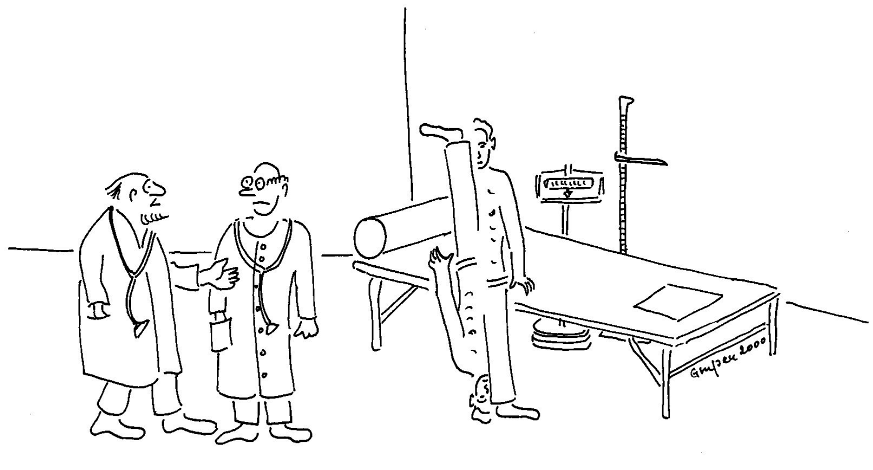
One can work out that

$$\begin{aligned} [P^\mu, Q_\alpha] &= 0 \\ [M^{\mu\nu}, Q_\alpha] &= -i(\sigma^{\mu\nu})_\alpha^\beta Q_\beta \\ \{Q_\alpha, Q_\beta\} &= 0 \\ \{Q_\alpha, Q_\beta^\dagger\} &= 2(\sigma^\mu)_{\alpha\beta} P_\mu \end{aligned}$$

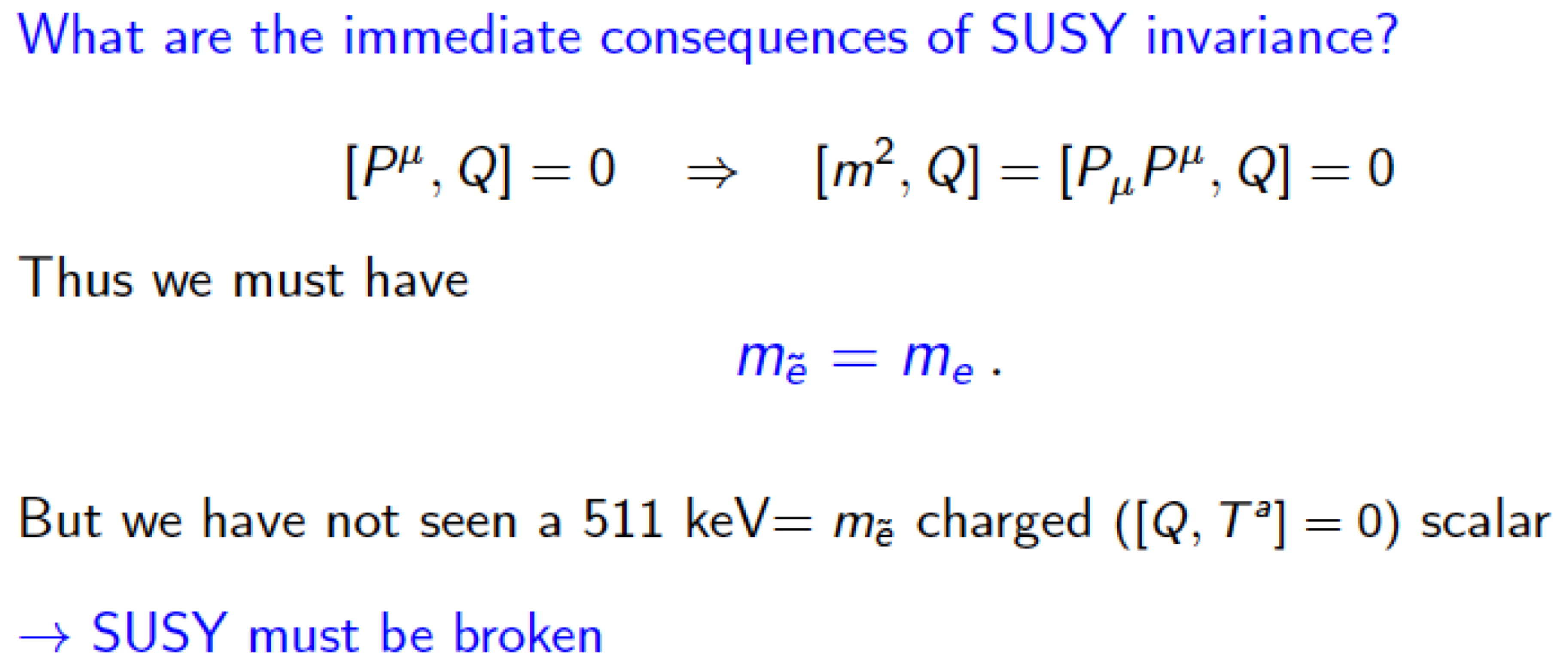
where $\sigma^\mu = (1, \sigma^i)$, $\bar{\sigma}^\mu = (1, \sigma^i)$, $\sigma^{\mu\nu} = (\sigma^\mu \bar{\sigma}^\nu - \sigma^\nu \bar{\sigma}^\mu)/4$.

Q raises by spin 1/2, $Q^\dagger$ lowers by spin 1/2

SUSY invariance….



“A severe case of symmetry breaking!”



What are the immediate consequences of SUSY invariance?

$$[P^\mu, Q] = 0 \quad \Rightarrow \quad [m^2, Q] = [P_\mu P^\mu, Q] = 0$$

Thus we must have

$$m_{\tilde{e}} = m_e \, .$$

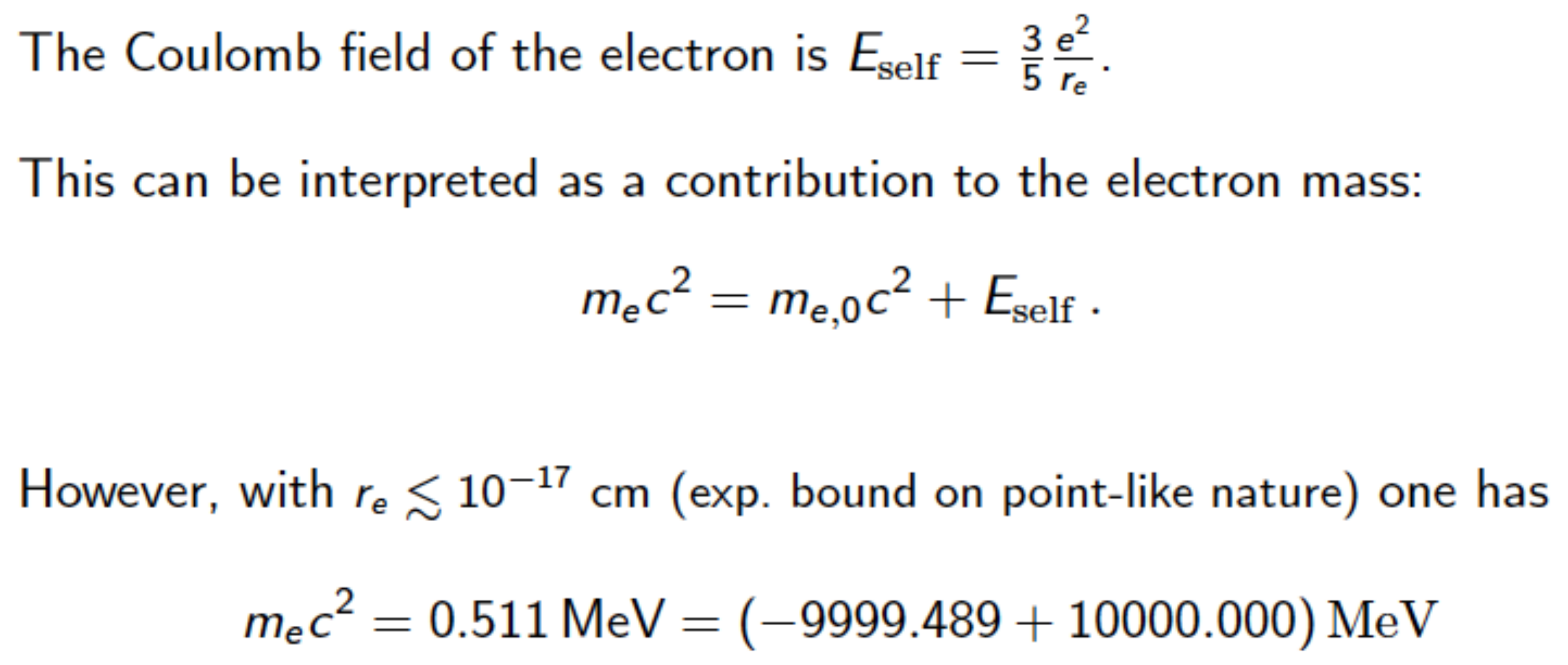
But we have not seen a 511 keV$= m_{\tilde{e}}$ charged ($[Q, T^a] = 0$) scalar

$\rightarrow$ SUSY must be broken

Hierarchy Problem

- *Electron case*
- *Higgs*

In electrodynamics



The Coulomb field of the electron is $E_{\mathrm{self}} = \frac{3}{5}\frac{e^2}{r_e}$.

This can be interpreted as a contribution to the electron mass:

$$m_e c^2 = m_{e,0} c^2 + E_{\mathrm{self}} \, .$$

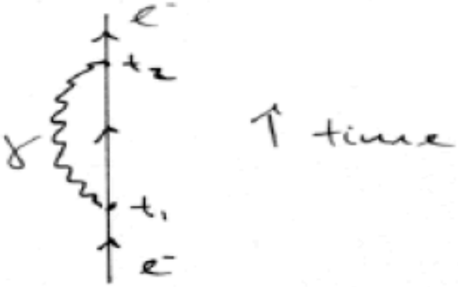
However, with $r_e \lesssim 10^{-17}$ cm (exp. bound on point-like nature) one has

$$m_e c^2 = 0.511\,\mathrm{MeV} = (-9999.489 + 10000.000)\,\mathrm{MeV}$$

→ In principle this points into a problem of fine-tuning !

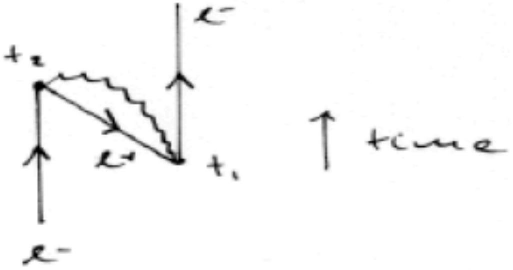
Fine tuning ??..not really.

Coulomb self-energy in time-ordered perturbation theory:



But also have positron e^+ with $Q(e^+) = -Q(e^-)$ and $m(e^+) = m(e^-)$

→ new diagram

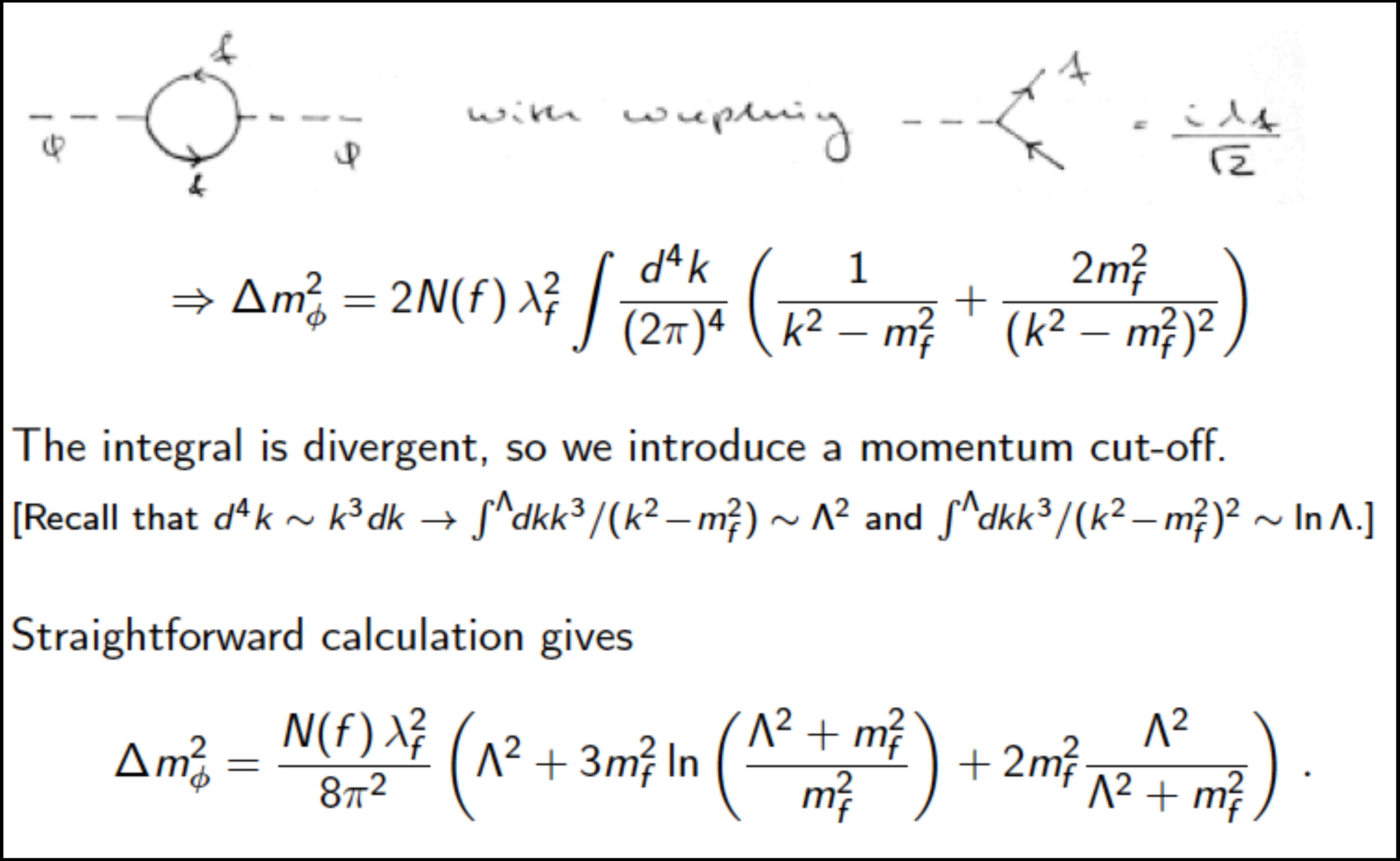


$$\rightarrow m_e c^2 = m_{e,0} c^2 \left(1 + \frac{3\alpha}{4\pi} \ln\left(\frac{\hbar}{m_e c r_e}\right)\right)$$

So even if $r_e = 1/M_{\mathrm{Planck}} = 1.6 \times 10^{-33}$ cm, the corrections to the electron mass are small

$$m_e c^2 \approx m_{e,0} c^2 (1 + 0.1) \ .$$

Scalar (Higgs) case



with coupling $= \frac{i\lambda_f}{\sqrt{2}}$

$$\Rightarrow \Delta m_\phi^2 = 2N(f)\,\lambda_f^2 \int \frac{d^4k}{(2\pi)^4}\left(\frac{1}{k^2-m_f^2}+\frac{2m_f^2}{(k^2-m_f^2)^2}\right)$$

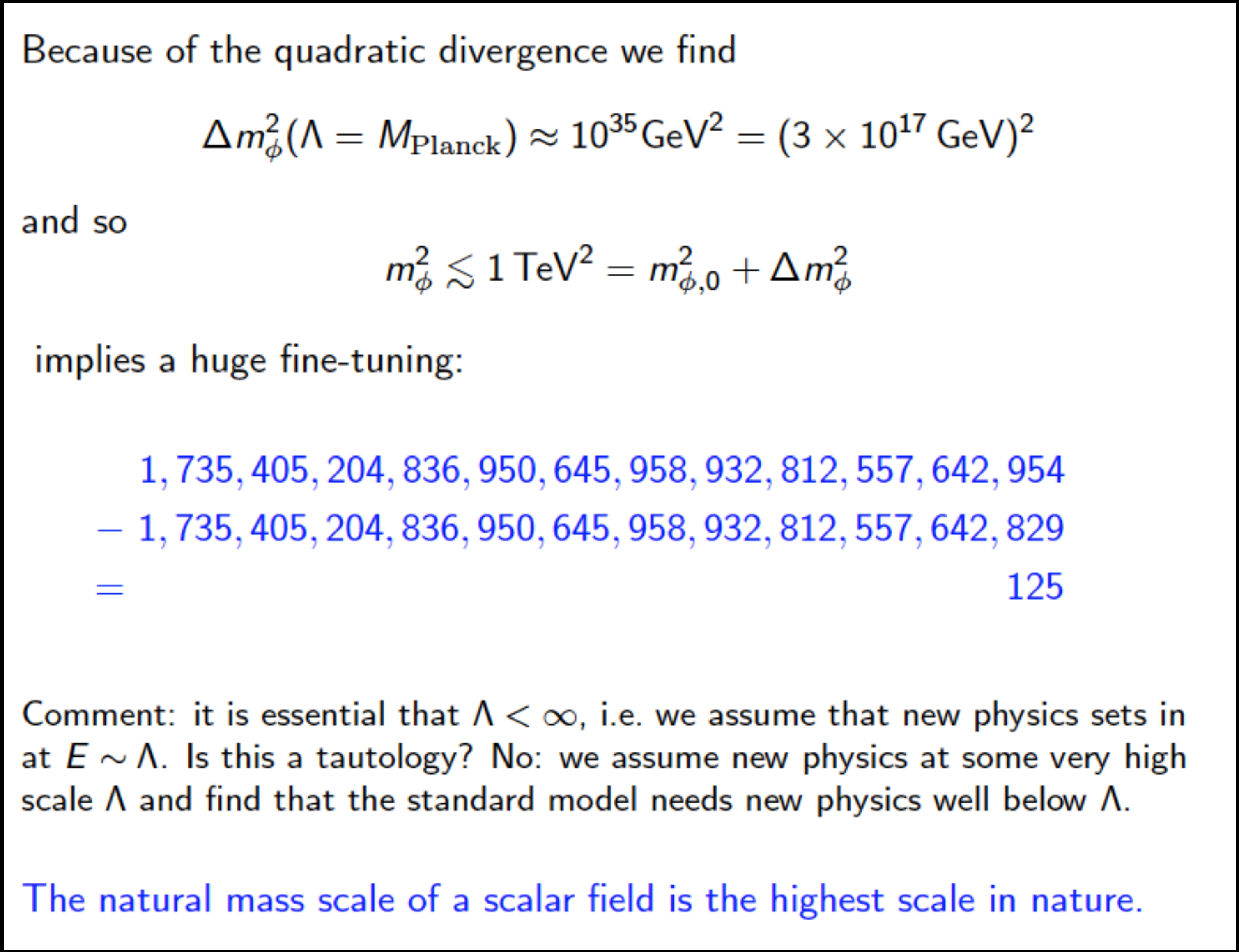
The integral is divergent, so we introduce a momentum cut-off.

[Recall that $d^4k \sim k^3dk \rightarrow \int^\Lambda dkk^3/(k^2-m_f^2) \sim \Lambda^2$ and $\int^\Lambda dkk^3/(k^2-m_f^2)^2 \sim \ln\Lambda$.]

Straightforward calculation gives

$$\Delta m_\phi^2 = \frac{N(f)\,\lambda_f^2}{8\pi^2}\left(\Lambda^2 + 3m_f^2\ln\left(\frac{\Lambda^2+m_f^2}{m_f^2}\right) + 2m_f^2\frac{\Lambda^2}{\Lambda^2+m_f^2}\right)\,.$$

Huge fine-tuning…



Because of the quadratic divergence we find

$$\Delta m_\phi^2(\Lambda = M_{\mathrm{Planck}}) \approx 10^{35}\,\mathrm{GeV}^2 = (3 \times 10^{17}\,\mathrm{GeV})^2$$

and so

$$m_\phi^2 \lesssim 1\,\mathrm{TeV}^2 = m_{\phi,0}^2 + \Delta m_\phi^2$$

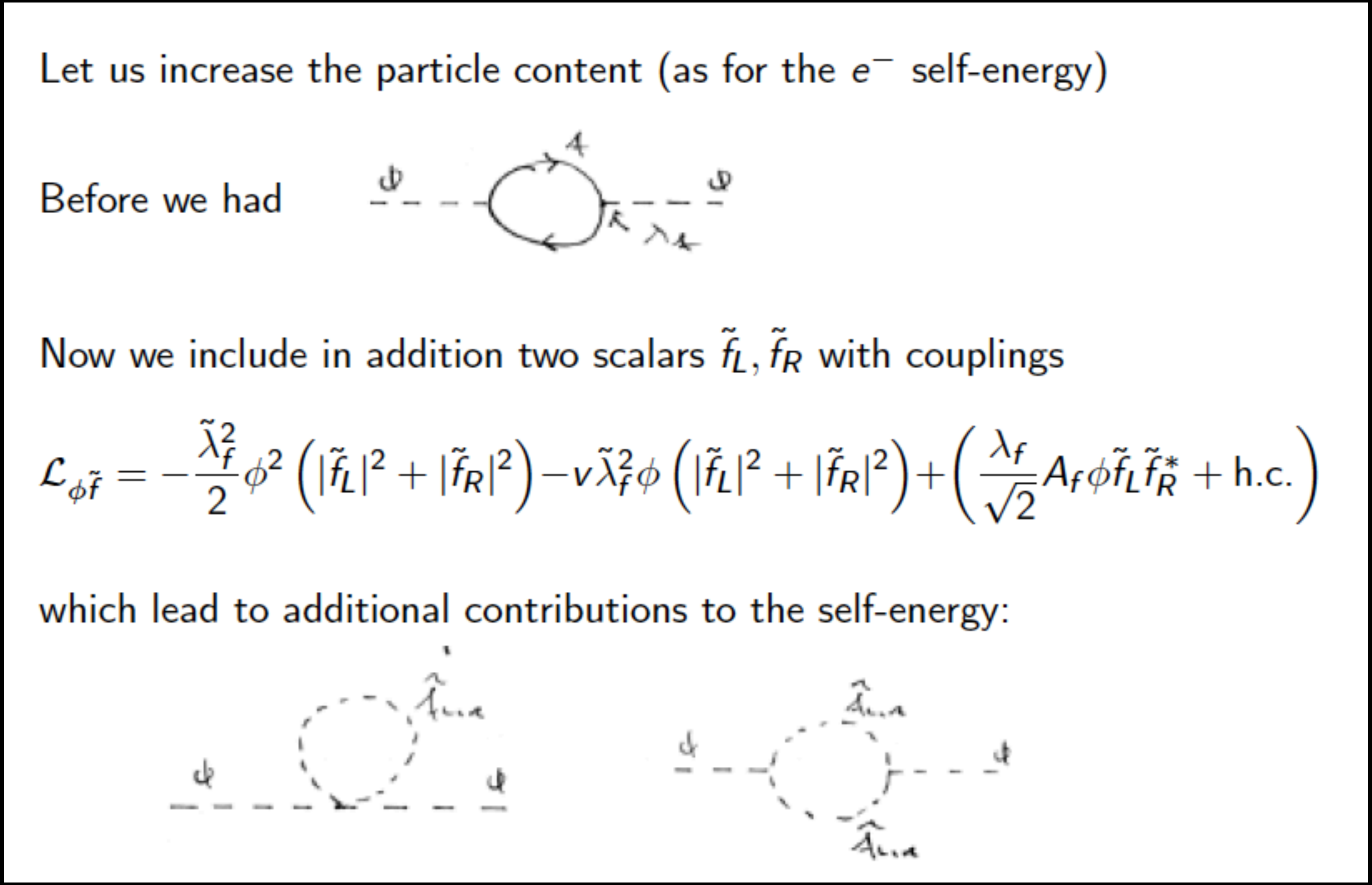
implies a huge fine-tuning:

$$\begin{array}{rr} & 1,735,405,204,836,950,645,958,932,812,557,642,954 \\ - & 1,735,405,204,836,950,645,958,932,812,557,642,829 \\ = & 125 \end{array}$$

Comment: it is essential that $\Lambda < \infty$, i.e. we assume that new physics sets in at $E \sim \Lambda$. Is this a tautology? No: we assume new physics at some very high scale Λ and find that the standard model needs new physics well below Λ.

The natural mass scale of a scalar field is the highest scale in nature.

SUSY coming to rescue you..



Let us increase the particle content (as for the e^- self-energy)

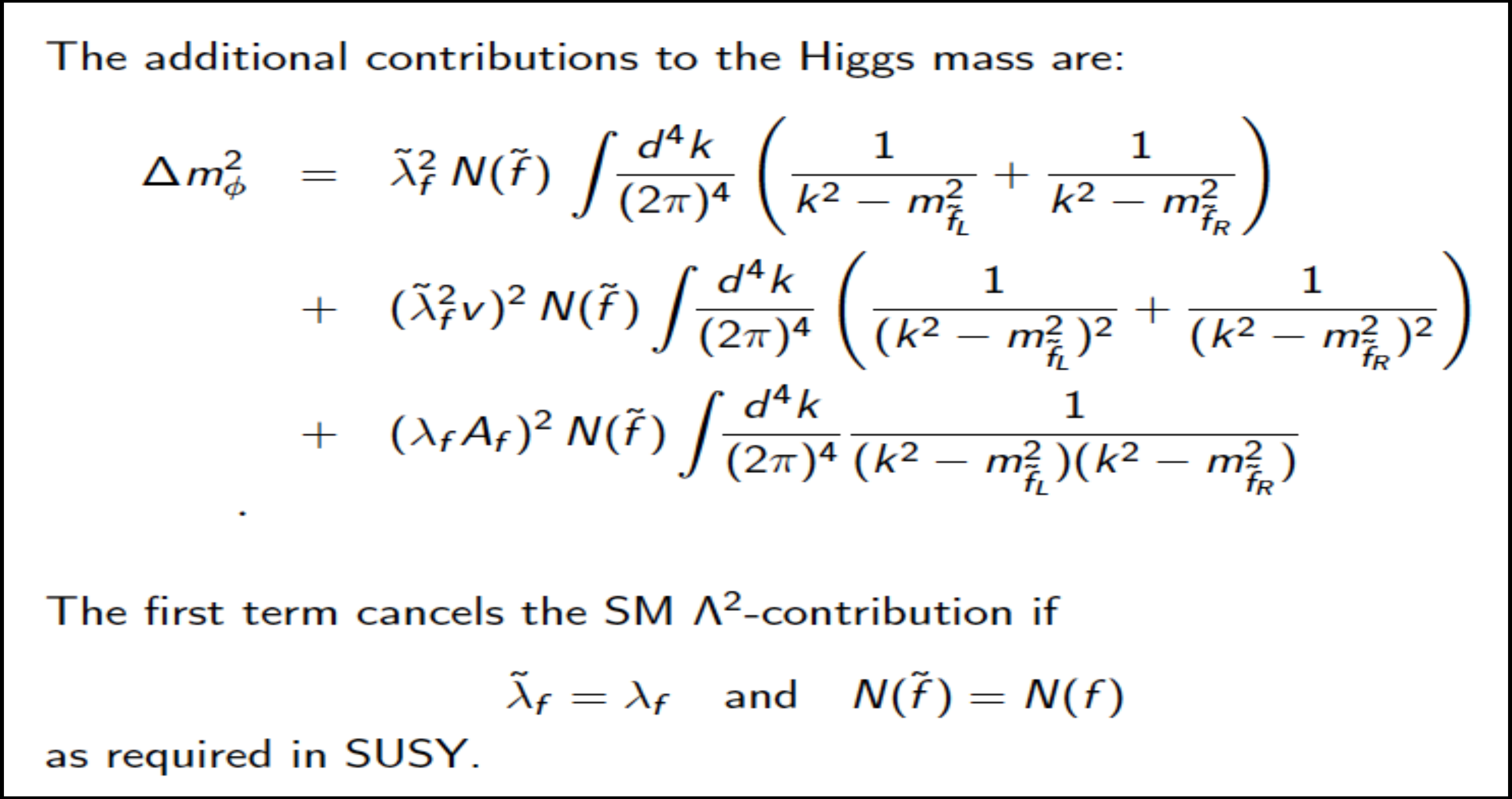
Before we had

Now we include in addition two scalars $\tilde f_L, \tilde f_R$ with couplings

$$\mathcal{L}_{\phi\tilde f} = -\frac{\tilde\lambda_f^2}{2}\phi^2\left(|\tilde f_L|^2+|\tilde f_R|^2\right) - v\tilde\lambda_f^2\phi\left(|\tilde f_L|^2+|\tilde f_R|^2\right)+\left(\frac{\lambda_f}{\sqrt{2}}A_f\phi\tilde f_L\tilde f_R^* + \text{h.c.}\right)$$

which lead to additional contributions to the self-energy:

SUSY coming to rescue you..



The additional contributions to the Higgs mass are:

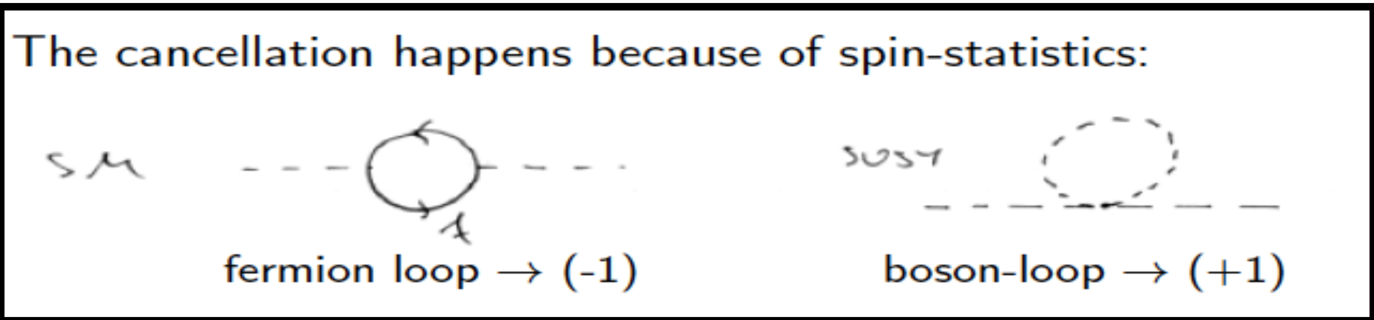
$$\begin{aligned}\Delta m_\phi^2 &= \tilde{\lambda}_f^2\, N(\tilde{f}) \int \frac{d^4k}{(2\pi)^4} \left(\frac{1}{k^2 - m_{\tilde{f}_L}^2} + \frac{1}{k^2 - m_{\tilde{f}_R}^2} \right) \\ &+ (\tilde{\lambda}_f^2 v)^2\, N(\tilde{f}) \int \frac{d^4k}{(2\pi)^4} \left(\frac{1}{(k^2 - m_{\tilde{f}_L}^2)^2} + \frac{1}{(k^2 - m_{\tilde{f}_R}^2)^2} \right) \\ &+ (\lambda_f A_f)^2\, N(\tilde{f}) \int \frac{d^4k}{(2\pi)^4} \frac{1}{(k^2 - m_{\tilde{f}_L}^2)(k^2 - m_{\tilde{f}_R}^2)}\end{aligned}$$

.

The first term cancels the SM Λ^2-contribution if

$$\tilde{\lambda}_f = \lambda_f \quad \text{and} \quad N(\tilde{f}) = N(f)$$

as required in SUSY.



The cancellation happens because of spin-statistics:

fermion loop → (-1)

boson-loop → (+1)

→ *Note the cancellation does not depend on the SUSY masses or A_f*

Soft SUSY breaking…

$$\mathcal{L}_{\phi\tilde{f}} = -\frac{\tilde{\lambda}_f^2}{2}\phi^2\left(|\tilde{f}_L|^2 + |\tilde{f}_R|^2\right) - v\tilde{\lambda}_f^2\phi\left(|\tilde{f}_L|^2 + |\tilde{f}_R|^2\right) + \left(\frac{\lambda_f}{\sqrt{2}}A_f\phi\tilde{f}_L\tilde{f}_R^* + \text{h.c.}\right)$$

This term breaks supersymmetry but will not create a quadratic divergences ~Λ^2

$$\begin{aligned}\Delta m_\phi^2 \quad = \quad & \frac{\lambda_f^2 N(f)}{16\pi^2}\Bigg(-2m_f^2\left(1 - \ln\frac{m_f^2}{\mu^2}\right) + 4m_f^2\ln\frac{m_f^2}{\mu^2} \\ & + 2m_{\tilde{f}}^2\left(1 - \ln\frac{m_{\tilde{f}}^2}{\mu^2}\right) - 4m_{\tilde{f}}^2\ln\frac{m_{\tilde{f}}^2}{\mu^2} - |A_f|^2\ln\frac{m_{\tilde{f}}^2}{\mu^2}\Bigg),\end{aligned}$$

where we have assumed $m_{\tilde{f}_L} = m_{\tilde{f}_R} = m_{\tilde{f}}$.

One has

$$\Delta m_\phi^2 = 0 \quad \text{for} \quad A_f = 0 \;\; \text{and} \;\; m_{\tilde{f}} = m_f \quad \text{(SUSY)}$$

But SUSY is broken, i.e. $m_{\tilde{f}}^2 = m_f^2 + \delta^2$. Thus

$$\Delta m_\phi^2 = \frac{\lambda_f^2 N(f)}{8\pi^2}\,\delta^2\left(2 + \ln\frac{m_f^2}{\mu^2}\right) + \mathcal{O}(\delta^4)$$

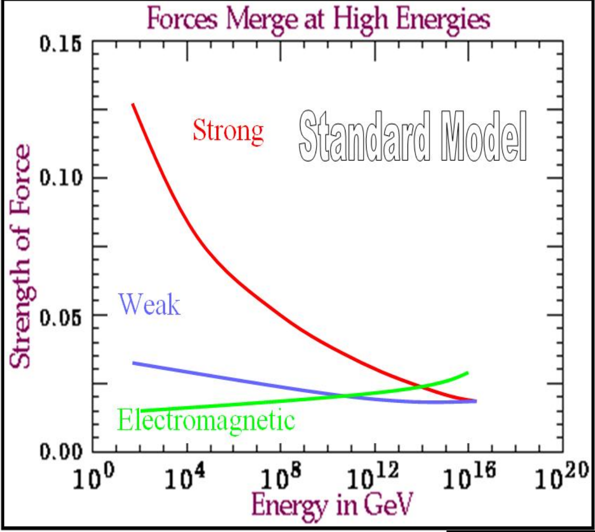
To have Δm_ϕ^2 small, we thus need $m_{\tilde{f}}^2 = m_f^2 + \delta^2 = \mathcal{O}(1\,\mathrm{TeV}^2)$

→ *SUSY spectra at the TeV scale ??*

SUSY Breaking

- *Unification of Forces ?*
- *MSSM*
- *SUSY Spectrum & Mixing*
- *R parity*

Unification of Forces…



In QFT the gauge couplings “run”:

$$\frac{d\alpha_i(\mu)|}{d\ln\mu^2} = \beta_i(\alpha_i(\mu))$$

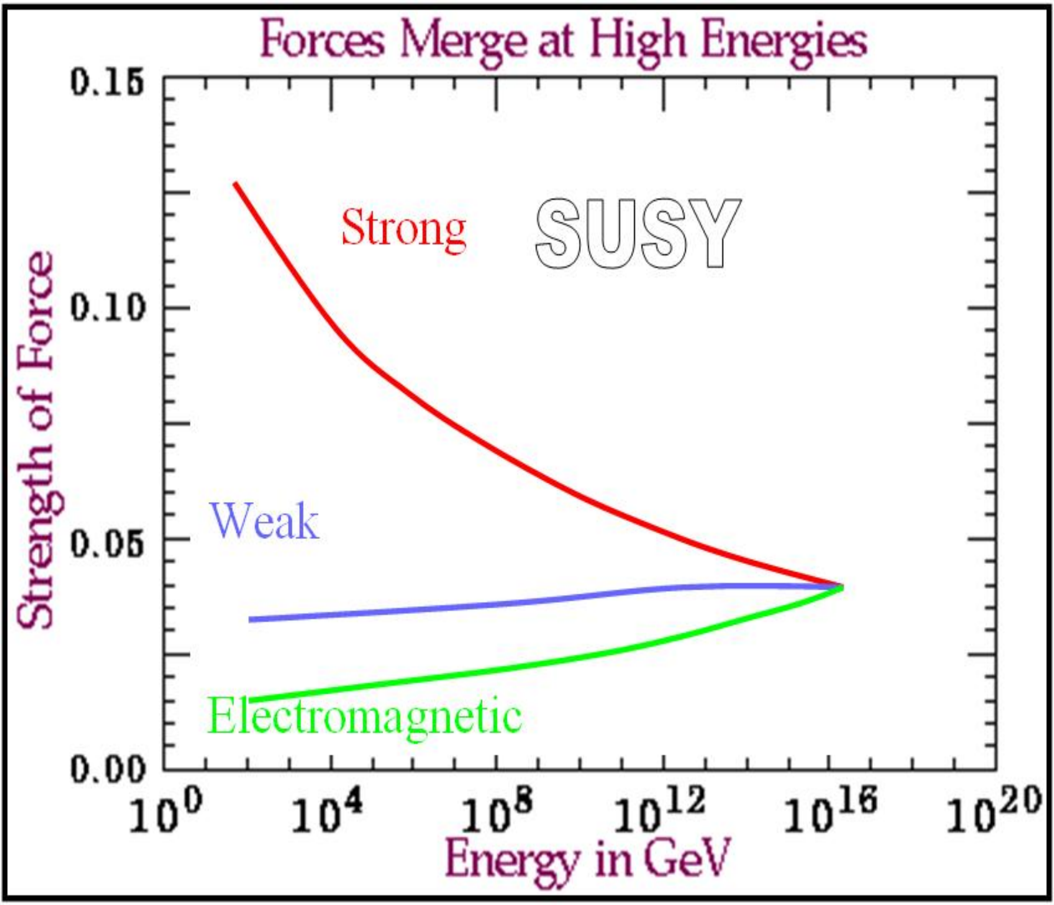
The beta-functions β_i depend on the gauge group and on the matter multiplets to which the gauge bosons couple. Only particles with mass $< \mu$ contribute to the β_i and to the evolution of the coupling at any given mass scale μ.

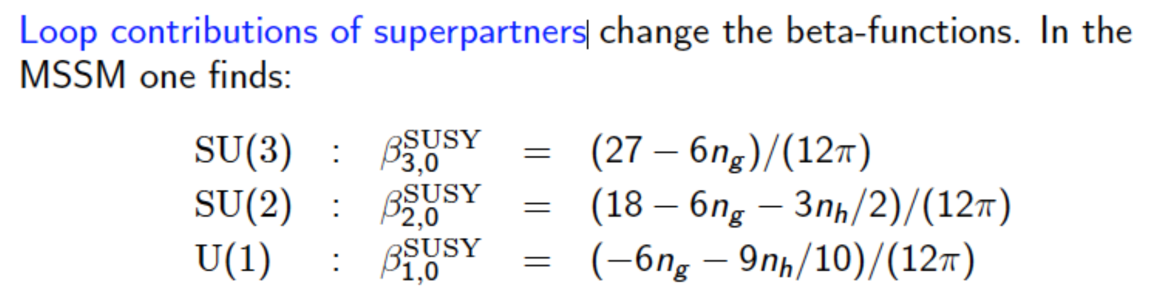
The Standard Model couplings evolve with μ according to

$$\begin{array}{lcccl} \mathrm{SU}(3) & : & \beta_{3,0} & = & (33 - 4n_g)/(12\pi) \\ \mathrm{SU}(2) & : & \beta_{2,0} & = & (22 - 4n_g - n_h/2)/(12\pi) \\ \mathrm{U}(1) & : & \beta_{1,0} & = & (-4n_g - 3n_h/10)/(12\pi) \end{array}$$

where $n_g = 3$ is the number of quark and lepton generations and $n_h = 1$ is the number of Higgs doublet fields in the Standard Model.

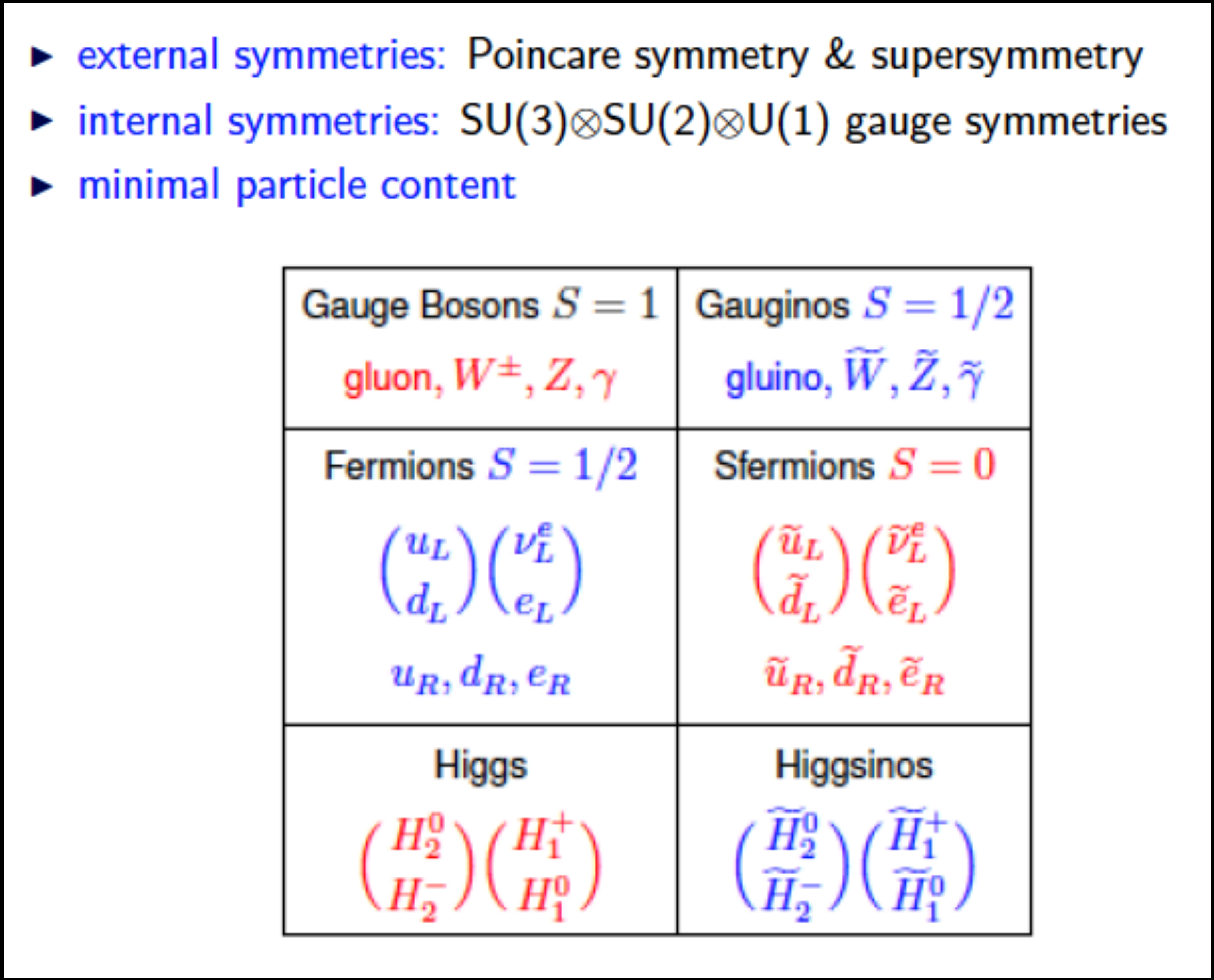
Unification of Forces (?!)




Loop contributions of superpartners change the beta-functions. In the MSSM one finds:

$$\begin{array}{lcccl} \mathrm{SU}(3) & : & \beta_{3,0}^{\mathrm{SUSY}} & = & (27-6n_g)/(12\pi) \\ \mathrm{SU}(2) & : & \beta_{2,0}^{\mathrm{SUSY}} & = & (18-6n_g-3n_h/2)/(12\pi) \\ \mathrm{U}(1) & : & \beta_{1,0}^{\mathrm{SUSY}} & = & (-6n_g-9n_h/10)/(12\pi) \end{array}$$

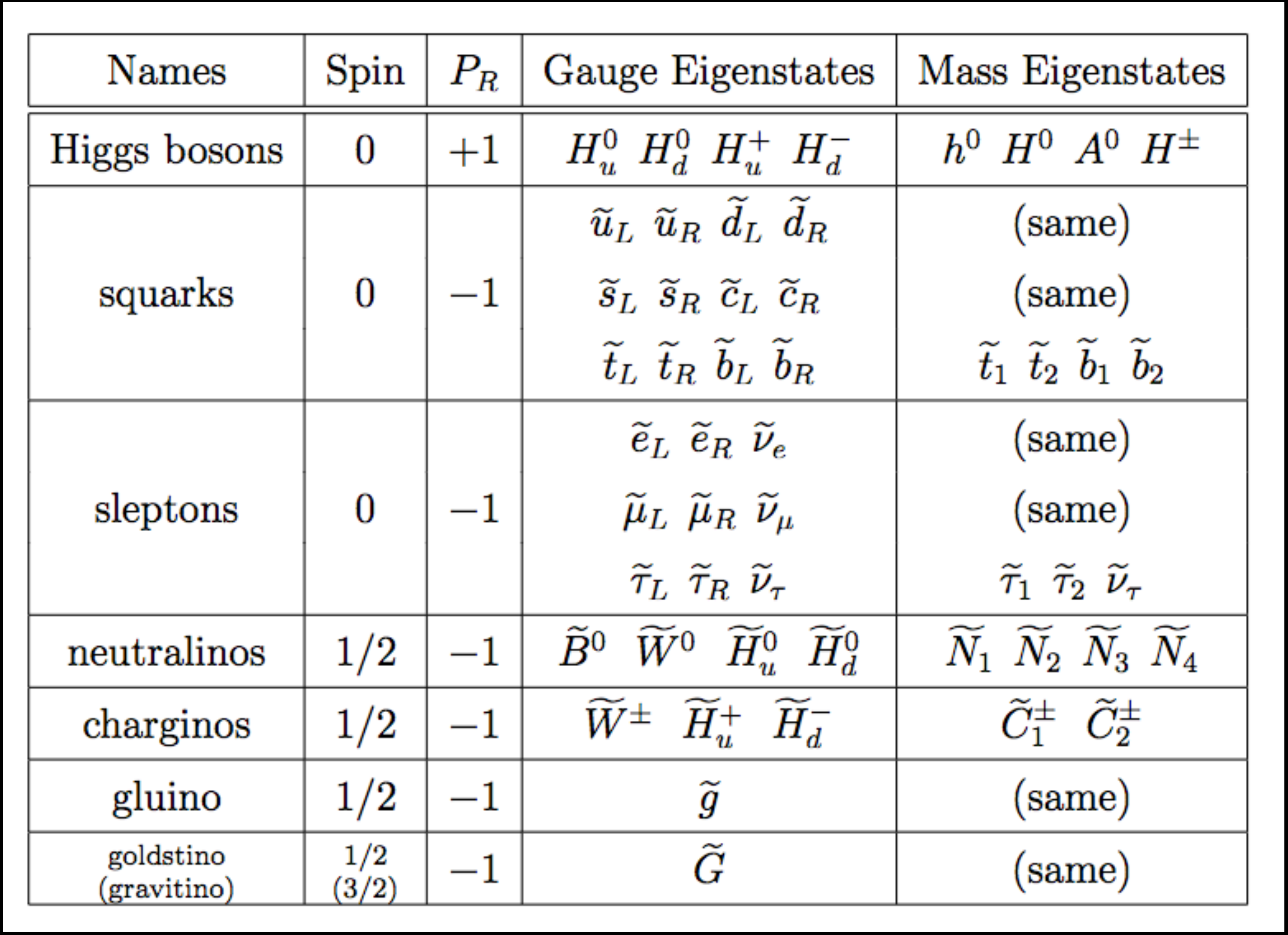
MSSM



- external symmetries: Poincare symmetry & supersymmetry
- internal symmetries: SU(3)⊗SU(2)⊗U(1) gauge symmetries
- minimal particle content

Gauge Bosons $S = 1$ gluon, $W^{\pm}, Z, \gamma$	Gauginos $S = 1/2$ gluino, $\widetilde{W}, \tilde{Z}, \tilde{\gamma}$
Fermions $S = 1/2$ $\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} \nu_L^e \\ e_L \end{pmatrix}$ u_R, d_R, e_R	Sfermions $S = 0$ $\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix} \begin{pmatrix} \tilde{\nu}_L^e \\ \tilde{e}_L \end{pmatrix}$ $\tilde{u}_R, \tilde{d}_R, \tilde{e}_R$
Higgs $\begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix} \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}$	Higgsinos $\begin{pmatrix} \widetilde{H}_2^0 \\ \widetilde{H}_2^- \end{pmatrix} \begin{pmatrix} \widetilde{H}_1^+ \\ \widetilde{H}_1^0 \end{pmatrix}$

MSSM with mixing



Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \ \widetilde{W}^0\ \ \widetilde{H}_u^0\ \ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \ \widetilde{H}_u^+\ \ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

Mixing neglected

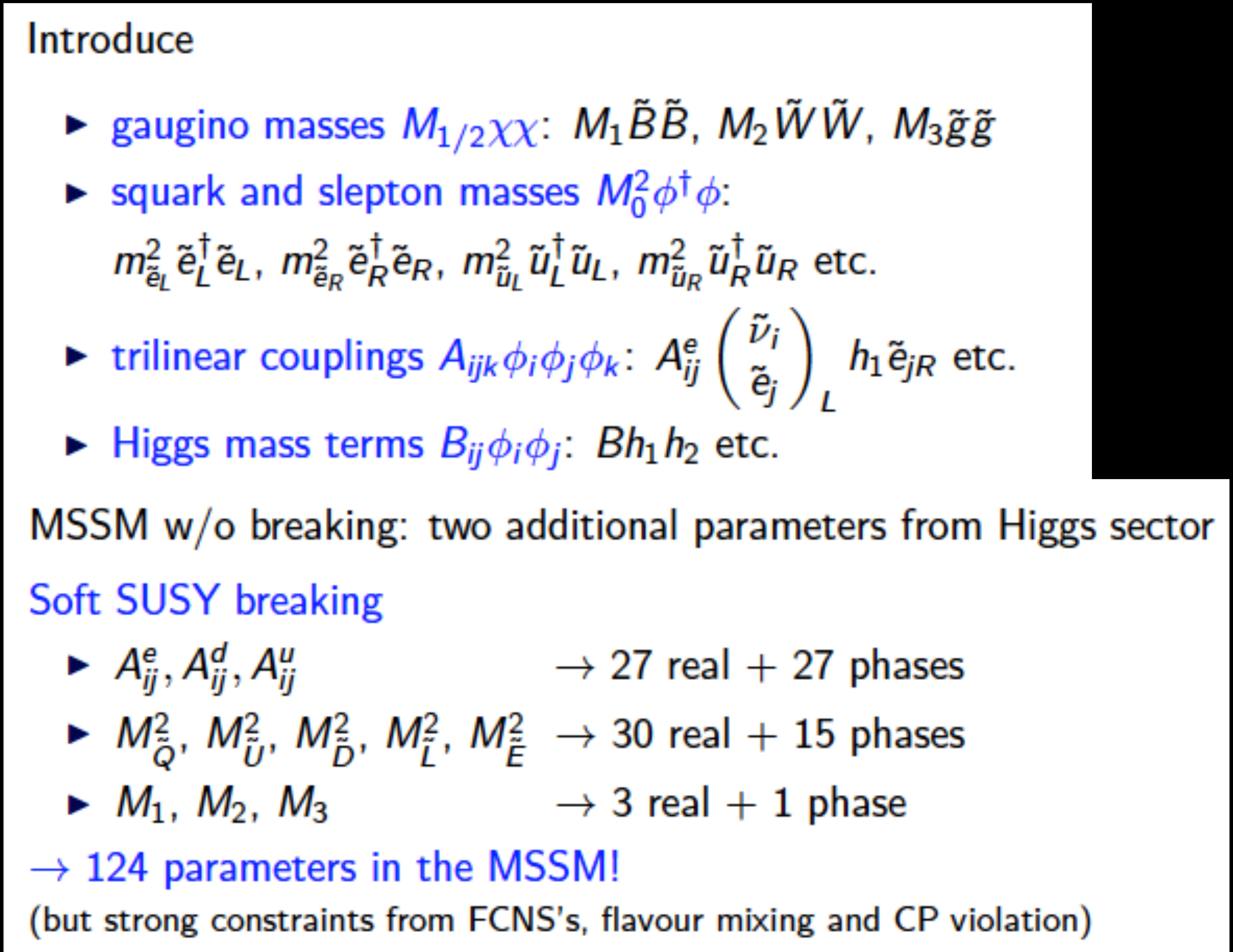
Mixing neglected

Neutralinos X^0_1 …. X^0_4

Charginos $X_{1,2}$

Soft SUSY Breaking

(soft to keep solving the hierarchy problem)



Introduce

- gaugino masses $M_{1/2}\chi\chi$: $M_1\tilde{B}\tilde{B}$, $M_2\tilde{W}\tilde{W}$, $M_3\tilde{g}\tilde{g}$
- squark and slepton masses $M_0^2\phi^\dagger\phi$:
  $m^2_{\tilde{e}_L}\tilde{e}^\dagger_L\tilde{e}_L$, $m^2_{\tilde{e}_R}\tilde{e}^\dagger_R\tilde{e}_R$, $m^2_{\tilde{u}_L}\tilde{u}^\dagger_L\tilde{u}_L$, $m^2_{\tilde{u}_R}\tilde{u}^\dagger_R\tilde{u}_R$ etc.
- trilinear couplings $A_{ijk}\phi_i\phi_j\phi_k$: $A^e_{ij}\begin{pmatrix}\tilde{\nu}_i\\ \tilde{e}_j\end{pmatrix}_L h_1\tilde{e}_{jR}$ etc.
- Higgs mass terms $B_{ij}\phi_i\phi_j$: Bh_1h_2 etc.

MSSM w/o breaking: two additional parameters from Higgs sector

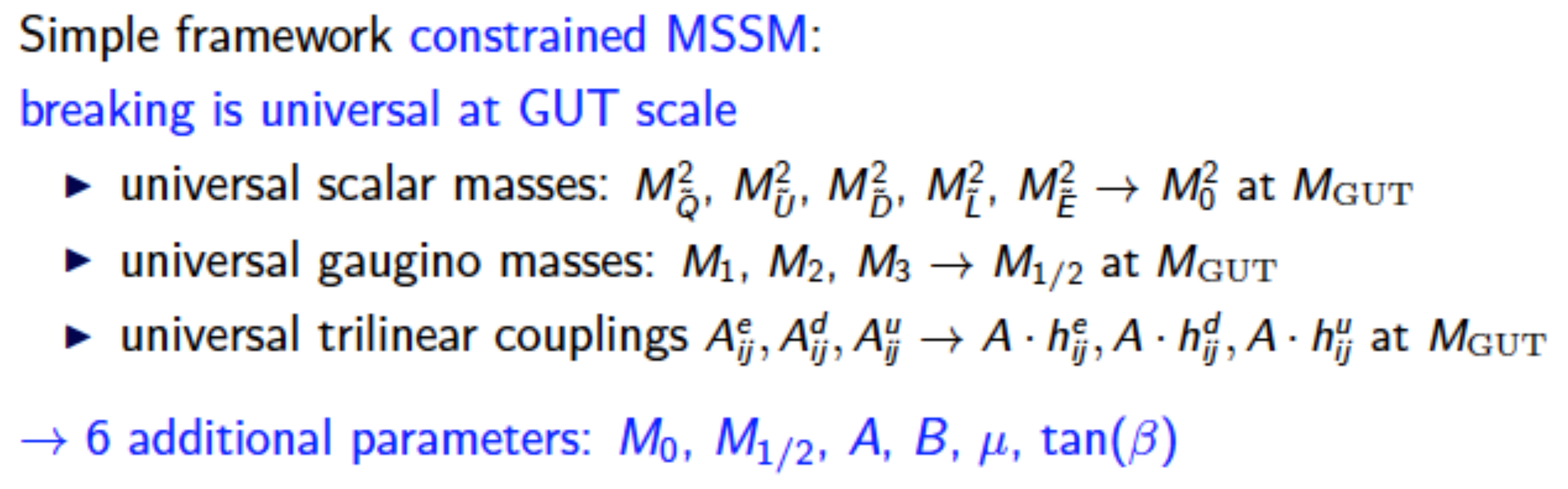
Soft SUSY breaking

- $A^e_{ij}, A^d_{ij}, A^u_{ij}$ $\rightarrow$ 27 real + 27 phases
- $M^2_{\tilde{Q}}$, $M^2_{\tilde{U}}$, $M^2_{\tilde{D}}$, $M^2_{\tilde{L}}$, $M^2_{\tilde{E}}$ $\rightarrow$ 30 real + 15 phases
- M_1, M_2, M_3 $\rightarrow$ 3 real + 1 phase

$\rightarrow$ 124 parameters in the MSSM!

(but strong constraints from FCNS's, flavour mixing and CP violation)

Constrained MSSM



Simple framework constrained MSSM:

breaking is universal at GUT scale

- universal scalar masses: $M^2_{\tilde{Q}}$, $M^2_{\tilde{U}}$, $M^2_{\tilde{D}}$, $M^2_{\tilde{L}}$, $M^2_{\tilde{E}} \rightarrow M^2_0$ at M_{GUT}
- universal gaugino masses: M_1, M_2, $M_3 \rightarrow M_{1/2}$ at M_{GUT}
- universal trilinear couplings $A^e_{ij}, A^d_{ij}, A^u_{ij} \rightarrow A \cdot h^e_{ij}, A \cdot h^d_{ij}, A \cdot h^u_{ij}$ at M_{GUT}

→ 6 additional parameters: M_0, $M_{1/2}$, A, B, μ, $\tan(\beta)$

The masses of W and Z bosons will fix B and $|\mu|$ → reduced to 5 parameters

M_0: common scalar mass at GUT

$M_{1/2}$: the common gaugino mass at GUT

$\tan\beta$: Ratio of Higgs VEVs

A_0: common $(\text{scalar})^3$ coupling

Sign(μ): Higgs mass term

$$\frac{dM_i(\mu)}{d\ln\mu^2} = \gamma_i M_i$$

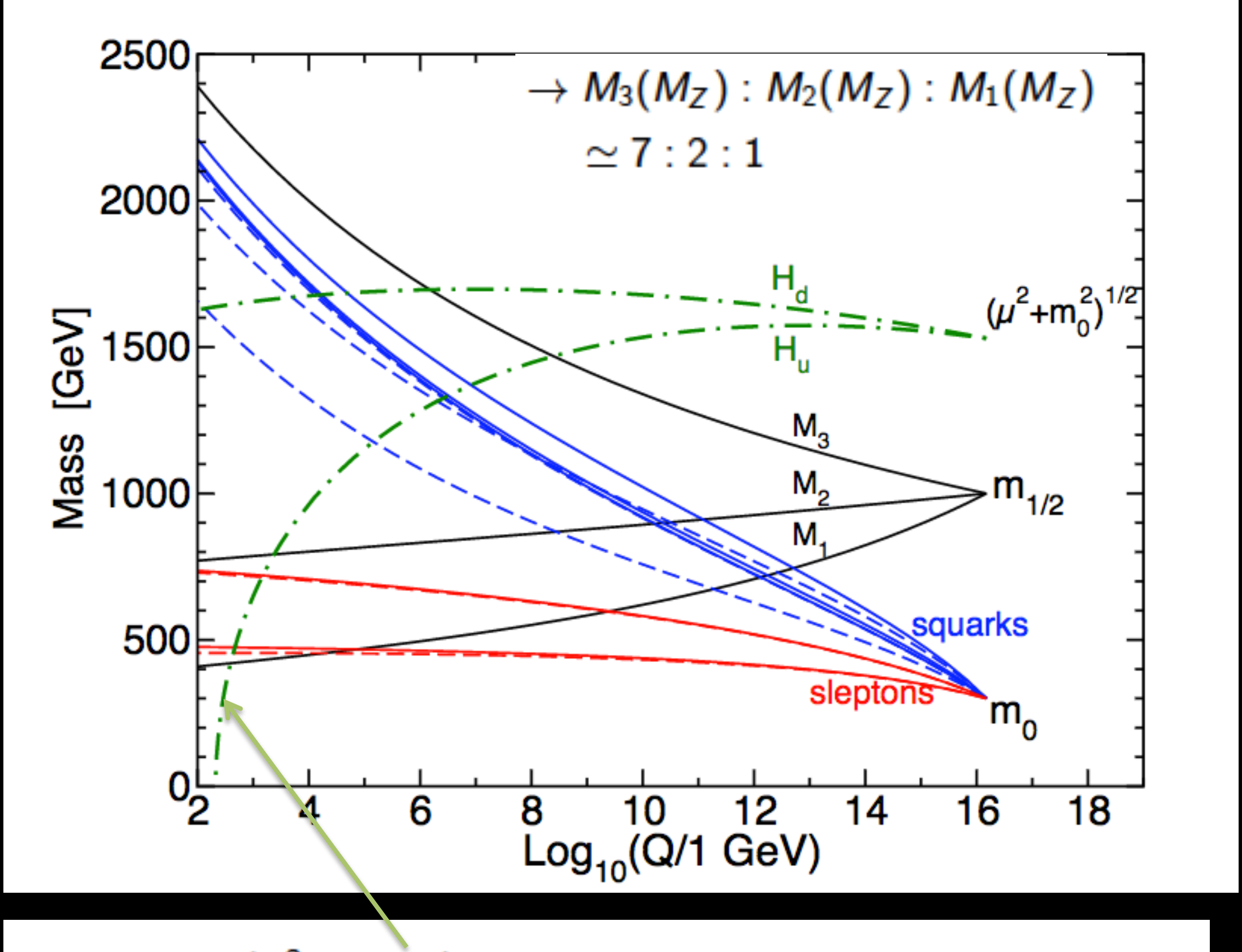
SUSY spectra

$$\frac{M_1(\mu)}{\alpha_1(\mu)} = \frac{M_2(\mu)}{\alpha_2(\mu)} = \frac{M_3(\mu)}{\alpha_3(\mu)}$$

Heavy squarks/gluinos

Not so heavy Charginos

Light neutralinos



RGE drives $(\mu^2 + m_{H_u^2})$ negative → EWK symmetry breaking

Mixing

After SU(2)$_L$ × U(1)$_Y$ breaking, mixing will occur between any two or more fields which have the same color, charge and spin

- $(\tilde{W}^{\pm}, \tilde{H}^{\pm}) \rightarrow \tilde{\chi}^{\pm}_{i=1,2}$: charginos
- $(\tilde{B}, \tilde{W}^3, \tilde{H}^0_{1,2}) \rightarrow \tilde{\chi}^0_{i=1,2,3,4}$: neutralinos
- $(\tilde{t}_L, \tilde{t}_R) \rightarrow \tilde{t}_{1,2}$ etc.: sfermion mass eigenstates

Note:

- mixing involves various SUSY parameters

  $\rightarrow$ cross sections and branching ratios become model dependent
- sfermion mixing $\propto m_f$

  $\rightarrow$ large only for 3rd generation $(\tilde{t}_{1,2}, \tilde{\tau}_{1,2})$

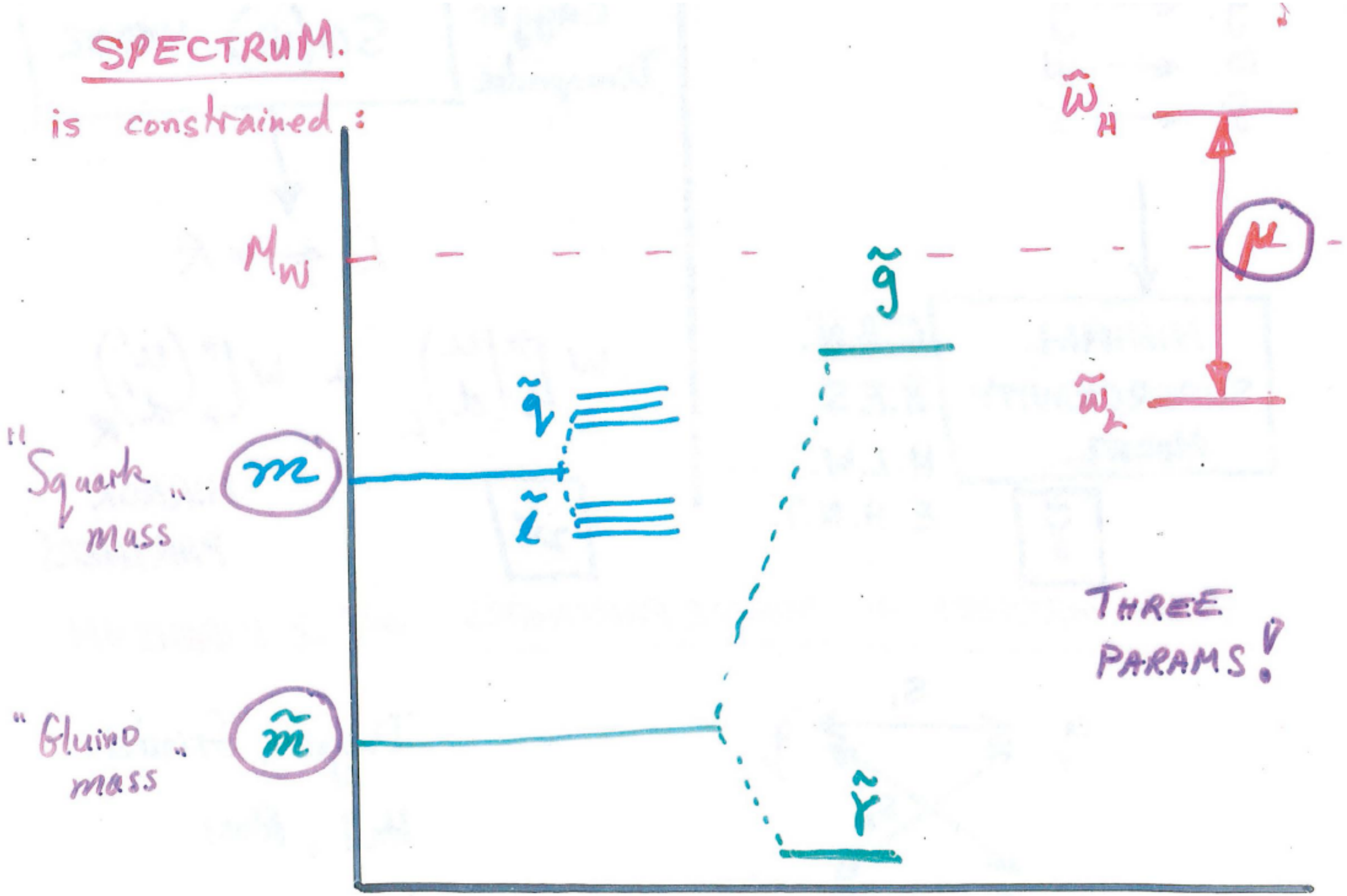
$$\mathcal{L}_{\text{stop masses}} = -\begin{pmatrix} \tilde{t}^*_L & \tilde{t}^*_R \end{pmatrix} \mathbf{m}^2_{\tilde{\mathbf{t}}} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$$\mathbf{m}^2_{\tilde{\mathbf{t}}} = \begin{pmatrix} m^2_{Q_3} + m^2_t + \Delta_{\tilde{u}_L} & v(a^*_t \sin\beta - \mu y_t \cos\beta) \\ v(a_t \sin\beta - \mu^* y_t \cos\beta) & m^2_{\bar{u}_3} + m^2_t + \Delta_{\tilde{u}_R} \end{pmatrix}$$

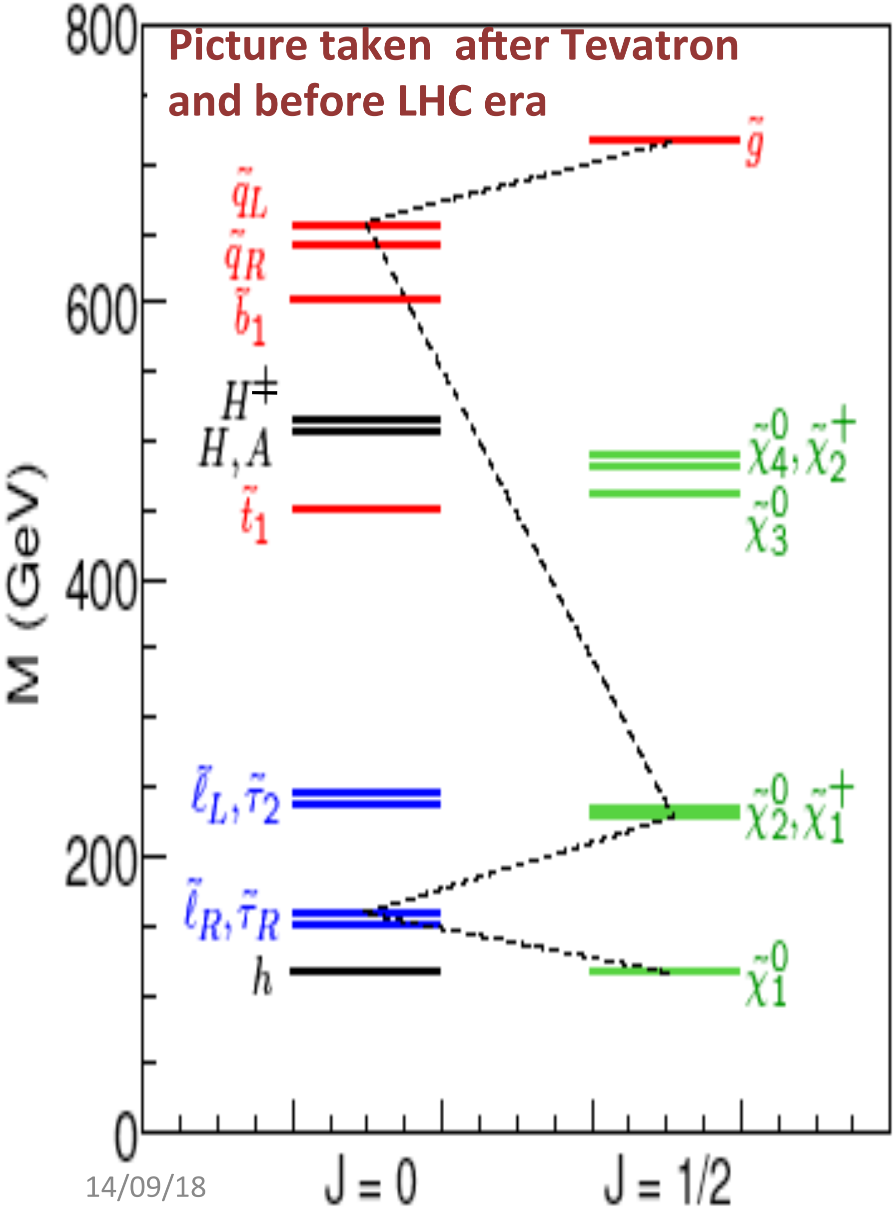
Lightest squark

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} c_{\tilde{t}} & -s^*_{\tilde{t}} \\ s_{\tilde{t}} & c^*_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

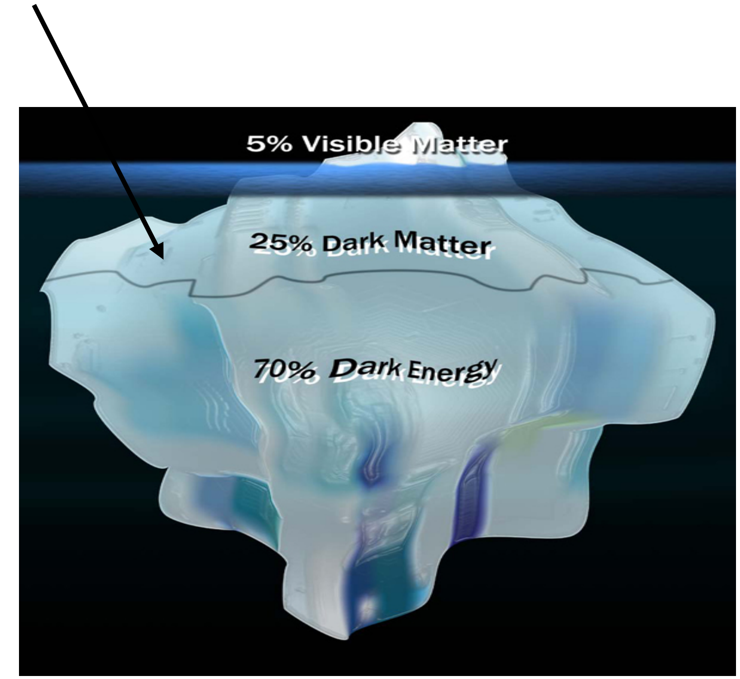
"Natural SUSY in 1984"



SUSY Spectra



1. **Squarks and Gluinos are heavy**
2. **mixing of third generation leads to light stop and sbottom**
3. χ_1^0 **Lightest supersymmetric particle**



4. **One higgs is very light (< 135 GeV)**

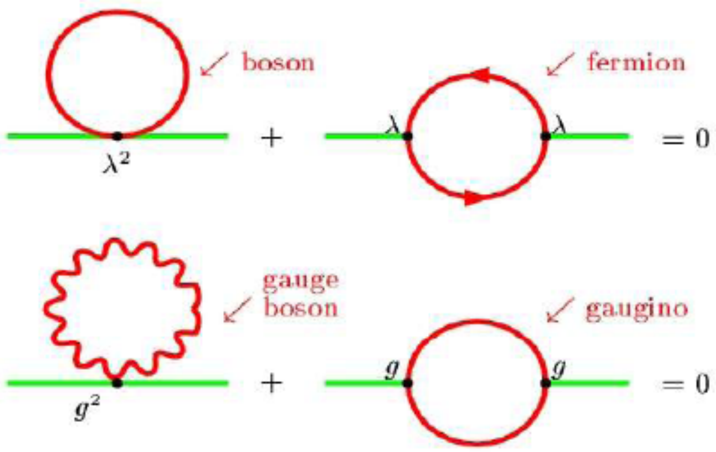
In summary....

- Fermion/Boson symmetry

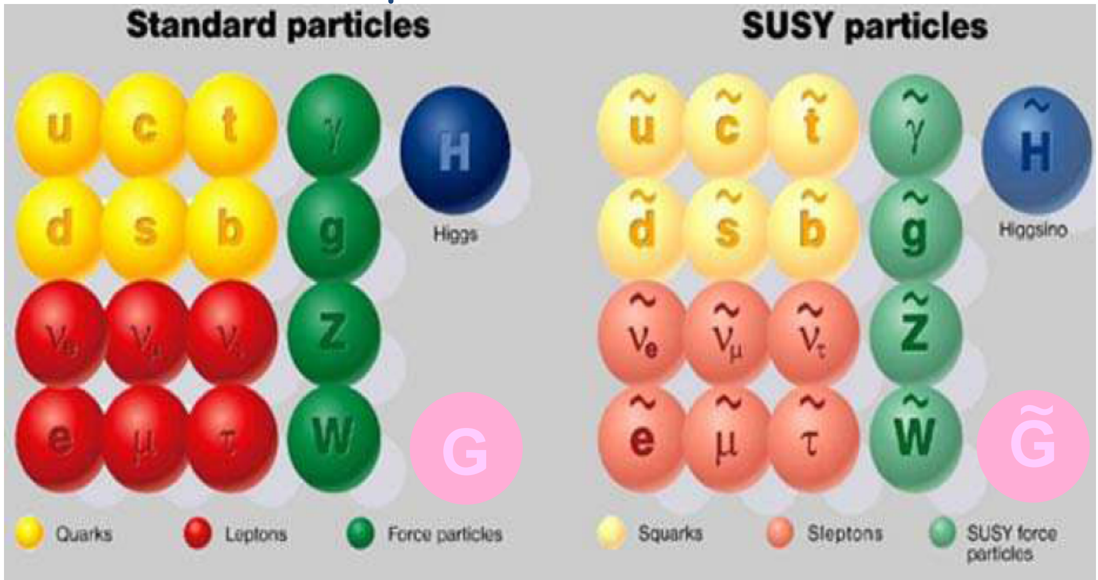
$$Q\,|\,\text{fermion}> = |\,\text{boson}>$$

$$Q\,|\,\text{boson}> = |\,\text{fermion}>$$

- Exact cancellation between fermion & boson loops for Higgs



Double Spectra of Particles



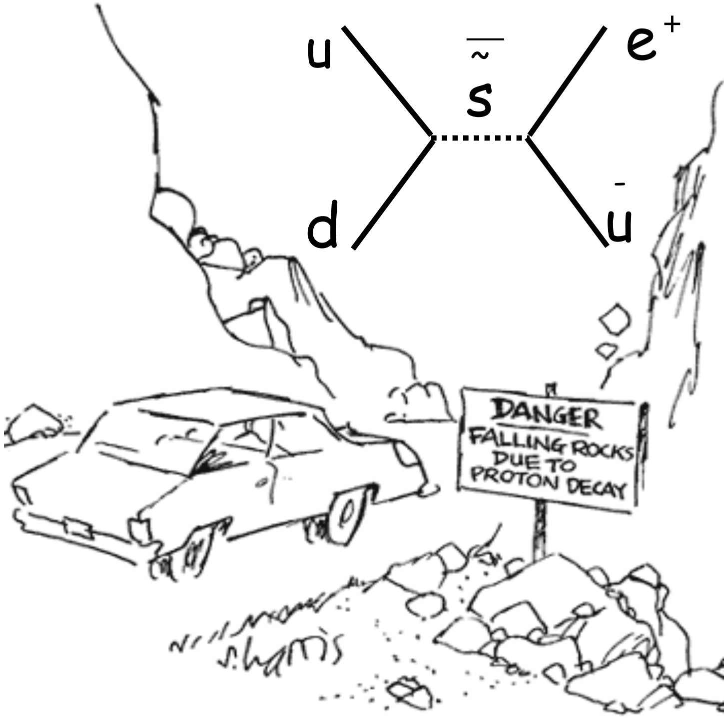
..will mix to form mass eigenstates..

Higgs sector with 2 doublets

$$H_U, H_D \longrightarrow h, H, A, H^{\pm}$$

..SUSY must be broken..... model-dependent phenomenology

R-Parity



Most general superpotential includes terms Violating Baryon number and Lepton number

$$W_{\Delta L=1} = \frac{1}{2}\lambda^{ijk}L_iL_j\bar{e}_k + \lambda'^{ijk}L_iQ_j\bar{d}_k + \mu'^{i}L_iH_u$$

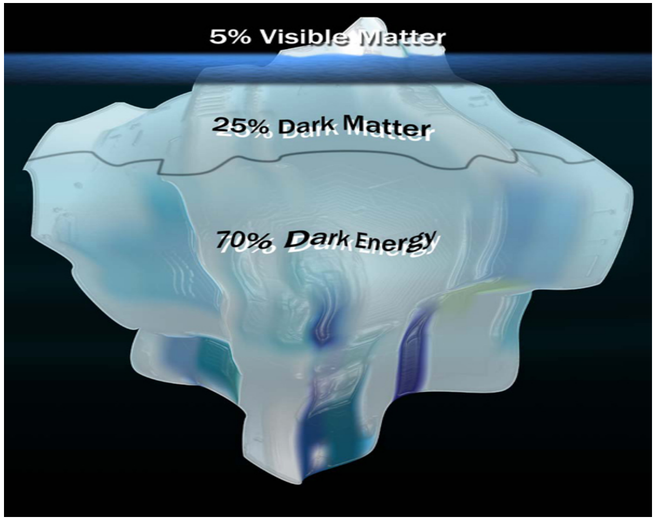
$$W_{\Delta B=1} = \frac{1}{2}\lambda''^{ijk}\bar{u}_i\bar{d}_j\bar{d}_k$$

New symmetry is postulated…

$$R_P = (-1)^{3(B-L)+2s} \Rightarrow$$

R_P = +1 (particles)

R_P = -1 (sparticles)



- SUSY particles produced in pairs
- The lightest SUSY particle stable (χ_1^0)
- Valid candidate for Dark Matter

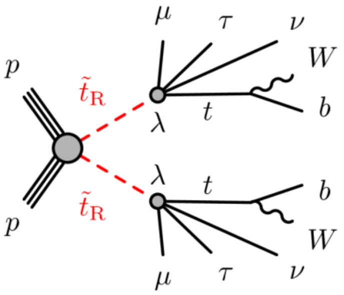
- Distinctive Signature at Colliders

Large Missing E_T

RPV scenarios

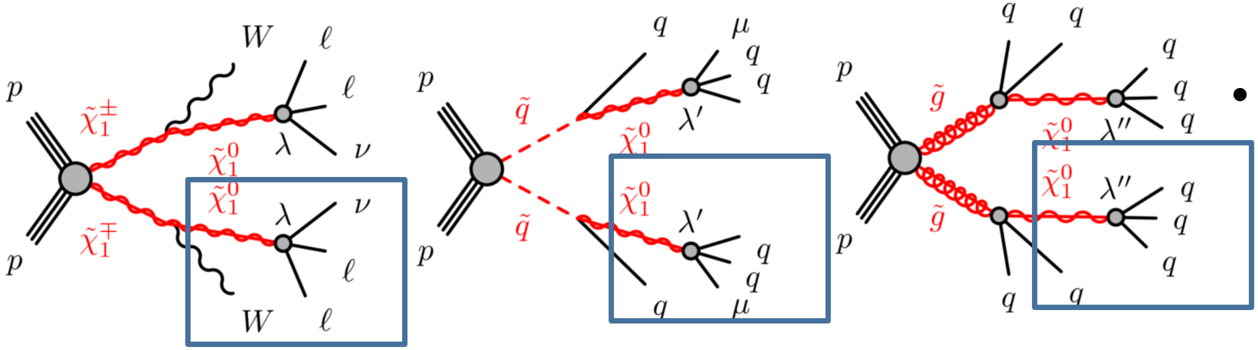
Many final states to explore:

- Couplings via **λ, λ',λ''. Ie:**



$$\left(\begin{array}{c}\text{pair production: } \tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}\\ \text{resonant } \tilde{\ell} \text{ production}\end{array}\right) \otimes \left(\begin{array}{c}\underline{\text{LSP}}\\ \tilde{\chi}_1^0\\ \tilde{\chi}_1^\pm\\ \tilde{\nu}_L\\ \tilde{\ell}^\pm_{L,R}\\ \tilde{\tau}_1^\pm\\ \tilde{q}_{L,R}\\ \tilde{t}_1\\ \tilde{g}\end{array}\right) \otimes \left(\begin{array}{c}\underline{\text{Operator}}\\ L_1L_2\bar{E}_1\\ \vdots\\ L_2L_3\bar{E}_3\\ L_eQ_1\bar{D}_1\\ \vdots\\ L_\mu Q_1\bar{D}_1\\ \vdots\\ L_\tau Q_3\bar{D}_3\\ \bar{U}_i\bar{D}_j\bar{D}_k\end{array}\right)$$

- LSP no longer stable



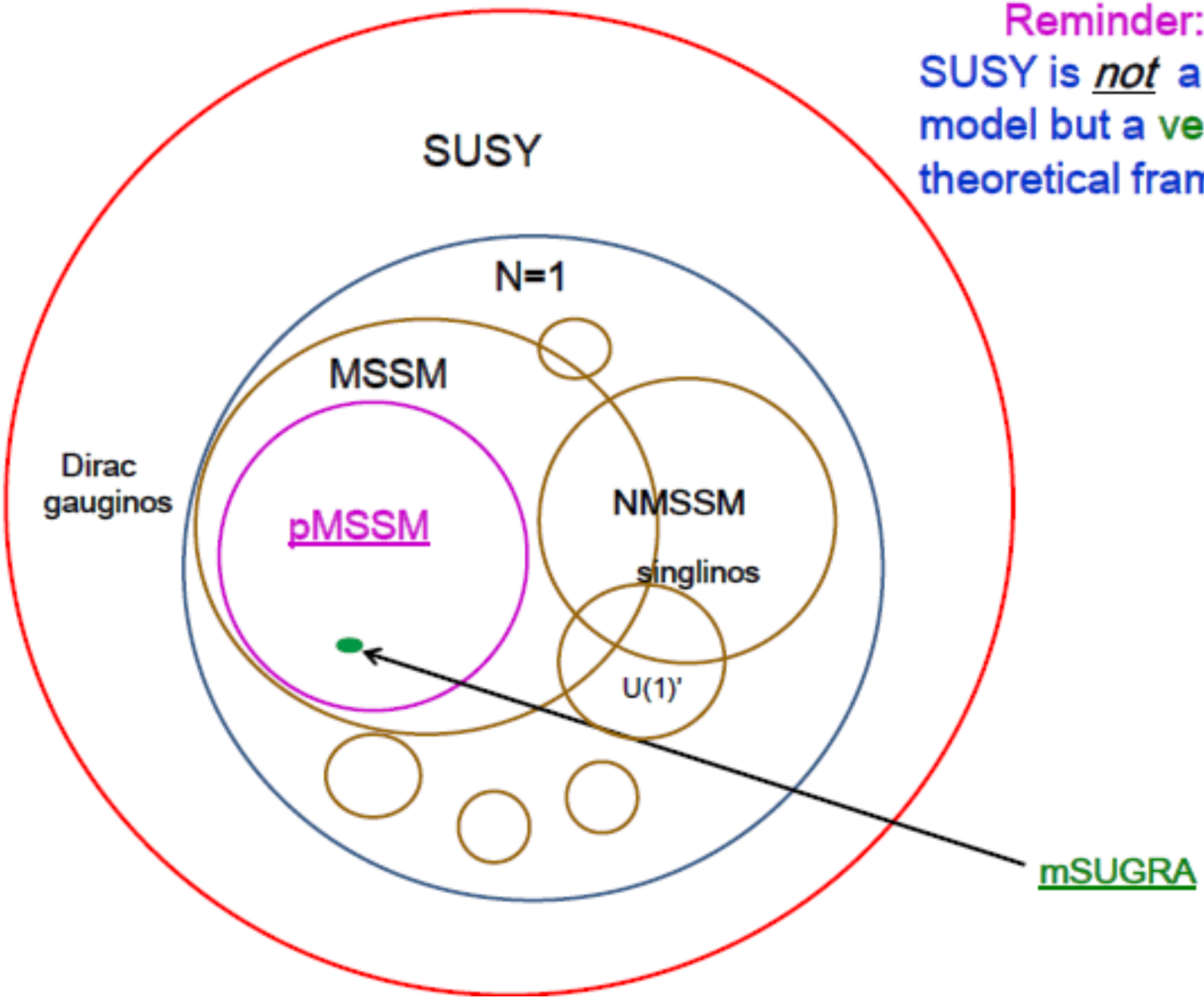
- Something like > 700 possibilities, final state signatures involving leptons and/or jets

- Multilepton production (including taus)
- Multijets, possibly resonances (ie 2 x 3 jets)

- If λ, λ',λ'' very small, can lead to long-lived LSP

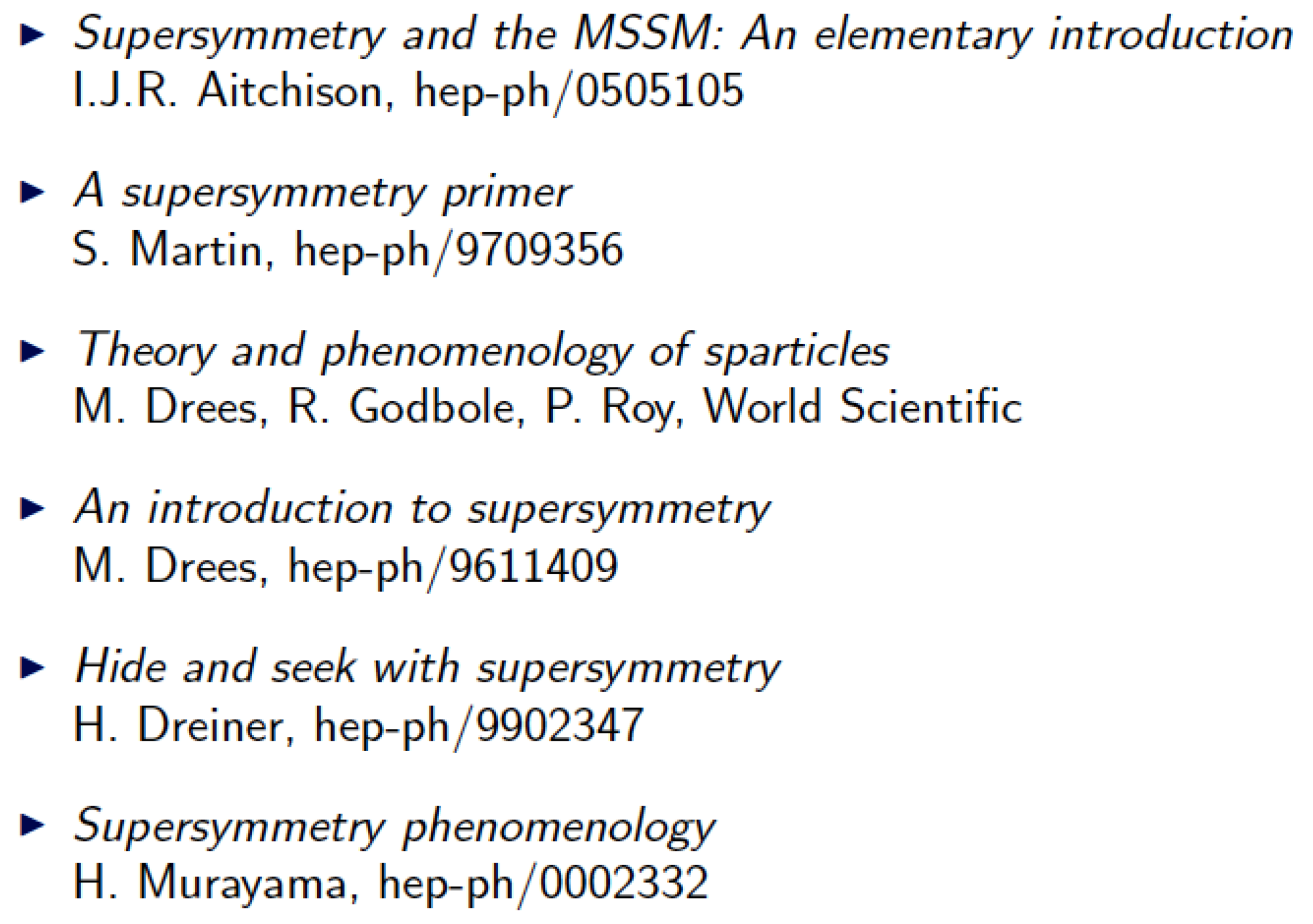
Taken from T. Rizzo

SUSY ZOO



Reminder:
SUSY is *not* a single model but a very large theoretical framework

Some references

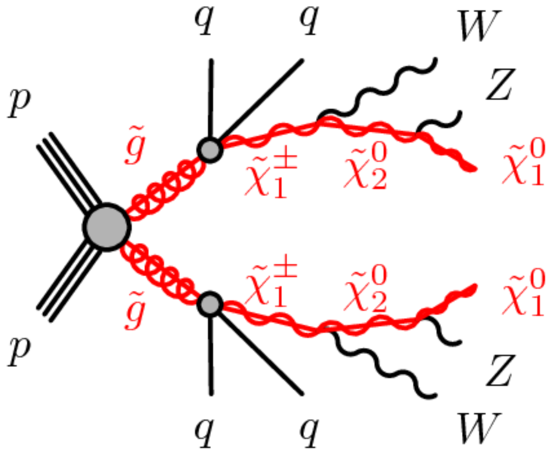


- *Supersymmetry and the MSSM: An elementary introduction*
  I.J.R. Aitchison, hep-ph/0505105
- *A supersymmetry primer*
  S. Martin, hep-ph/9709356
- *Theory and phenomenology of sparticles*
  M. Drees, R. Godbole, P. Roy, World Scientific
- *An introduction to supersymmetry*
  M. Drees, hep-ph/9611409
- *Hide and seek with supersymmetry*
  H. Dreiner, hep-ph/9902347
- *Supersymmetry phenomenology*
  H. Murayama, hep-ph/0002332

Basic Guidelines on how to perform a Search

Background Estimation

Likelihood Fits


p
p
q
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W
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Z
W
$\tilde{g}$
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$\tilde{\chi}_1^{\pm}$
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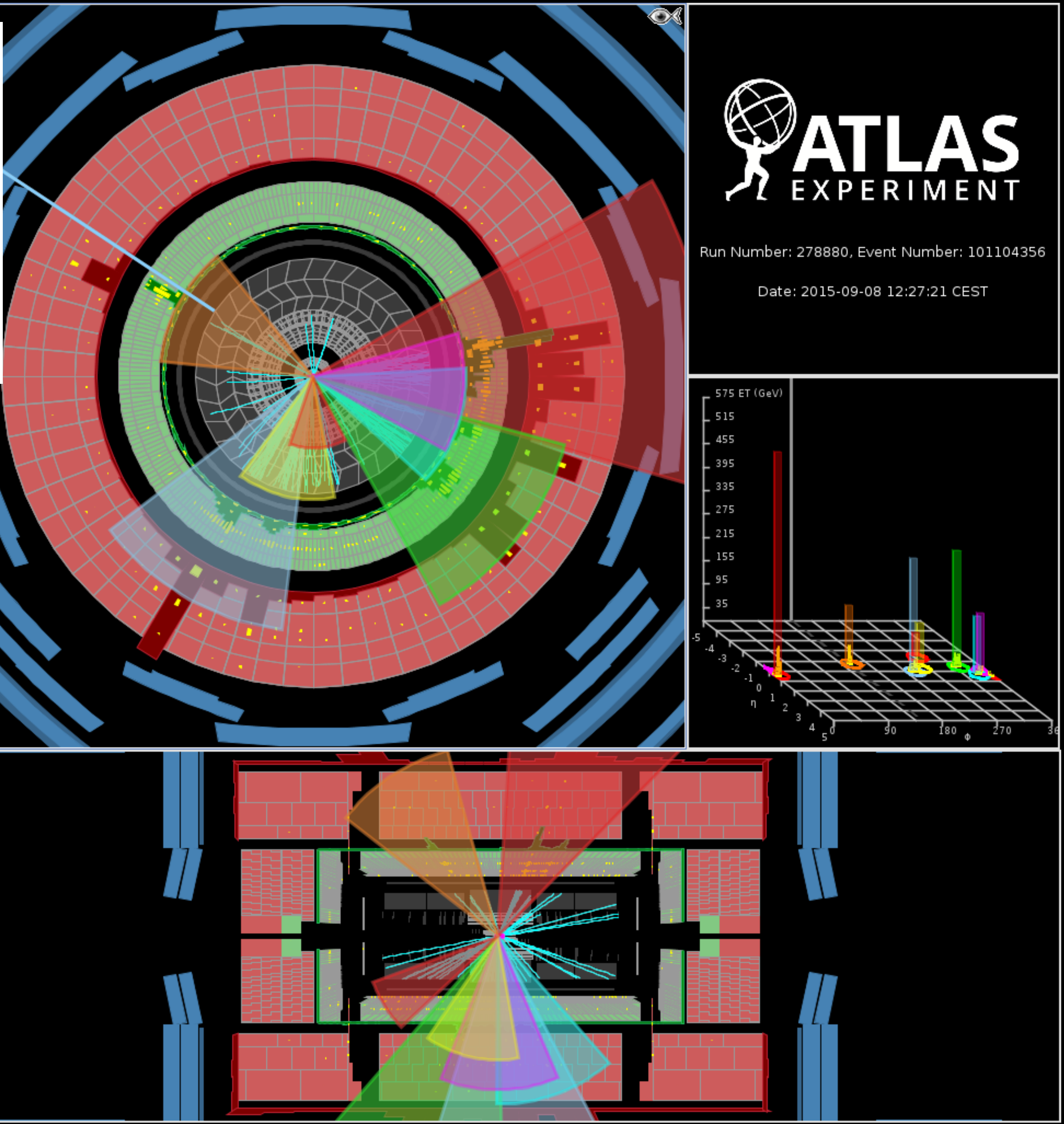
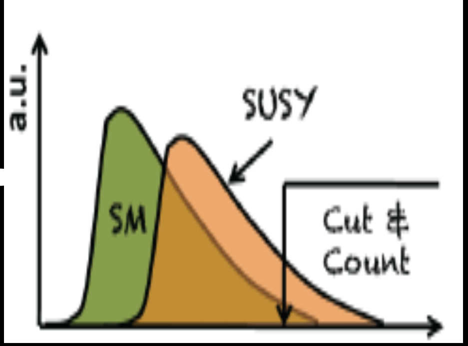
$\tilde{\chi}_1^0$


ATLAS
EXPERIMENT
Run Number: 278880, Event Number: 101104356
Date: 2015-09-08 12:27:21 CEST
575 ET (GeV)
515
455
395
335
275
215
155
95
35
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
36
φ

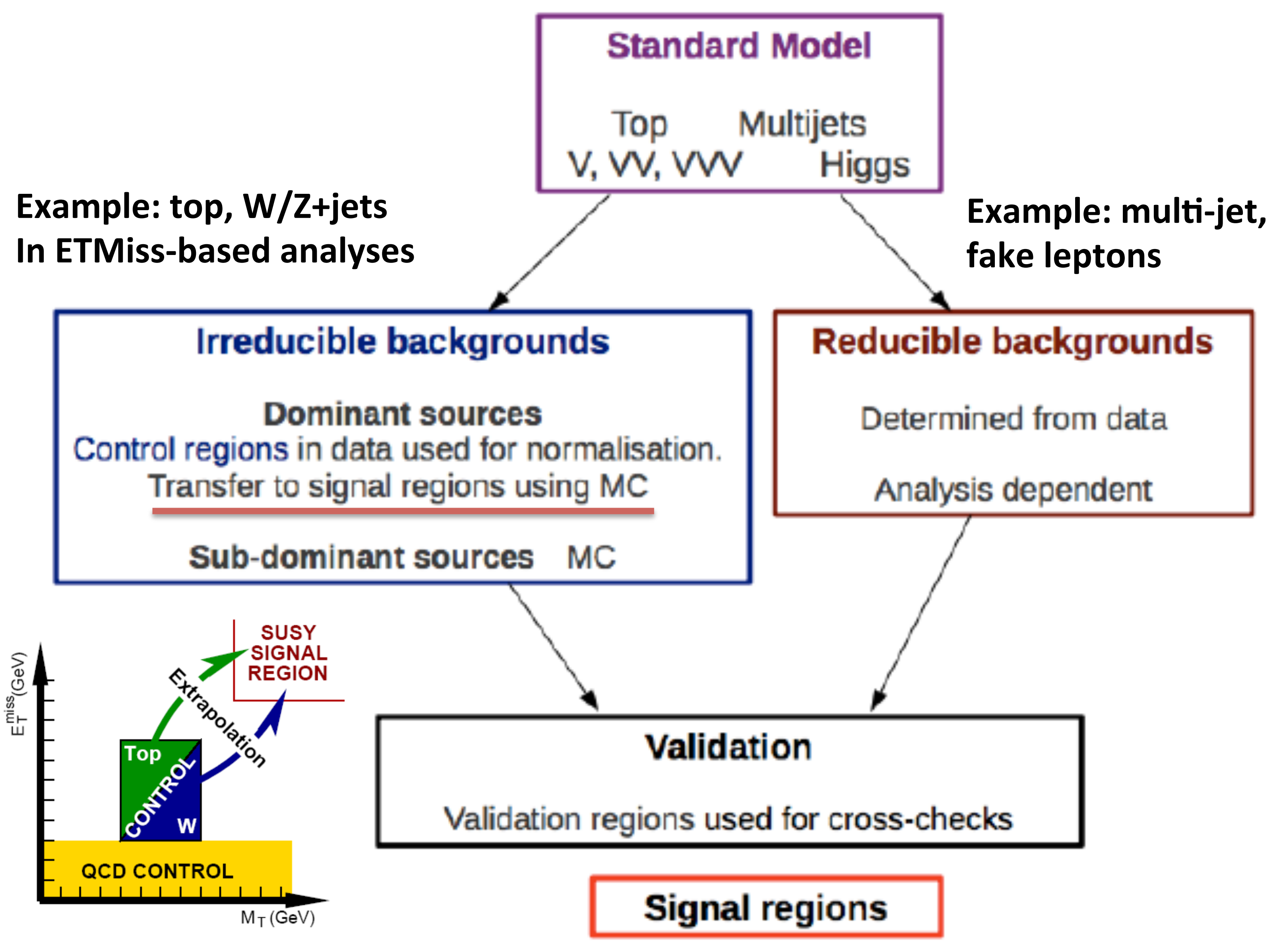
?

How to make your search…



1. Find good discriminant(s) → signal region (blind it!)
2. Determine your SM background + related systematics
    1. As much as possible from data
    2. If taken from theory/simulations → define control regions in data (orthogonal to your signal regions) to constrain the predictions with data (and to reduce systematics from models)
    3. Validate your predictions in regions close to the signal region (similar kinematics) where you do not expect new physics
    4. Convince your collaborators all is under control and open box
3. Use a sophisticated Likelihood fit to determine whether your data is statistically consistent with a background only hypothesis in the signal region taking into account correlations of systematic uncertainties, etc..
    1. Buy a ticket to Stockholm or compute exclusion limits @ 95% CL

Background strategy



Standard Model

Top Multijets
V, VV, VVV Higgs

Example: top, W/Z+jets
In ETMiss-based analyses

Example: multi-jet,
fake leptons

Irreducible backgrounds

Dominant sources
Control regions in data used for normalisation.
Transfer to signal regions using MC

Sub-dominant sources MC

Reducible backgrounds

Determined from data

Analysis dependent

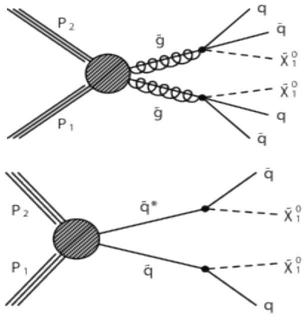
Validation

Validation regions used for cross-checks

Signal regions

An example: 0-lepton signature

- Searches in inclusive jets + E_t^{miss} events
  - **from 2 (A) to 6 (E) jets**



→ ≥ 4 jets

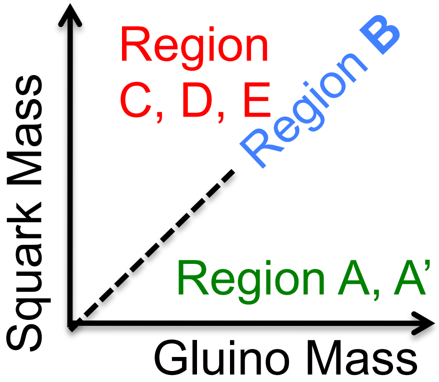
→ ≥ 2 jets

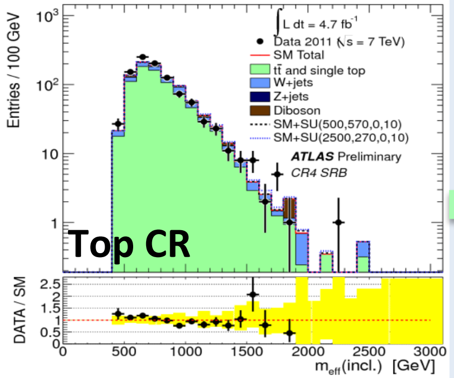
$\tilde{q} \rightarrow q\tilde{\chi}_1^0$

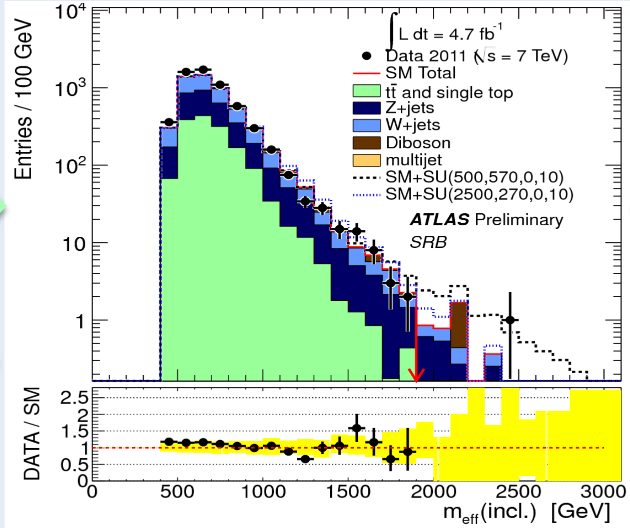
$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$

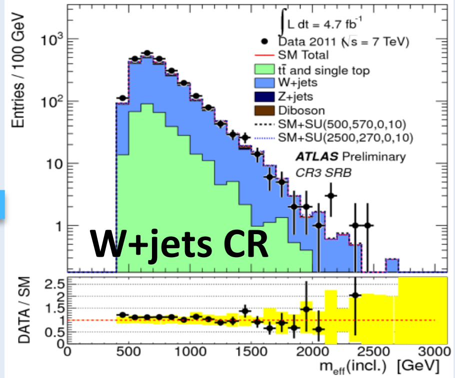
Expect significant "effective mass"

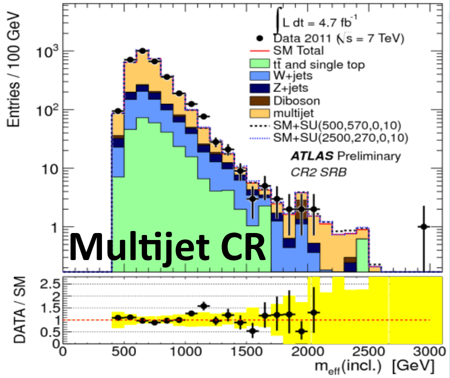
$$\sum_{jet} E_{T,jet} + E_T^{miss}$$



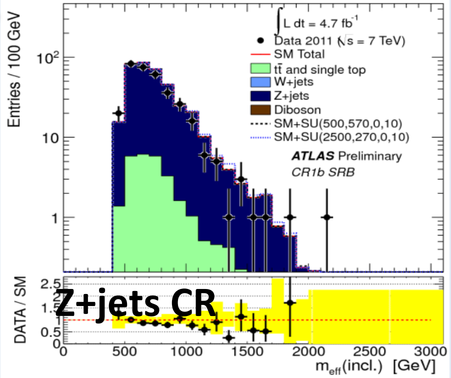








Normalizations obtained in all CR and extrapolated to signal regions simultaneously by combined maximum likelihood fit



The mother of all fits…

- Combine all info in a global fit. Likelihood based on CR and SR (mutually exclusive)

$$L(n\,|\,\mu,b,\theta) = P_{SR} \times P_Z \times P_W \times P_{Top} \times P_{QCD} \times C_{syst}$$

b=background
θ= systematics treated as nuisance parameters with Gaussian
n=Number of observed events in data
μ= SUSY signal strength to be tested

- Each region described with a **Poisson p.d.f**
- Statistical and systematic uncertainties on the expected values included in the fit as nuisance parameters → typically constrained by a **Gaussian function** with width corresponding to the size of the uncertainty considered
  - correlations between these parameters are taken into account
- **Inputs:** Transfer factors (c), N events for data in SR(s) and CRj(bj)

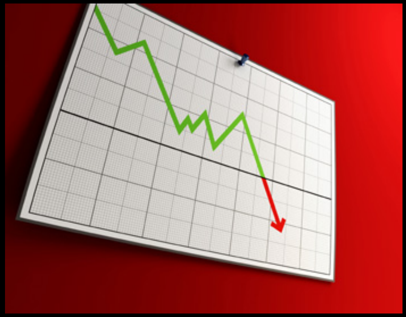
$$P_{SR} = P(n\,|\,\lambda_S(\mu,b,\theta)) = \mu \bullet c_{sR->SR}(\theta) \bullet s + \sum_j c_{jR->SR}(\theta) \bullet \mathrm{b}_j$$

$$P_i = P(n\,|\,\lambda_i(\mu,b,\theta)) = \mu \bullet c_{sR->iR}(\theta) \bullet s + \sum_j c_{jR->iR}(\theta) \bullet \mathrm{b}_j$$

λ (μ, b, θ) = expected number of events

CL_s

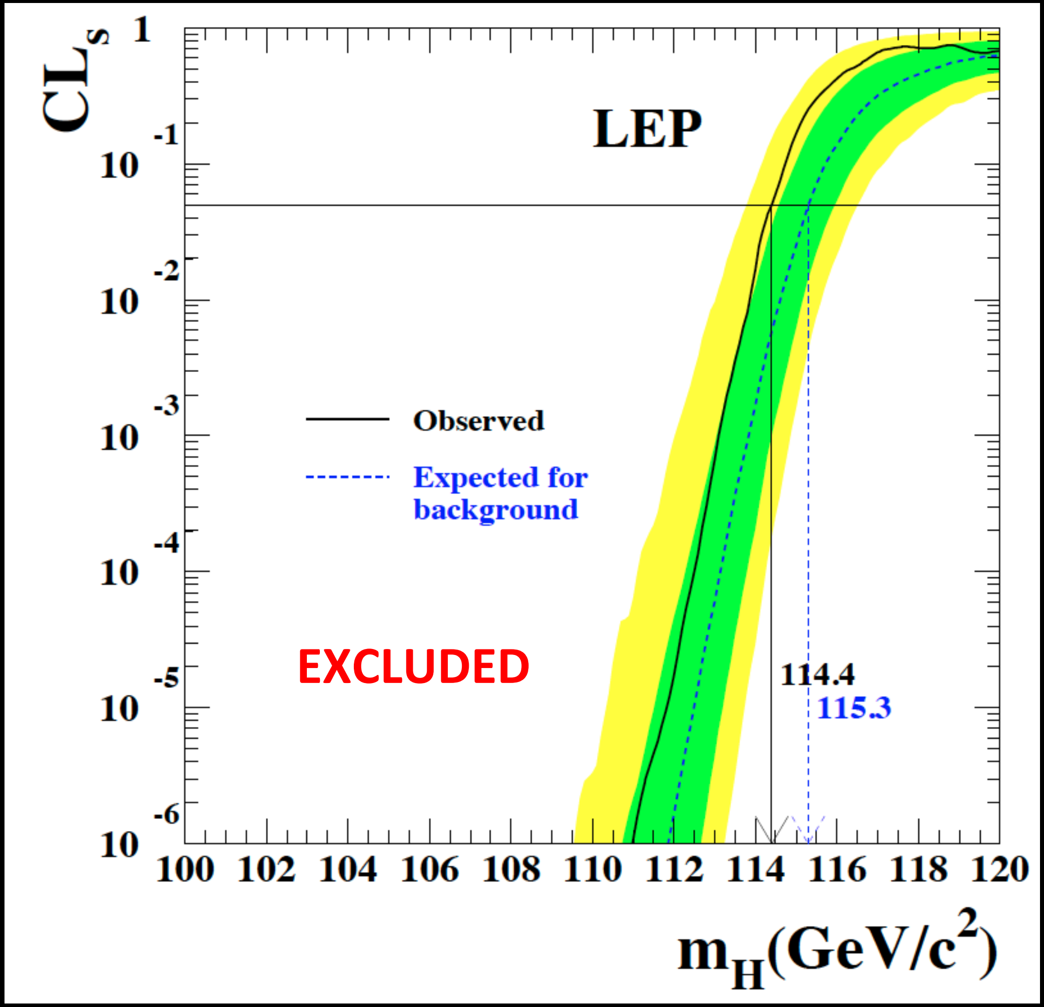
(do not exclude your signal…)



$$CL_S = \frac{p_s}{1-p_b}$$

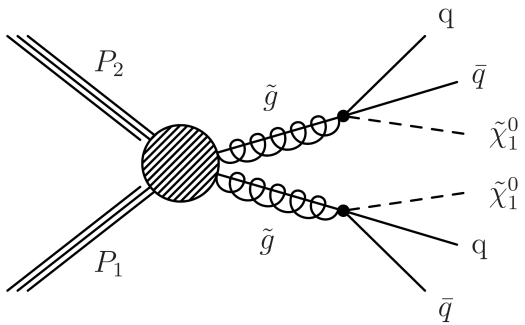
In the case of very small signals (limited sensitivity) the use of p_s to exclude signals can lead to false exclusions if the data fluctuates down….

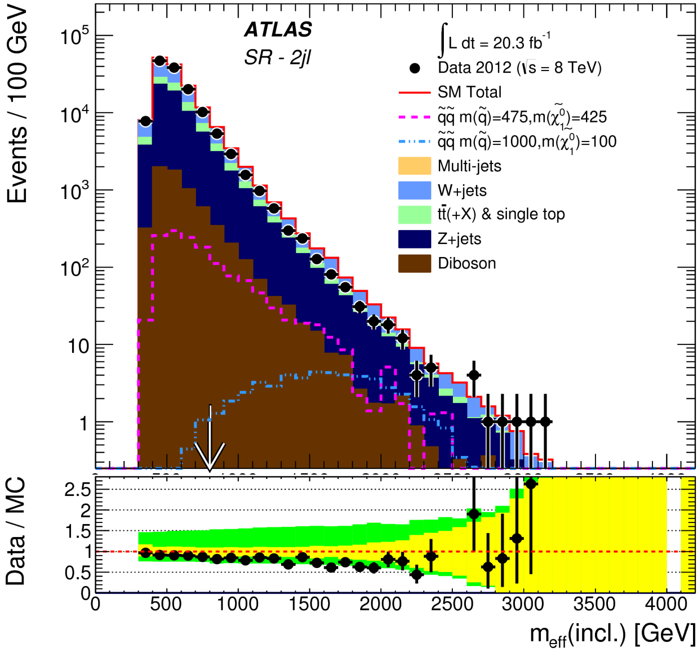
In these cases it is better to use CLs … which is conservative in the exclusion

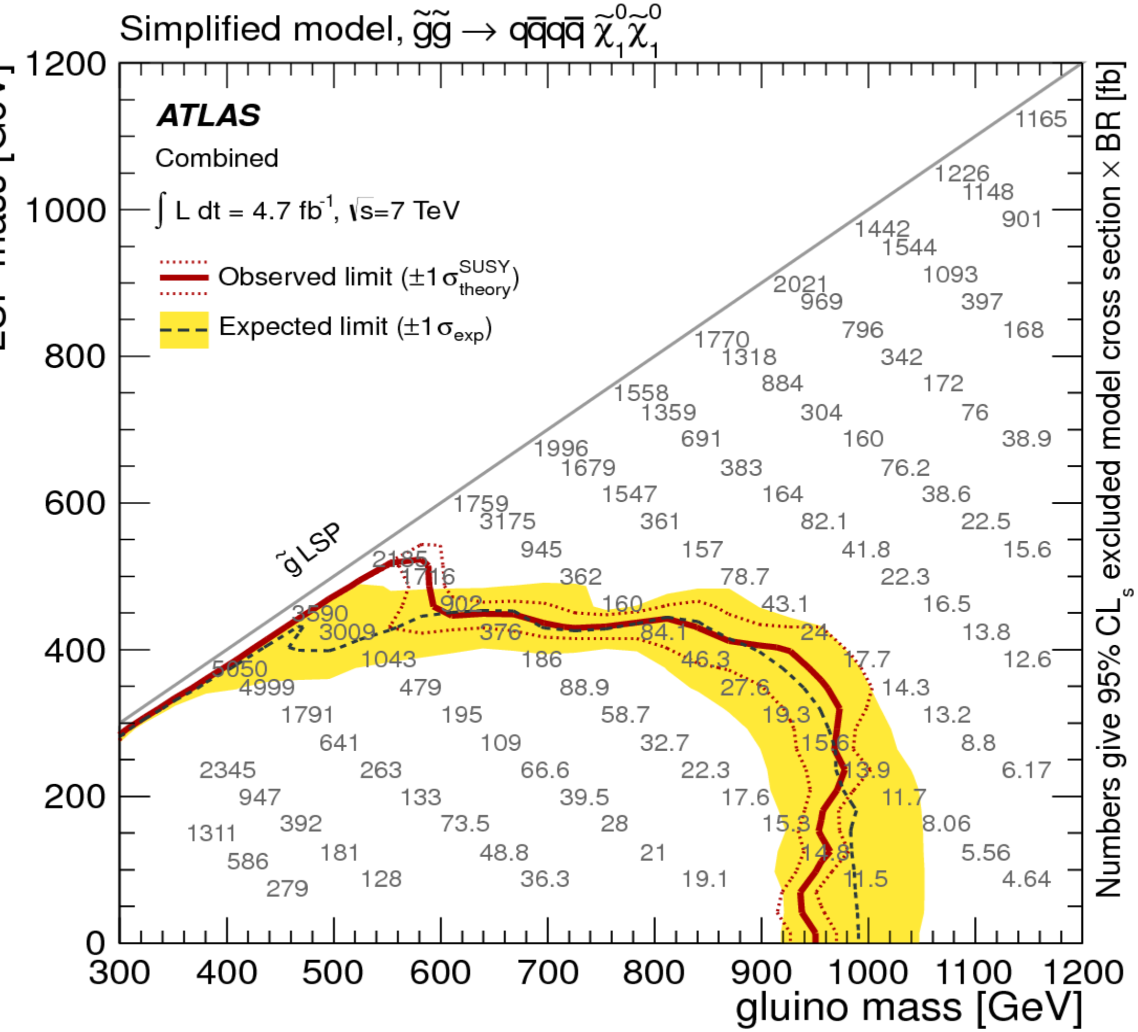


If CLs < 0.05 → excluded at 95% CL

Typical SUSY exclusion plot..







Expected: use SM prediction as data (yellow band reflects uncertainties in SM prediction)
Observed: what the data tells you (dashed band depends on the model uncertainties)
Numbers inside: 95% CL signal exclusion (if your signal is larger than this.. You excluded it)

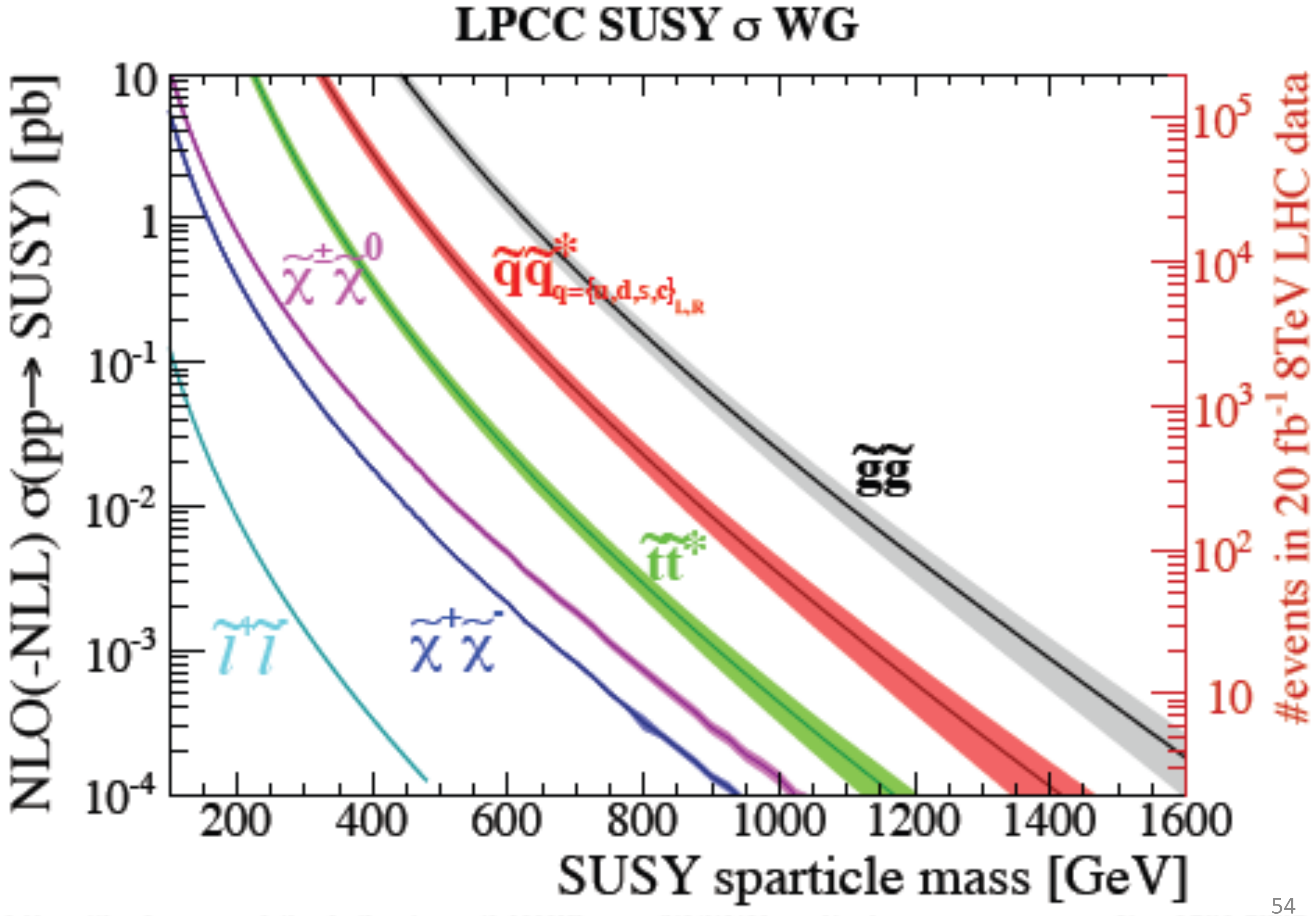
SUSY Searches

Inclusive searches

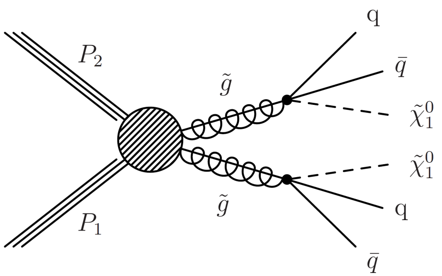
3rd generation squarks

EWK searches

SUSY Cross Sections @ LHC (8 TeV)



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections arXiv:1206.2892



Inclusive Searches

Multiple-jets and large E_T^{miss}

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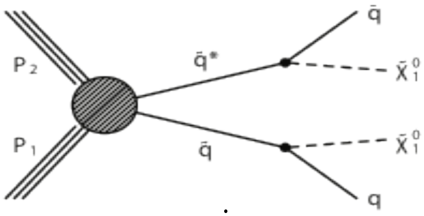
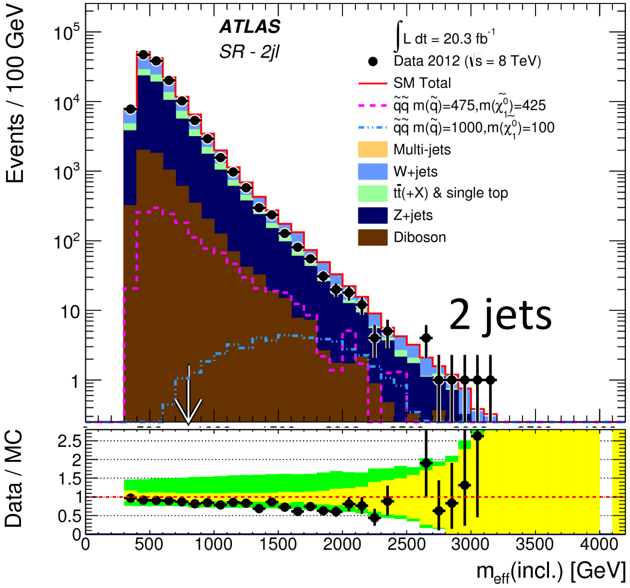
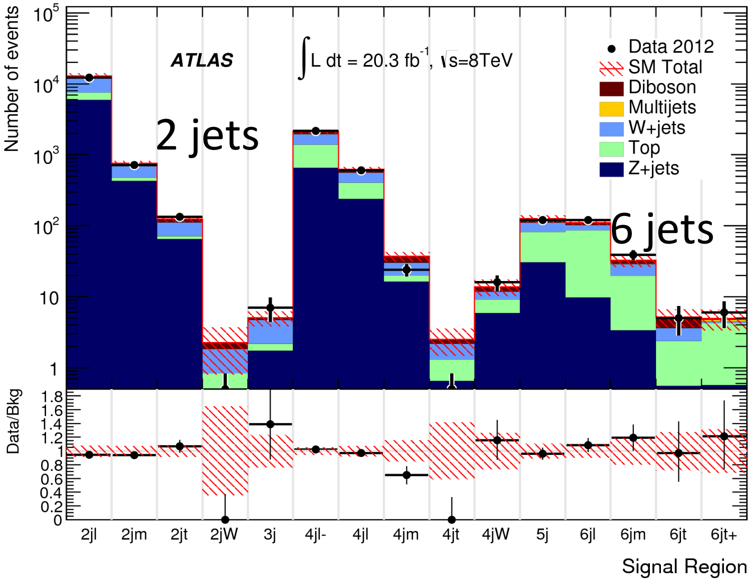


$$m_{eff} = E_T^{miss} + H_T$$

$$H_T = \sum_{jets} p_T$$



2 jets

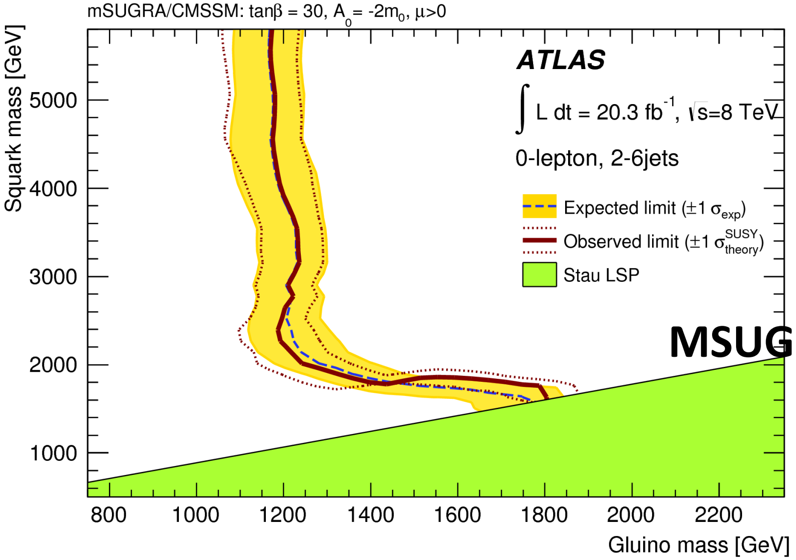


2 jets

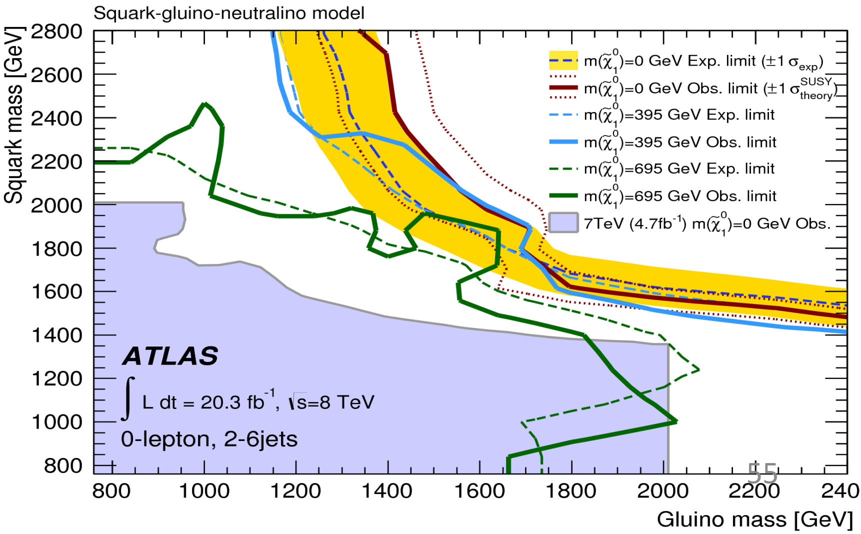
6 jets

Background from 1 lepton b-tag/veto & photon CRs with similar jet and kinematic selections as in SRs

SIMPLIFIED SCENARIO



MSUGRA



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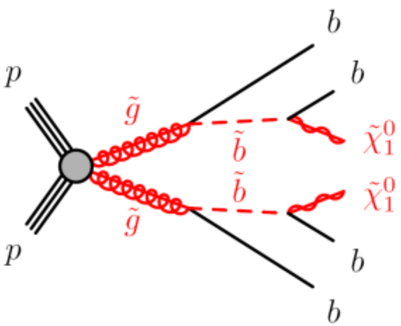
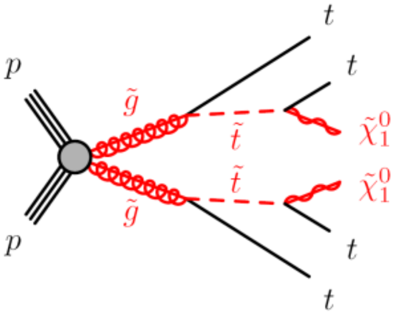
Gluino-mediated

Stop/Sbottom Production

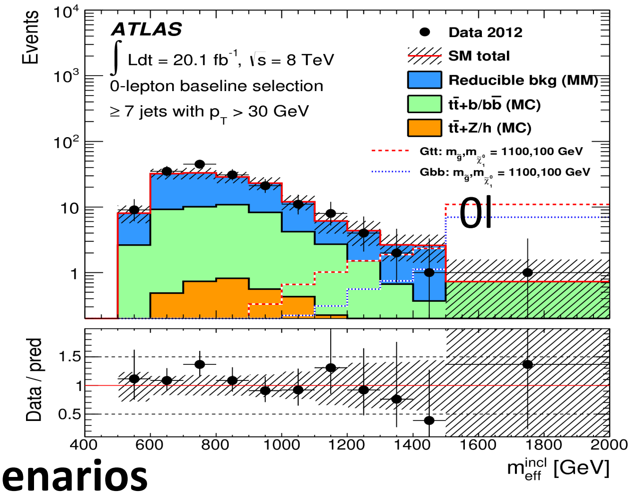


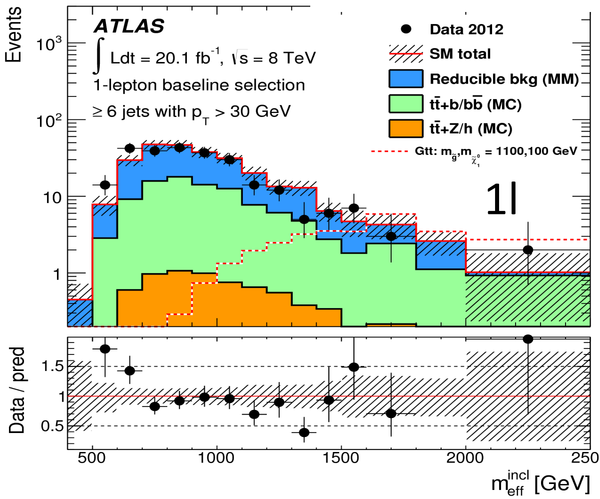


0/1 lepton + 3b-jets + E_t^{miss}

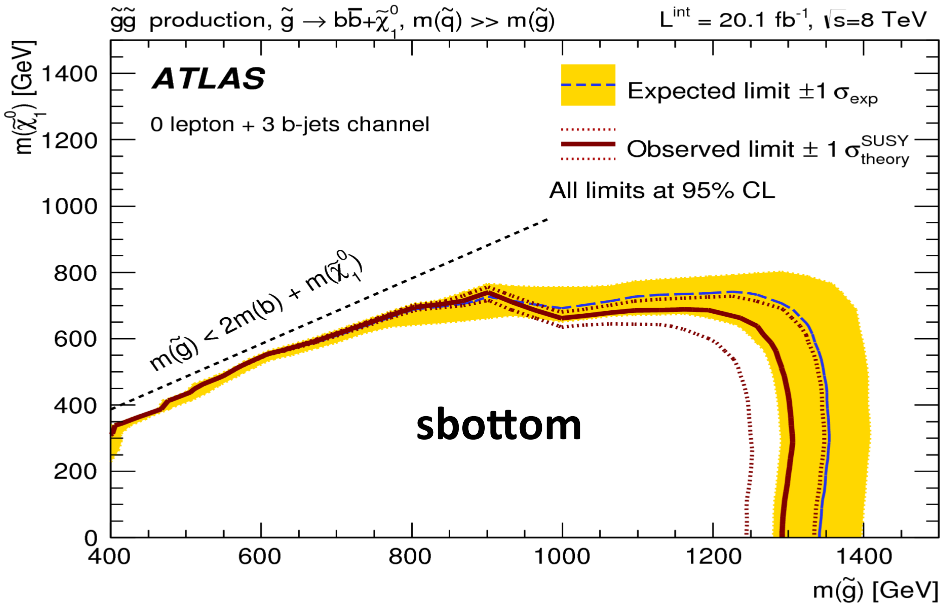
Background dominated by tt+bb, tt+V and tt+fakes

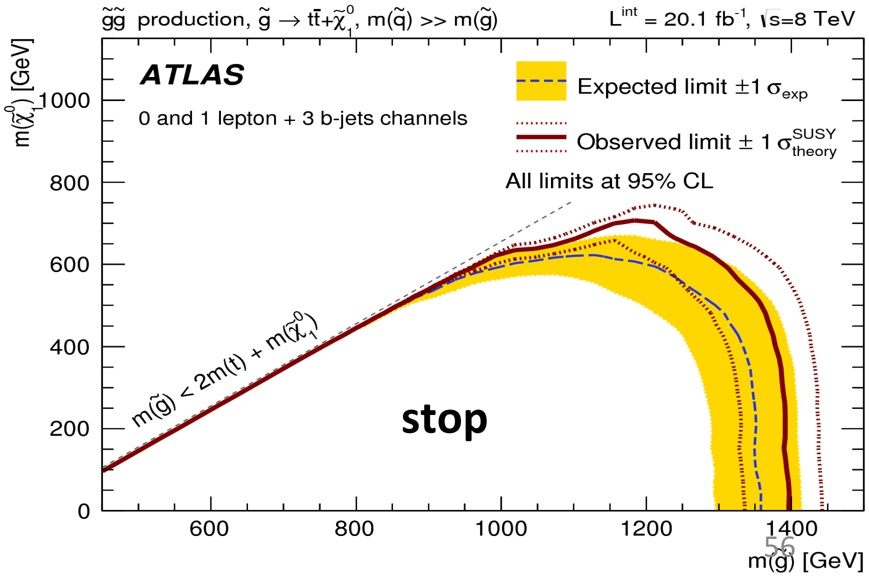
most powerful for very heavy gluinos





Interpreted in simplified scenarios

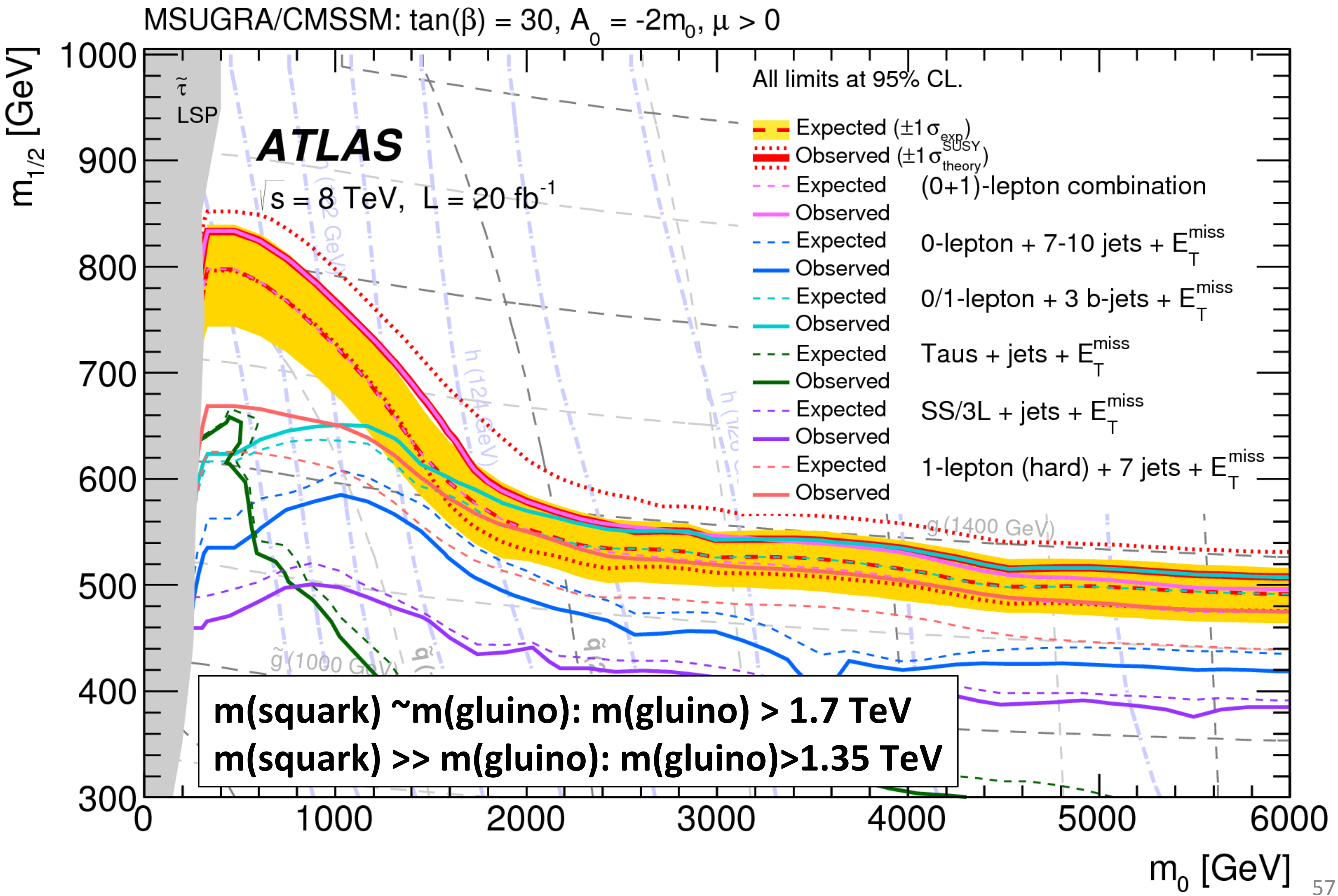




MSUGRA Scenario

arXiv:1507.05525

Run-1 summary on inclusive squark and gluino searches

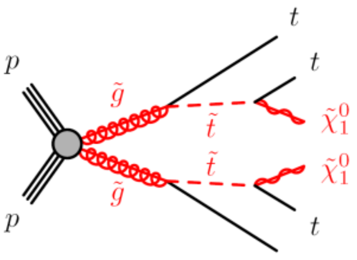


m(squark) ~m(gluino): m(gluino) > 1.7 TeV

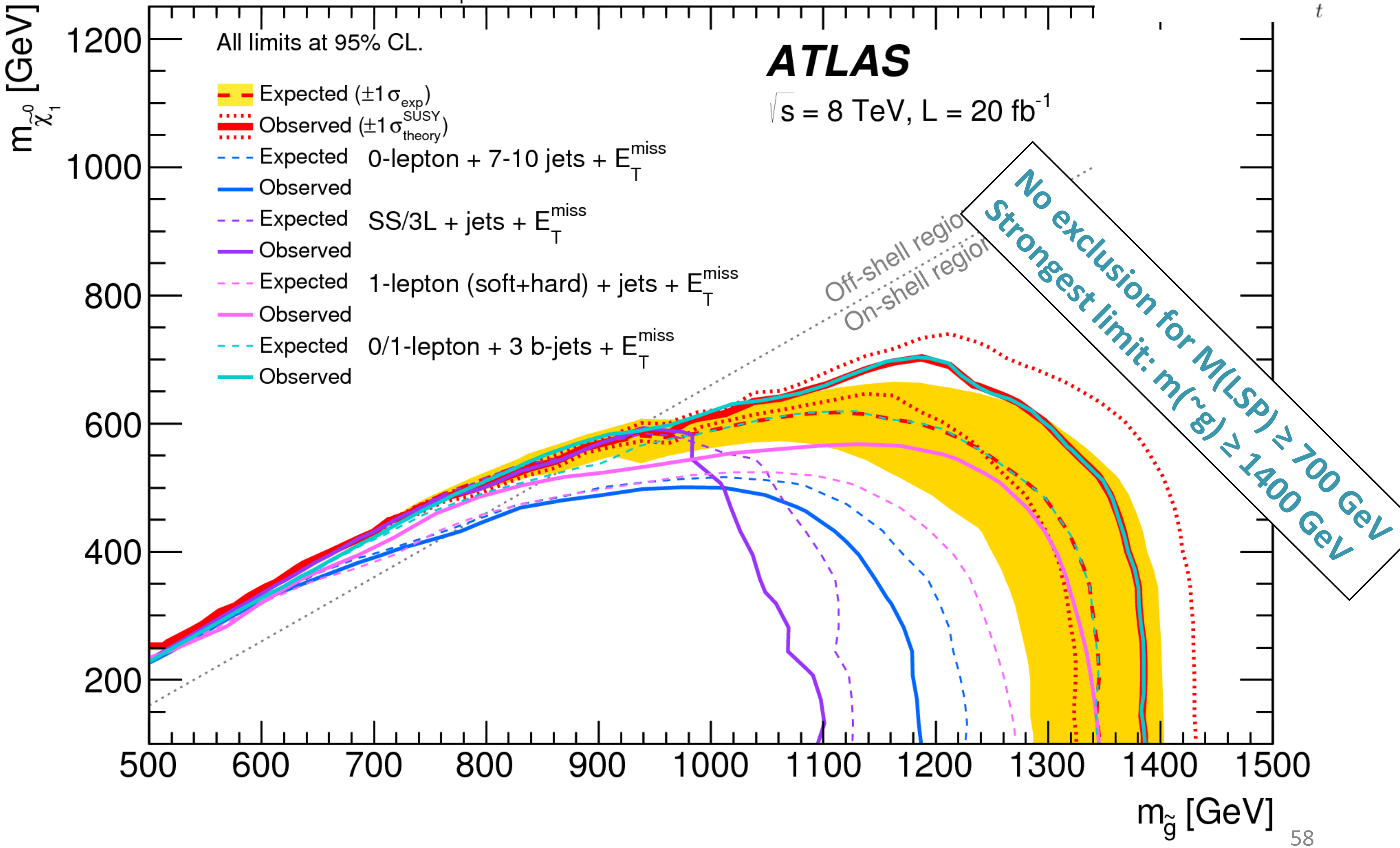
m(squark) >> m(gluino): m(gluino)>1.35 TeV

Part of the model plane accommodates a lightest neutral scalar Higgs boson mass of 125 GeV arXiv:1507.05525

Simplified model

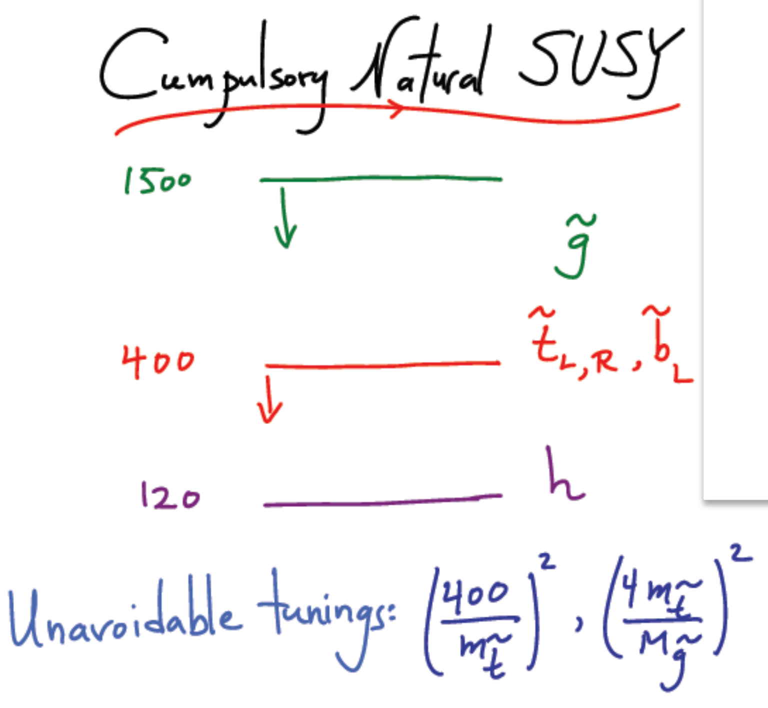


$\tilde{g}\tilde{g}$ production, $\tilde{g} \to tt^{(*)}\tilde{\chi}_1^0$; $m(\tilde{t}) >> m(\tilde{g})$, including up to five-body decays



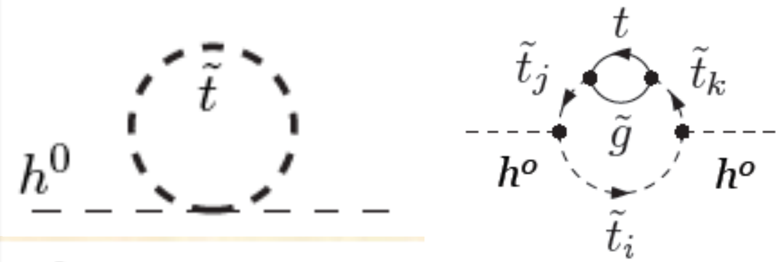
No exclusion for M(LSP) ≥ 700 GeV
Strongest limit: m(~g) ≥ 1400 GeV

"Natural SUSY 2012"



Unavoidable tunings: $\left(\frac{400}{m_{\tilde t}}\right)^2, \left(\frac{4 m_{\tilde t}}{M_{\tilde g}}\right)^2$

N. Arkani-Hamed talk at CERN Oct. 2012



$$\frac{m_H^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

$$\delta m_H^2\Big|_{stop} \cong -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{TeV}\right)$$

$$\delta m_H^2\Big|_{gluino} \cong -\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_3|^2 \ln^2\left(\frac{\Lambda}{TeV}\right)$$

$$\begin{pmatrix}\tilde t_1 \\ \tilde t_2\end{pmatrix} = \begin{pmatrix}\cos\theta_t & \sin\theta_t \\ -\sin\theta_t & \cos\theta_t\end{pmatrix}\begin{pmatrix}\tilde t_L \\ \tilde t_R\end{pmatrix}$$

- → Light higgsinos
- → Light stop (t_1 < 1 TeV)
- → Light gluinos (< 1-2 TeV)

One light stop and sbotton ….rest of sparticles can be decoupled….

$$\begin{pmatrix}\tilde t_L \\ \tilde b_L\end{pmatrix} \quad \tilde t_R \quad \tilde b_R$$

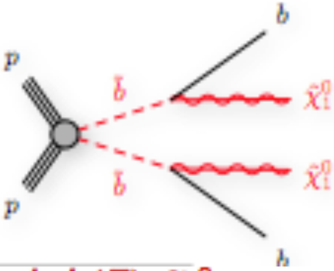
(same weak isospin multiplet)

Direct Stop/Sbottom

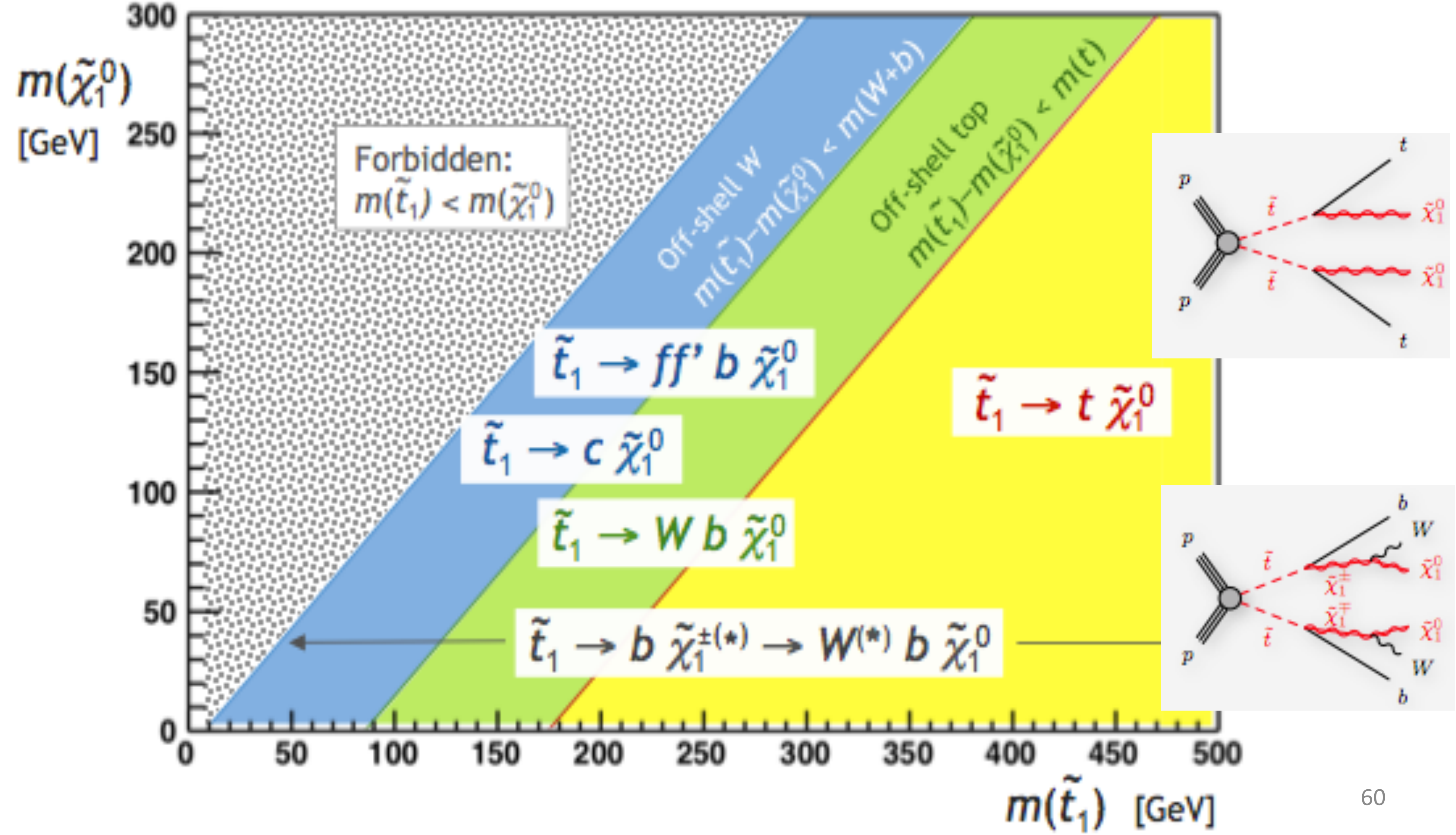
$\tilde{b}_1 \rightarrow b\,\tilde{\chi}_1^0$

$\tilde{b}_1 \rightarrow t\,\tilde{\chi}_1^\pm$

$\tilde{b}_1 \rightarrow b\,\tilde{\chi}_2^0 \rightarrow b\,h(Z)\,\tilde{\chi}_1^0$



In the scenario with TeV gluinos / squarks (1st/2nd generations)
All the attention is put now in searches for stop/sbottom
Multiple channels according to the decays



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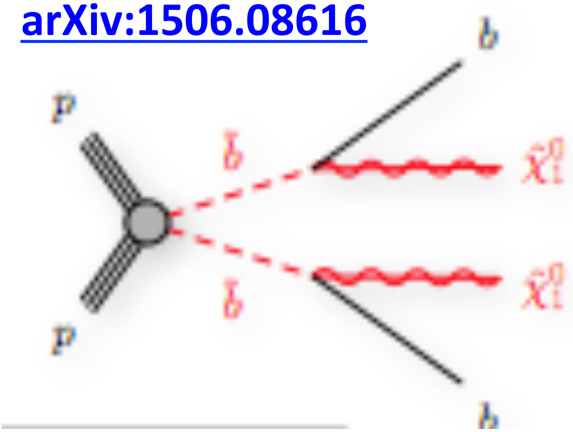
arXiv:1506.08616

Sbottom Direct Production

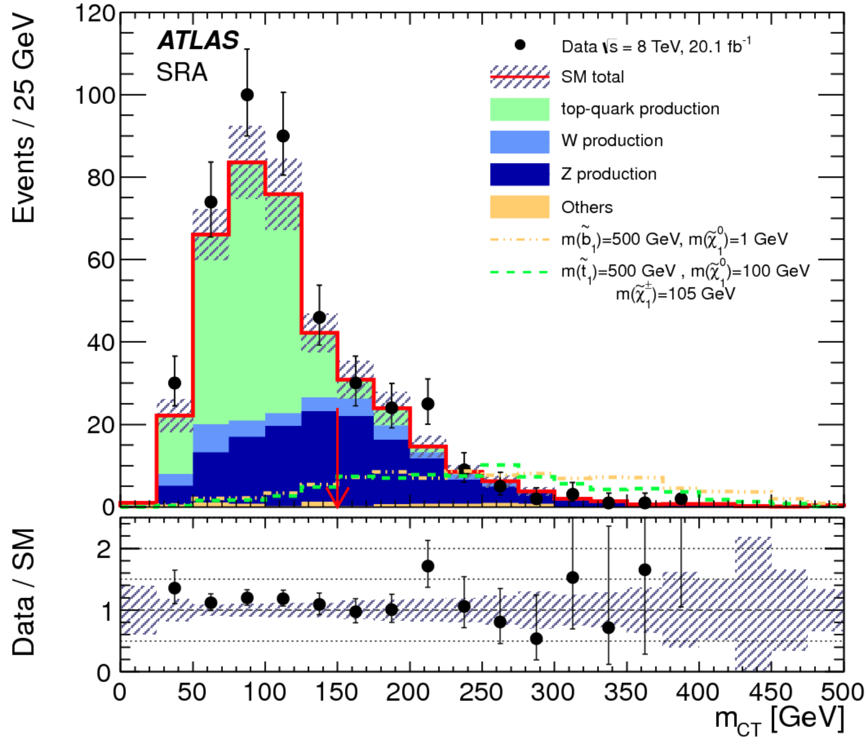


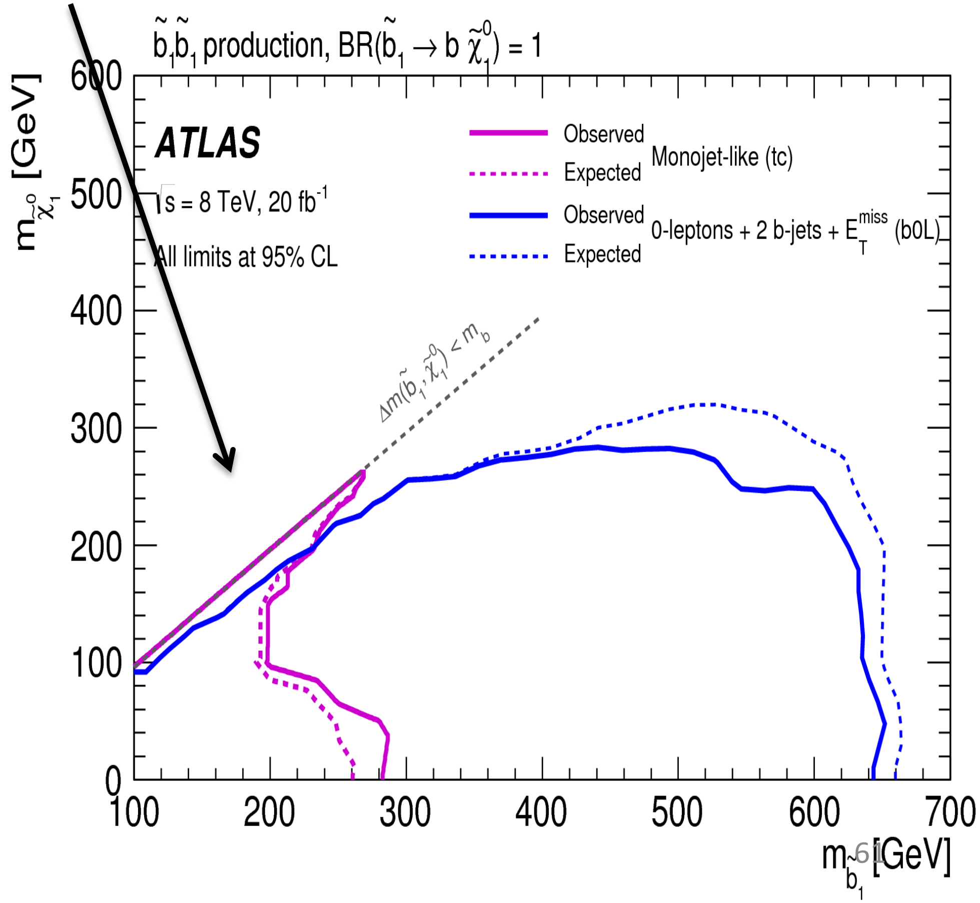
Large E_T^{miss} and 2 b-jets

Discriminating variable MCT

Additional selections to target also compressed scenarios (assisted with ISR jets)

$$m_{\mathrm{CT}}^2(v_1, v_2) = [E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)]^2 - [\boldsymbol{p}_{\mathrm{T}}(v_1) - \boldsymbol{p}_{\mathrm{T}}(v_2)]^2$$





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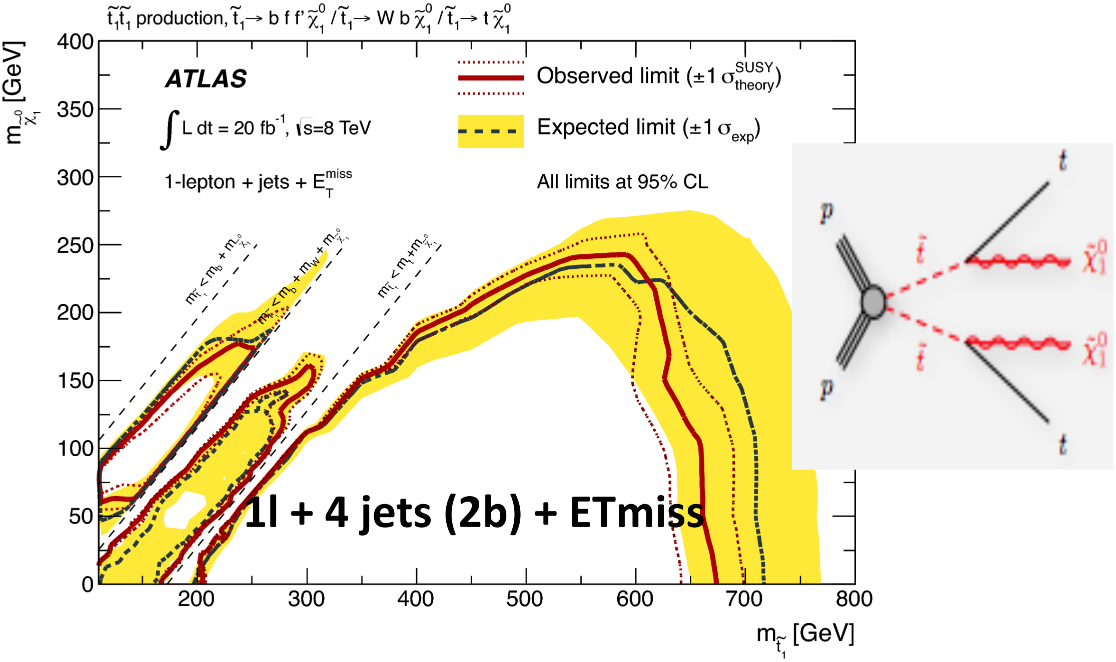
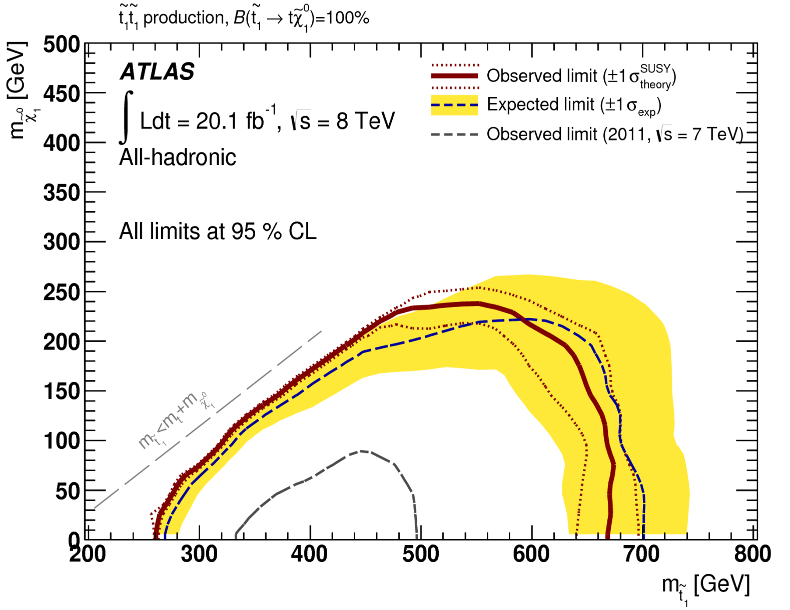
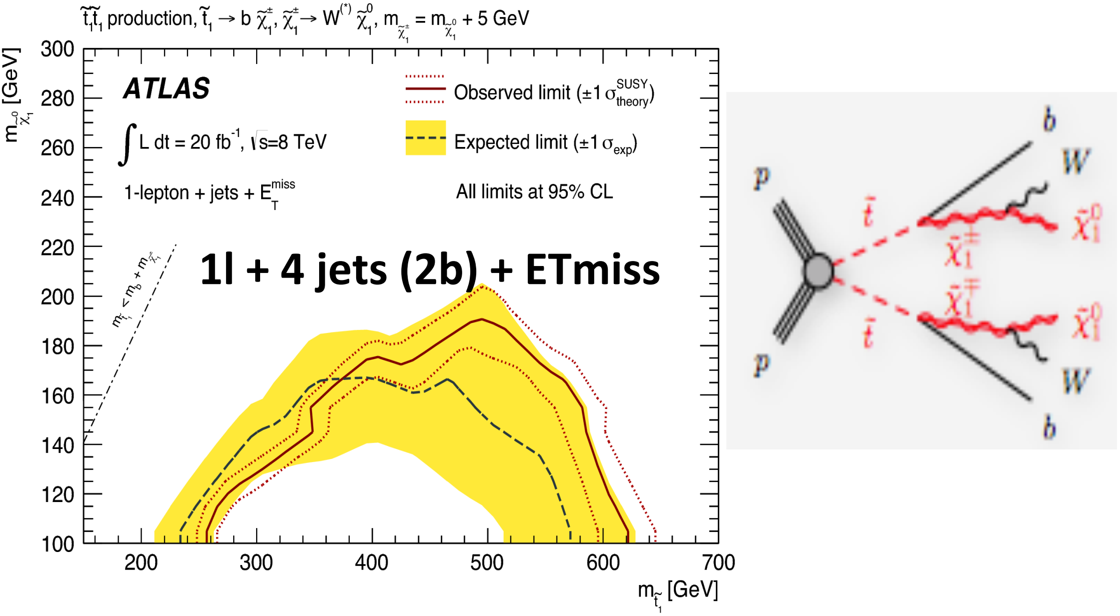
Direct Stop

JHEP 09 (2014) 015

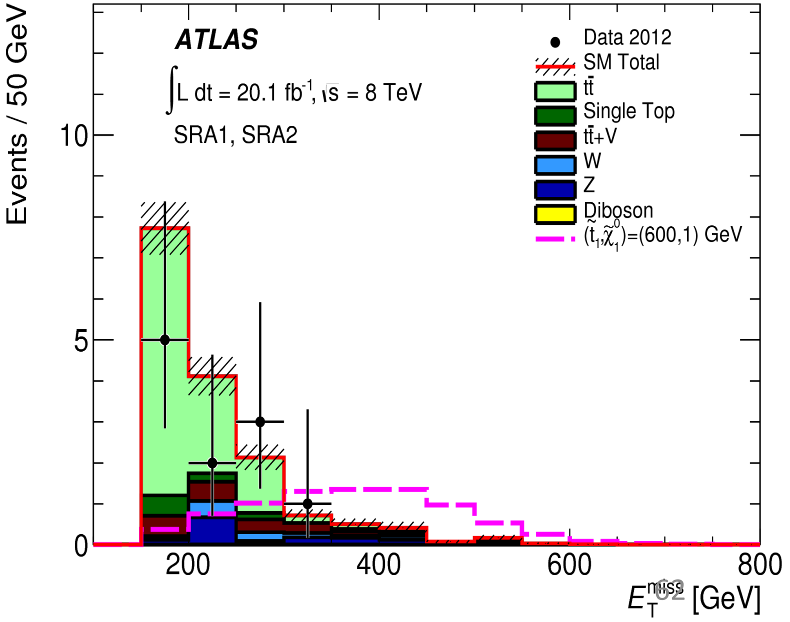


1l + 4 jets (2b) + ETmiss





1l + 4 jets (2b) + ETmiss



Phys. Rev. D. 90, 052008 (2014)

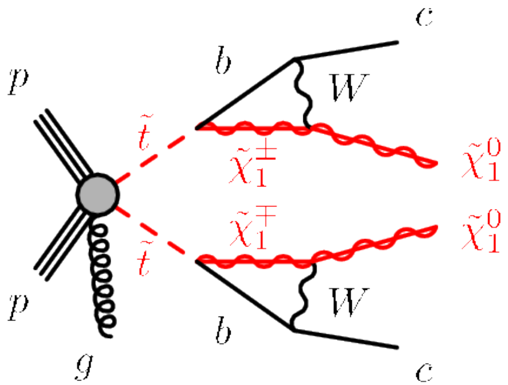
Direct Stop

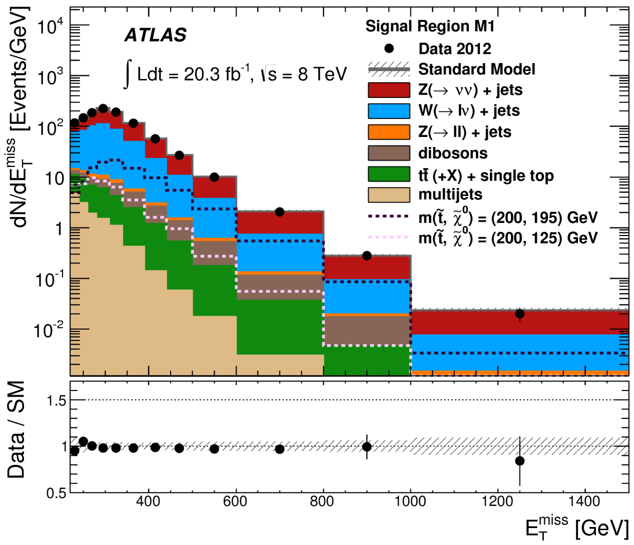
Two selections:

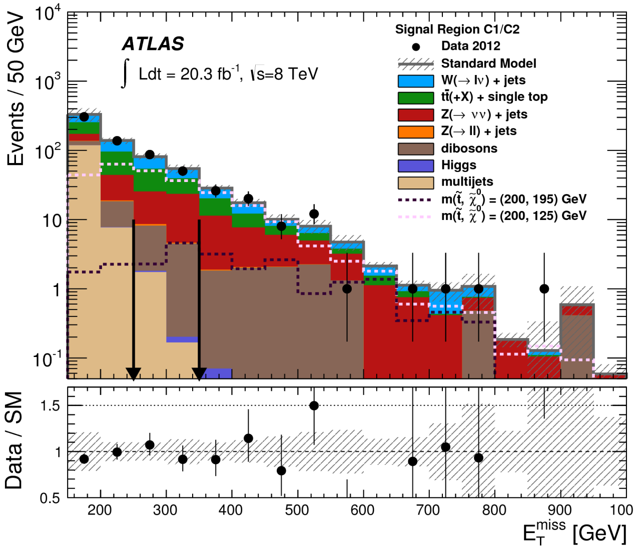
Monojet for compressed scenario

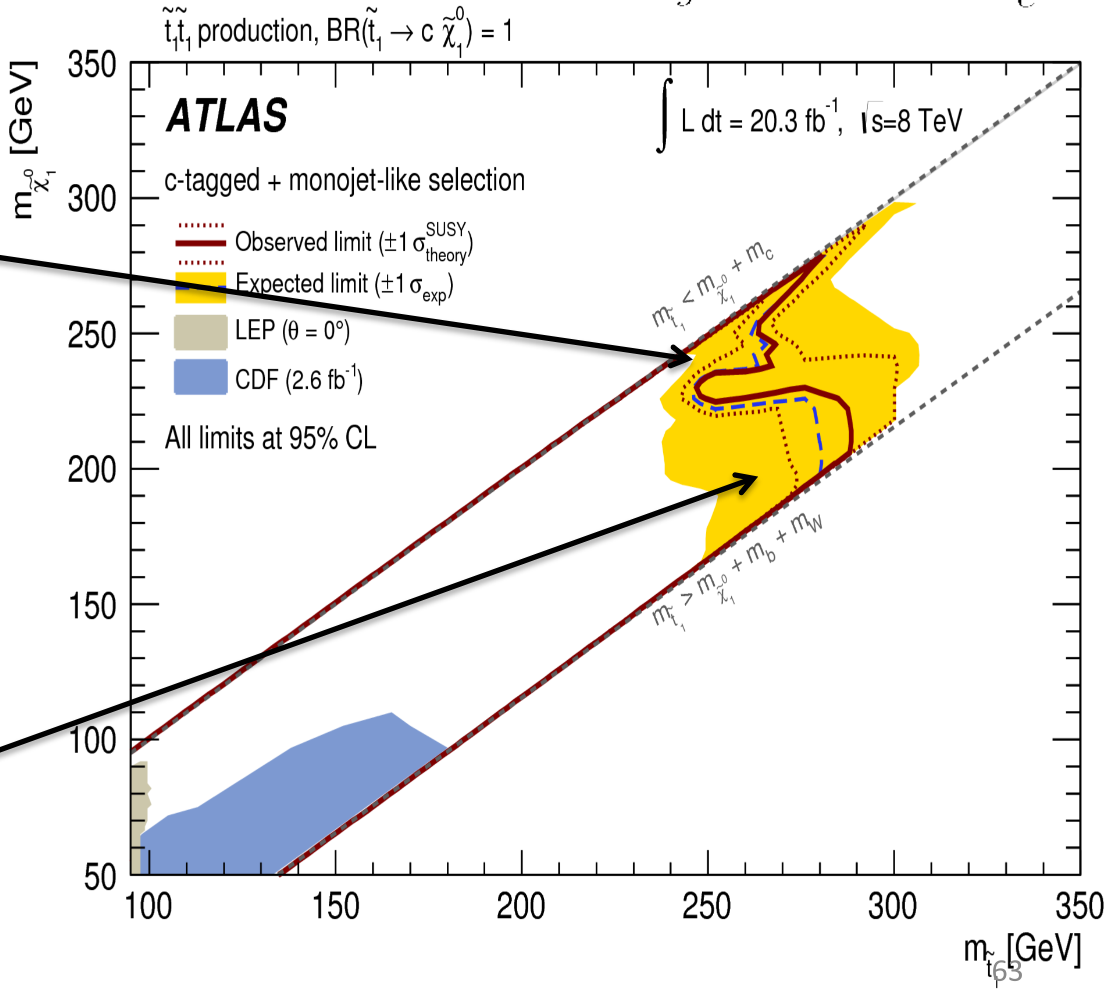
Large E_T^{miss} and c-jets

Very light stop





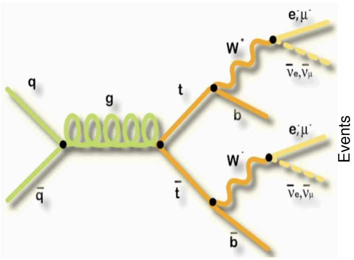


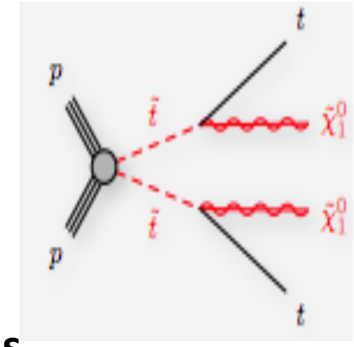


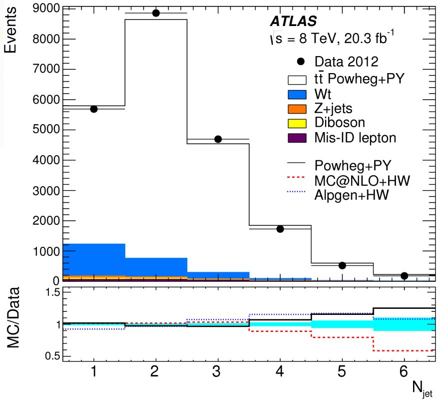
Eur. Phys. J. C74 (2014) 3109

Further stop constrains

(using the top cross section measurements)

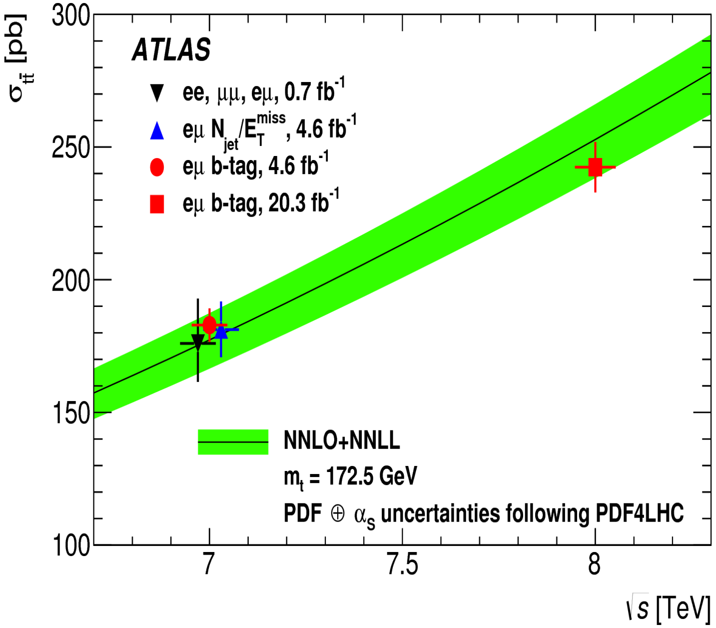


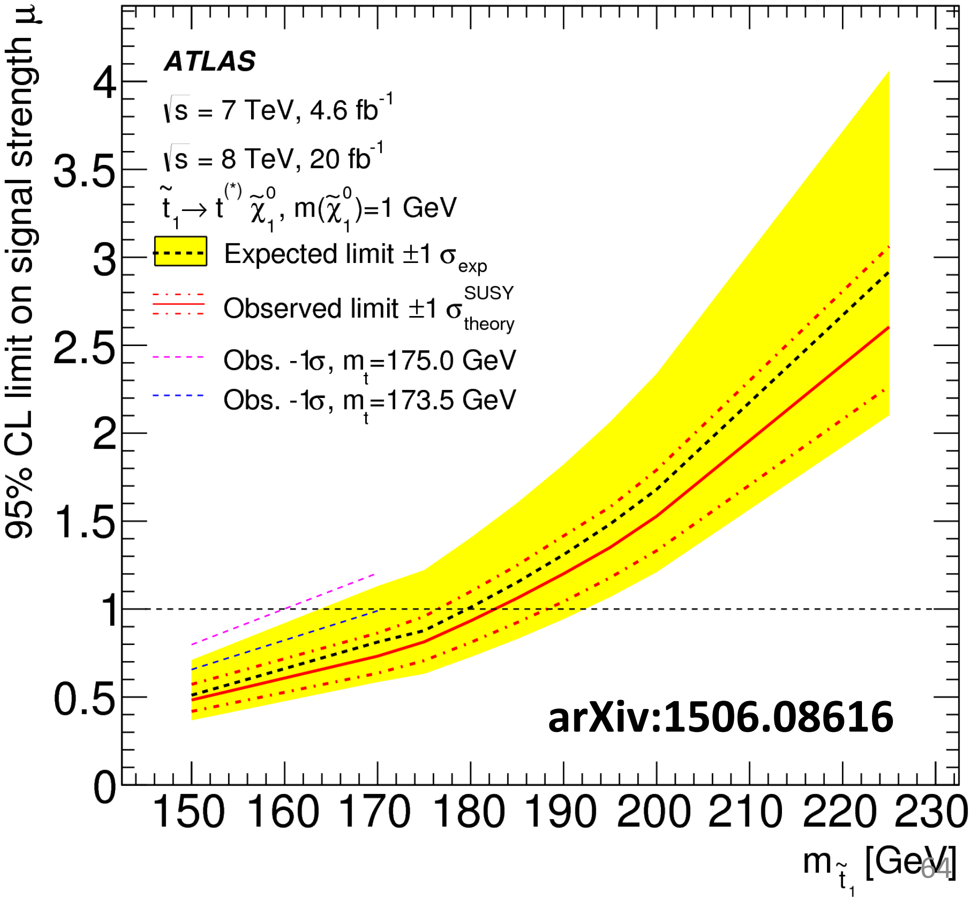




For stop masses close to the top mass the separation of SUSY signal and background is very challenging → use top cross section

Dilepton (e-μ) channel with exactly one and two b-jets



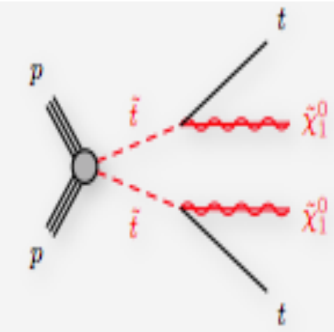


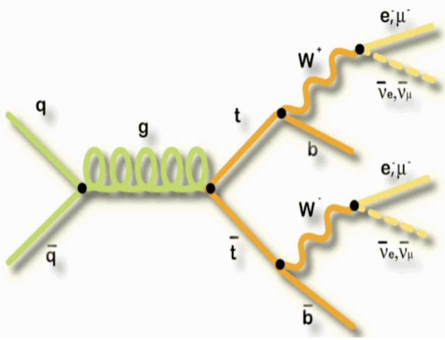
arXiv:1506.08616

Phys. Rev. Lett. 114. 142001 (2015)

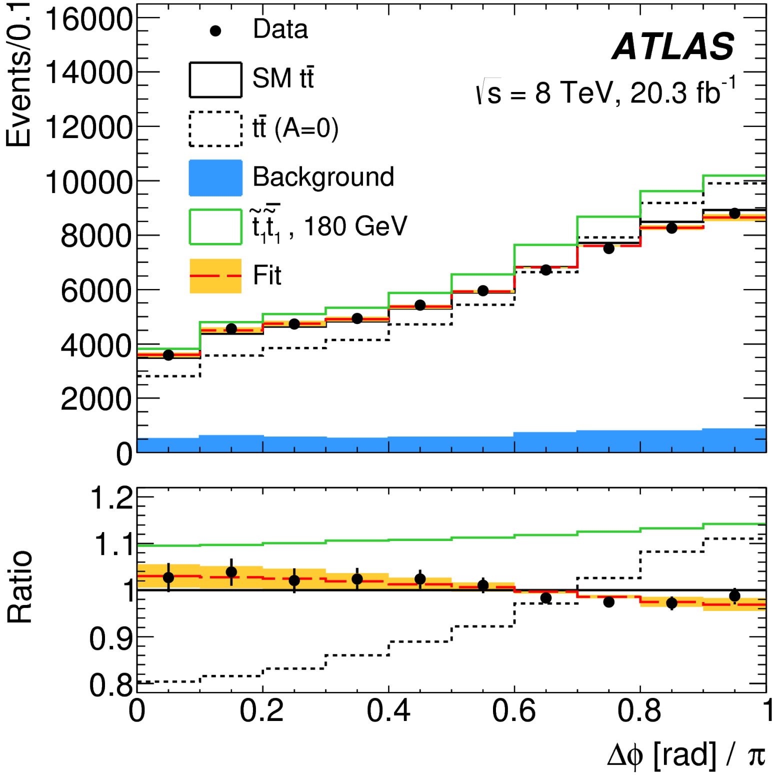
Further stop constrains

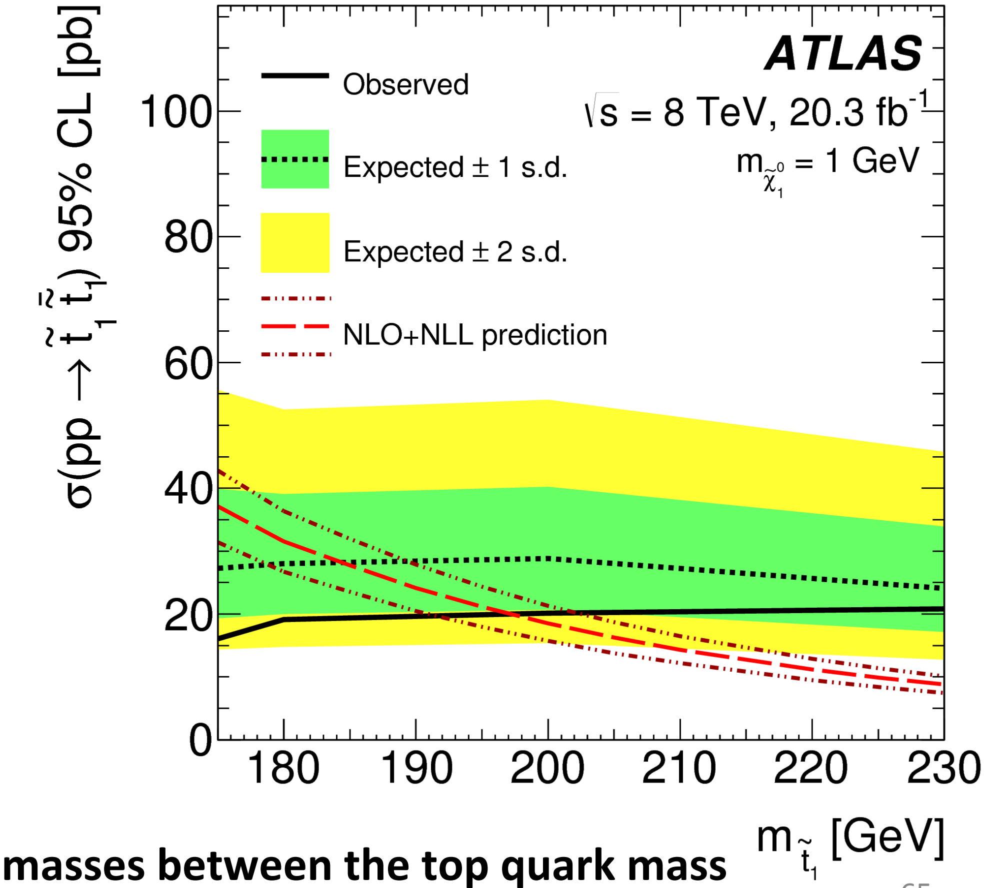
(using the top-(anti)top spin correlations)





using azimuthal separation of leptons from top-(anti)top decays in the final state

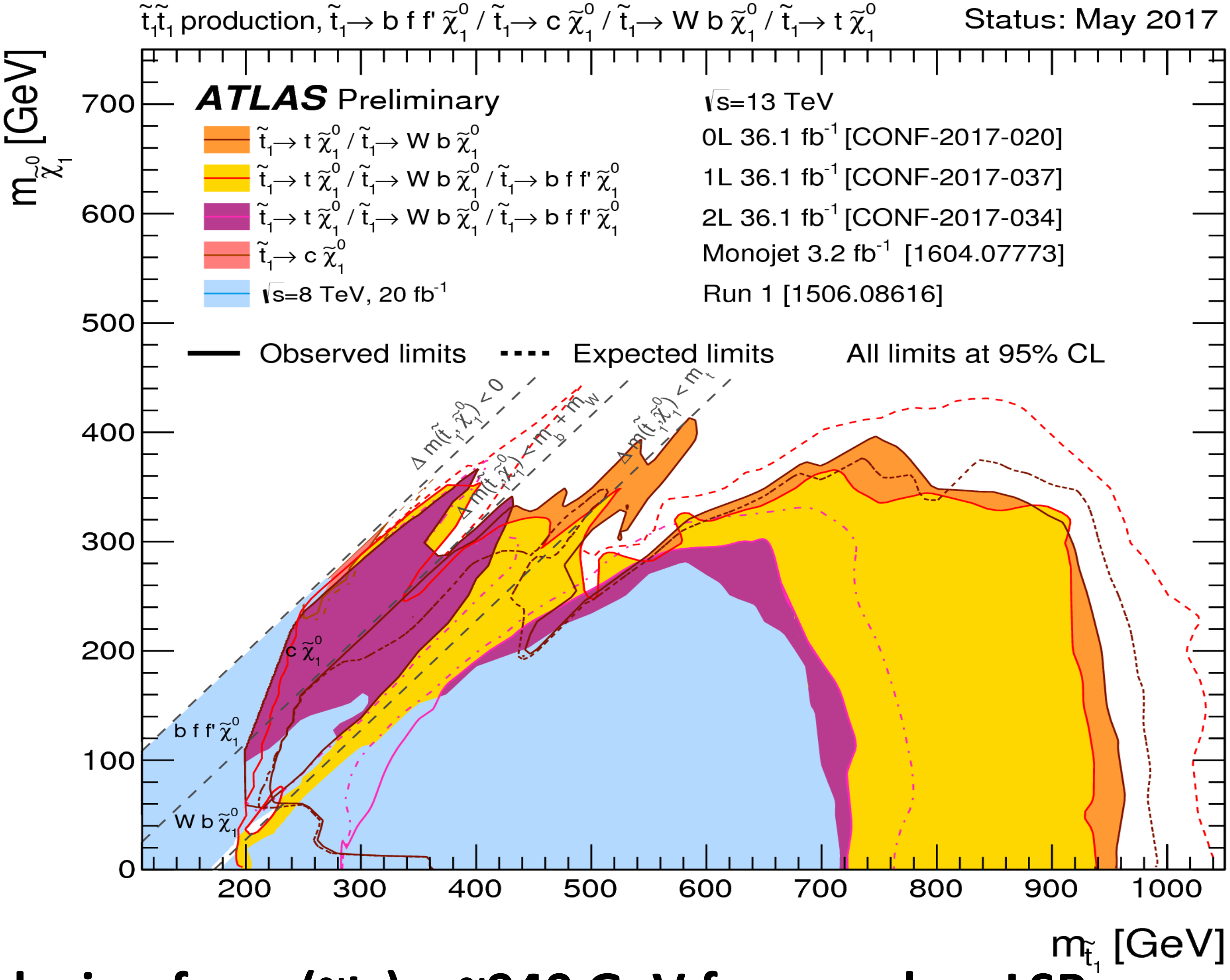




masses between the top quark mass and 191 GeV are excluded

Summary Searches for Stop

(different mass hierarchies, simplified models)



May 2017

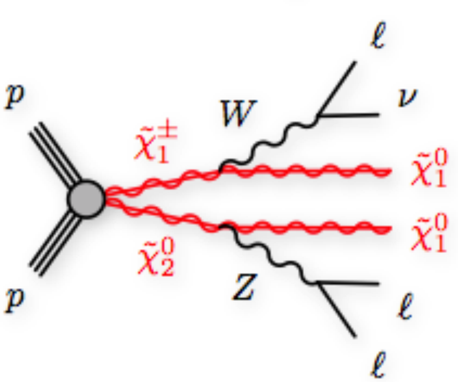
Exclusion for $m(\sim t_1) <$ ~940 GeV for massless LSP

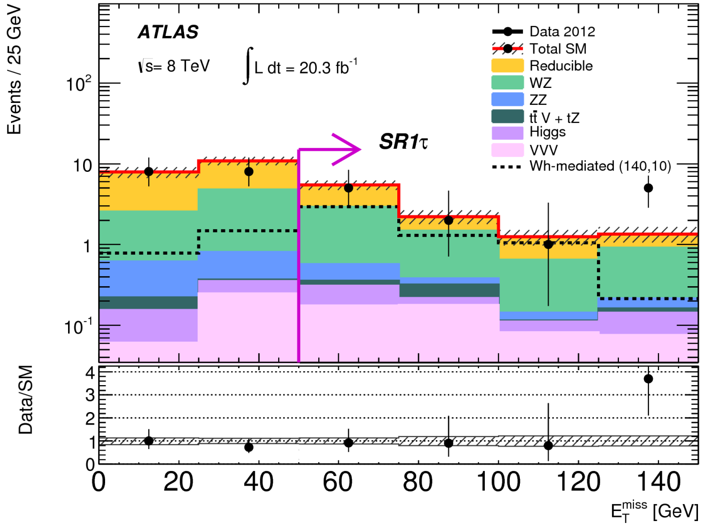
Exclusion up to m(LSP) ~400 GeV

JHEP04(2014)169

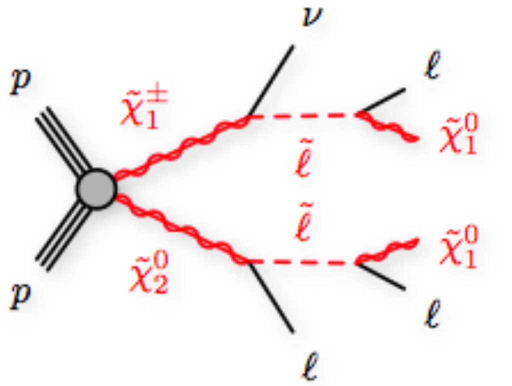
Chargino/Neutralino

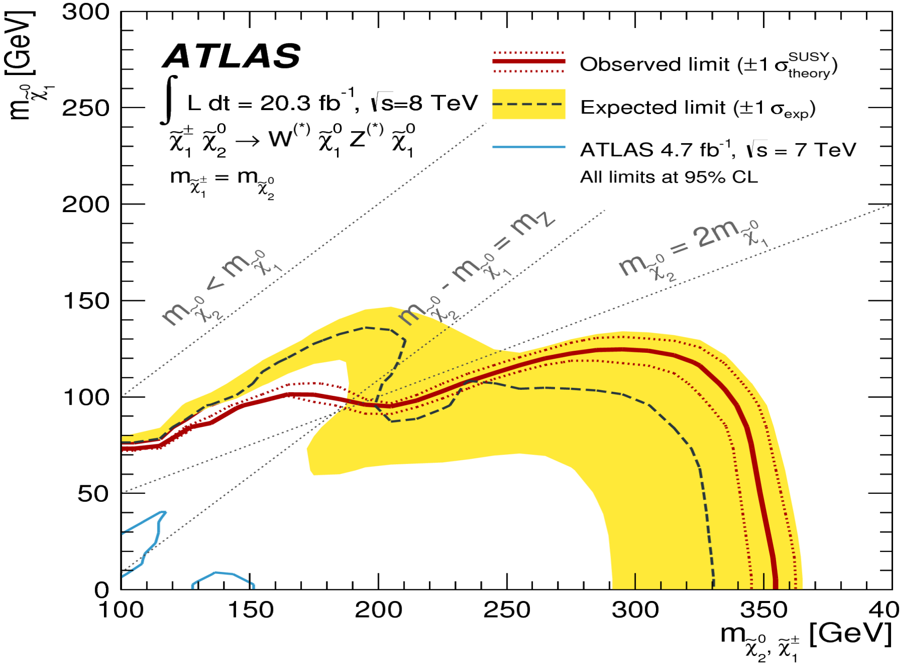
3 leptons + E_T^{miss}

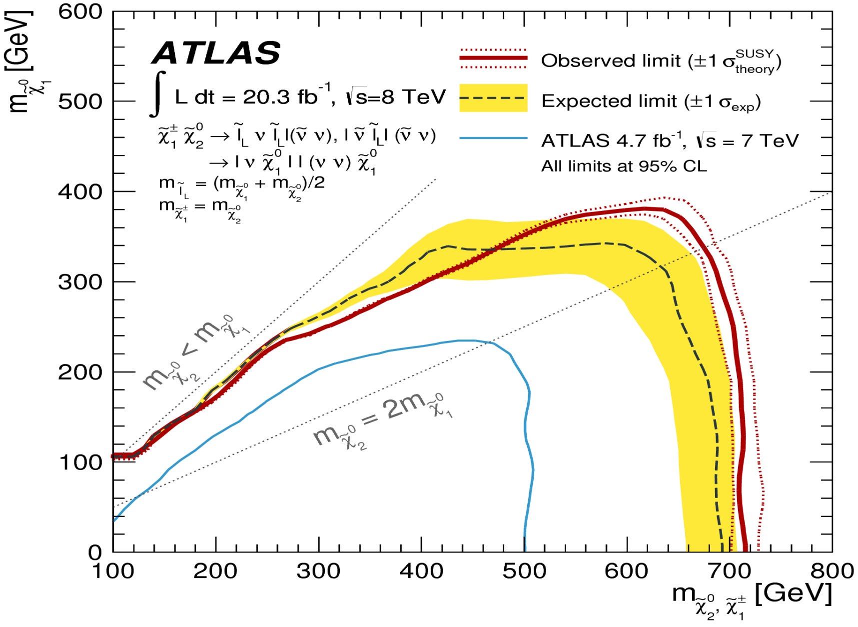




Background mostly WZ, ZZ followed by ttV and tribosons

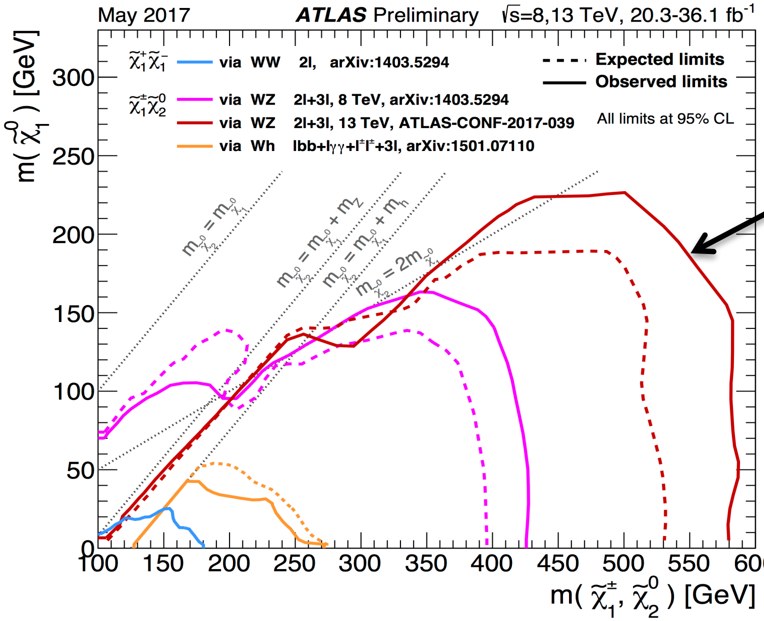


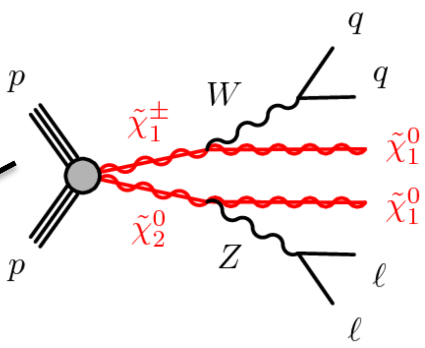




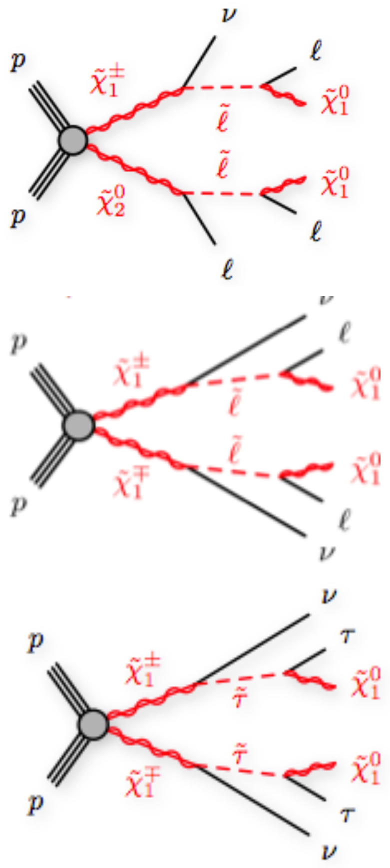
EWK production

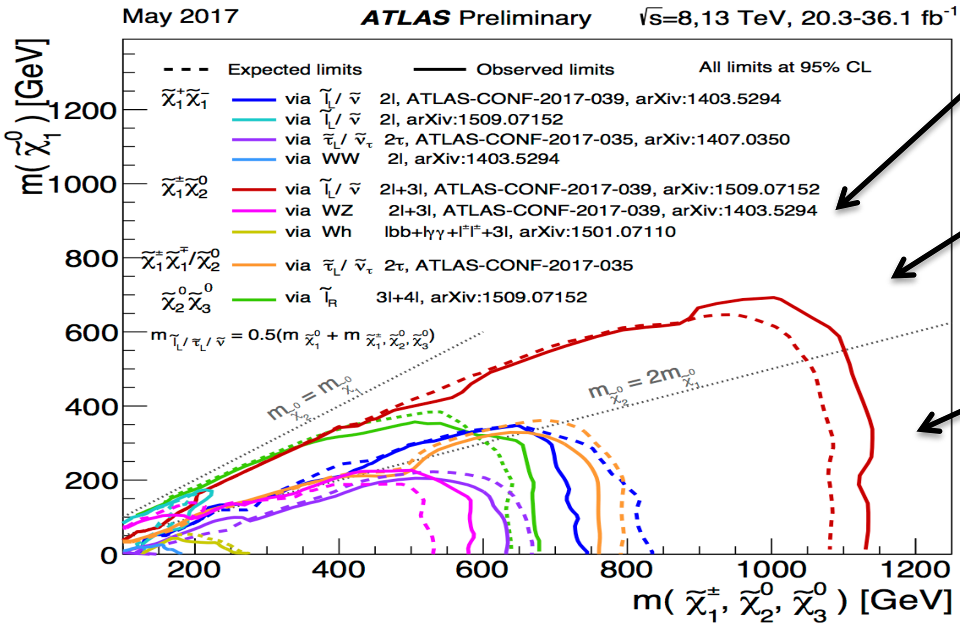
MAY 2017





2 or 3 leptons + E_T^{miss}





Chargino mass > ~1100 GeV

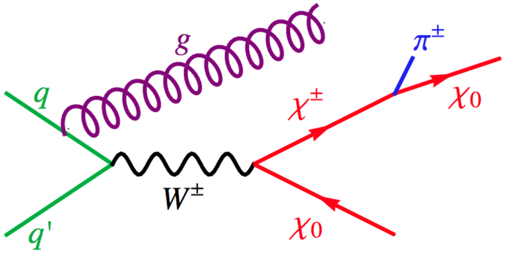
Neutralino mass > 600 GeV

Very sensitive to the details of the scenario considered

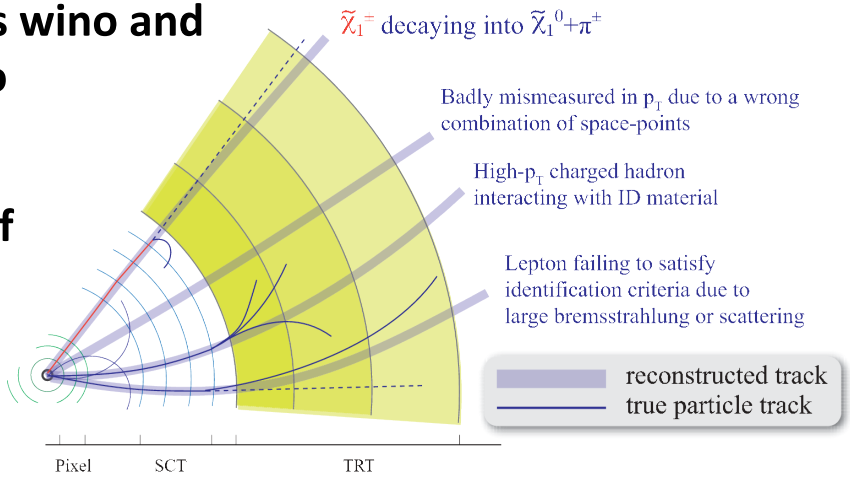
Phys. Rev. D 88 112006 (2013)

Disappearing track

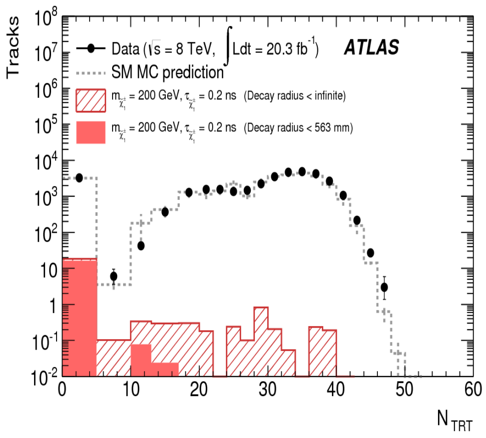
In AMSB model where the lightest chargino (N)LSP is wino and nearly mass-degenerate with the lightest neutralino

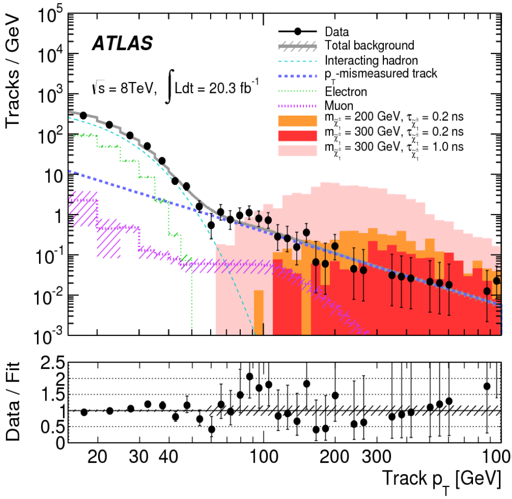


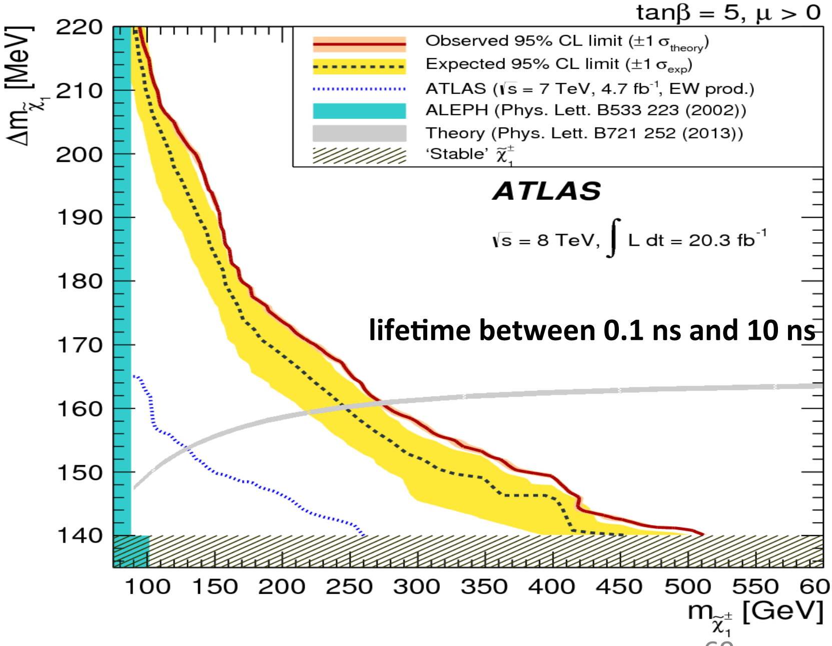
The signal reveals itself as disappearing tracks in the outer ID volume



At least one jet with PT > 90 GeV, Etmiss > 90 GeV
Lepton (electron and muon) vetoes
One good isolated track with pT > 15 GeV
and less than 5 hits in the TRT







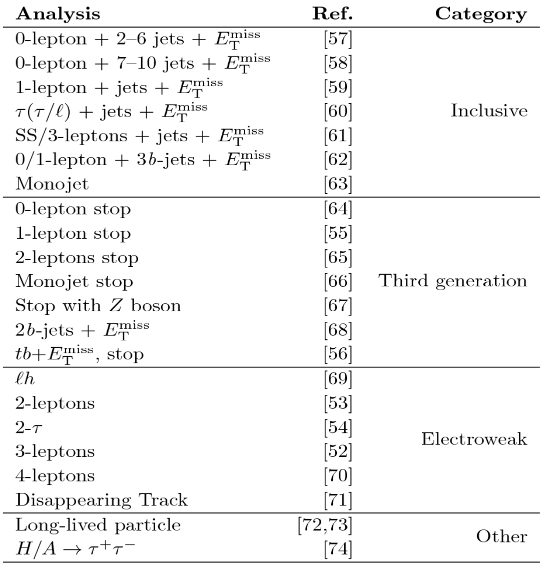
lifetime between 0.1 ns and 10 ns

A chargino mass below 270 GeV is excluded at 95% CL

pMSSM

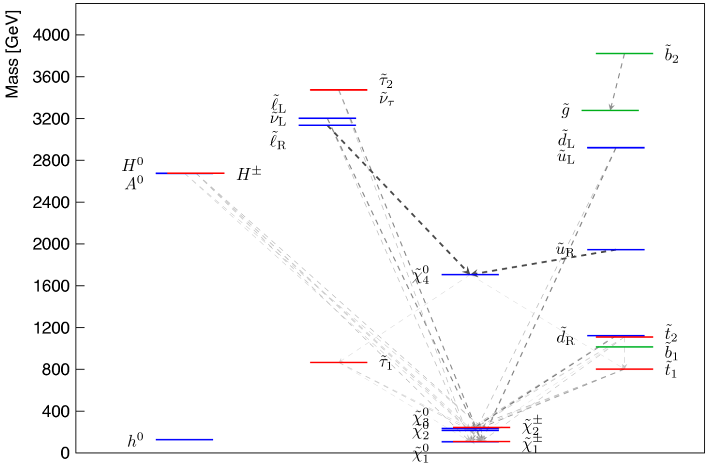
arXiv:1508.06608

Up to 22 different ATLAS searches considered

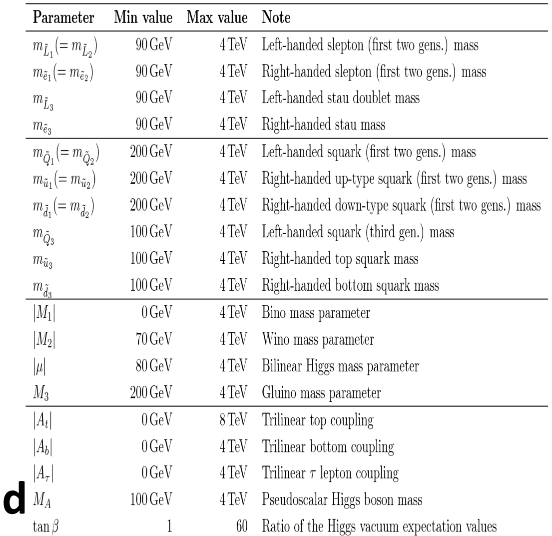


Analysis	Ref.	Category
0-lepton + 2–6 jets + E_T^{miss}	[57]	Inclusive
0-lepton + 7–10 jets + E_T^{miss}	[58]	
1-lepton + jets + E_T^{miss}	[59]	
$\tau(\tau/\ell)$ + jets + E_T^{miss}	[60]	
SS/3-leptons + jets + E_T^{miss}	[61]	
0/1-lepton + 3b-jets + E_T^{miss}	[62]	
Monojet	[63]	
0-lepton stop	[64]	Third generation
1-lepton stop	[55]	
2-leptons stop	[65]	
Monojet stop	[66]	
Stop with Z boson	[67]	
2b-jets + E_T^{miss}	[68]	
tb+E_T^{miss}, stop	[56]	
ℓh	[69]	Electroweak
2-leptons	[53]	
2-τ	[54]	
3-leptons	[52]	
4-leptons	[70]	
Disappearing Track	[71]	
Long-lived particle	[72,73]	Other
$H/A \to \tau^+\tau^-$	[74]	

One example of particle spectra

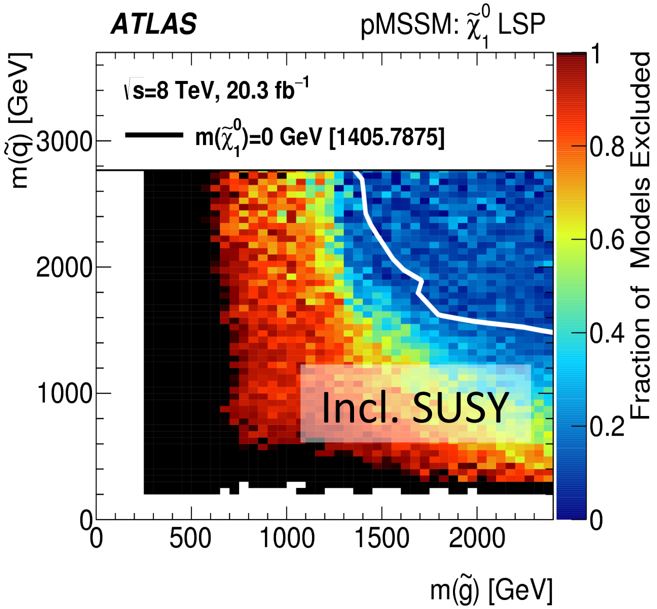


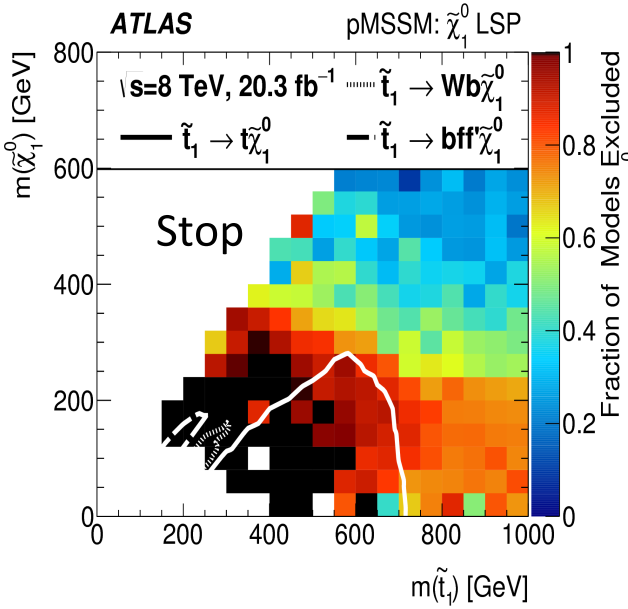
The results are interpreted in the context of 19-parameter

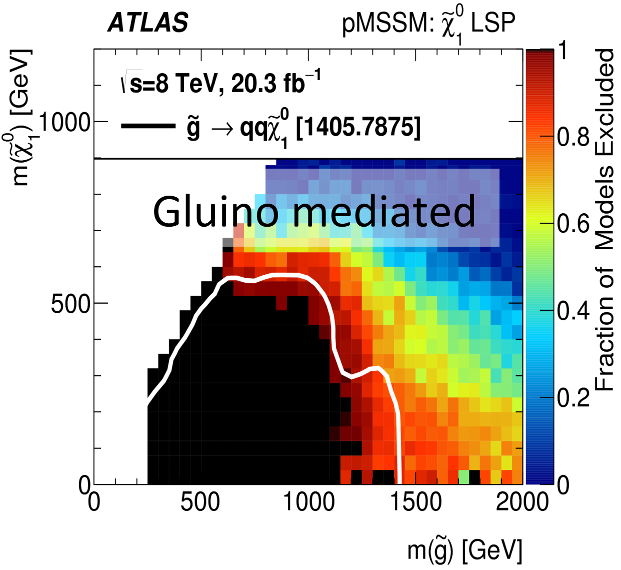


Parameter	Min value	Max value	Note
$m_{\tilde{L}_1}(=m_{\tilde{L}_2})$	90 GeV	4 TeV	Left-handed slepton (first two gens.) mass
$m_{\tilde{e}_1}(=m_{\tilde{e}_2})$	90 GeV	4 TeV	Right-handed slepton (first two gens.) mass
$m_{\tilde{L}_3}$	90 GeV	4 TeV	Left-handed stau doublet mass
$m_{\tilde{e}_3}$	90 GeV	4 TeV	Right-handed stau mass
$m_{\tilde{Q}_1}(=m_{\tilde{Q}_2})$	200 GeV	4 TeV	Left-handed squark (first two gens.) mass
$m_{\tilde{u}_1}(=m_{\tilde{u}_2})$	200 GeV	4 TeV	Right-handed up-type squark (first two gens.) mass
$m_{\tilde{d}_1}(=m_{\tilde{d}_2})$	200 GeV	4 TeV	Right-handed down-type squark (first two gens.) mass
$m_{\tilde{Q}_3}$	100 GeV	4 TeV	Left-handed squark (third gen.) mass
$m_{\tilde{u}_3}$	100 GeV	4 TeV	Right-handed top squark mass
$m_{\tilde{d}_3}$	100 GeV	4 TeV	Right-handed bottom squark mass
$\|M_1\|$	0 GeV	4 TeV	Bino mass parameter
$\|M_2\|$	70 GeV	4 TeV	Wino mass parameter
$\|\mu\|$	80 GeV	4 TeV	Bilinear Higgs mass parameter
M_3	200 GeV	4 TeV	Gluino mass parameter
$\|A_t\|$	0 GeV	8 TeV	Trilinear top coupling
$\|A_b\|$	0 GeV	4 TeV	Trilinear bottom coupling
$\|A_\tau\|$	0 GeV	4 TeV	Trilinear τ lepton coupling
M_A	100 GeV	4 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

Fraction of pMSSM models excluded (in general, similar to simplified models)







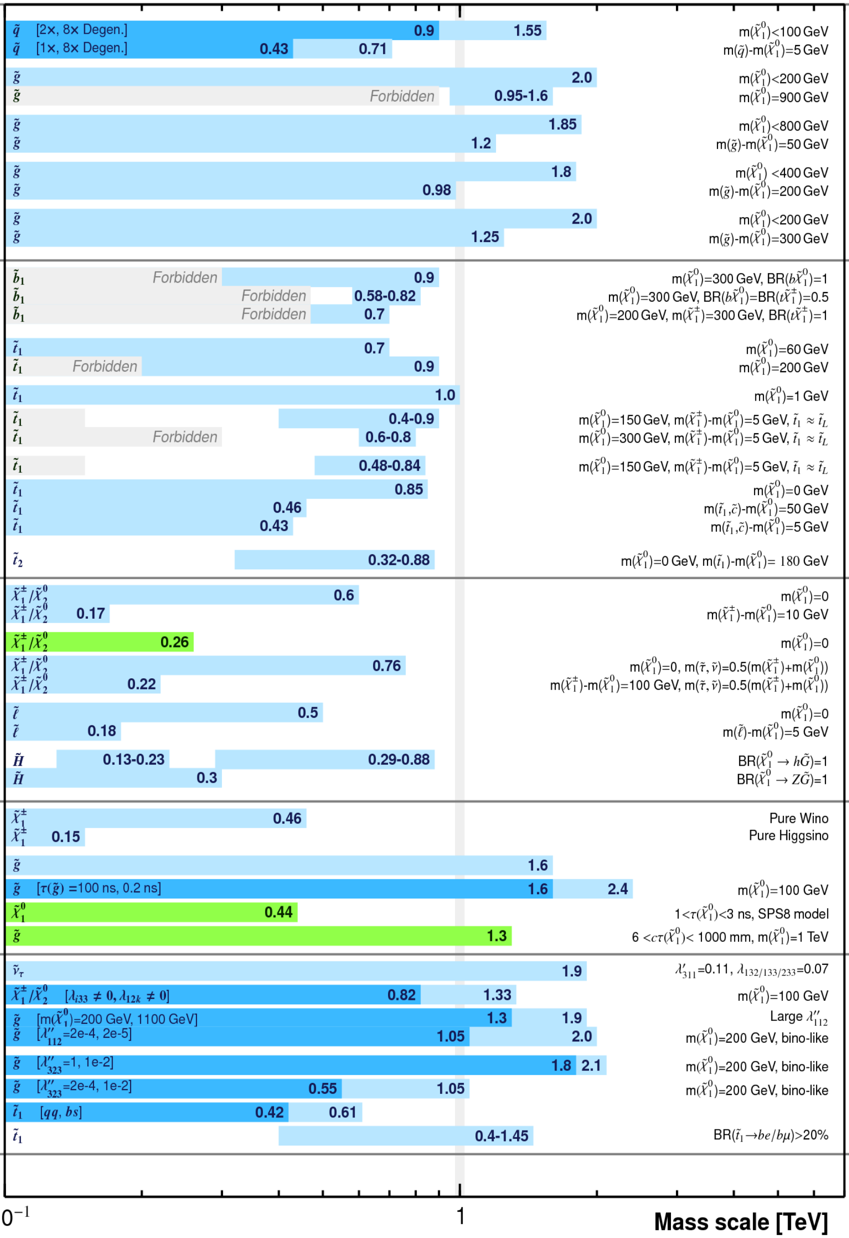
ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

July 2018

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

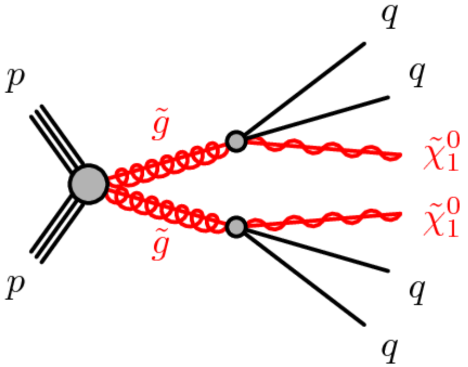


	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.]	0.9 1.55	m($\tilde{\chi}^0_1$)<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.]	0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.0	m($\tilde{\chi}^0_1$)<200 GeV	1712.02332
						$\tilde{g}$ Forbidden	0.95-1.6	m($\tilde{\chi}^0_1$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	36.1	$\tilde{g}$	1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	Yes	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-11 jets	Yes	36.1	$\tilde{g}$	1.8	m($\tilde{\chi}^0_1$) <400 GeV	
		3 e,μ	4 jets	-	36.1	$\tilde{g}$	0.98	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$	2.0	m($\tilde{\chi}^0_1$)<200 GeV	
		3 e,μ	4 jets	-	36.1	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$ Forbidden	0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	
			Multiple		36.1	$\tilde{b}_1$ Forbidden	0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	
			Multiple		36.1	$\tilde{b}_1$ Forbidden	0.7	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$	0.7	m($\tilde{\chi}^0_1$)=60 GeV	1709.0
			Multiple		36.1	$\tilde{t}_1$ Forbidden	0.9	m($\tilde{\chi}^0_1$)=200 GeV	1709.0
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$	1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.0
	$\tilde{t}_1\tilde{t}_1, \tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$	0.4-0.9	m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	
			Multiple		36.1	$\tilde{t}_1$ Forbidden	0.6-0.8	m($\tilde{\chi}^0_1$)=300 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$	0.48-0.84	m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}^0_1$	0	2c	Yes	36.1	$\tilde{t}_1$	0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$	0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.17	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=10 GeV	1712.08119
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.26	m($\tilde{\chi}^0_1$)=0	1501.07110
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2, \tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}^0_2\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.76	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
						$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.22	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=100 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$	0.5	m($\tilde{\chi}^0_1$)=0	1803.02762
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$	0.18	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1 \to h\tilde{G}$)=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}^0_1 \to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}^\pm_1$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$	0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$	1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns]	1.6 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$	0.44	1<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$	1.3	6 <$c\tau(\tilde{\chi}^0_1)$< 1000 mm, m($\tilde{\chi}^0_1$)=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$]	0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1 \to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV]	1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5]	1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g} \to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1, \tilde{\chi}^0_1 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2]	1.8 2.1	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

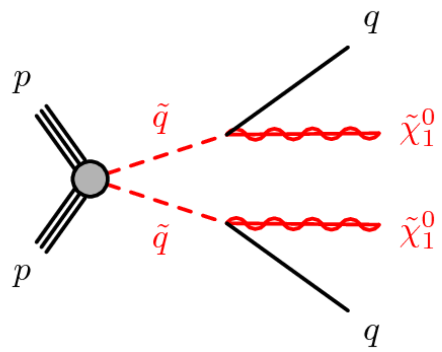
ATL-PHYS-PUB-2013-011
ATL-PHYS-PUB-2014-010

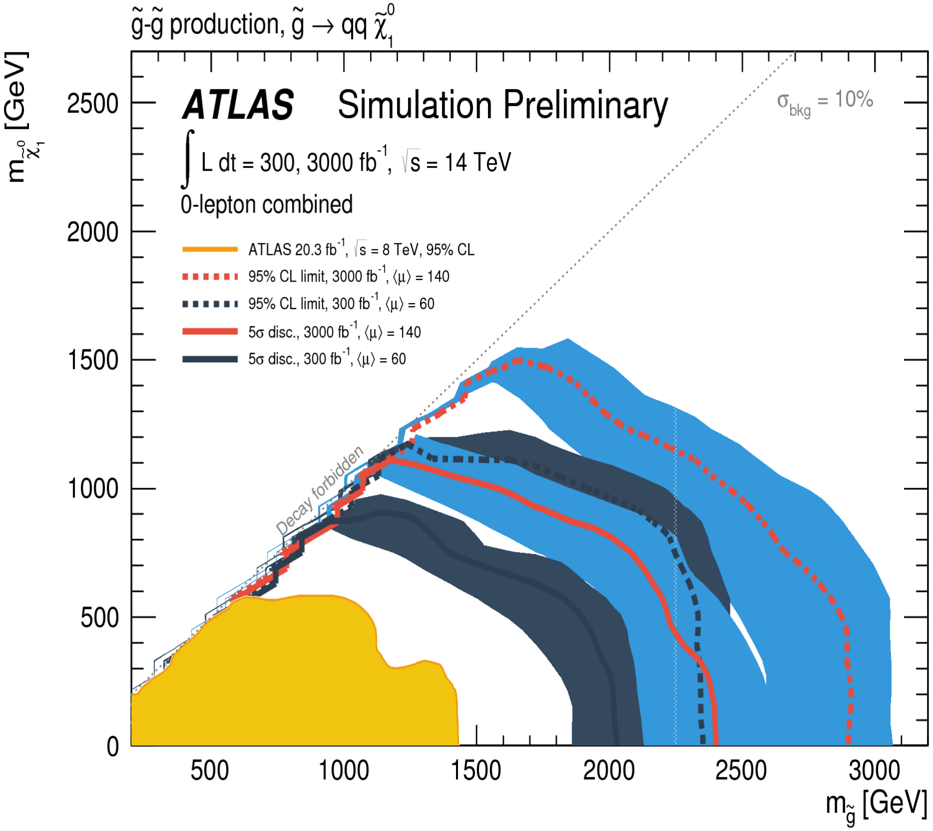
HL-LHC prospects

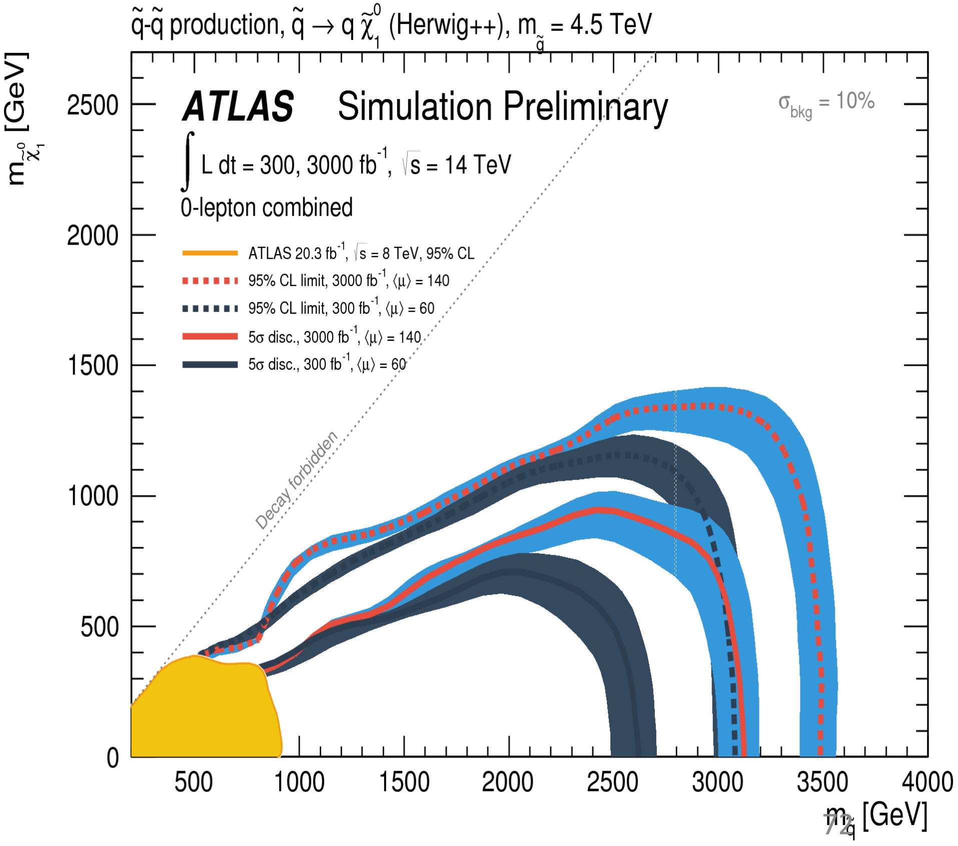


Will be in the position to “kill natural SUSY”

Sensitivity up to 3 – 3.5 TeV

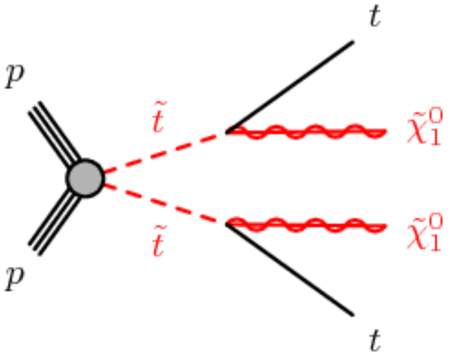






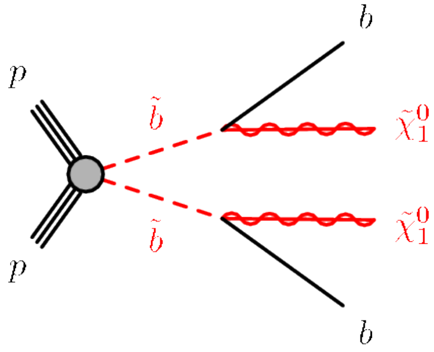
ATL-PHYS-PUB-2013-011
ATL-PHYS-PUB-2014-010

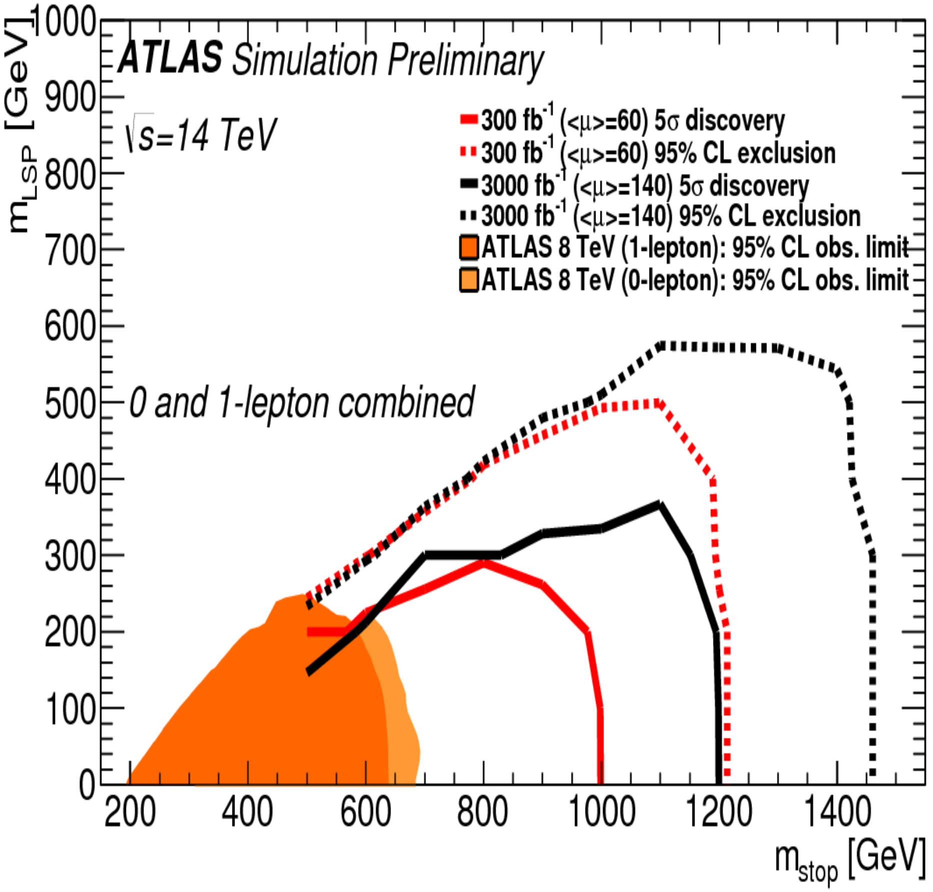
HL-LHC prospects

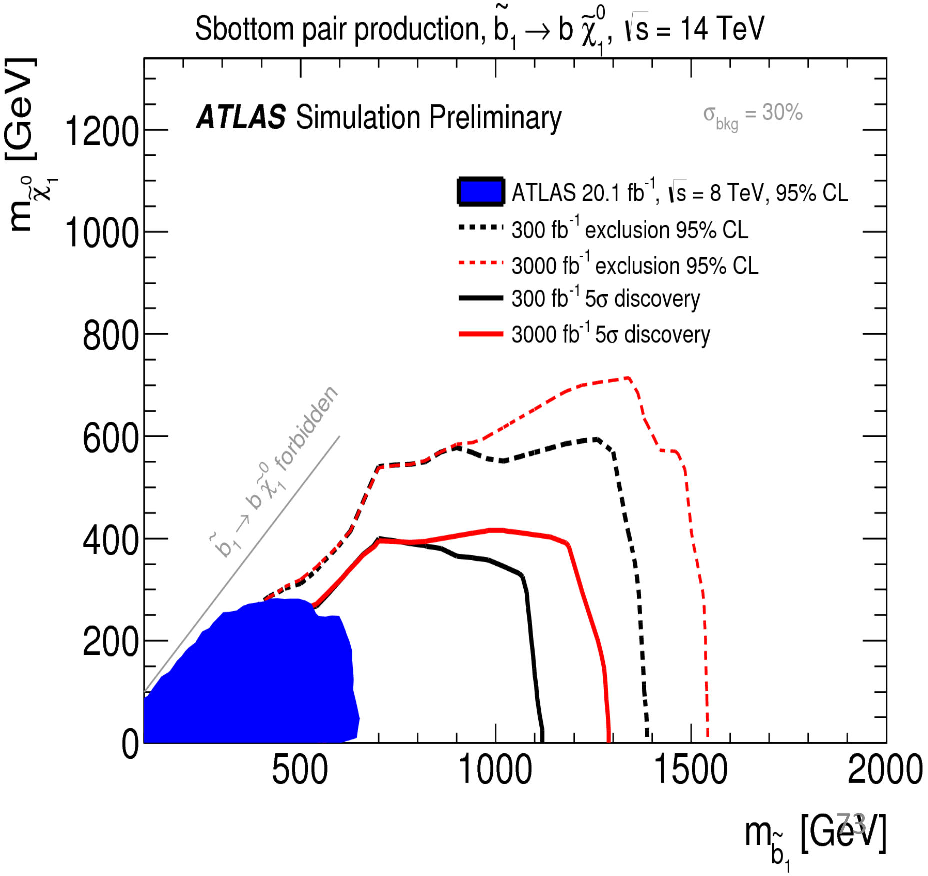


Will be in the position to “kill natural SUSY”

Sensitivity up to 1 – 1.5 TeV

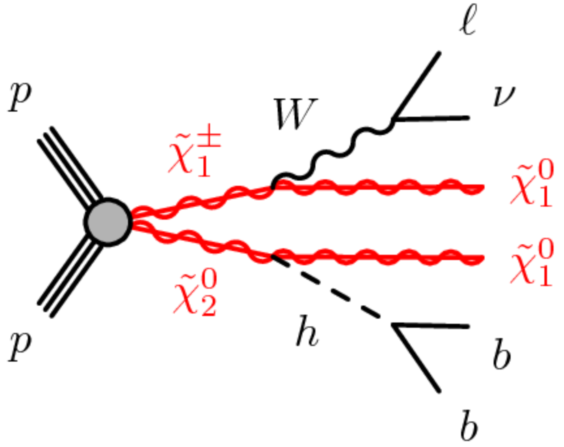






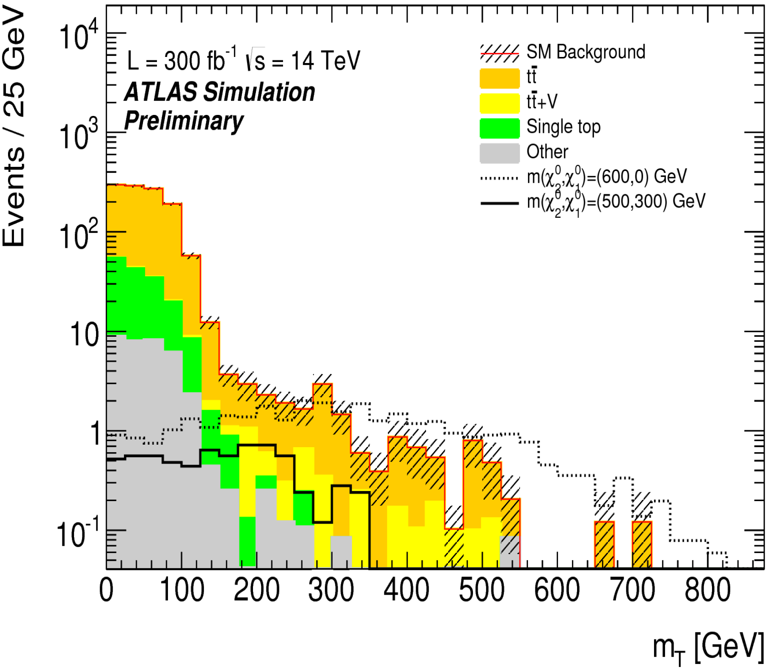
ATL-PHYS-PUB-2015-032

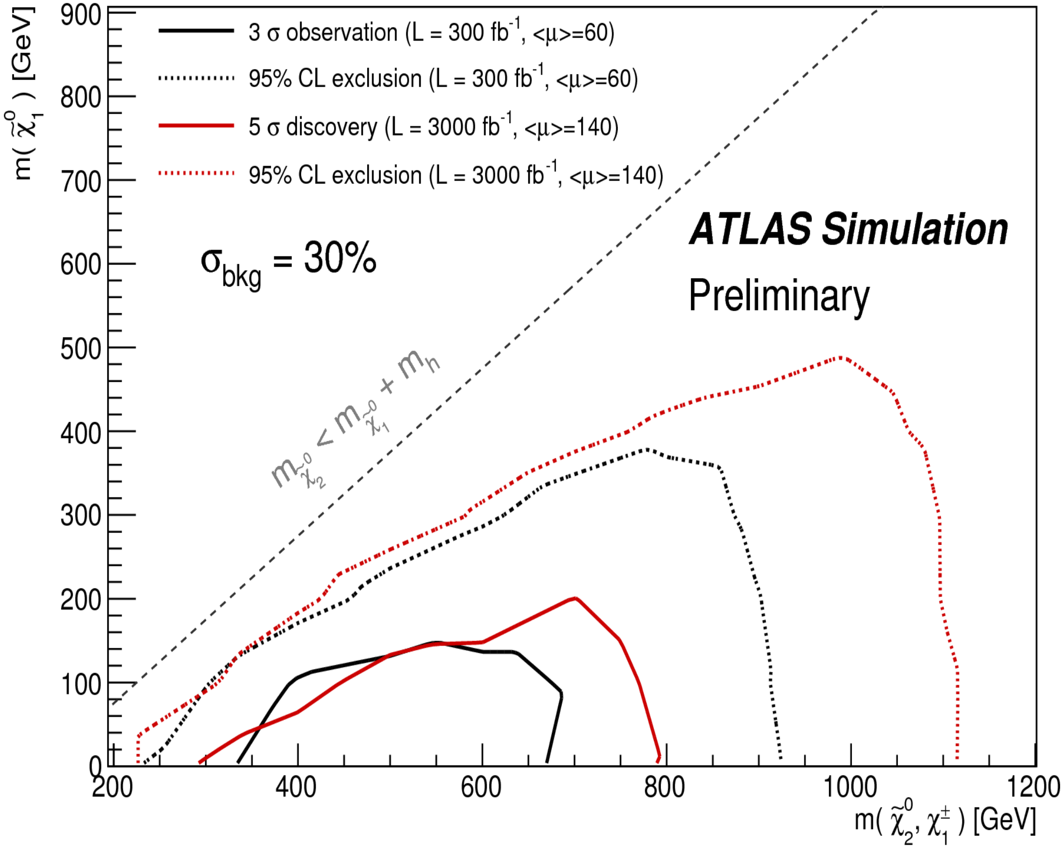
HL-LHC prospects



SUSY Weakly interacting

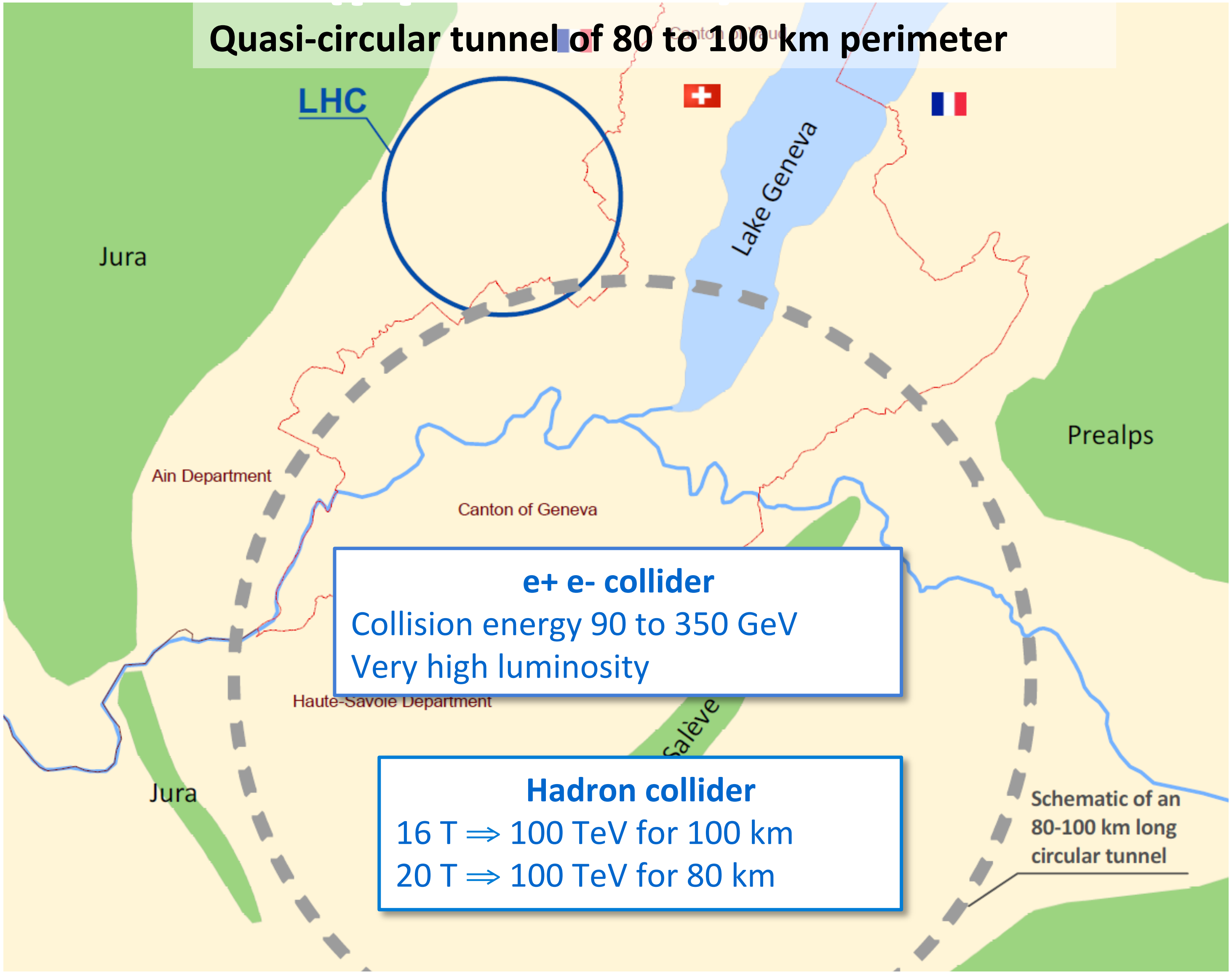
Sensitivity up to 1.1 TeV





Only time will tell…..

Quasi-circular tunnel of 80 to 100 km perimeter



Schematic of an 80-100 km long circular tunnel

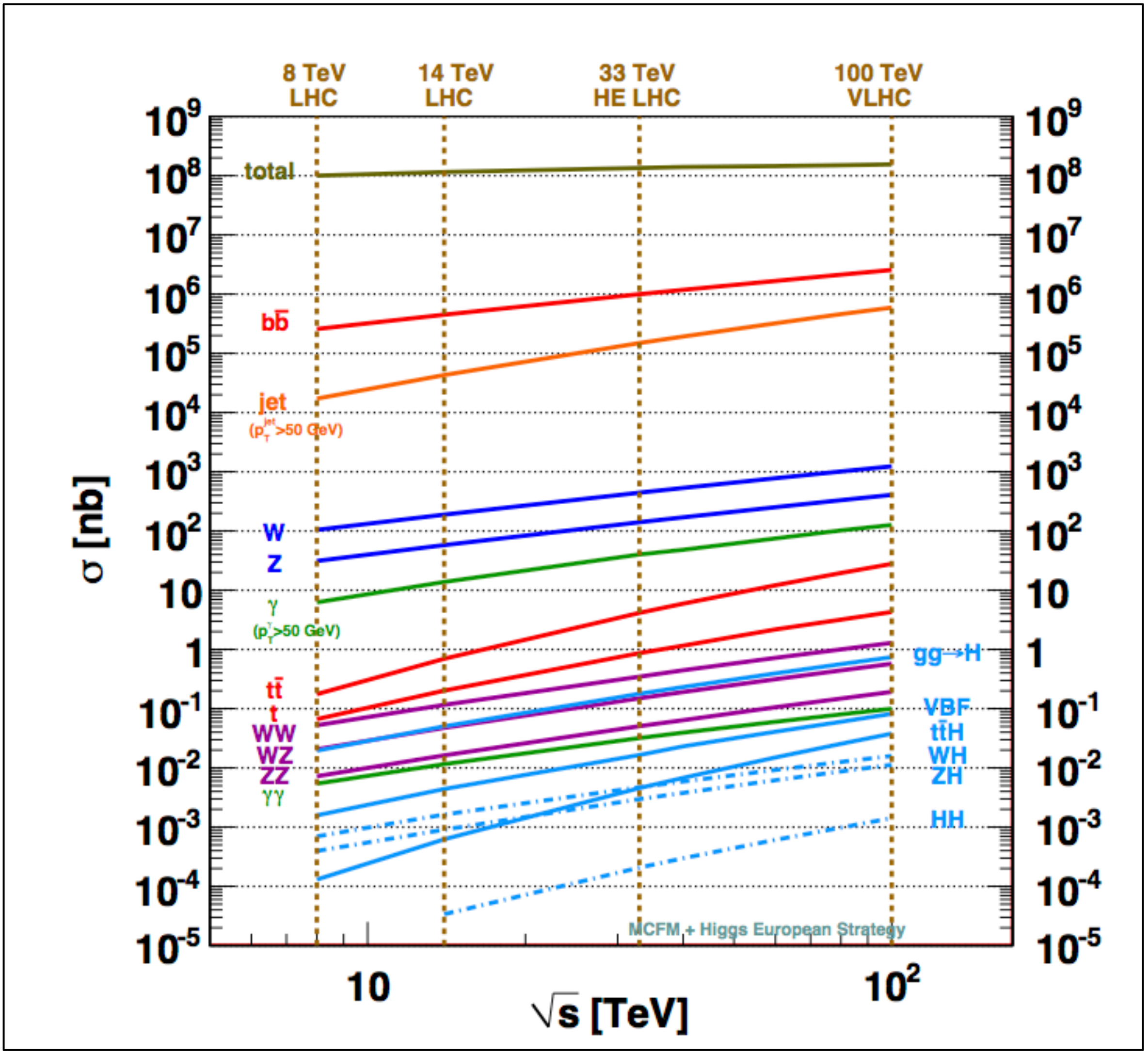
e+ e- collider
Collision energy 90 to 350 GeV
Very high luminosity

Hadron collider
16 T ⇒ 100 TeV for 100 km
20 T ⇒ 100 TeV for 80 km

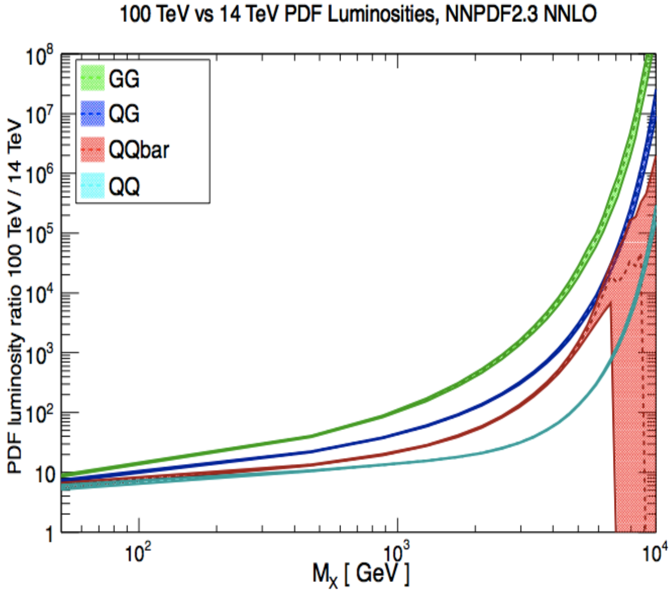
Key technologies are high-field magnets for the hadron collider and an efficient high-power superconducting RF (SRF) system for the lepton collider.

Snowmass report: arXiv:1310.5189

100 TeV pp collisions

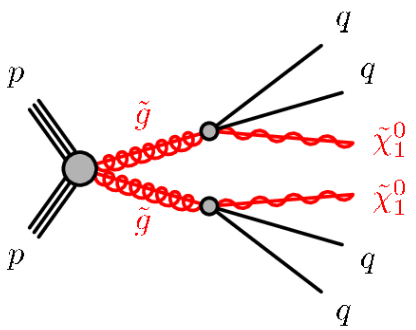


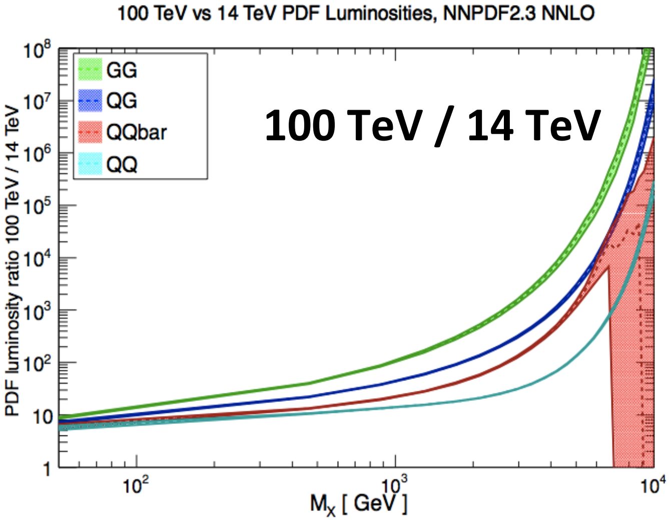
Process	σ (100 TeV)/σ (14 TeV)
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

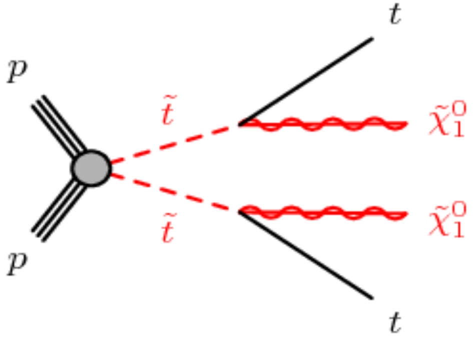


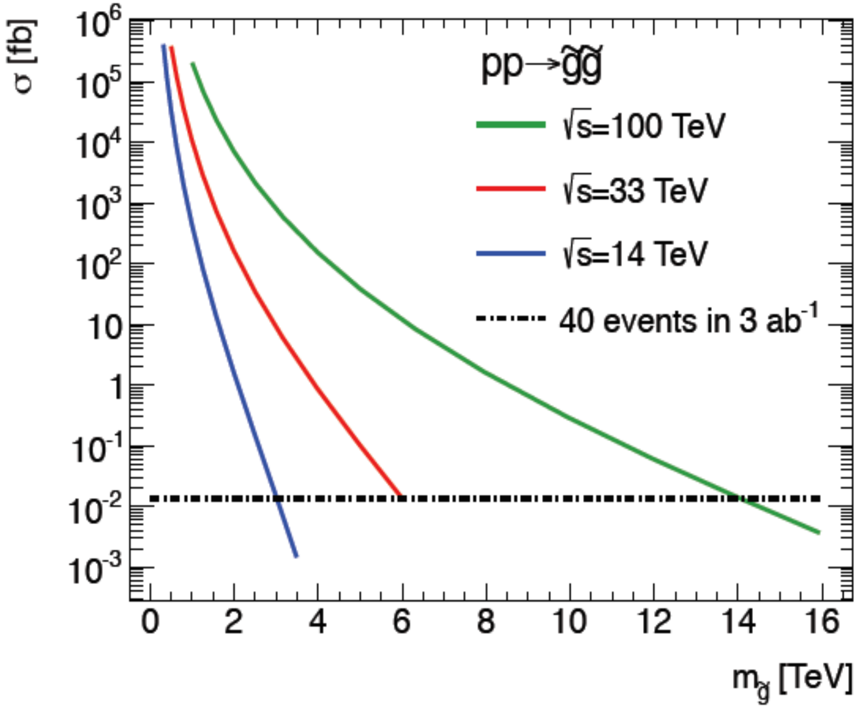
It really opens a new energy frontier---

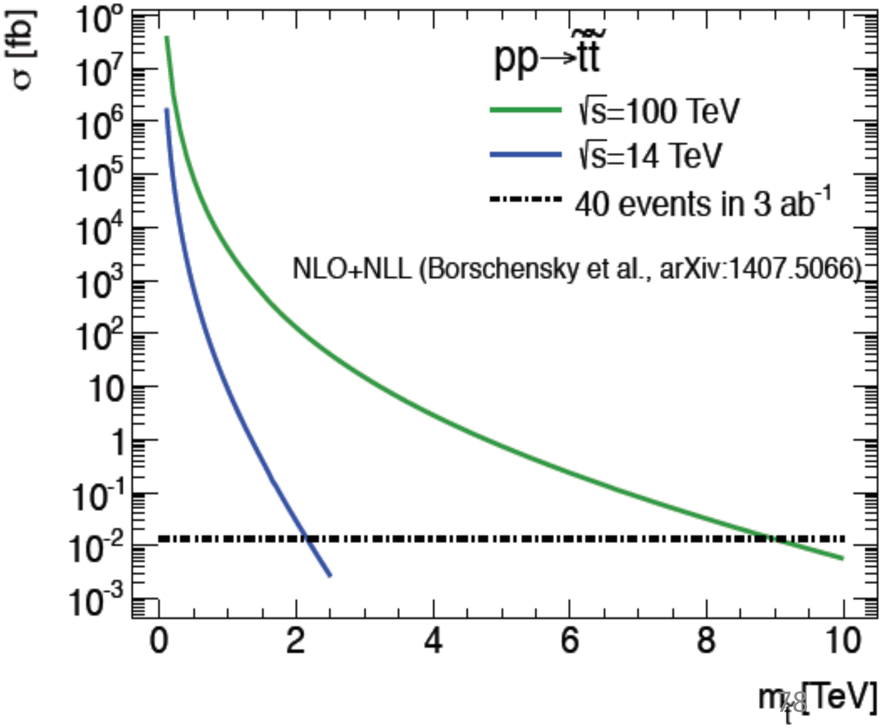
SUSY Reach for pp @ 100 TeV



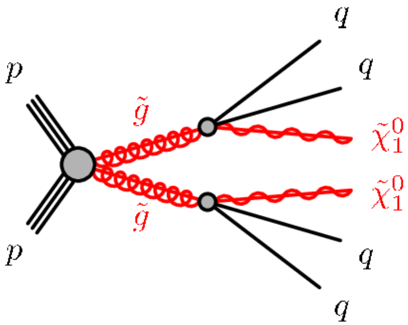






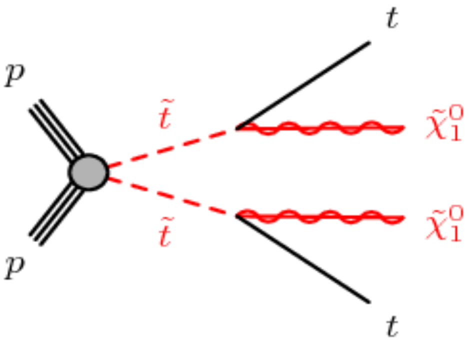


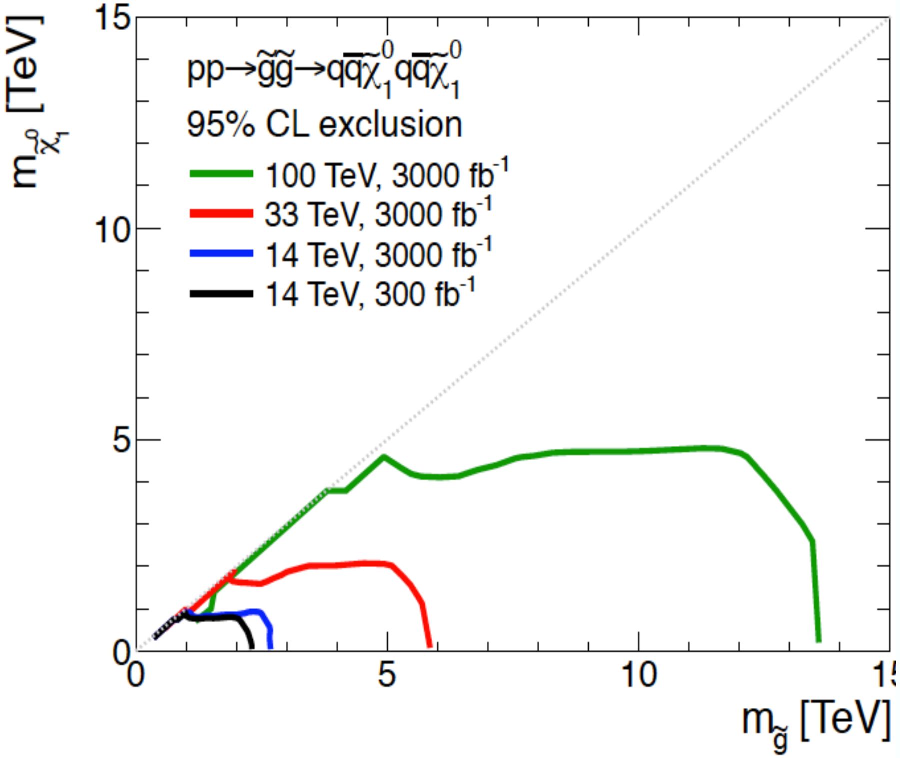
SUSY Reach for pp @ 100 TeV

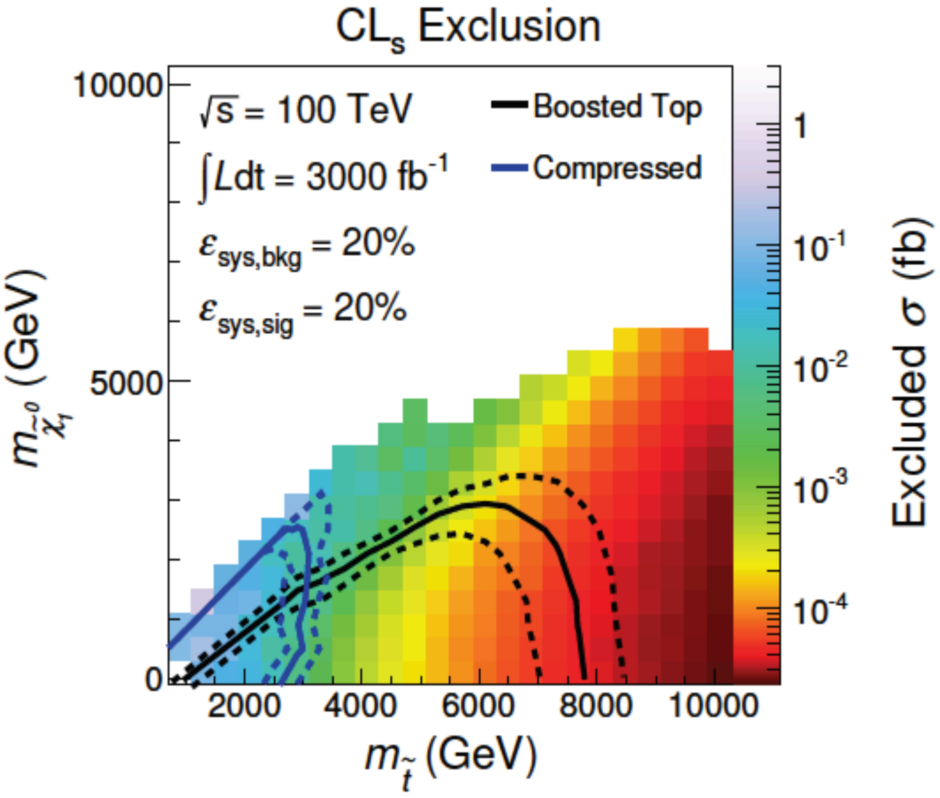


In terms of Higgs/EWK hierarchy problem

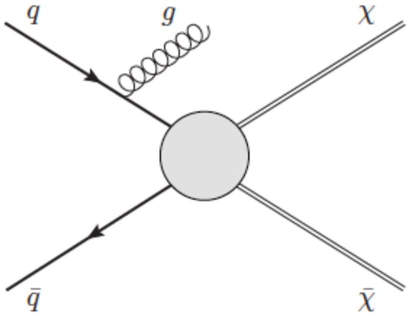
This scenario implies a tuning of the level of 0.05%



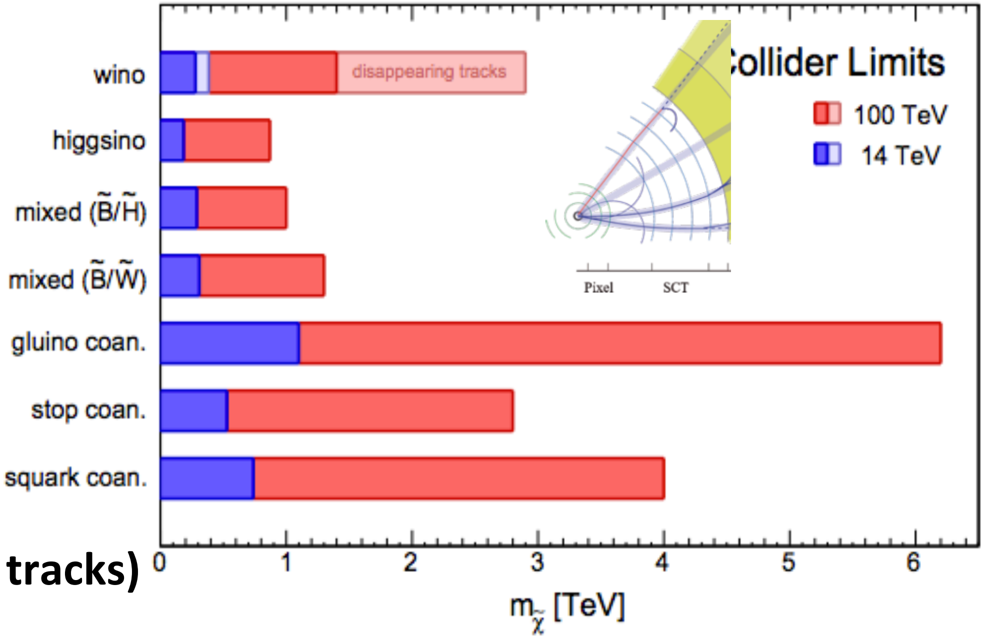


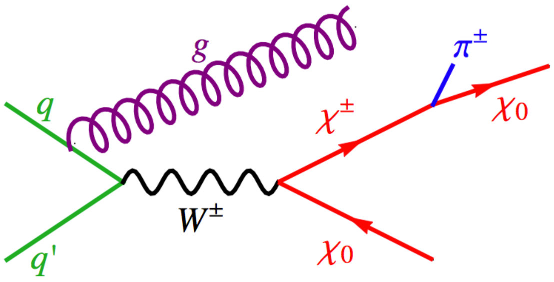


SUSY EWK @ 100 TeV

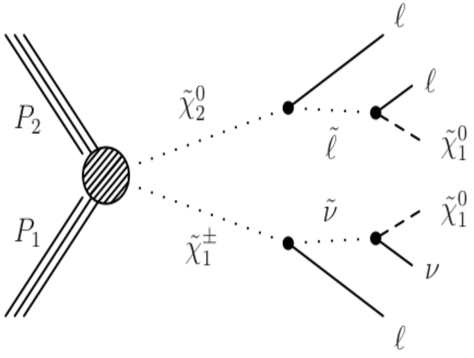


Monojets

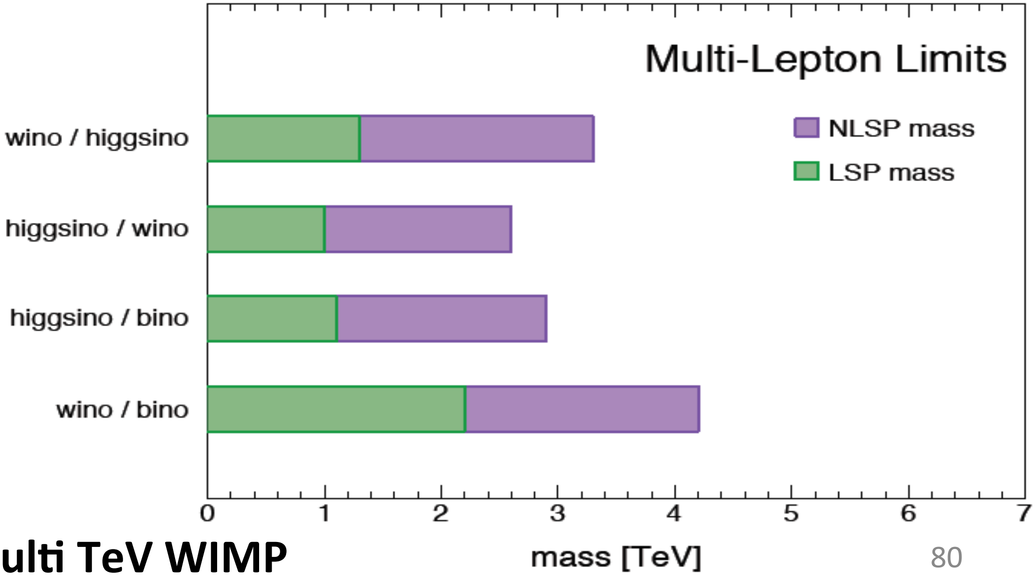




Long-lived (disappearing tracks)



Multileptons



A 100 TeV pp collider would probe the multi TeV WIMP

End Part III