La Supersymétrie : résultats de recherche au LHC

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Marie-Hélène Genest

Séminaire du LPSC

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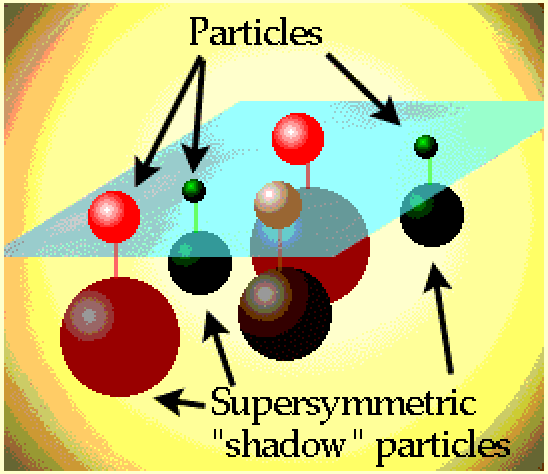
Plan

- Part 0: Cookies and juice. Sadly already over (at least for me!).
- Part 1:
  - What is Supersymmetry (SUSY) ?
    - A new symmetry
    - The predictions
    - The motivations behind introducing SUSY
- Part 2:
  - Looking for SUSY at the LHC
    - LHC / ATLAS
    - What do we expect?
    - What are the backgrounds?
    - Some search examples

PART 1:
WHAT IS SUSY



Symmetries

- The Pointcaré group is full symmetry of special relativity ; relativistic invariance is given by invariance under :

  - translations in space and time

  - rotations in space

  - boosts

- In particle physics, one also has internal symmetries (symmetries in an abstract space), which relate similar types of particles

  An example : the weak interaction is invariant under a rotation in the 'weak isospin' space. Such a rotation would for example convert an electron into its associated neutrino.

A bit of history

Can we add as many new symmetries as we want ?

- In the 60's, many attempts to combine internal symmetries with spacetime symmetries

- But it was proven to be impossible in 1967 by Coleman and Mandula : any such combination would overconstrain the physics

« In a theory with non-trivial scattering in more than 1+1 dimensions, the only possible conserved quantities that transform as tensors under the Lorentz group are the energy-momentum P_μ , Lorentz transformations $M_{\mu\nu}$, and scalar quantum numbers (electric charge, lepton number,...). »

Another no-go with a loophole

<u>But there was one loophole:</u>

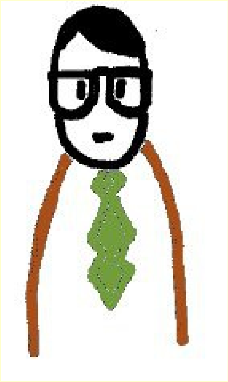
the no-go theorem assumed that the new charges should have integer spin

What about a spinorial charge Q ? This would not only be a way out, but the only possible extension of the Poincaré group

The simplest SUSY model

- We are thus allowed to introduce supersymmetry, a new symmetry which relates bosons and fermions through a spinorial operator, such that each known Standard Model particle gets associated to a new *superparticle* (or *sparticle* for short), denoted by a ~ above the particle symbol

$$|fermion\rangle$$



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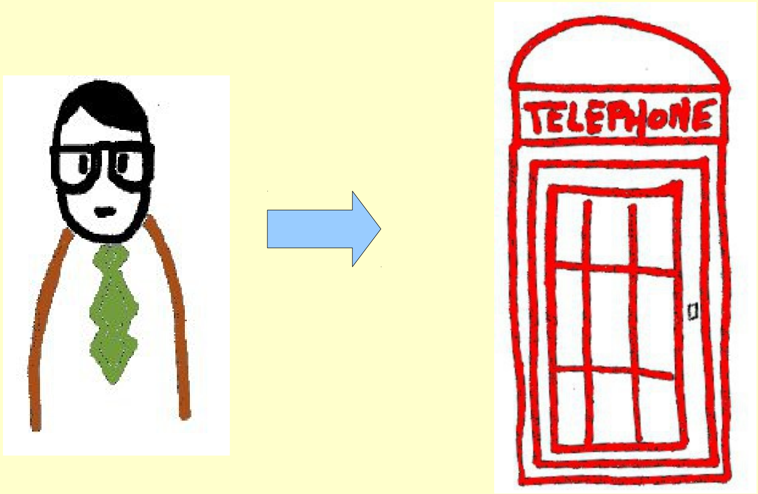
$$Q|fermion\rangle$$

Q itself has a spin ½

Somehow here, the phone booth analogy fails



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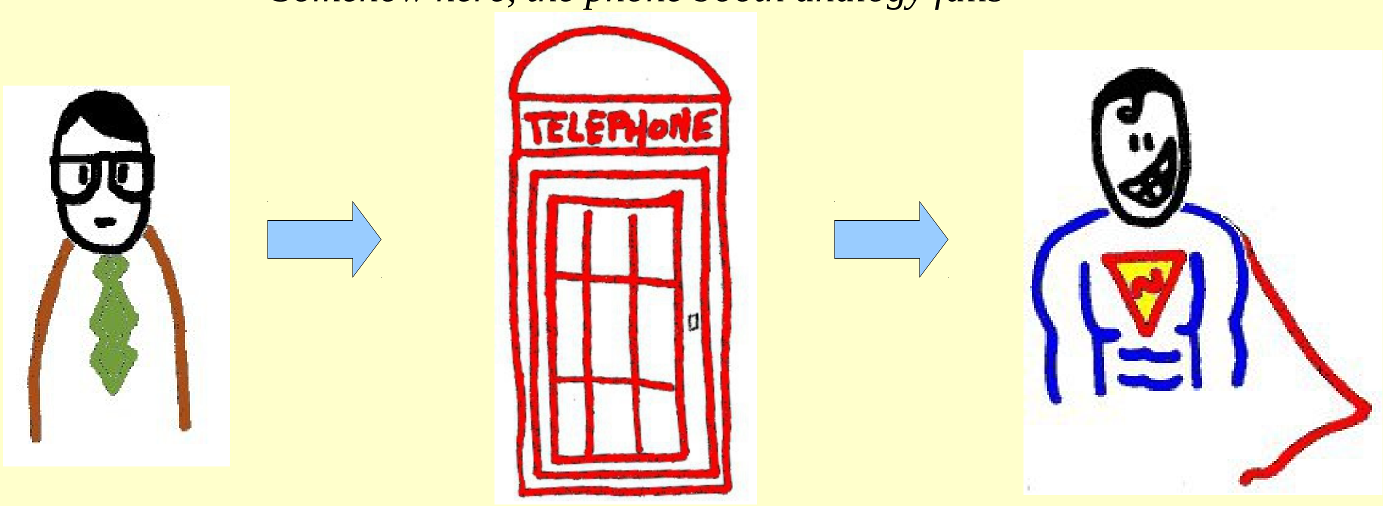

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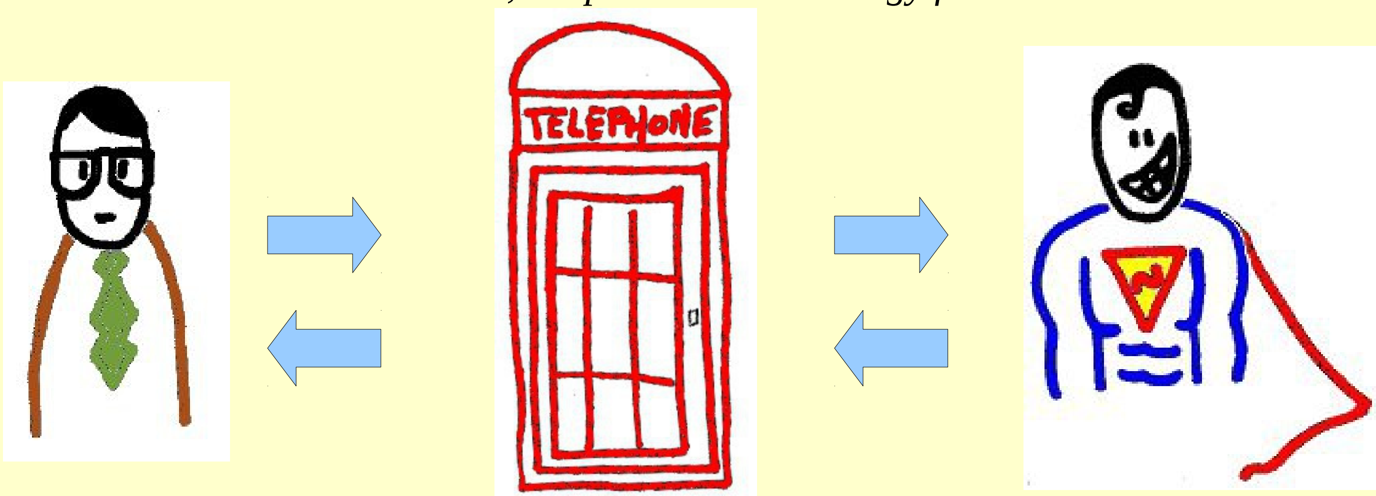

The simplest SUSY model

$$\{Q_a, \bar{Q}_b\} = -2\gamma^{\mu}_{ab} P_{\mu}$$

$$[P_{\mu}, Q_a] = 0$$

A SUSY transformation is the 'square root' of a spacetime translation !

Consequences:

- Each state has a spartner with spin difference ± ½
- Q commutes with P^2 and with the gauge transformation generators. The particle and its spartner therefore have:
  - The same mass ← *viable??? We will come back to this later*
  - The same electric charge
  - The same weak isospin
  - The same colour degrees of freedom

In other words, the same interactions as their SM partner…

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Supermultiplets

The particles are then grouped in supermultiplets:

- **The chiral ones** which contain a fermion (spin 1/2) and a boson (spin 0)

- **The vectorial ones** which contain a vector (spin 1) and a fermion (spin 1/2)

And, in a framework which includes gravity:

- **The gravitational one** which contains a Rarita-Schwinger particle, the gravitino (spin 3/2) and the graviton (spin 2).

For each : equal number of fermionic and bosonic degrees of freedom

So we double the number of particles: is that all?

Well, there is a bit more to say...

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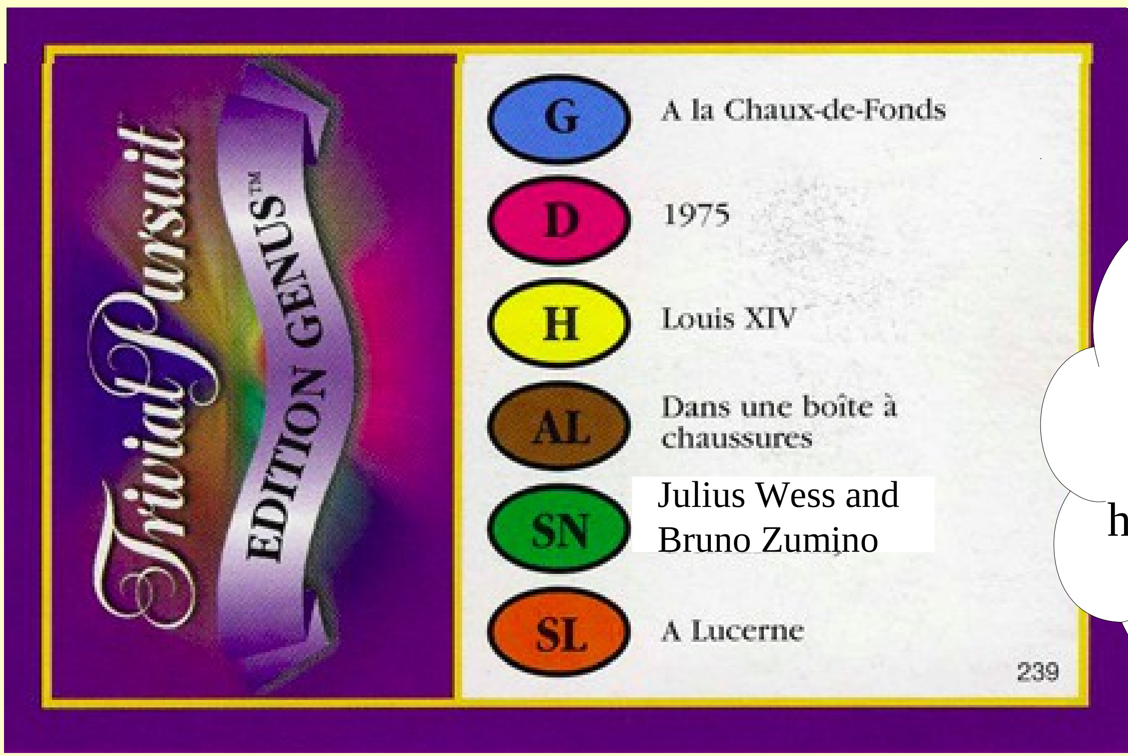
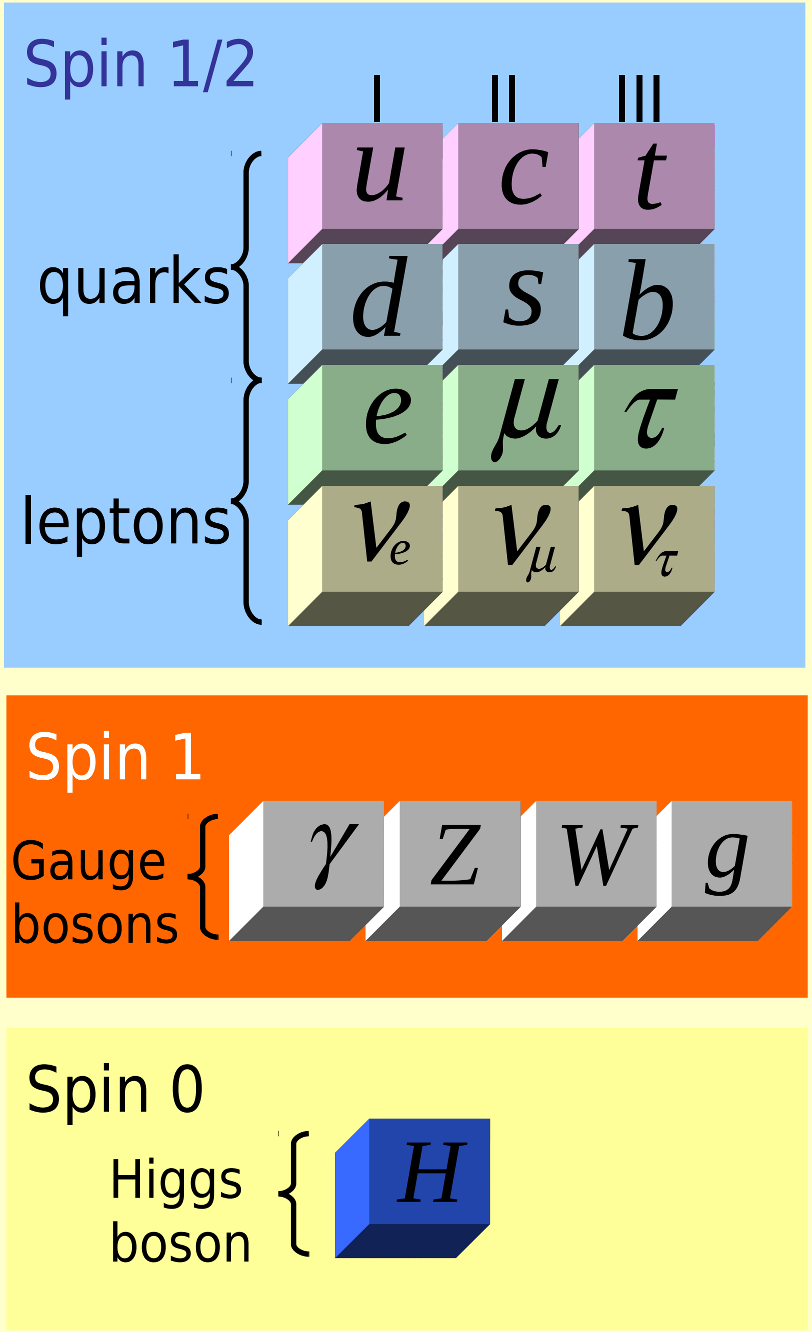
The culture corner

*This is **not** a paid placement*

Who wrote the first action invariant under supersymmetry, which contained only kinetic terms (massless, interactionless) for the scalar and fermion fields in 1974?



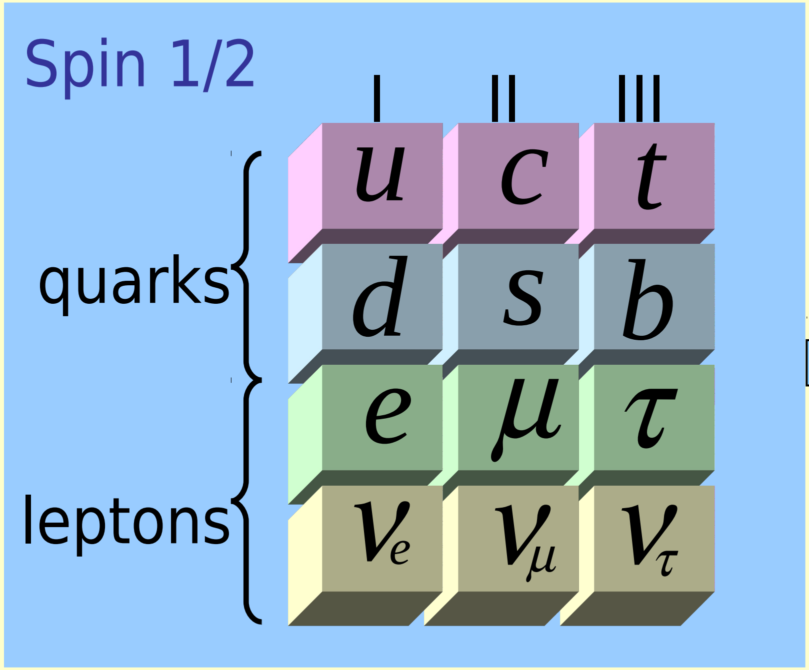
Ok, but we may want a more complete model... hopefully done since !

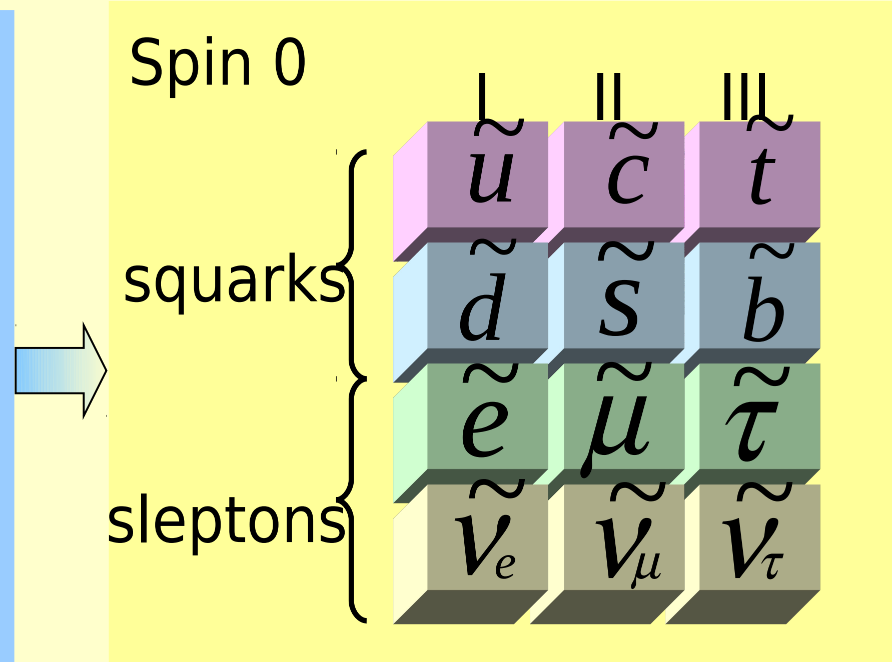


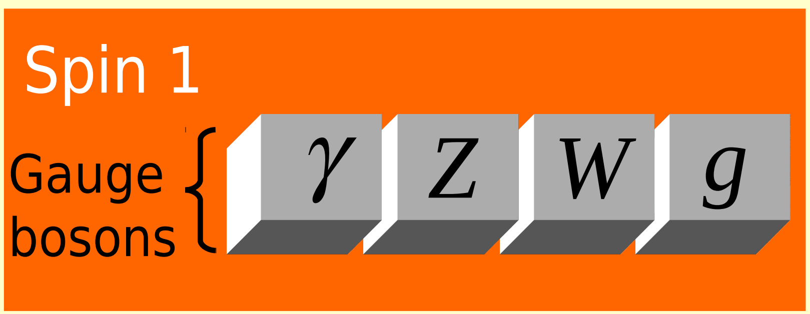
In supersymmetry, each Standard Model particle has a supersymmetric partner, generically called a sparticle

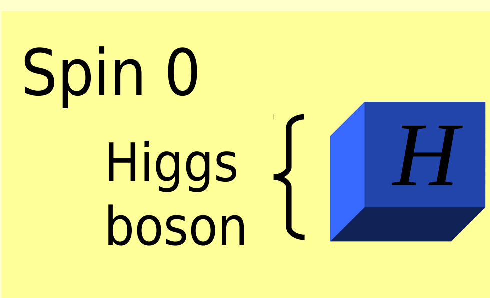
Nomenclature :

- The spartner of a standard model fermion is a sfermion
- The spartner of a standard model boson is a bos*ino*









Here, things are a bit more complicated...

Five physical Higgses

In SUSY, one also needs two Higgs doublets:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

$$\langle H_1^0 \rangle = v_1 \neq 0$$
$$\langle H_2^0 \rangle = v_2 \neq 0$$

$$(v_1^{\,2} + v_2^{\,2})^{1/2} \sim 246 \text{ GeV}$$

$$\tan\beta = \frac{v_2}{v_1}$$

- Before the symmetry breaking:
  Two complex Higgs doublets = 8 degrees of freedom
- 3 d.o.f are 'used' to give mass to W^+, W^- and Z
- 5 d.o.f. remain, which are the physical states:
  - Two charged Higgses, $H^\pm$
  - One neutral pseudoscalar Higgs, A
  - Two neutral scalar Higgses, h et H (definition: $m_h < m_H$)

The Higgs masses

One can compute relations between the different masses:

$$M_W \leq M_{H^\pm}$$
$$M_Z \leq M_H$$
$$0 \leq M_h \leq M_Z |\cos 2\beta|$$
$$M_h \leq M_A \leq M_H$$

⇒ ***$M_h < M_Z$?!?***

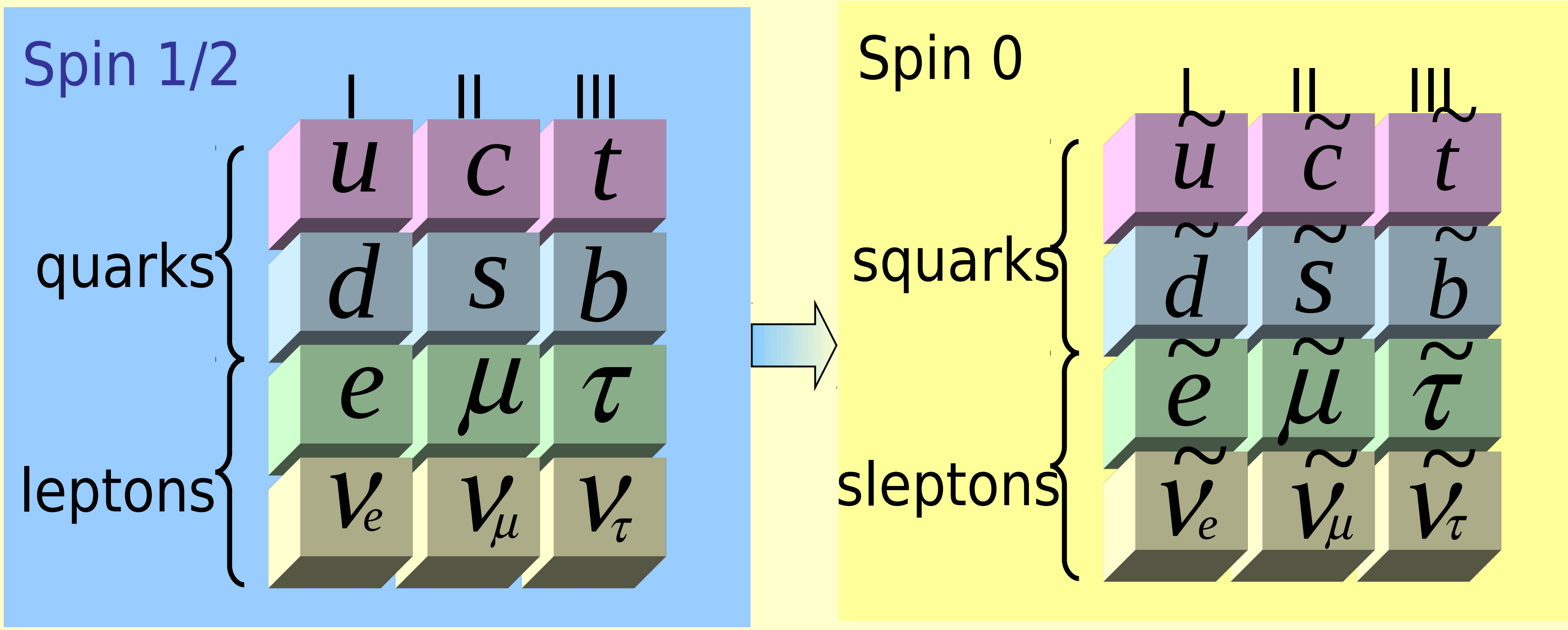
$M_Z = 91.1876 \pm 0.0021$ GeV

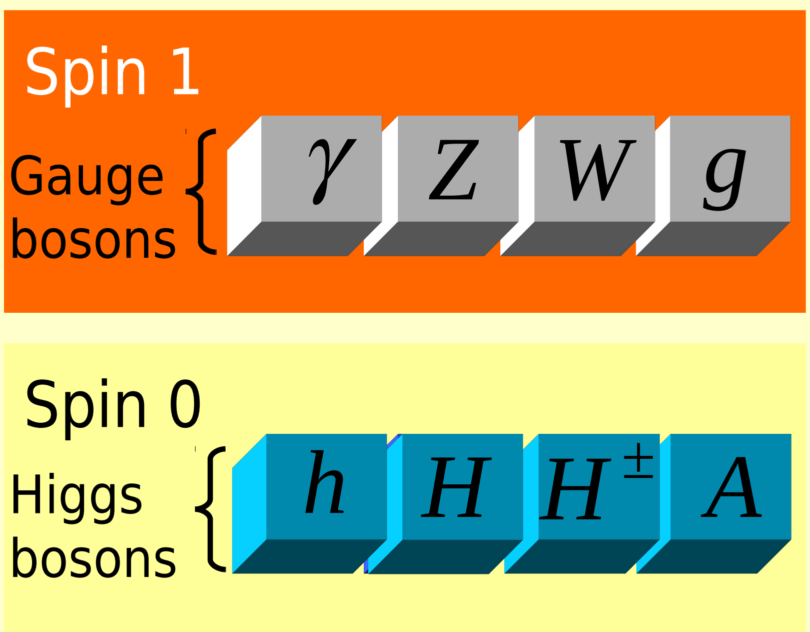
BUT LEP:
$M_h > 114.4$ GeV

Radiative corrections:

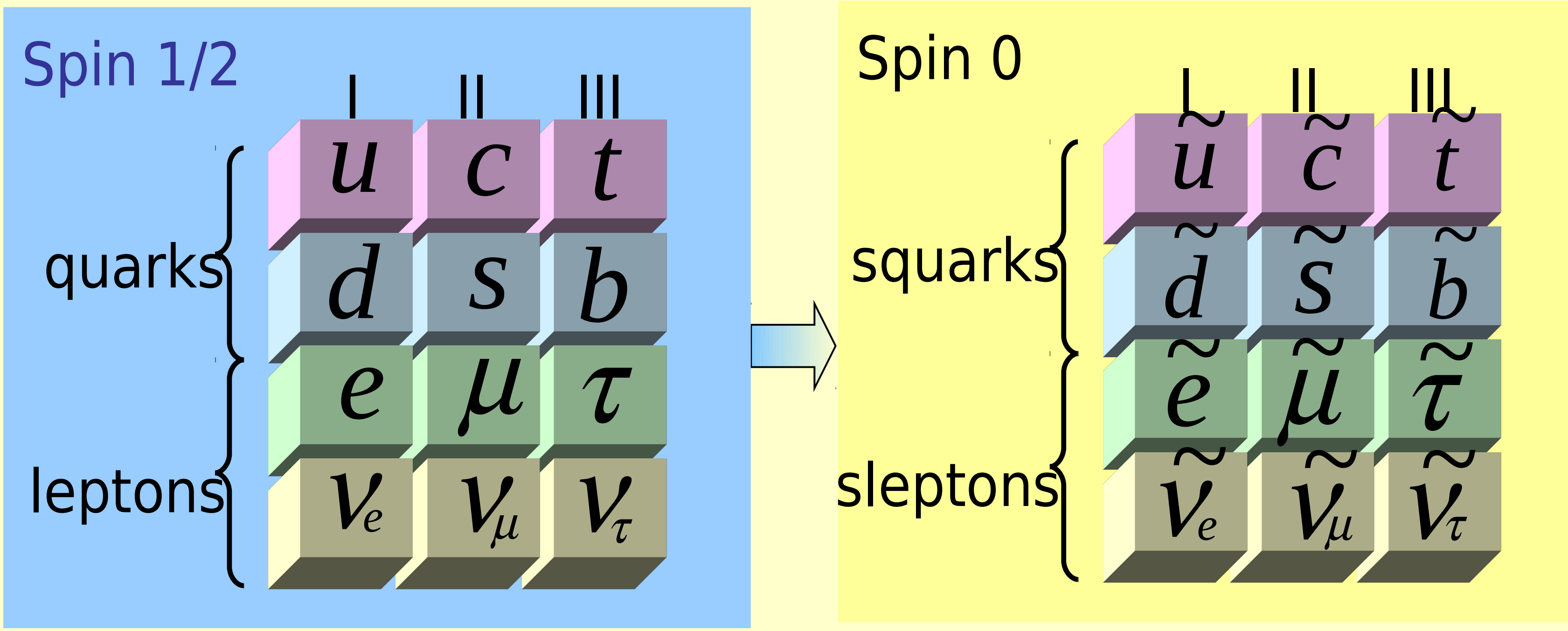
$$M_h^2 = M_h^2(tree) + \frac{3M_t^4}{\pi^2 v^2 \sin^2\beta} \ln\left(\frac{M_{\tilde{t}}}{M_t}\right) \leq 130 \text{ GeV}$$

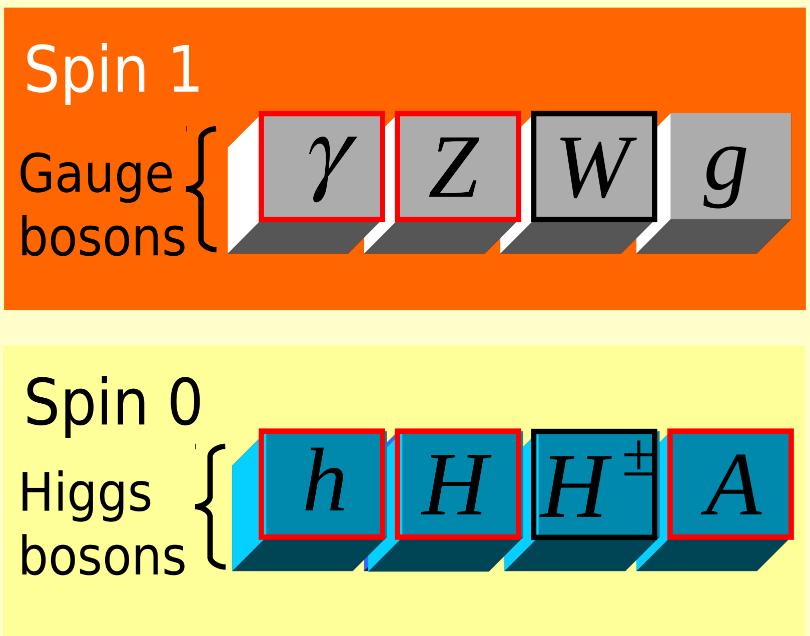
⇒ ***h is light***





The Higgs sector is larger and h should be rather light





Here, things are a bit more complicated...

Mass eigenstates

- The spartners of the Higgses (Higgsinos) and of the electroweak gauge bosons (gauginos) can actually mix and give the following mass eigenstates :
  - Charged higgsinos + charged gauginos : *charginos*
  - Neutral higgsinos + neutral gauginos : *neutralinos*

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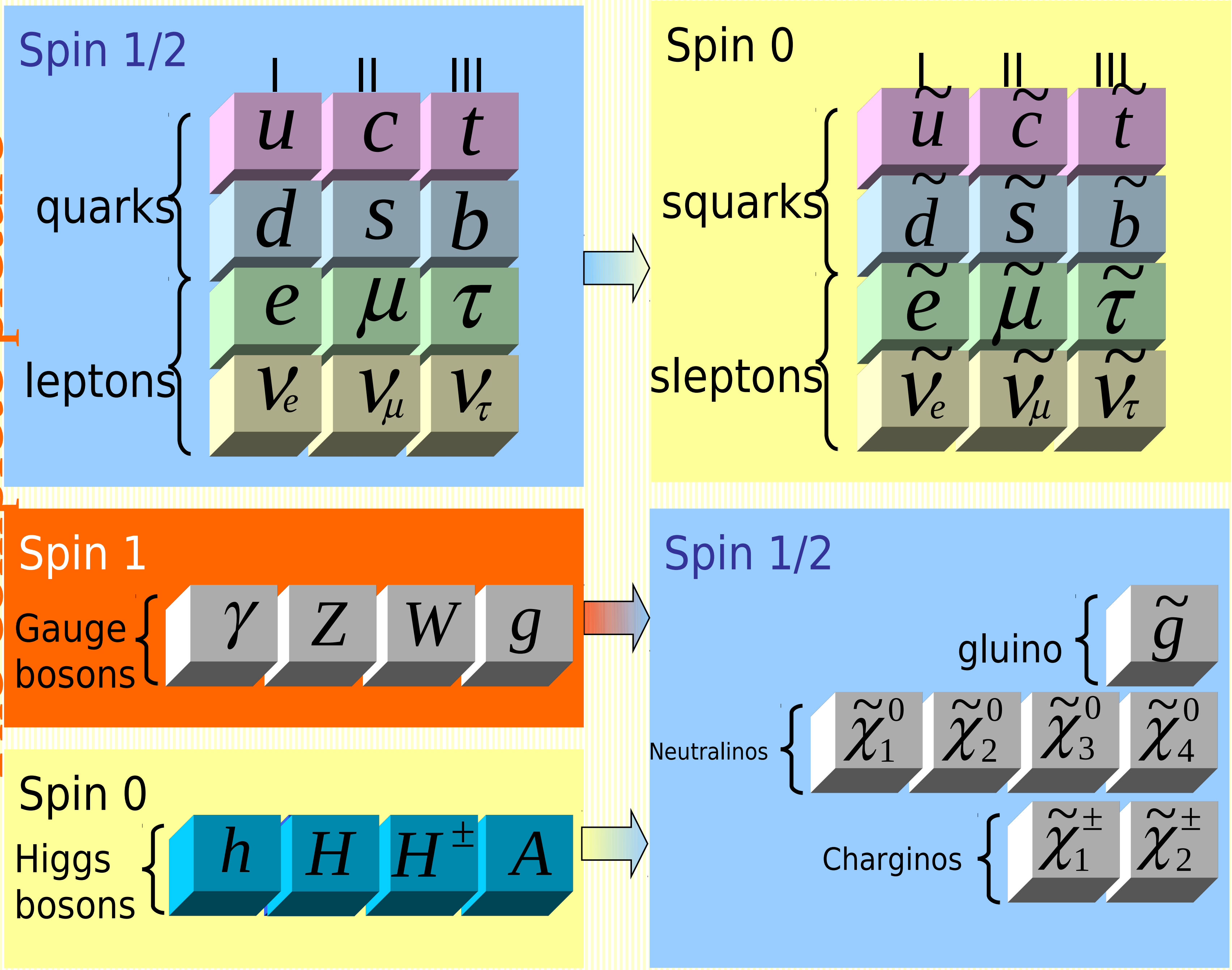
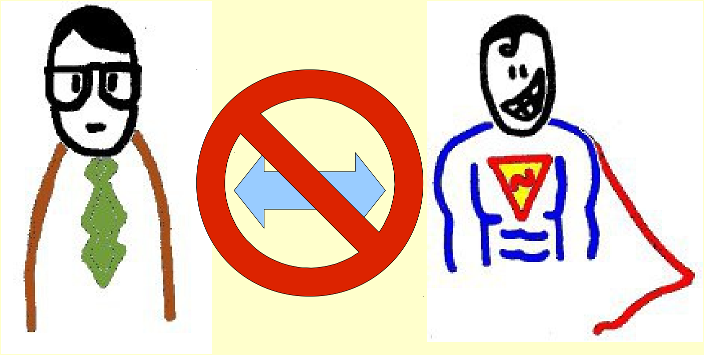
The complete picture



Breaking supersymmetry

- No sparticle has ever been observed… yet
  Their masses must be different from the ones of their SM partner!



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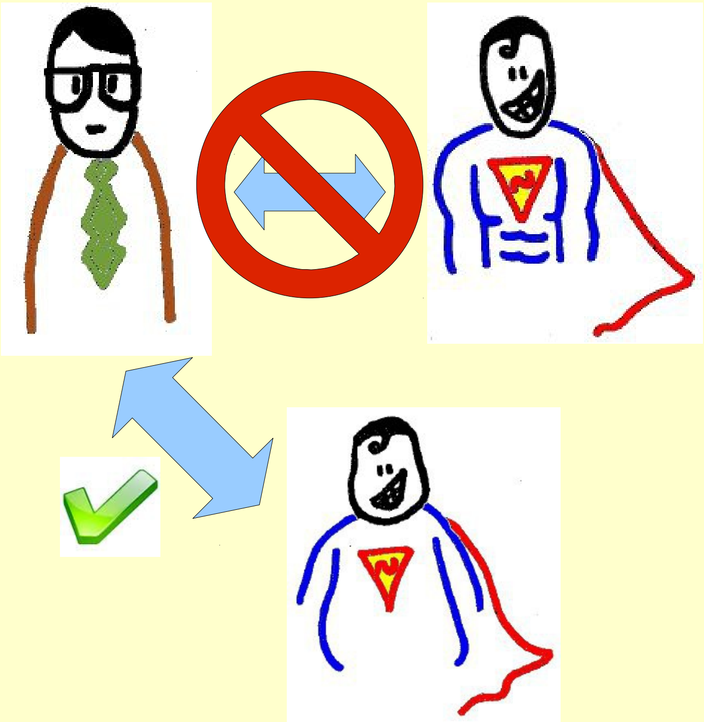


Breaking supersymmetry

- Leave it free :

  Introduction of ad-hoc terms explicitely breaking SUSY in the Lagrangian (manifestation of a more fundamental unknown theory)

  -> generic, but very many free parameters...

- Or think of some scenarios in which SUSY is broken (in a gravity-mediated way : SUGRA, through virtual gauge boson messengers : GMSB, ...)

  -> less free parameters, but not a 'generic' SUSY anymore...

cMSSM (constrained)

- 124 independant parameters - 18 from the SM

106 new parameters!

- Hypotheses on the number of independant parameters at the GUT scale:
  - o Gaugino mass $m_{1/2}$
  - o Scalar mass m_0
  - o Scalar tri-linear coupling A_0 $\left(\tilde{\bar{u}} a_u \tilde{Q} H_u - \tilde{\bar{d}} a_d \tilde{Q} H_d - \tilde{\bar{e}} a_e \tilde{L} H_d\right)$

- Which leaves also:
  - o The Higgs mixing parameter, tan β
  - o The Higgs mass parameter sign: sign(μ)

For simplicity, results shown today are shown in this scenario, but it's not the only one and LHC results in other SUSY scenarios are of course available

R parity

- Define: $$R = (-1)^{(L+3B+2J)} \text{ where } \begin{cases} L = \text{leptonic number} \\ B = \text{baryonic number} \\ J = \text{spin} \end{cases}$$
- R = -1 for sparticles
- R = +1 for SM particles
- If R parity is conserved:
  - SUSY particles always produced in pair
  - The decay of SUSY particles always contain an odd number of SUSY particles
  - The lightest sparticle (LSP) is thus stable
  - The lightest neutralino is the LSP in many models

In some models, R parity is violated by adding terms which violate leptonic or baryonic number conservation, but I will disregard this option here.

Why is SUSY considered attractive?

And it's all physical motivations

As we have seen, SUSY was introduced as the only way spacetime and internal symmetries can be consistently combined

It turned out it had many other interesting features which made its popularity grow, for example :

1- It can solve the mass hierarchy problem

2- It offers the possibility of gauge coupling unification

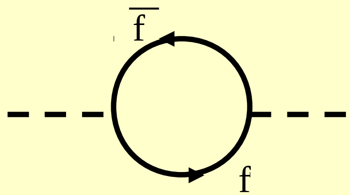
3- It predicts credible candidates to the dark matter

1- The hierarchy problem

Say the SM is valid up to the Planck scale (where gravity kicks in)

$$\Lambda_{Planck} = \sqrt{\frac{\hbar c}{G}} \sim 10^{19}\ \text{GeV}$$

But, the Higgs mass is given by a tree term $m_{H,\,tree}^2$ + some radiative corrections :

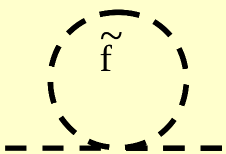


$$\delta m_H^2 \sim -\Lambda^2$$

The sum of both terms should give O(100 GeV)^2 !

SM solution: postulate $m_{H,\,tree}^2$ to be very nearly equal and opposite to the correction. This can *mathematically* be done: Something like $m_H^2 = (10000000000000000100)^2 - (10000000000000000000)^2$ ... But this seems awfully fine-tuned.

In SUSY, add new loop correction with spartner: no divergence!



Exact SUSY: $\delta m_H^2 \approx \left[\left(\Lambda^2 + m_B^2\right) - \left(\Lambda^2 + m_F^2\right)\right] = 0$

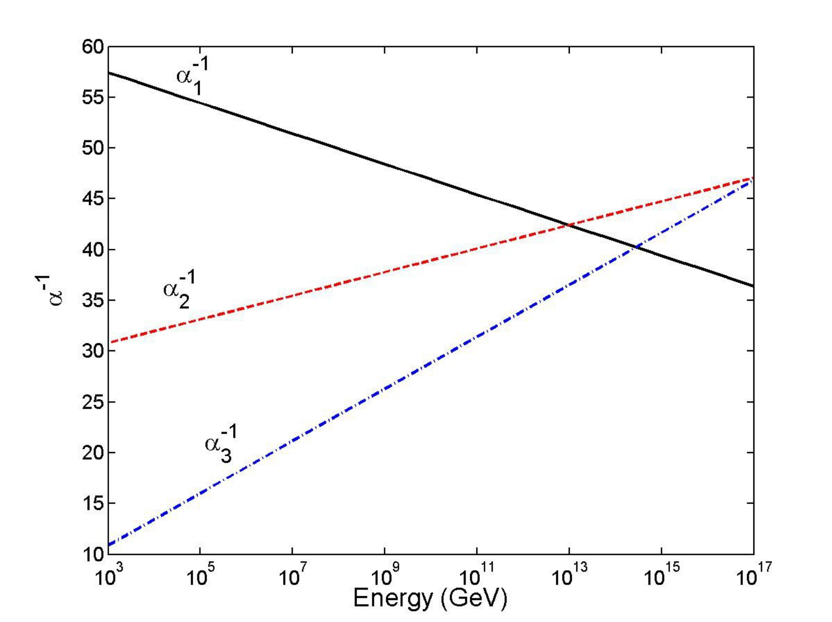
To avoid fine-tuning: $\left|m_B^2 - m_F^2\right|^{1/2} < O(1\ \text{TeV})$

LHC range!

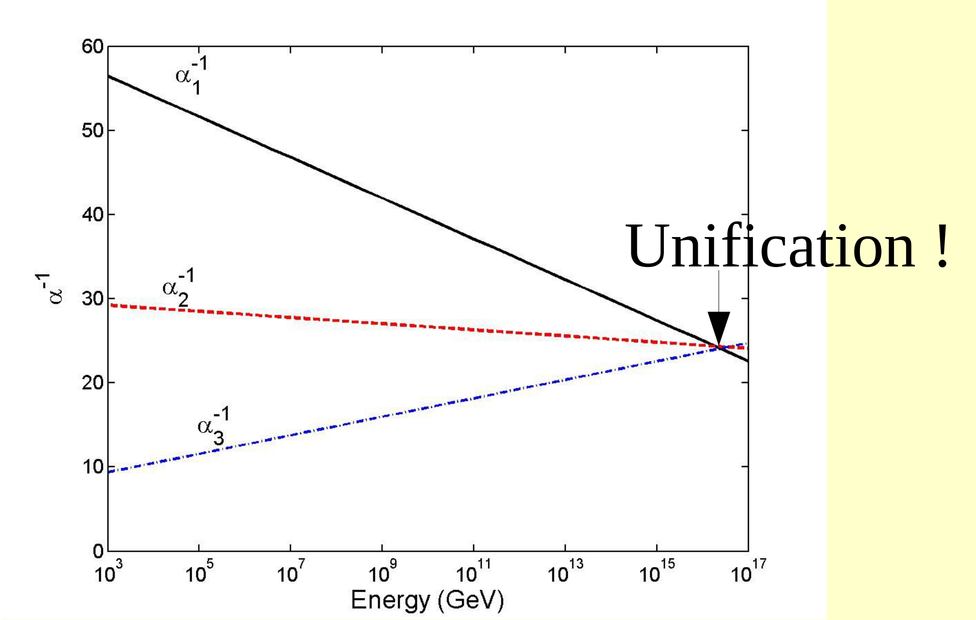
2- Gauge coupling unification

- Renormalisation Group Equations describe the running of the coupling constants with energy, with the slope depending on the number and masses of the particles in the model
- As an example: $\alpha_s = \frac{4\pi}{\beta_0 \ln(Q^2/\Lambda^2)}$ $\beta_0 = 11 - \frac{2}{3} n_f$

Without SUSY:



With SUSY:



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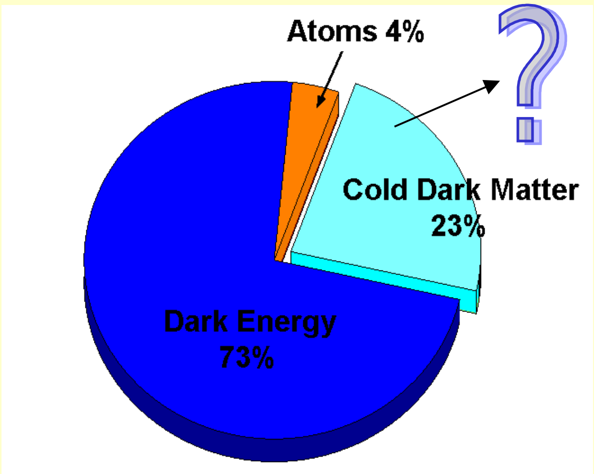
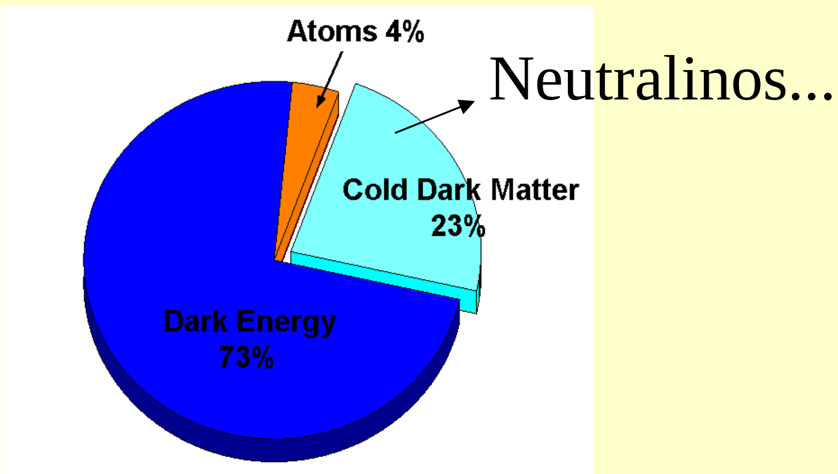
3- Dark matter candidate

Without SUSY:



With SUSY:



If R parity is conserved, SUSY can provide weakly interacting massive particles which are stable…

Ideal Cold Dark Matter candidate!

- SUSY is a symmetry which has many interesting features even if it must be broken
- It predicts new particles yet to be discovered

Does it have anything to do with the real world ?

Looking for SUSY

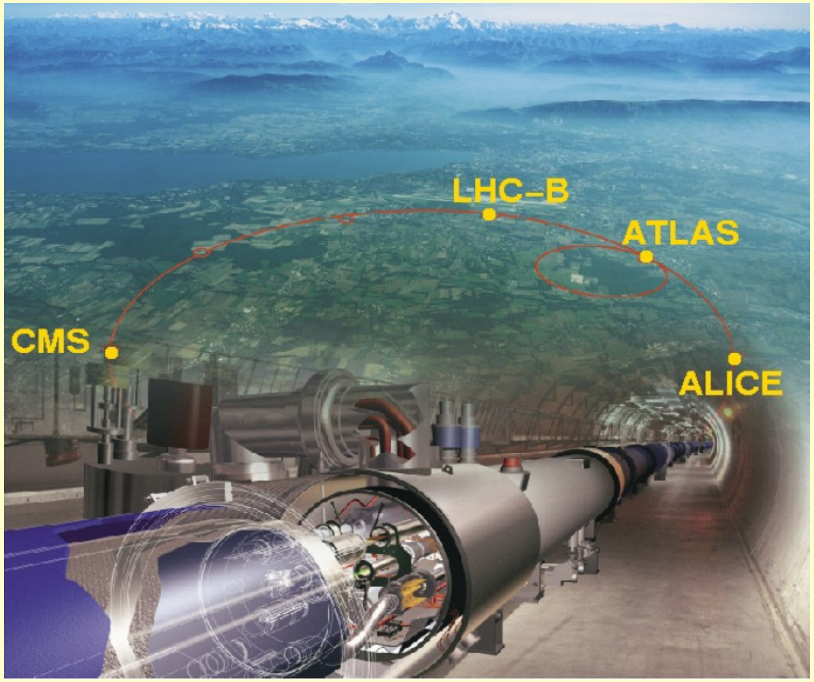
- There are many ways to look for SUSY :
  - Indirectly through precision measurement of quantities which could be affected by the presence of sparticles
  - Indirectly, if SUSY is the solution to dark matter, by looking for the presence of products of co-annihilation of neutralinos in the universe
  - Directly, if SUSY is the solution to dark matter, by searching for rare interactions of neutralinos from the galactic halo with detector material
  - Directly, by producing sparticles in colliders

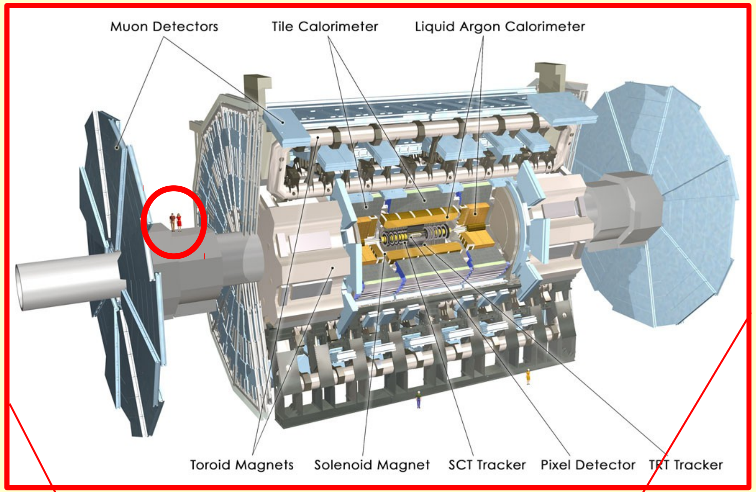
PART 2:
LOOKING FOR SUSY with the ATLAS detector at the LHC

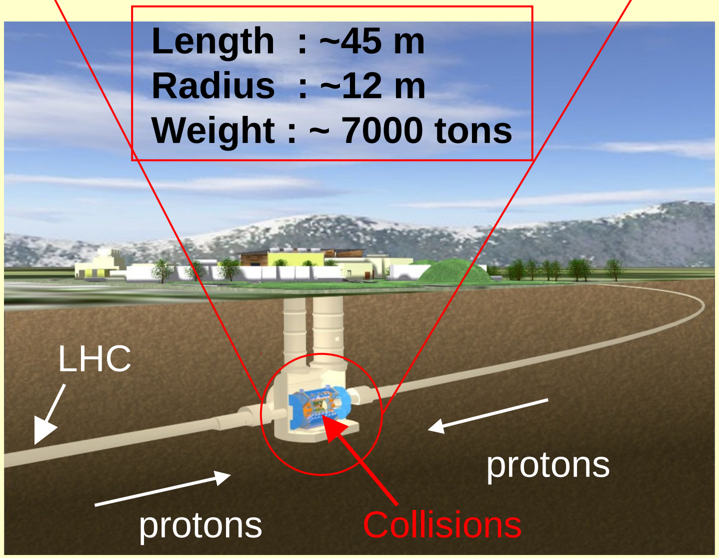
ATLAS and the LHC

The CERN Large Hadron Collider

Proudly colliding protons* since 2009





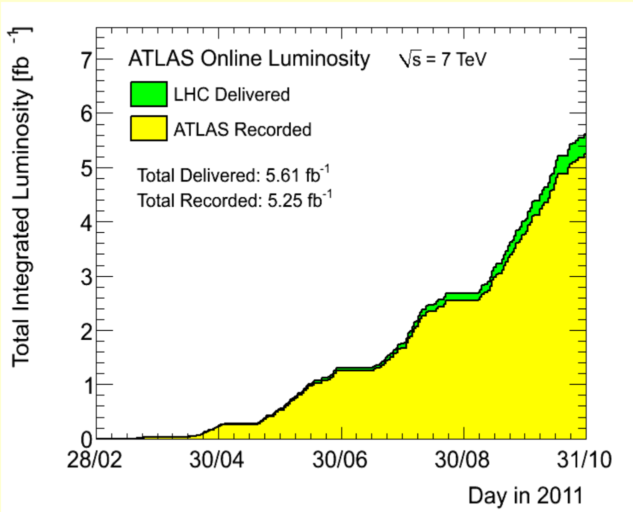


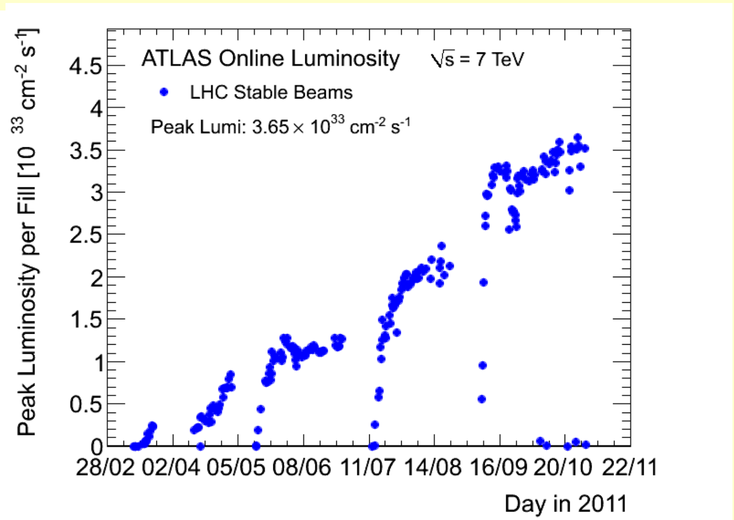
- proton-proton collisions
- Circumference: 27 km
- Center of mass energy (2010-2011): 7 TeV

**may contain some heavy ions*

Data accumulated in 2011

- Excellent LHC performance



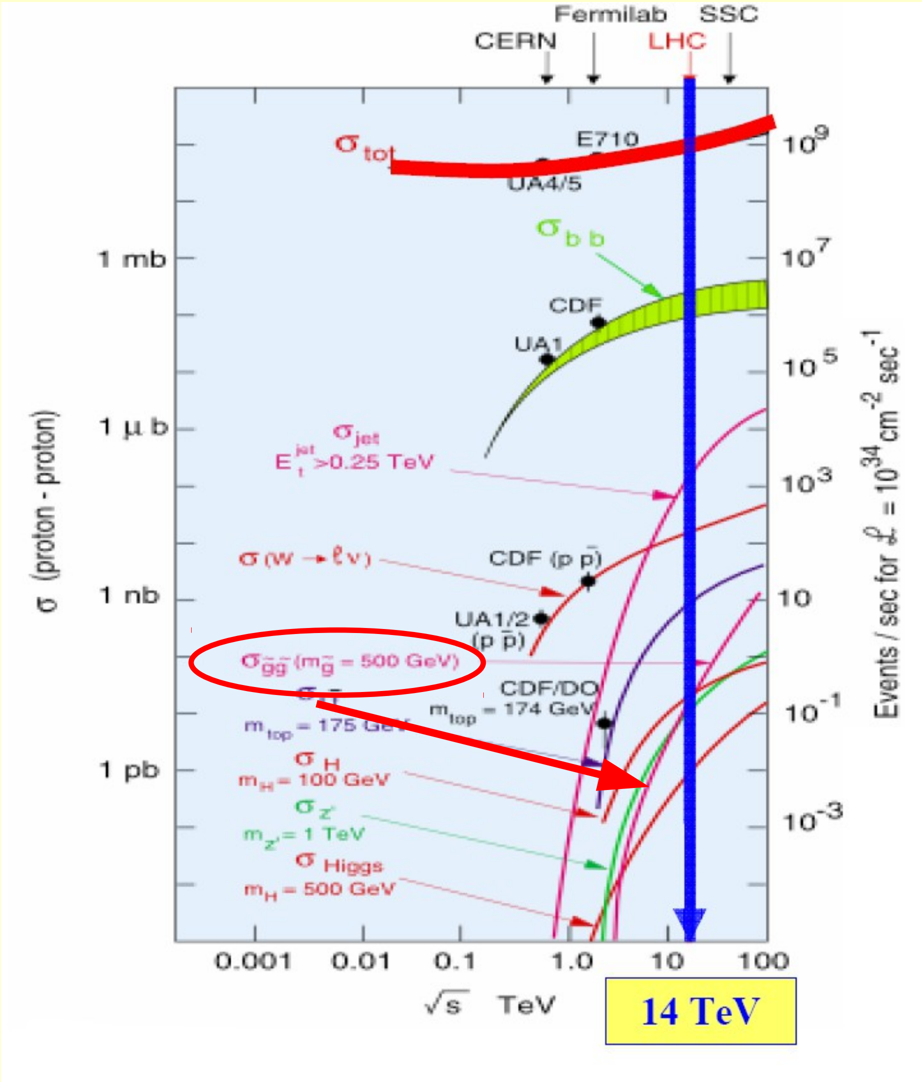


- Very good detector efficiency:

Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	97.5	99.2	99.5	99.2	99.4	98.8	99.4	99.1	99.8	99.3

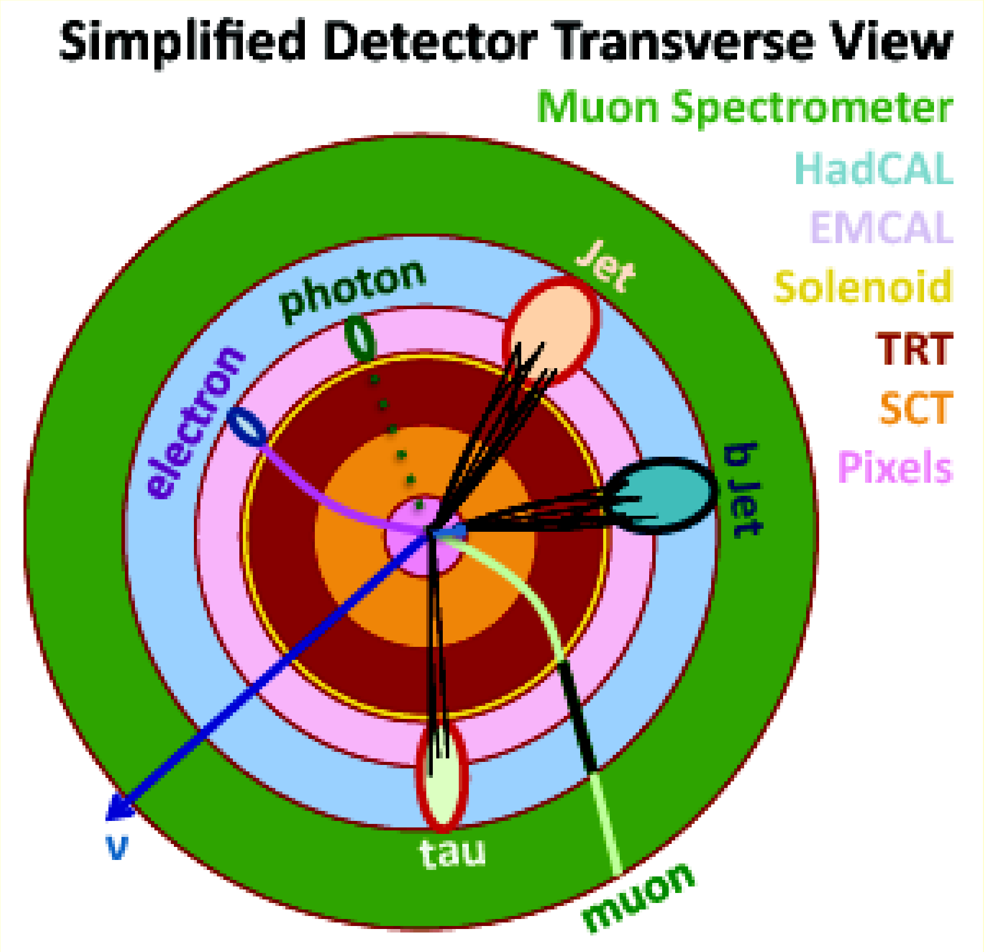
Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and October 30th (in %), after the summer 2011 reprocessing campaign

SUSY production



For example, with σ_{prod}=1 pb for 5000 pb^{-1} (=5 fb^{-1}) of integrated luminosity → 5000 events

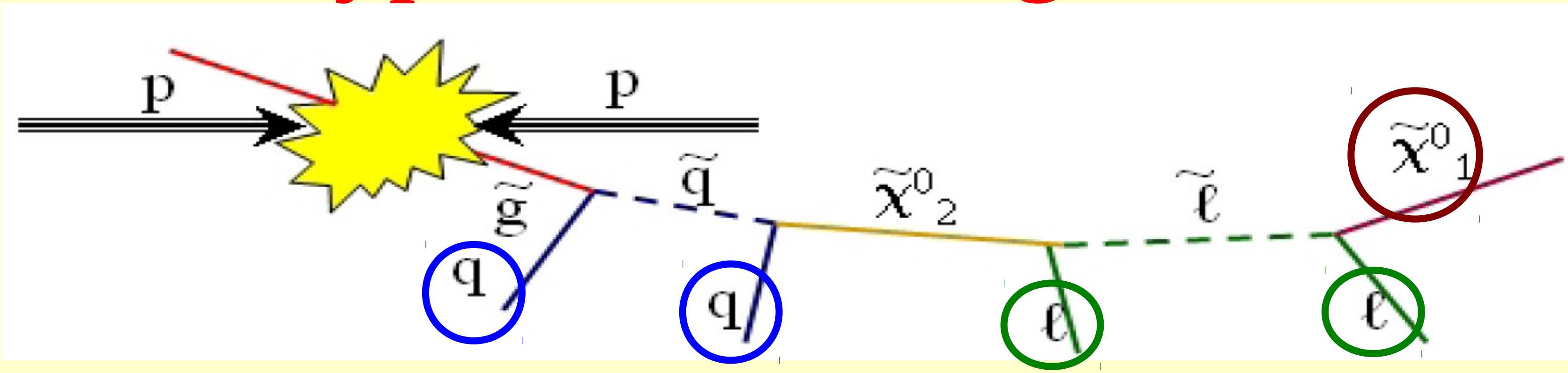
ATLAS



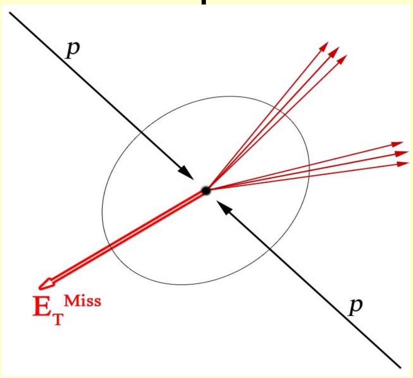
Simplified Detector Transverse View
Muon Spectrometer
HadCAL
EMCAL
Solenoid
TRT
SCT
Pixels
photon
electron
Jet
b Jet
tau
muon
ν

How could we find SUSY ?

Typical SUSY signature



- Pair of gluinos/squarks produced by strong interactions
- Their decays give high-p_T jets and charginos/neutralinos
- Charginos/neutralinos decays can give leptons and the decay chain stops when the LSP is produced (R-parity conserving scenarios)
- The pair of stable LSP produced escapes the detector undetected leading to high transverse missing momentum

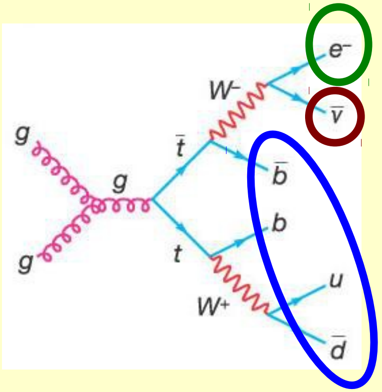


multi-Jets + n leptons + E_T^{miss}

BUT: Standard Model backgrounds can also mimic this signature...

Possible backgrounds...

- SUSY's nightmare : top pair production



- Boson production : e.g. W+jets
- A generic worry : QCD
  - The biggest production at the LHC is just jets. It must be considered because jets can be misidentified as leptons or mismeasured (leading to fake leptons, fake missing momentum).

Searches

Compare the expected background to the data: is there an excess?

- Trigger on the events; make sure the interesting physics you're after is recorded !

- Define **signal regions**; define selections which will enhance the signal with respect to the background ('cuts on variables' : e.g. asking for at least one lepton in the event, at least one jet with p_T>100 GeV, ...)

- Define **control regions** ; cross check your background expectations in regions orthogonal to your signal regions

- Look at the **results** ; Compare the background expectations in the signal region to the number of observed events : is there an excess?

- If no excess is seen : what does it exclude in terms of possible models ?

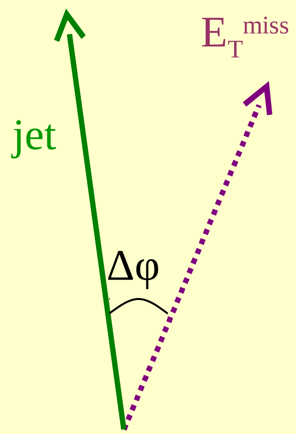
The trigger system

What to keep and what not

- Interaction rate : ~1 GHz
- The trigger has to reduce it to ~200-400 Hz
- Three-level trigger to decide what to keep
- Compromise:
  - low trigger thresholds (maximal coverage)
  - high thresholds (keep rate down)

You were right: There's a needle in this haystack...

Signal regions : some useful variables



$\Delta\phi(\text{jets}, E_T^{miss})$

Cutting on $\Delta\phi$ eliminates events in which E_T^{miss} is closely related to one of the leading jets (QCD)

Effective mass m_{eff}

Scalar sum of jets & leptons p_T and E_T^{miss}; it peaks at a value which is strongly correlated with the mass of the pair of SUSY particles produced in the *pp* interaction

Transverse mass m_T

$$m_T^2 \equiv 2|\mathbf{p}_T^\ell||E_T^{miss}| - 2\mathbf{p}_T^\ell \cdot \vec{E}_T^{miss}$$

Useful to remove BG in which a W decays in a lepton and a neutrino

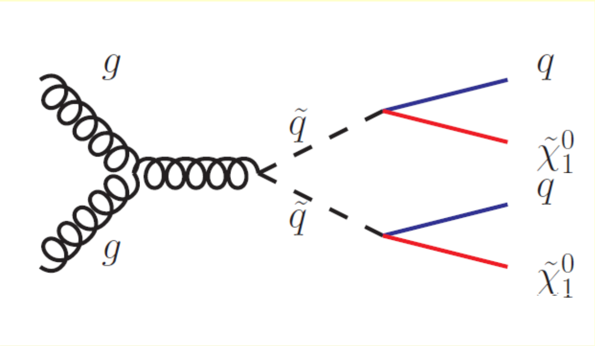
An example : the 0-lepton channel

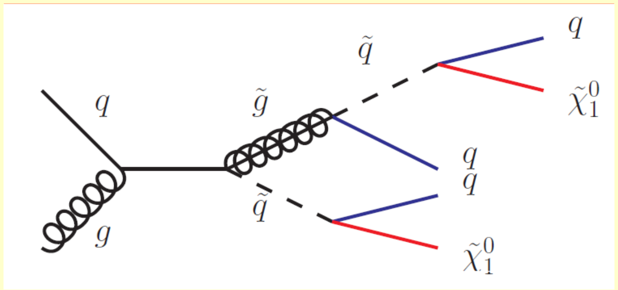
Select events with jets, missing transverse momentum and no lepton (veto e/μ)

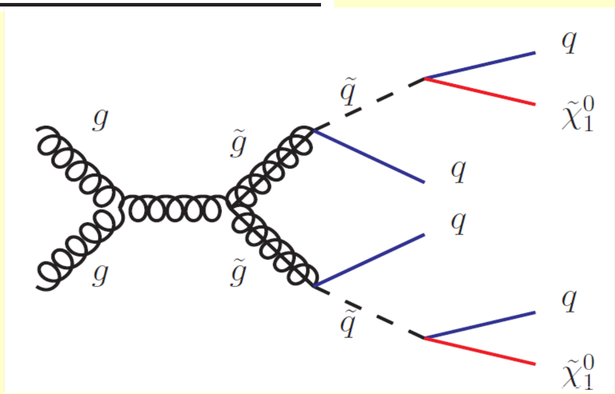
arXiV:1109.6572
submitted to PLB

Defining the signal regions

Signal Region	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet	High mass
E_T^{miss}	> 130	> 130	> 130	> 130
Leading jet p_T	> 130	> 130	> 130	> 130
Second jet p_T	> 40	> 40	> 40	> 80
Third jet p_T	–	> 40	> 40	> 80
Fourth jet p_T	–	–	> 40	> 80
$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff}	> 1000	> 1000	> 500/1000	> 1100







Depending on the signal, you can have 2, 3 or 4 jets...

Defining the signal regions

Signal Region	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet	High mass
E_T^{miss}	> 130	> 130	> 130	> 130
Leading jet p_T	> 130	> 130	> 130	> 130
Second jet p_T	> 40	> 40	> 40	> 80
Third jet p_T	–	> 40	> 40	> 80
Fourth jet p_T	–	–	> 40	> 80
$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff}	> 1000	> 1000	$> 500/1000$	> 1100

Trigger requirements

Reject the QCD BG

Optimize for SUSY

Main backgrounds

- Z+jets: Z decays to $\nu\nu$

- W+jets: W decays to $\tau\nu$ or W->$e\nu$ or $\mu\nu$ but the lepton is missed

- Top pair production: t->Wb with W as above

- QCD multijets: mismeasured jet leading to missing energy or heavy flavour decay

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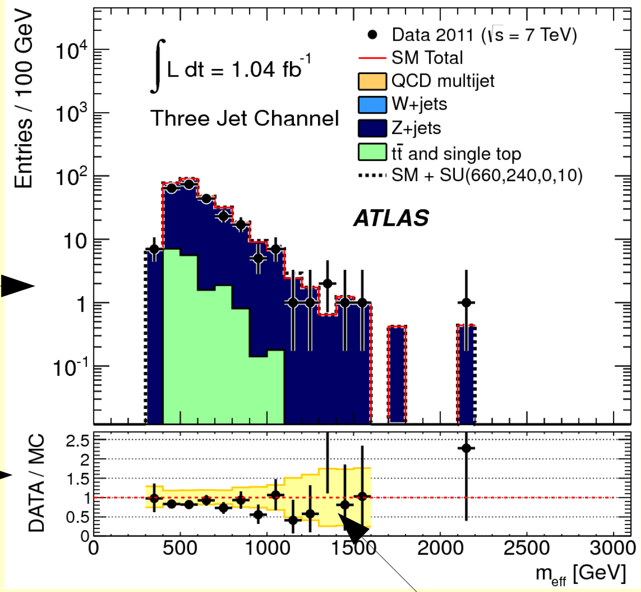
Z+jets BG : a control region example

Data vs expectation

Data / expectation



Uncertainty on the expectation

- Take Z(→ll)+jets events (orthogonal to the signal region where a veto is made on the leptons)
- To mimic the Z(→νν)+jets BG in the signal region, remove the leptons from the event and add them as missing energy instead

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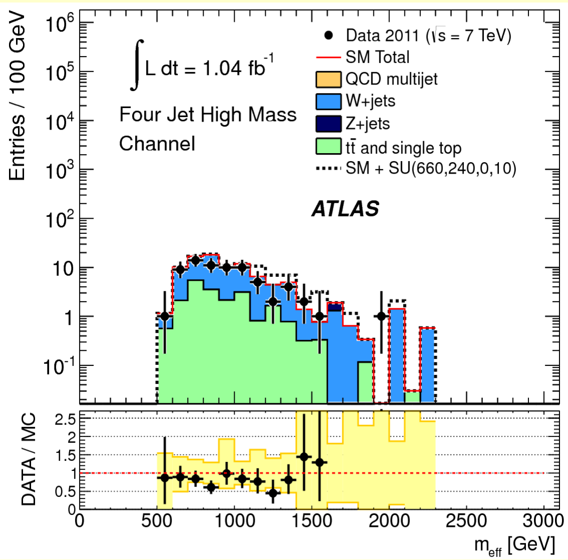
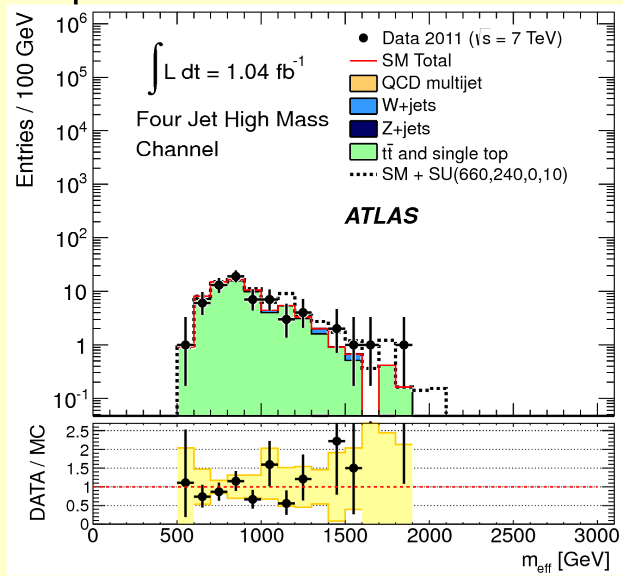
Other control regions

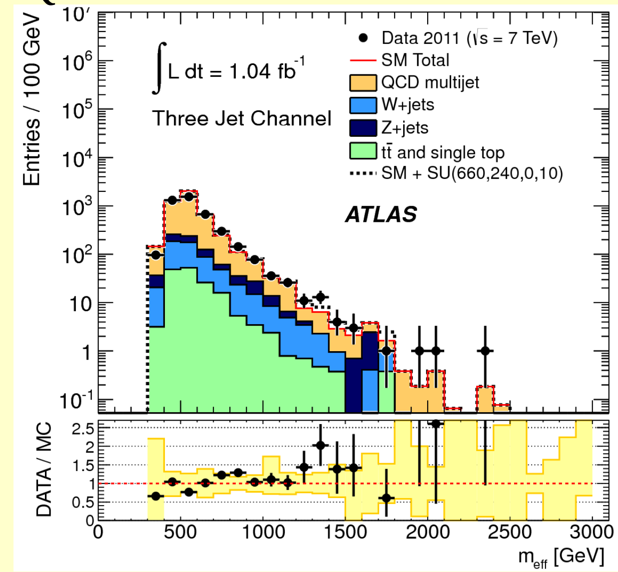
W CR



Top CR



QCD CR



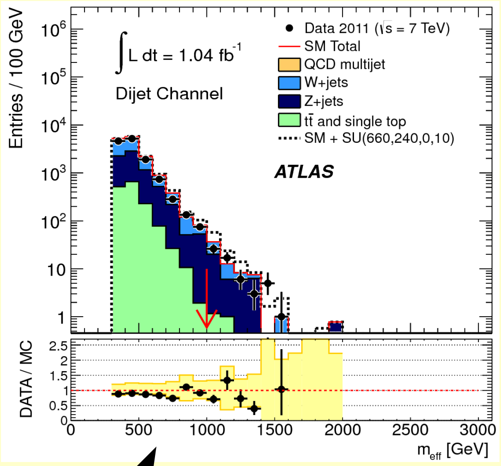
- Select 1-lepton events with 30 < m_T < 100 GeV (enriched in W and top, where a W decays to a lepton and a neutrino)

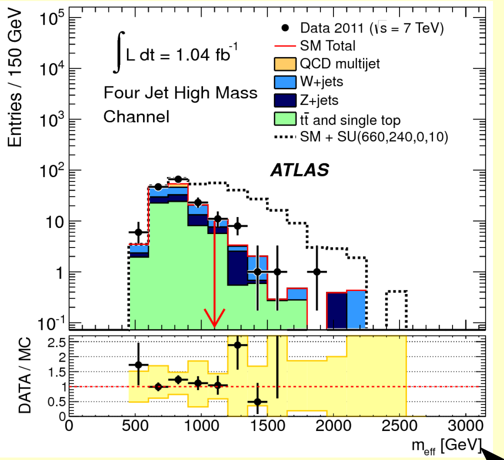
- Split the top from W by asking for no b-tagged jet (W) or at least one b-tagged jet (top)

- Treat the lepton as a jet (for further processing)

Reverse and tighten the cut: $\Delta\varphi(\mathrm{jet}, E_T^{miss})_{min} < 0.2$

Results

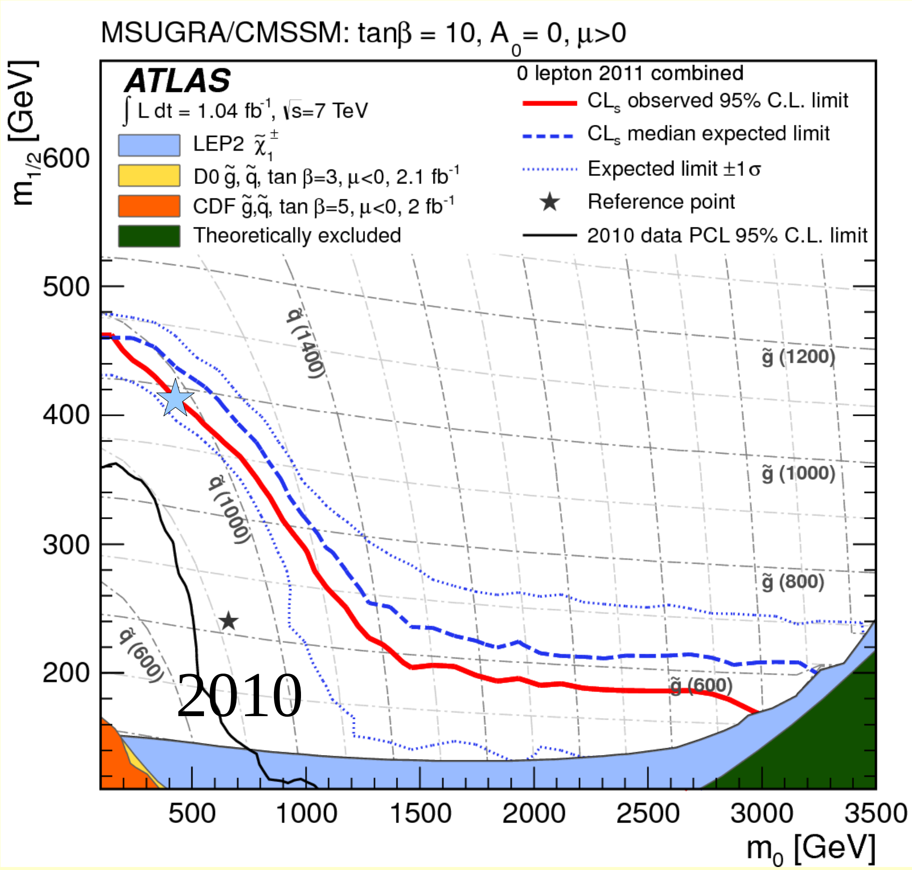




Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, $m_{eff} > 500$ GeV	$\geq$ 4-jet, $m_{eff} > 1000$ GeV	High mass
Z/γ+jets	32.3 ± 2.6 ± 6.9	25.5 ± 2.6 ± 4.9	209 ± 9 ± 38	16.2 ± 2.2 ± 3.7	3.3 ± 1.0 ± 1.3
W+jets	26.4 ± 4.0 ± 6.7	22.6 ± 3.5 ± 5.6	349 ± 30 ± 122	13.0 ± 2.2 ± 4.7	2.1 ± 0.8 ± 1.1
$t\bar{t}$+ single top	3.4 ± 1.6 ± 1.6	5.9 ± 2.0 ± 2.2	425 ± 39 ± 84	4.0 ± 1.3 ± 2.0	5.7 ± 1.8 ± 1.9
QCD multi-jet	0.22 ± 0.06 ± 0.24	0.92 ± 0.12 ± 0.46	34 ± 2 ± 29	0.73 ± 0.14 ± 0.50	2.10 ± 0.37 ± 0.82
Total	62.4 ± 4.4 ± 9.3	54.9 ± 3.9 ± 7.1	1015 ± 41 ± 144	33.9 ± 2.9 ± 6.2	13.1 ± 1.9 ± 2.5
Data	58	59	1118	40	18

95% CL limits on cross section · acceptance · efficiency:
22 fb, 25 fb, 429 fb, 27 fb and 17 fb

Exclusion plot

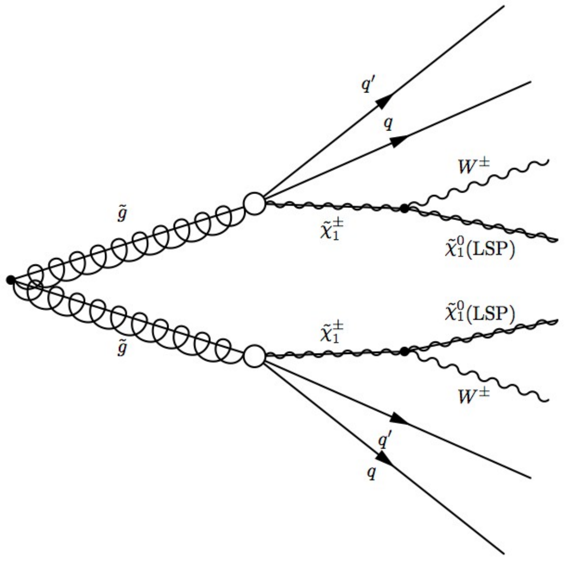


parameters at GUT scale

1. Unified gaugino(scalar) mass $m_{1/2}(m_0)$
3. Ratio of H_1, H_2 vevs $\tan\beta$
4. Trilinear coupling A_0
5. Higgs mass term $sgn(\mu)$

☆ → equal mass squarks and gluinos are excluded below 950 GeV

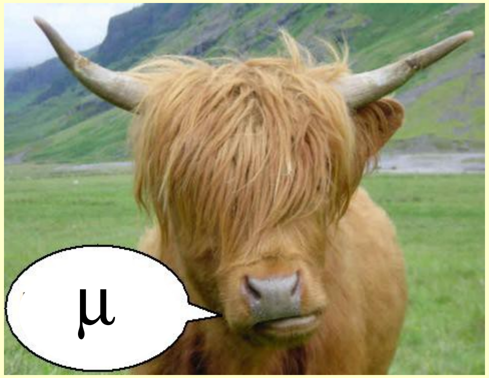
There are also searches in many other channels !



The 1-lepton channel

Select events with jets, missing transverse momentum and exactly one lepton (e/μ)

arXiV:1109.6606
Submitted to PRD



Defining the signal region

- Exactly one lepton (e/μ) with pT>20 GeV

Again different jet multiplicity requirements

Event Selection in SRs	3JL	3JT	4JL	4JT
Leading jet p_T [GeV]	60	80	60	60
Subsequent jets p_T [GeV]	25	25	25	40
M_T [GeV]	100	100	100	100
E_T^{miss} [GeV]	125	240	140	200
E_T^{miss} /M_{eff}	0.25	0.15	0.30	0.15
M_{eff} [GeV]	500	600	300	500

$\Delta\phi$ (jet, E_t^{miss}) >0.2

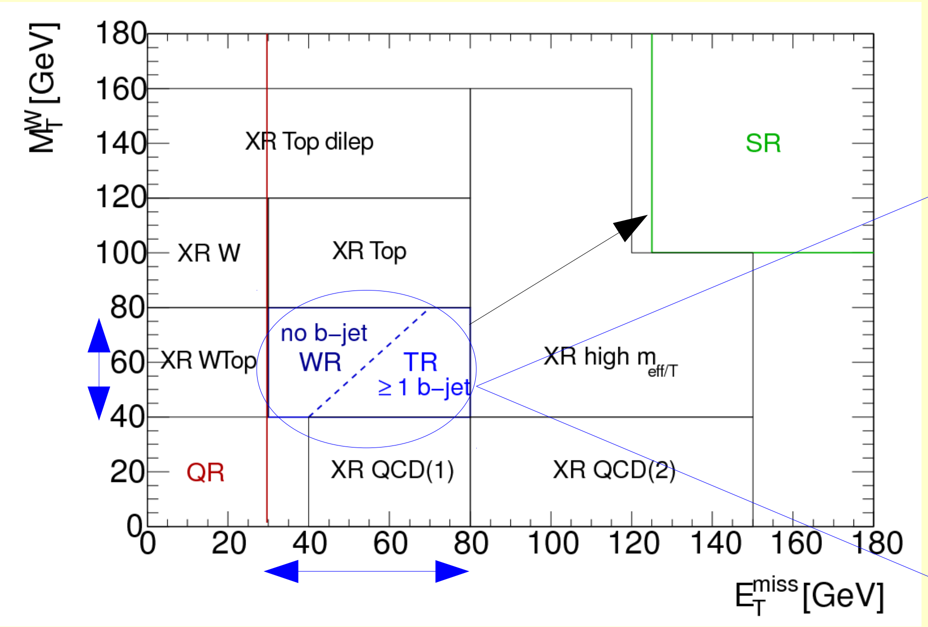
Suppresses W+jets and tt

Reduce the QCD BG further

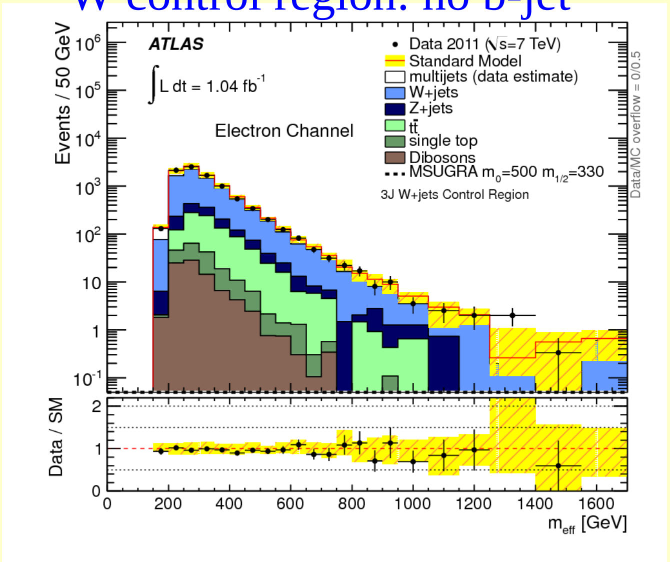
Optimize for SUSY

Again, various cuts to reduce the BG
Based on the variables introduced before

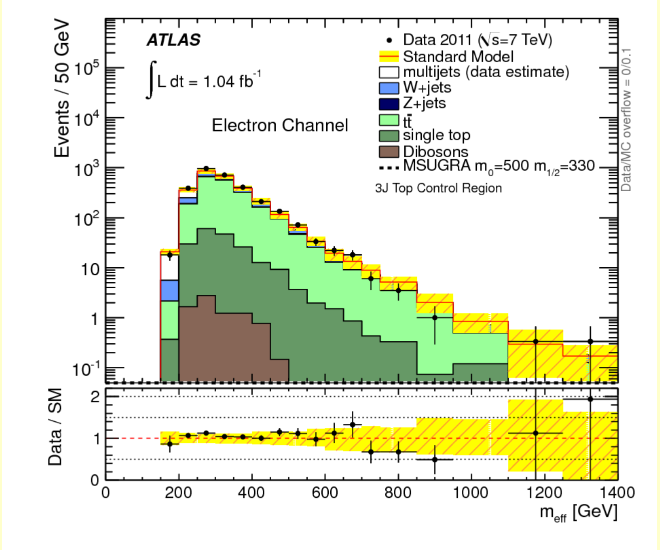
Main backgrounds: W+jets and tt



W control region: no b-jet



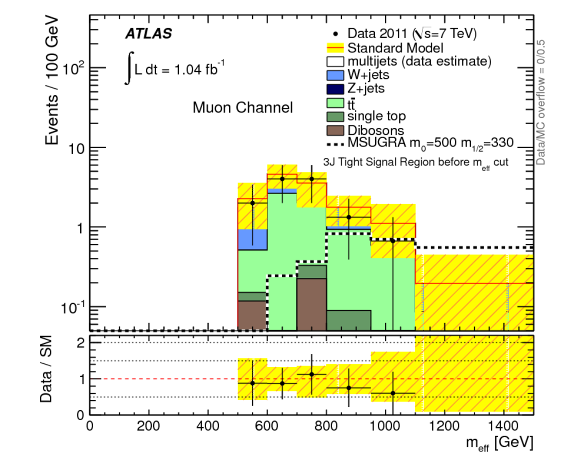
Top control region: ≥ 1 b-jet



Again, a control region for each background, to cross check the expectations

Again, good agreement between data and expected background

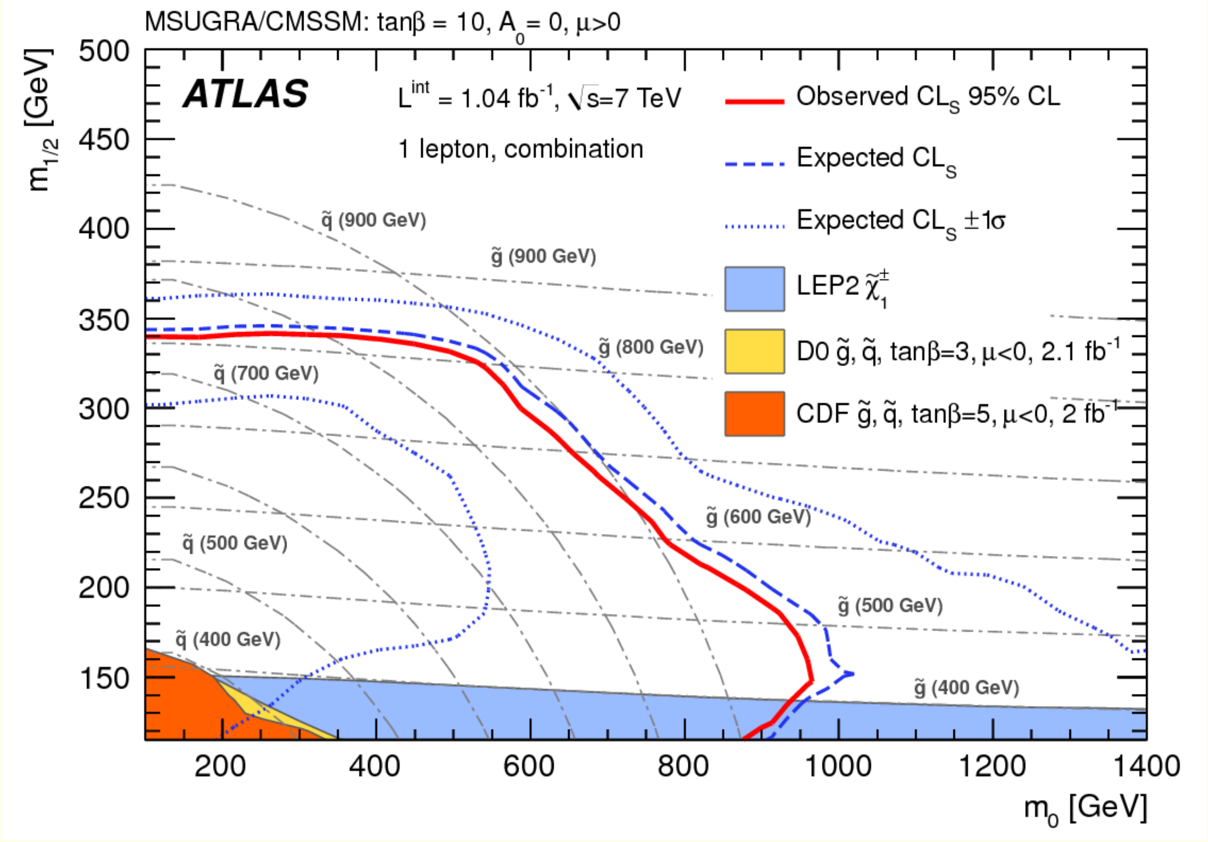
Results



Electron channel	3JL Signal region	3JT Signal region	4JL Signal region	4JT Signal region
Observed events	71	14	41	9
Fitted top events	56 ± 20 (51)	7.6 ± 3.0 (6.8)	38 ± 15 (34)	4.5 ± 2.6 (4.1)
Fitted W/Z events	35 ± 20 (34)	10.5 ± 6.5 (10.1)	9.5 ± 7.5 (9.2)	3.5 ± 2.2 (3.4)
Fitted multijet events	$6.0^{+2.3}_{-1.4}$	$0.46^{+0.37}_{-0.22}$	$0.90^{+0.54}_{-0.37}$	$0.00^{+0.02}_{-0.00}$
Fitted sum of background events	97 ± 30	18.5 ± 7.4	48 ± 18	8.0 ± 3.7

Muon channel	3JL Signal region	3JT Signal region	4JL Signal region	4JT Signal region
Observed events	58	11	50	7
Fitted top events	47 ± 16 (38)	8.9 ± 3.2 (7.[illegible])	39 ± 13 (36)	4.7 ± 2.2 (4.3)
Fitted W/Z events	16.6 ± 9.4 (20.1)	5.0 ± 3.2 (6.1)	14.1 ± 8.5 (14.2)	1.4 ± 1.1 (1.4)
Fitted multijet events	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.6}_{-0.0}$	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.6}_{-0.0}$
Fitted sum of background events	64 ± 19	13.9 ± 4.3	53 ± 16	6.0 ± 2.7

Exclusion plot

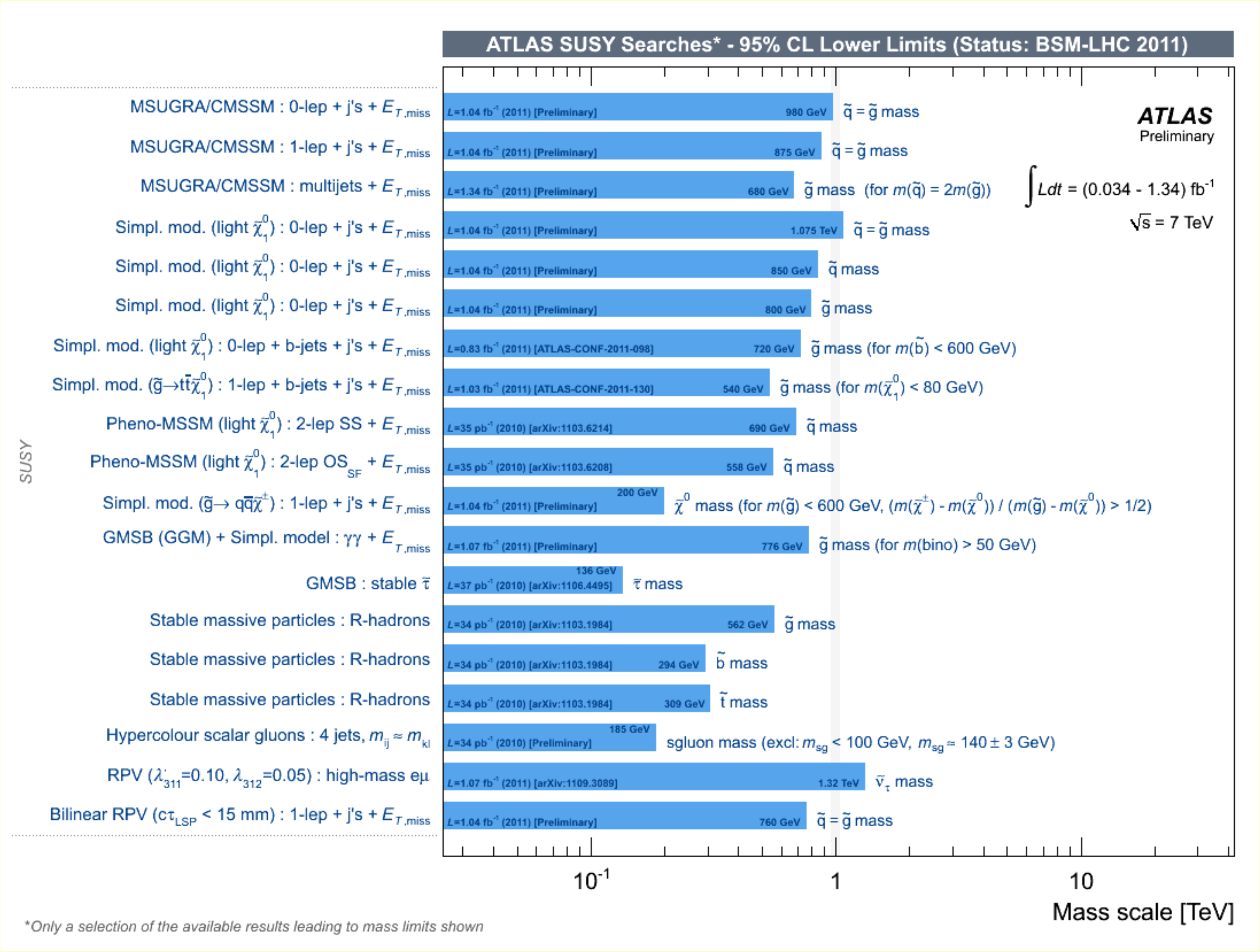


Exclude $m_{gluino} = M_{squark} < 875$ GeV

Again, exclude some SUSY models

Summary and outlook

- Way more results than I could show today!



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Is SUSY almost dead ?

- The searches so far have concentrated mostly on strongly interacting sparticles because they are expected to be produced copiously if massive enough
- Furthermore, the searches so far do not cover all possibilities in terms of spectra, decays, ... more search channels under way...
- With more data, we will be able to probe more effectively direct neutralino/chargino production (with greater impact on what we can say about DM...)

So, no, not yet.

The quest continues

Mass eigenstates

Charged Higgsinos + winos 1 and 2 → **charginos**

$$\tilde{C}_1^{\pm} = \cos\varphi_{\pm}\,\tilde{W}^{\pm} - \sin\varphi_{\pm}\,\tilde{H}^{\pm}$$

$$\tilde{C}_2^{\pm} = \sin\varphi_{\pm}\,\tilde{W}^{\pm} + \cos\varphi_{\pm}\,\tilde{H}^{\pm}$$

$$m^2_{\tilde{C}_{1,2}} = \frac{1}{2}\left(M_2^2 + \mu^2 + 2\mathrm{m}_W^2\right) \mp \sqrt{4\left(M_2^2 + \mu^2 + 2\mathrm{m}_W^2\right)^2 - \left(\mu M_2 - m_W^2 \sin 2\beta\right)^2}$$

$$m^2_{\tilde{C}_1} < m^2_{\tilde{C}_2}$$

Neutral Higgsinos + bino + neutral wino → **neutralinos**

In the basis $\left(\tilde{b}, \tilde{w}^3, \tilde{h}_1^0, \tilde{h}_2^0\right)$:

$$M_{\tilde{\chi}_i^0} = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin\theta_W & M_Z \sin\beta \sin\theta_W \\ 0 & M_2 & M_Z \cos\beta \cos\theta_W & -M_Z \sin\beta \cos\theta_W \\ -M_Z \cos\beta \sin\theta_W & M_Z \cos\beta \sin\theta_W & 0 & \mu \\ M_Z \sin\beta \sin\theta_W & -M_Z \sin\beta \cos\theta_W & \mu & 0 \end{pmatrix}$$

Matrix diagonalization → neutralino masses ($m_1 < m_2 \ldots$)

R parity violation

- The R parity can be violated by adding terms which violate leptonic or baryonic number conservation to the Lagrangian, while being invariant under SU(3)xSU(2)xU(1) :

$$\Delta W = \lambda_B^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k + \lambda_L^{ijk} Q_i L_j \bar{d}_k + \lambda_e^{ijk} L_i L_j \bar{e}_k + \mu_L^i L_i h_2$$

- Different phenomenology expected if one takes as non zero λ_B (the baryonic number violating coupling) or one of the other leptonic-number violating couplings…

- ***However***: one can't pick and mix any violation terms at will: this could lead to rapid proton decay!

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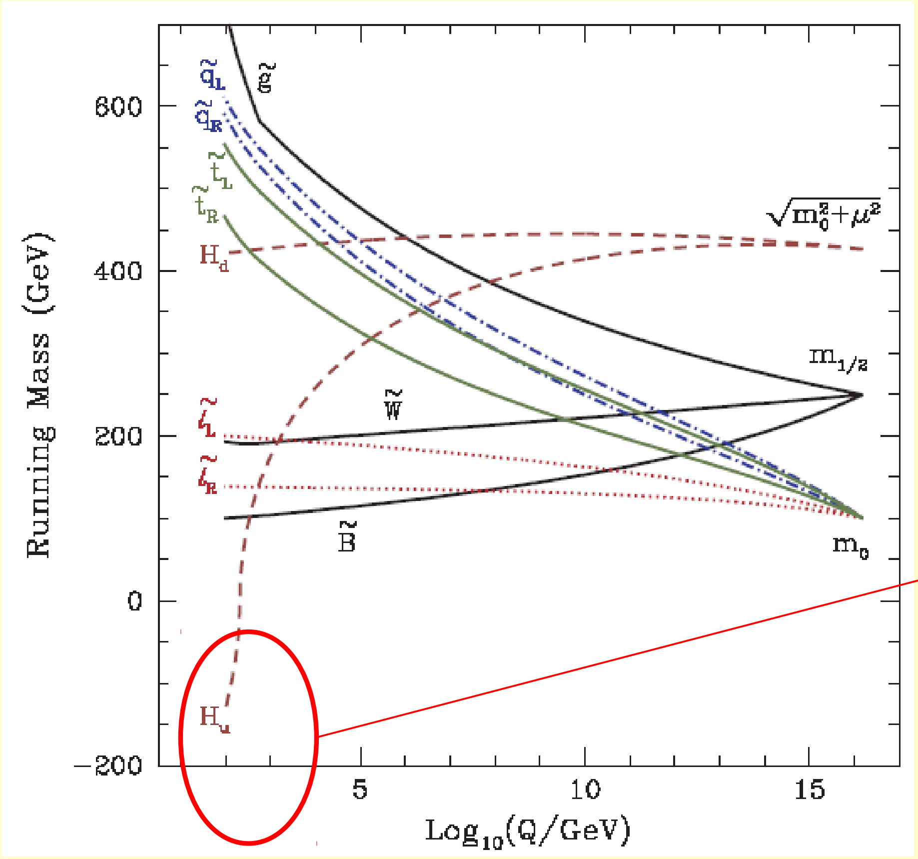
More reasons to like SUSY

Radiative electroweak symmetry breaking :

The renormalization-group evolution of the soft supersymmetry-breaking parameters in the MSSM



< 0 at ~1 TeV

"It is also needed in string theory to go from a 26d world containing tachyons to a 11d world without them"

- A string theorist

Heavier sparticles?

Is there any reason to believe that the sparticles should be more massive or are we only trying to match the experimental facts and 'denaturalizing' the theory???

All the SM particles would be massless without electroweak symmetry breaking

$W^{\pm}$,Z^{0},leptons and quarks all obtain their mass after the EWSB – photons and gluons remain massless due to the strong and EM gauge invariance

All the sparticles can have a mass term without EWSB

Squarks, sleptons and Higgs are allowed to have mass terms of the form $m^2|\phi|^2$

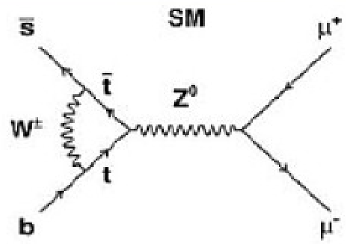
Higgsinos and gauginos can also have masses because their left and right components can have the same interactions

$B_s \to \mu\mu$

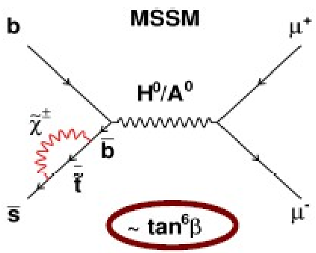
More information:
CDF: ArXiv:1107.2304
CMS/LHCb: CMS-PAS-BPH-11-019

Very rare process in SM:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{SM} = (3.2 \pm 0.2) \times 10^{-9}$$



In MSSM, the process can be enhanced with the contribution of new diagrams:



$$BR(B_s \to \mu^+\mu^-) \propto \tan^6\beta / m_A^4$$

Newest result from CDF:

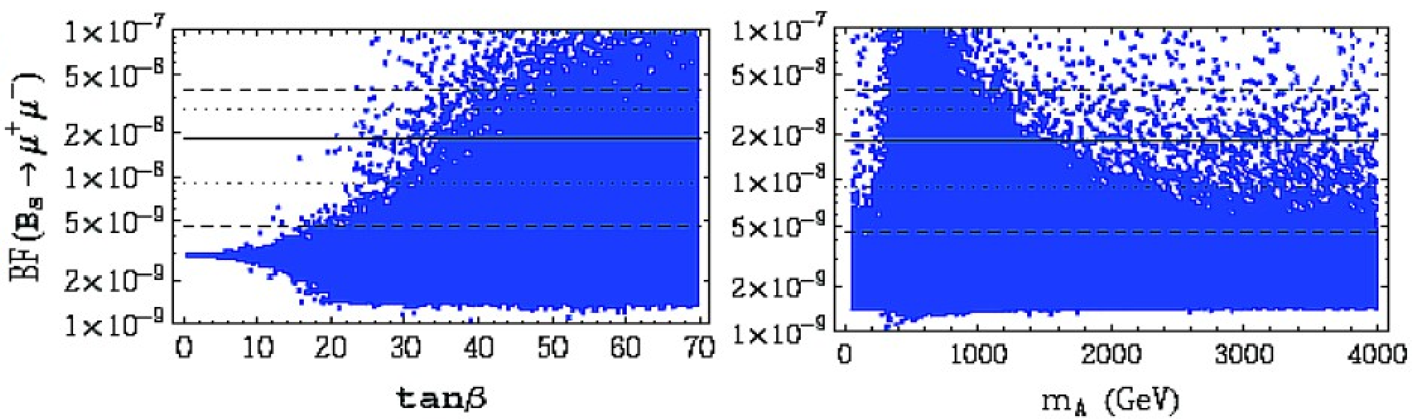
$$BR = 1.8^{+1.1}_{-0.9} \times 10^{-8}$$

Newest result from LHCb and CMS combination:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.08 \times 10^{-8} \text{ at } 95\,\% \text{ CL},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 0.90 \times 10^{-8} \text{ at } 90\,\% \text{ CL},$$

New results constrain some MSSM scenarios (without further assumptions rather than experimental bounds)

D. Hooper, C. Kelso, ArXiv: hep-ph/107.3858

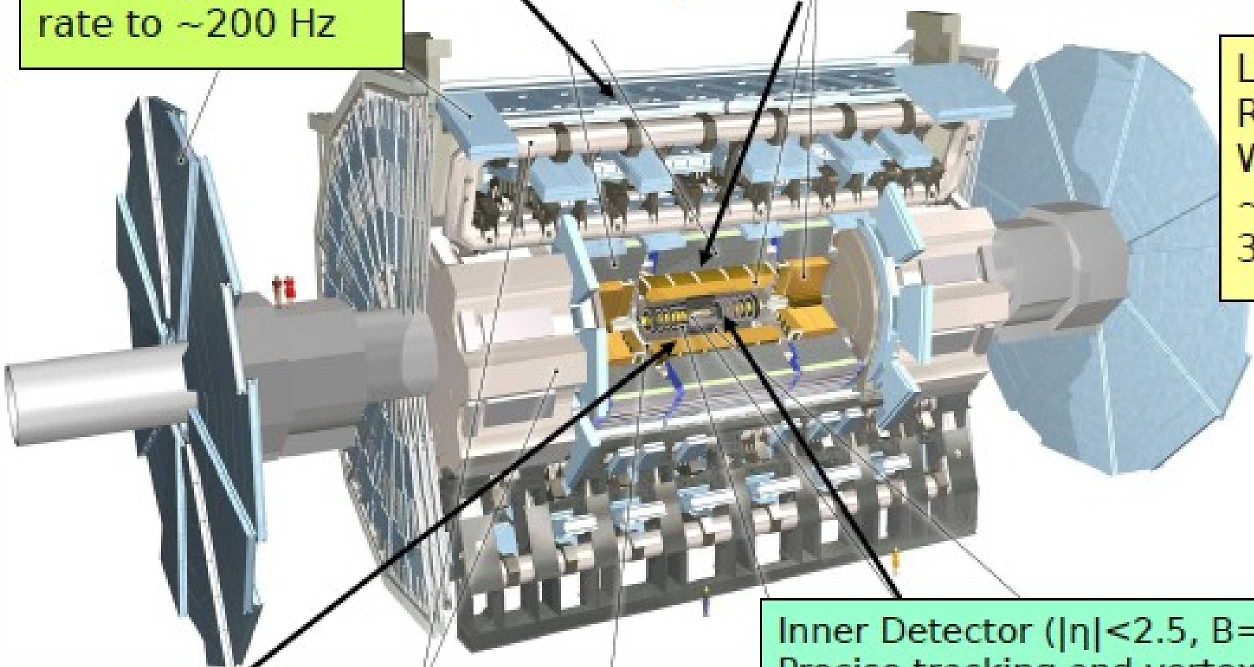


Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution **< 10% up to E_μ ~ 1 TeV**

Hadronic calorimetry ($|\eta|<3$): segmentation **0.1 x 0.1**
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
E-resolution: **$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$**
Forward calorimetry:W/LAr **$\sigma/E \sim 90\%/\sqrt{E} \oplus 0.07$**

3-level trigger
reducing the
rate to ~200 Hz

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables



Inner Detector ($|\eta|<2.5$, B=2T):
Precise tracking and vertexing,
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

Electromagnetic calorimeter: Pb-Liquid Argon Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim$ **$10\%/\sqrt{E} \oplus 0.007$**
granularity :.025 x .025 $\oplus$ strips

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Object identification

- Jets (anti-Kt, R=0.4): p_T>20 GeV, $|\eta|<2.8$
  – Reject events compatible with noise or cosmics
  – Remove if ΔR(jet,electron)<0.2
- Electrons: p_T>20 GeV, $|\eta|<2.47$
  – Remove if ΔR(jet,electron)<0.4
- Muons: p_T>10 GeV, $|\eta|<2.4$
  – Remove if ΔR(jet,muon)<0.4
- Missing transverse momentum (E_T^{miss}):
  – sum over the transverse momentum of all jets (up to $|\eta|<4.9$), electrons, muons and all calorimeter clusters not associated to such objects

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

ϕ: azimuthal angle around the beam pipe
η= -ln tan(θ/2) where θ is the polar angle

QCD BG

Evaluated using the 'matrix method' which plays on the difference in isolation between the leptons in QCD events with respect to signal leptons

- ***Loose*** control sample with isolation criteria relaxed with respect to the ***tight*** SUSY selections
- Define two categories: QCD leptons (***Q***) and non-QCD leptons ($\not{Q}$)
– ε is the probability that a loose lepton is also tight

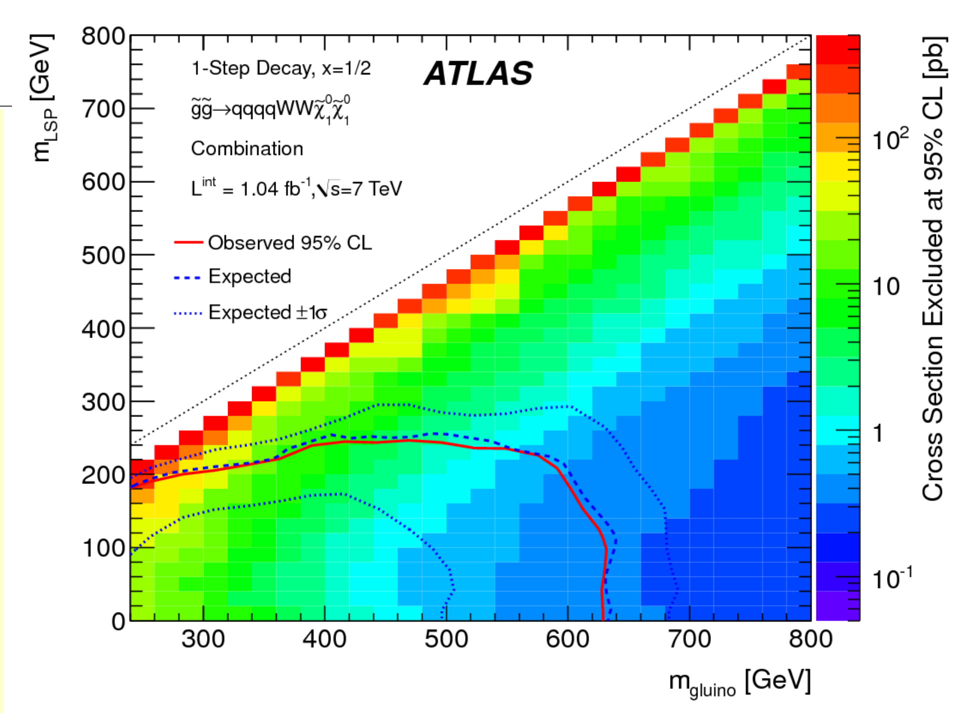
$$N^{obs}_{tight} = N^{\not{Q}}_{tight} + N^{Q}_{tight}$$

$$N^{obs}_{loose\ not\ tight} = (1/\epsilon_{\not{Q}} - 1)\, N^{\not{Q}}_{tight} + (1/\epsilon_{Q} - 1)\, N^{Q}_{tight}$$

The quantities in red are measured: solve the equations and extract the number of QCD events

Electron channel	$\langle\epsilon\sigma\rangle^{95}_{\rm obs}$ [fb]
3JL	50
3JT	14
4JL	33
4JT	10
Muon channel	$\langle\epsilon\sigma\rangle^{95}_{\rm obs}$ [fb]
3JL	36
3JT	10
4JL	31
4JT	9

1-lepton exclusion



Limits also provided for simplified models:

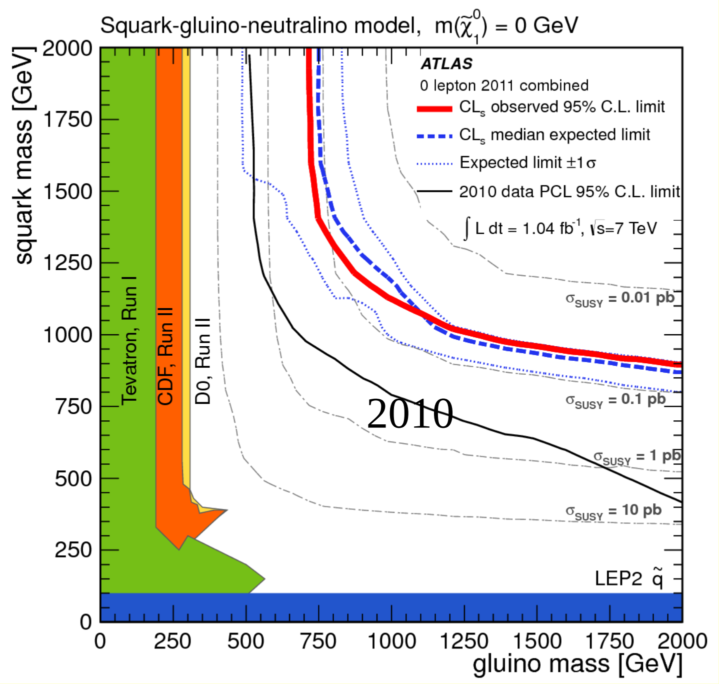
1-step gluino (squark) decay and x= ¼, ½ , ¾

where $x=(m_{\chi\pm}-m_{\chi0})/(m_{squark,gluino}-m_{\chi0})$

Color coding: Cross section limit,

Full line: Obs. Excl. limit for 100% BR to assumed decay mode

Exclusion plot



→ gluino and squark masses below 700 GeV and 875 GeV are excluded (for squark or gluino masses below 2 TeV)

→ limit at 1075 GeV for equal mass squarks and gluinos

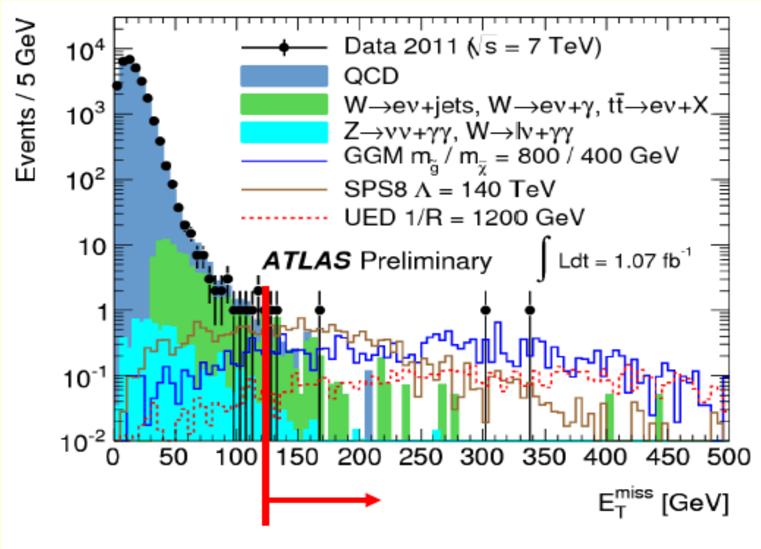
Quickly, more summer results

Di-photon searches

Preliminary results

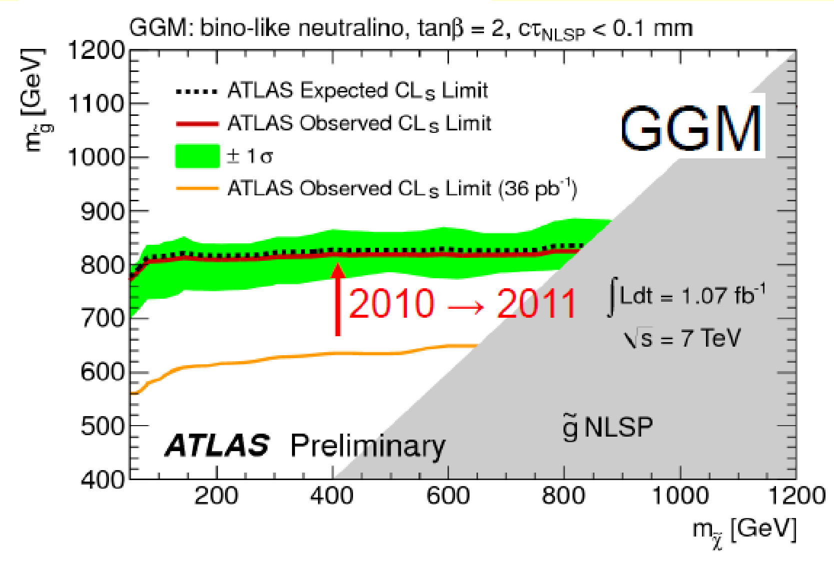
Signal region:

- ≥ 2 photons with $E_T > 25$ GeV
- $E_T^{miss} > 125$ GeV

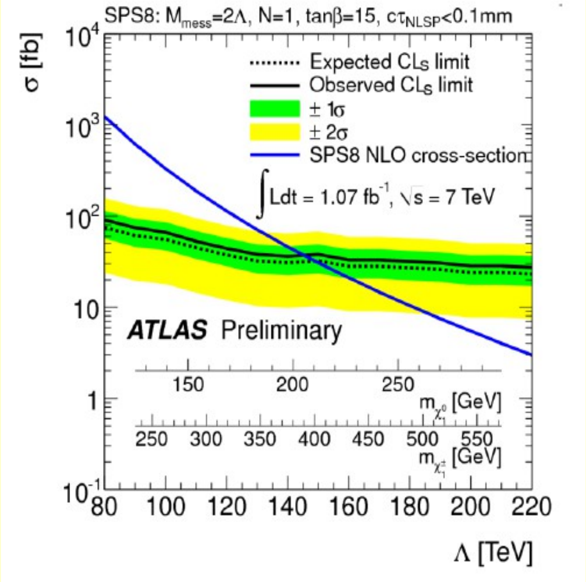


Gluino for production

Bino-like neutralino as NLSP



minimal GMSB / SPS8 slope



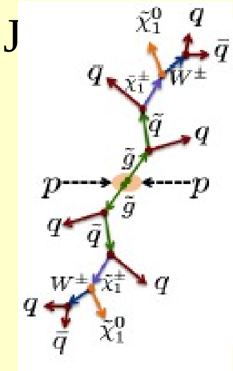
Quickly, more summer results

Multijets

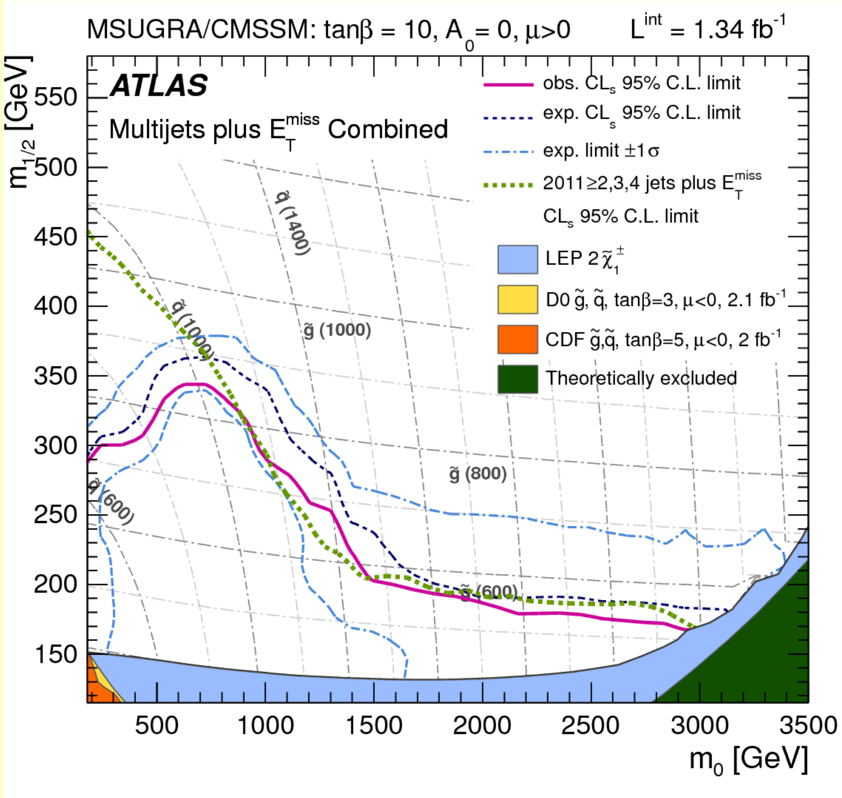
On the arXiv since yesterday!

ArXiV:1110.2299, submitted to

J



Signal region	7j55	8j55	6j80	7j80
Jet p_T	> 55 GeV		> 80 GeV	
Jet $\|\eta\|$	< 2.8			
ΔR_{jj}	> 0.6 for any pair of jets			
Number of jets	≥ 7	≥ 8	≥ 6	≥ 7
$E_T^{miss} / \sqrt{H_T}$	> 3.5 GeV$^{1/2}$			



Signal region	7j55	8j55	6j80	7j80
Multi-jets	26 ± 5.2	2.3 ± 0.7	19 ± 4	1.3 ± 0.4
$t\bar{t} \to q\ell, \ell\ell$	10.8 ± 6.7	$0^{+4.3}$	6.0 ± 4.6	$0^{+0.13}$
W + jets	0.95 ± 0.45	$0^{+0.13}$	0.34 ± 0.24	$0^{+0.13}$
Z + jets	$1.5^{+1.8}_{-1.5}$	$0^{+0.75}$	$0^{+0.75}$	$0^{+0.75}$
Total Standard Model	39 ± 9	$2.3^{+4.4}_{-0.7}$	26 ± 6	$1.3^{+0.9}_{-0.4}$
Data	45	4	26	3
$N^{95\%}_{BSM,max}$	26.0	11.2	16.3	6.0
$\sigma^{95\%}_{BSM,max} \times \epsilon$/fb	19.4	8.4	12.2	4.5
p_{SM}	0.30	0.36	0.49	0.16

Quickly, more summer results

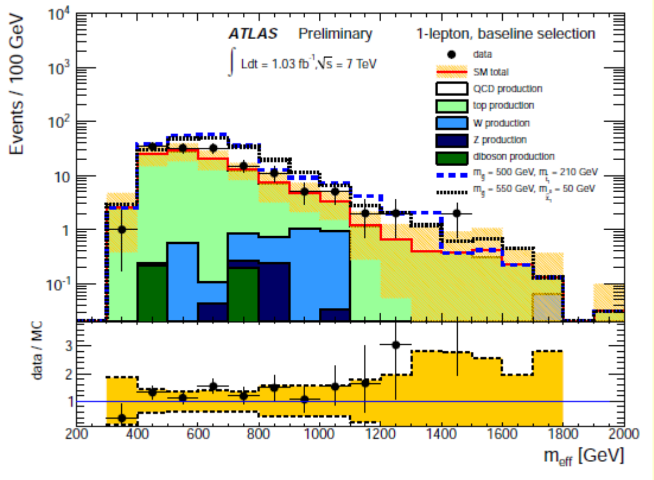
b-jet with 1 lepton

ATLAS-CONF-2011-130

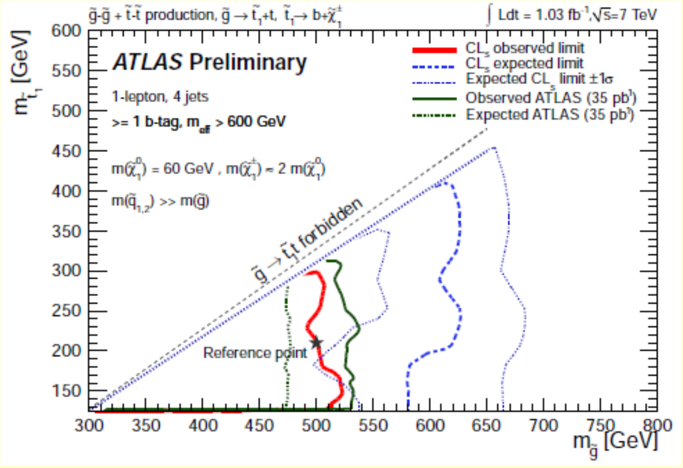
4 jets ($p_T > 50$ GeV), ≥ 1 b-jet ($p_T > 50$ GeV)
Exactly 1 lepton (e or μ)
$E_T^{Miss} > 80$ GeV

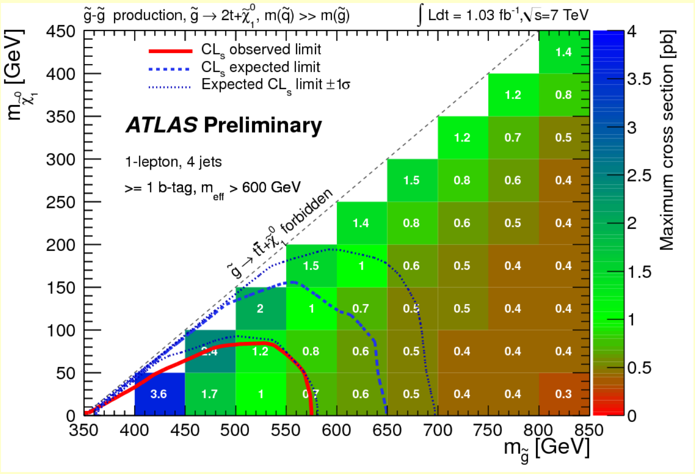
$$m_T = \sqrt{2p_T^{lep}E_T^{Miss} - 2\vec{p}_T^{\,lep}\vec{E}_T^{Miss}} > 100 \text{ GeV}$$

$$m_{Eff} = \sum_{i\leq 4}(p_T^{jet})_i + p_T^{lep} + E_T^{Miss} > 600 \text{ GeV}$$



Scenario 1: $\tilde{g}\tilde{g}$ and $\tilde{t}_1\tilde{t}_1$ production with $\tilde{g} \rightarrow \tilde{t}_1 t$ (BR=100%) and $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^{\pm}$ (BR=100%)
Scenario 2: $\tilde{g}\tilde{g}$ production with $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ (BR=100%) via off-shell stop decay.





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Quickly, more summer results

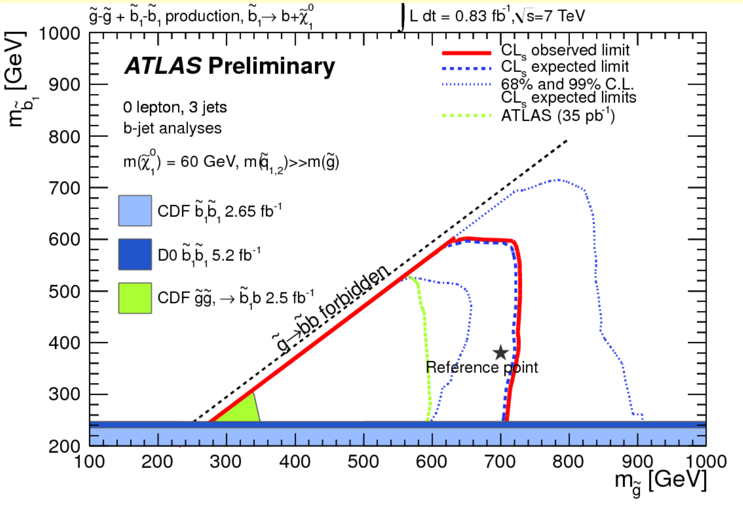
b-jet with no lepton

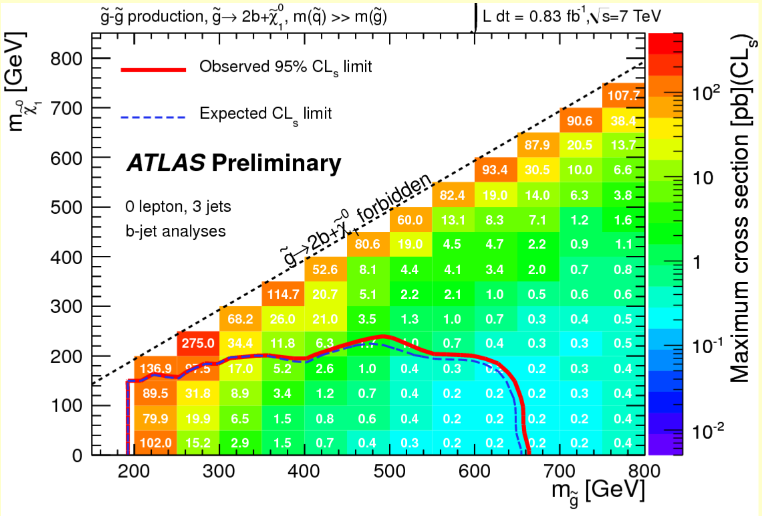
ATLAS-CONF-2011-098

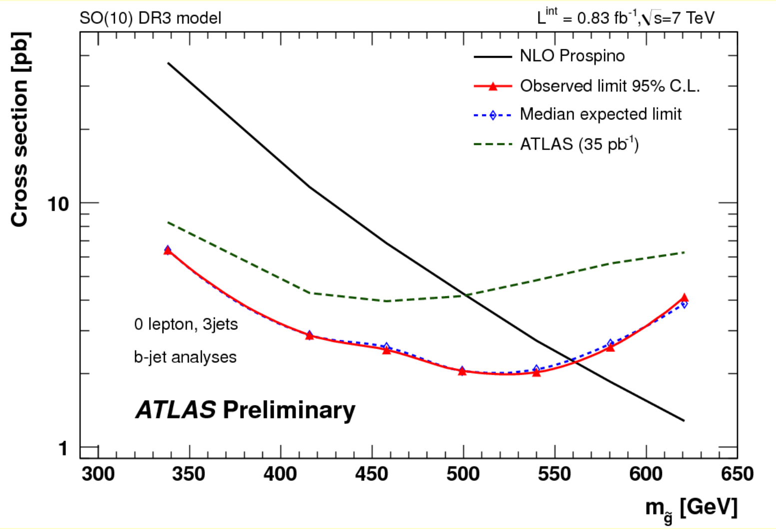
lepton veto with $p_T > 20$ GeV (electron), 10 GeV (muon)

- jet p_T>130,50,50 GeV
- $E_T^{miss} > 130$ GeV
- $\Delta\varphi_{min} > 0.4$ rad
- $E_T^{miss}/m_{eff} > 0.25$

- $\geq$1 *b*-jet, $m_{eff} > 500$ GeV
- $\geq$1 *b*-jet, $m_{eff} > 700$ GeV
- $\geq$2 *b*-jet, $m_{eff} > 500$ GeV
- $\geq$2 *b*-jet, $m_{eff} > 700$ GeV







What about CMS ?