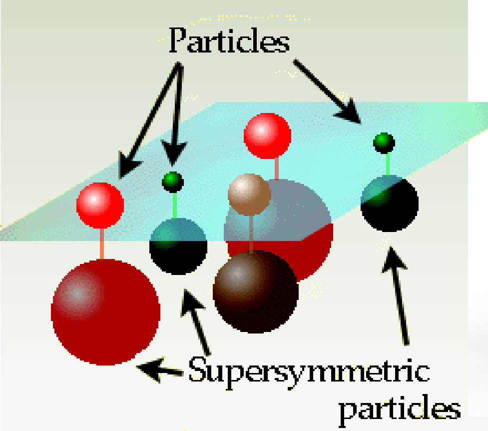
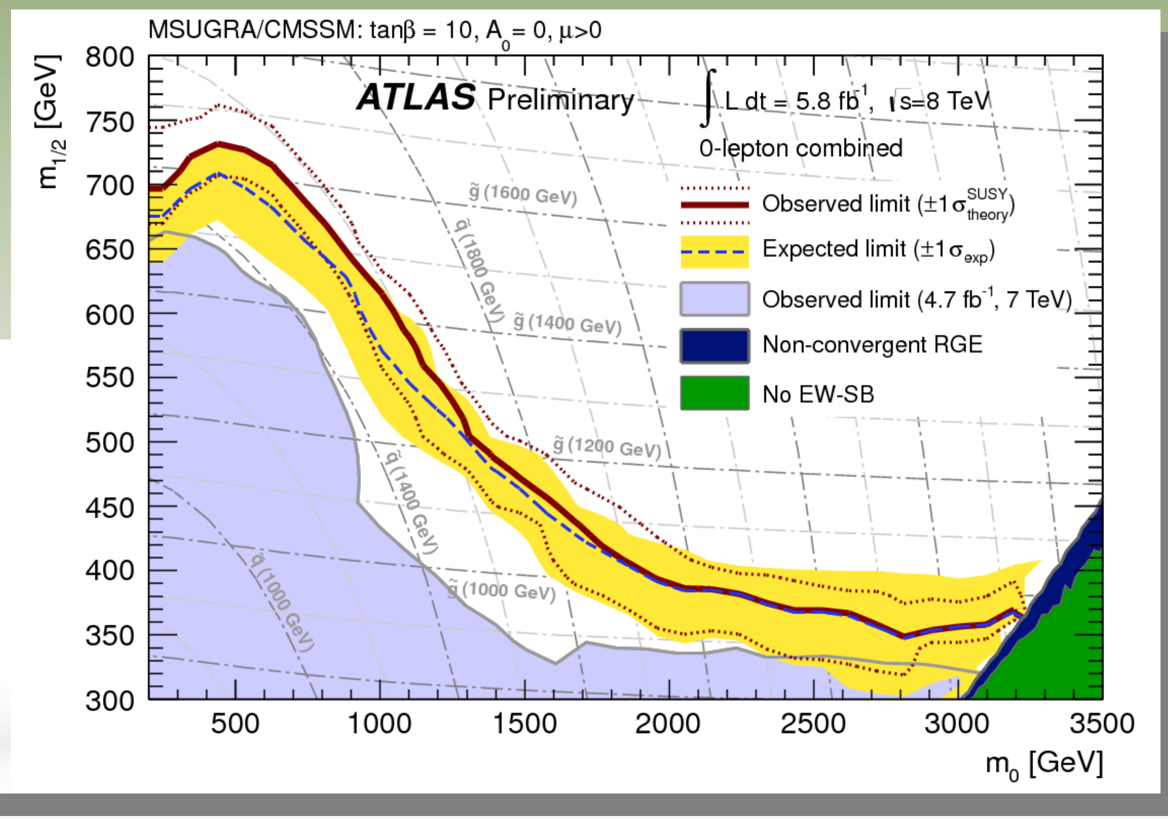
Overview of Supersymmetry Searches and their statistical interpretation

Xavier Portell (CERN)

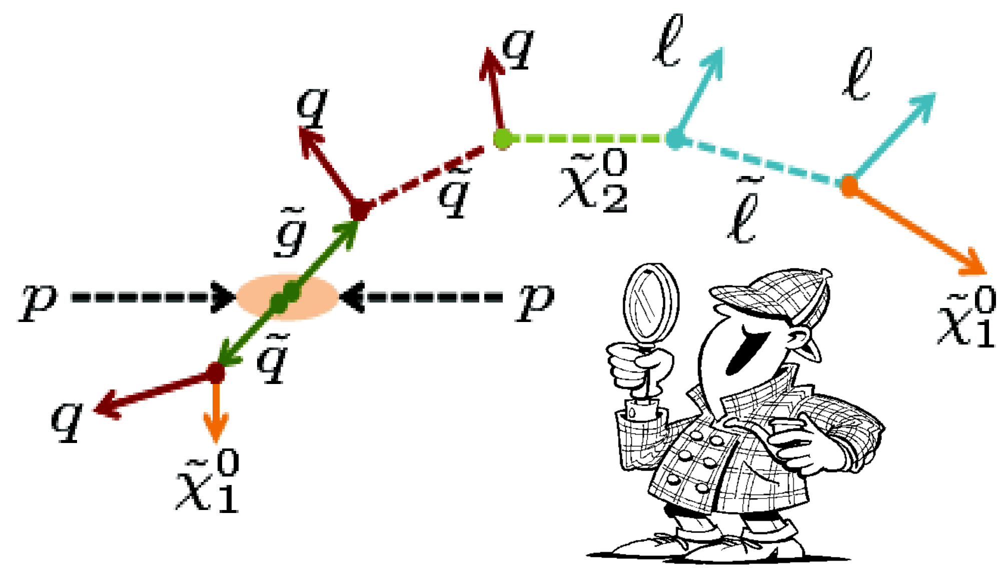




"Prejudice meets reality: school" Physics at the Terascale.
Bonn 20th-24th August 2012

Outline

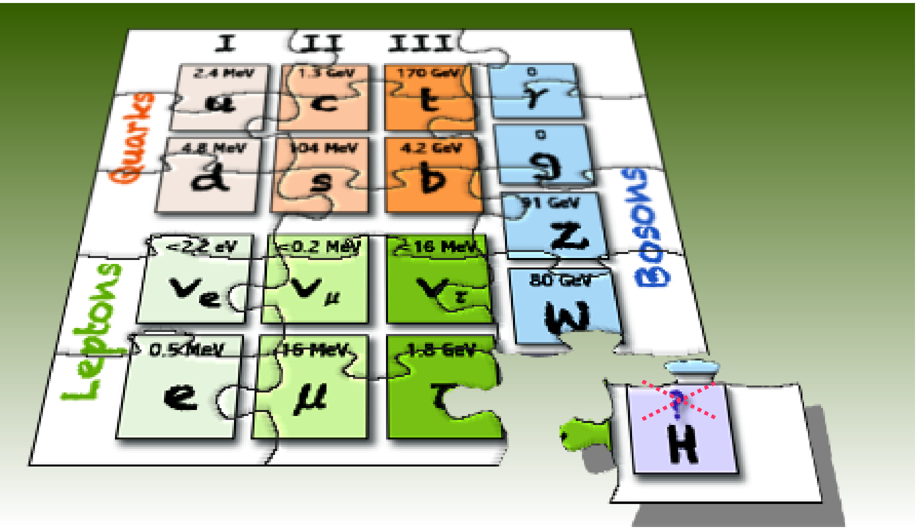
- The limitations of the Standard Model (SM)
- Introduction to Supersymmetry (SUSY)
- General tools/strategies for searches
- Interpretation of results
- Assumptions behind interpretations
- Example: stop
- Is SUSY too much constraint?
- Summary



Disclaimer: this is a general talk not pretending to cover the different analyses from ATLAS and CMS in any detail. Examples are taken ATLAS-biased, which doesn't mean they are better or worse than CMS ones.

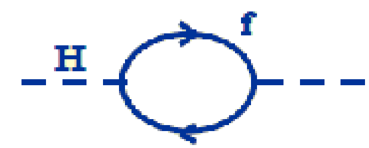
The Standard Model (SM)

No significant deviation found in many years of investigation



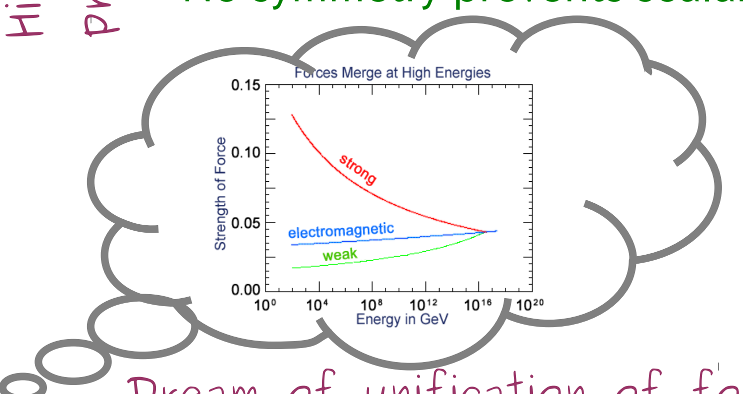
- Matter is made out of fermions:
  - 3 generations of quarks and leptons
- Forces carried by bosons:
  - Electroweak (EWK): g, W, Z
  - Strong: gluon
- Missing piece: origin of masses
  - Higgs particle

However, there are some theoretical problems in the above picture:



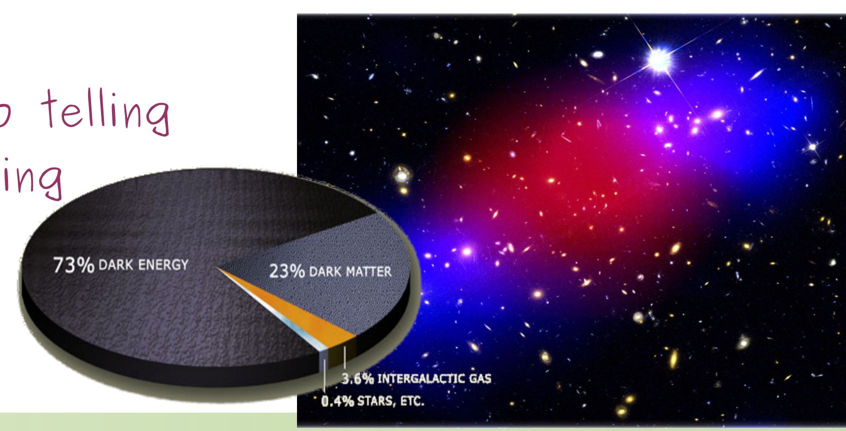
Hierarchy problem

- Higgs mass should be small to preserve unitarity (~<1 TeV)
- If no new physics: $\Lambda \sim \Lambda_{Pl}$ --> why m_W scale << m_{Pl}?
- No symmetry prevents scalars from acquiring mass via radiative corrections: $\delta m_H^2 \sim \Lambda^2 \sim \Lambda_{Pl}^2$



Dream of unification of forces

Universe is also telling us we are missing something...

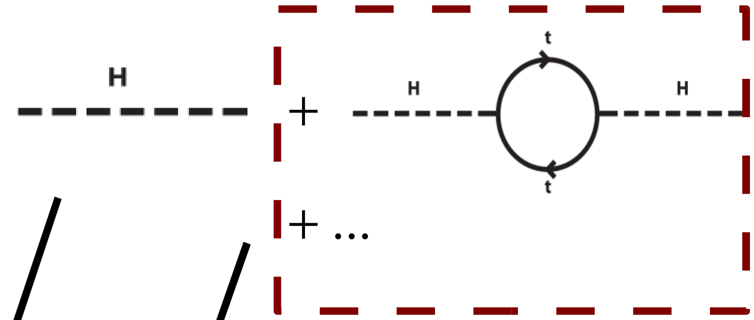


Hierarchy Problem

Can the SM be valid up to the Planck scale?

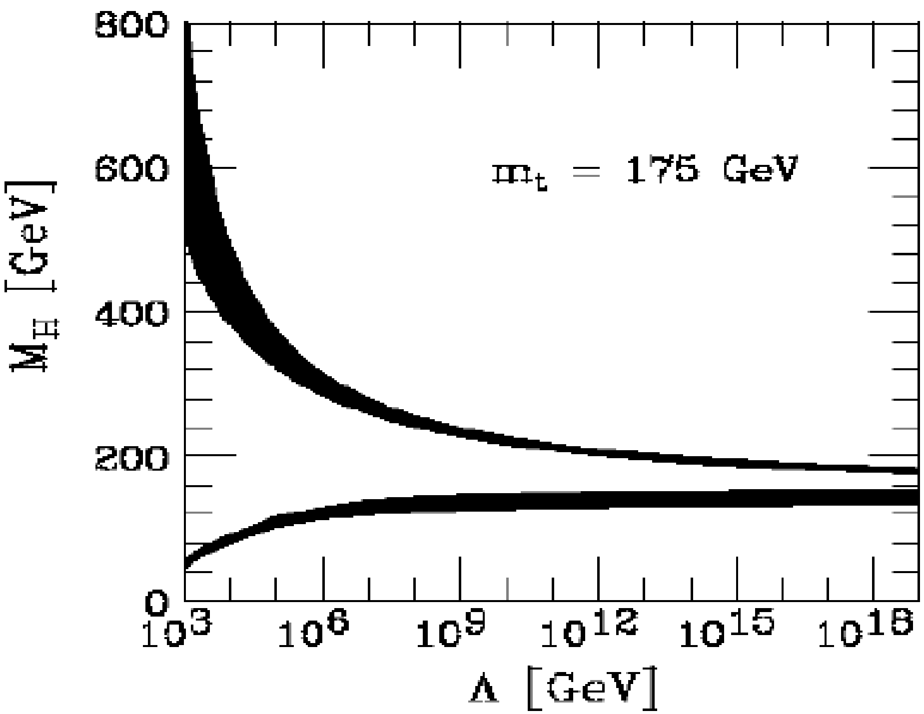
- Yes, but unstable situation.
- The Higgs should have a very precise mass (probably it has... but why?)
- Main problem: sensitivity of the theory to the presence of new physics at large scales:

Higgs mass:



$$m_{h_{SM}}^2 = (m_h^2)_0 + \frac{kg^2\Lambda^2}{16\pi^2},$$

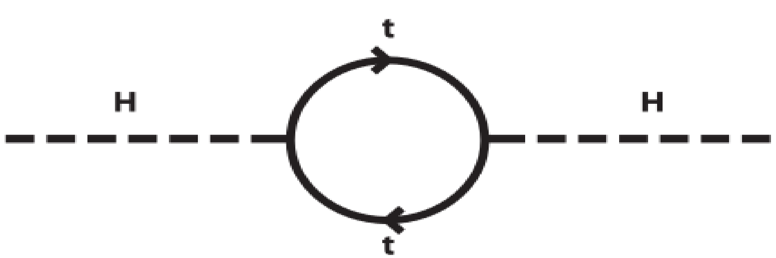
Scalars sensitive to the scale of the theory



- The two terms come from independent origin and should ~cancel.
- Any unknown physics (and there is much to accommodate still: baryogenesis, see-saw mechanism, gravity...) will affect corrections
- Supersymmetry is a very elegant way to solve this problem (even if small fine-tuning is finally required!)

Supersymmetry

- Supersymmetry (SUSY) is a new symmetry between bosons and fermions
  - Every SM particle has a superpartner *differing by half a unit of spin*
  - Higgs sector extended to 5 Higgs: h, H, A, $H^{\pm}$
- It naturally solves the hierarchy problem
  - Loop contributions cancel
- It could provide solution to other problems
  - Gauge unification
  - Dark matter candidate
  - ...



Different spins in the loop --> different sign --> Exact cancellation

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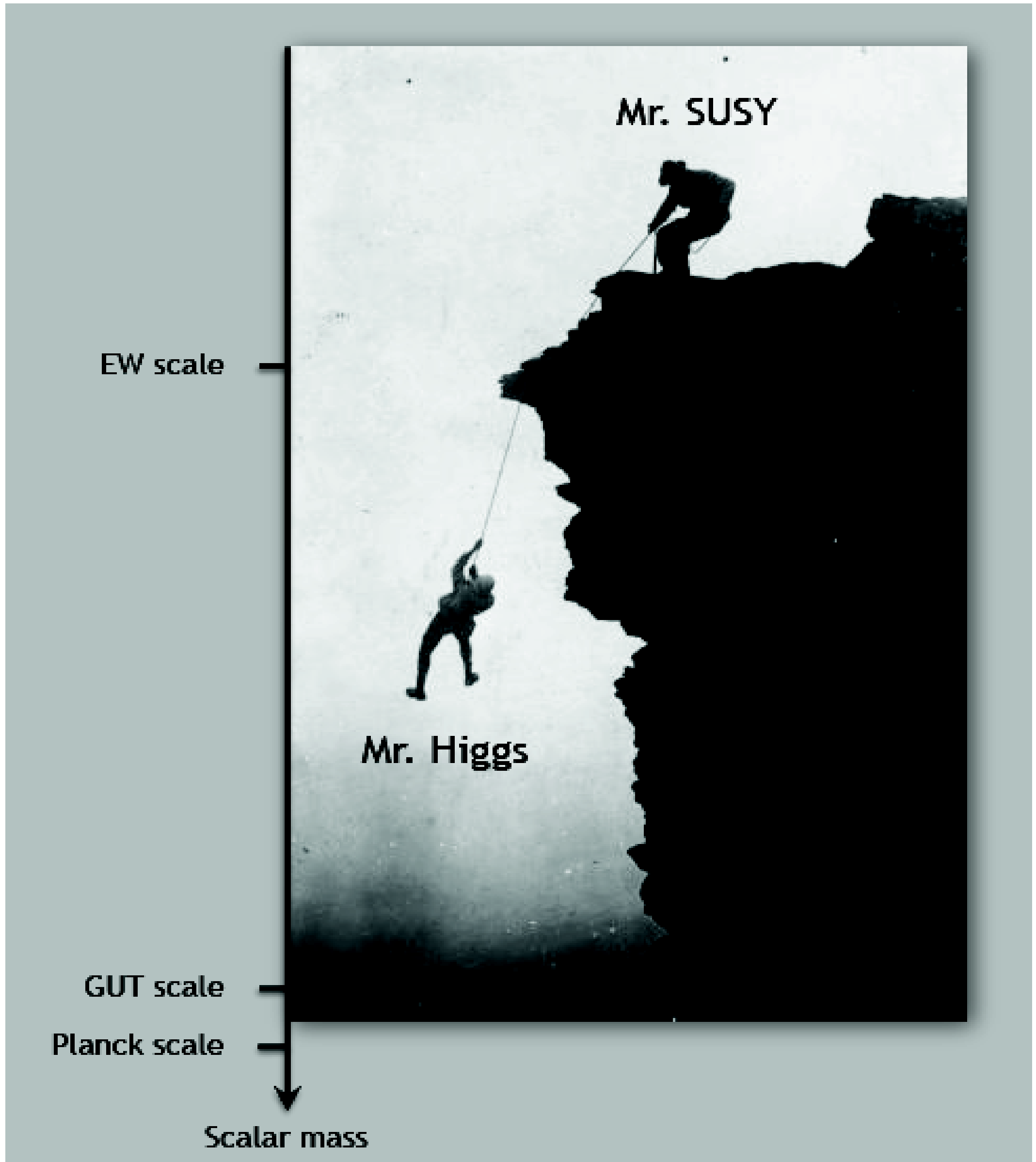
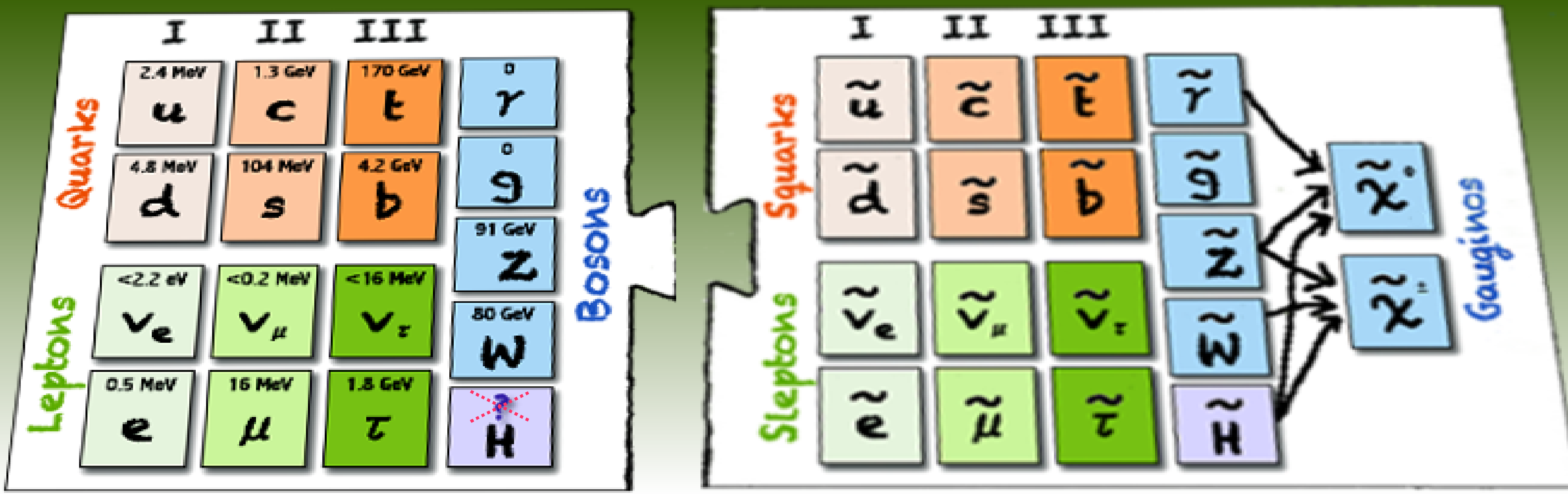
Different spins in the loop --> different sign --> Exact cancellation (if masses are equal)

SUSY particles not too far away...
whatever that means!

SUSY solving the hierarchy problem?



Supersymmetry



New problem:

Particles with same mass but different spin are not observed.

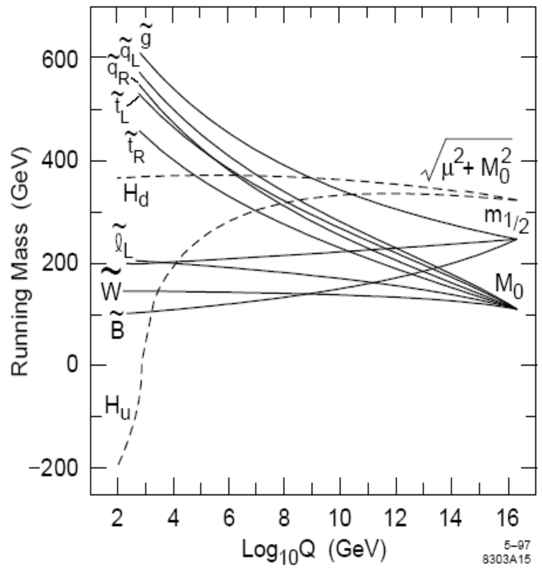
SUSY must be broken: mechanism unknown

SUSY modelling

- The minimal SUSY extension of the SM (MSSM): 105 new parameters. Need different approaches.

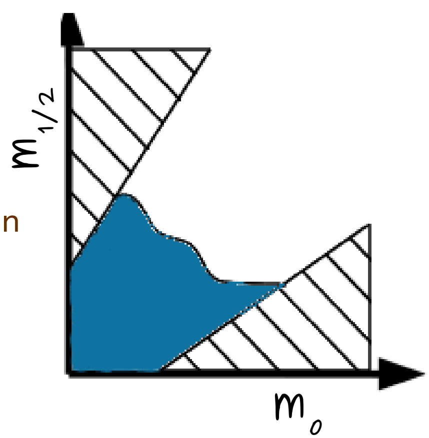
Top-down approach

- Model of SUSY breaking: gravity mediated, gauge mediated...
- Assume GUT scale parameters (few)
- Predict phenomenology at the EWK scale



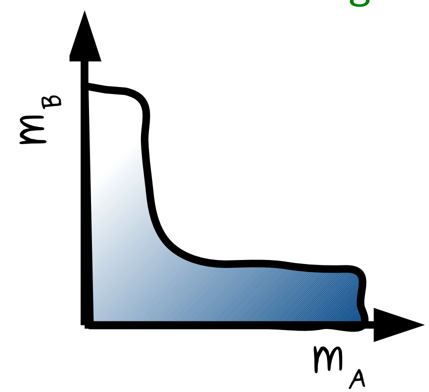
E.g. mSUGRA/CMSSM:

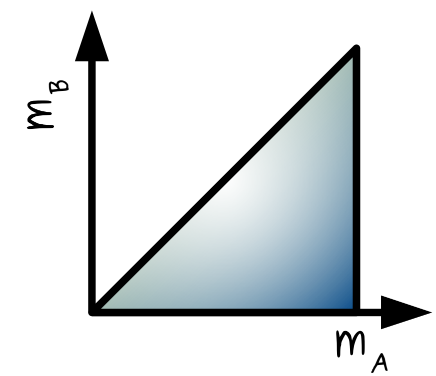
m_0: common scalar mass (GUT)
$m_{1/2}$: common gaugino mass (GUT)
$\tan\beta$: Ratio of Higgs vaccum expectation values
A_0: Trilinear coupling
Sign(μ): Higgs mass term



Bottom-up approaches

- Phenomenological models
  - ➜ Assume mass & hierarchy for SUSY particles
- Simplified models:
  - ➜ Assume single decay chain (building block)

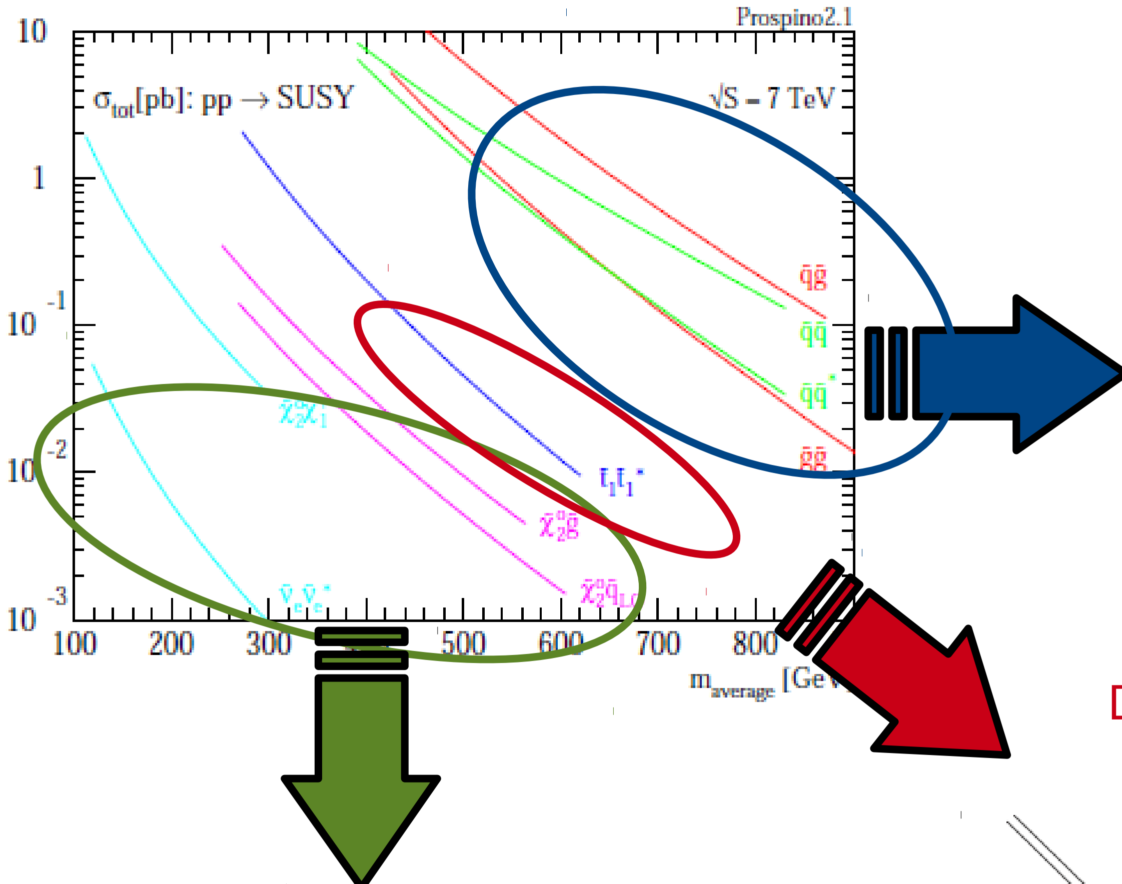




General limits

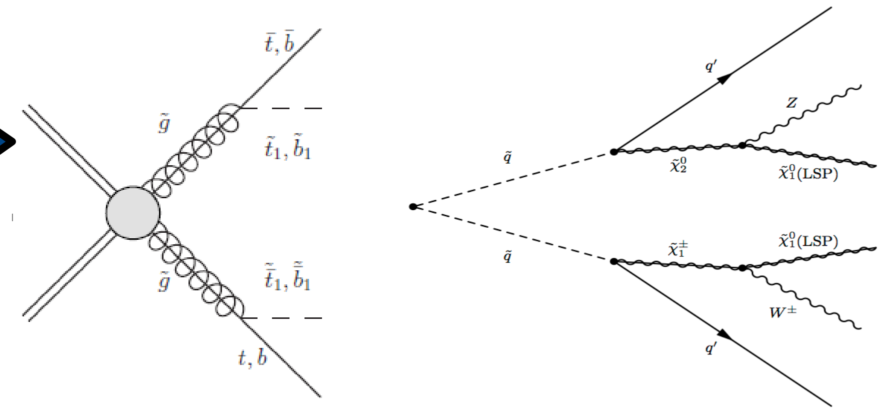
Data & background: how much signal can be accommodated?
Provide $\sigma \cdot$ efficiency $\cdot$ acceptance

Sensitivity to SUSY

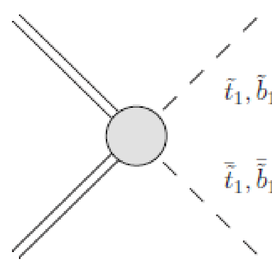


Gluino and squark production (strong-production)

- Dominates at hadron colliders



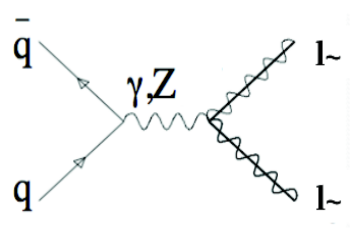
Direct stop/sbottom production



- Lower cross sections
- Large backgrounds: need dedicated analyses per topology.

(see later for details)

Direct gaugino/slepton production



- Low cross sections: weak production
- Make use of leptonic final states to reduce backgrounds (in general, low branching ratios)

Expected signatures

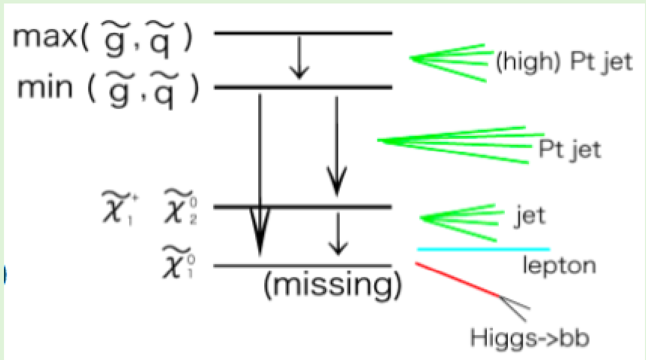
General MSSM lagrangian violates leptonic and baryonic numbers in the superpotential → New symmetry postulated: $R=(-1)^{2S+3(B-L)}$

Impact on the expected phenomenology

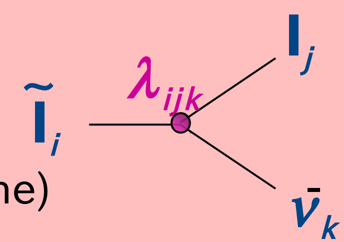
SM: R-parity=+1
SUSY: R-parity=-1

R-parity conservation (RPC)

- SUSY particles created in pairs
- Lightest Supersymmetric Particle (LSP) stable
  - ✔ Missing transverse momentum (EtMiss)
  - ✔ No mass peak expected (tails)
  - ✔ Excellent detector understanding



R-parity violation (RPV)



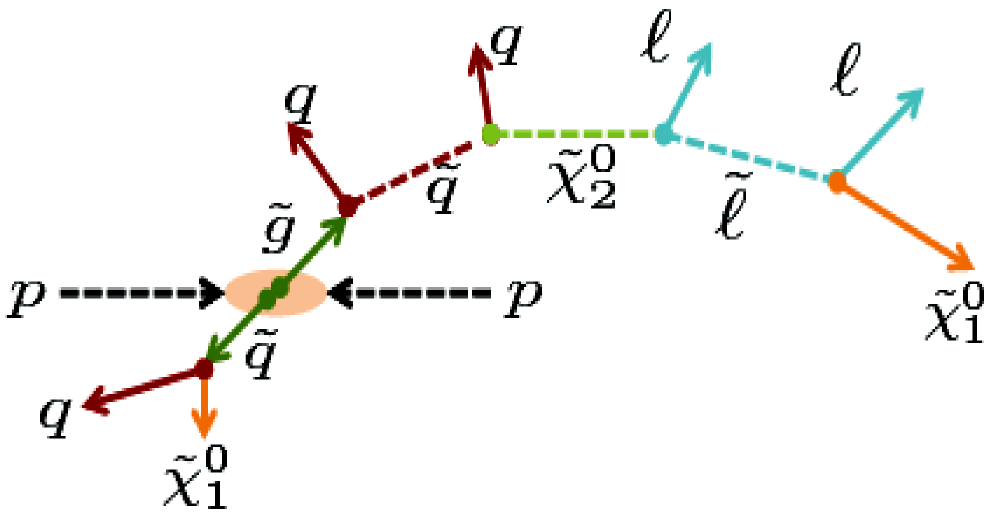
- The LSP decays
- Some constraints (e.g. proton lifetime)
  - ✔ Exploit invariant masses
  - ✔ EtMiss can also be expected (e.g. neutrinos) but can be relaxed

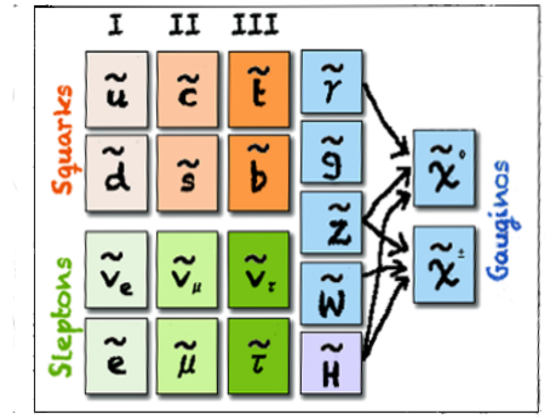
Other more exotic situations

- Depending on the mass splitting/hierarchy
  - ✔ Displaced vertices
  - ✔ Slow moving ionizing particles
  - ✔ Delayed decay
  - ✔ …

Indirect searches (e.g. $B_s \rightarrow \mu\mu$)

Overview of SUSY analyses





Rich phenomenology:

- ✔ short/long cascades
- ✔ with/without leptons
- ✔ Different flavours of jets/leptons
- ✔ Large/small EtMiss (SUSY masses)

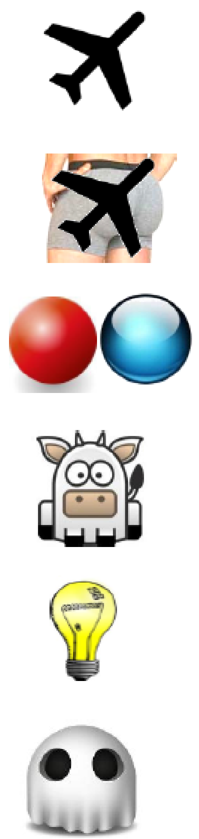
R-Parity conserving searches (RPC)

- 0-lepton
- 1-lepton
- 2-leptons
- Multi-leptons
- b-jet searches
- Photon searches
- τ-searches

R-Parity violating searches (RPV)

Possible final states: objects

(original idea from Alan Barr)



Jets

"bottom"-jets (b-jets)

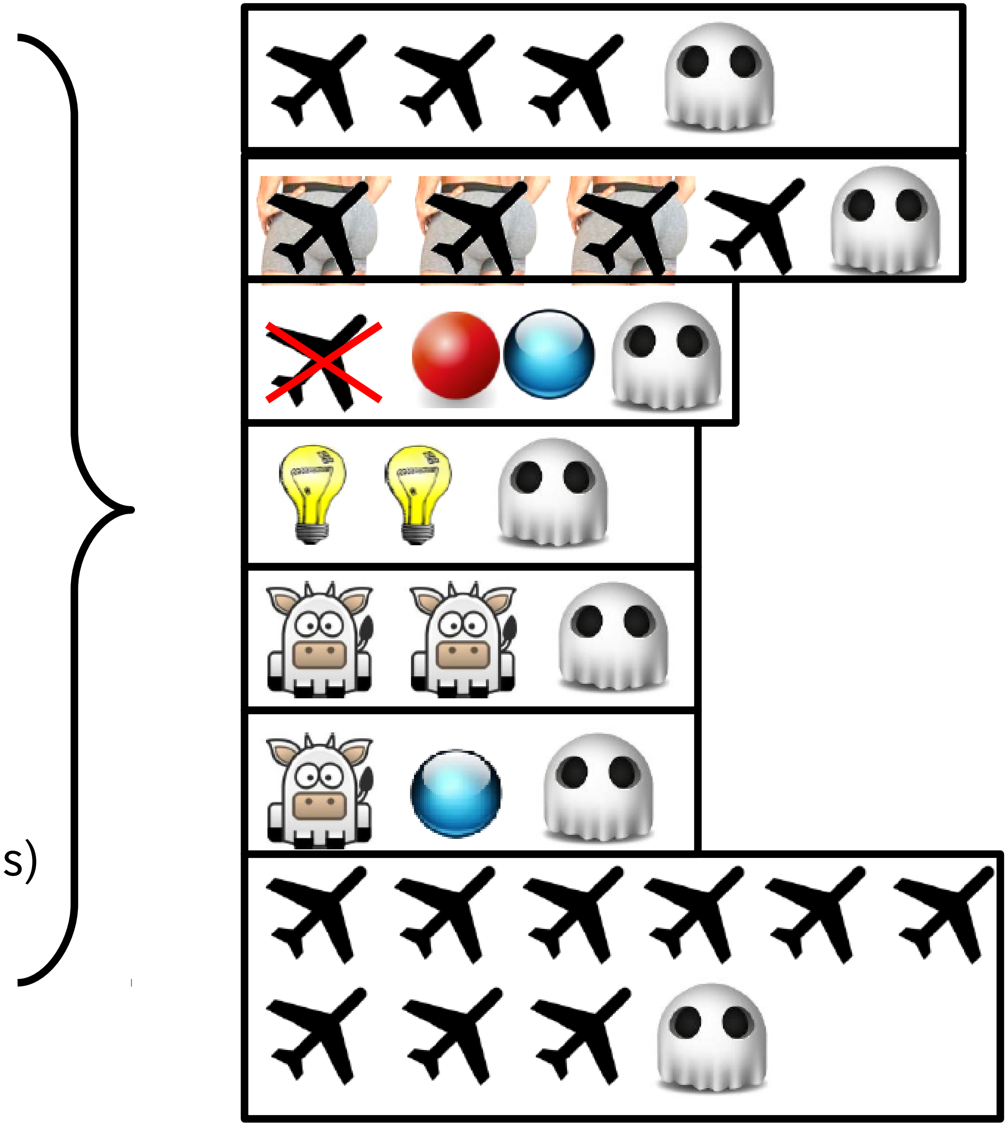
Leptons (electrons or muons)

Taus

Photons

Missing transverse energy (EtMiss)

Analyses use combination of these objects. E.g:



...

For the complete list:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

See Till Eifert's talk for details

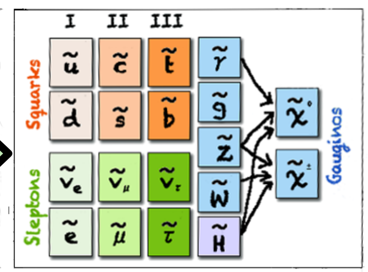
General tools/strategies

Motivation

- ✔ Inclusive search? i.e. maximise coverage (e.g. jets+EtMiss)
- ✔ Exclusive search? i.e. aim to a particular process (e.g. stop search)

Optimisation

- ✔ What variables will better discriminate against backgrounds? How to trigger?
- ✔ How many signal regions? Fit or counting experiment?
- ✔ Complement/overlap with other searches?



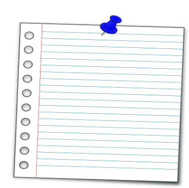
Background control and validation

- ✔ Consider all backgrounds
- ✔ How to estimate them? Rely on Monte Carlo (MC)? Semi data-driven? Completely data-driven?
- ✔ How to trust the estimation? Validation regions.

Experiment: "open the box"

- ✔ Look at data event yields in the signal region(s)

Estimation



- ✔ SM expectations
- ✔ Signal expectations
- ✔ Systematics for signal and background and their correlations

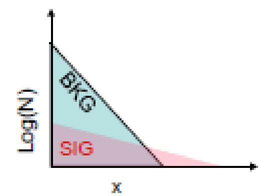
Interpretation

- ✔ Is there an excess? Evaluate the p-value of the excess
- ✔ Is it compatible? Establish 95% CL exclusion limits (general and in particular motivated models)
- ✔ Combine with other analyses if applicable

Examples on optimisation

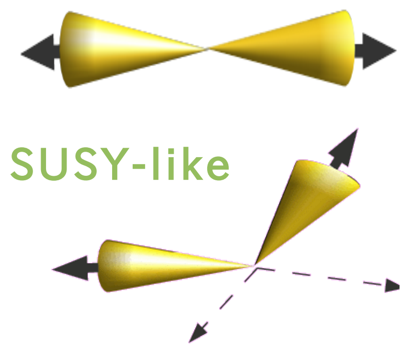
There is a large number of quantities that have been used to discriminate signal from background in order to boost analysis sensitivity

EtMiss, HT, MHT, m_{eff}...



- Vectorial or scalar sum of jet/leptons pT
- Relies on SUSY being more massive and with extra EtMiss (LSP)
- They are the most inclusive variables (high sensitivity to many models)

QCD-like



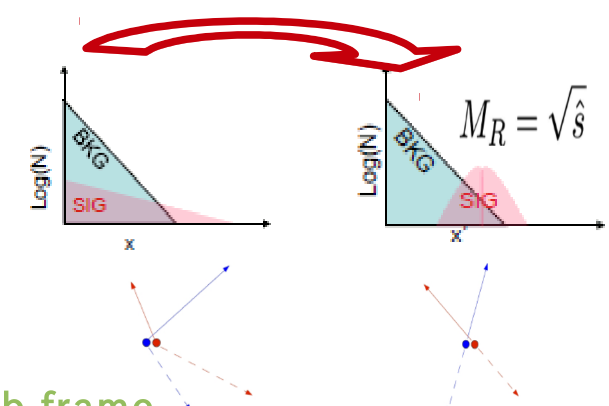
SUSY-like

Transverse mass (mT), Contransverse mass (mct), mT2, α_T ...

- Combination of angular distributions and momenta of objects and/or the EtMiss
- Some of them really model dependent (e.g. assuming pair production of particles with same mass...)
- Involve certain amount of combinatorics in some cases

Razor, $\mathrm{sqrt(s)}_{min}^{sub}$...

- Complex event reconstruction
- Involve guess on missing particle masses, p_Z, boost information...



Lab frame

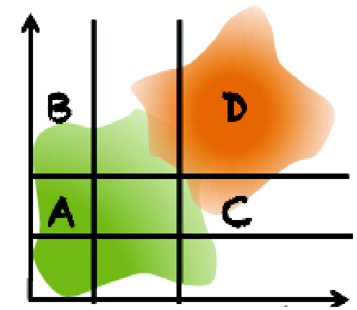
Centre-of-mass frame

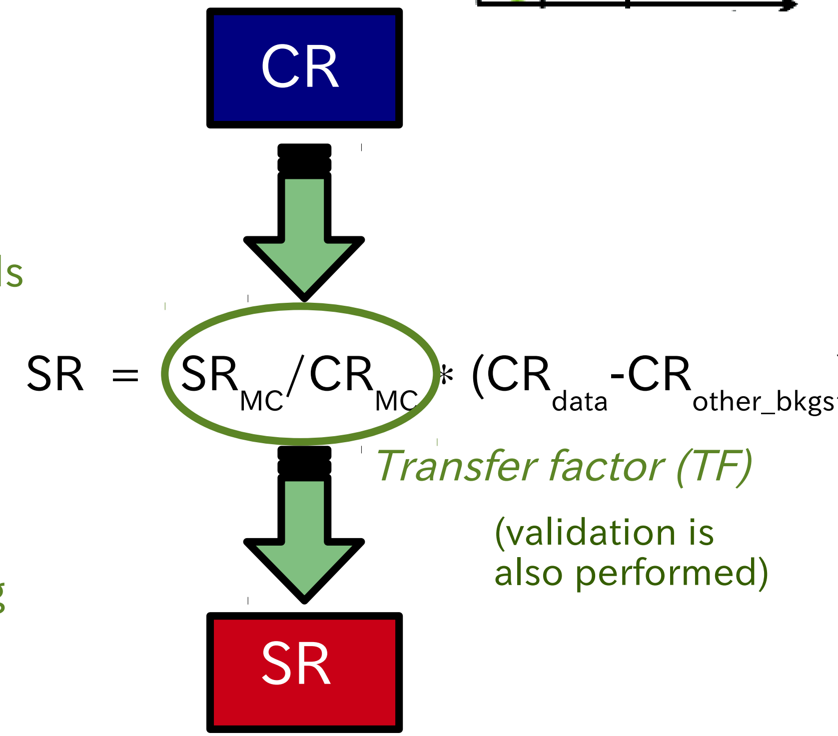
Impossible to cover all of them here: look for details in the analysis papers themselves

Controlling the background

Depending on the type of background, different techniques are used:

- **Data-driven** (large σ, low accept.)
  - When the cross section is huge and the acceptance low
  - E.g: QCD jet smearing technique or matrix method ("loose"-->"tight" probabilities taken from CRs)...
- **Semi data-driven**
  - When completely data-driven is challenging or affected by significant signal contamination.
  - Define a control region (CR) for each of the backgrounds to test MC performance
  - Control region kinematically close to signal region (but need enough stats and low signal contamination)
  - Normalise MC yields to data
  - Transfer factor from CR to signal region (SR) subtracting other backgrounds in the region
  - Systematics reduced due to ratio SR/CR
- **MC-only estimation**
  - When contribution is too low to define meaningful CRs





Interpretation: general limits

*at 95% CL

Question: what is the maximum number* of new physics events that we can allow given the observed constraints?

- ✔ Nobs: observed events
- ✔ Nexp: SM expectation
- ✔ Δ(Nexp): stat++sys uncertainties on SM expectation

Upper limits on number of events can also be translated to upper limits on cross section (taking into account the luminosity uncertainty):

$$N^{95}=\sigma^{95}*Lumi$$

How to make use of this number?

1) take a signal process

2) pass through (approximate?) detector simulation

3) apply same cuts

4) if final number of expected events is above the upper limits, it is excluded

There exist different programs on the market to approximately simulate the ATLAS detector (e.g. PGS, Delphes...)

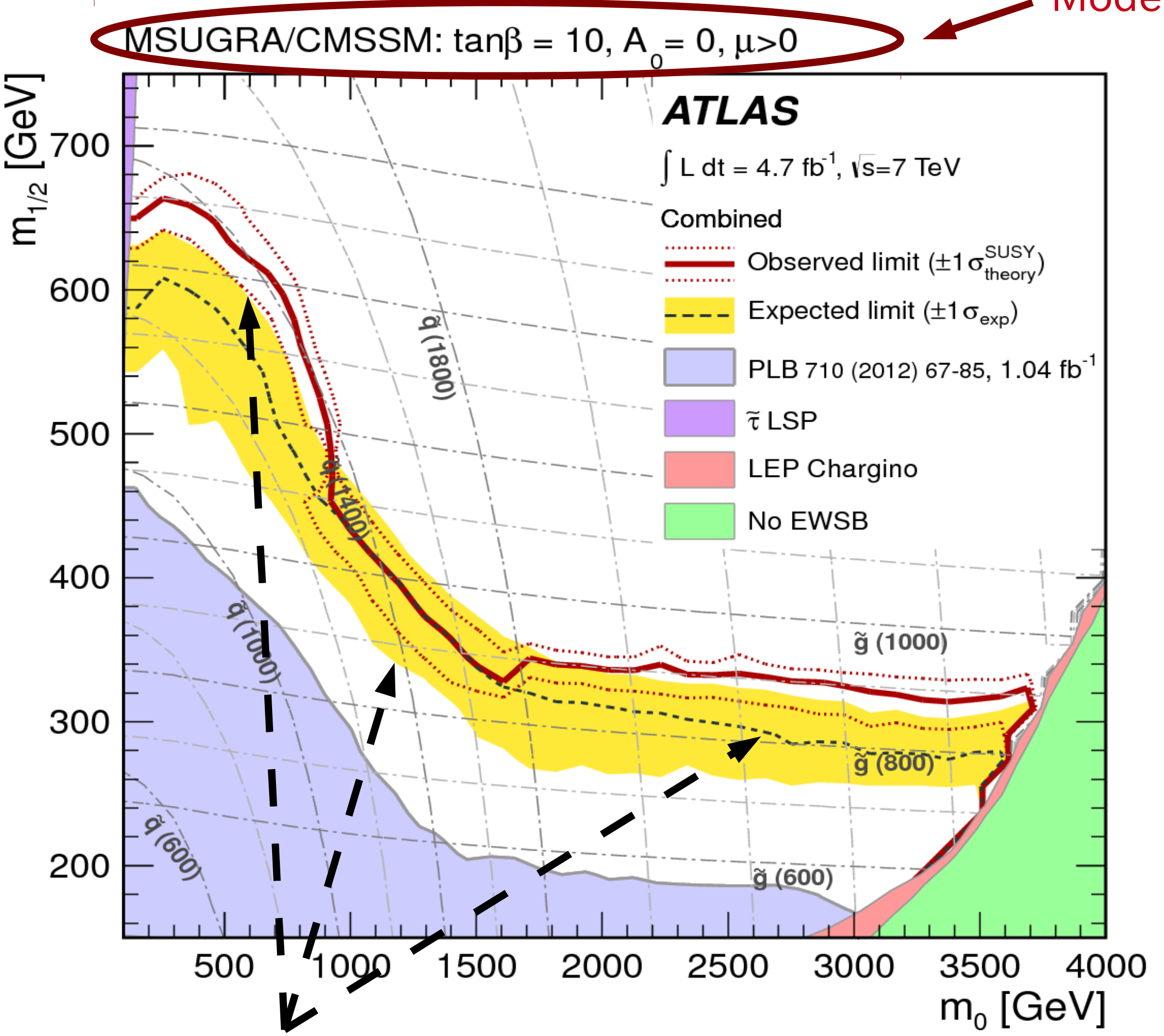
Experiments provide plenty of information and even parameterisations to validate models.

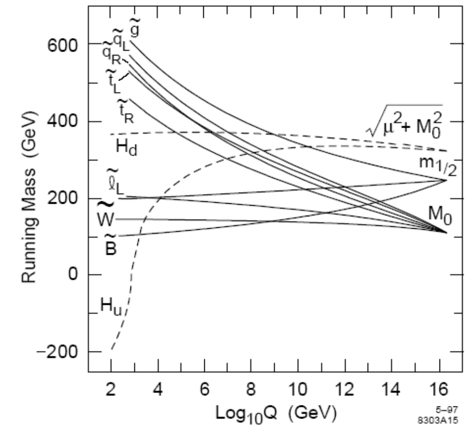
Used in tutorial

Details on limits setting: Till Eifert's talk and tutorial

Interpretation: SUSY model

Model parameters





Every point: combination of parameters that determines particular phenomenology

Different production processes per point: gluino-gluino, squark-gluino... Considered separately and then added together.

If multiple SRs, best *expected* chosen per point.

Signal contamination in CRs is also taken into account (worsens limits)

Information to extract:

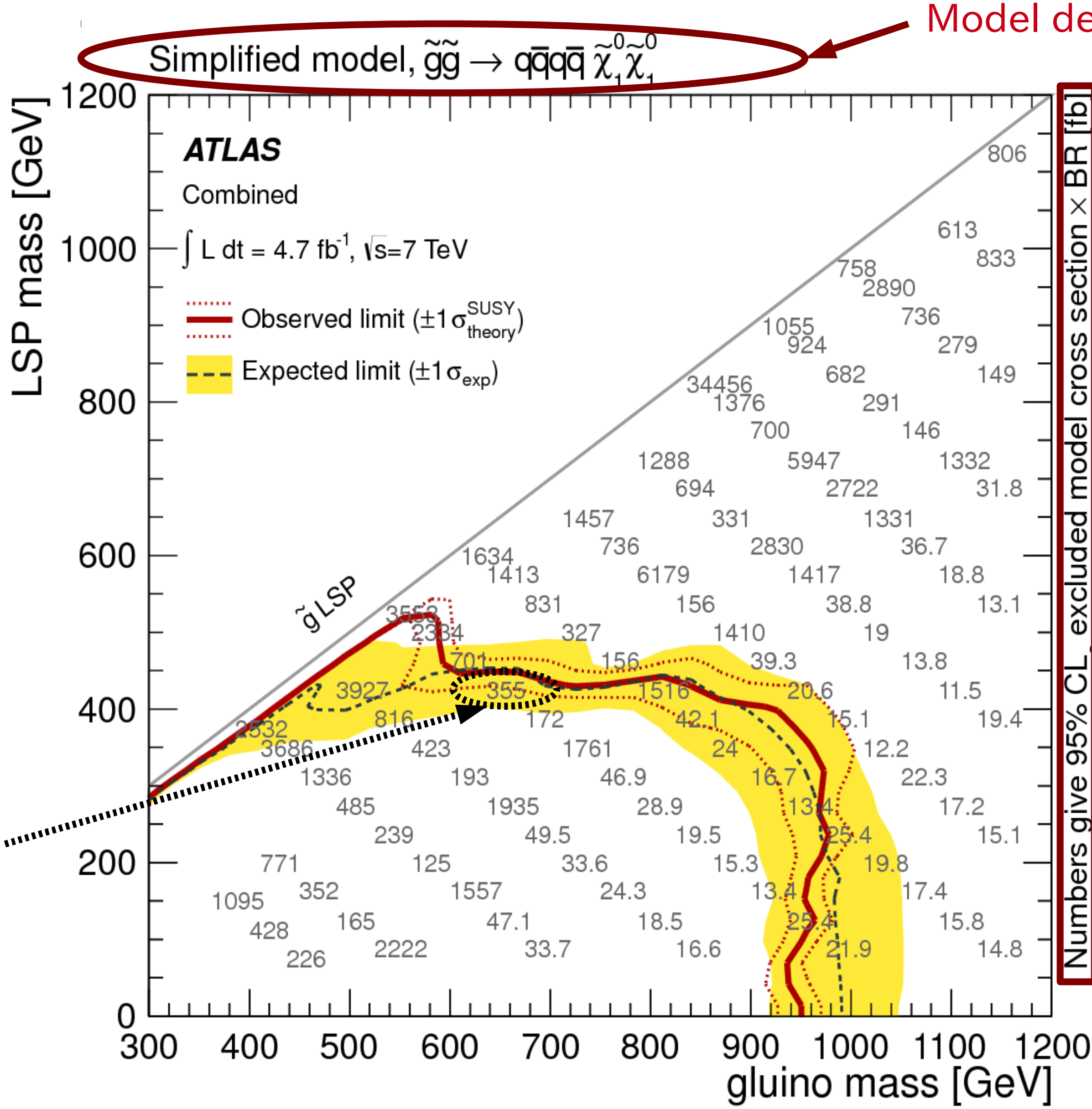
- ✔ Is data over-(under-)fluctuating?
- ✔ Is the fluctuation compatible with 1 σ experimental uncertainty?
- ✔ Size of the experimental uncertainty?
- ✔ What is the impact of the theory uncertainties (PDF and scale)?
- ✔ What is the final observed limit? Look at -1σ contour

Interpretation: Simple Model

Simplified phenomenology:

- consider only few particles at the reach of the LHC
- rest of particles decoupled

Model details



If a model has similar phenomenology but different cross sections limits can be directly read.

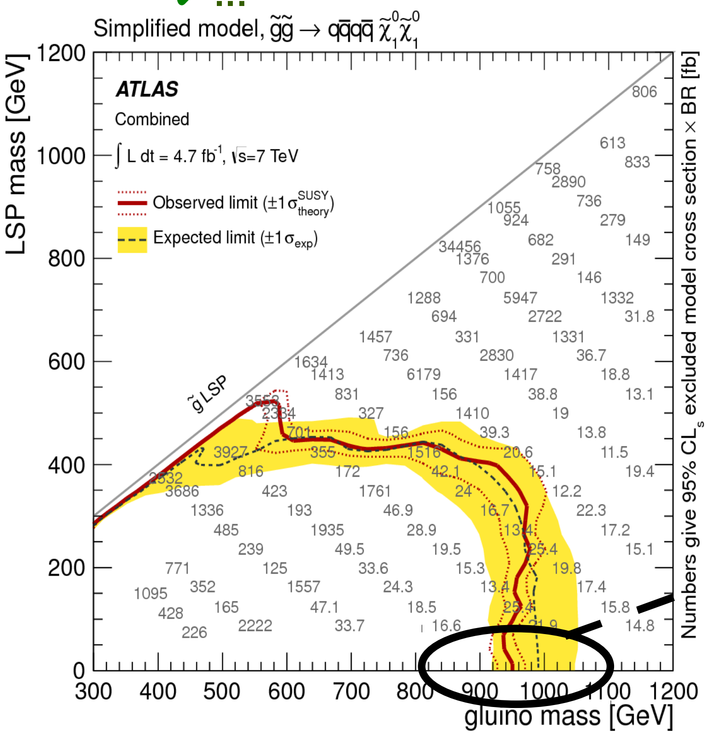
E.g. gluino mass of 650 GeV has a gluino pair-production cross section of 389 fb. Thus, it is excluded.

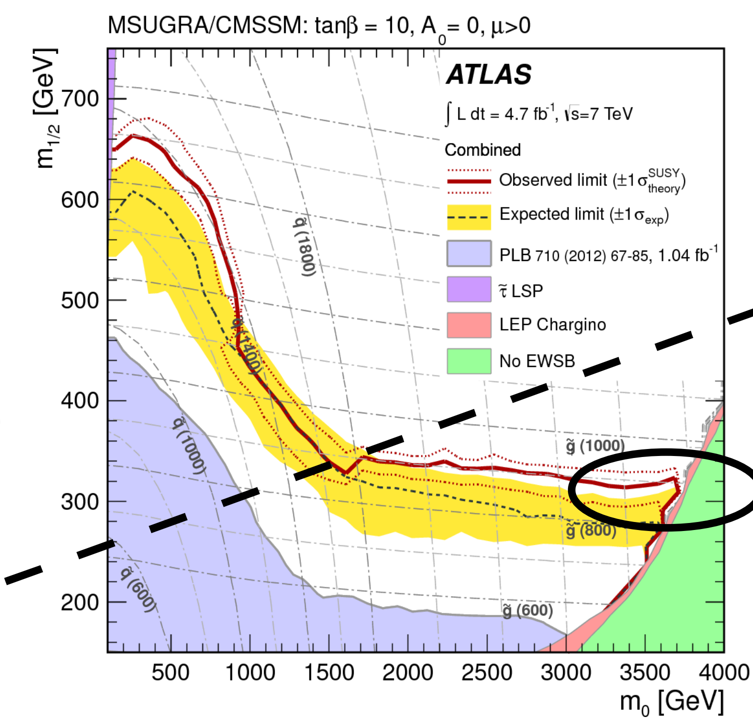
Assumptions behind interpretation

Importance of being cautious when quoting limits because it can strongly depend on the model (this is why multiple interpretations are useful)

Simplified models are, for its simplicity, an easy trap for dangerous extrapolations:

- ✔ Cross section of the process may not be the same if other sparticles are present (e.g. gluino pair-production cross section with (non-)decoupled squarks)
- ✔ Simplifications impose 100% BR in both sides of the decay.
- ✔ Other decays may take over at some point, altering the limits.
- ✔ Squark polarisation may play a role
- ✔ ...





Simplified gluino pair production is excluded up to 920 GeV for LSP below 300 GeV

However, only up to ~850 GeV for similar conditions in CMSSM

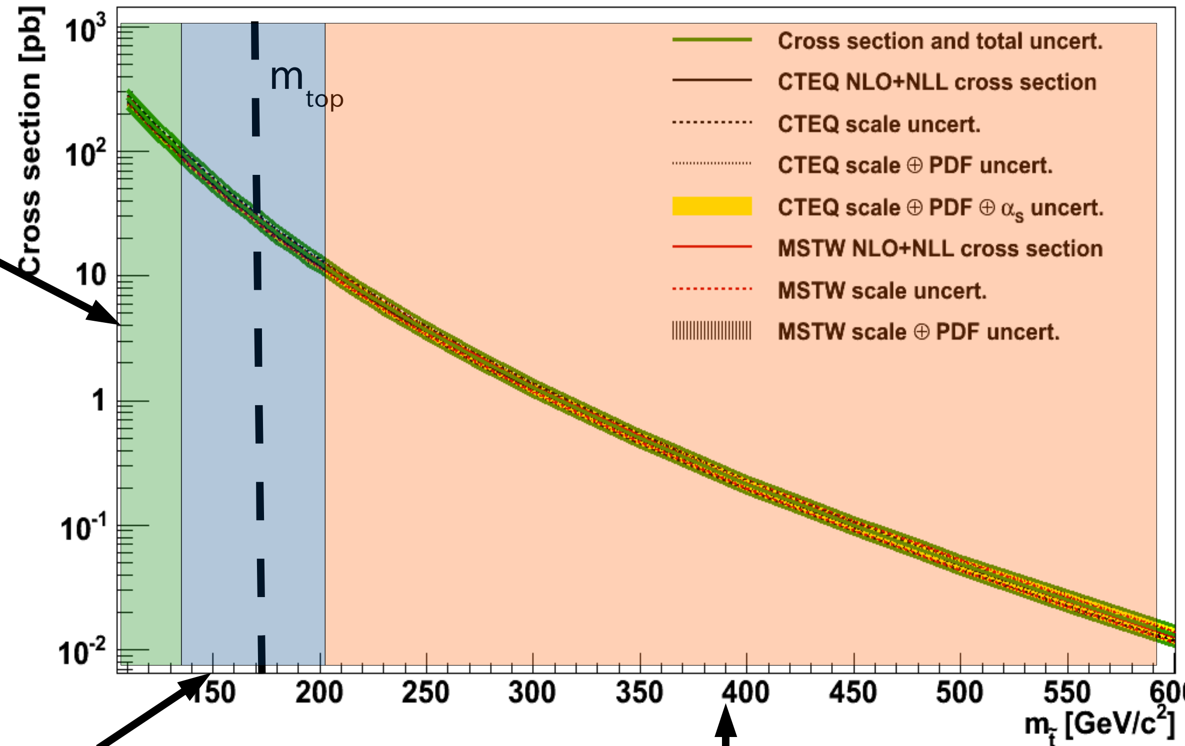
Assumptions example: stop searches

As an example, take the limits on stop (hot topic!)

ATLAS defined a careful strategy to cover different possibilities:

Challenge: large SM background and soft objects

2-lepton + jets (very light stop) (4.7 fb^{-1})
ATLAS-CONF-2012-059
http://cdsweb.cern.ch/record/1453787



b-jets + 1-2 lep. (light stop) (4.7 fb^{-1})
ATLAS-CONF-2012-070
http://cdsweb.cern.ch/record/1460267

Challenge: signatures mimic ttbar decay

Challenge: low cross sections

2-leptons + jets (heavy stop) (4.7 fb^{-1})
ATLAS-CONF-2012-071
http://cdsweb.cern.ch/record/1460268

0-lepton + jets (heavy stop) (4.7 fb^{-1})
ATLAS-CONF-2012-074
http://cdsweb.cern.ch/record/1460271

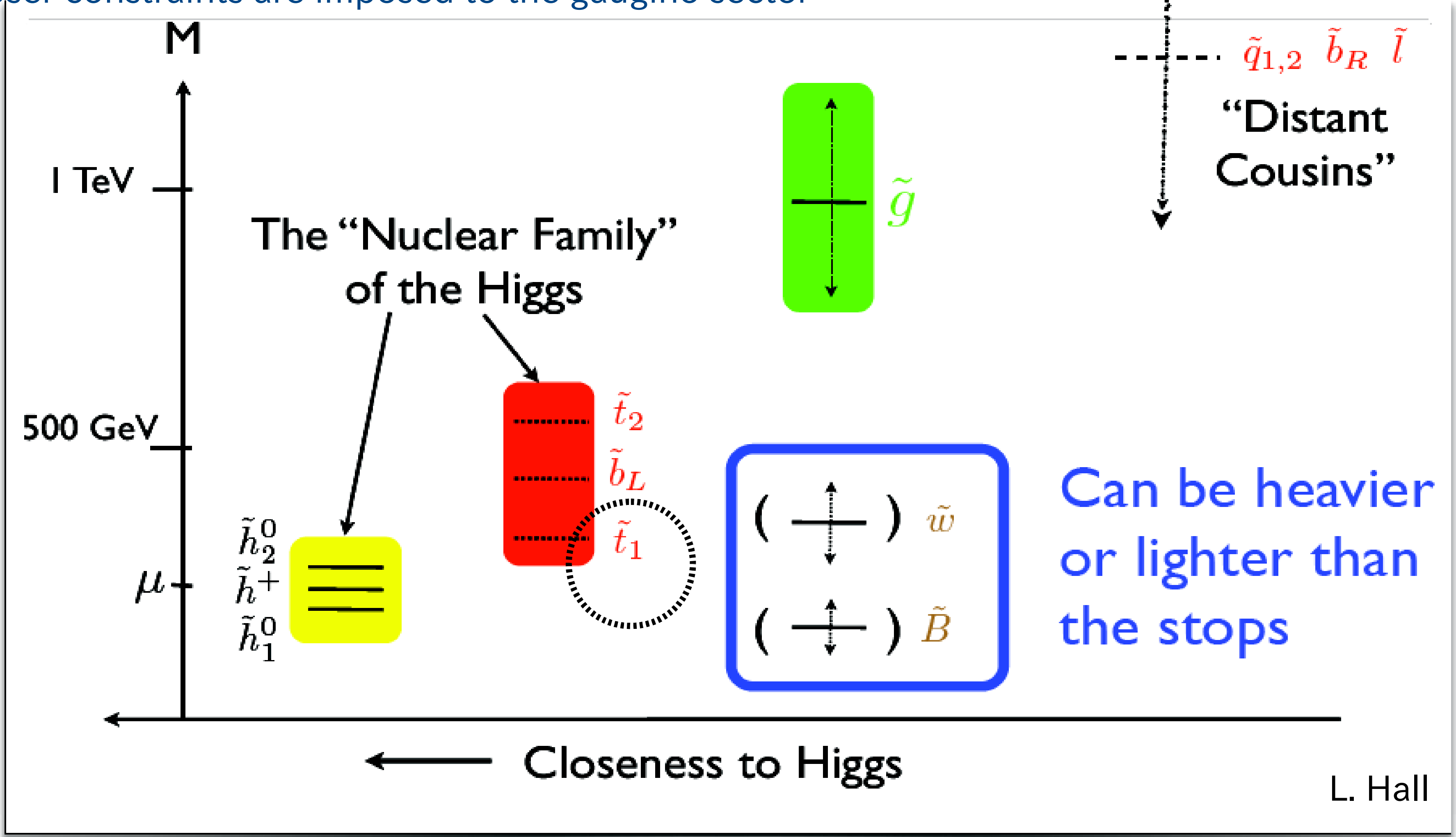
1-lepton + jets (heavy stop) (4.7 fb^{-1})
ATLAS-CONF-2012-073
http://cdsweb.cern.ch/record/1460270

Why stop is hot topic? (I)

If SUSY has to solve the gauge-hierarchy problem, the 3[rd] generation particles are bound to be relatively light and the gluino not too far away.

Stop is lightest due to large top Yukawa coupling.

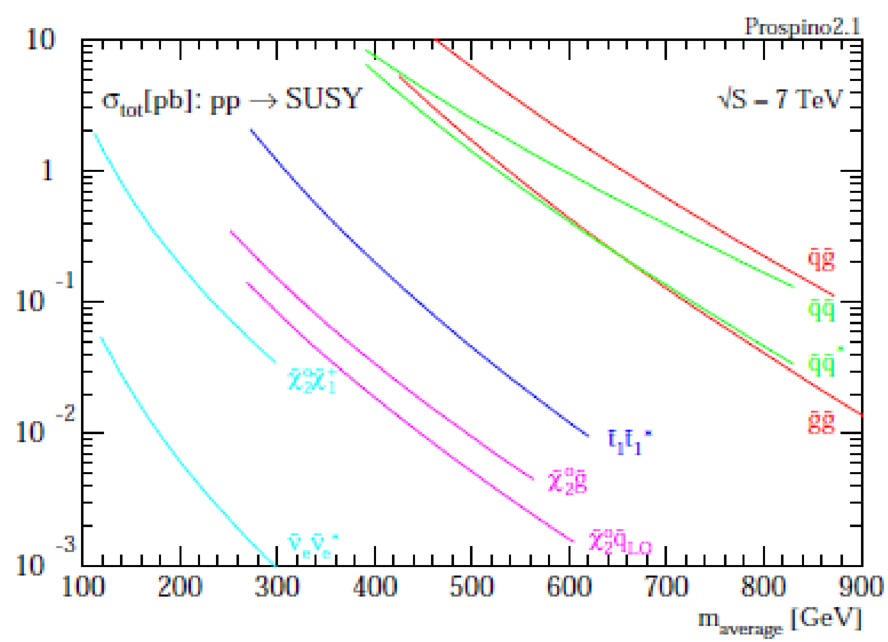
Looser constraints are imposed to the gaugino sector



Why stop is hot topic? (II)

Stop has to be light but it has not been observed so far: why?

- Low cross sections: isolated squark is 1/12 of the “squark” cross section and suppressed t-channel contribution (need b-/t-quark in the initial state)
- Large backgrounds: signatures are almost identical to ttbar decays. Need of dedicated analyses per topology.



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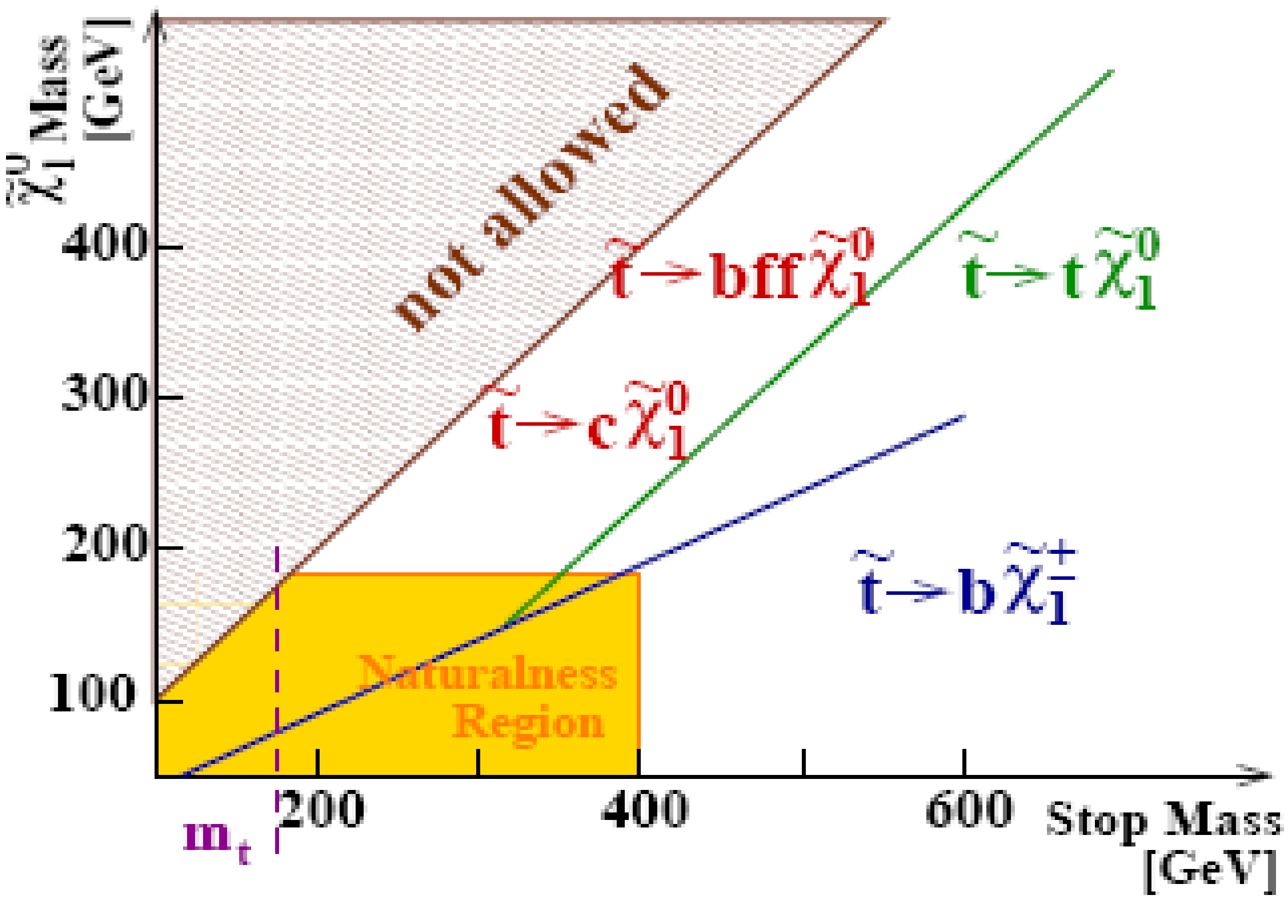
This picture shows how easy is to get confused when looking for "stop signs"

Stop decays



Rich phenomenology:

- ✔ Mass difference: stop and LSP
- ✔ Presence of other sparticles (e.g. charginos, neutralino2, sleptons...) in between.

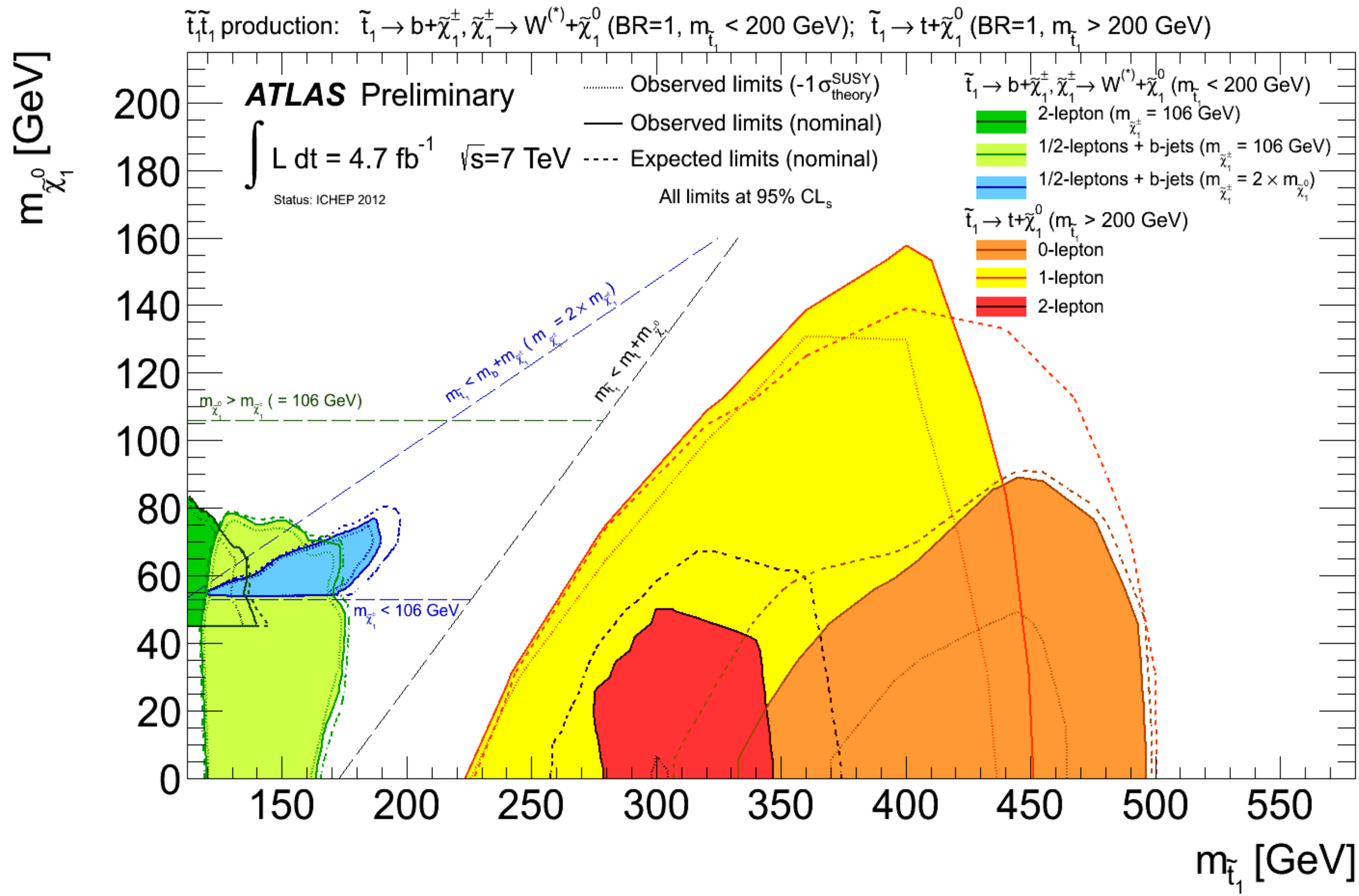
Stop decay preference (general):

- top+LSP *if kinematically allowed (and gauginos not around)*
- chargino+b *if chargino is present*
- virtual W *if chargino is not present*
- charm+LSP *as a last option, via loop*

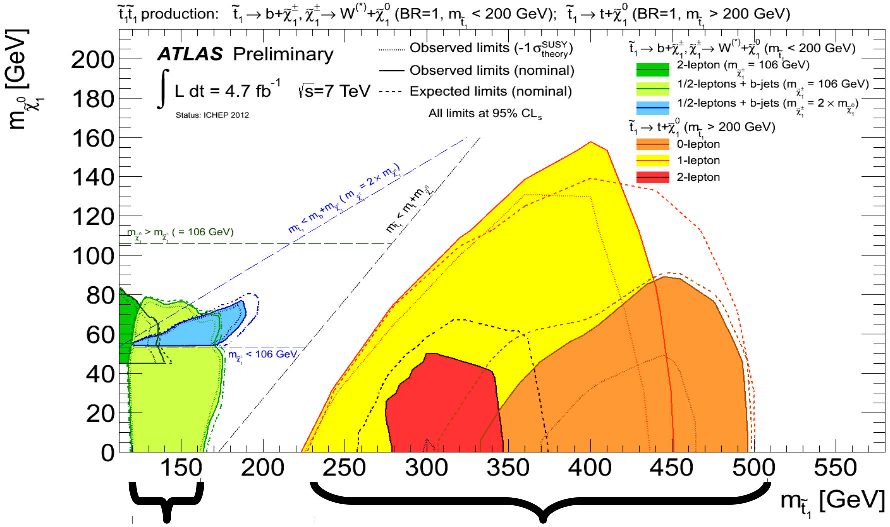
Other options (not represented) are also possible if sparticles available: chi02, sleptons...

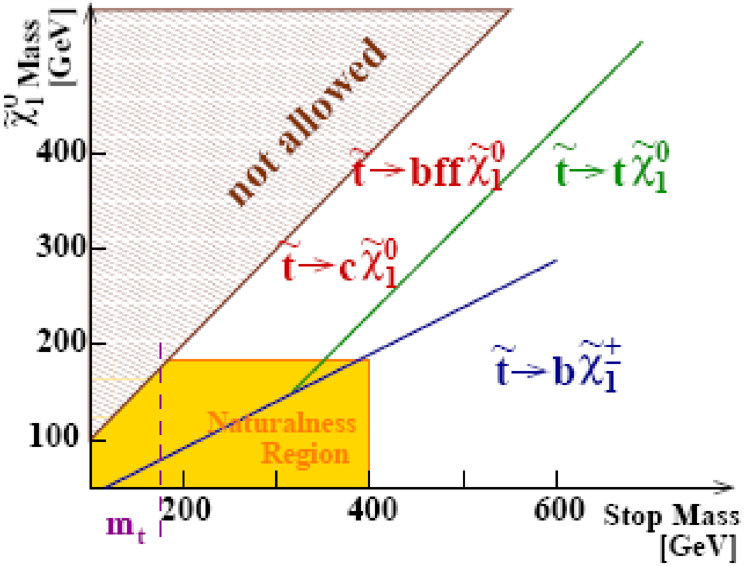
Some theoretical models offer different phenomenology: GMSB...

Stop results (I)



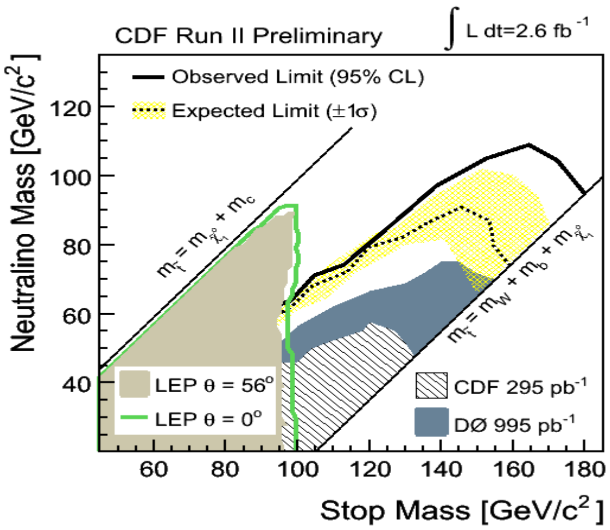
Stop results (II)





Is the stop excluded below 165 GeV and between ~230-500 GeV?

Obviously not! Only under the assumptions imposed in every case.



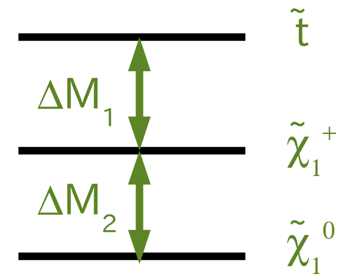
- stop decay to b+chargino reduces the 100% BR of stop to top + LSP
- Presence of neutralino2: reduce the BR and could make limits worse (or better depending on the analysis)
- Presence of sleptons could also alter the picture
- Compressed spectra: p_T of the objects (next slide) and decay assumptions (e.g. stop to charm+LSP decay has no direct constraint beyond LEP and Tevatron).

Stop results (III)

Example of the impact of considering different assumptions: light stop (mass below or ~top)

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{\chi}_1^0 W^{\pm(*)} \rightarrow b\tilde{\chi}_1^0 l\nu$$

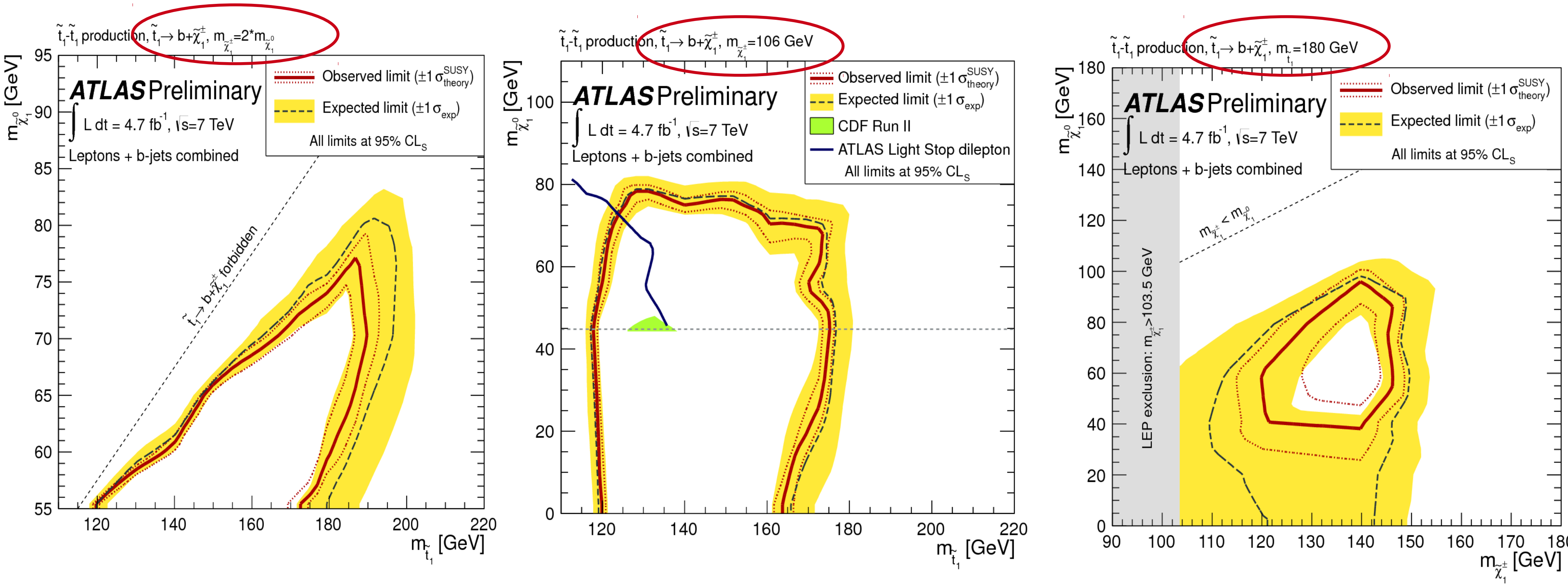
100% 100% ~26% (no hadr taus)



→ Determines the b-jet p_T

→ Determines the lepton p_T

Different impact on the limits depending on the constraints imposed to the ΔM_1 and ΔM_2



Is SUSY compromised?

Extending the discussion of the assumptions to the whole SUSY…
There are some ways out:

- Is it “just around the corner”?
- Is the spectrum so compressed that has escaped the current searches?
- Is EtMiss small? RPV, Stealth SUSY…
- Is it that the stop is extremely close to the top mass and is hidden?

Your choice!

- Like/dislike?
- Desperation?
- Fine-tunning?
- It is what it is?
- …

Going back to the beginning: there exist dark matter, it seems to exist a scalar (Higgs?) with a low mass difficult to fit without enormous fine-tunning…

SUSY is heavily under attack from many sides but it is definitely not ruled out as an answer, yet.

Is SUSY compromised?

Extending the discussion of the assumptions to the whole SUSY…
There are some ways out:

Experiments keep searching:

- Is it "just around the corner"? → ✔ Now: exploring 8 TeV
- Is the spectrum so compressed that has escaped the current searches? → ✔ Experiments constraining these scenarios more and more
- Is EtMiss small? RPV, Stealth SUSY… → ✔ Analyses addressing it
- Is it that the stop is extremely close to the top mass and is hidden? → ✔ Future analyses may tell

Your choice!

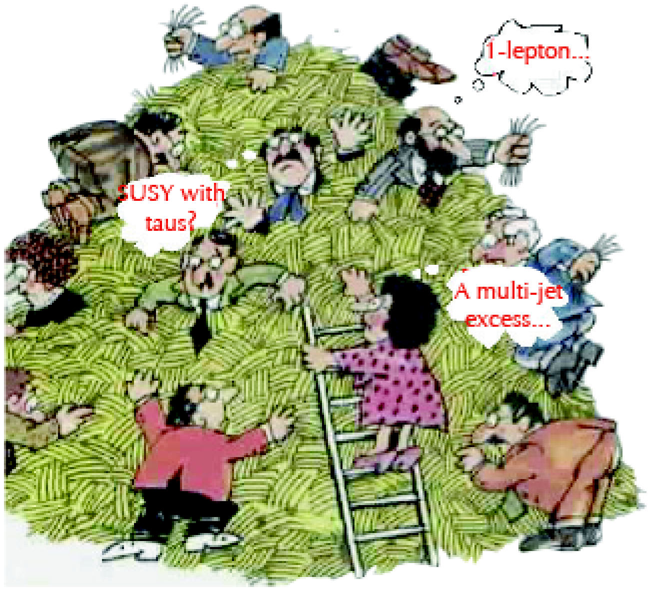
- Like/dislike?
- Desperation?
- Fine-tunning?
- It is what it is?
- …

Going back to the beginning: there exist dark matter, it seems to exist a scalar (Higgs?) with a low mass difficult to fit without enormous fine-tunning…

SUSY is heavily under attack from many sides but it is definitely not ruled out as an answer, yet.

Summary

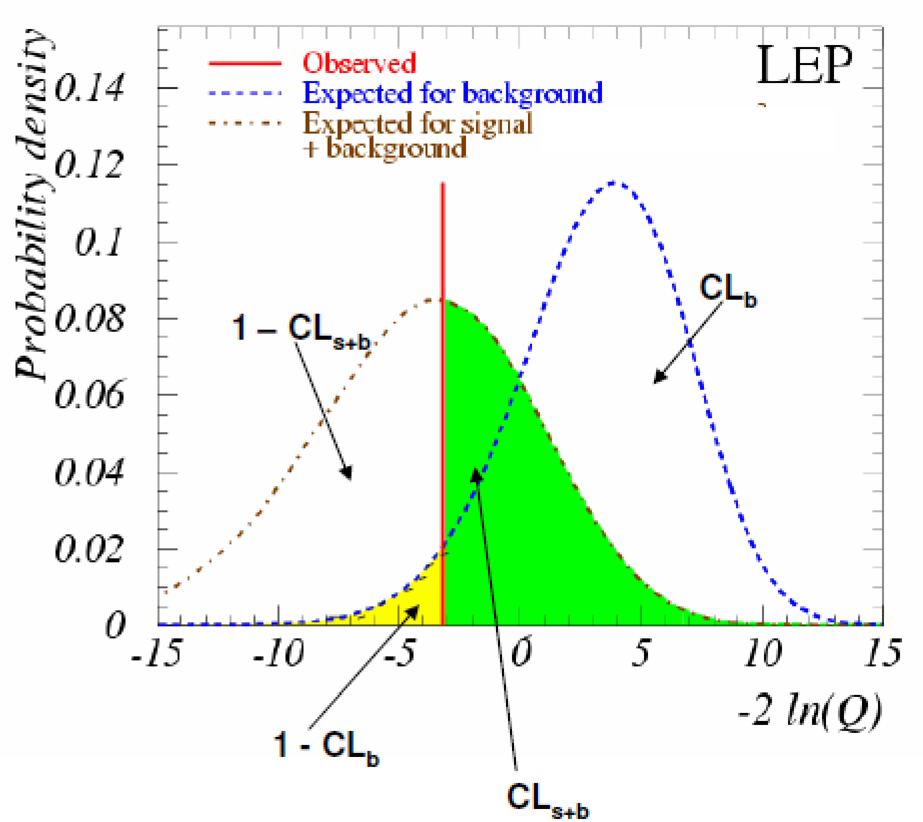
- Supersymmetry is an appealing theory:
  - Theory: solve hierarchy problem, dark matter candidate, unification of forces…
  - Experiment: plethora of new particles to be discovered ensures a lot of fun!
- Many different searches developed at the LHC
- Importance of optimisation, complementarity…
- Many different possible interpretations
  - Theoretical models
  - Phenomenological models
  - Simplified models
- Analyses provide general constraints to new physics
- Every interpretation has an associated limitation
- Importance of knowing the assumptions!
- Experiments provide plenty of information to reinterpret limits



"SUSY cannot be ruled out; it can only be discovered… or abandoned" Leszek Rozkowski

BACKUPS

CLs limits



1-CLs+b: discovery potential
CLs+b: false exclusion rate
CLb: exclusion potential
1-CLb: false discovery rate (power)

The CLS (confusing naming!) is:
CLS = CLs+b/CLb

To exclude at a given CL:
1-CLs>=CL so at 95% CL:
1-CLs>=0.95
(or CLs<=0.05 or CLs+b/CLb<=0.05

So the CLs+b cannot be any more than 5% of the exclusion potential (CLb)

Higgs constraints to SUSY

- The Higgs mass term can be splitted in a tree-level and loop corrections:

Tree-level — Radiative corrections (approximation only)

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

Below mZ (cos 2β dependence)

Fixed

Logarithmic dependence on stop mass

Mixing term

$m_{\tilde{t}}^2$ Scale of stop mass (usually taken as $m_{st1} * m_{st2}$)

X_t Stop mixing term (off-diagonal terms in the stop mass matrix)

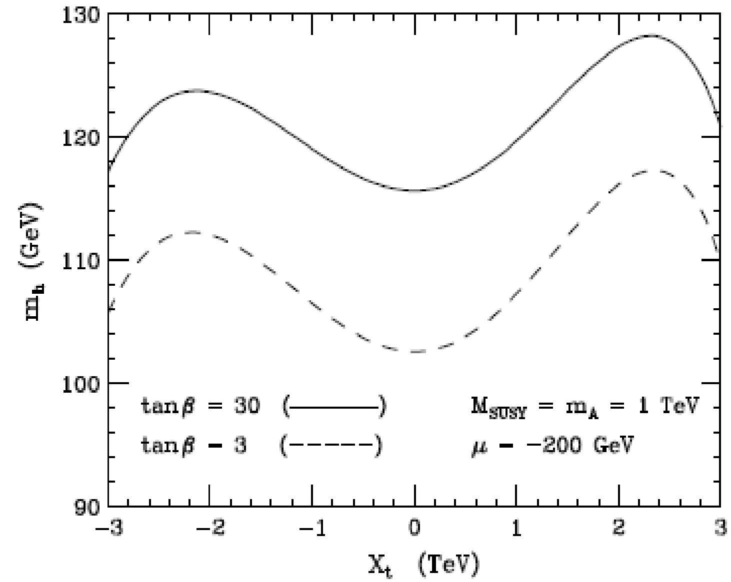
Large Higgs mass if:

- Stop masses are large: introduce fine-tuning (log-dependence require large values)
- Maximize the mixing (maximal mixing scenario): this is when $|X_t|=\text{sqrt}(6)*m_{\tilde{t}}$ (in this case, the term is 3)

$X_t = A_t - \mu\cot\beta$

- A_t should be large and negative
- tanβ cannot be too large in maximal mixing:

- cos2β term is also affecting (tanβ=3 drop of ~13 GeV)
- sbottom/stau contributions start becoming important (tanβ ≥ 35)



$$\Delta M_h^2 = -\frac{\mu^4 \tan^4\beta}{48\pi^2 v^2}\left[\left(\frac{m_\tau}{m_{\tilde{\tau}}}\right)^4 + 3\left(\frac{m_b}{m_{\tilde{b}}}\right)^4\right]$$