SUSY status and next steps

Giacomo Polesello

INFN Sezione di Pavia

On behalf of the ATLAS and CMS Collaborations

Introduction and outline

- ATLAS and CMS have performed, based on 2010 and 2011 searches for SUSY
- Main results shown yesterday, with relevant experimental details
- Today:
  - Look at these results in perspective, as a part of a global research strategy
  - Discuss the different interpretations offered in terms of SUSY searches
  - Show some early examples on how the strategy is developing

SUSY modelling

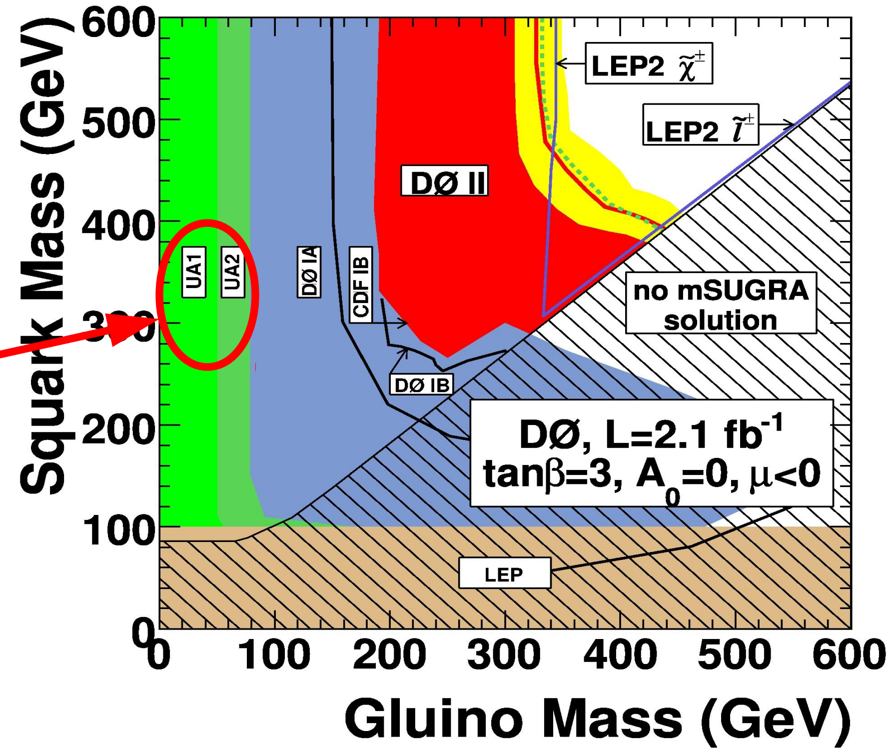
- Unbroken minimal SUSY is well-defined
  - Modify SM Lagrangian so that it is invariant under transformation:

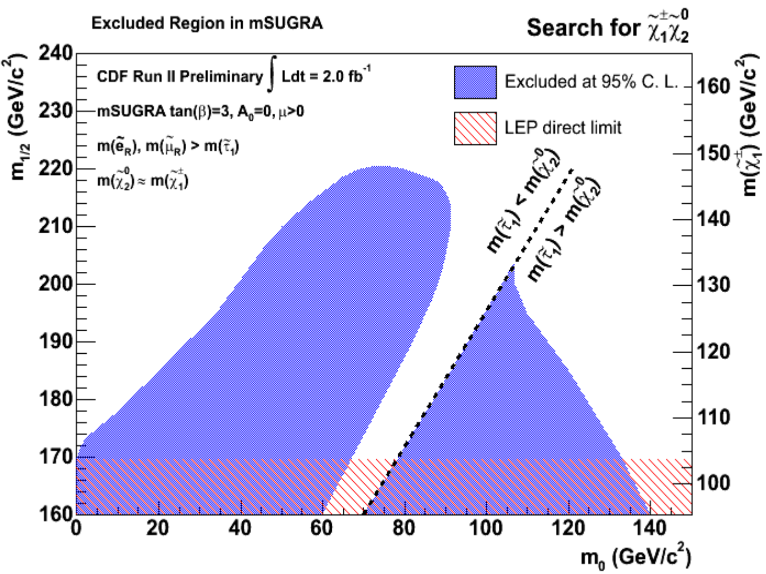
$$Q|\text{boson}\rangle = |\text{fermion}\rangle \qquad Q|\text{fermion}\rangle = |\text{boson}\rangle$$

  - SUSY partners have same quantum numbers as SM particles, except spin, including mass
- But SUSY is broken: no partner pairs in observed spectrum
- Phenomenology driven by how SUSY breaking is performed: two main approaches
  - Totally agnostic: insert in SUSY Lagrangian all allowable SUSY breaking terms (MSSM)
    - 105 parameters
    - 19 parameters if flavour aligned with SM
  - Assume pattern driven by physical considerations: mass spectrum and couplings defined in terms of 4-5 parameters ex.: MSUGRA, GMSB
- What we are testing in first instance is the breaking pattern!

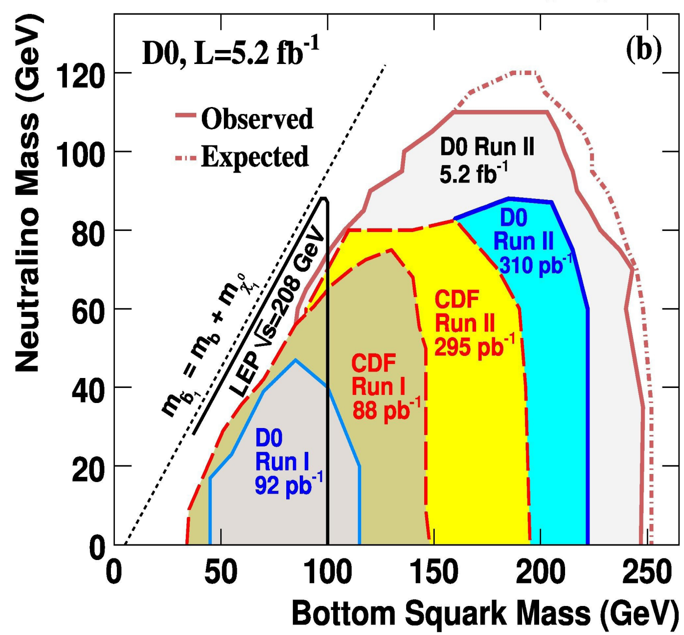
SUSY before LHC: Hadron colliders

Asymptotic sensitivity on squark-gluino production:
SppS : ~100 GeV (1989)
Tevatron: ~400 GeV
LHC 7 TeV: ~1.5 TeV (2012)



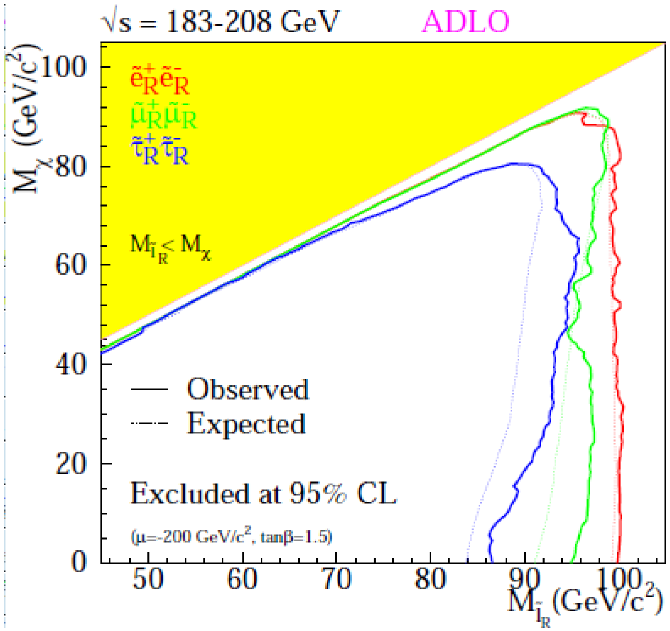


EW production of Chargino-neutralino: mSUGRA interpretation



Dedicated 3[rd] generation searches

SUSY before LHC: LEP

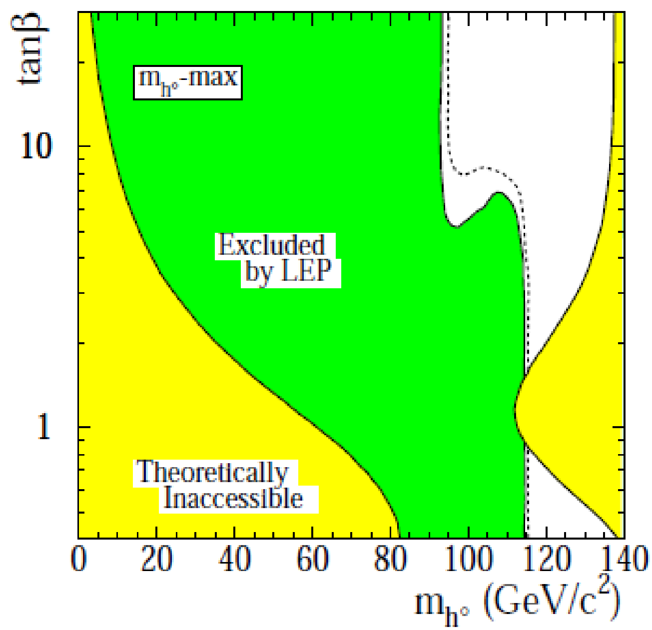


Model-independent limits of ~100 GeV on all sparticles coupling to the Z, in particular:

- Sleptons
- Chargino

Results also interpreted in terms of cMSSM/mSUGRA

Very stringent limits on m(higgs)-tanβ plane from Higgs direct searches



SUSY at the LHC: the menu

- Generic searches based on models with
  - Duplicate spectrum of particles w.r.t. Standard Model (sparticles)
  - For each sparticle complex decay chain involving jets and one or more leptons, photons, taus, b-jets +
  - E_T^{miss} (R-parity conservation)
    - Sparticles produced in pairs, decay to Lightest Supersymmetric Particle (LSP), in most cases chi01
    - One invisible particle (LSP) per decay chain $\rightarrow E_T^{miss}$
  - R-parity violating signatures:
    - Resonant peaks: single sparticle production or LSP decay
    - Displaced vertices from LSP decay
  - Long lived particles from:
    - Degeneracies (e.g. MSSM with m(chargino)=m(chi01) or AMSB)
    - Weak couplings (e.g. GMSB decays of NLSP into gravitino LSP)
    - Heavy virtual intermediate states (gluino decays in split SUSY)
- Concentrate on the following on E_T^{miss} searches

Search strategy with early LHC data

- Initial strategy driven by:
  - Accessible cross-section with low integrated luminosity
  - Reliance on robust signatures under good experimental control from early data taking
  - Reducibility of Standard Model backgrounds and ability to predict them precisely
  - Within this framework address simple signatures covering the broadest possible range of SUSY models

SUSY cross-sections

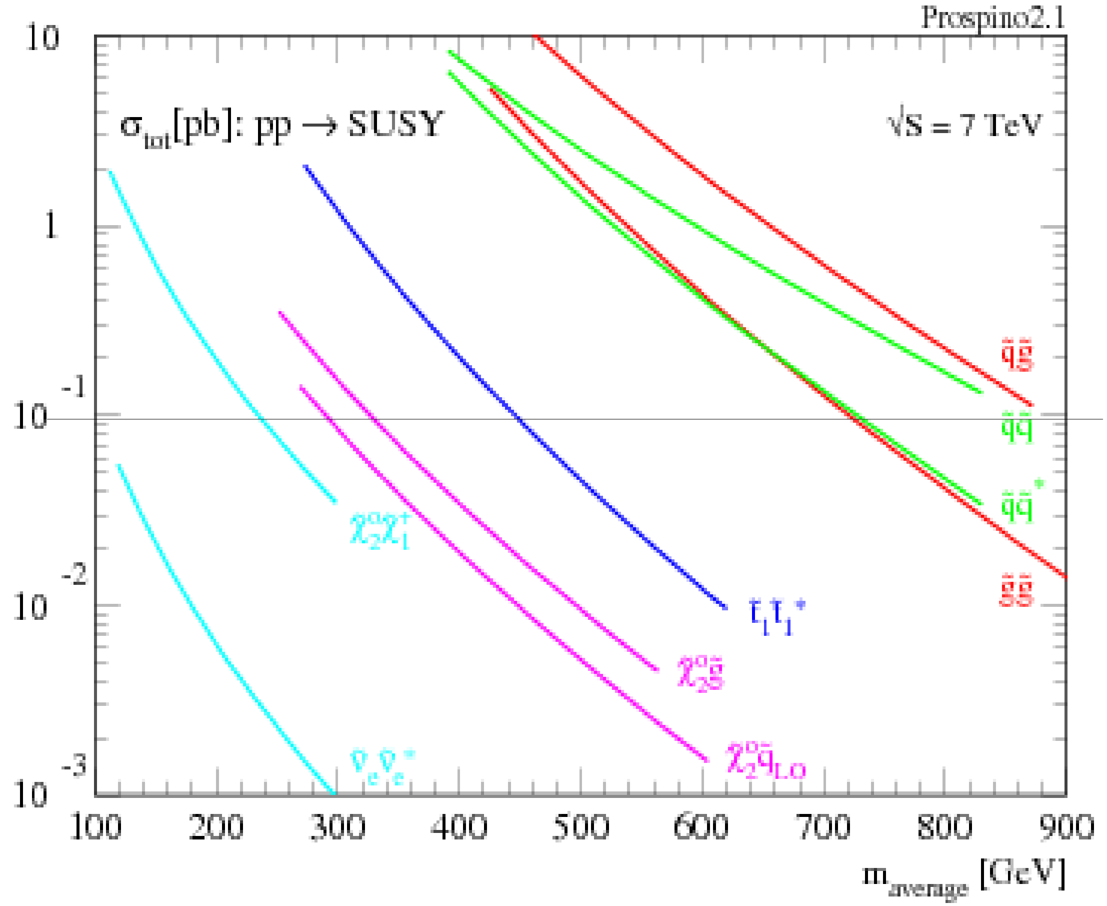
Consider an integrated luminosity of 1 fb^{-1}

Squarks and gluinos accessible up to TeV scale with large branching fractions and efficiencies.
Backgrounds after E_T^{miss} cut manageable

For direct stop, cross-section up to 400 GeV,
10k-fold top background: need dedicated strategy

Charginos-neutralinos to 200 GeV if leptonic BR's Considered: deal with WZ and top backgrounds

Sleptons to < 200 GeV: need to handle top and WW



First round: concentrate on production of Gluinos and squarks of first two generations

Analysis definition

- For squark and gluino production and R parity conserved, signature common to all models is E_T^{miss}+ jets
- Preselection: Cuts on jet p_T and E_T^{miss} such as to guarantee high trigger efficiency
- Optimisation 1: Define signal regions based on decay topologies occurring in generic models
- Optimisation 2: Set final cut on discriminant variable (some combination of jet momenta and ETmiss) to optimize sensitivity to reference models with appropriate mass scale

  Ex: $$m_{eff} \equiv \sum_{i-1}^{n} | p_T^{(i)} | + E_T^{miss}$$
- Compare SM predictions with data
- Interpret results in different SUSY models

0-lepton signatures optimisation

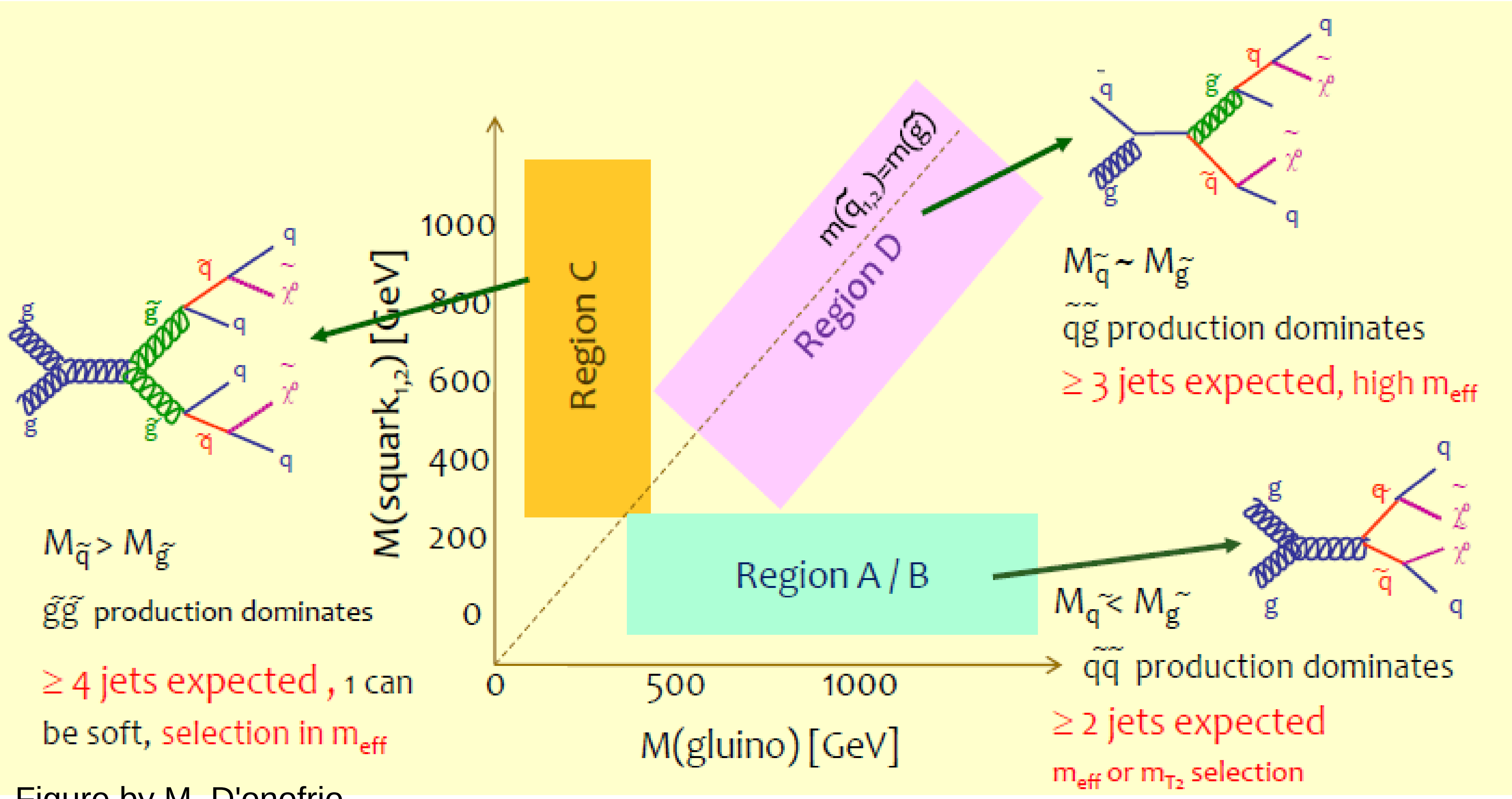


Figure by M. D'onofrio

For two-jets topologies exploit kinematics of two heavy particles decaying into jets plus invisibles through ad-hoc variables: M_{T2}, α_T, R

MSSM interpretation

Simplifying assumptions to map 19 parameters onto 2-dim space:

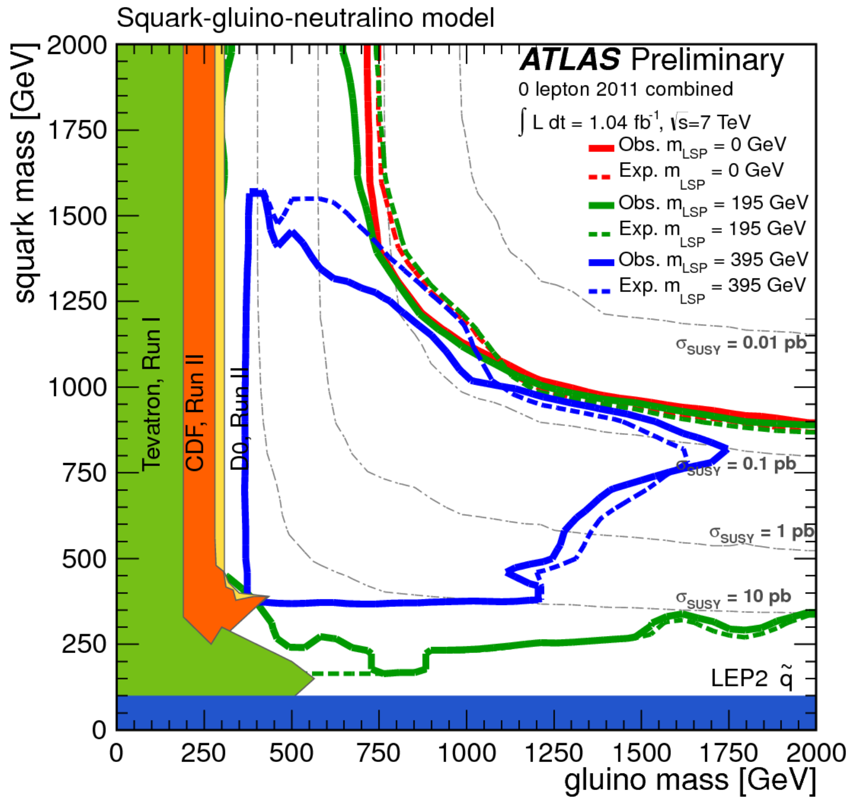
- Only production of gluinos and squarks of first two generations
- Other sparticle masses= 5 TeV
- m(LSP)=0

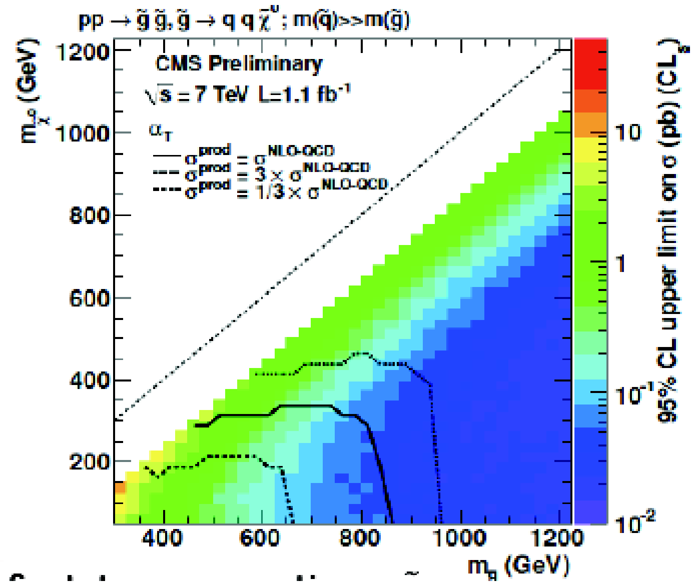
Only allowed decays:

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

Equal squark-gluino masses excluded below 1075 GeV

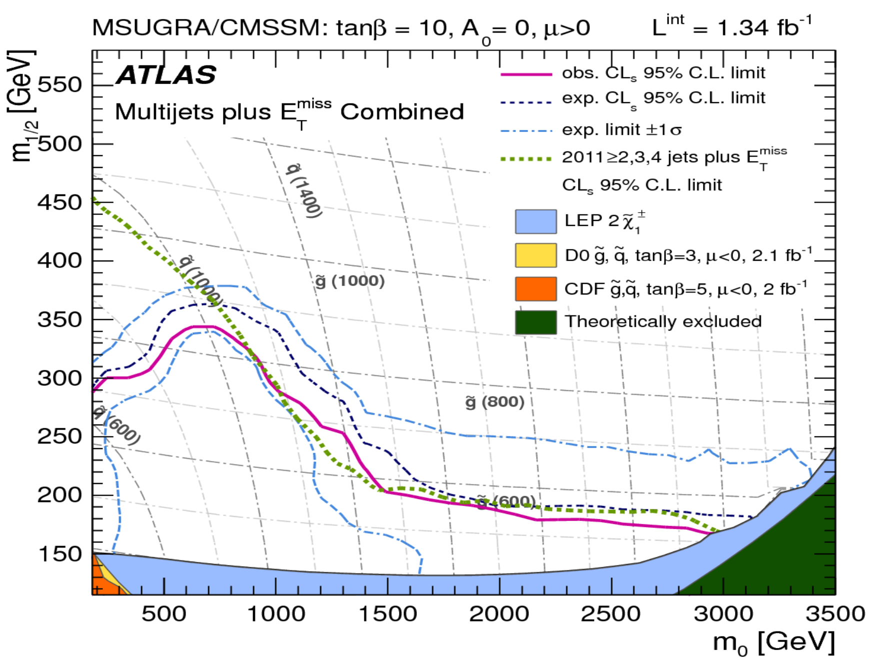
Generic exclusion valid for m(LSP)<200 GeV
For heavier LSP cannot put absolute Limits on squark or gluino masses

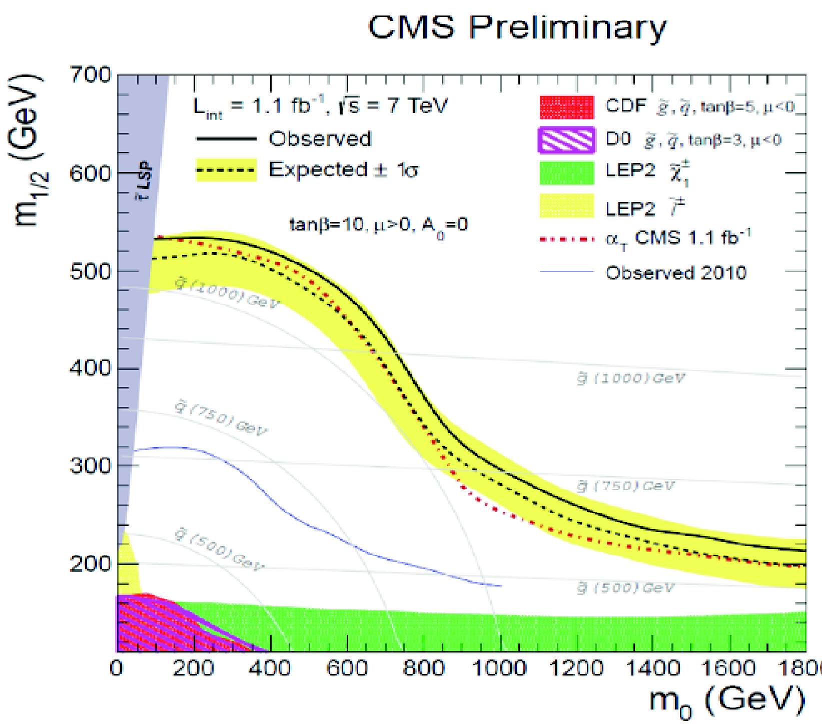




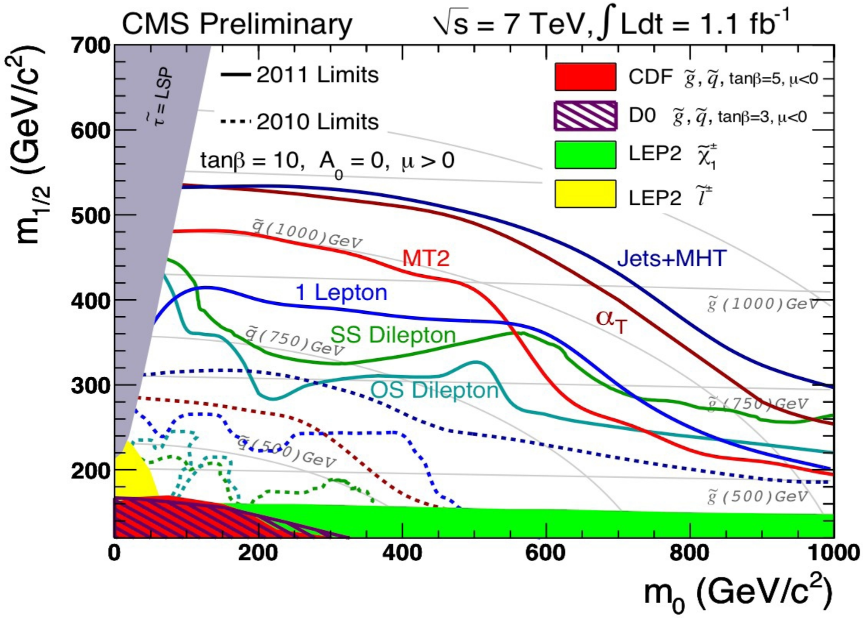
All hadronic results in cMSSM/mSUGRA

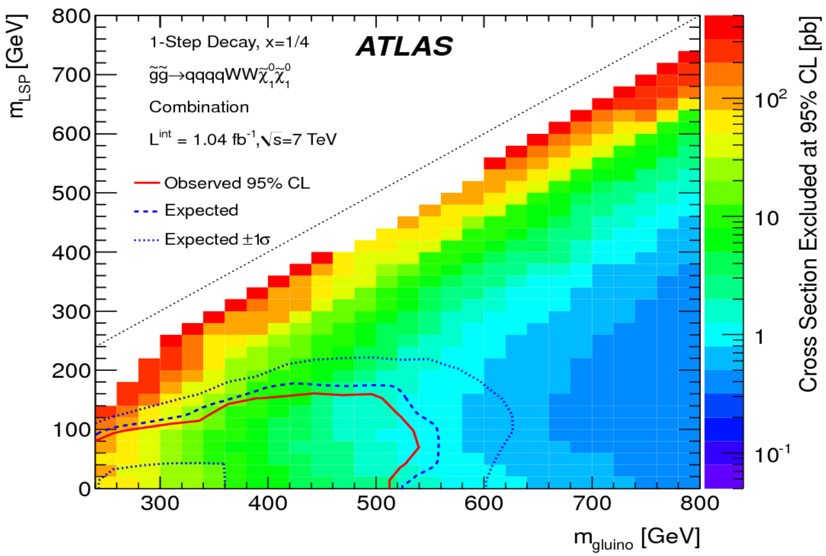
- Even with more complex decays than simplified MSSM limits above 1 TeV for m(squark)=m(gluino)
- Weaker limits high m_0: only gluino production, and dominant decay: g $\rightarrow$qq χ, softer kinematics as χ in this case can be also higher mass chargino/neutralino





Role of lepton+jet analyses





Several analyses requiring E_T^{miss}+jets+leptons performed by ATLAS and CMS: 1, 2, multileptons

Essential to address models which may escape standard E_T^{miss}+jets analysis because of soft hadronic part

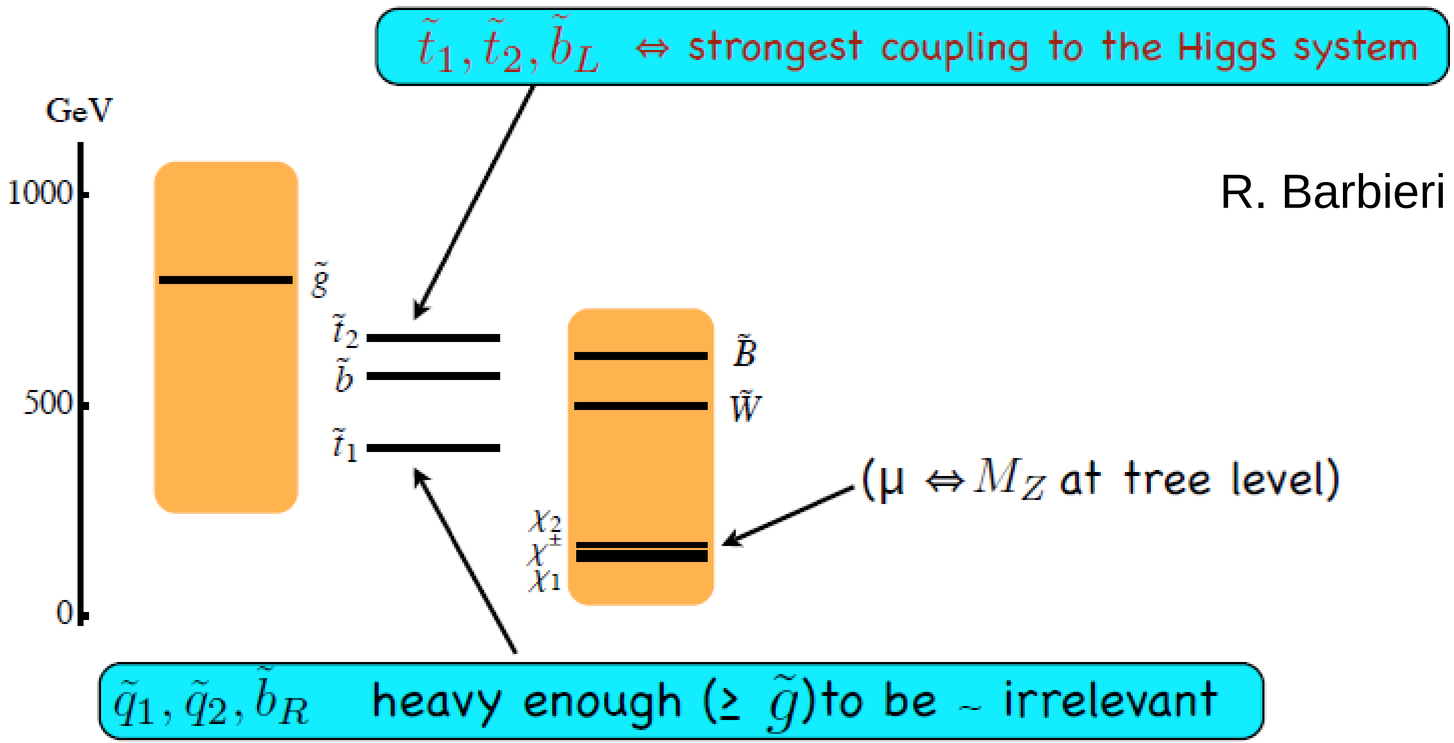
Rates dependent on all model parameters: difficult to quote results in terms of limits on sparticle production

Two approaches to interpret results:

- Constrained models: e.g. mSUGRA,
- Simplified models: isolate specific chains with given kinematics and compute excluded rate for the chain as a function of two involved masses

Additional gluino decays: theory guidance

SUSY spectrum required by naturalness

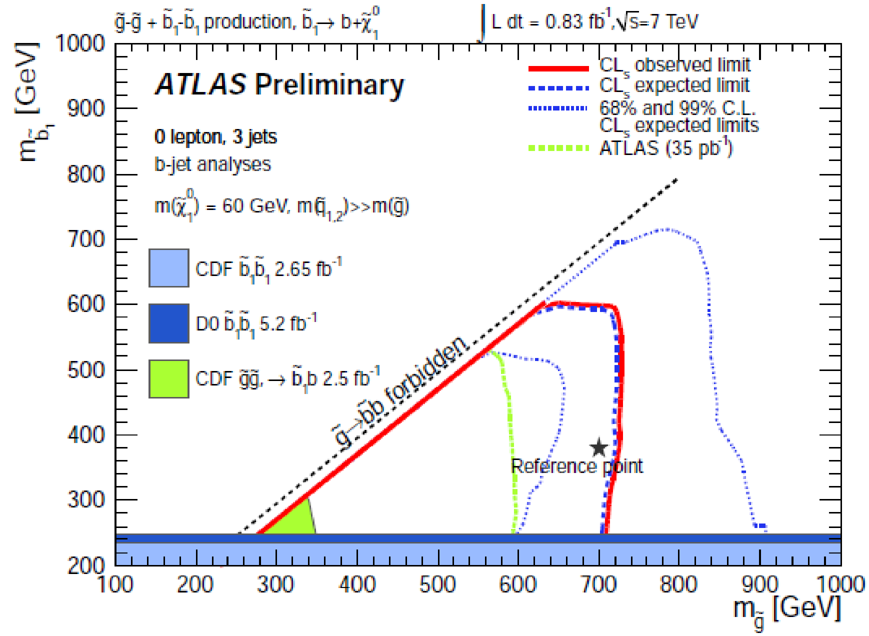


Decays of gluinos involving 3rd generation squarks not addressed by generic searches: dedicated searches in final states with b-jets

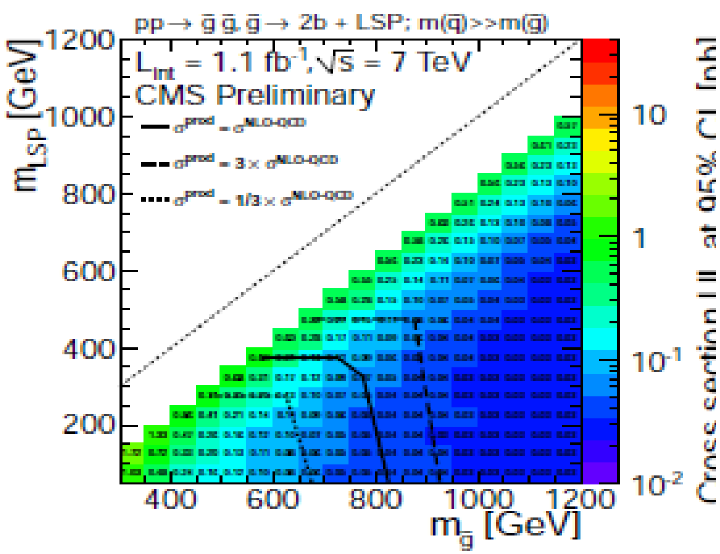
Additional gluino decays: b-jets

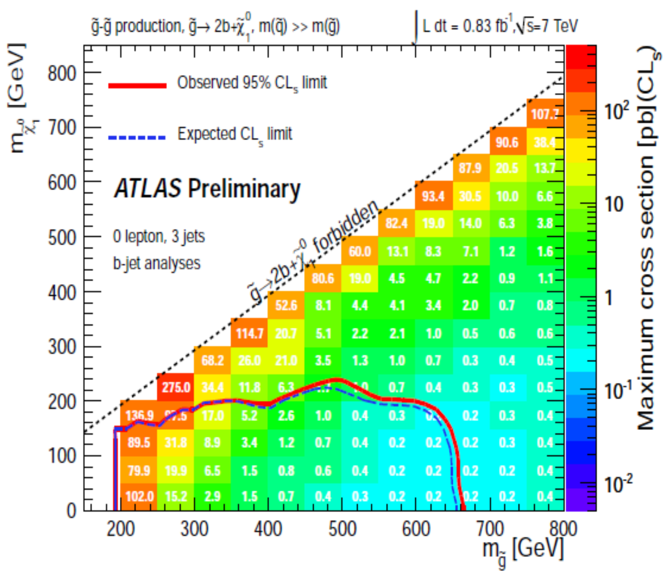
Analysis: 0 leptons + jets + E_T^{miss} with 1 tagged b-jet. Interpretations:

- $\tilde{g}\tilde{g} + \tilde{b}_1\tilde{b}_1$ production
- $\tilde{g} \rightarrow \tilde{b}_1 b$ (BR=1), $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ (BR=1)
- $m(\tilde{\chi}^0) = 60$ GeV, $m(\tilde{\chi}_1^{\pm}) \approx 2\tilde{\chi}_1^0$

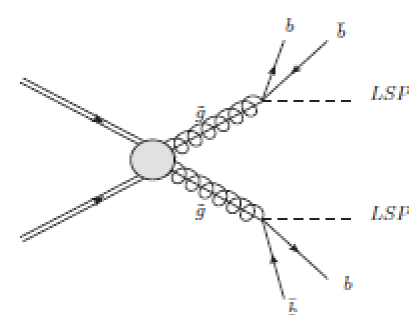


Exclude gluino masses below ~700 GeV





Simplified model:
Gluino 3-body decay

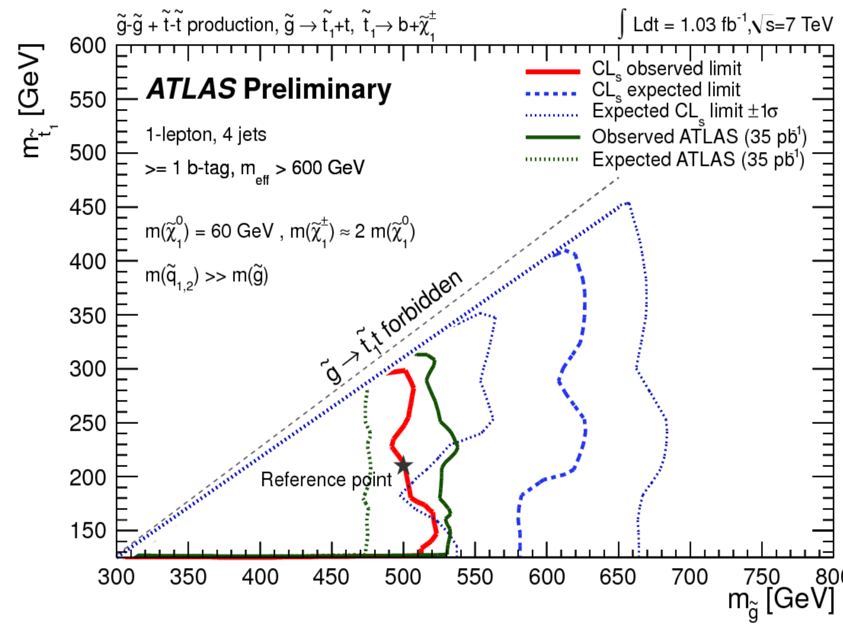


Additional gluino decays: top

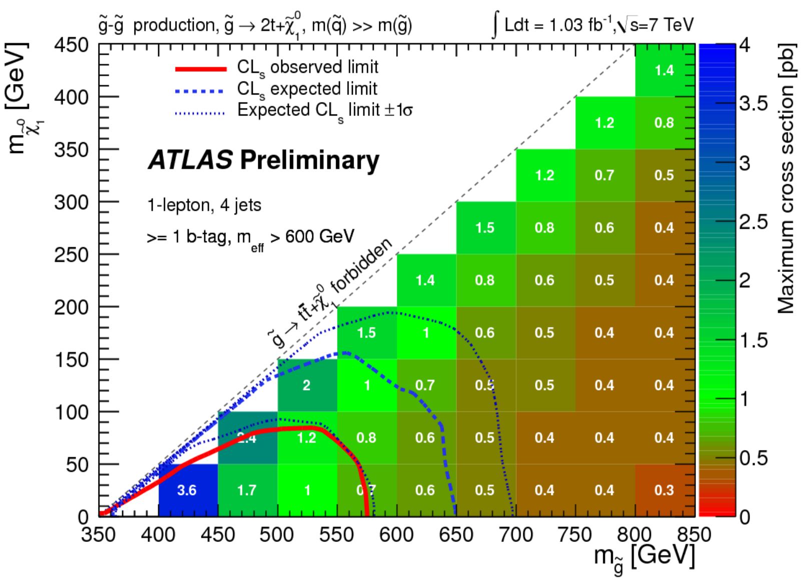
Analysis: 1 lepton + 4 jets + E_T^{miss}

1 jet tagged as b

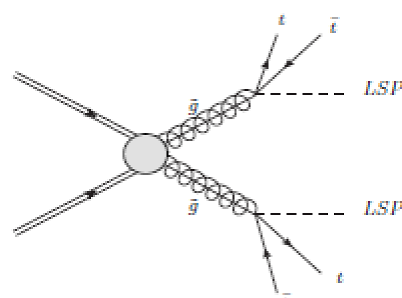
- $\tilde{g}\tilde{g} + \tilde{t}_1\tilde{t}_1$ production
- $\tilde{g} \rightarrow \tilde{t}_1 t$ (BR=1), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$ (BR=1)
- $m(\tilde{\chi}^0) = 60$ GeV, $m(\tilde{\chi}_1^{\pm}) \approx 2\tilde{\chi}_1^0$



Exclude gluino mass below 520 GeV



$\tilde{g}$ 3 body decay into $t\bar{t}\tilde{\chi}_1^0$

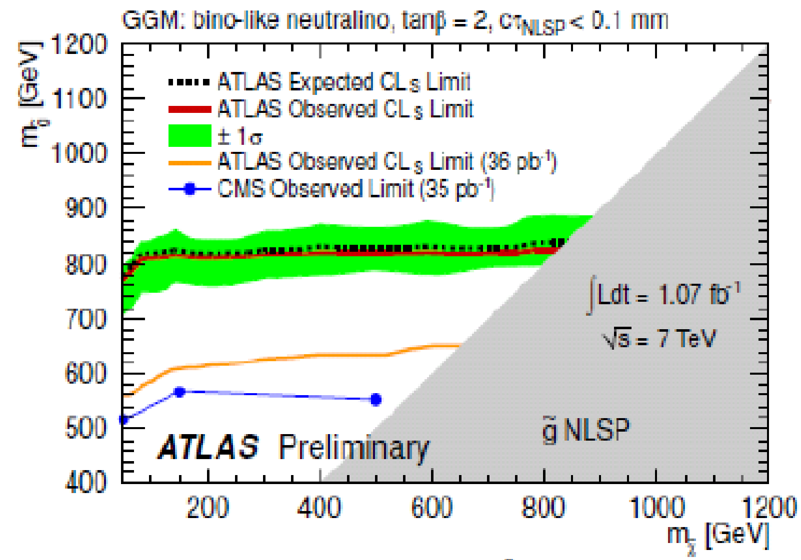


m(gluino)>560 GeV

General Gauge Mediation (GGM) models

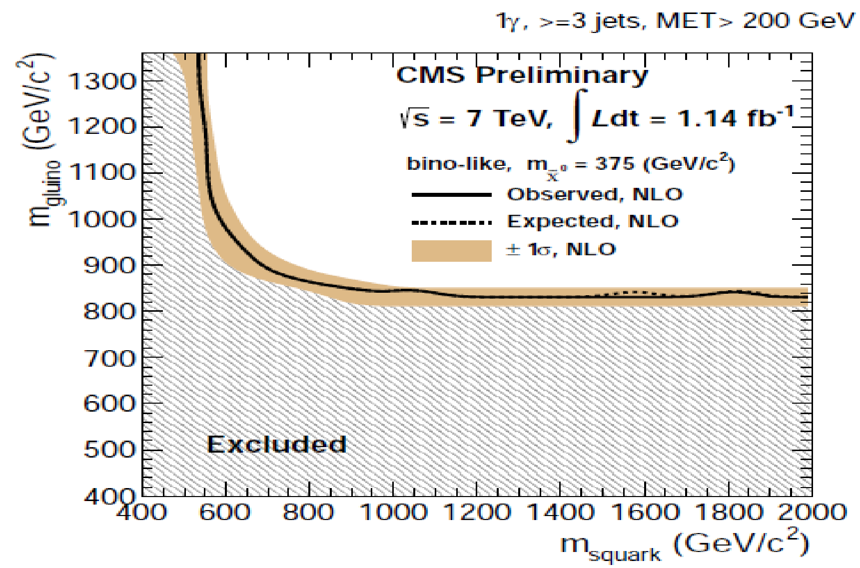
- Standard E_T^{miss} analysis assumes chi01 LSP
- If gravitino (G) LSP and chi01 NLSP, additional photons in events with photons from the decay

  chi01→Gγ
- Additional handle, select events with E_T^{miss}, jets and 1 or 2 photons
- For only gluino production exclude gluinos below ~800 GeV



✓ σ < 0.02 – 0.04 pb ($m(\tilde{\chi}_1^0) = 150\,\mathrm{GeV}$)

✓ Excluding gluino mass < 776 GeV



Conclusions on SUSY with 1 fb^{-1} from Etmiss searches

- We exclude generic models where

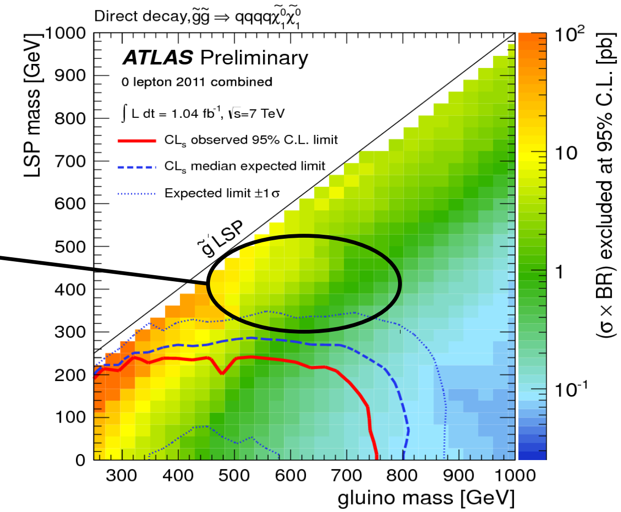
1) 1st and 2nd generation quarks and gluinos are
   - Below 1.1 TeV if they have similar masses
   - Below 7-800 GeV if one of the two is much heavier
2) Squark decays q->q chi01, and gluino decays g->qq chi01
3) m(chi01)< 200 GeV

Weaker limits for heavier chi01

- Conclusions valid when specialising to CMMSM/mSUGRA
  - Confirmed by searches with leptonic signatures
  - For high m0 region where decays in heavy flavours important, and also heavier gauginos involved limits somewhat less stringent (mg<600 GeV)
- Generic limit extended to cases with different gluino decays
  - For gluino decaying 100% bb chi01, direct or sbottom-mediated, limit is between 700 and 800 GeV from dedicated searches requiring tagged b-jets
  - For gluino decaying 100% stop-top limit is around 520 GeV
- If chi01 decays chi01->Gγ gluino limits at 800 GeV

Perspectives (1)

- Effectively volume of 19-parameter MSSM covered to date not very large. Question is how to enhance coverage of our searches
- First step is to lift limitations on generic squark-gluino interpretation:
  - Develop ad-hoc strategies for when chi01 gets near squark and gluino mass (degenerate spectra)
  - Study decays happening through long chains with many visible objects: high multiplicity searches



  - In both cases softer kinematics of final state objects: enhanced role of leptonic signatures: loss in BR's but higher trigger and selection efficiencies. Watch same-sign leptons
  - Increase range of considered final state objects: e.g hadronic tau decays

Perspectives (2)

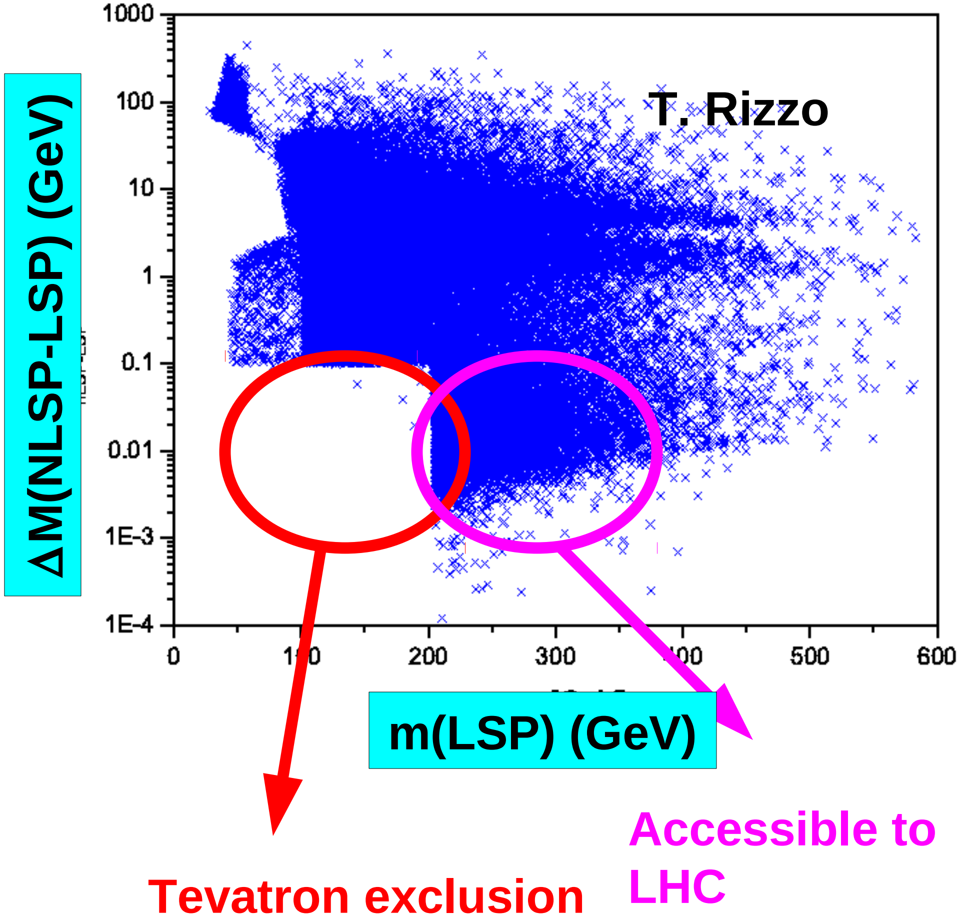
Focus on signatures which appear as 'forgotten' in scans of 19-MSSM

Example:
If chargino is degenerate with chi01, it can be metastable

Signature already addressed in Specific SUSY breaking models:

- Searches for heavy muon-like particles
- Searches for decays inside detector (broken tracks)

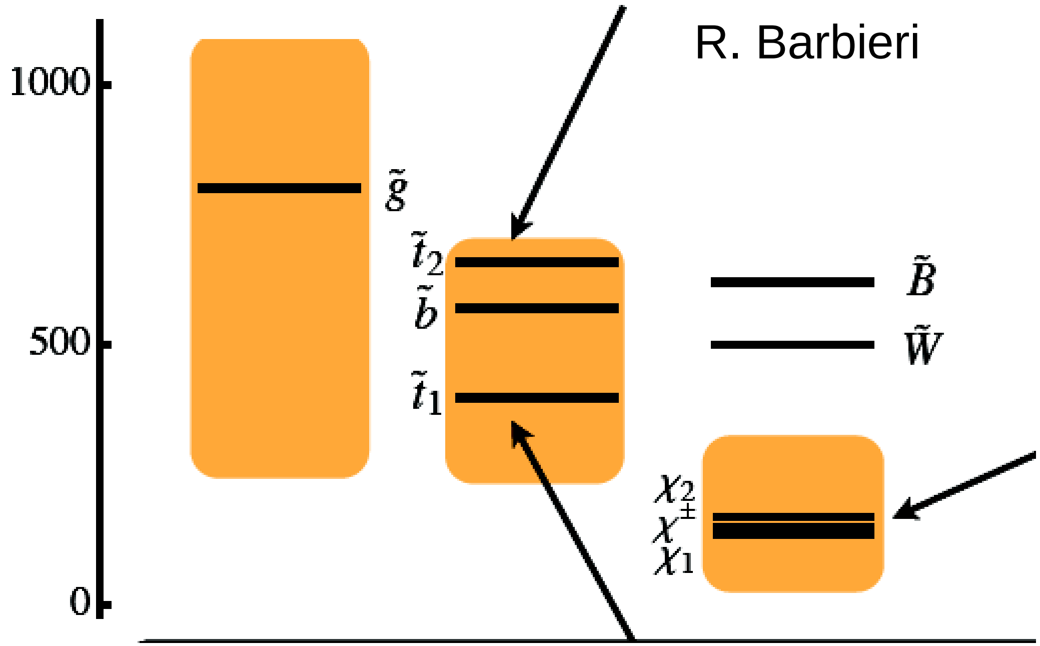
Increase emphasis on such Signatures and extend Interpretation to MSSM



Perspectives (3)

- Even if squark & gluinos are inaccessible at the LHC, other sparticles may/should be lighter
- Focus on sparticles which must be light if SUSY wants to solve the fine-tuning problem. From theoretical guidance:

- Look for direct production of light stop/sbottom:
  - Consider all possible decay chains
  - Ad hoc selections taking into account kinematics
- Look for EW production of gauginos:
  - mostly leptonic signatures
  - go as low as possible in lepton p_T



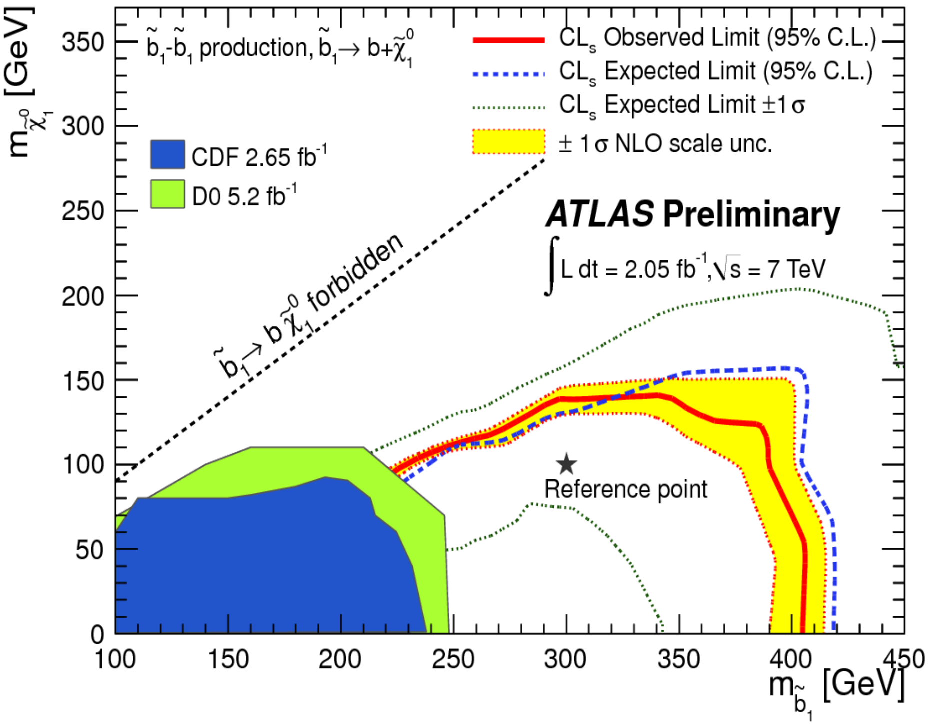
Example: direct sbottom production

Analysis: 2 b-tagged jets and Etmiss (0 leptons)

$\tilde{b}_1 \tilde{b}_1$ production

$\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ (BR=1)

Exclude sbottom lighter than ~350-390 GeV if chi01 lighter than ~120 GeV

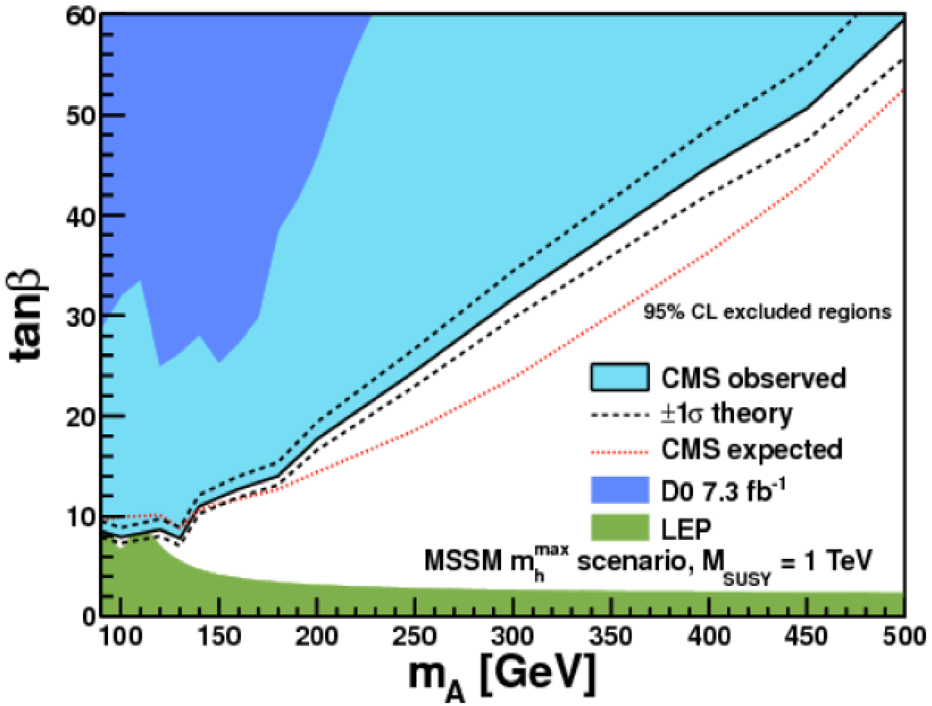


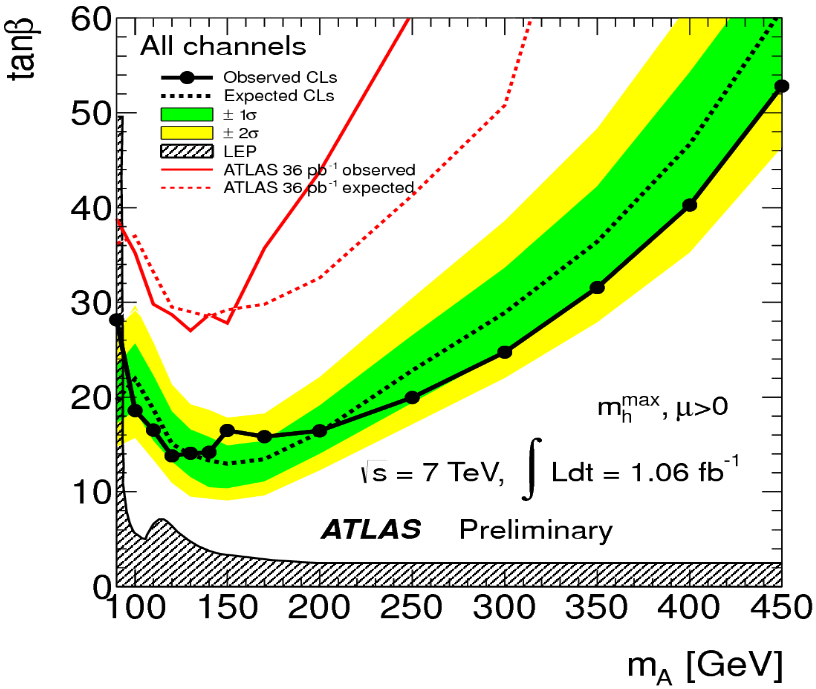
Pioneering direct production analysis.
Illustrate characteristic issue: need enough mass gap with chi01 to ensure triggerable and detectable hadronic system

Conclusions

- With early LHC data ATLAS and CMS started probing the TeV scale
- Null results of searches are eroding the number of SUSY breaking scheme candidate for describing our world
- Early generation searches based on simplifying assumptions and on very constrained models yield limits on squarks and gluinos in the TeV range
- Complete exploration of SUSY requires:
  - Extending the mass coverage in 'basic' scenarios
  - Searching for squarks and gluinos in more complex/general scenarios
  - Addressing exotic signatures
  - Look for low cross-section direct production of sparticles which should be light in SUSY
- For all of the above points both experiments have active analysis groups, and in many cases results are available already with 2010/early 2011 data
- By the time of 2012 winter conferences results based on this approach with the full 5 fb^{-1} will be available

Info from other LHC searches: Higgs





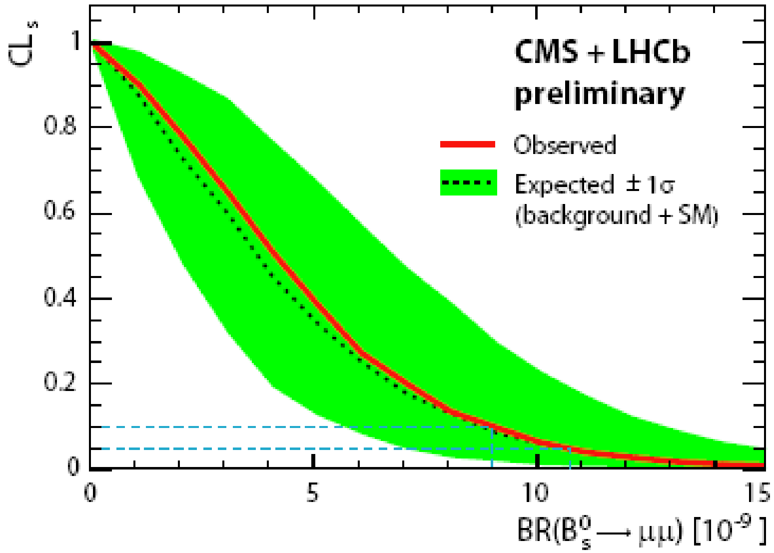
Direct searches sparticle searches have low sensitivity to tanβ and m(A) parameters of MSSM

Higgs searches provide highest sensitivity on these parameters

Already significant coverage from A→ττ

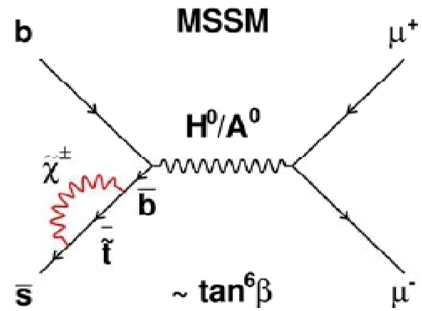
As we become sensitive to light higgs below 135-140 GeV more and more of the plane will be covered

Info from other LHC searches: rare decays



$BR(B_s \rightarrow \mu^+\mu^-) < 1.08$ (0.9) $\times 10^{-8}$

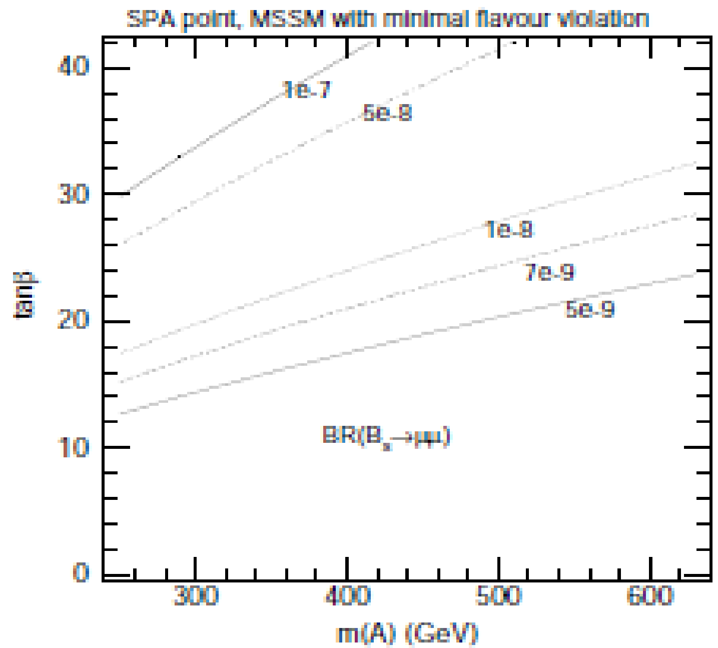
@ 95% (90%) C.L.



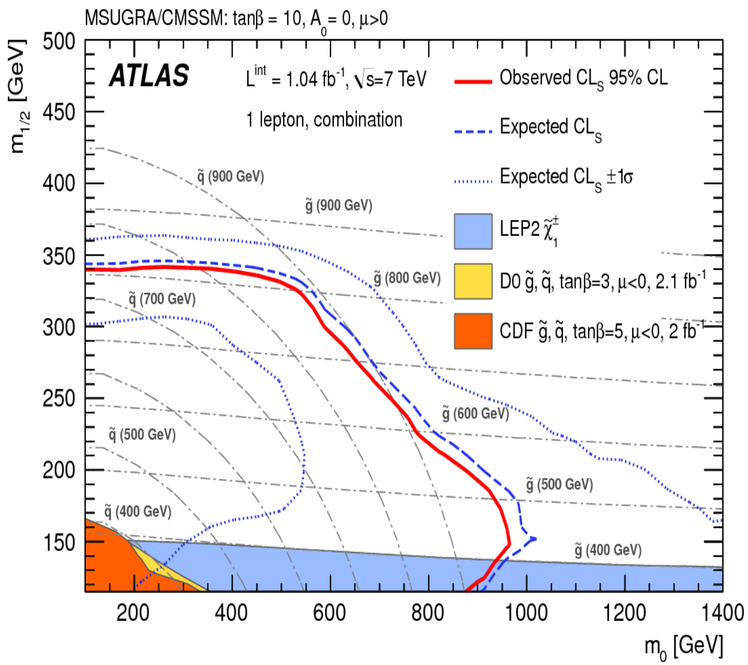
Very strong dependence on m(A) and tanb

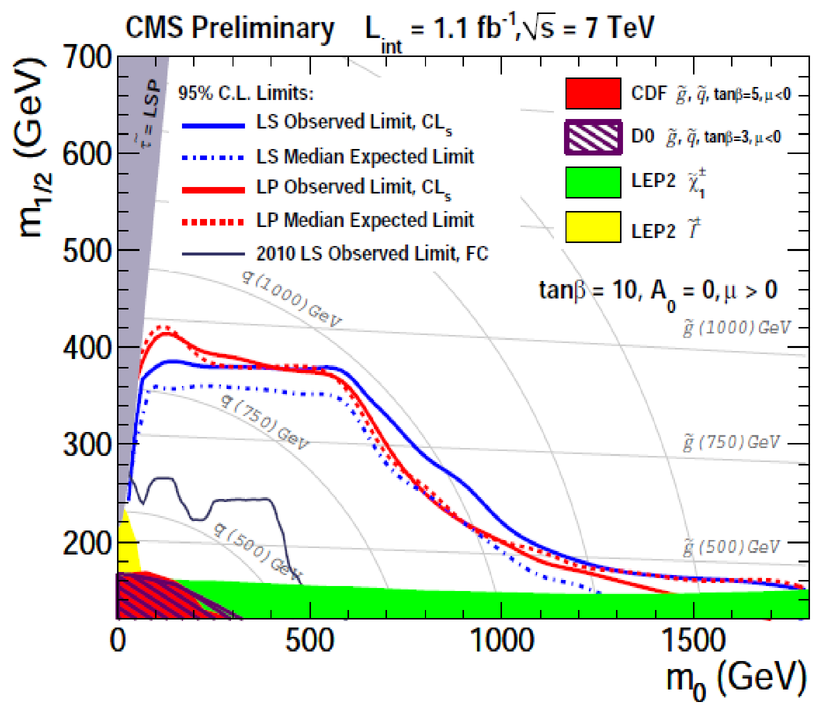
$$BR(B_s \rightarrow \mu\mu) \propto \tan\beta^6 / m(A)^4$$

For given assumptions on the SUSY Mass spectrum very stringent limits On the m(A)-tanb plane,



1 lepton + jets + E_T^{miss} in CMSSM



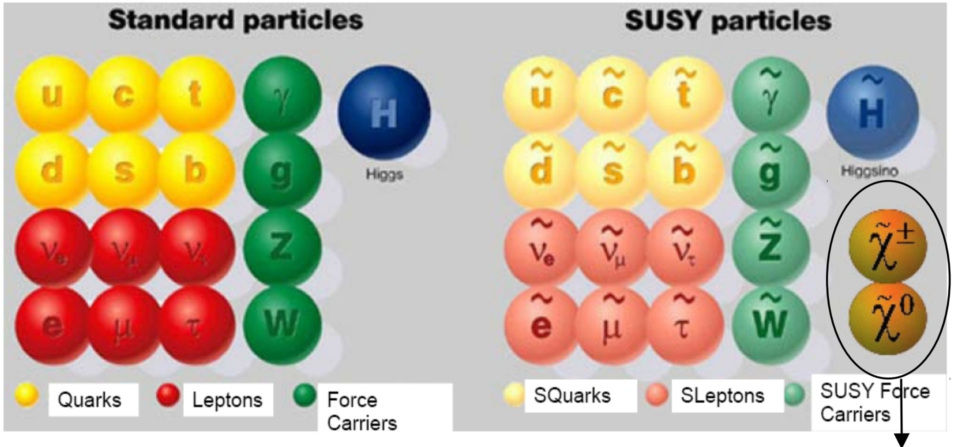


Limits comparable but lower than 0 lepton analysis
Difficult to represent in less-constrained model: use approach in which
Results are not compared to a model but to a specific model-independent
decay chain (simplified model) → work ongoing to map this approach to
Realistic SUSY models

Minimal Supersymmetric Standard Model (MSSM)

Minimal particle content:

- A superpartner for each SM particle
- Two Higgs doublets and spartners: 5 Higgs bosons: h,H,A,H+,H-



gaugino/higgsino mixing

- Insert in Lagrangian all soft breaking terms: 105 parameters.
- If we assume that flavour matrices are aligned with SM ones (minimal flavour violation): 19 parameters

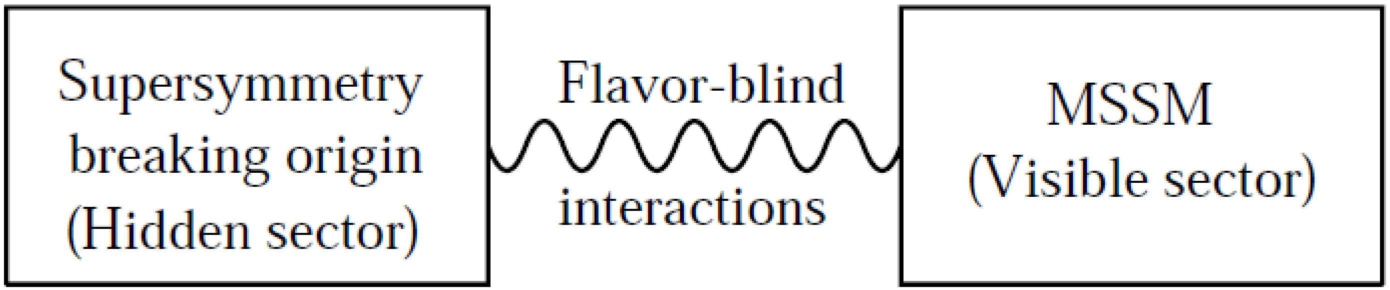
Additional ingredient: R-parity conservation: $R=(-1)^{3(B-L)+2S}$

- Sparticles are produced in pairs
- The Lightest SUSY particle (LSP) is stable, neutral weakly interacting
  - Excellent dark matter candidate
  - It will escape collider detectors providing Etmiss signature

Models with R-parity violating terms are also studied: no E_T^{miss} signature, but often 'easier' kinematic signatures

SUSY breaking models

Spontaneous breaking not possible in MSSM, need to postulate hidden sector



Phenomenology of the model and free parameters determined by the nature of the messenger field mediating the breaking. Examples:

- Gravity: mSUGRA. Parameters: $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sgn}\,\mu$

  LSP is $\tilde{\chi}^0_1$: E_T^{miss} + jets signatures

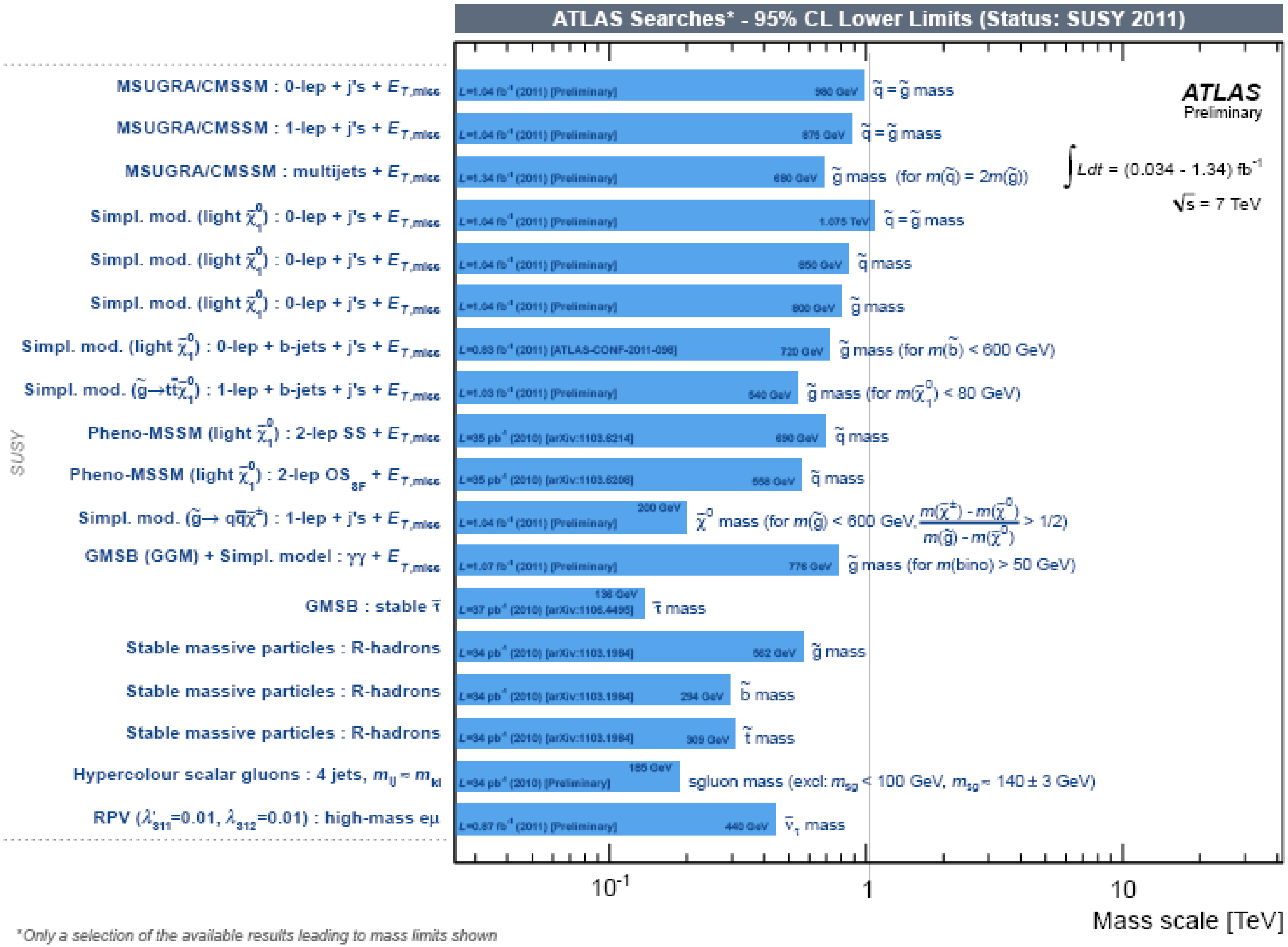
- Gauge interactions: GMSB. Parameters: $\Lambda = F_m/M_m,\ M_m,\ N_5$
  $\tan\beta,\ sgn(\mu),\ C_{grav}$

  LSP is light gravitino $\tilde{G}$. Signatures: $\gamma+E_T^{miss}$ from $\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$ if $\tilde{\chi}^0_1$ NLSP
  leptons+E_T^{miss} or long-lived leptons if slepton NLSP

- Anomalies: AMSB. Parameters: $m_0,\ m_{3/2},\ \tan\beta,\ sign(\mu)$

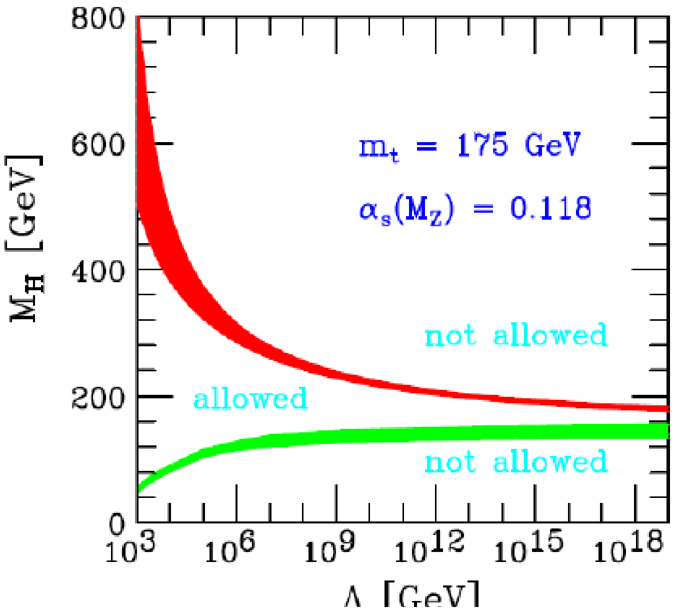
  Can have sparticle degeneracy with metastable decays

Summary table



Why physics beyond Standard Model?

- Gravity is not yet incorporated in the model
- Hierarchy/naturalness problem

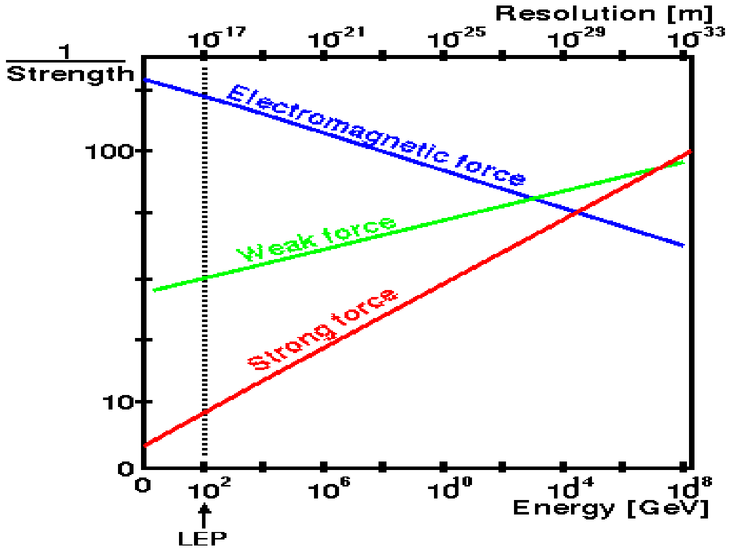


Standard Model valid only up to scale $\Lambda < M_{pl}$

Example: m_h=115 GeV $\Lambda < 10^6$ GeV

Therefore Higgs mass becomes instable to quantum corrections from fermion loops:

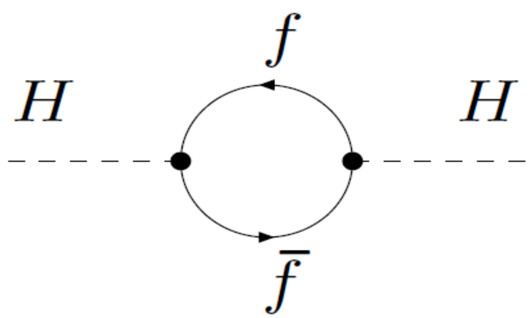
$$\delta m_H^2 \propto \lambda_f^2 \Lambda^2$$



- Lack of unification of couplings in SM
- Dark Matter problem: SM particles only account for a small fraction of the matter observed in the universe

Naturalness problem and SUSY solution

Correction to higgs mass from fermion loop:



$$\Delta m_H^2 \sim \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + m_f^2) +$$

Where Λ high energy cutoff
For Λ~M_{Planck}~10^{18} GeV corrections explode

Correction from scalar $\tilde{f}$

$$\Delta m_H^2 \sim -\frac{\lambda_{\tilde{f}}^2}{4\pi^2}(\Lambda^2 + m_{\tilde{f}}^2) + \ldots\ldots$$

Corrections have opposite sign. Cancellations if for each fermion degree of freedom one has scalars such that: $\lambda_{\tilde{f}}^2 = \lambda_f^2 \quad m_{\tilde{f}} = m_f$

Achieved in theory invariant under transformation Q:

$Q|\text{boson}\rangle = |\text{fermion}\rangle \quad Q|\text{fermion}\rangle = |\text{boson}\rangle$ Supersymmetry

Very general class of theories, specialize to minimal model: MSSM

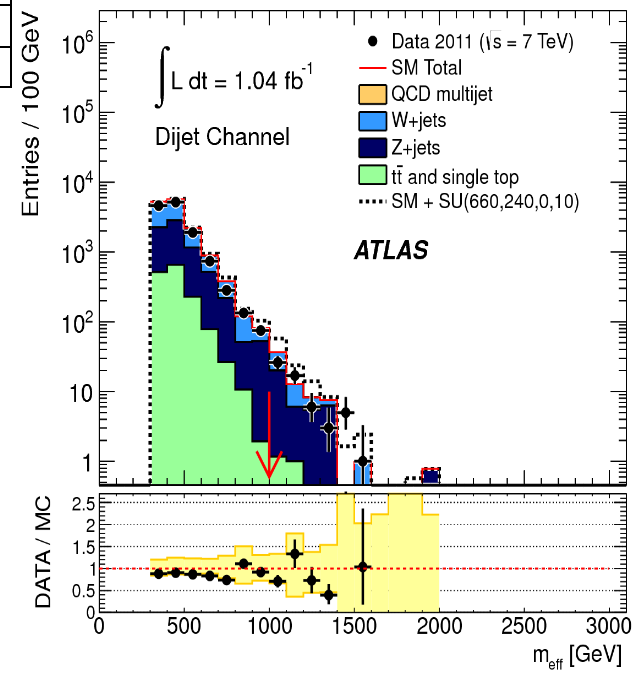
Results on 0-lepton+Etmiss

CMS

	Baseline (H_T >350 GeV) ($\not{H}_T$ >200 GeV)	Medium (H_T >500 GeV) ($\not{H}_T$ >350 GeV)	High H_T (H_T >800 GeV) ($\not{H}_T$ >200 GeV)	High $\not{H}_T$ (H_T >800 GeV) ($\not{H}_T$ >500 GeV)
$Z \to \nu\bar{\nu}$ from γ+jets	$376 \pm 12 \pm 79$	$42.6 \pm 4.4 \pm 8.9$	$24.9 \pm 3.5 \pm 5.2$	$2.4 \pm 1.1 \pm 0.5$
$t\bar{t}/W \to e,\mu$+X	$244 \pm 20^{+30}_{-31}$	$12.7 \pm 3.3 \pm 1.5$	$22.5 \pm 6.7^{+3.0}_{-3.1}$	$0.8 \pm 0.8 \pm 0.1$
$t\bar{t}/W \to \tau_h$+X	$263 \pm 8 \pm 7$	$17 \pm 2 \pm 0.7$	$18 \pm 2 \pm 0.5$	$0.73 \pm 0.73 \pm 0.04$
QCD	$31 \pm 35^{+17}_{-6}$	$1.3 \pm 1.3^{+0.6}_{-0.4}$	$13.5 \pm 4.1^{+7.3}_{-4.3}$	$0.09 \pm 0.31^{+0.05}_{-0.04}$
Total background	928 ± 103	73.9 ± 11.9	79.4 ± 12.2	4.6 ± 1.5
Observed in data	986	78	70	3

ATLAS

Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, $m_{\rm eff}$ > 500 GeV	$\geq$ 4-jet, $m_{\rm eff}$ > 1000 GeV	High mass
Z/γ+jets	$32.3 \pm 2.6 \pm 6.9$	$25.5 \pm 2.6 \pm 4.9$	$209 \pm 9 \pm 38$	$16.2 \pm 2.2 \pm 3.7$	$3.3 \pm 1.0 \pm 1.3$
W+jets	$26.4 \pm 4.0 \pm 6.7$	$22.6 \pm 3.5 \pm 5.6$	$349 \pm 30 \pm 122$	$13.0 \pm 2.2 \pm 4.7$	$2.1 \pm 0.8 \pm 1.1$
$t\bar{t}$+ single top	$3.4 \pm 1.6 \pm 1.6$	$5.9 \pm 2.0 \pm 2.2$	$425 \pm 39 \pm 84$	$4.0 \pm 1.3 \pm 2.0$	$5.7 \pm 1.8 \pm 1.9$
QCD multi-jet	$0.22 \pm 0.06 \pm 0.24$	$0.92 \pm 0.12 \pm 0.46$	$34 \pm 2 \pm 29$	$0.73 \pm 0.14 \pm 0.50$	$2.10 \pm 0.37 \pm 0.82$
Total	$62.4 \pm 4.4 \pm 9.3$	$54.9 \pm 3.9 \pm 7.1$	$1015 \pm 41 \pm 144$	$33.9 \pm 2.9 \pm 6.2$	$13.1 \pm 1.9 \pm 2.5$
Data	58	59	1118	40	18
Limits (fb)	22	25	429	27	17



Limits on $\sigma_{new} = \sigma A \epsilon$

Production X-section   Cut acceptance   Reconstruction efficiency

Next step is matching these limits with Specific SUSY models

Fine tuning equations and SUSY spectrum

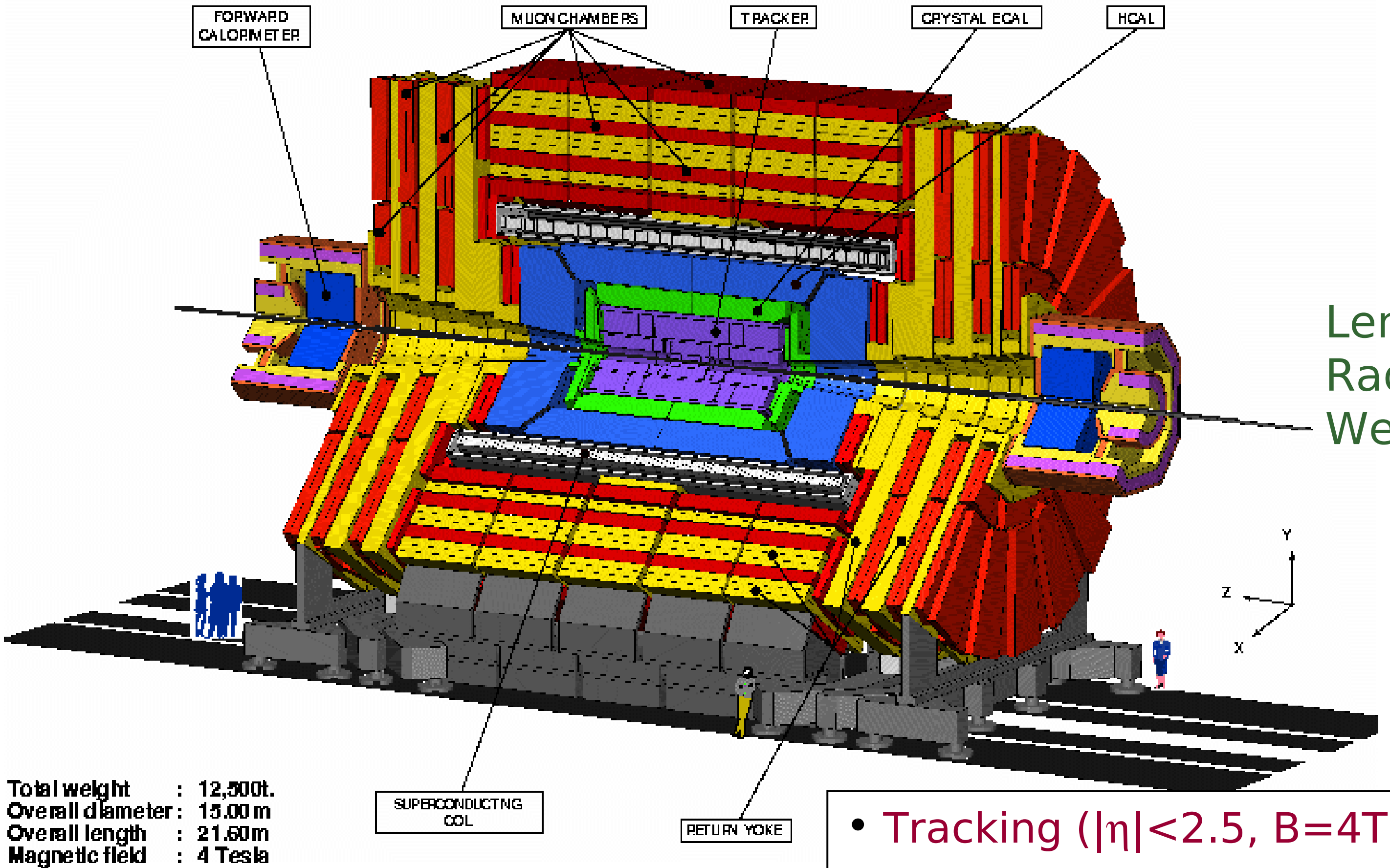
The key equations:

$$\frac{m_h^2}{2} \approx -|\mu|^2 + m_u^2 + \ldots$$

$$\delta m_u^2 \approx -\frac{3y_t^2}{8\pi^2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2) \log M/m_{\tilde{t}}$$

$m_{\tilde{b}_L}$

$$\delta m_{\tilde{t}}^2 \approx \frac{8\alpha_s}{3\pi} m_{\tilde{g}}^2 \log M/m_{\tilde{t}}$$



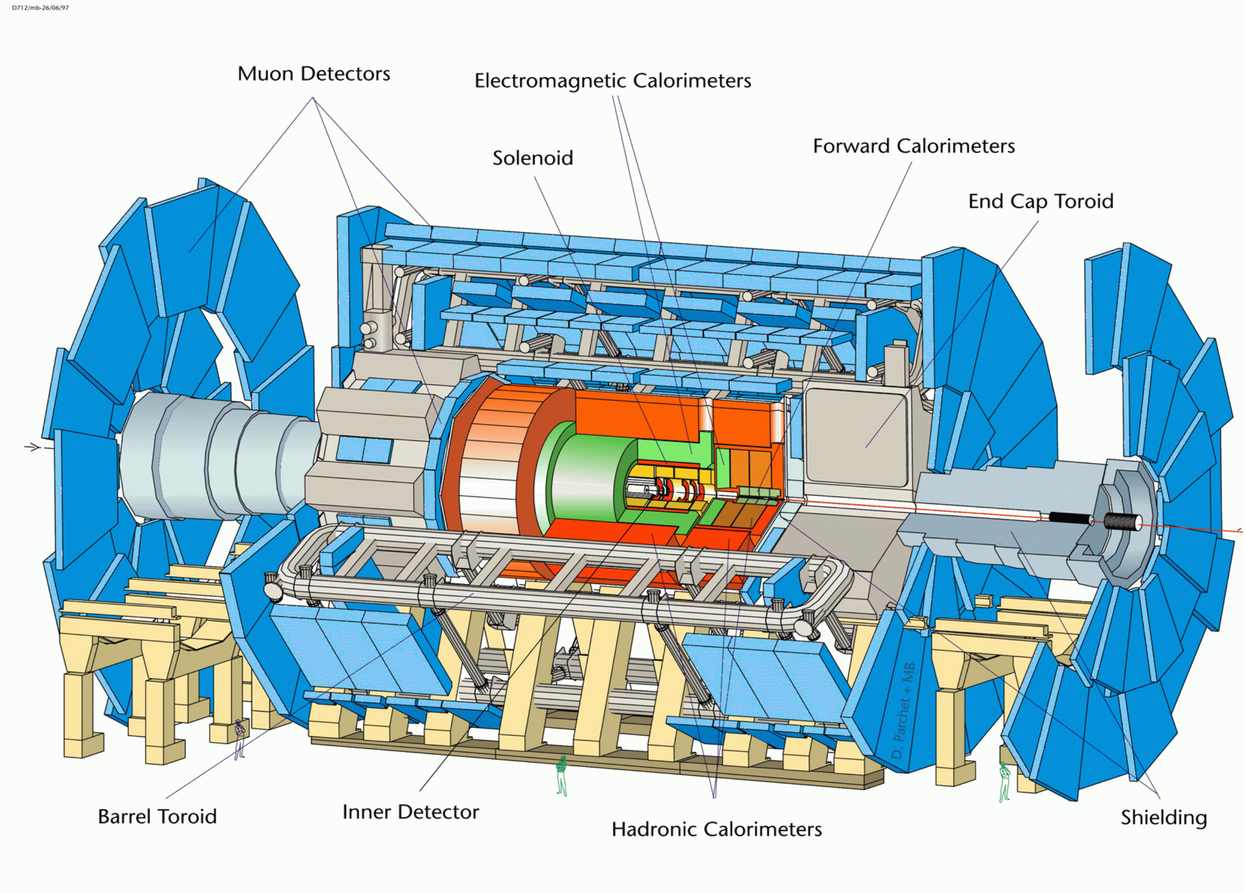
CMS

Length : ~22 m
Radius : ~7 m
Weight : ~ 12500 tons

- Tracking (|η|<2.5, B=4T) : Si pixels and strips
- Calorimetry (|η|<5) :
  -- EM : $PbWO_4$ crystals
  -- HAD: brass/scintillator (central+ end-cap),
  Fe/Quartz (fwd)
- Muon Spectrometer (|η|<2.5) : return yoke of solenoid instrumented with muon chambers

And .... > 2500 physicists from 180 Institutions from 38 countries from 5 continents

ATLAS



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

- Inner Detector (|η|<2.5, B=2T) :
  -- Si pixels and strips
  -- Transition Radiation Detector (e/π separation)
- Calorimetry (|η|<5) :
  -- EM : Pb-LAr
  -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)
- Muon Spectrometer (|η|<2.7) :
  air-core toroids with muon chambers

And ~2800 physicists from 169 Institutions, 37 countries, 5 continents