Status of SUSY searches at the LHC

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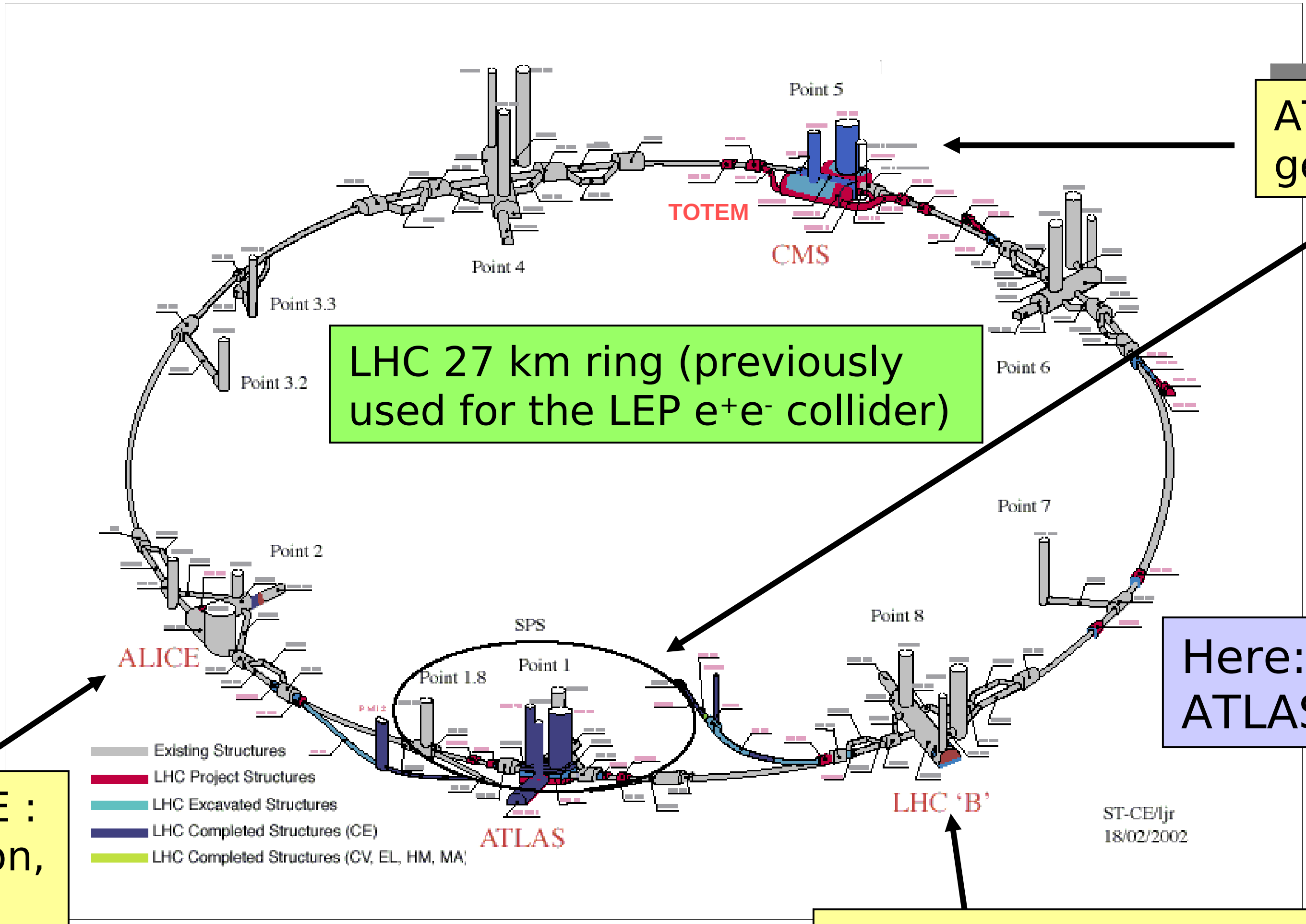
Introduction and outline

- The data taken in 2010 and 2011 at the LHC have been used for searching for SUSY signal
- No signal seen. Questions to address:
  – Review critically the prejudices which went into the first round of analyses
  – Assess the actual parameter space now excluded
  – Make proposals on how to proceed for the next round of searches:
- SUSY is a template for models with duplicate spectrum and stable lightest particle most of the material discussed can be applied to alternate models with the same phenomenology

LHC

- pp $\sqrt{s}$ = 14 TeV L_{design} = 10^{34} cm^{-2} s^{-1} (after 2012)
  $\sqrt{s}$ = 7 TeV $L_{initial}$ < few x 10^{33} cm^{-2} s^{-1} (before 2012)
  Note: $\sqrt{s}$ is x7 Tevatron, L_{design} is x30 Tevatron
- Heavy ions



LHC 27 km ring (previously used for the LEP e^+e^- collider)

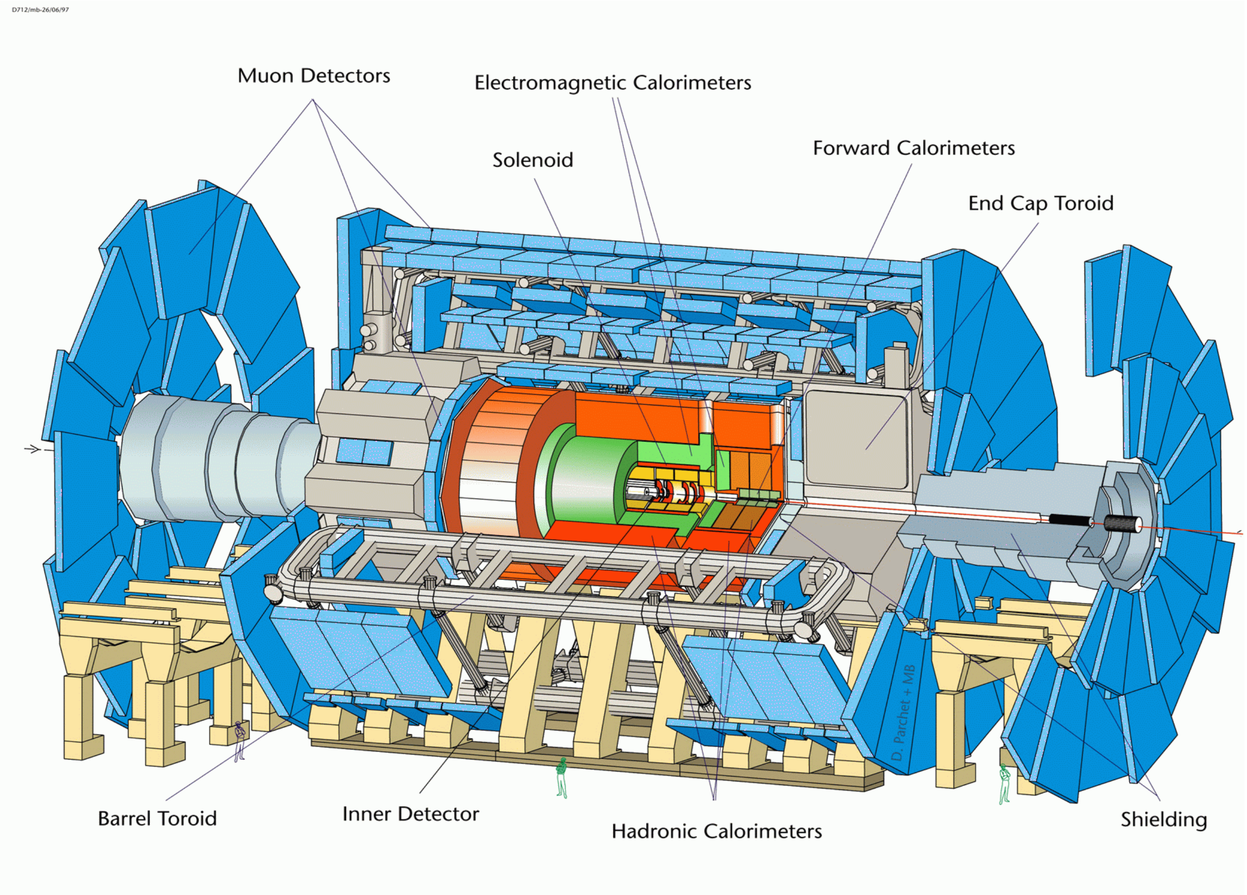
ATLAS and CMS : general purpose

Here: concentrate on ATLAS

ALICE : ion-ion, p-ion

LHCb : pp, B-physics, CP-violation

ATLAS

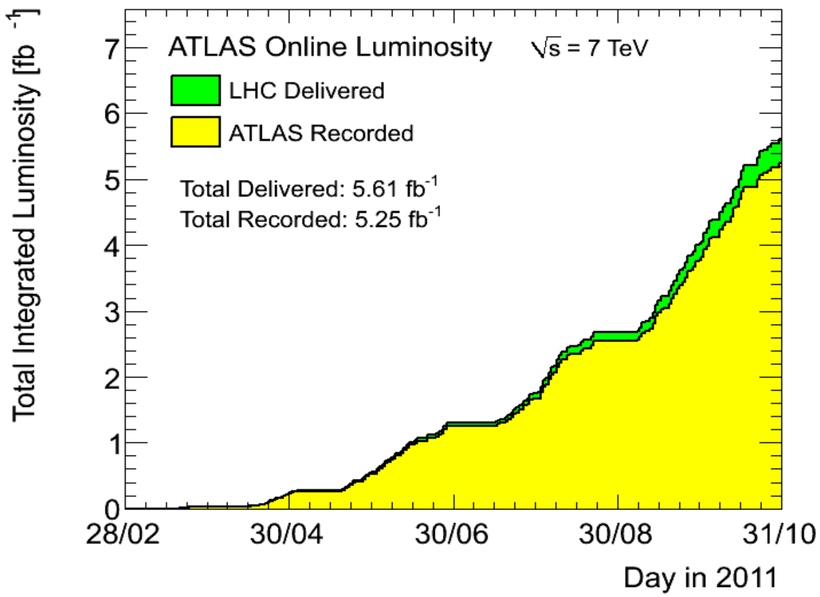


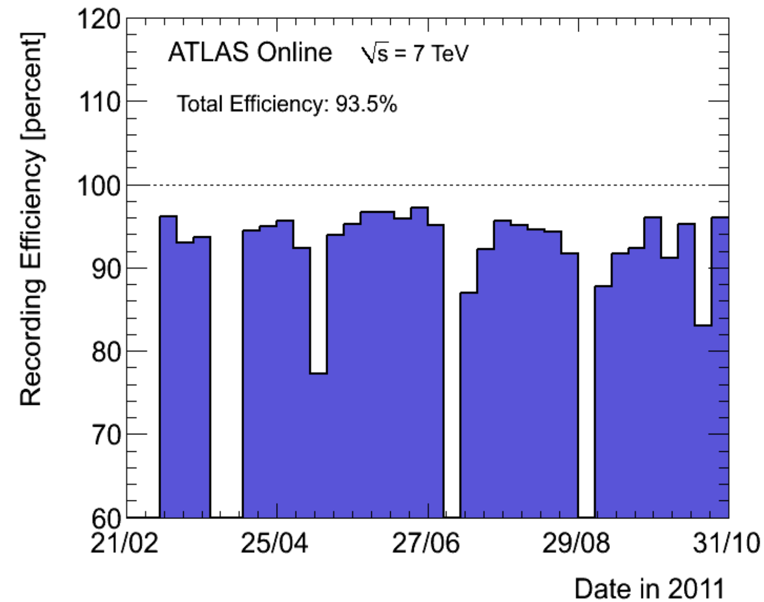
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
~ 3000 km of cables

- 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

Collected luminosity and detector performance





Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.9	100	98.4	99.3	99.4	98.3	99.8	99.5	99.8	99.9	99.7	99.5

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 August 24th (in %), after the summer 2011 reprocessing campaign.

Outstanding Performance from Both LHC and detector

DAQ efficiency: 93.5% (5.25/5.61)

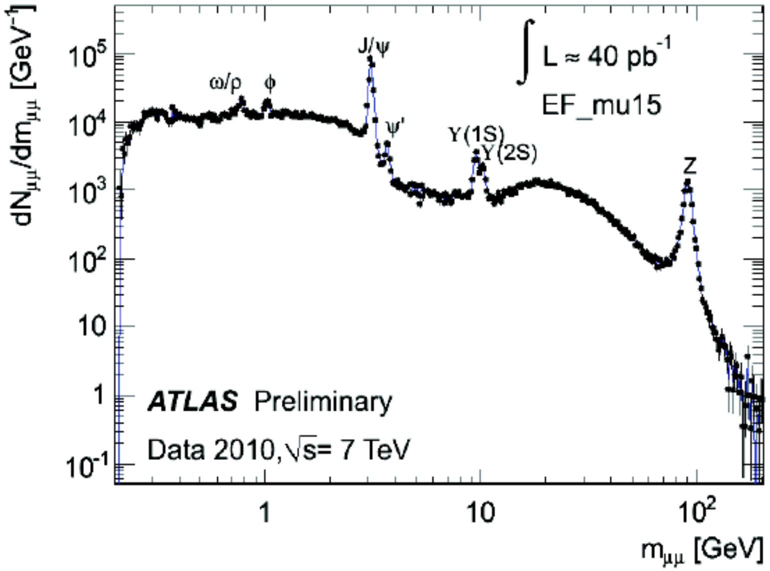
Data analysis flow

- Once good data on disk the work has just begun:
  - Calibration has to be determined and applied
  - Detector objects to be reconstructed
  - Reconstructed data to be made available on the grid
    - Complete calibration loop within 48 hours of data taking

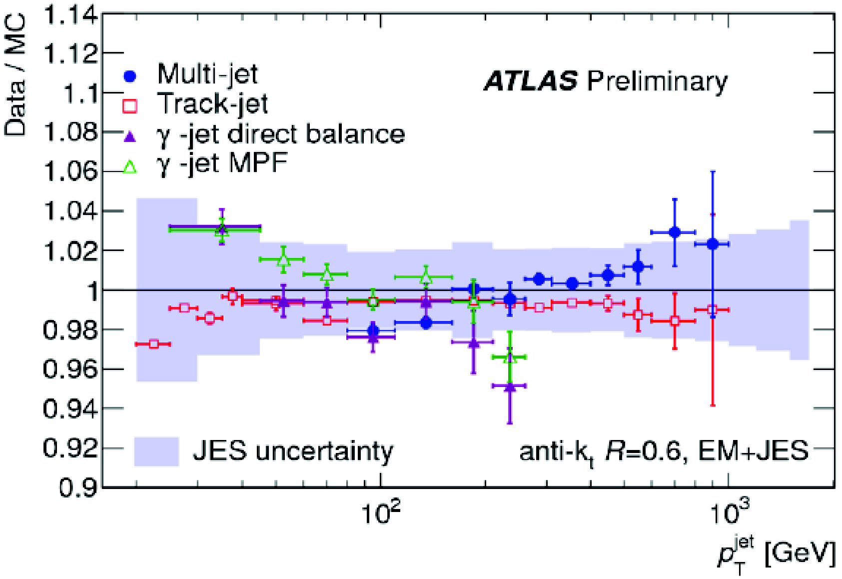
Enormous work very efficiently performed by dedicated teams

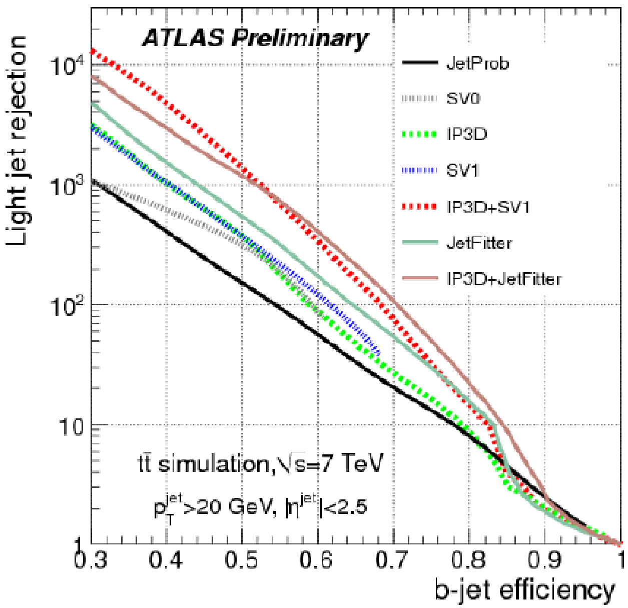
- Starting from reconstructed data, two steps necessary before going for new physics searches:
  - Understanding of detector performance for main objects: leptons, jets, photons, b-jets, τ-jets, Etmiss
  - Measurements of Standard Model processes to ensure that our detector understanding is adequate to look for deviations

Performance examples



Leptons: excellent id capabilities from the beginning, resolution at design value

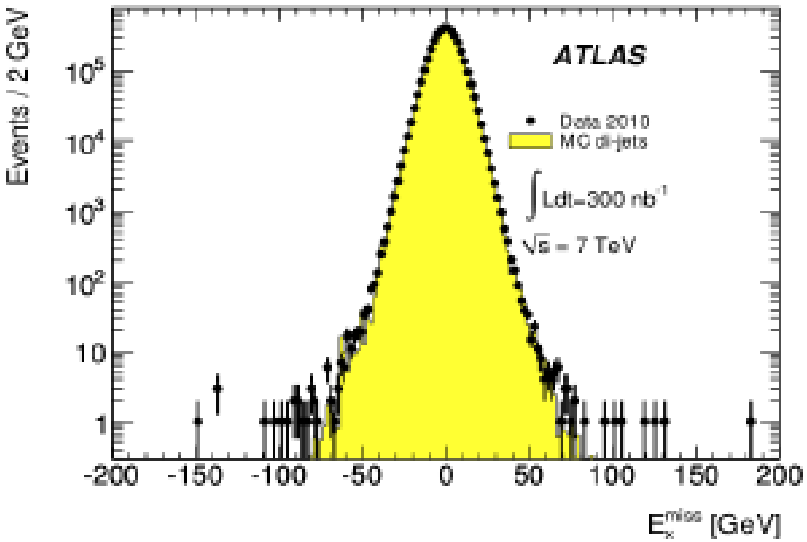




Jet energy scale known to 2-4% for
Jet PT>20 GeV

B-tagging: key to detailed searches
Advanced methods validated with 2011 data
For 60% efficiency rejection of several hundreds
On light jets

Understanding of detector performance: Etmiss



Key ingredient in SUSY analysis

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss,calo}} + E_{x(y)}^{\text{miss},\mu}$$

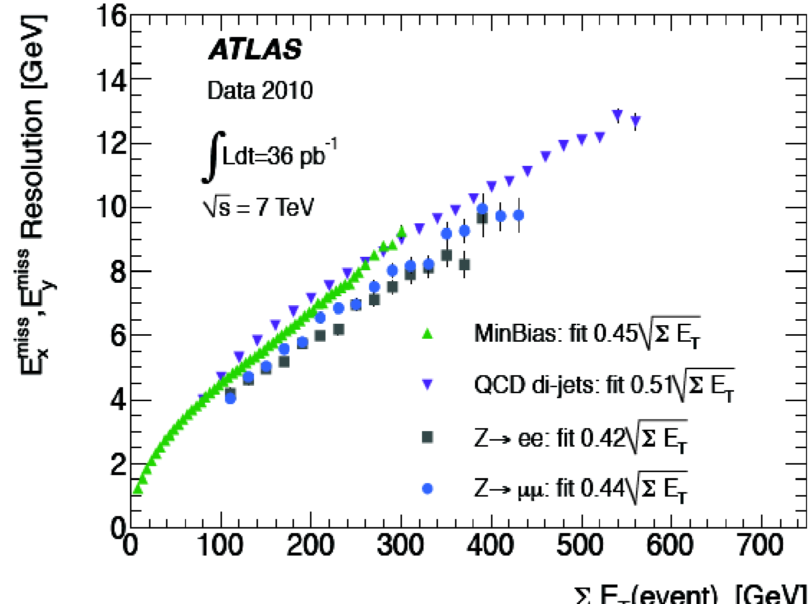
$$E_{x(y)}^{\text{miss,calo}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,softjets}} + (E_{x(y)}^{\text{miss,calo},\mu}) + E_{x(y)}^{\text{miss,CellOut}}$$

Vector sum of the measured energy deposit of all objects in the detector

If all particles detected: Etmiss=0
High Etmiss signals invisible particle
Such as a neutrino

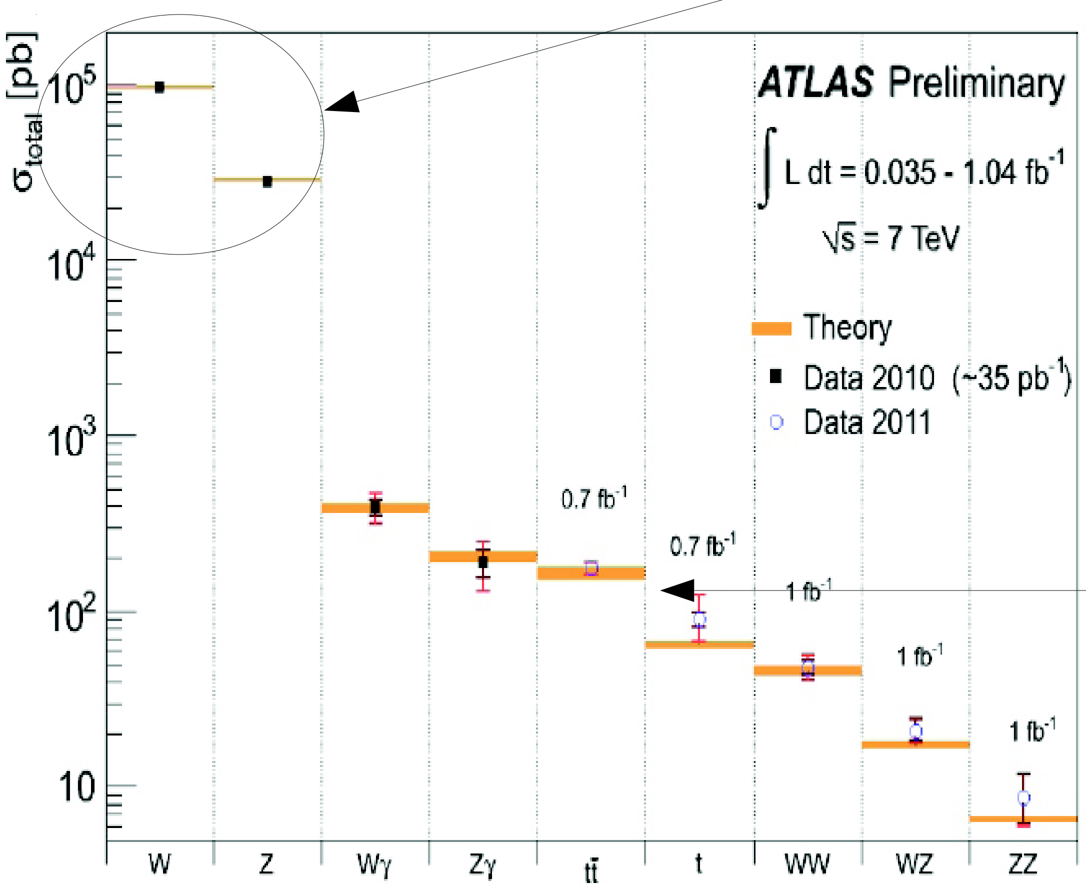
Any local malfunction in the detector would
Be registered as a tail in Etmiss distribution

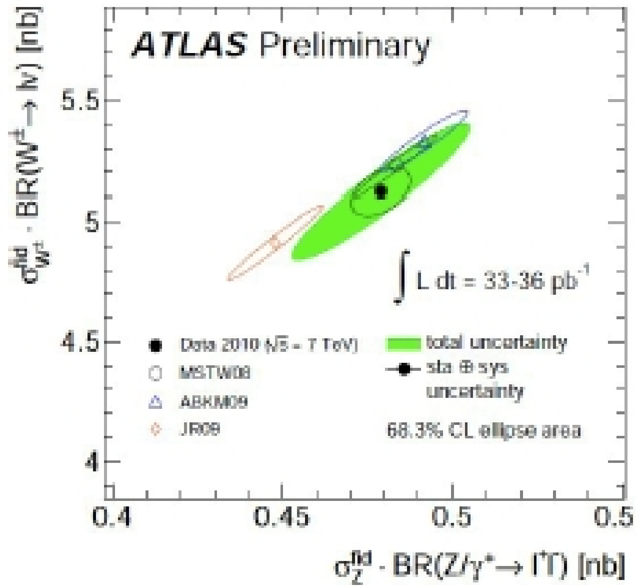
From early data taking tails under control
and measurement resolution in agreement
with expected value

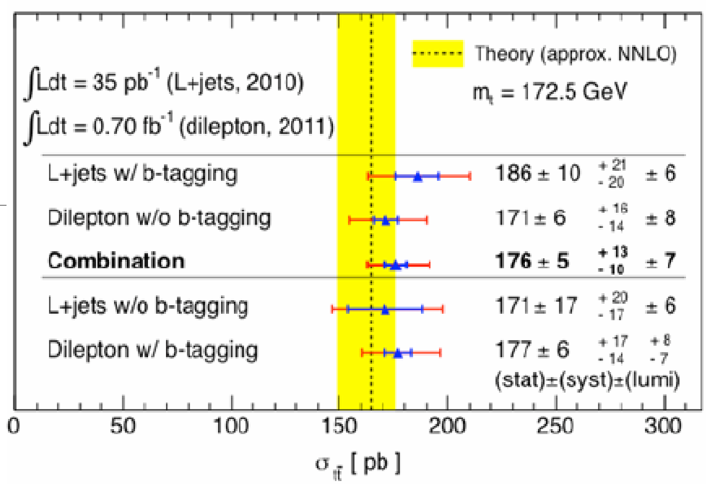


Standard model measurements

With increasing statistics measure rarer Standard model processes







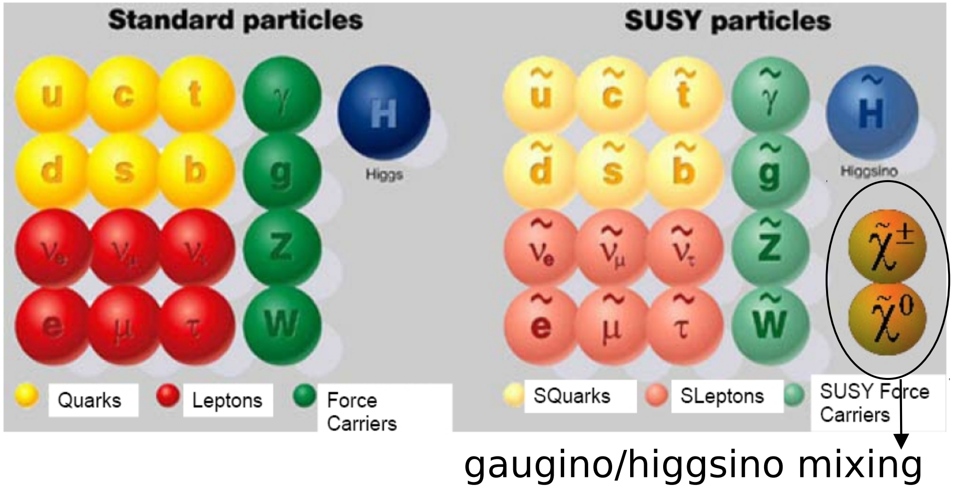
SUSY modelling

- 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)
  - 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!

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-

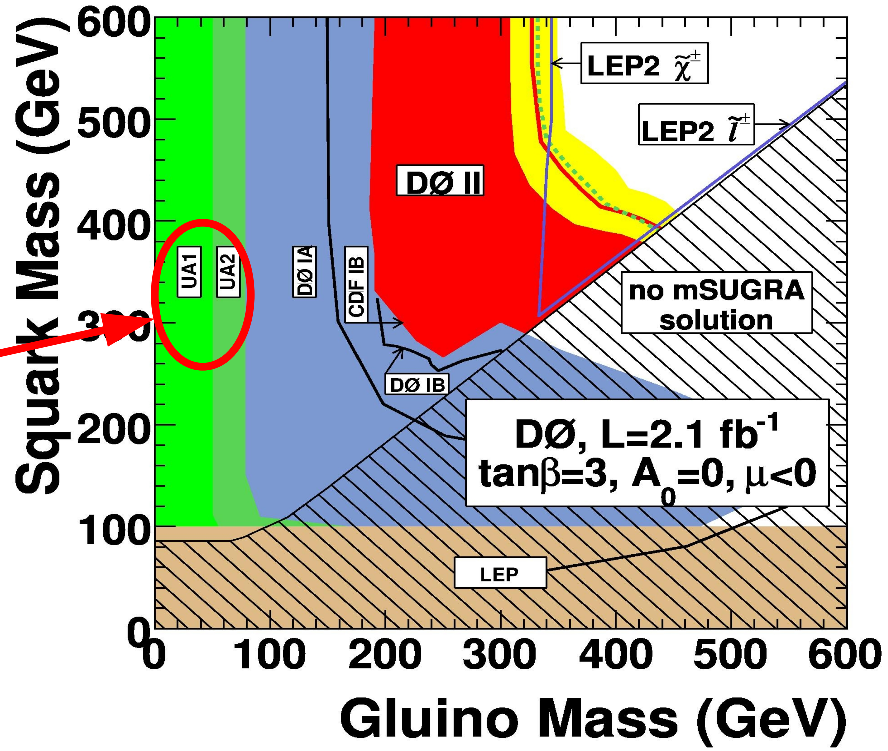
- Insert in Lagrangian all soft breaking terms: 105 parameters.
- If we assume that flavour matrices are aligned with SM ones
  (minimal flavour violation): 19 parameters

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 before LHC: Hadron colliders

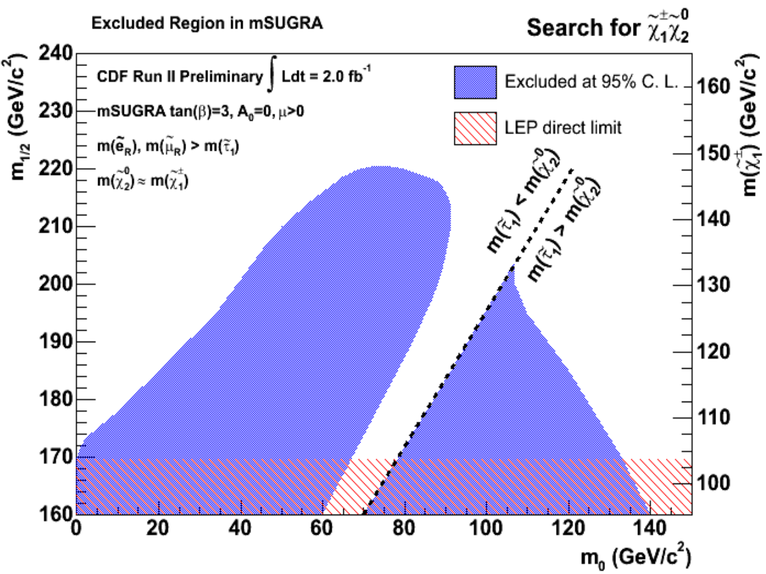


Asymptotic sensitivity on squark-gluino production:

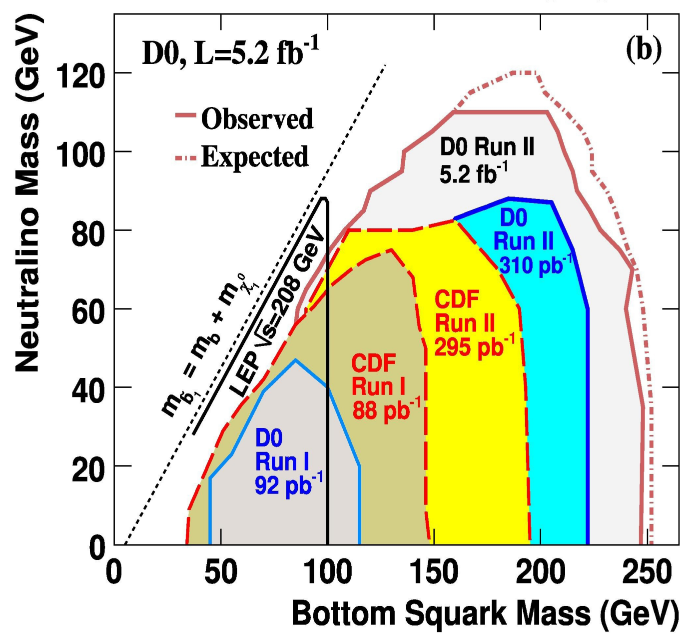
SppS : ~100 GeV (1989)

Tevatron: ~400 GeV

LHC 7 TeV: ~1.5 TeV (2012)

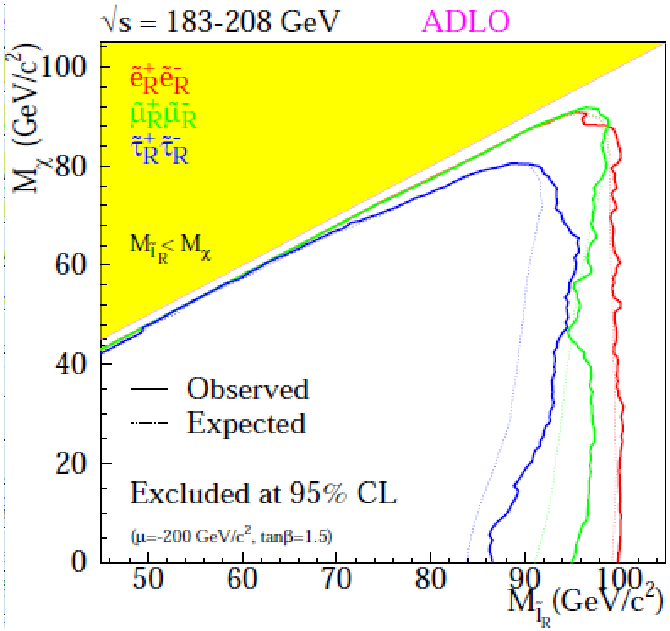


EW production of Chargino-neutralino: mSUGRA interpretation



Dedicated 3rd generation searches

SUSY before LHC: LEP

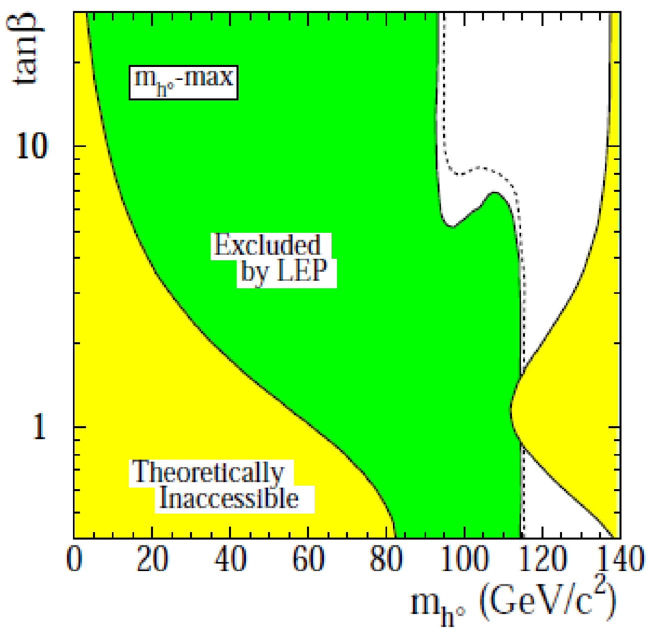


Model-independent limits of ~100 GeV on all sparticles coupling to the Z, in particular:

- 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 → 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 R-parity conserving SUSY:Etmiss

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

    (e.g. lepton ID '*easier*' than b or t tagging)
  - 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

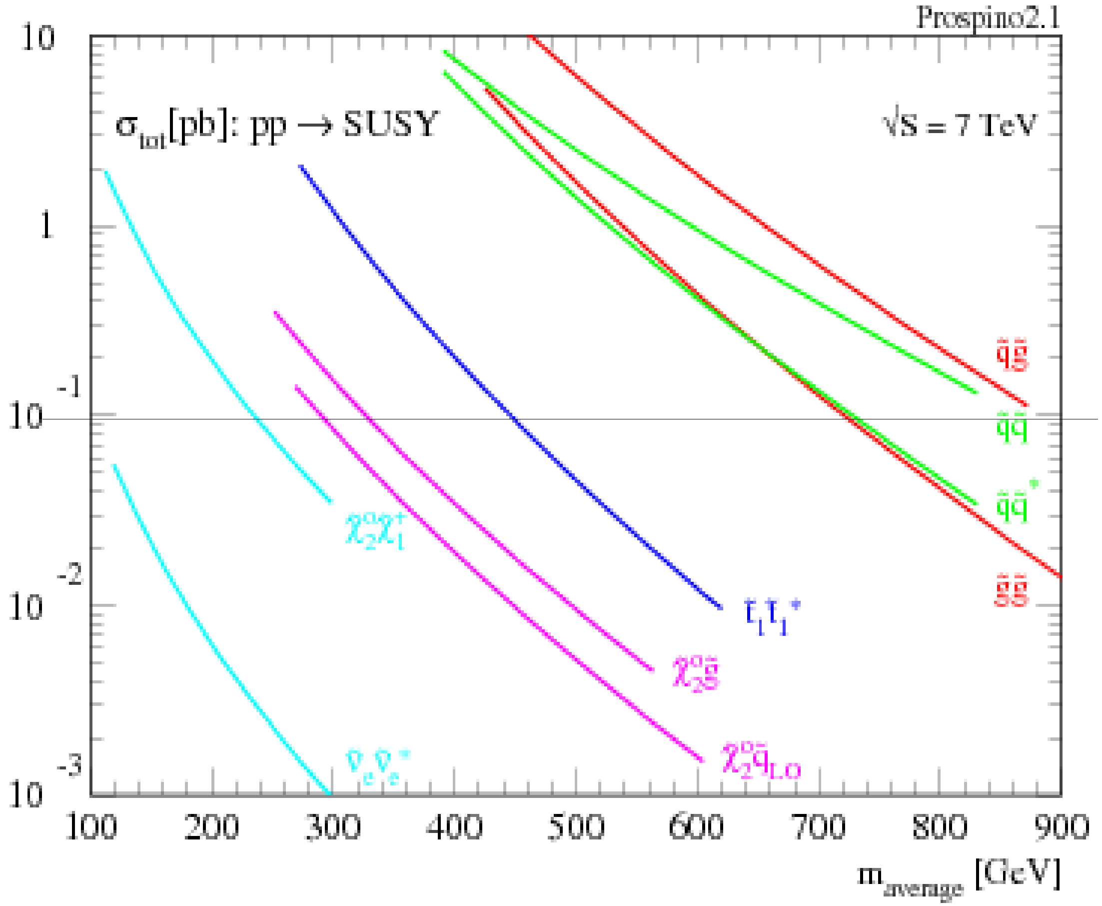
Consider an integrated luminosity of 1 fb^{-1}

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

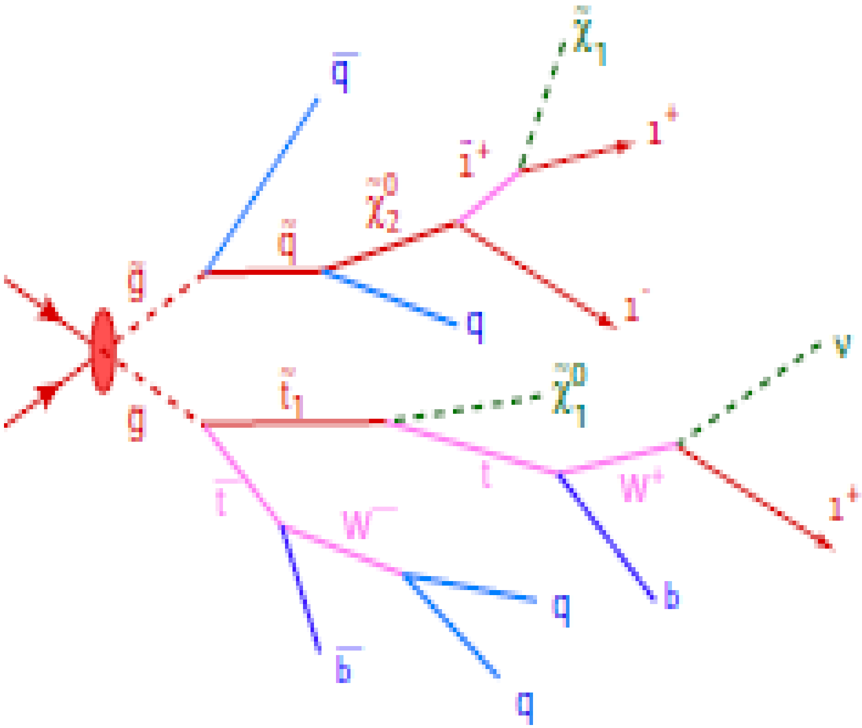
Sleptons to < 200 GeV: need to handle top and WW



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

SUSY decays

Develop **model-independent** analysis: focus on robust generic signatures
Common to most models and with high rejection of Standard Model



- Etmiss from LSP escaping detection+
- High PT jets from squark/gluino decay
- Leptons from chargino/neutralino decays
- b-jets and τ-jets from decays of third generation sparticles
- γ from decays of χ^0_1 into gravitino in models with light gravitino

Analysis published in all these channels: describe in detail flow of most general one

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

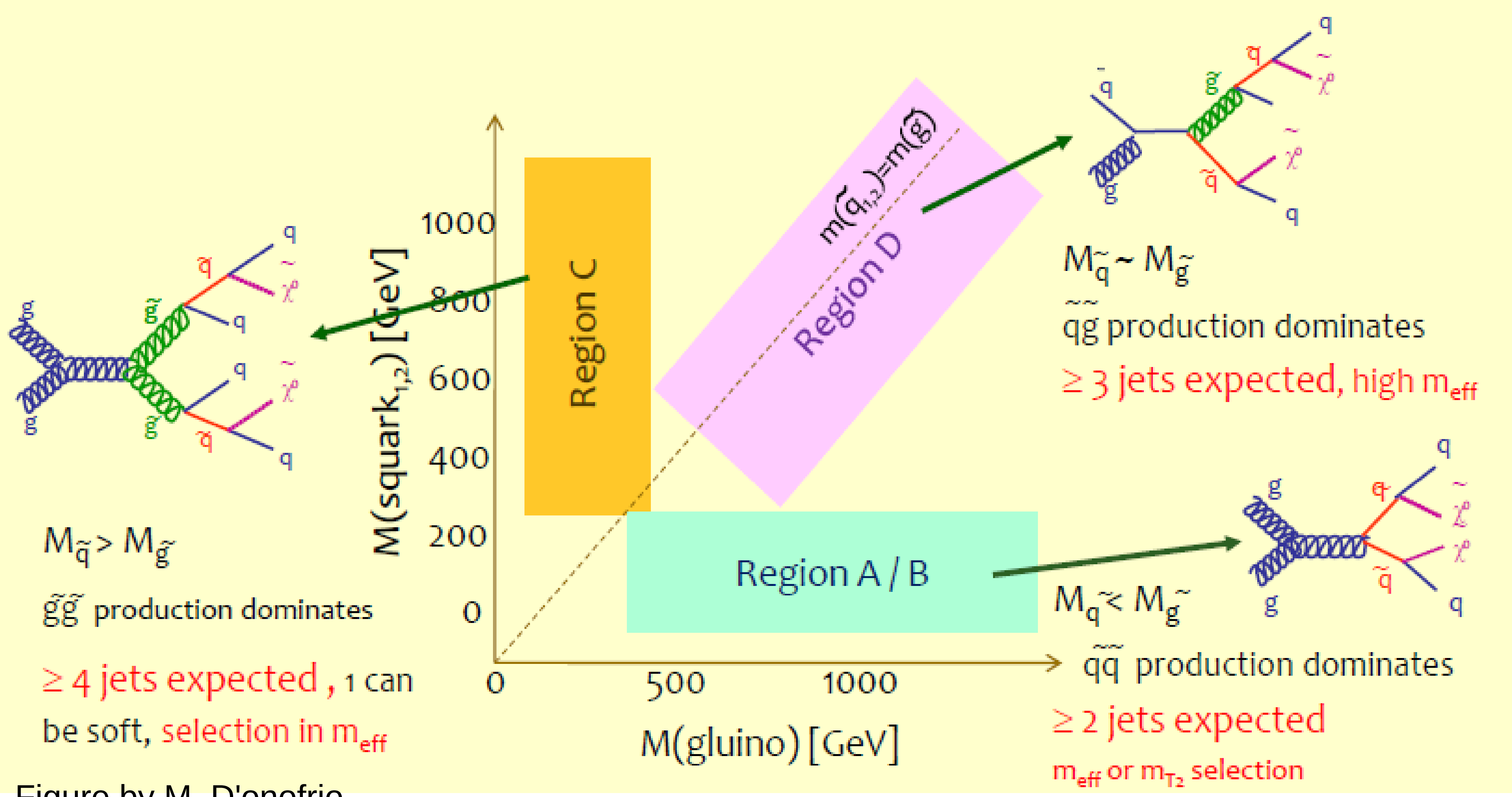


Figure by M. D'onofrio

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

SR definiton and backgrounds

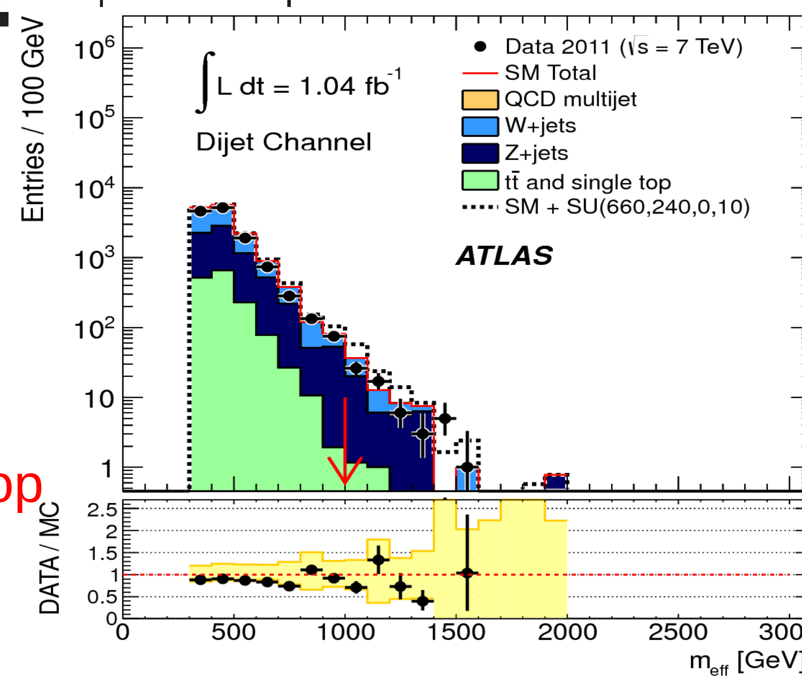
	Signal Region	≥ 2-jet	≥ 3-jet	≥ 4-jet	High mass
Trigger	E_T^{miss}	> 130	> 130	> 130	> 130
	Leading jet p_T	> 130	> 130	> 130	> 130
Channel definition	Second jet p_T	> 40	> 40	> 40	> 80
	Third jet p_T	–	> 40	> 40	> 80
	Fourth jet p_T	–	–	> 40	> 80
QDC rejection	$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 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 drives the
Basic analysis cuts
High trigger selectivity
Necessary to achieve
High sensitivity

Main backgrounds:

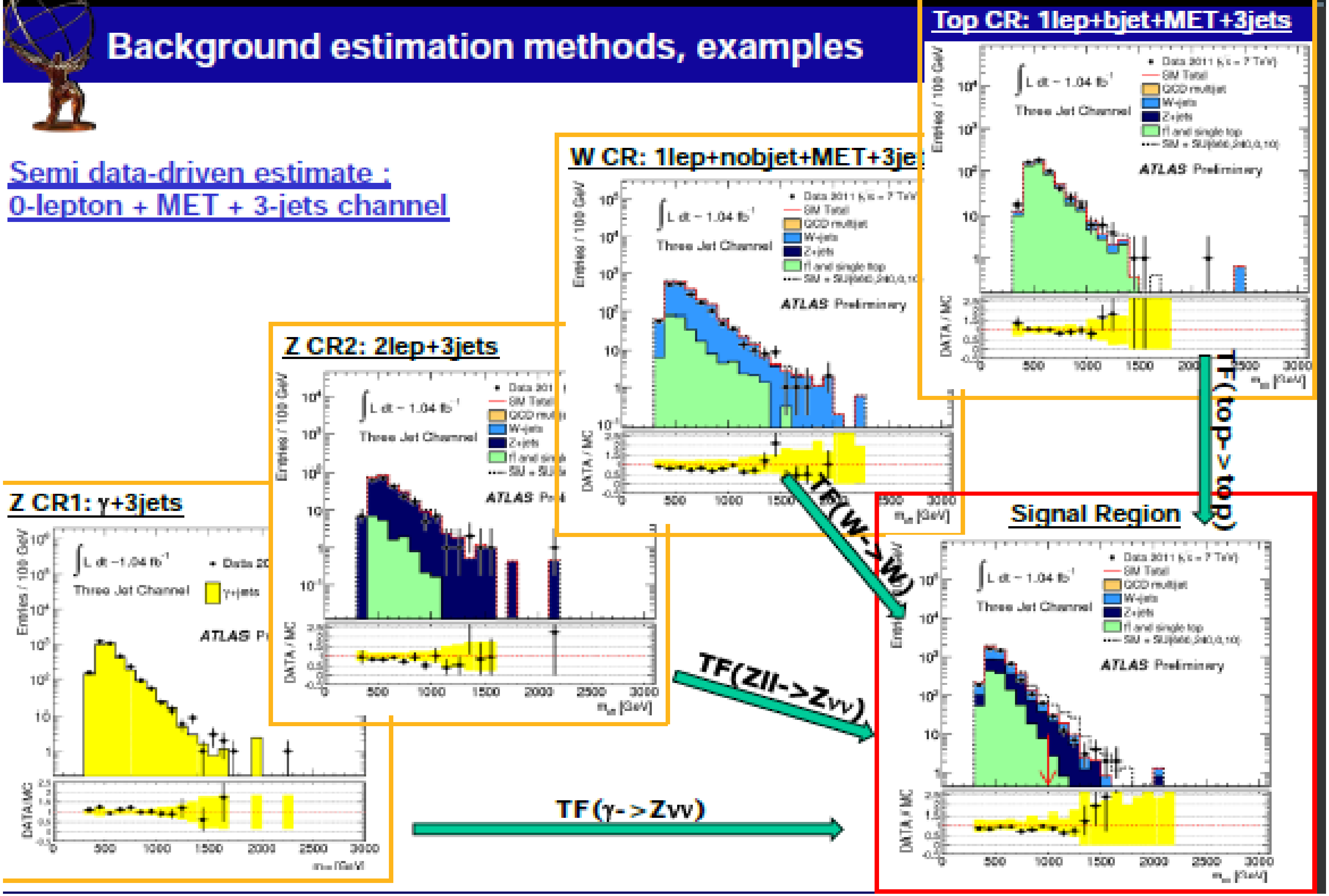
- QCD (small after cuts)
- W+jets
- Z+jets
- tt and single top

For each background we need to develop
An estimation method with minimal
Systematic uncertainty



Background estimation methods, examples

Semi data-driven estimate :
0-lepton + MET + 3-jets channel



Method for top/EWK backgrounds: define region in data (CR) where a given background dominant, predict background in SR through a transfer function evaluated with Monte Carlo

Results on 0-lepton+Etmiss

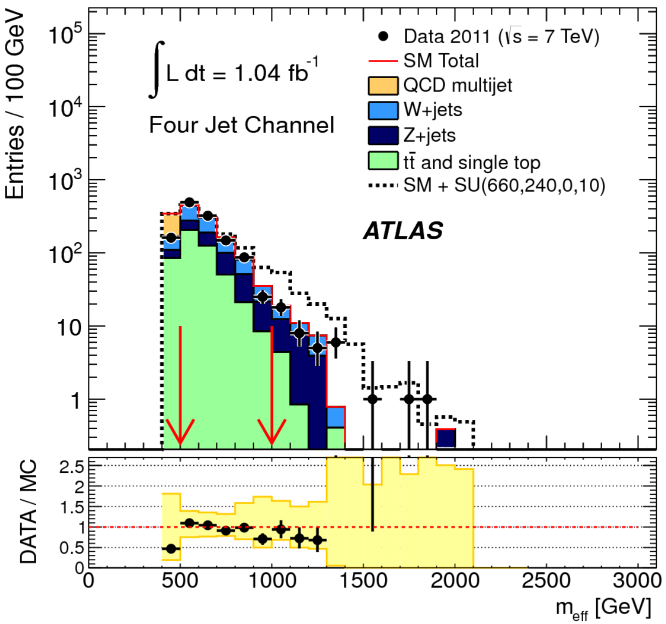
Process	Signal Region				
	≥ 2-jet	≥ 3-jet	≥ 4-jet, m_{eff} > 500 GeV	≥ 4-jet, m_{eff} > 1000 GeV	High mass
Z/γ+jets	32.3 ± 2.6 ± 6.9	25.5 ± 2.6 ± 4.9	209 ± 9 ± 38	16.2 ± 2.2 ± 3.7	3.3 ± 1.0 ± 1.3
W+jets	26.4 ± 4.0 ± 6.7	22.6 ± 3.5 ± 5.6	349 ± 30 ± 122	13.0 ± 2.2 ± 4.7	2.1 ± 0.8 ± 1.1
$t\bar{t}$+ single 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
Limits (fb)	22	25	429	27	17

Limits on

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

Production X-section
Cut acceptance
Reconstruction efficiency

15-20% uncertainty on background prediction



Next step is matching
these limits with
Specific SUSY models

MSSM interpretation

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

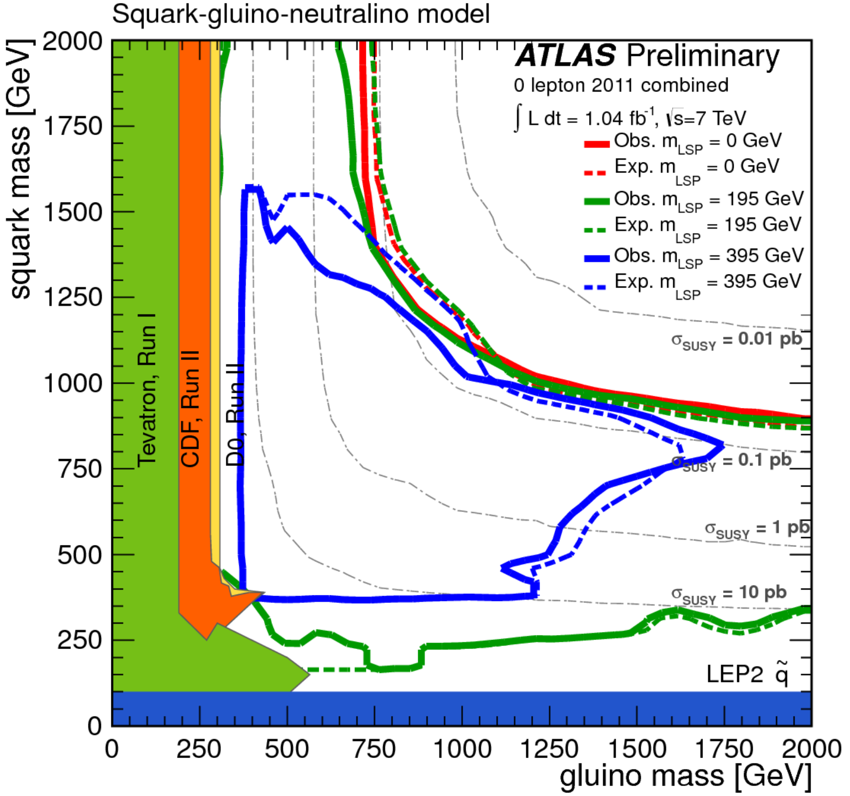
- Only production of gluinos and squarks of first two generations
- Other sparticle masses= 5 TeV
- m(LSP)=0

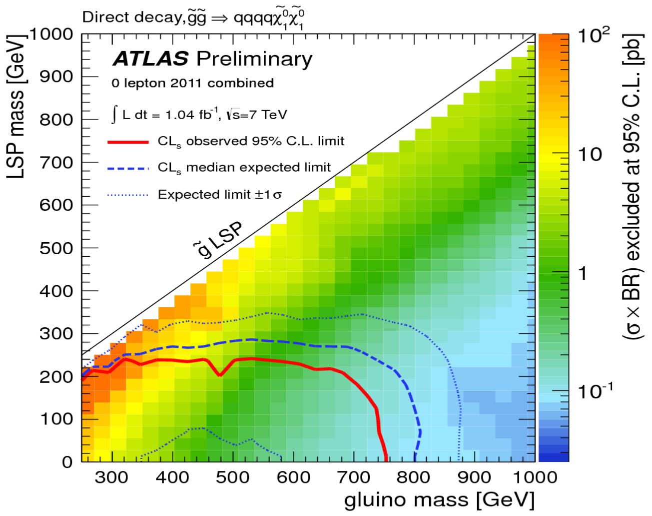
Only allowed decays:

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

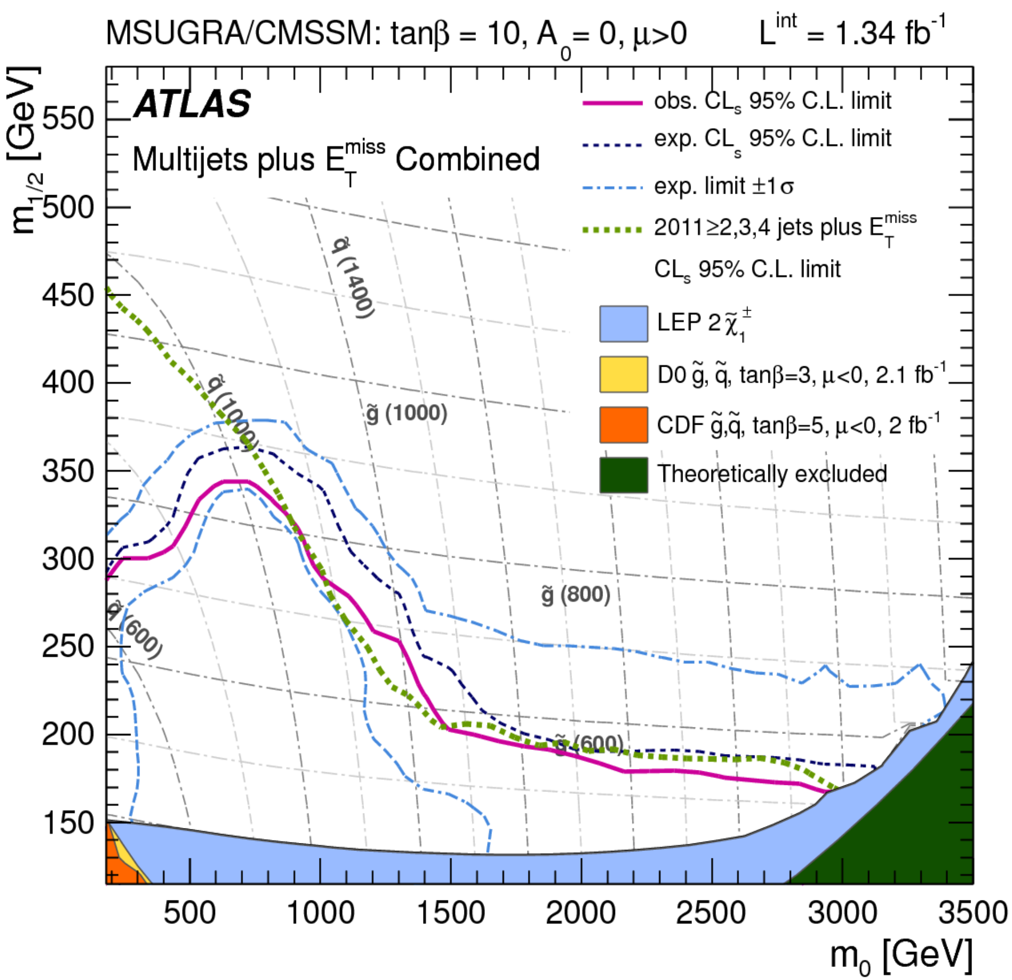
Equal squark-gluino masses excluded below 1075 GeV

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





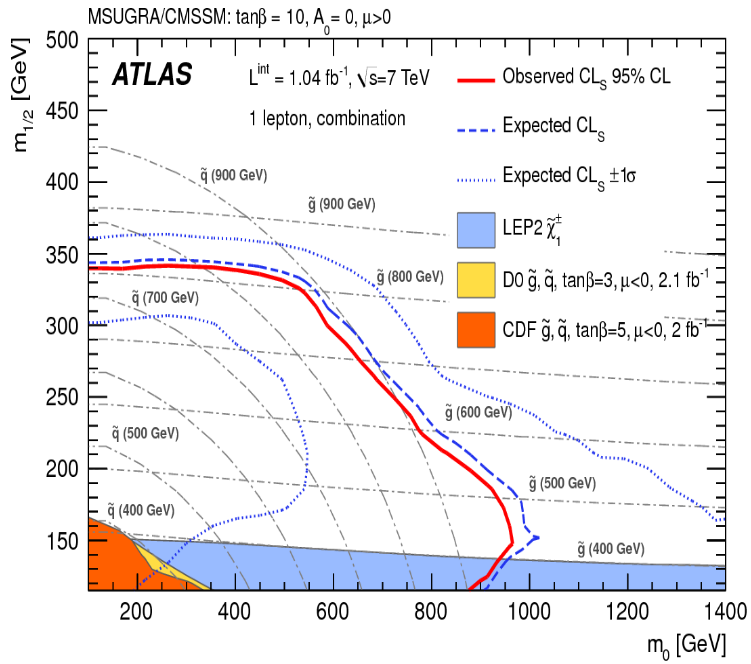
All hadronic results in cMSSM/mSUGRA

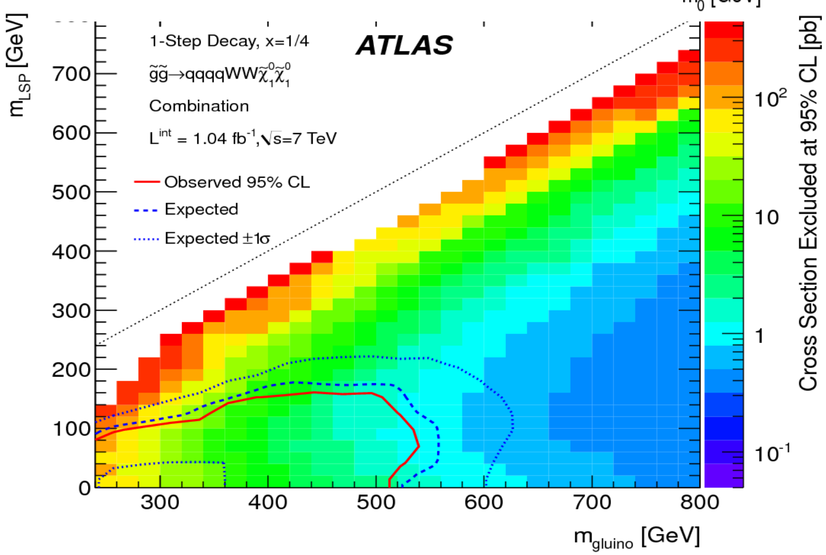


- Even with more complex decays than simplified MSSM limits above 1 TeV for m(squark)=m(gluino)
- Weaker limits high m_0: only gluino production, and dominant decay:

  g →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

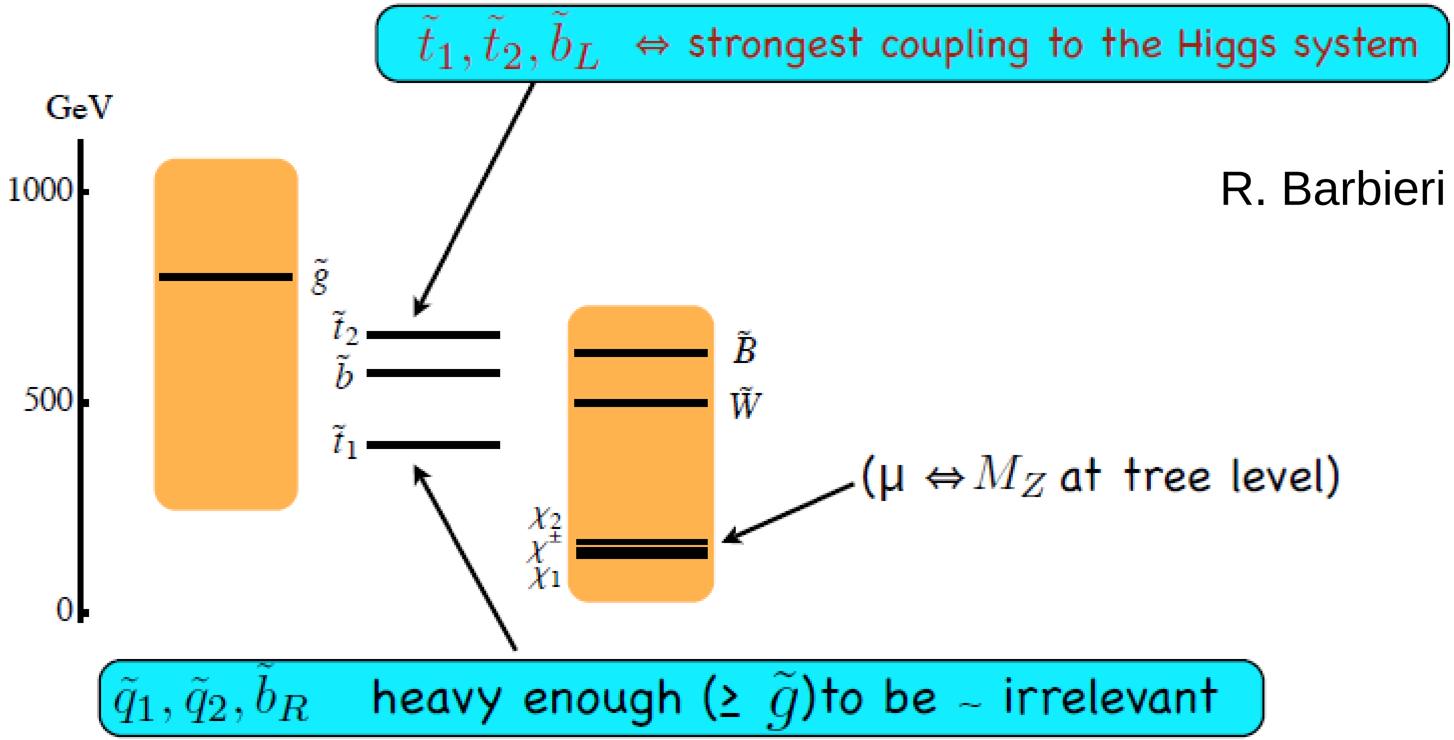
Rates dependent on all model parameters: difficult to quote results in terms of limits on sparticle production

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



R. Barbieri

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

Gluino decays into third generation

Template models for first round:

$$\tilde{g} \rightarrow \tilde{b}_1 b$$

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

$$\tilde{g} \rightarrow \tilde{t}_1 t$$

$$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \qquad \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$$

$$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + f\,f'$$

Assume gluino to decay 100% in each of these channels

Final state 4 b-jets + Etmiss

Final state: 4 bjets + 4W (*) + Etmiss

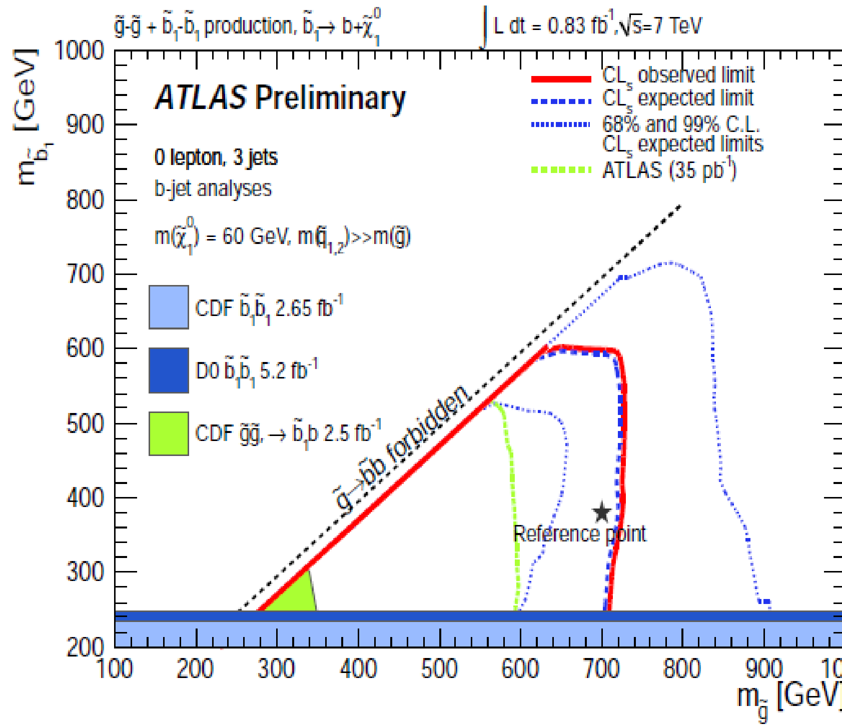
B-jets + 0 -lepton analysis

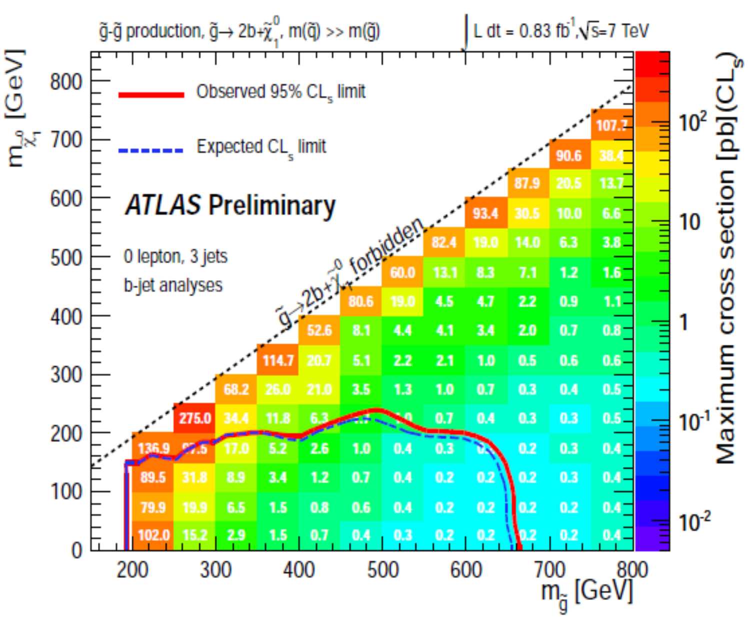
B jets with 0, 1, 2 lepton analysis

0 jet analysis

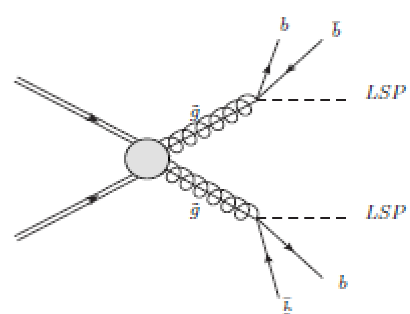
Analysis: 0 leptons + 3 jets + E_T^{miss} with 1 or 2 tagged b-jets

- $\tilde{g}\tilde{g} + \tilde{b}_1\tilde{b}_1$ production
- $\tilde{g} \to \tilde{b}_1 b$ (BR=1), $\tilde{b}_1 \to b\tilde{\chi}_1^0$ (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



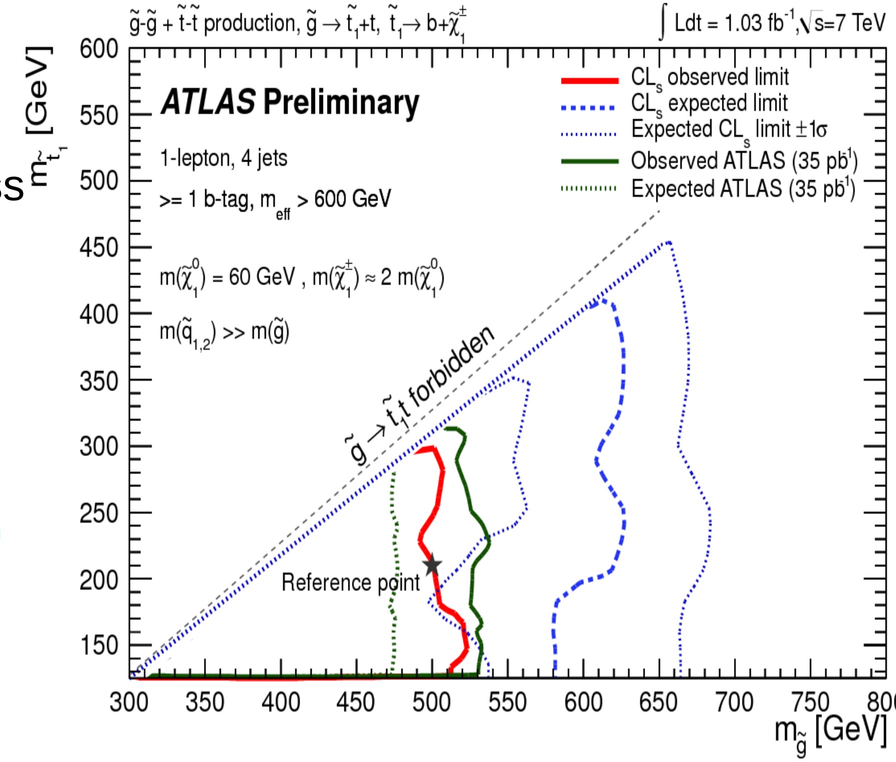
Simplified model:
Gluino 3-body decay

1 lepton analysis

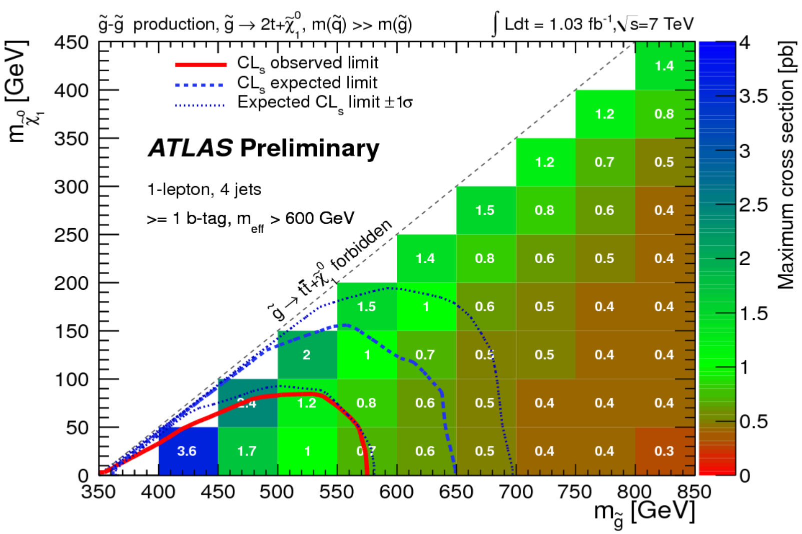
Analysis: 1 lepton + 4 jets + E_T^{miss}

1 jet tagged as b

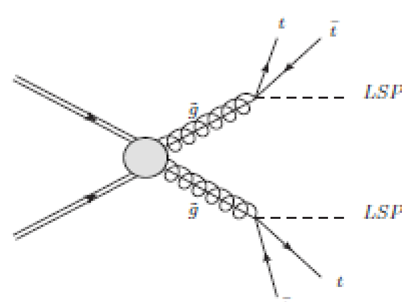
- $\tilde{g}\tilde{g} + \tilde{t}_1\tilde{t}_1$ production
- $\tilde{g} \rightarrow \tilde{t}_1 t$ (BR=1), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$ (BR=1)
- $m(\tilde{\chi}^0) = 60$ GeV, $m(\tilde{\chi}_1^{\pm}) \approx 2\tilde{\chi}_1^0$



Exclude gluino mass below 520 GeV



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



m(gluino)>560 GeV

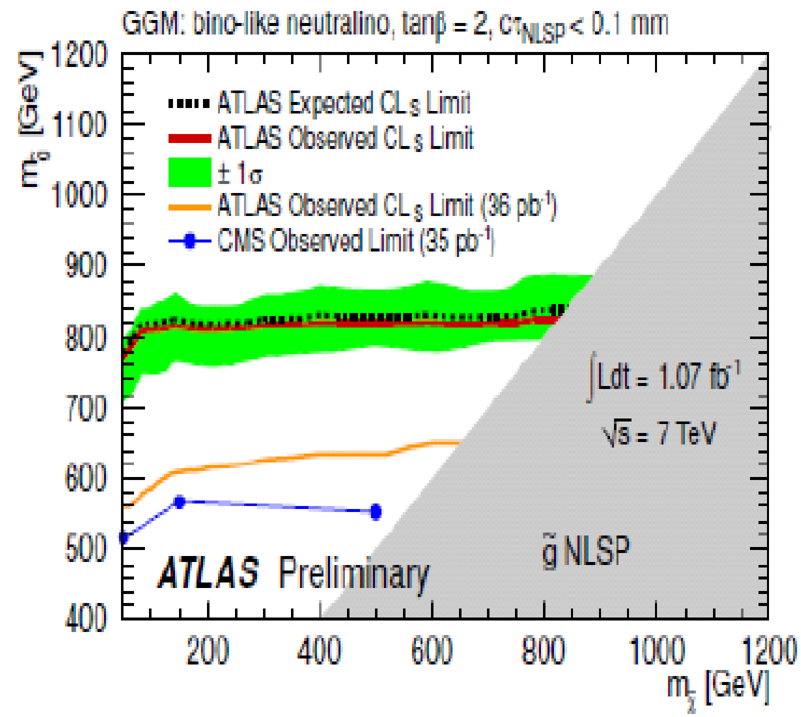
Outlook on gluino-mediated third generation

- Work going on to extend the range of stop/sbottom decays for which analyses are optimised/interpreted
- Two analyses in advanced state of approval
  - Re-optimised 0 and 1 lepton analyses on 2 fb-1
  - Same-sign lepton analysis
- Further signatures under study for winter conferences

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

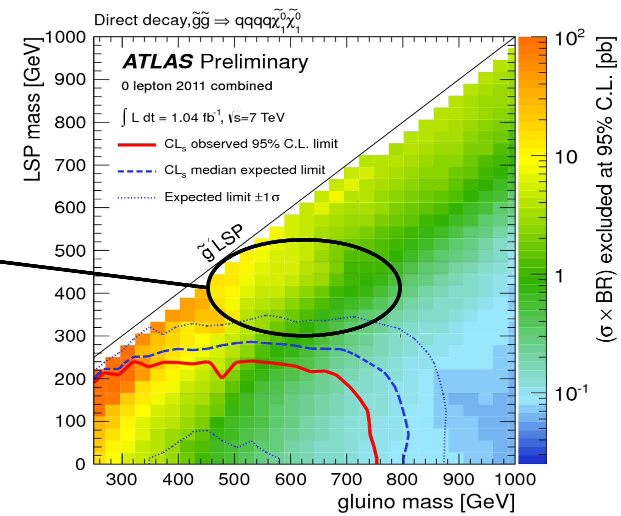
1) 1st and 2nd generation quarks and gluinos are
   - Below 1.1 TeV if they have similar masses
   - Below 7-800 GeV if one of the two is much heavier
2) Squark decays q->q chi01, and gluino decays g->qq chi01
3) m(chi01)< 200 GeV

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



Example: monojets

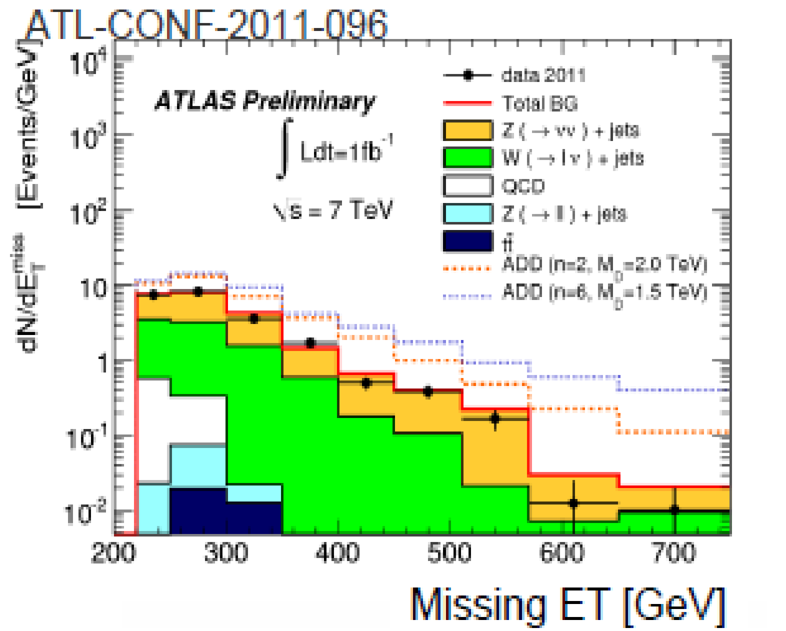
Search done in framework of ADD searches

3 Selections:

Low PT: Jet with PT>120 GeV, |η|<2, Etmiss>120 GeV, veto on Additional jets with PT>30 GeV

High PT Jet with PT>220 GeV, |η|<2, Etmiss>220 GeV, veto on Additional jets with PT>60 GeV, Veto on 3rd jet pt>30 GeV $\Delta\phi$(J2>Etmiss)>0.5

V. High PT: Same as High pt with J1>300 J2>350



Model independent limits:
1.7 pb Low PT
0.11 pb High PT
0.035 pb V High PT
For Moriond analyses oriented to SUSY signatures as well

Perspectives (2)

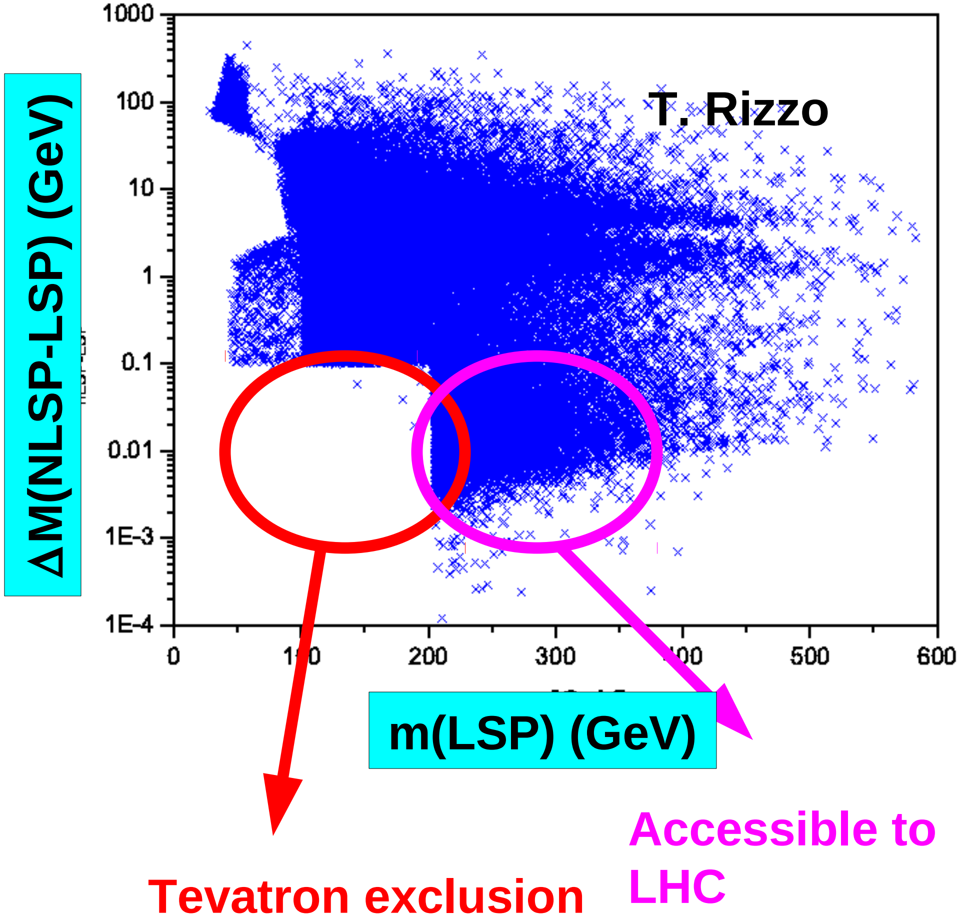
Focus on signatures which appear as 'forgotten' in scans of 19-MSSM

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)

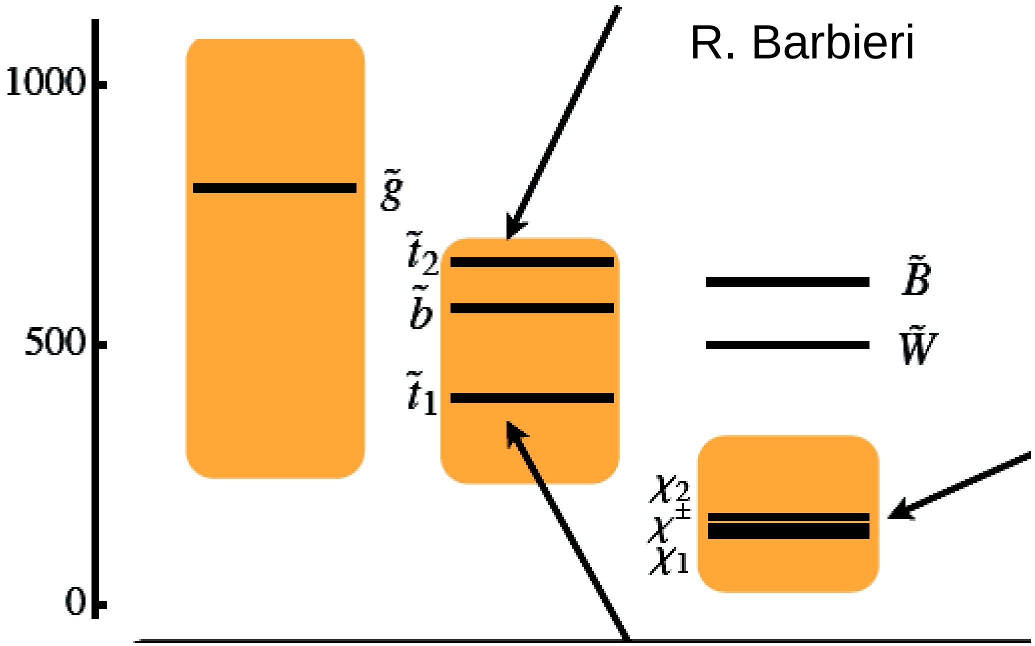
Increase emphasis on such Signatures and extend Interpretation to MSSM



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



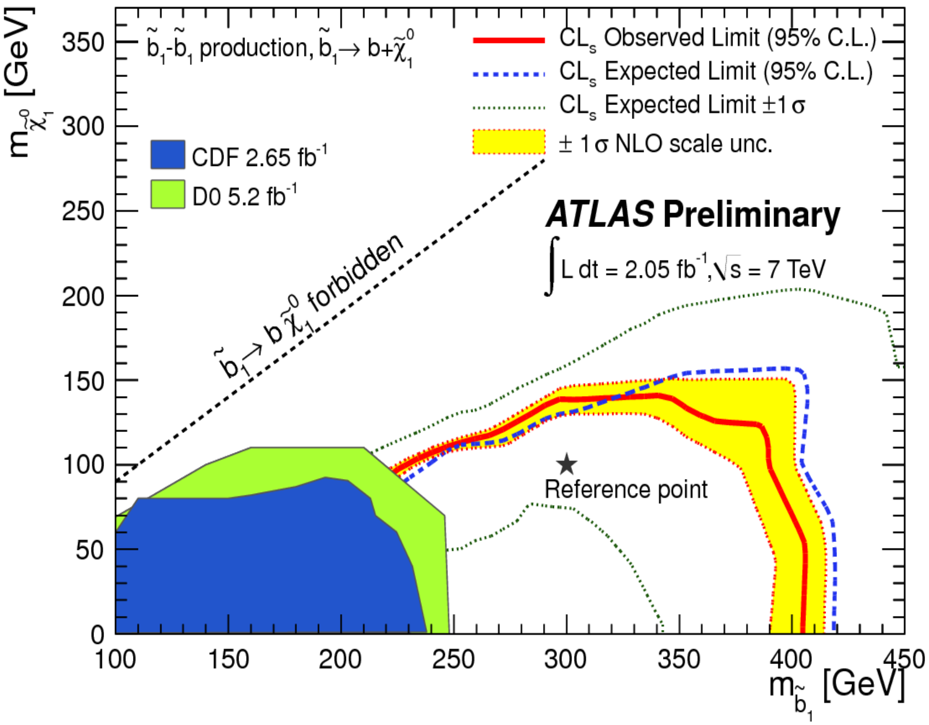
Example: direct sbottom production

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

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

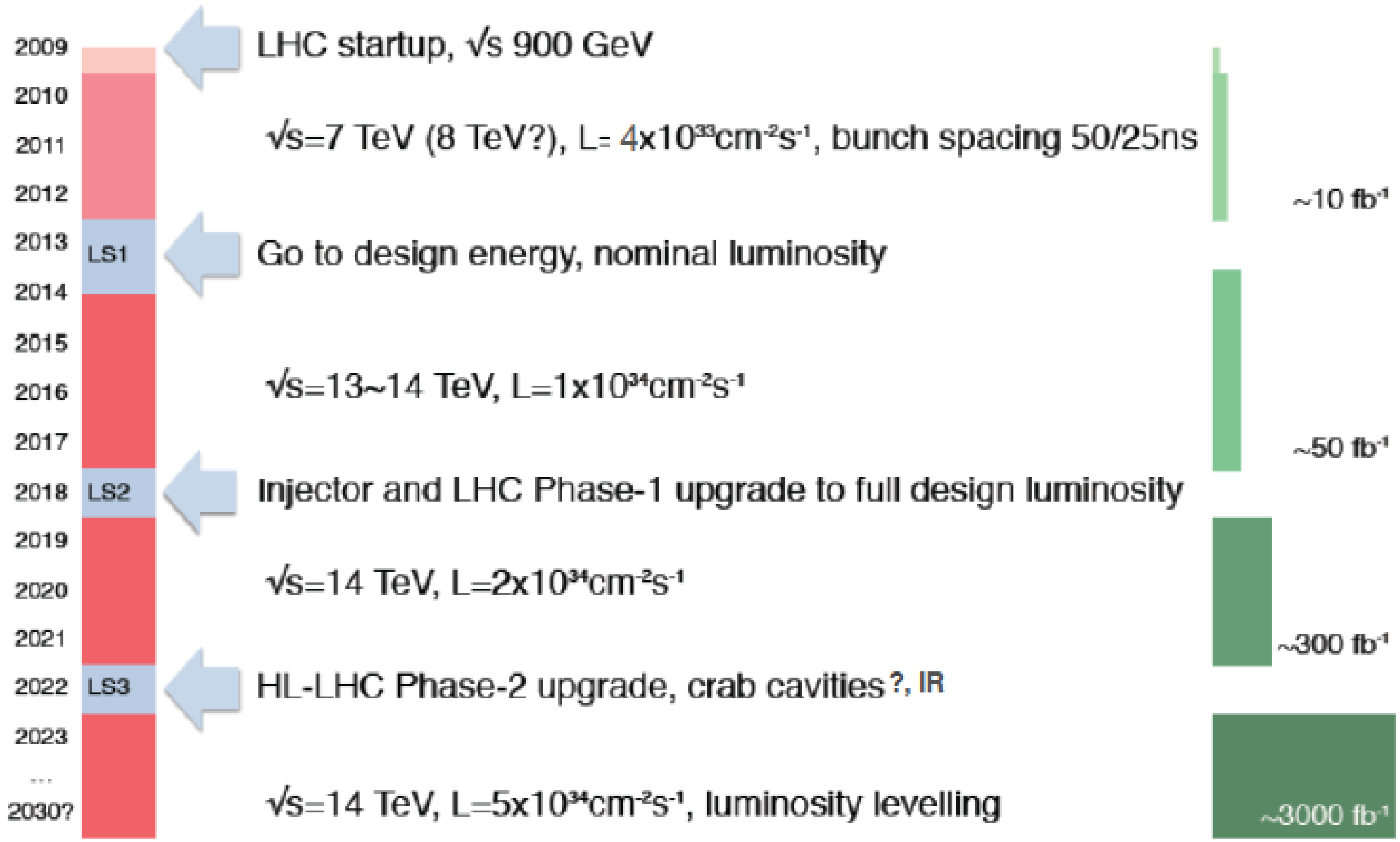
$\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ (BR=1)

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

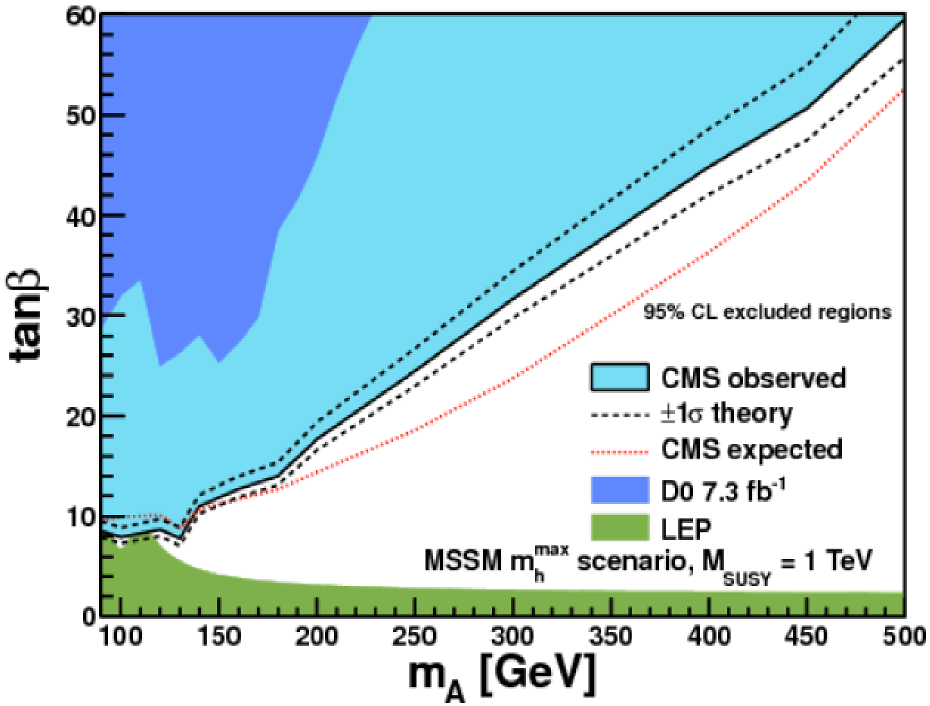
The further future: LHC timeline

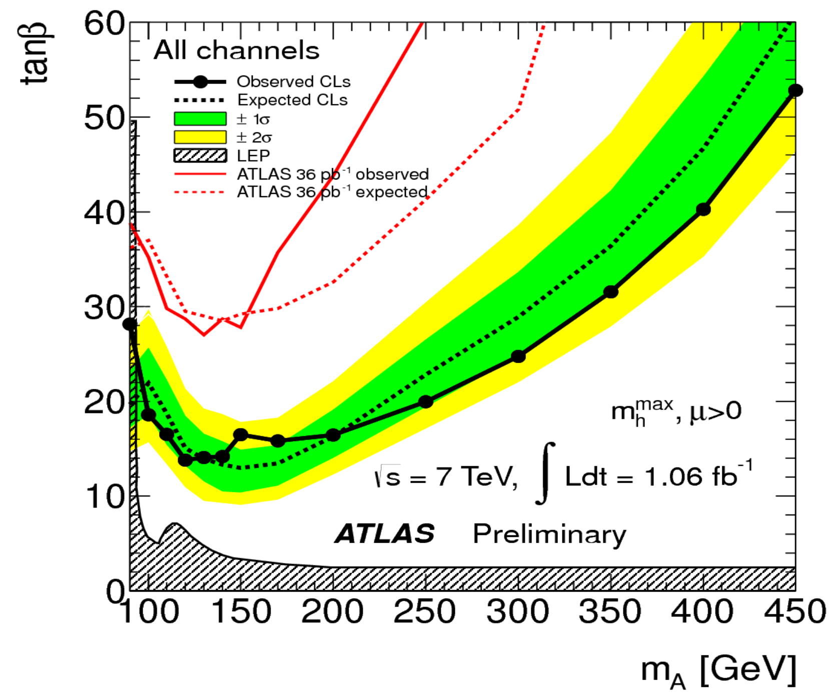


Conclusions

- 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

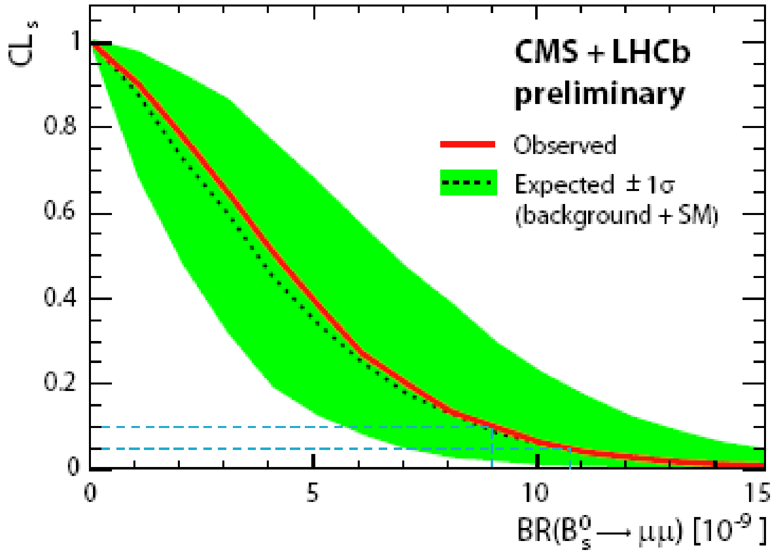
Info from other LHC searches: MSSM Higgs



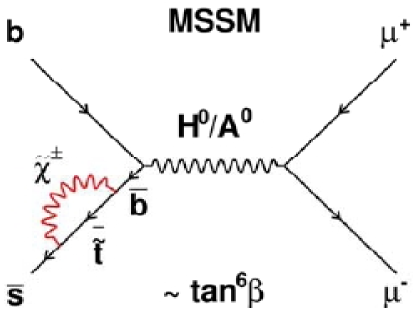


Direct searches sparticle searches have low sensitivity to tanβ and m(A) parameters of MSSM
Higgs searches provide highest sensitivity on these parameters
Already significant coverage from A→ττ
As we become sensitive to light higgs below 135-140 GeV more and more of the plane will be covered

Info from other LHC searches: rare decays



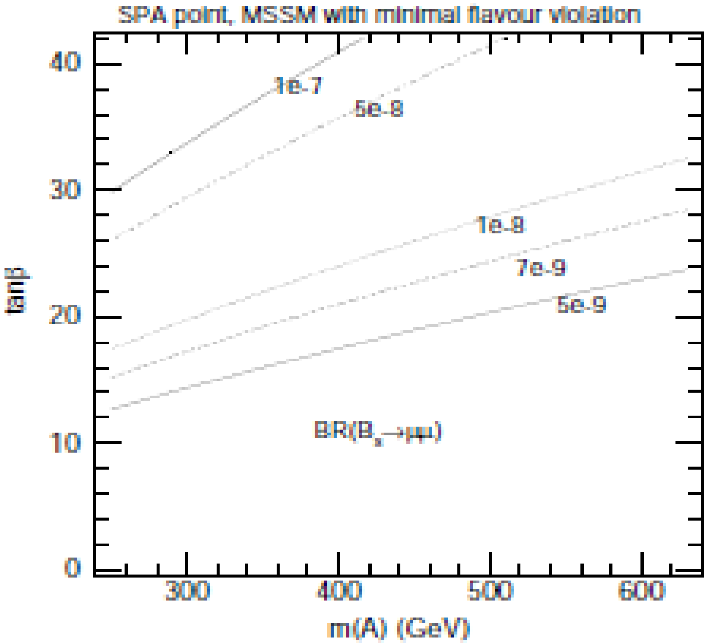
$BR(B_s \to \mu^+\mu^-) < 1.08\ (0.9) \times 10^{-8}$ @ 95% (90%) C.L.



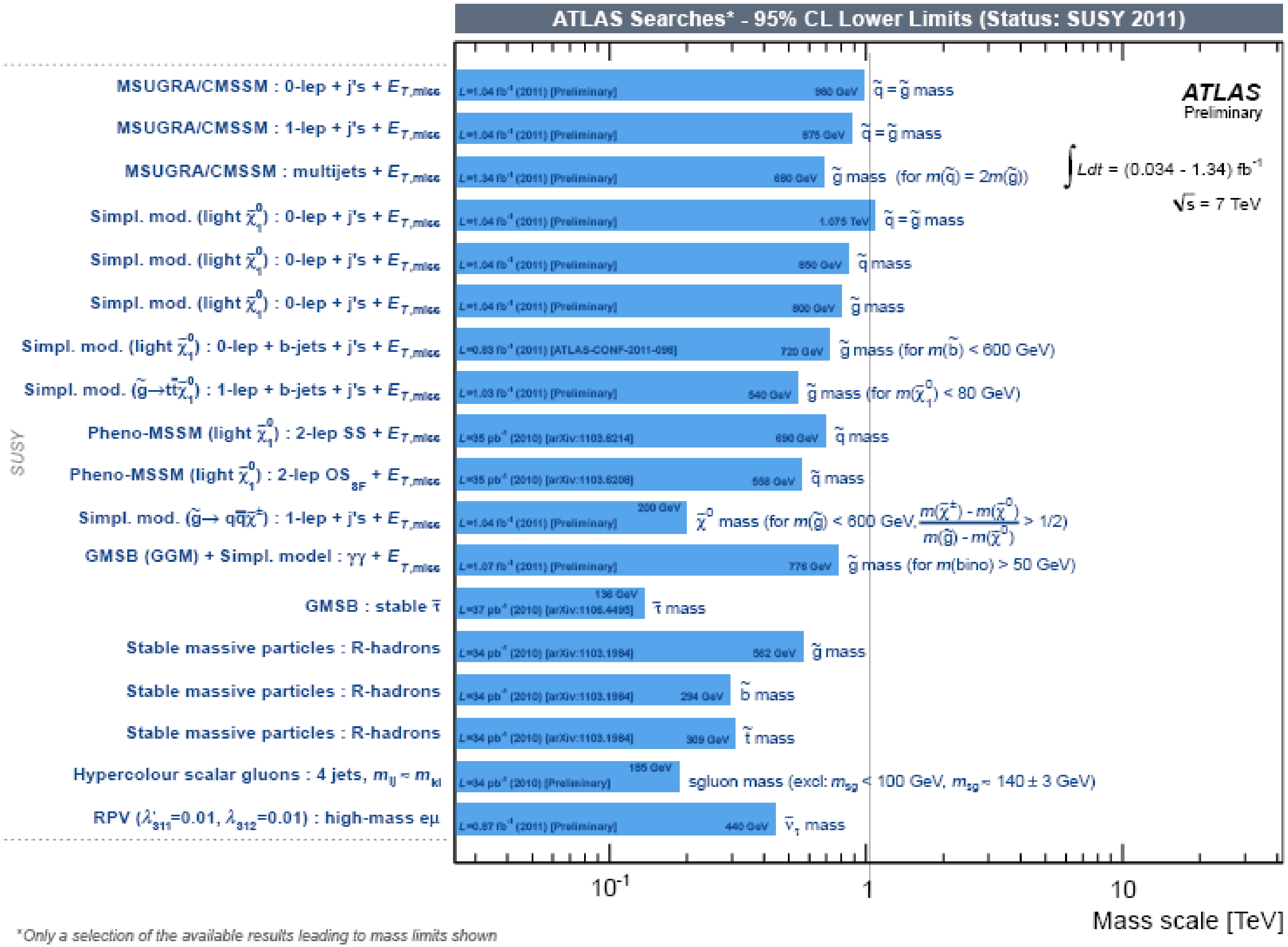
Very strong dependence on m(A) and tanb

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

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



Summary table



Fine tuning equations and SUSY spectrum

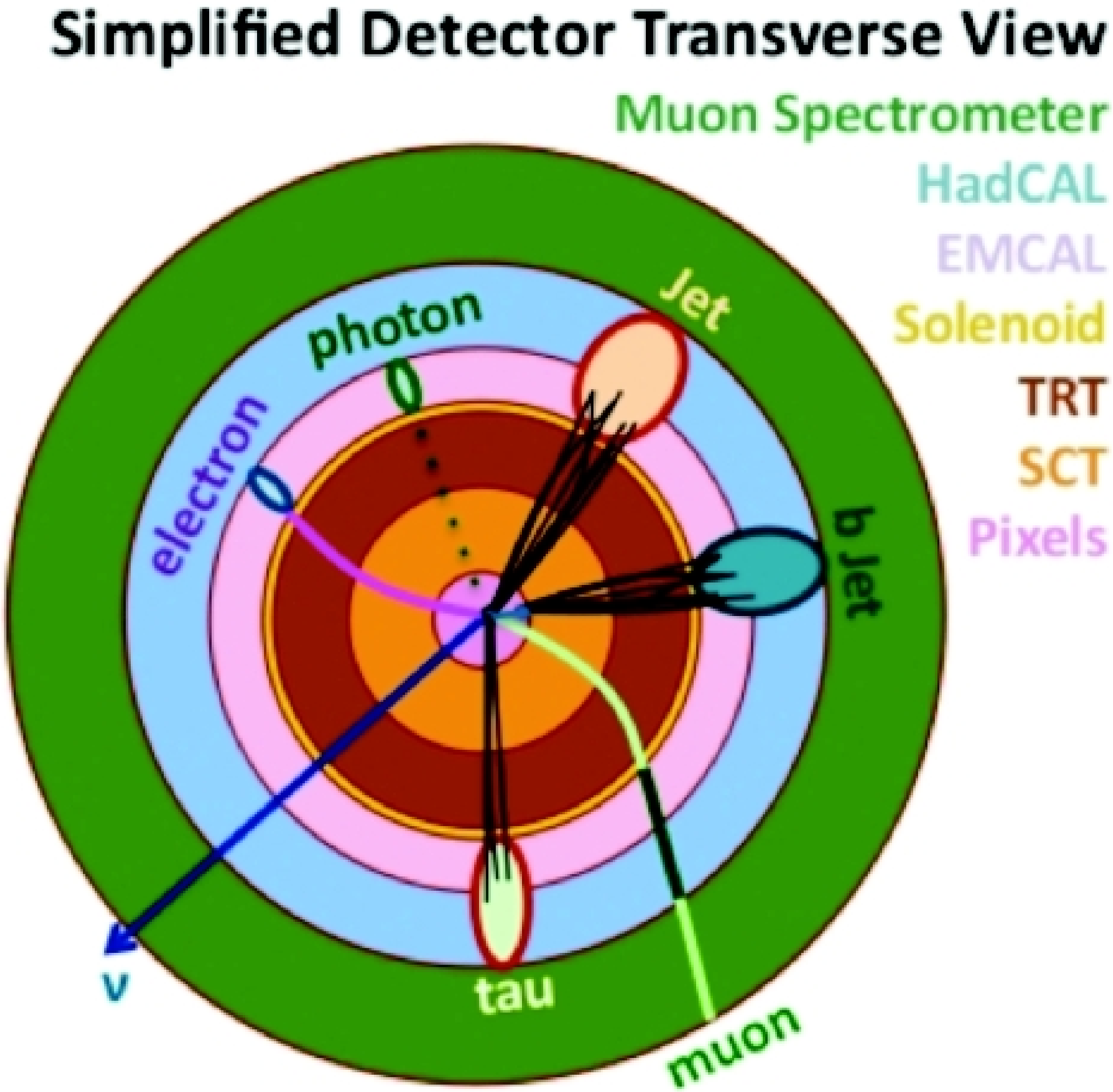
The key equations:

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

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

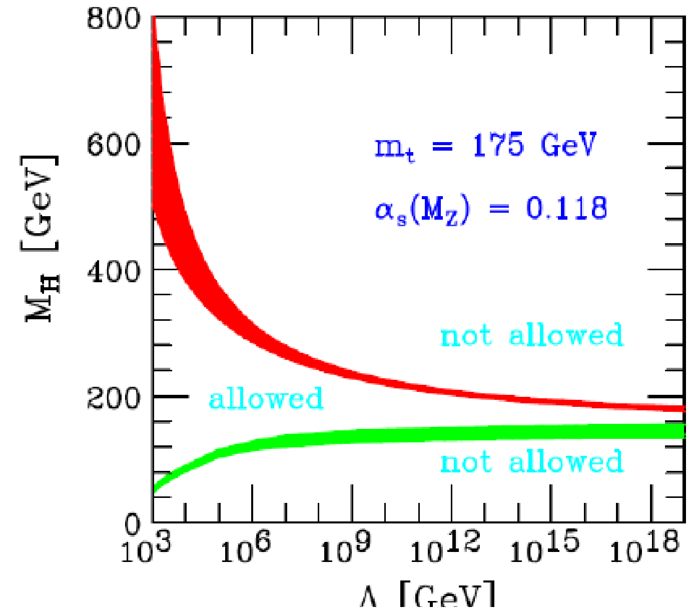
$m_{\tilde{b}_L}$

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


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

Why physics beyond Standard Model?

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

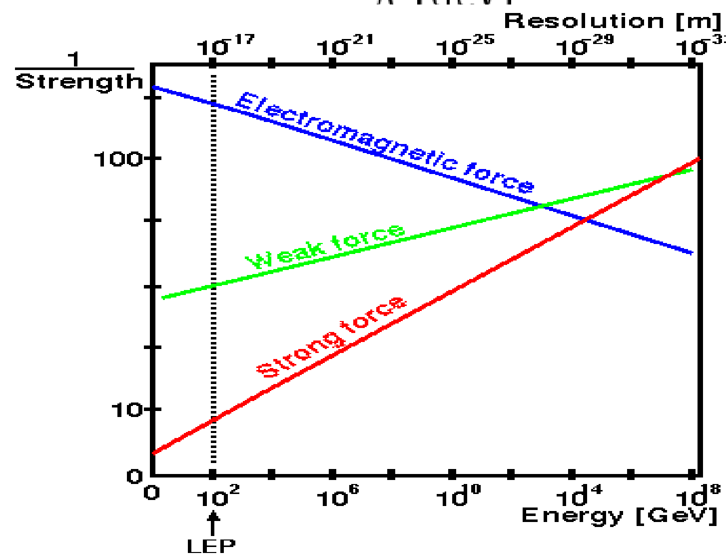


Standard Model valid only up to scale $\Lambda < M_{pl}$

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

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

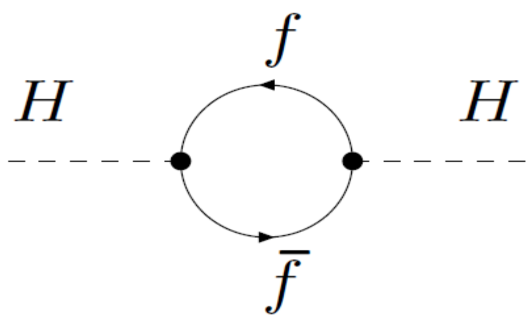
$$\delta m_H^2 \propto \lambda_f^2 \Lambda^2$$



- 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:

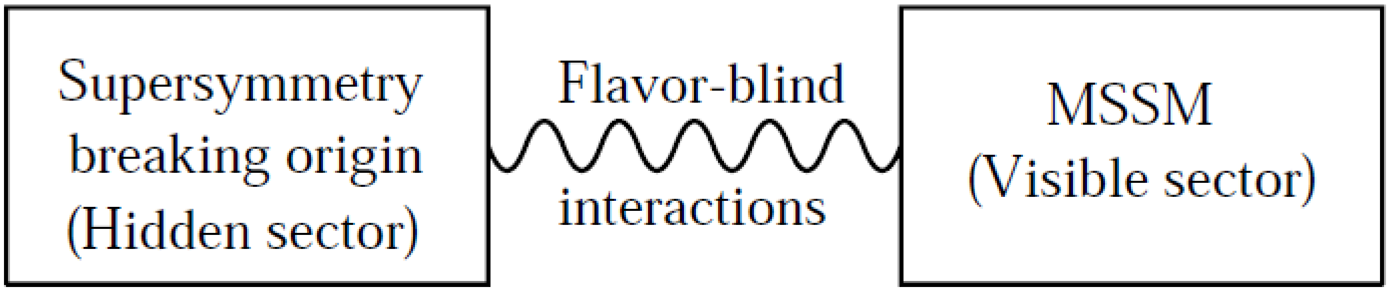
$$Q|\text{boson}\rangle = |\text{fermion}\rangle \qquad Q|\text{fermion}\rangle = |\text{boson}\rangle$$

Supersymmetry

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

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