BSM physics at the LHC

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On behalf of the ATLAS and CMS Collaborations

Introduction and outline

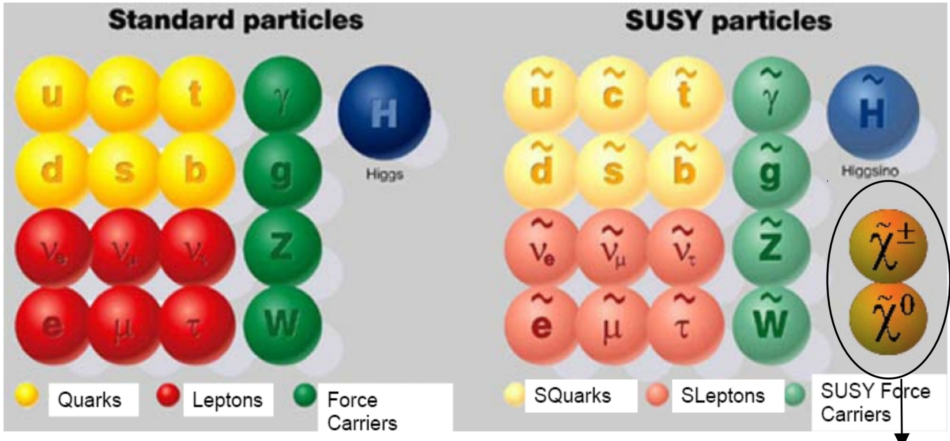
- ATLAS and CMS have performed, based on 2010 and 2011 searches for physics beyond the Standard Model (BSM). At winter conferences many new results, often with full 2011 statistics (~5 fb-1)
- Large number of analyses, impossible to review them in 20 minutes, try to avoid a flat listing of (negative) results
- Approach:
  - Look at these results in perspective, as a part of a global research strategy, assess what we have learned
  - Discuss the implications in terms of BSM modeling
  - Show how, on the basis of the early results, the strategy for 2012 analyses is evolving
- Addressed topics:
  - SuperSymmetry (SUSY): an example of a complex class of theories for which a focused research program is ongoing
  - Other BSM: highlights of search results distributed by classes of signatures

Search strategy with early LHC data

- We are looking for something badly defined, which is “beyond”
- Need to define a strategy which optimises the chances of discovery from the very first analyses
- 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 BSM models
- Evolution of strategy builds on exploitation of understanding gained with first round of searches, and on better and better understanding of detector and Standard Model

SUSY and MSSM

(Minimal SuperSymmetric Standard Model)



gaugino/higgsino mixing

Minimal particle content:

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

SUSY is broken: sparticle masses
Function of SUSY breaking terms

- Insert in Lagrangian all soft breaking terms: 105 parameters.
- Assume flavour matrices aligned with SM ones
  (minimal flavour violation): 19 parameters
- Assume SUSY breaking communicated from ineractions in hidden
  sector: (cMSSM,mSUGRA, GMSB, AMSB): 4-5 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 violation also studied: concentrate on Etmiss signatures

SUSY cross-sections

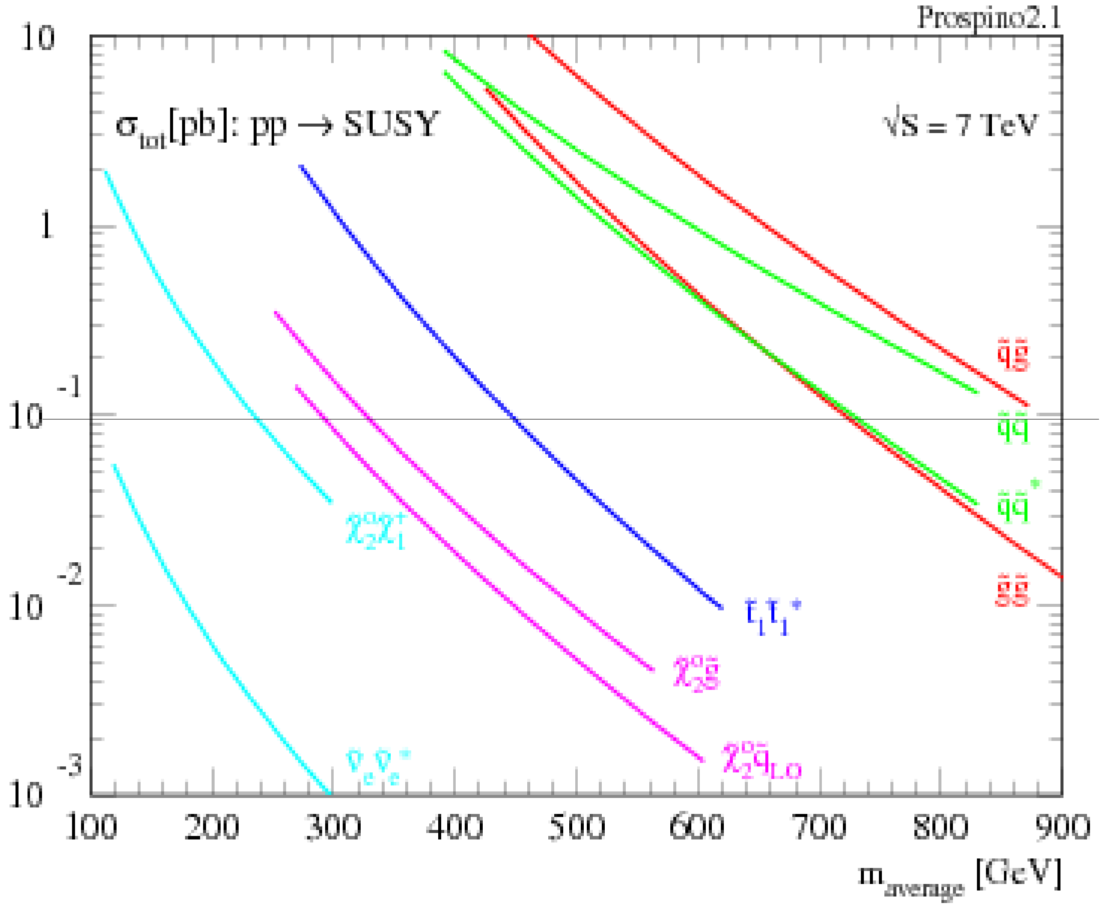
Consider an integrated luminosity of order 1 fb^{-1}

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

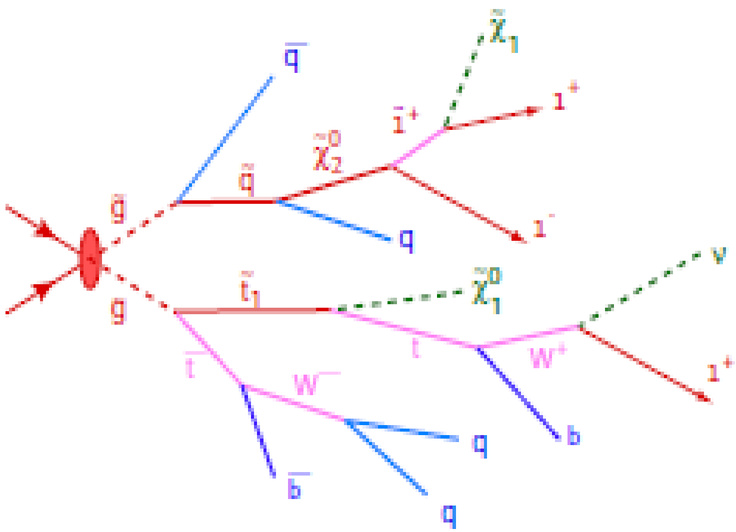
Sleptons to < 200 GeV: need to handle top and WW



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

SUSY decays and analysis definition

Starting from strongly produced squark and gluino, consider final state signatures for generic decay chains in the 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 light gravitino

Describe here most general one, common to all R-parity conserving models: **Etmiss+jets**

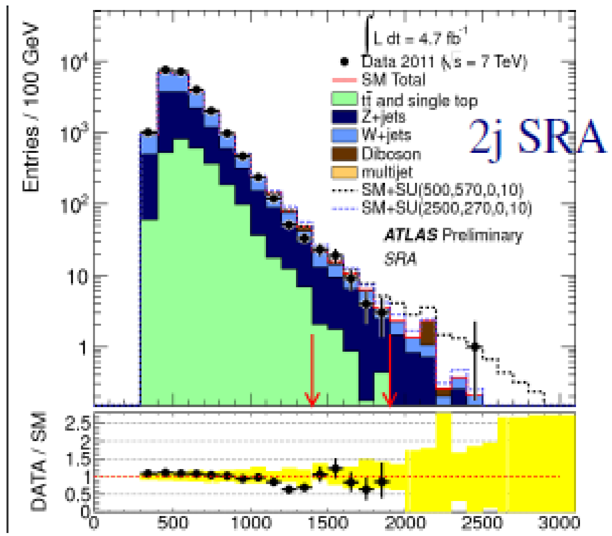
Preselection: Cuts on jet p_T and E_T^{miss} determined by trigger selections: extremely severe constraint at high luminosity

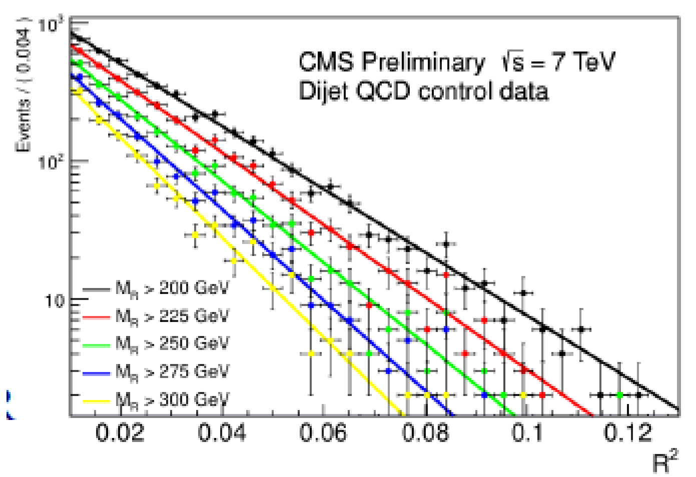
Topology selection: Decide on number of jets and topology based on decay topologies occurring in generic models

Final selection: Cut on discriminant variable (some combination of jet momenta and ETmiss) to optimize sensitivity to reference models with appropriate mass scale

ATLAS and CMS Etmiss+jets analyses with 5 fb-1

- ATLAS analyses: 4.7 fb-1: $H_T = \Sigma p_T$ $m_{Eff} = E_T^{Miss} + H_T$
  - 2 to 6 jets
    - Loose-Medium-tight cuts on Meff
  - 6 to 9 jets
    - Cut on Etmiss/HT
- CMS analysis 4.4 fb-1
  - Physics objects merged into 2 mega-jets
  - Discriminant variable is "Razor"
    - Exponentially falling for QCD
    - Appears as a 'bump' for signal
- Backgrounds estimated from the extrapolation of the events measured in different control regions (CR) to the Signal Regions (SR)
- **No excess found in any of the channels: interpret as limits in SUSY space**





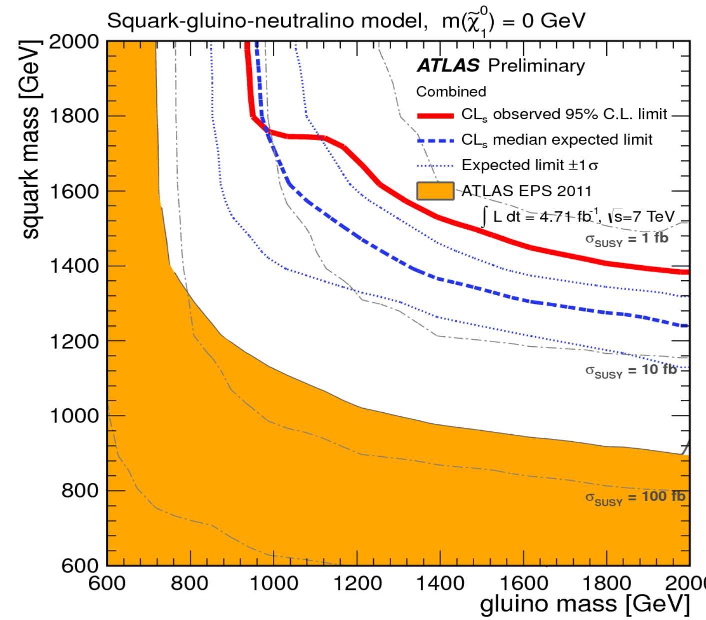
Jets+ Etmiss: MSSM interpretation

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:

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

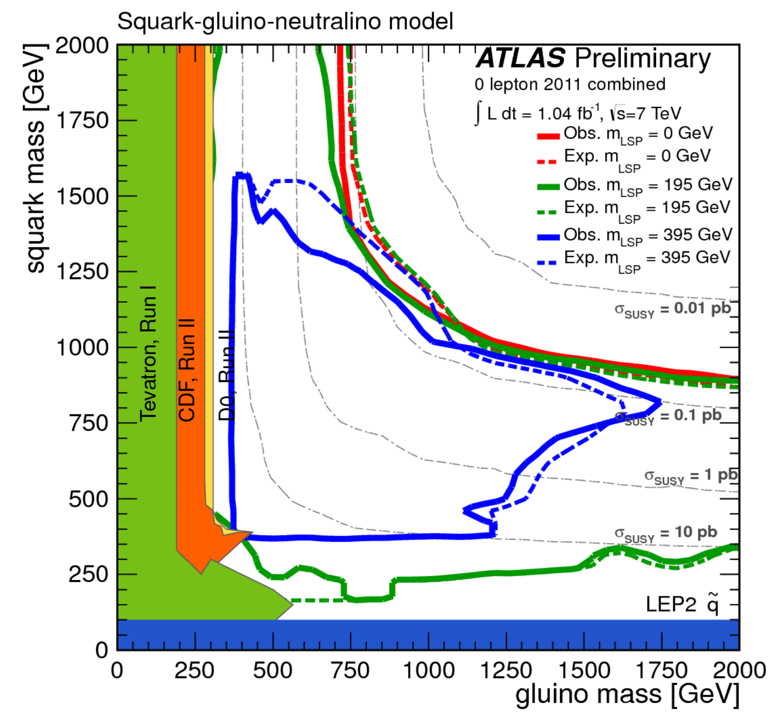


Final states with 2 to 4 jets depending on relative values of squark and gluino masses

Equal squark-gluino masses excluded below ~1.5 TeV

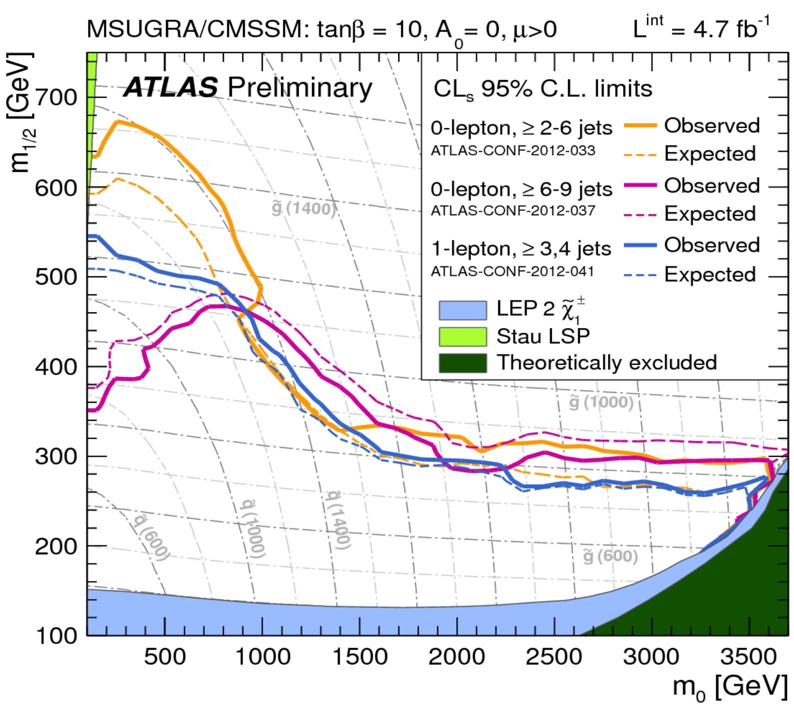
Generic exclusion valid for m(LSP)<200 GeV

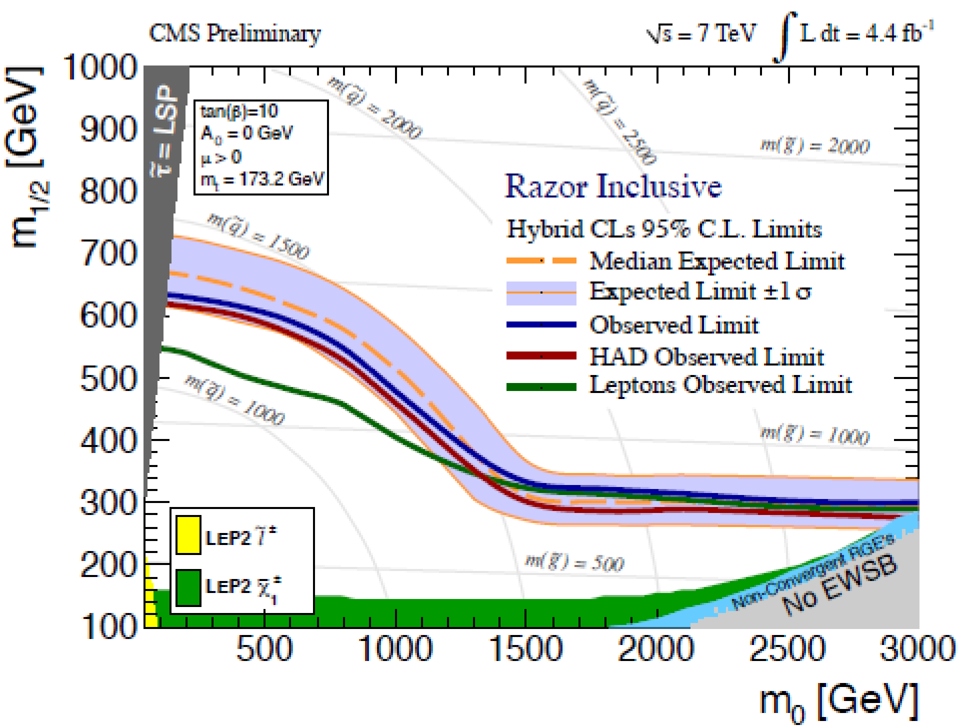
For heavier LSP cannot put absolute Limits on squark or gluino masses



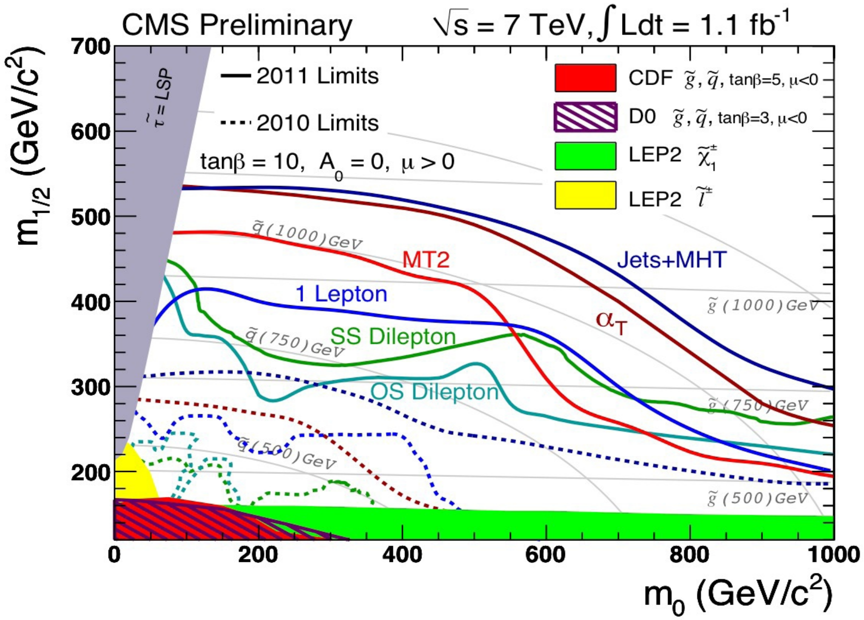
All hadronic results in cMSSM/mSUGRA

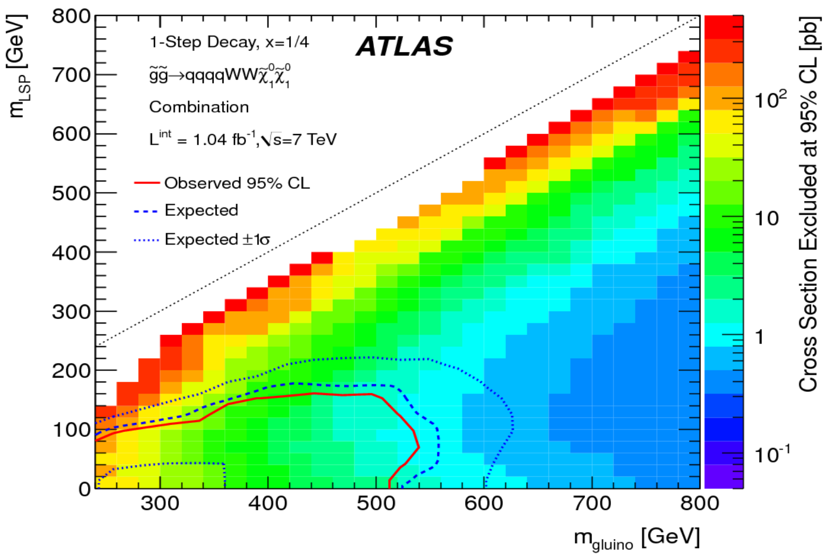
- Even with more complex decays than simplified MSSM limits around 1.4 TeV for m(squark)=m(gluino)
- Weaker limits high m_0: only gluino production, and dominant decay: g $\rightarrow$qq χ, softer kinematics as χ in this case can be also higher mass chargino/neutralino
- Some gain at high m0 when going to high jet multiplicity





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

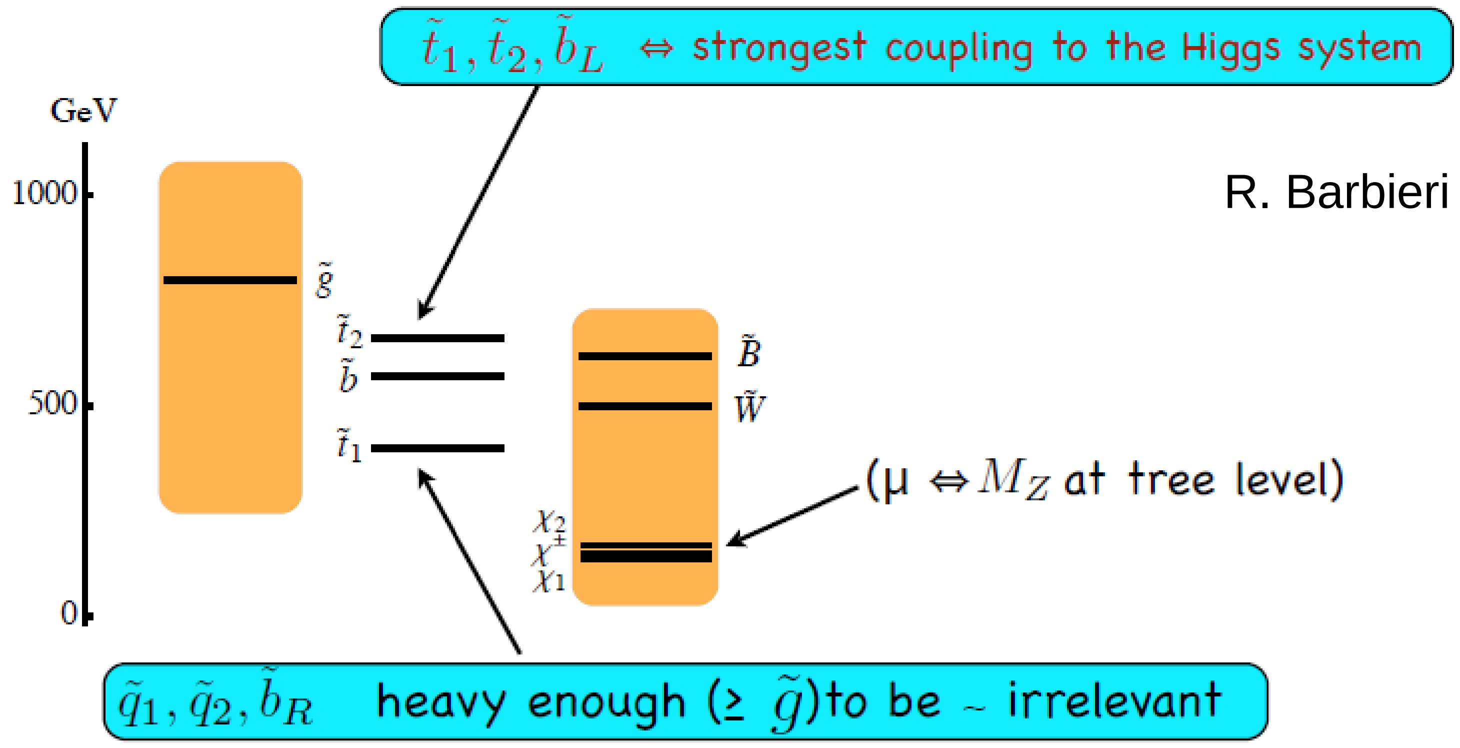
Rates dependent on all model parameters: difficult to quote results in terms of limits on sparticle production

Three approaches to interpret results:

- Constrained models: e.g. mSUGRA,
- Simplified models: isolate specific chains with given kinematics and compute excluded rate
- Interpret results in terms of special topologies. e.g. gluino decay to 3rd generation

Additional gluino decays: theory guidance

SUSY spectrum required by naturalness



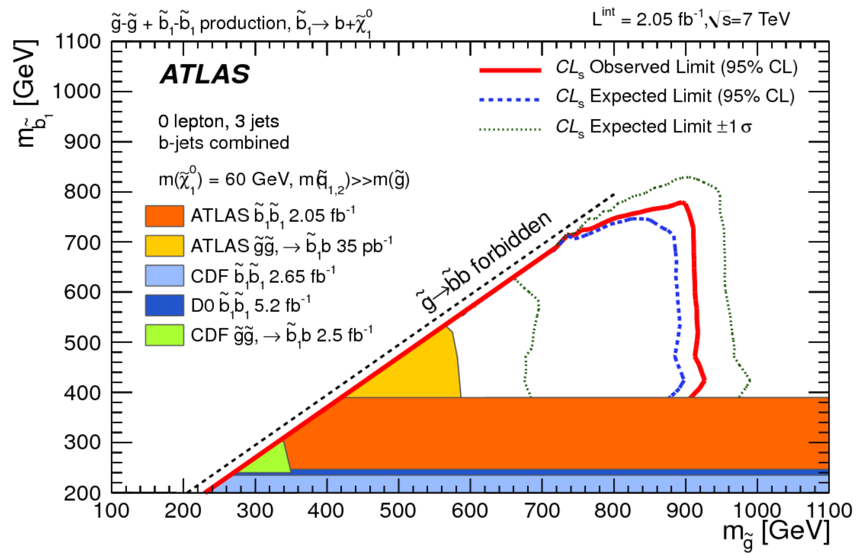
Decays of gluinos involving 3rd generation squarks not addressed by generic searches: dedicated searches in final states with b-jets

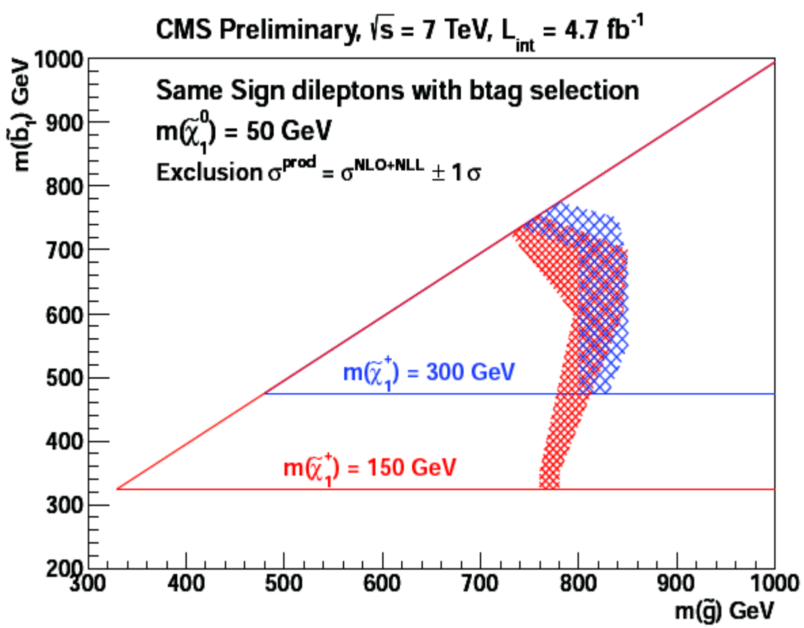
Sbottoms in gluino decays

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

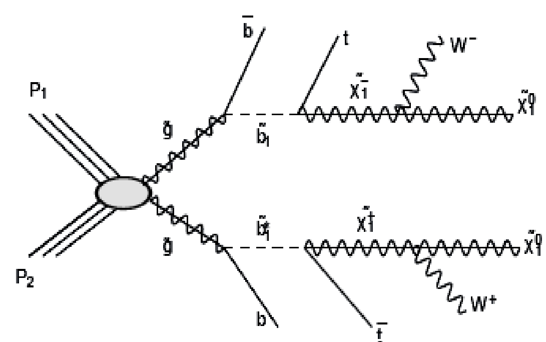
- $\tilde{g}\tilde{g} + \tilde{b}_1\tilde{b}_1$ production
- $\tilde{g} \to \tilde{b}_1 b$ (BR=1), $\tilde{b}_1 \to b\tilde{\chi}_1^0$ (BR=1)
- $m(\tilde{\chi}^0) = 60$ GeV, $m(\tilde{\chi}_1^{\pm}) \approx 2\tilde{\chi}_1^0$

Exclude: $m(\tilde{g}) < 920$ GeV for $m(\tilde{b}_1) < 800$ GeV





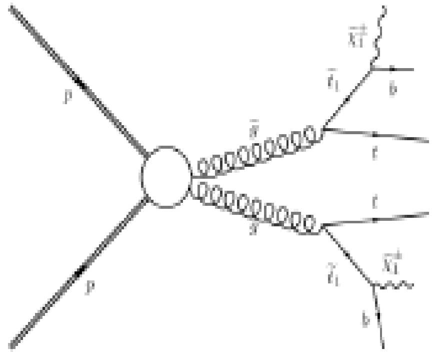
CMS: 2 Same-sign leptons and 2 b-jets



$\tilde{b}_1 \to t\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{\pm} \to W\tilde{\chi}^0$

Stops in gluino decays

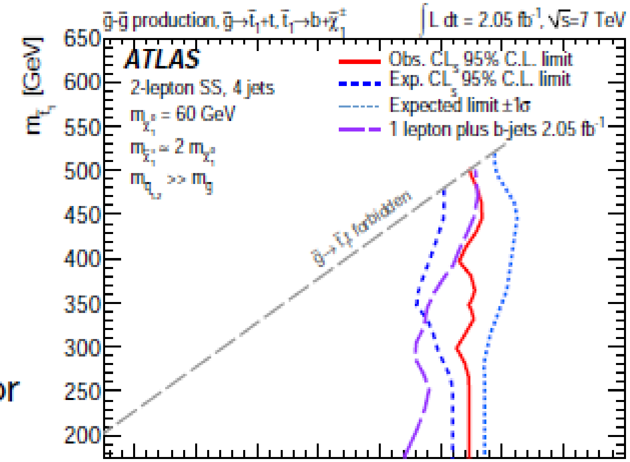
$m(\tilde{\chi}^0) = 60$ GeV, $m(\tilde{\chi}_1^{\pm}) \approx 2m(\tilde{\chi}^0)$

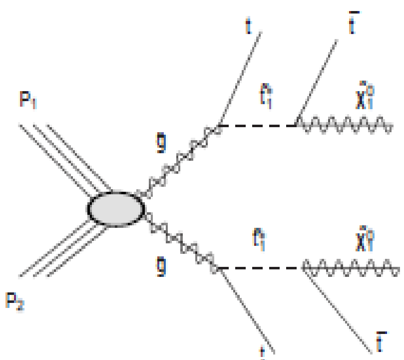


ATLAS 2.05 fb-1:
2 analyses:

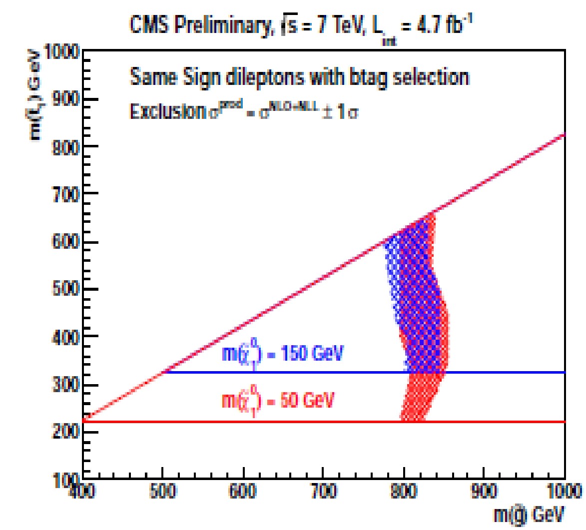
* 1 lepton + 4 jets (1 b)
* 2 Same-Sign leptons +4 Jets

Exclude: $m(\tilde{g}) < 650$ GeV for $m(\tilde{t}_1) < 450$ GeV





CMS 4.7 fb-1
2 Same-sign leptons+
2 b-jets
Exclude m(gluino)<~800 GeV
Depending on chi01 mass



Conclusions on SUSY with 1-5 fb^{-1} from Etmiss searches

- We exclude generic models where 1^{st} and 2^{nd} generation quarks and gluinos are
  - Below ~1.5 TeV if they have similar masses
  - Below 1000-1400 GeV if one of the two dominant

    Under the conditions

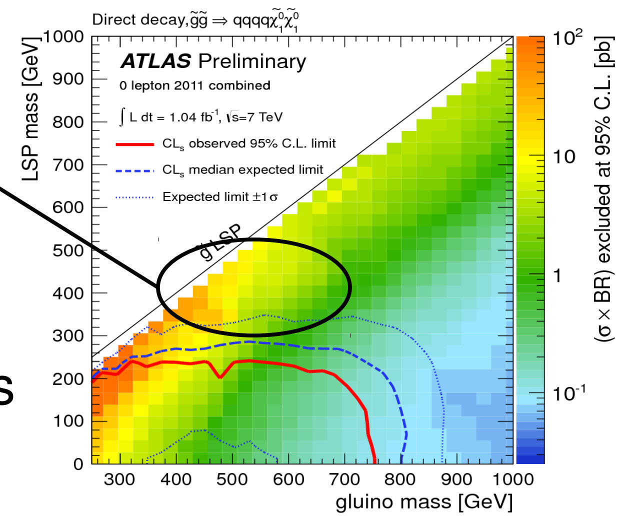
  1) Squark decays q->q chi01, and gluino decays g->qq chi01
  2) m(chi01)< 200 GeV

  Weaker limits for heavier chi01!

- Conclusions valid when specialising to CMMSM/mSUGRA
  - For high m0 region where decays in heavy flavours important, and also heavier gauginos involved limits somewhat less stringent (mg<~900 GeV)
- Generic limit extended to cases with different gluino decays
  - For gluino decaying 100% bb chi01, direct or sbottom-mediated, limit is between 800 and 900 GeV from dedicated searches requiring tagged b-jets
  - For gluino decaying 100% stop-top limit is around 650 GeV for stop decaying to chargino b and ~800 GeV for stop decaying to top neutralino

Perspectives

- Effectively volume MSSM covered to date not very large. How to enhance coverage of our searches?
- Lift limitations on generic squark-gluino searches
  - Ad-hoc strategies for when chi01 gets near squark and gluino
  - Study decays happening through long chains: high multiplicity searches
  - 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
- Study direct production of lighter particles with lower production cross-section than squarks-gluinos:
  - Third generation squarks
  - Electroweak gauginos

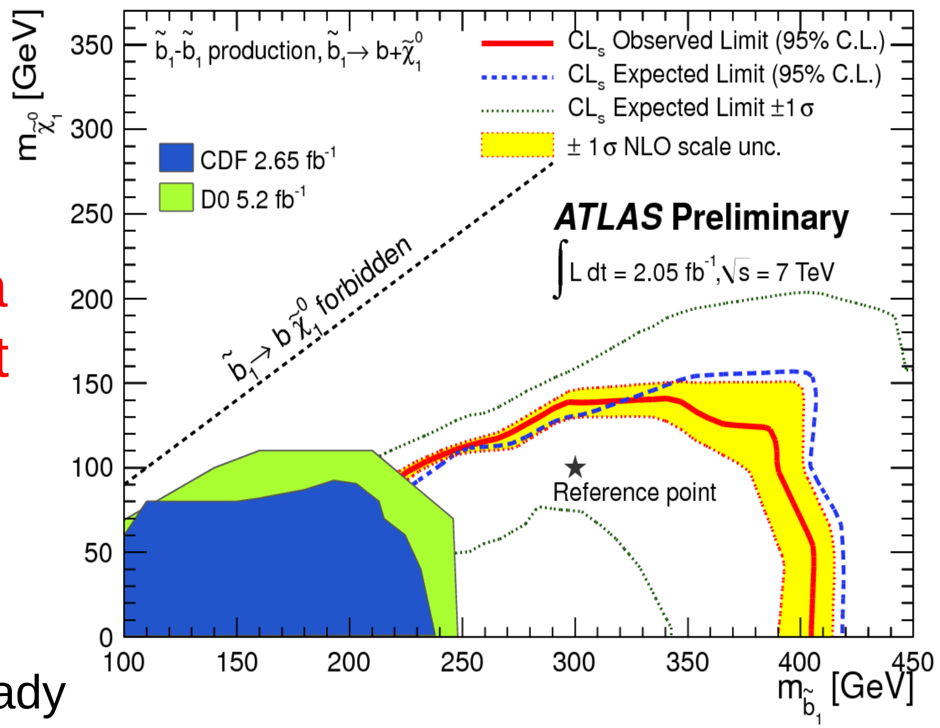
Example: direct sbottom production

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 tha ~350-390 GeV if chi01 light than ~120 GeV



CMS puts a limit on direct production
Of sbottom decaying to top chargino
through the SS 2-lepton analysis already
Described (m(sbottom)>370 GeV)

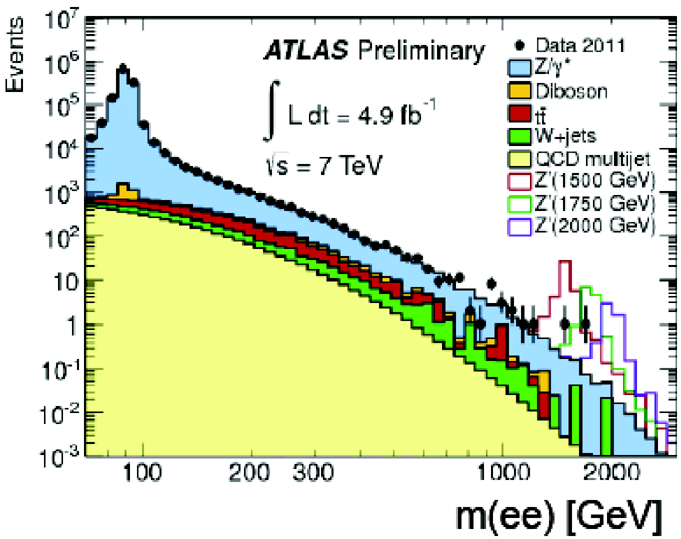
Pioneering direct production analysis.
Illustrate characteristic issue: need enough mass gap with chi01 to ensure triggerable and detectable hadronic system

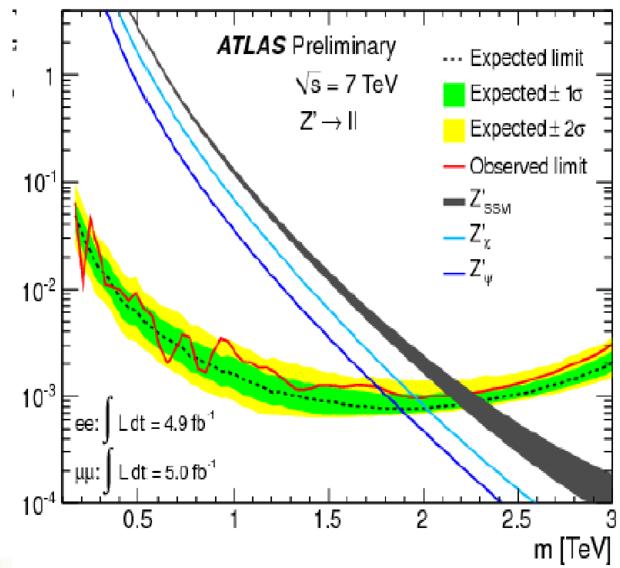
Non SUSY BSM

- Generic search for new particles, classified by signatures. Non exhaustive list:
  - New bosons:
    - Real: particle-particle resonances (Z', W', Gravitons in warped Extra Dimensions)
    - Real: escaping gravitons from Large Extra Dimensions: monojet signatures
    - Virtual: modification of lepton-lepton/jet-jet distributions from exchange of new particle or new contact terms
  - New fermions:
    - 4^{th} generation searches: final states with b's, T's and W's
  - Exotic particles:
    - Long lived particles: Hidden valley, degeneracies in SUSY
    - Mini Black holes in theories with low scale gravity: Large multiplicity events
- Searches for all these performed by experiments, with null results, starting from Z' searches in leptons, 'easiest' signature at LHC
- BSM searches often testing ground for novel reconstruction techniques, see e.g reconstruction of boosted hadronic decays with massive jets

Lepton resonances: Z', W'

SSM (Sequential Standard Model): new bosons have same couplings as SM W and Z





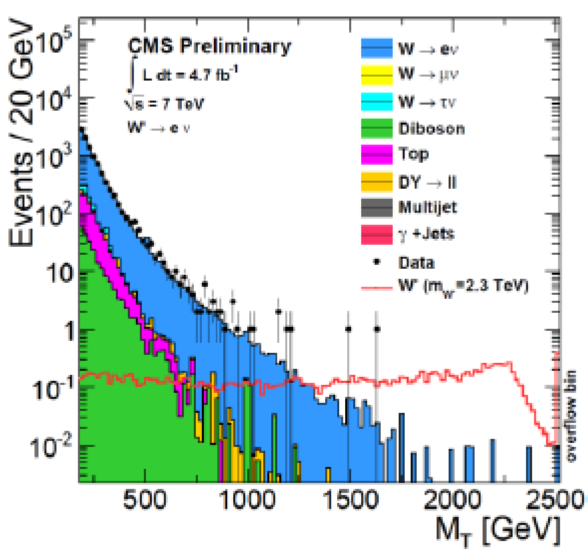
ATLAS (CMS) 95% limits 4.7-4.9 fb-1.

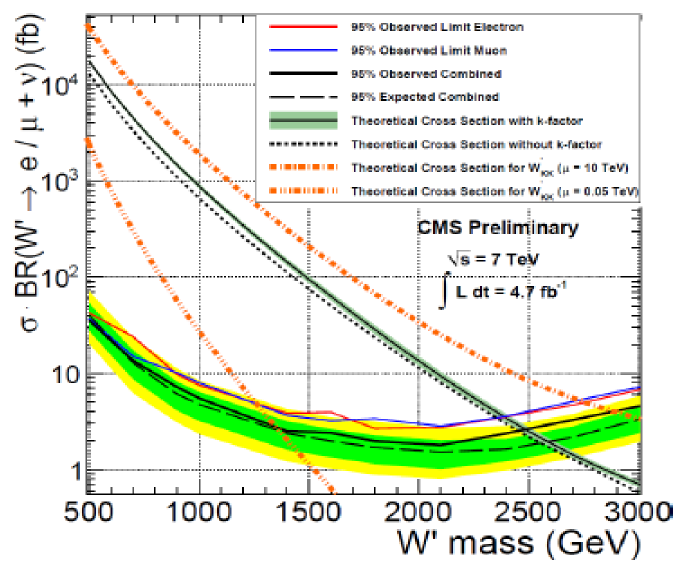
SSM:

m(Z')> 2.21 (2.32) TeV

Randall Sundrum graviton (k/Mpl=0.1):

m(Z')> 2.16 (2.14) TeV





CMS 95% limit 4.7 fb-1

SSM :

MW'>2.5 TeV

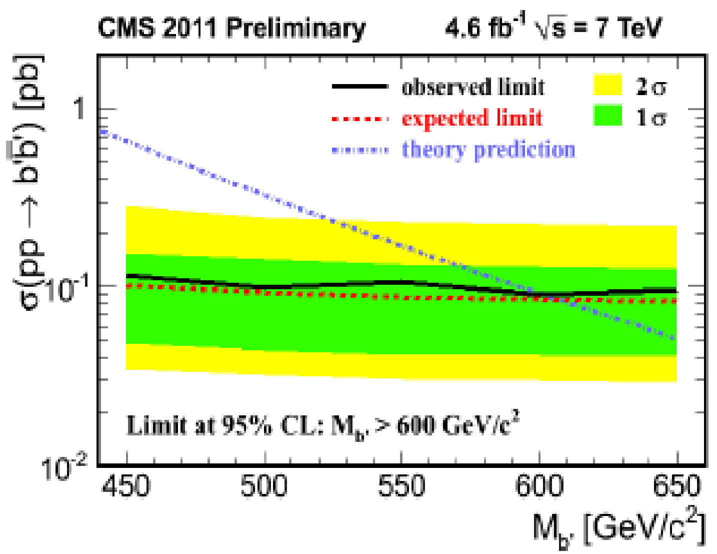
(ATLAS 2.15 TeV

With 1.1 fb-1)

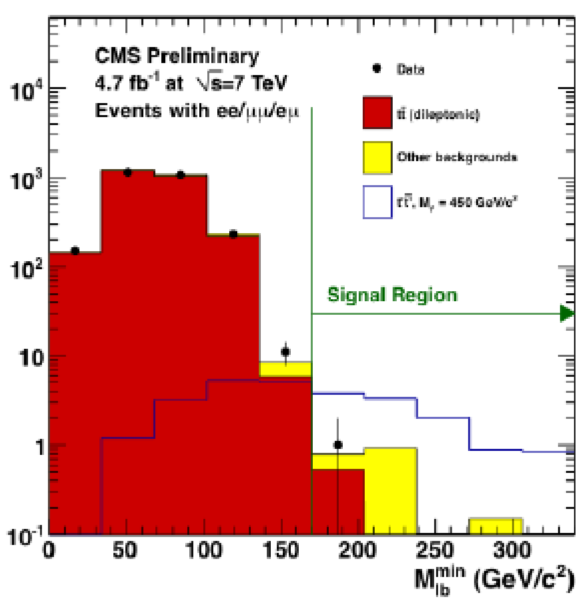
Fourth generation quarks

Several searches by ATLAS and CMS both for single and pair production of up (T) and down (B) 4th generation quarks
Several decays considered: T →Wb, B→ Wt and T→ Zt, T →A_0t, B→Zb

CMS 4.7 fb-1 search for
BB→(Wt)(Wt)
3 leptons or 2 same-sign leptons plus a b-jet
95% Limit: M_B>600 GeV



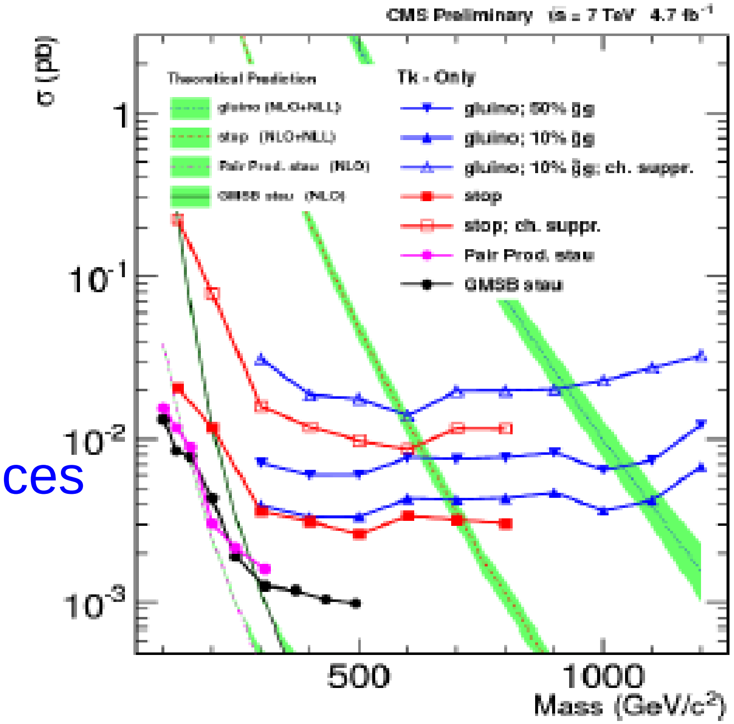
CMS 4.7 fb-1 search for
TT→(Wb)(Wb)→llX
2 leptons, 2 jets high Etmiss
95% limit: M_T>552 GeV



Heavy long-lived particles

Long lived either because of conserved quantum number, weak coupling or mass degeneracy appearing in theory

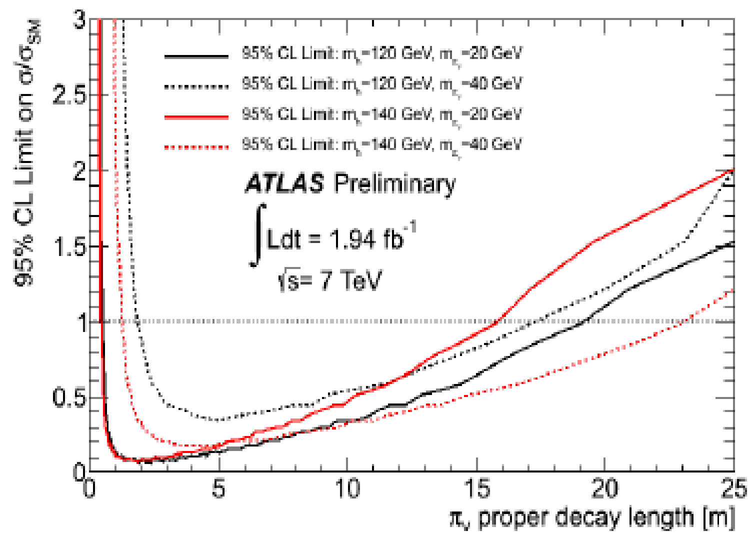
Different experimental signatures possible:
High ionisation, time of flight, displaced vertices

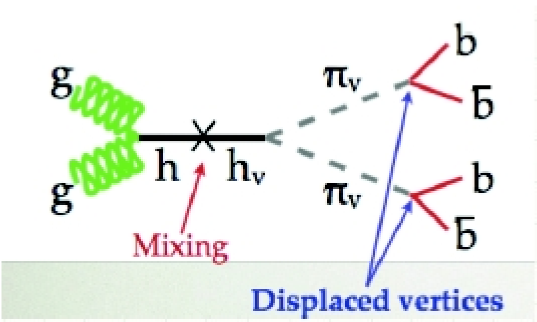


Hidden valley ATLAS search:

Look for long lived particles from hidden sector decaying in muon spectrometer

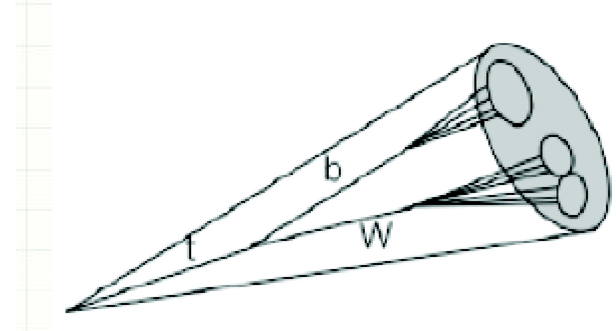
Signature: 2 back-to-back isolated vertices in muon spectrometer: exploit precision Reconstruction in ATLAS air toroids, and flexible trigger system



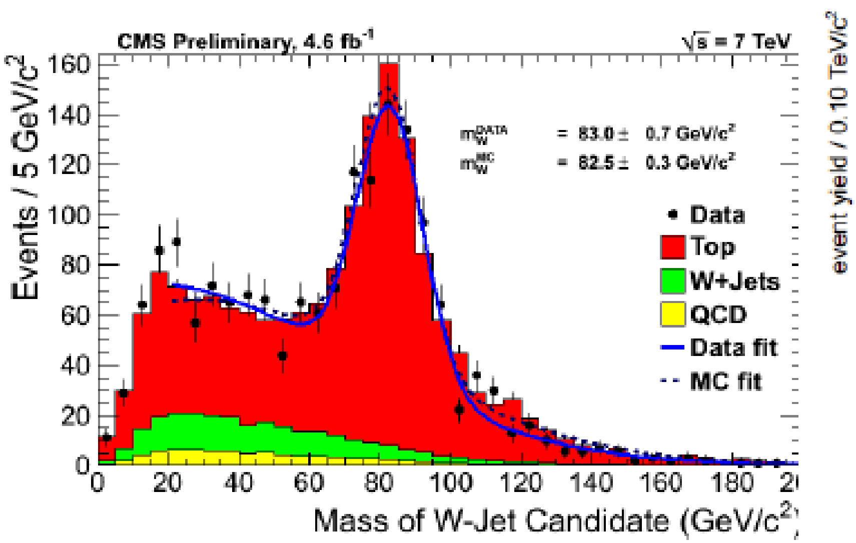


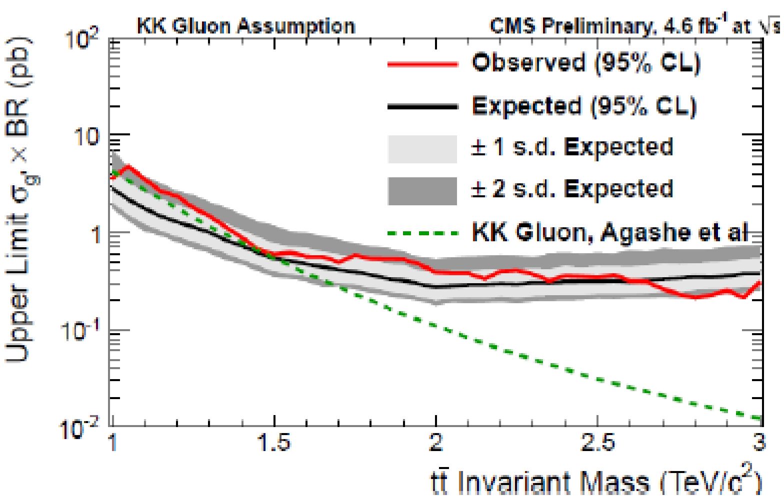
Hadronic tt resonances

For m(ttbar>1 TeV) specific boosted top reconstruction needed
Novel techniques based on deconstructing KT-style jet algorithm



CMS: Calibrate method looking for merged W in low mass semileptonic top events



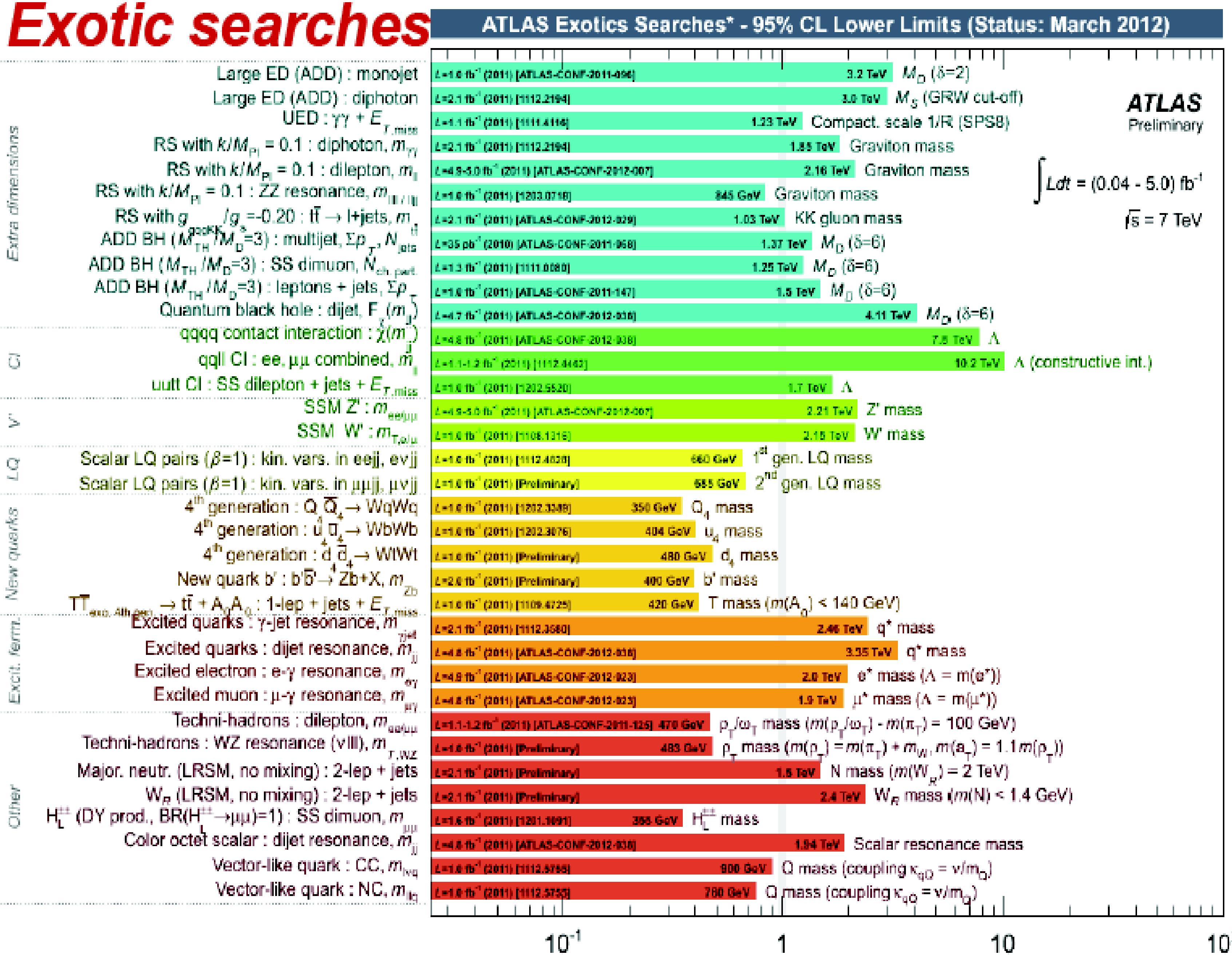


Sensitivity ~1.5 TeV in KK gluons

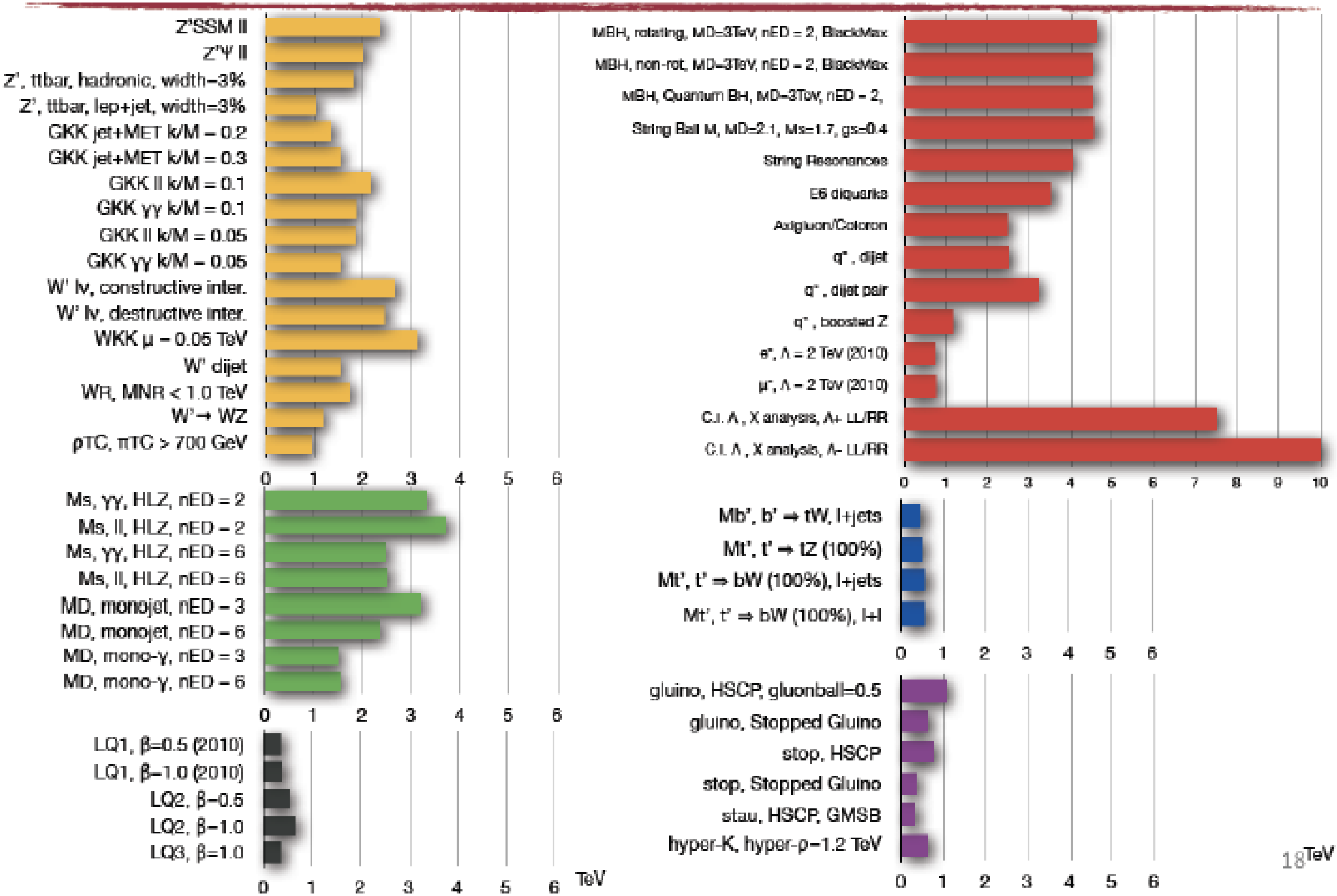
Conclusions

- With 7 TeV 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
- Squark and gluino searches based on simplifying assumptions and on very constrained models yield limits in the 1-1.5 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
- Similarly, searches for typical final state signatures from alternate BSM scenarios have yielded no signal, strongly bounding the paramters of several popular extensions of SM
- Second generation searches are ongoing both for SUSY and other BSM channels addressing more complex signatures to fully exploit the discovery potential of a 7-8 TeV machine

Exotic searches

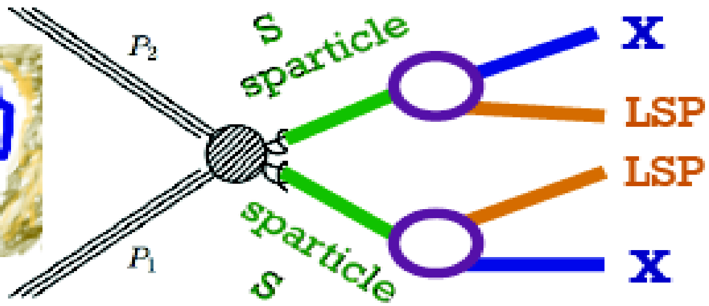


The Grand Summary

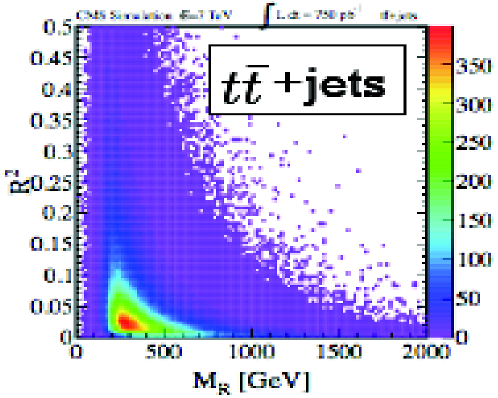


Inclusive final state search - Razor

CMS-SUS-12-005



General final state topology characteristic of R-parity SUSY



Selection:

Group all final state objects (jets, leptons) into two mega-jets

Calculate Razor variables R/M_R designed for this topology

In simple case:
S = squark
X = jet

$$M_R = \sqrt{(|\vec{p}_{j_1}| + |\vec{p}_{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

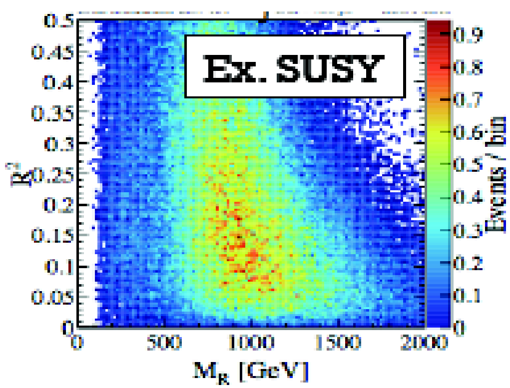
Peaks at

$$M_\Delta = \frac{M_S^2 - M_{LSP}^2}{M_S}$$

Edge at M_Δ

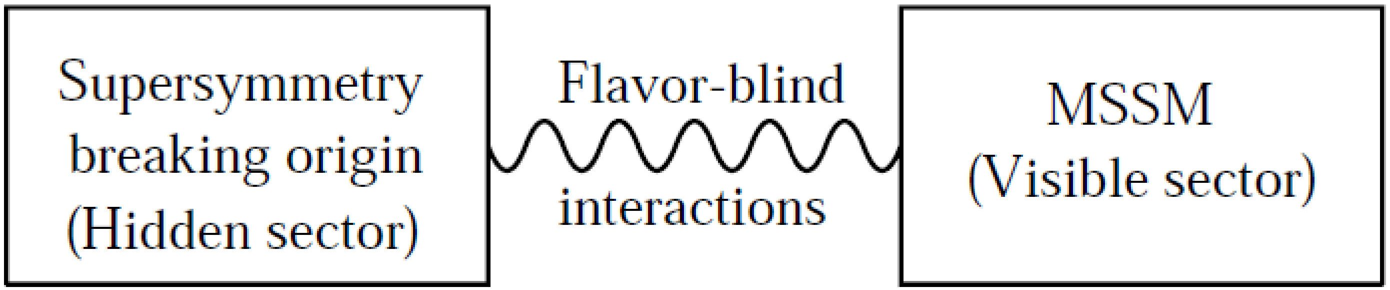
$$R = \frac{M_T^R}{M_R}$$

Ratio of two estimators of SUSY scale – describes transverse shape of event



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: $\Lambda = F_m/M_m,\ M_m,\ N_5$ $\tan\beta,\ sgn(\mu),\ C_{grav}$

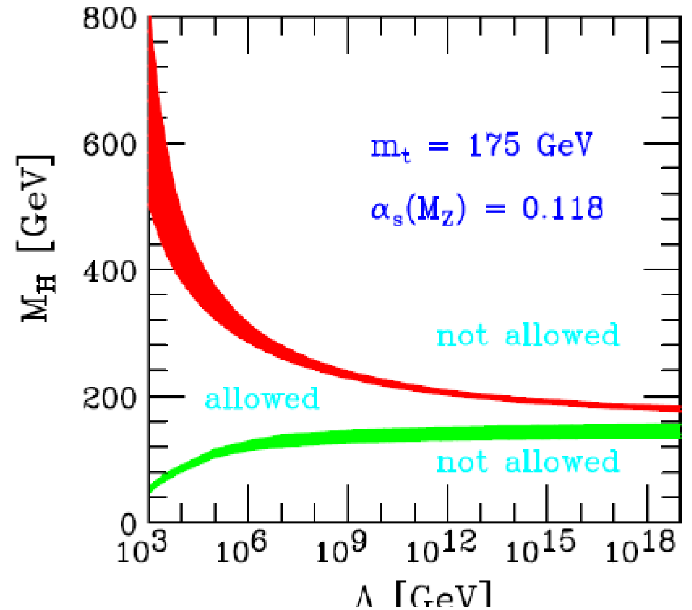
LSP is light gravitino $\tilde{G}$. Signatures: γ+E_T^{miss} from $\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$ if $\tilde{\chi}^0_1$ NLSP
leptons+E_T^{miss} or long-lived leptons if slepton NLSP

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

Can have sparticle degeneracy with metastable decays

Why physics beyond Standard Model?

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

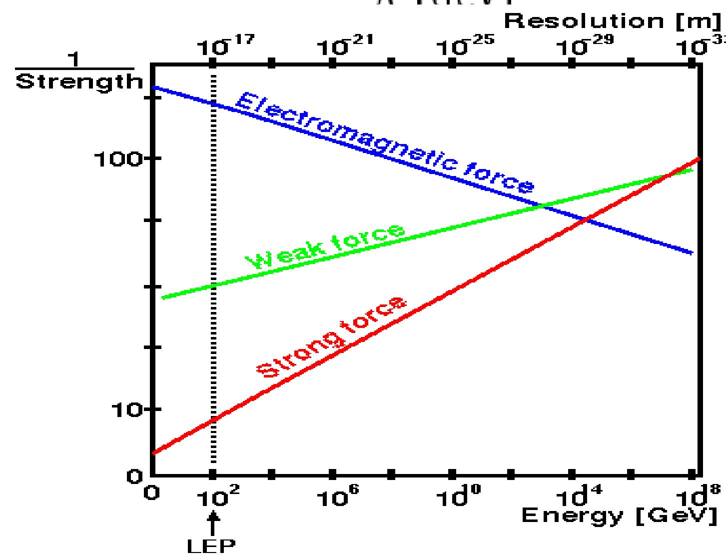


Standard Model valid only up to scale $\Lambda<M_{pl}$

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

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

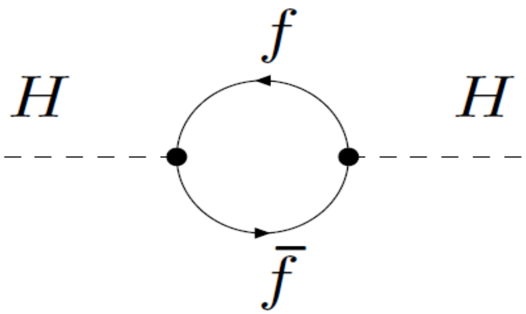
$$\delta m_H^2 \propto \lambda_f^2 \Lambda^2$$



- 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: $\lambda_{\tilde{f}}^2 = \lambda_f^2 \quad m_{\tilde{f}} = m_f$

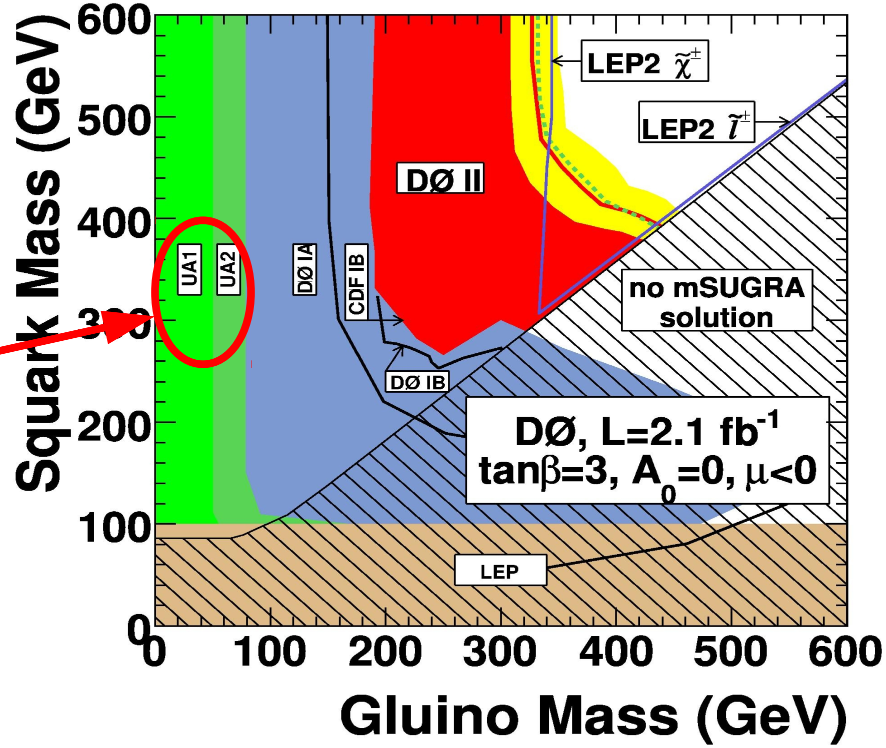
Achieved in theory invariant under transformation Q:

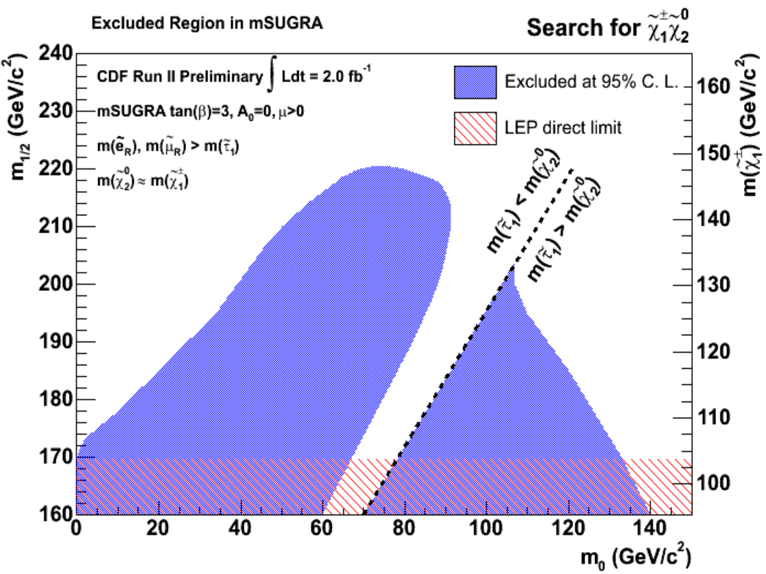
$Q|\text{boson}\rangle = |\text{fermion}\rangle \quad Q|\text{fermion}\rangle = |\text{boson}\rangle$ Supersymmetry

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

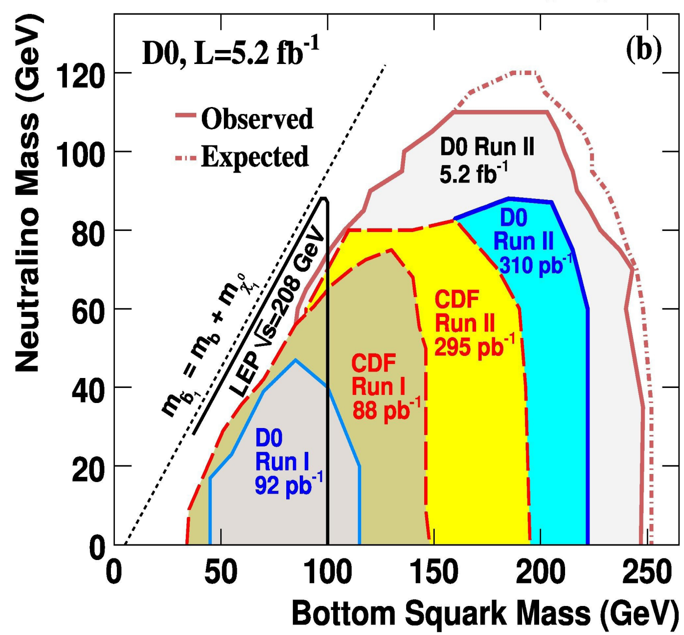
SUSY before LHC: Hadron colliders

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

Fine tuning equations and SUSY spectrum

The key equations:

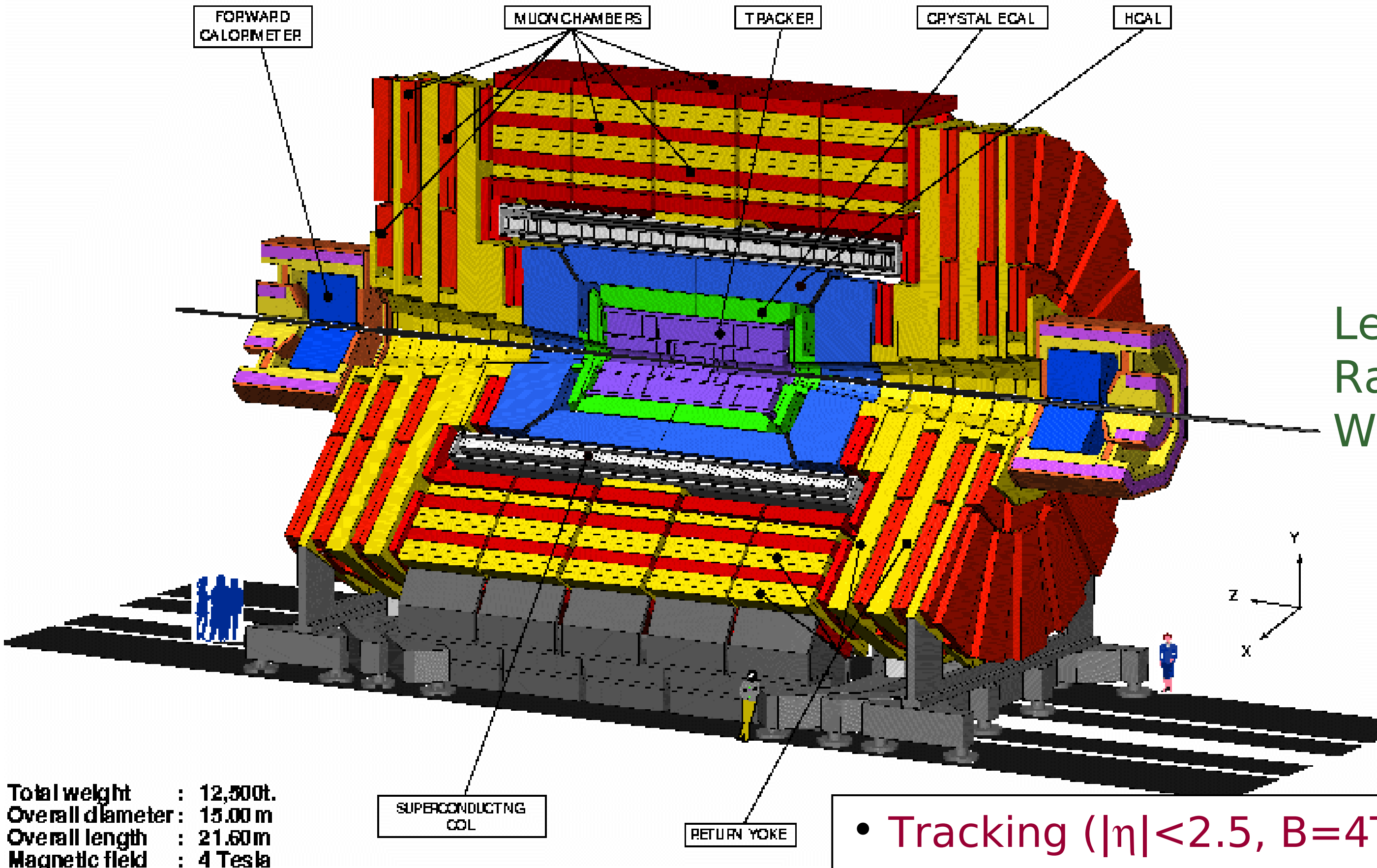
$$\frac{m_h^2}{2} \approx -|\mu|^2 + m_u^2 + \ldots$$

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

$m_{\tilde{b}_L}$

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

CMS

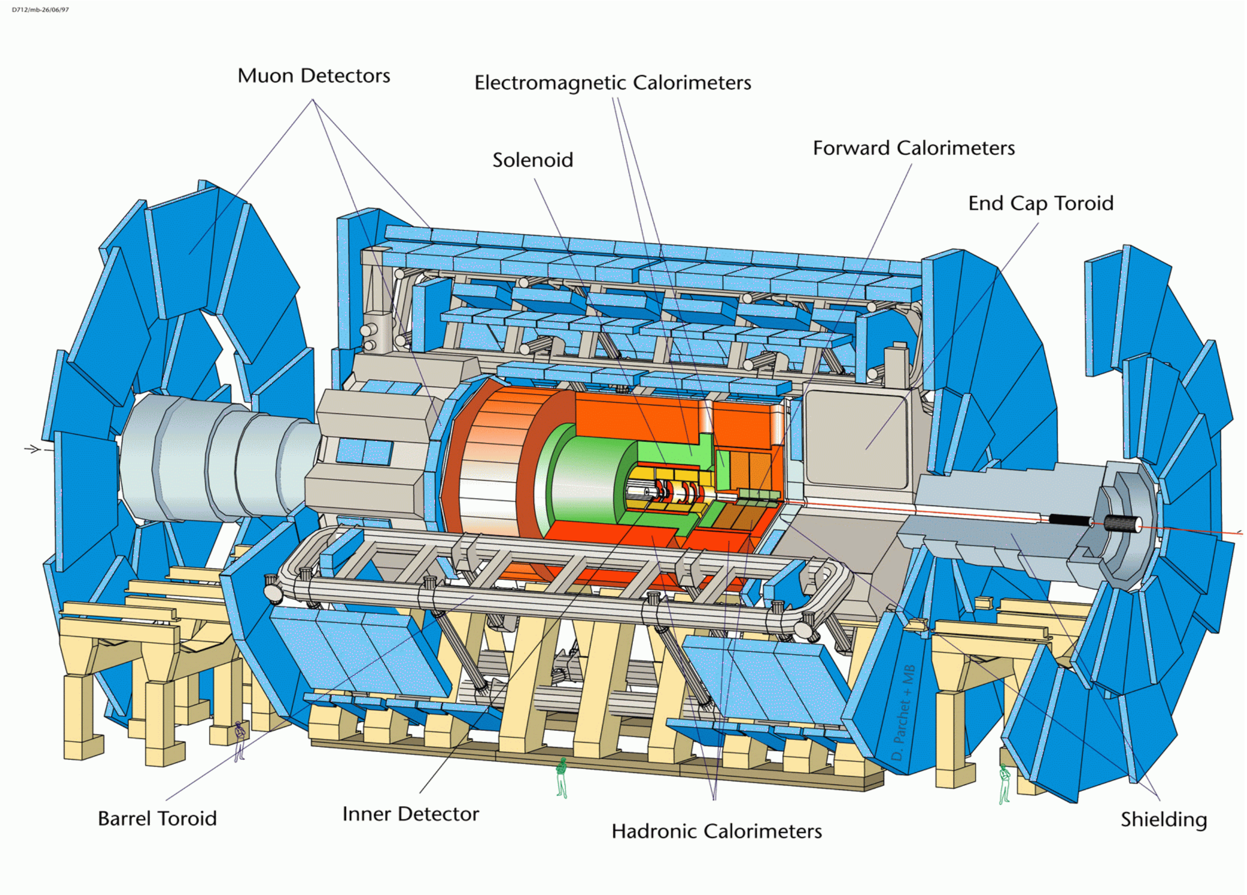


Length : ~22 m
Radius : ~7 m
Weight : ~ 12500 tons

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

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

ATLAS

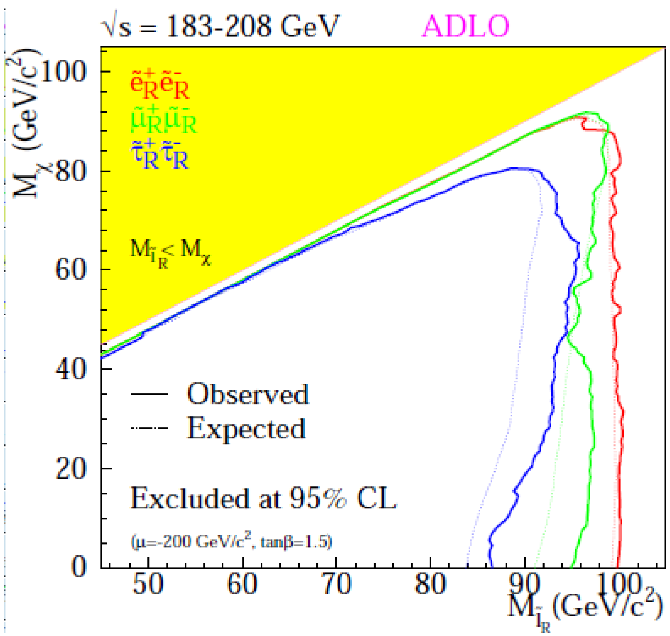


Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
~ 3000 km of cables

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

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

SUSY before LHC: LEP

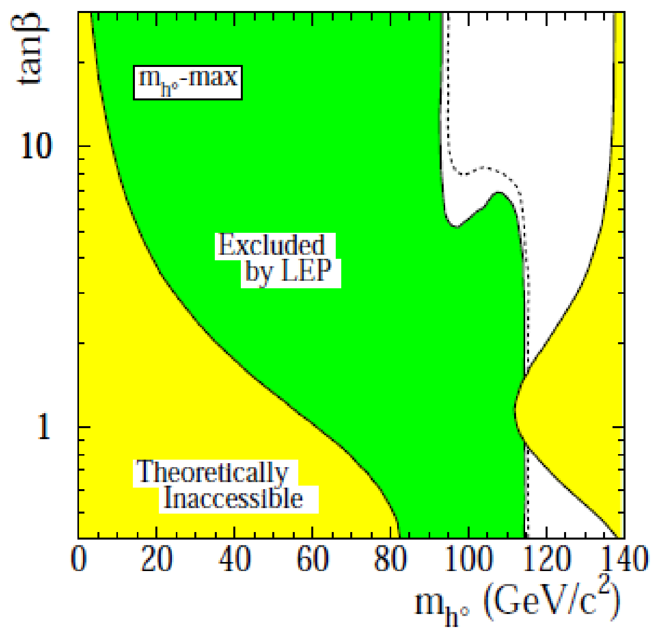


Model-independent limits of ~100 GeV on all sparticles coupling to the Z, in particular:

- Sleptons
- Chargino

Results also interpreted in terms of cMSSM/mSUGRA

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



0-lepton signatures optimisation

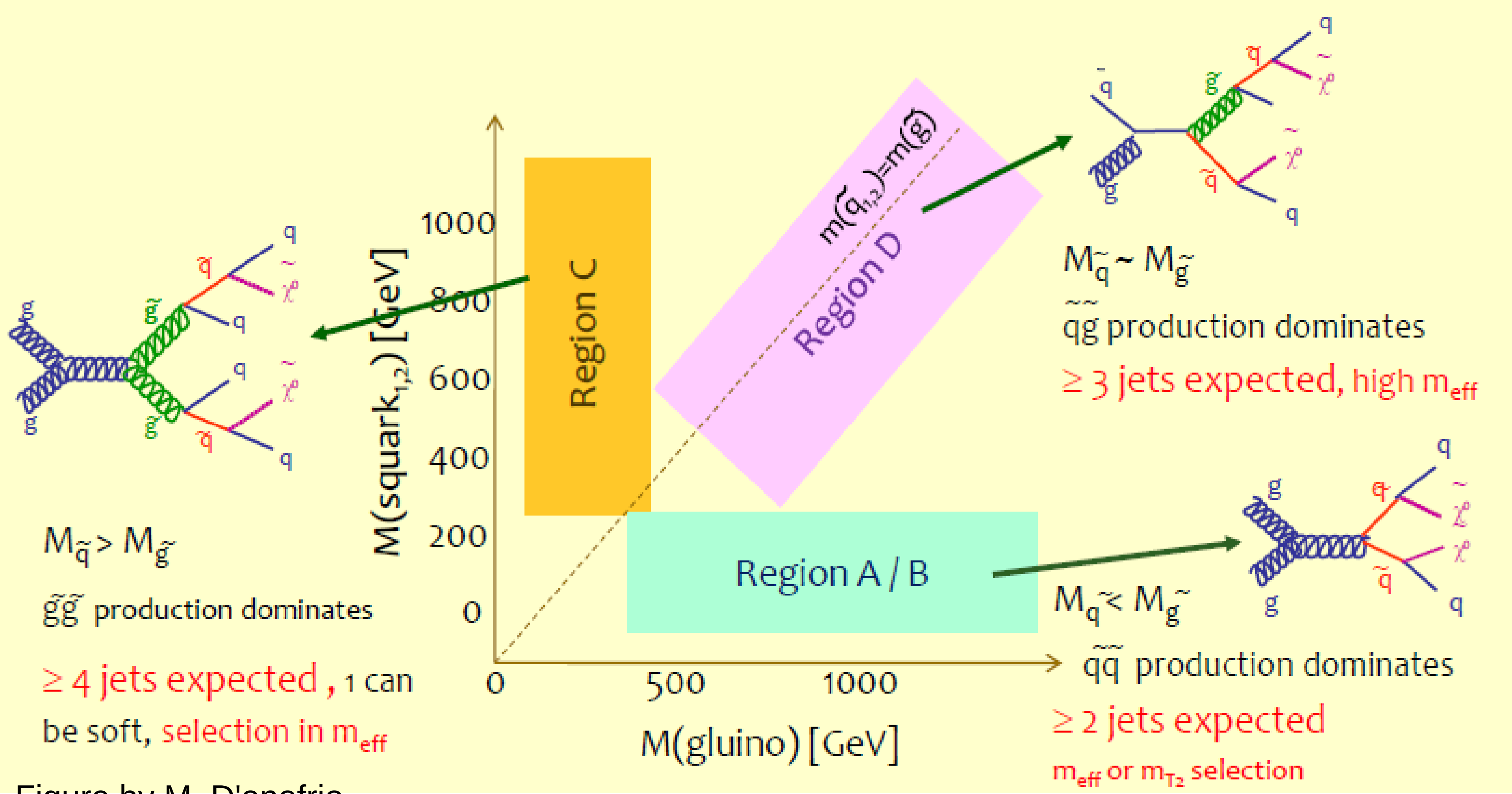


Figure by M. D'onofrio

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

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 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