Beyond Standard Model Searches with ATLAS detector at the LHC

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Gravity: New ideas for unsolved problems

(In honour of 67th birthday of Milutin Blagojević)

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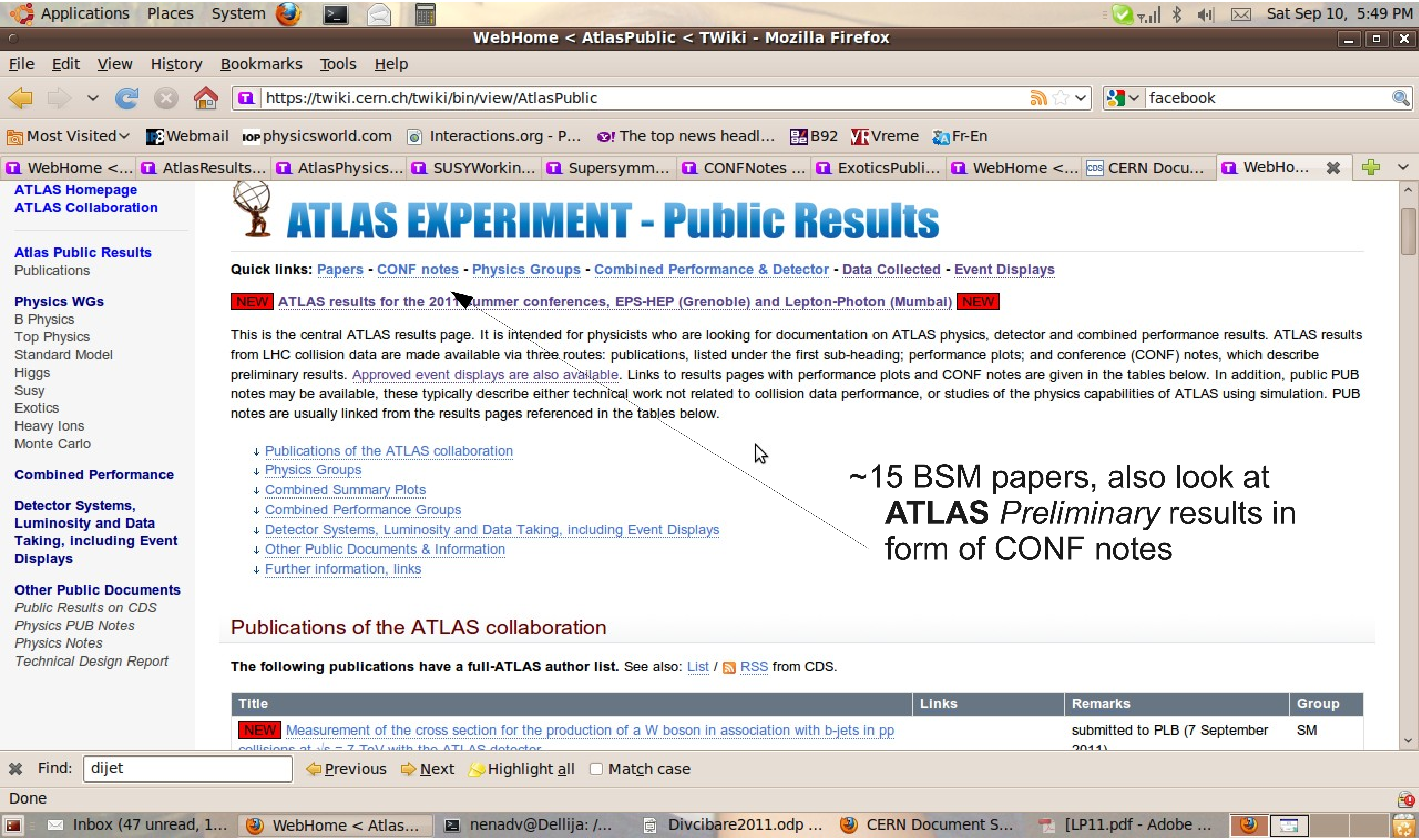
Outlook

- A brief overview of some of the results for BSM searches with ATLAS detector
- Constrained by AR x T x P

  AR = ATLAS Rules → only public results meaning restricted to up to 1.6 fb^{-1}
  T = time → for the presentation and for preparation
  P = personal → personal scientific capacity (don't really know all the details esp. theoretical ones)
- No comparison with CMS (but results similar)
- Will not go into the details mainly on experimental chalenges, event selections, systematic uncertainties, or statistical formalisms... This is of course HUGE amount of work done by the physicists in the collaboration, so please consult the papers and notes.
- Topics covered:
- SUSY with Missing Transverse Energy (MET) signatures
- Heavy Resonances
- Strong Gravity Searches
- MSSM Higgs

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

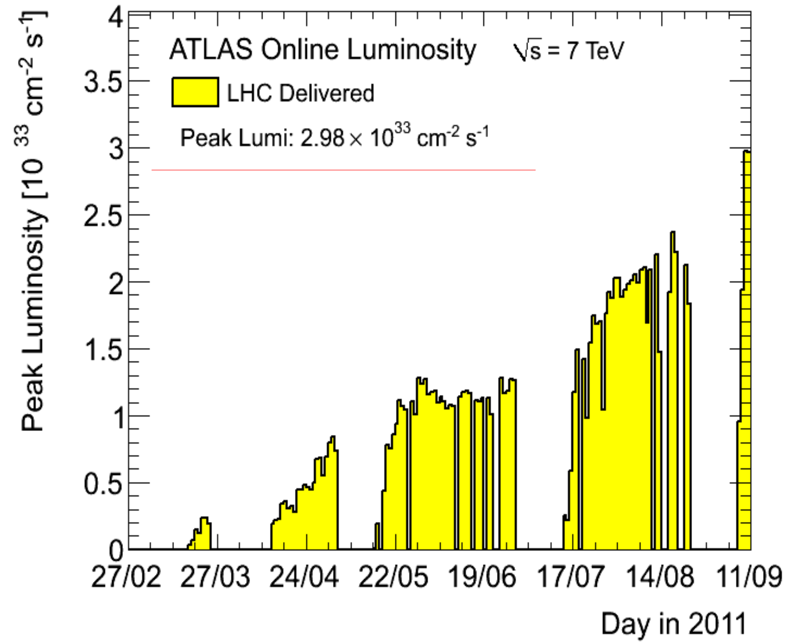


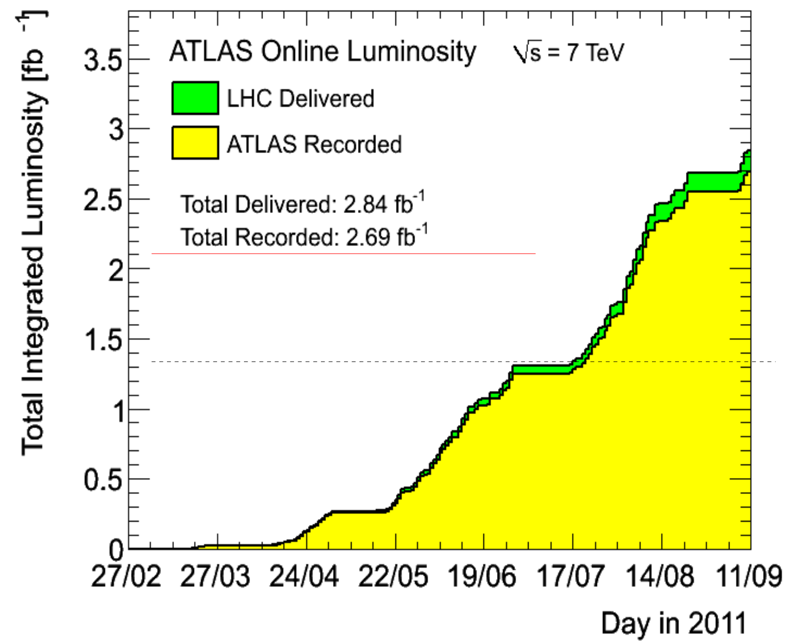
~15 BSM papers, also look at **ATLAS** *Preliminary* results in form of CONF notes

SUSY: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
Non-SUSY: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
Higgs: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

ATLAS data taking in 2011

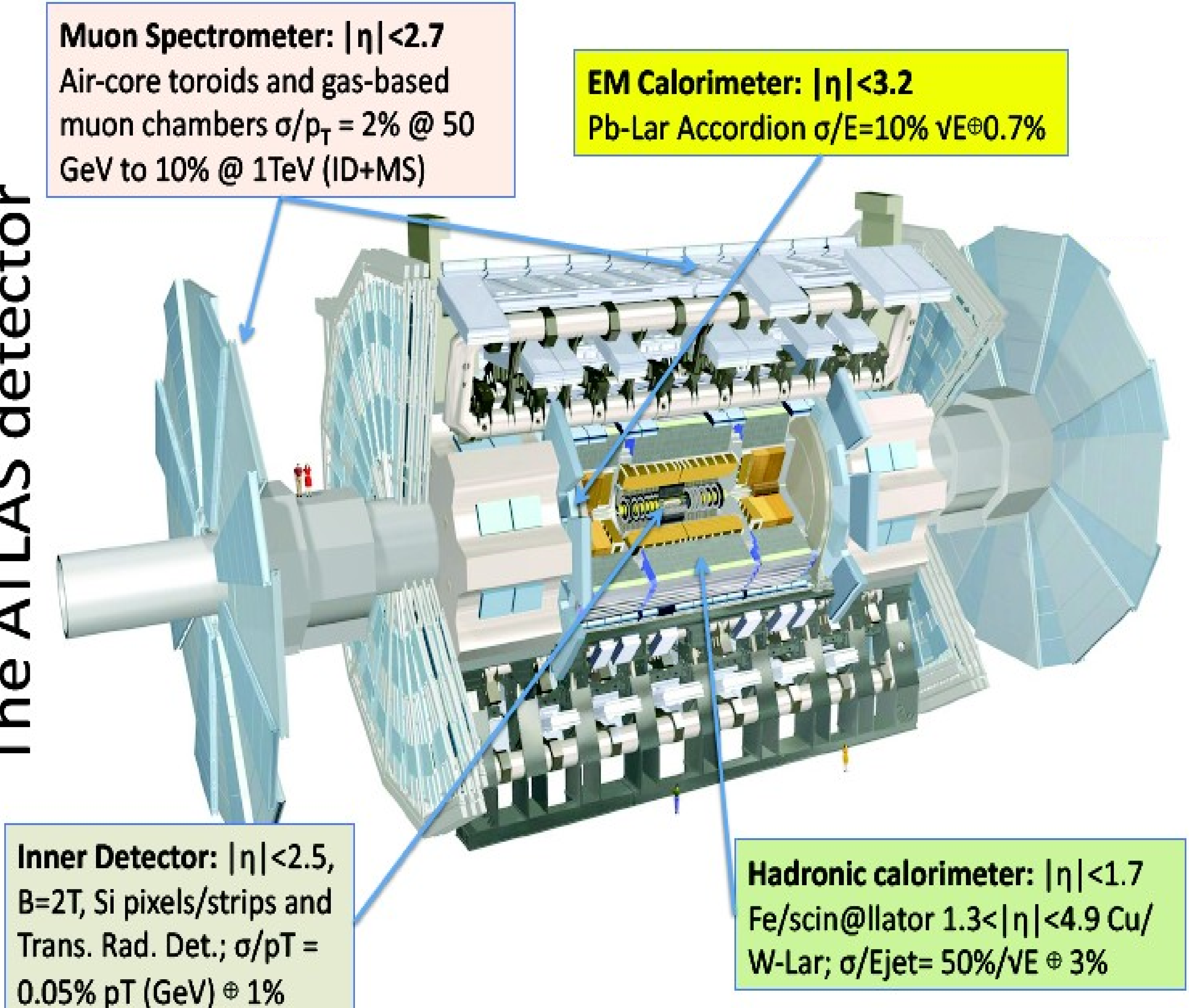
- pp collisions at 7 TeV
- LHC performance extremely well
  - peak lumi 2.96 x 10^{33}
  - max 100 /pb/day (>2 times the whole 2010!)
  - 2.9/fb delivered (~3 times 2011 target)
- ATLAS data taking efficiency 95%
  Relative fraction of good quality data:
  90-100%, depending on detector subsystem.
- 50 ns bunch spacing (25 ns designed).
  6 collisions /crossing (average).
- Substantial in-time and out-of-time pileup.
  Much effort on understanding impact on
  detector performance with data and simulation.





https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults#2011_pp_Collisions

The ATLAS detector



BSM, why we need it?

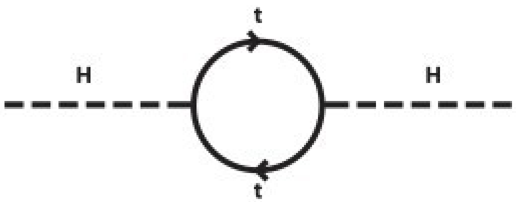
- Standard Model is a (very) effective theory that breaks down at a certain scale (hopefully TeV scale). But:

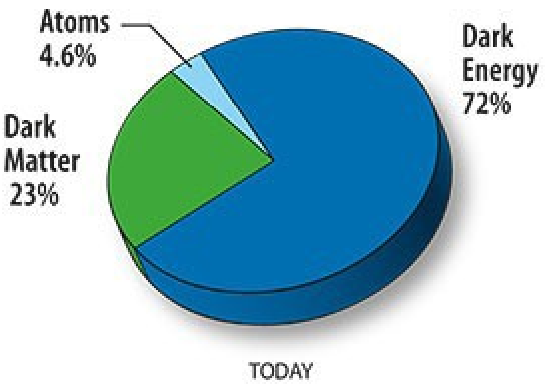
  → Hierarchy: quadratic divergence of the Higgs mass, extremely fine-tuned
  → What is the underlying nature of EWSB?

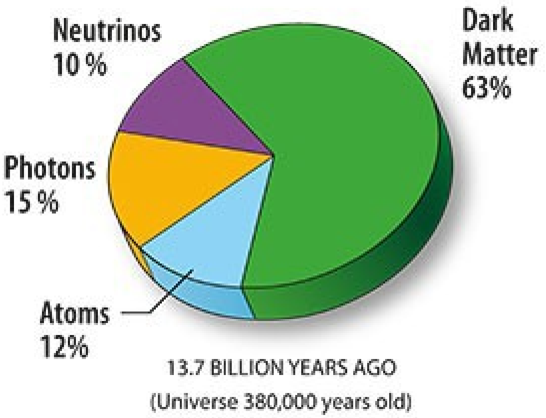
- Dark Matter
  → what is it? cannot be explained by SM

- Neutrinos have mass
  → where are the right-handed neutrinos?

- BSM models attempt to solve the SM limitations







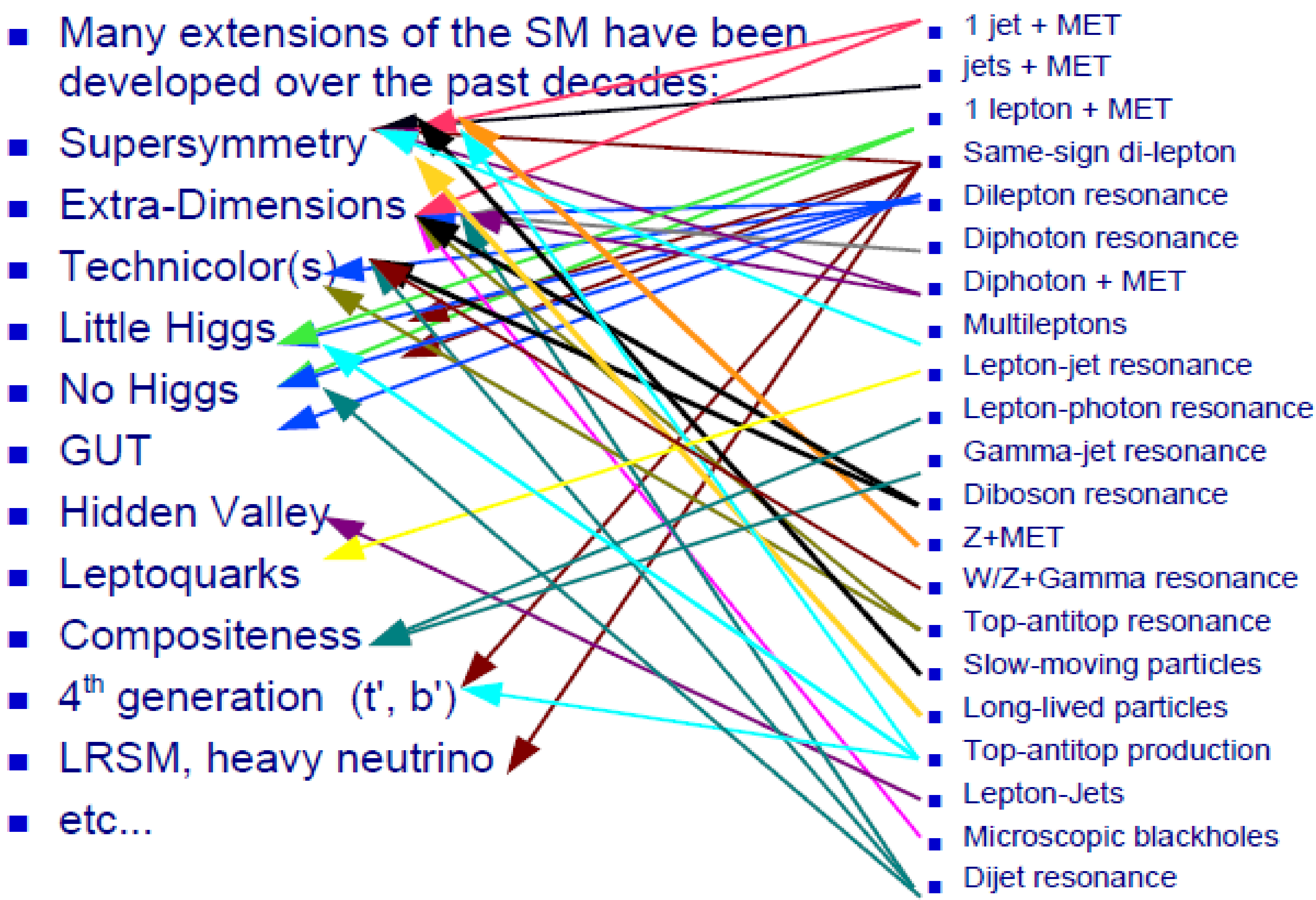
Models VS Experimental Signatures

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4[th] generation (t', b')
- LRSM, heavy neutrino
- etc...

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance

- **Experimental point of view: concentrate on signatures, studied with benchmark models!!**

Models VS Experimental Signatures

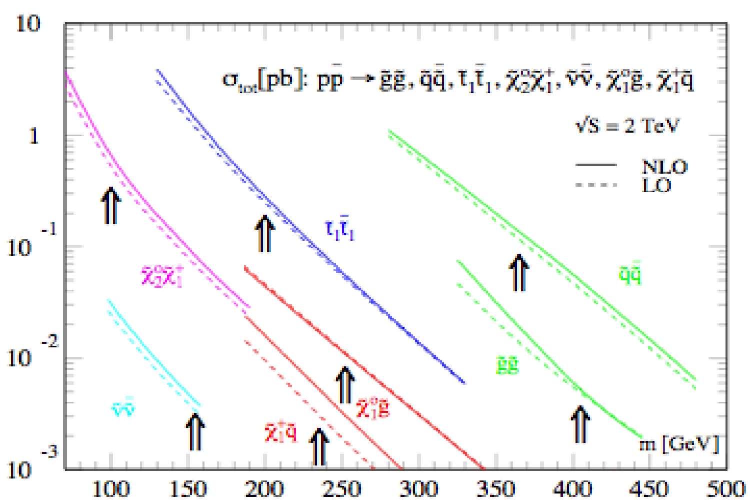


- *This would become important if/when significant deviations(s) from SM found.*

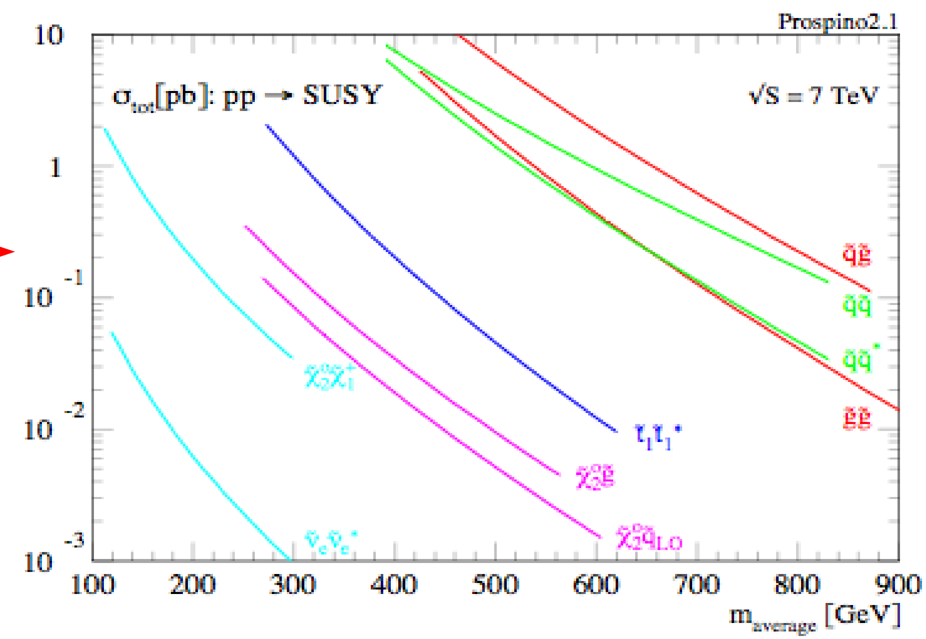
SUSY

SUSY - a brief overview

- Extension of SM solves many theoretical problems
- Each SM particle has a partner which differs by 1/2 unit of spin
- SUSY is a broken symmetry, to avoid fine-tuning masses ~<1 TeV
- The minimal extension of the SM (MSSM) introduces ~105 new parameters. Adopt some models (e.g. mSUGRA, CMMSM, GMSB...) or phenomenological assumptions to reduce this number of free handles.



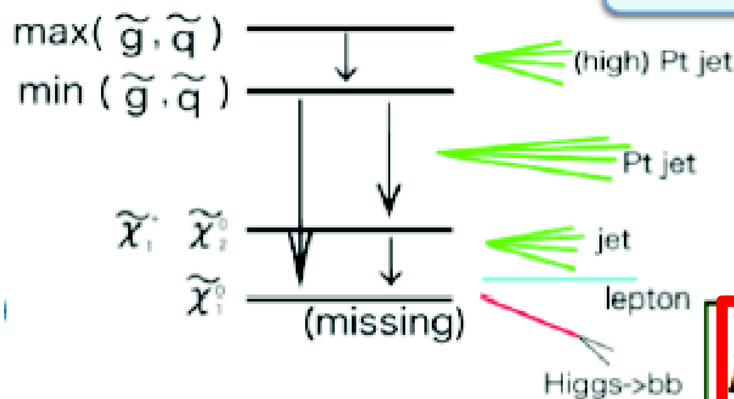
Tevatron



LHC

SUSY analyses

R-parity conserving models



- Missing transverse momentum
- Strongly interacting particles with high cross sections if kinematically accessible
- No mass peak expected: need to rely on excess in the tails of distributions

$$M_{\rm eff} \equiv \sum_{i=1}^{4} p_T^{{\rm jet},i} + \sum_{i=1} p_T^{{\rm lep},i} + E_{\rm T}^{\rm miss}$$

LSP stable and SUSY particles created in pairs

R-parity violating models

- Lepton and/or Baryon number violated (constrain from Proton lifetime)
- LSP decays – often little or no missing momentum
- Strongly interacting particles with high cross sections
- Can exploit invariant mass constraint and LSP decay properties in general

Trying to cover all possibilities in a model independent way: in/exclusive searches needed

Exotic SUSY scenarios

Depending on parameter choices and coupling strengths some particles can be long-lived

- Slow moving "heavy muon" (sleptons etc)
- Hadronize into R-hadrons (g/t/b)
- Stop – late decays (gluino, anything?)
- Decays in detector (slepton/chargino)

Distinctive, low-background signatures usually requiring ESD-level info and dedicated searches

Thanks to P.D.Jeckson for the slide

SUSY analyses

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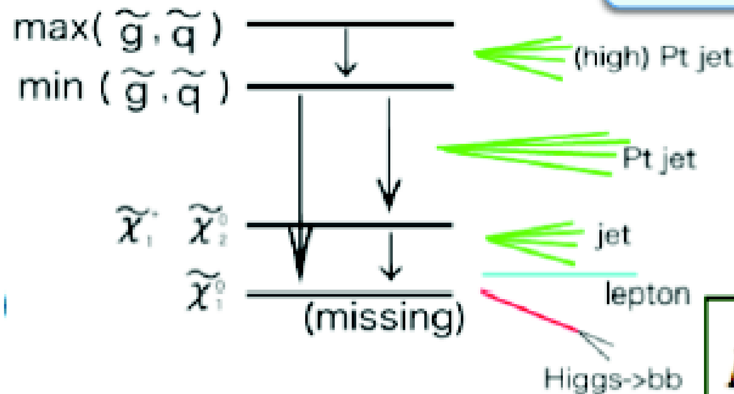

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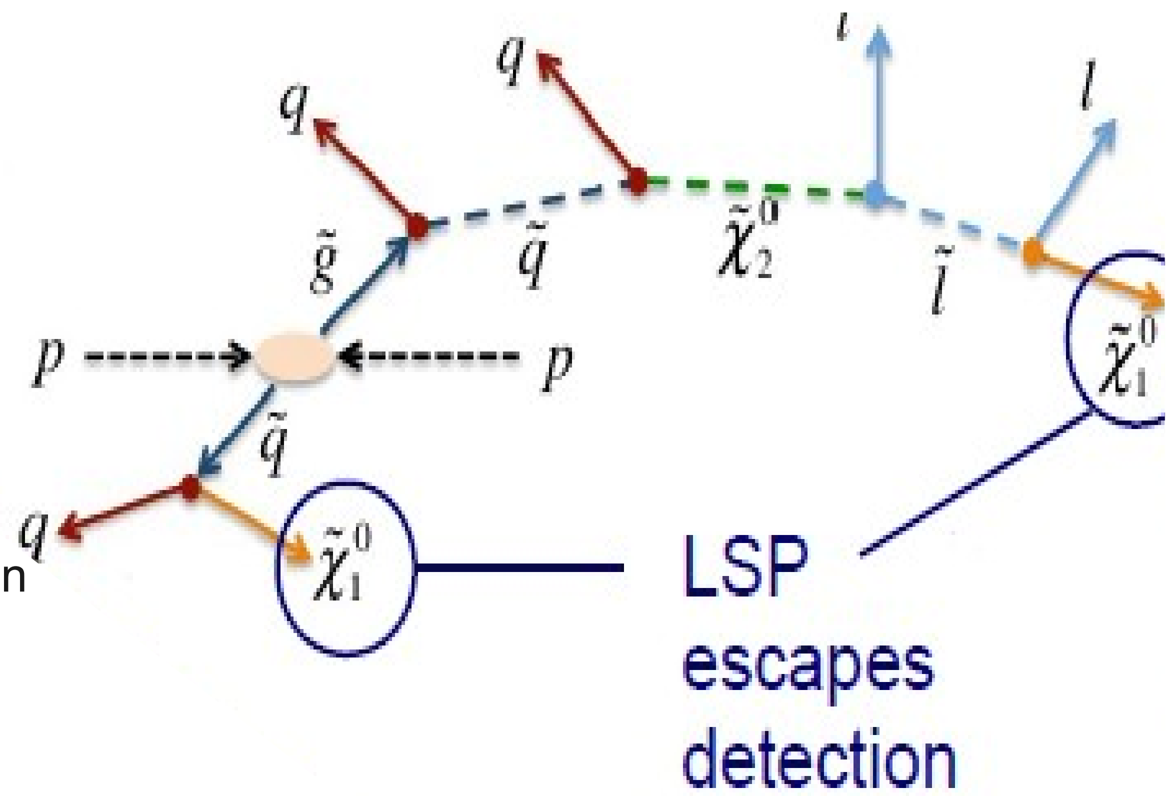
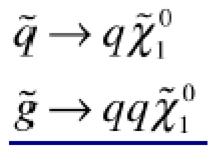
Signatures

- Jets + MET + 0 lepton
- Jets + MET + 1 lepton
- Jets + MET + 2 leptons
- Jets + MET + >=3 lep.
- MET + b-jets + 0/1 lepton
- MET + 2 gamma
- MET + taus

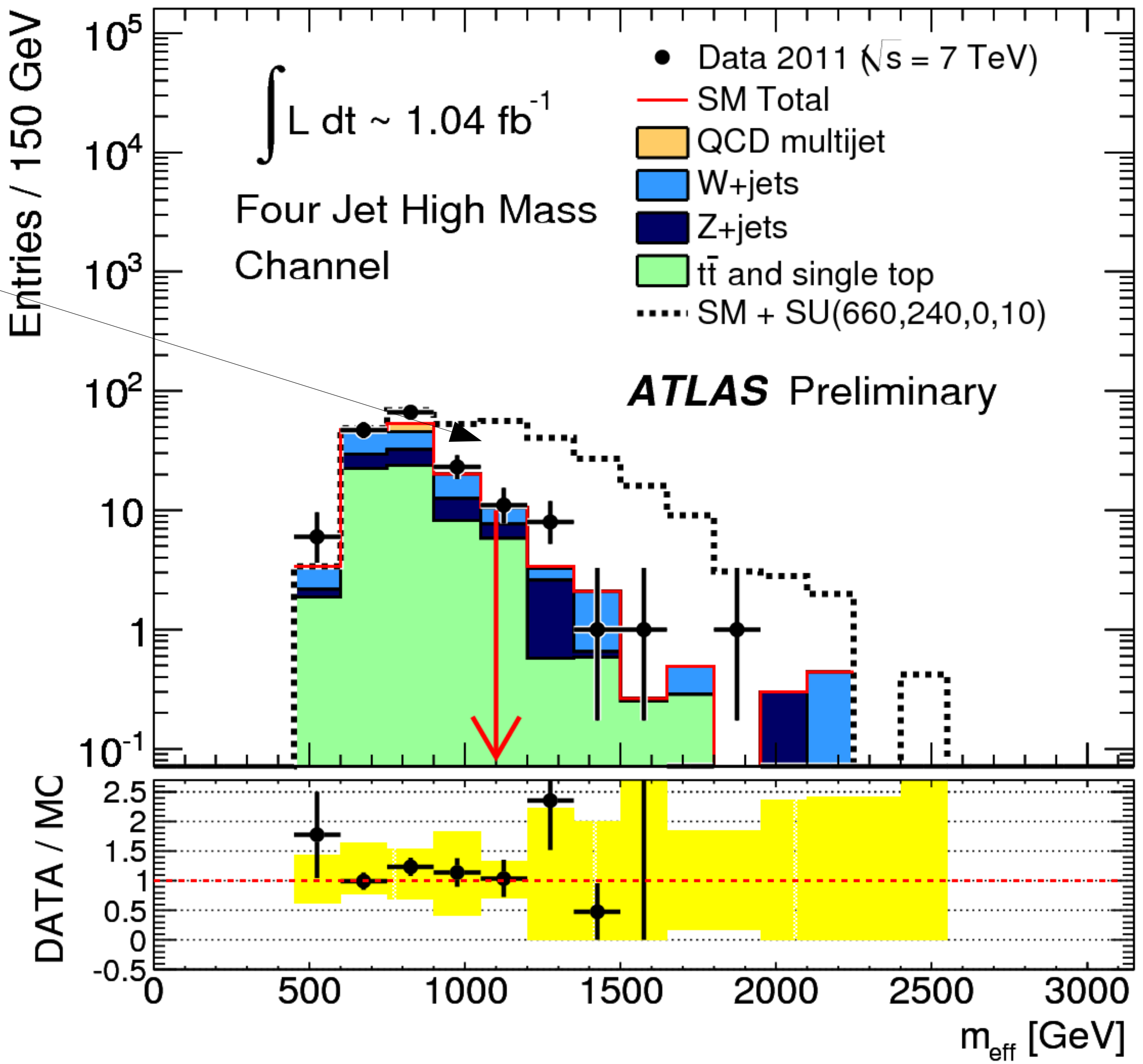


- 0 lepton: squarks and gluionos dominate
- Lepton(s) + Jets + MET: lower BR, but complementary
- 3[rd] generation (b/t), in cascade, direct production >1 /fb of data
- Photon(s) + MET → GMSB

Jets + MET (“0 lepton”)

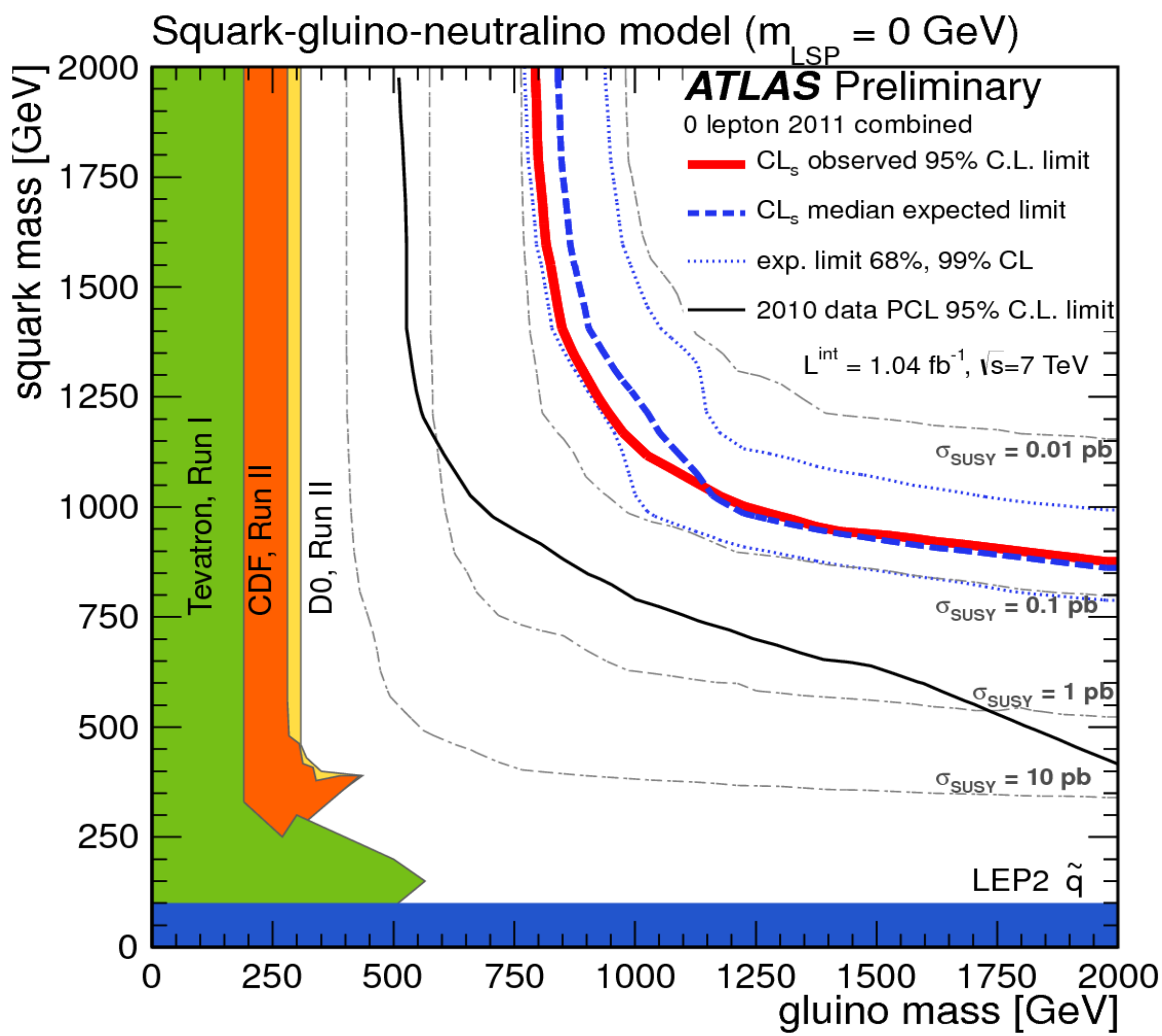


- Typical SUSY (ala CMSSM/mSUGRA)
- Cut on MET and Meff
- No resonance peak, Meff sensitive to SUSY scale
- Good understanding of SM background, esp. multijet production
- Cut and count: No excess above SM



95 % CL Limits on squark/gluino masses from 0-lepton analysis

- Simplified models
- Experimentalists-like plot (more intuitive)
- Squark-gluino mass plain, in which all other SUSY particles (except for the lightest) neutralino are set beyond the reach of the LHC
- Exclude squarks/glionos of ~1 TeV mass.
- Huge jump wrt 2010 result (cf. arXiv:1102.5290)



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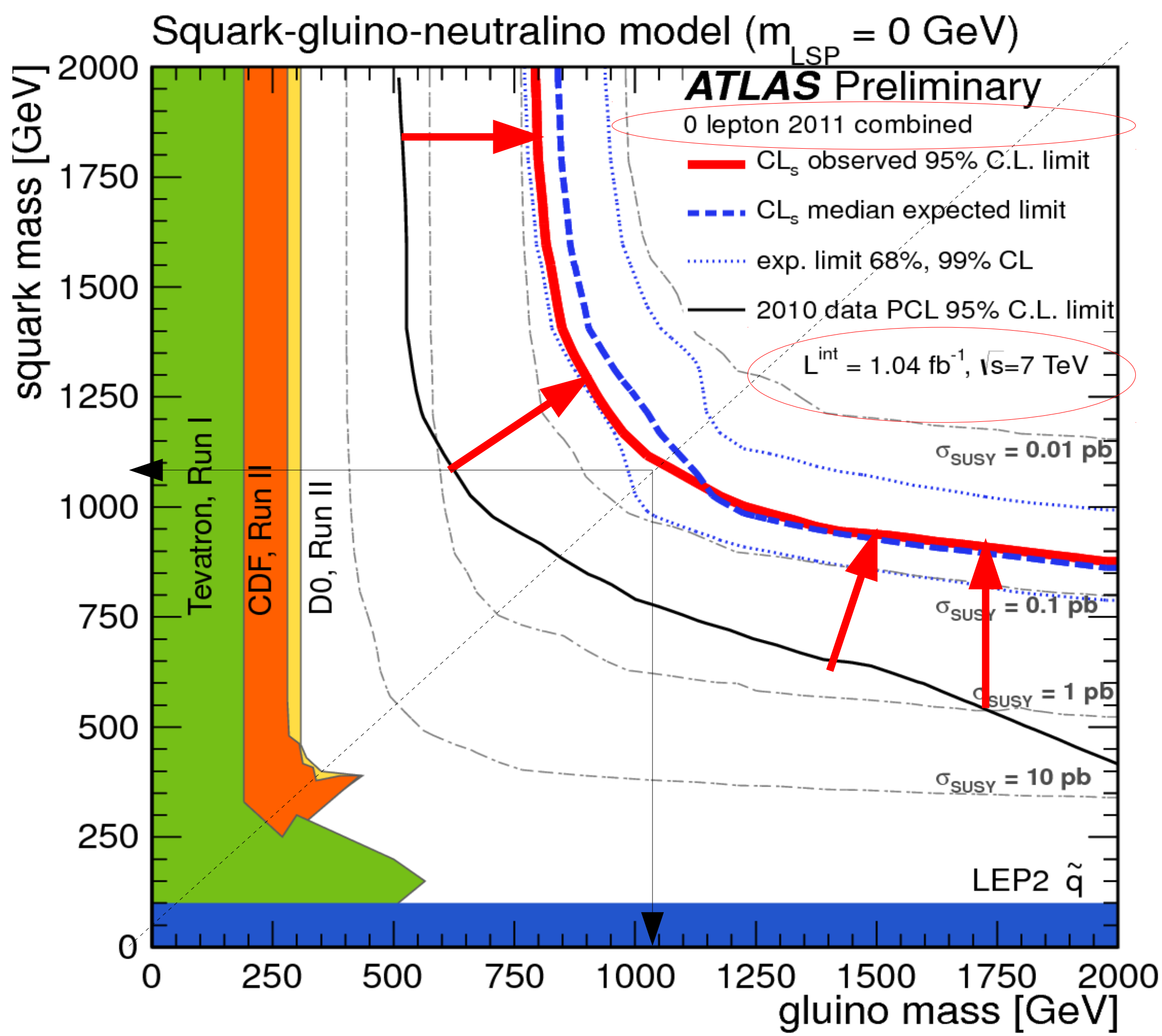
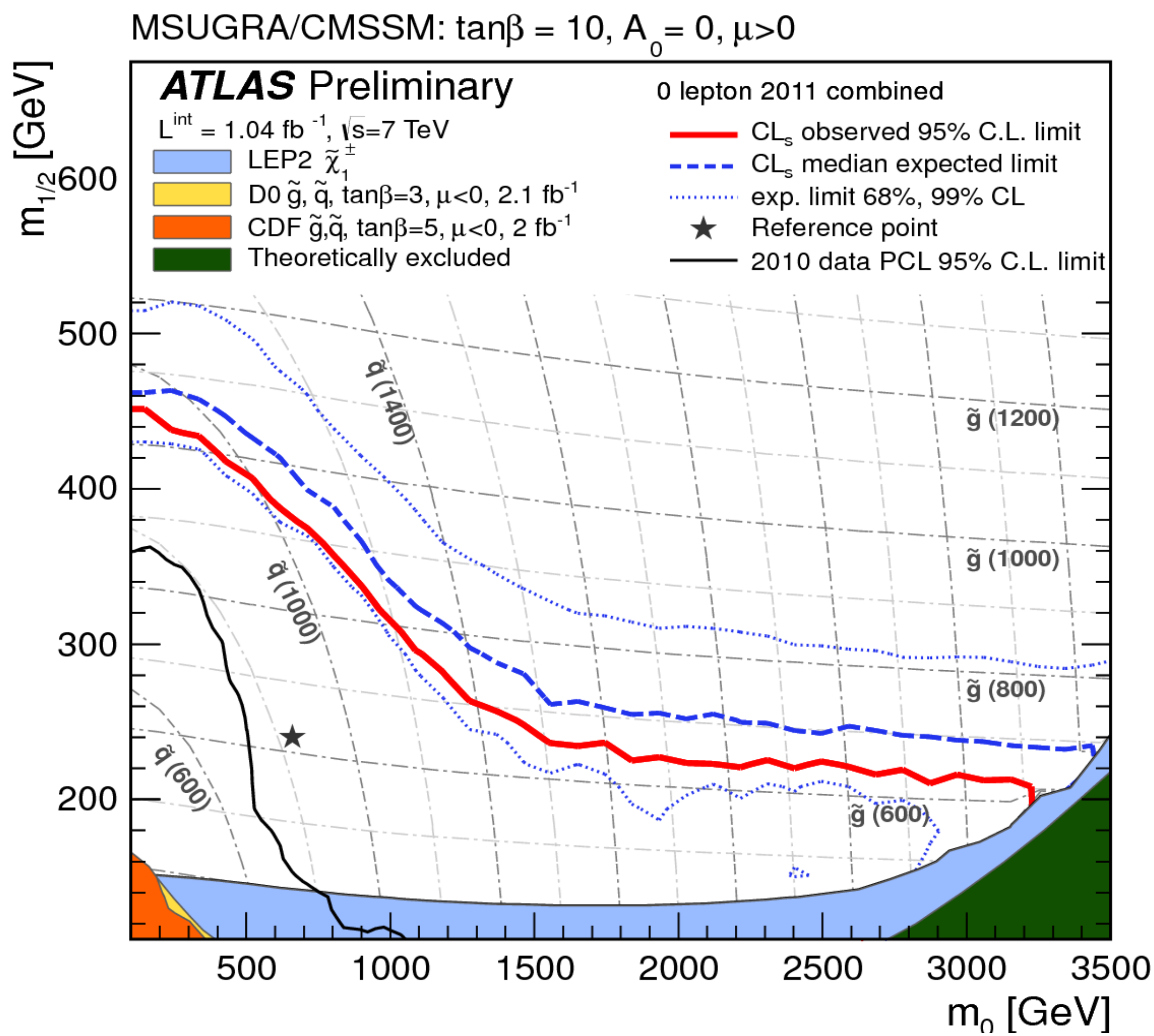


0GeV < m_{LSP} < 200 GeV

95 % CL Limits on squark/gluino masses from 0-lepton analysis

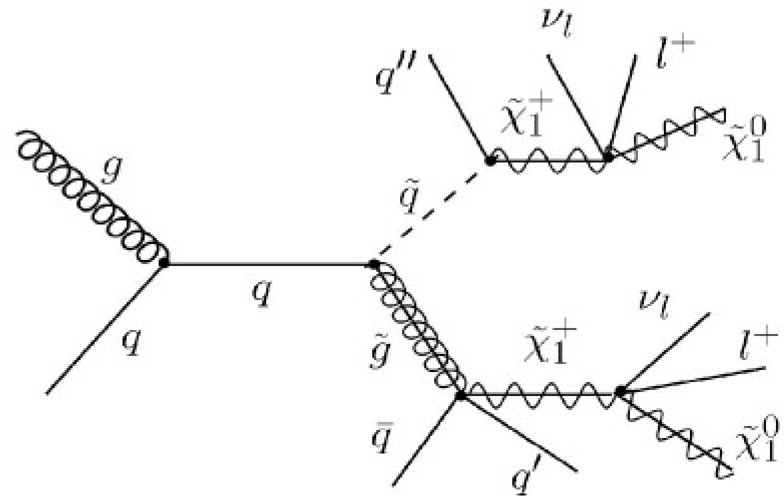
- Exclusion curves for MSUGRA/CMMSM models
- Theorists-like plot (with limits on the formalism)
- “Theorists seek to combine many constraints”
- Here an example of exclusion curves in (m_0 , $m_{1/2}$) plane
- NB:
  Limits from Tevatron and LEP generated with different parameter choices.

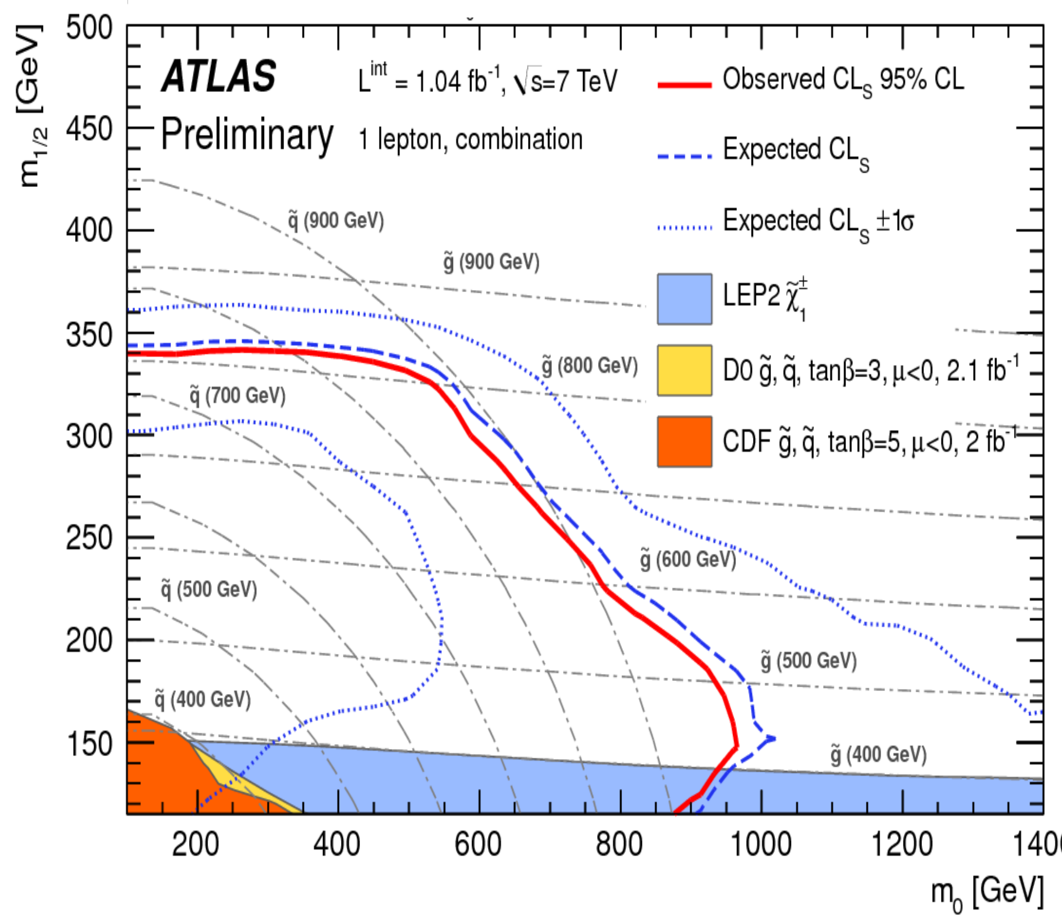


m_0 universal scalar mass, $m_{1/2}$ universal gaugino mass, A_0 universal trilinear scalar coupling, tanβ the ratio of vev of the two Higgs fields, μ sign of Higgsino mass par.

Jets + MET + 1,2 Lepton

- Leptons arise from slepton or charginos or W/Z decays
- Due to smaller Branching Ratio, less stringent limits than fully hadronic but complementary.
- Look for 1, 2 (same-sign or opposite sign) or more leptons.
- Flavor subtraction selects flavor-correlated decays.
- Can also look explicitly for heavy boson decay.





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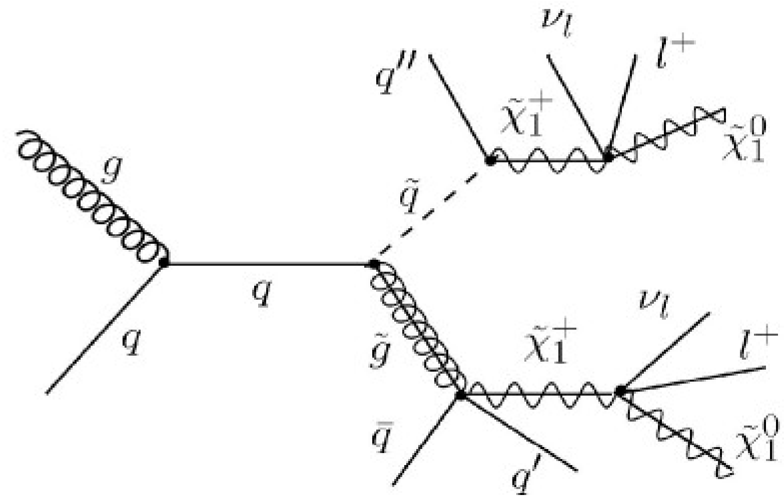
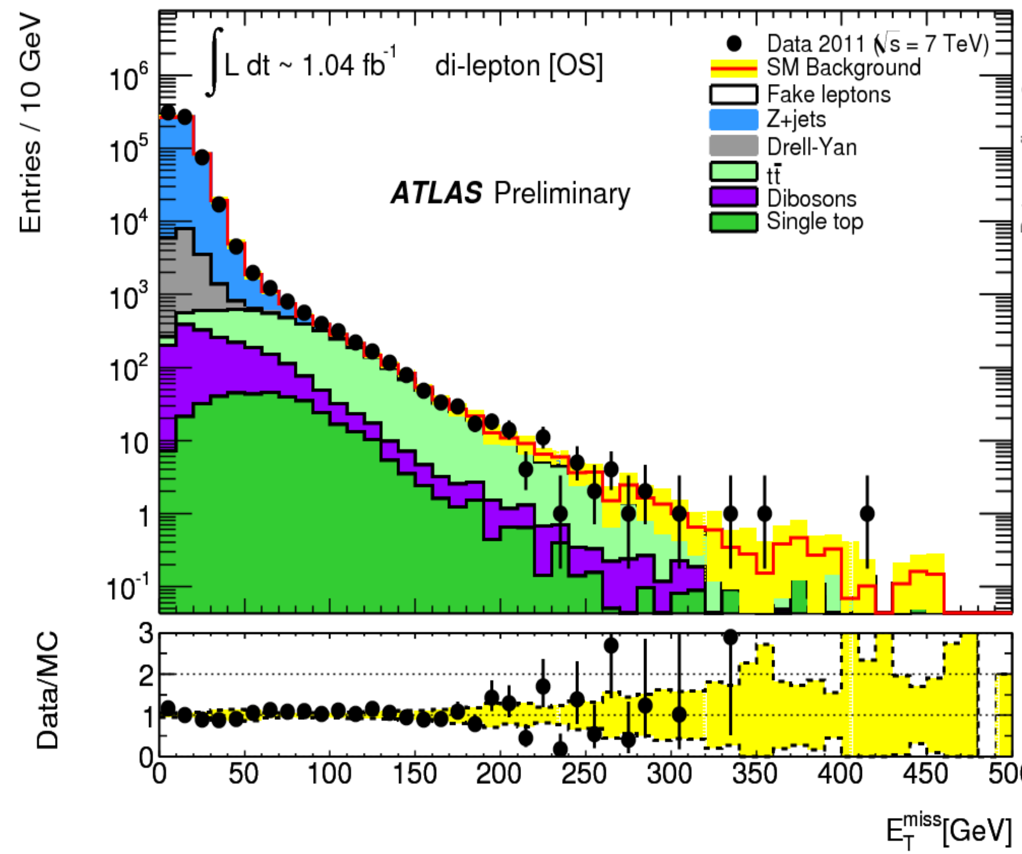


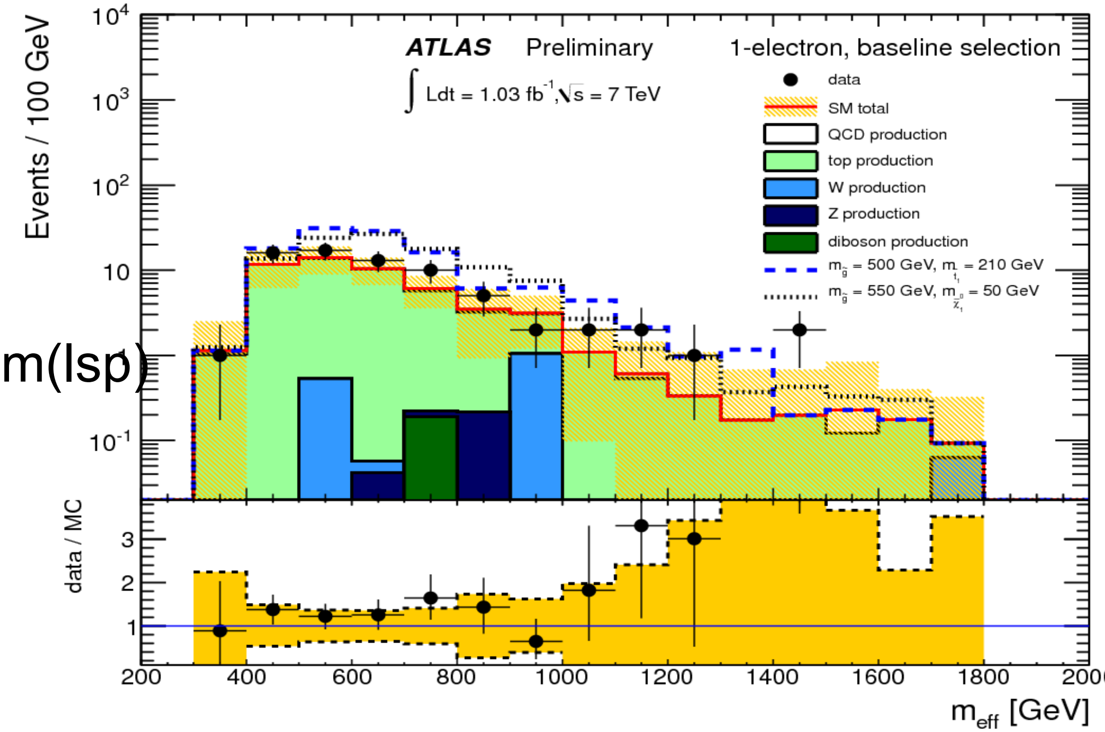


What if gluinos decay preferably to 3[rd] generation(?)

- Consider several pheno. scenarii, such as:

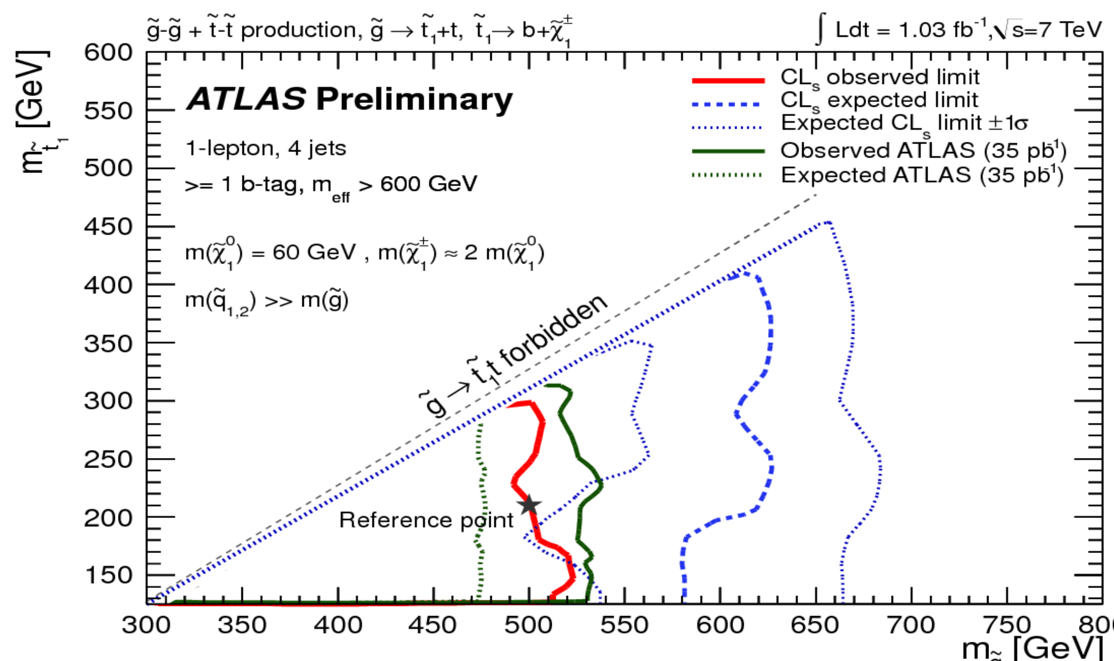
Assume
m(gluino) > m(stop) > m(neutr.) > m(lsp)
g → stop+top ; stop → b+LSP

→ Complex final states with lepton(s) and b-jets
→ Limit on gluino mass:
m(gluino) > 500 GeV at 95% C.L.

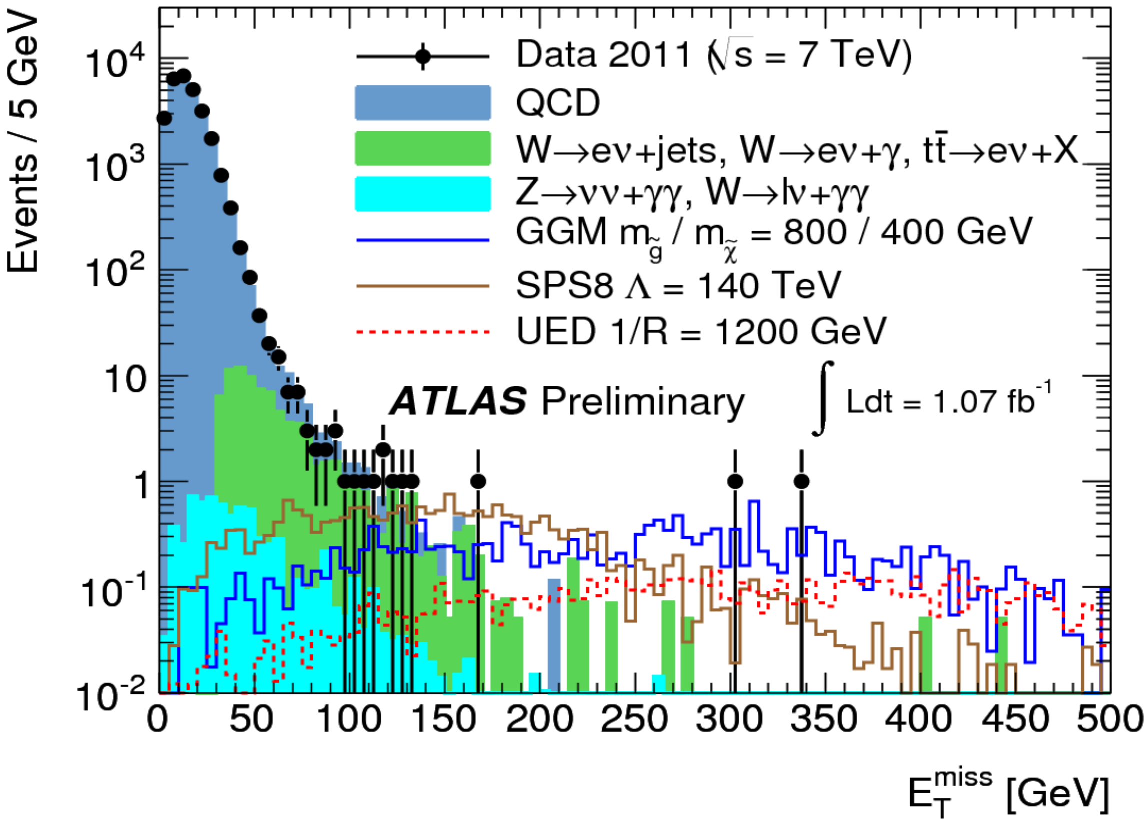


- Also gluino-gluino production followed by decay through off-shell stop:
g → stop top → ttbar+LSP

- Good performance of b-tagging required



Diphotons + MET (+ Jets)

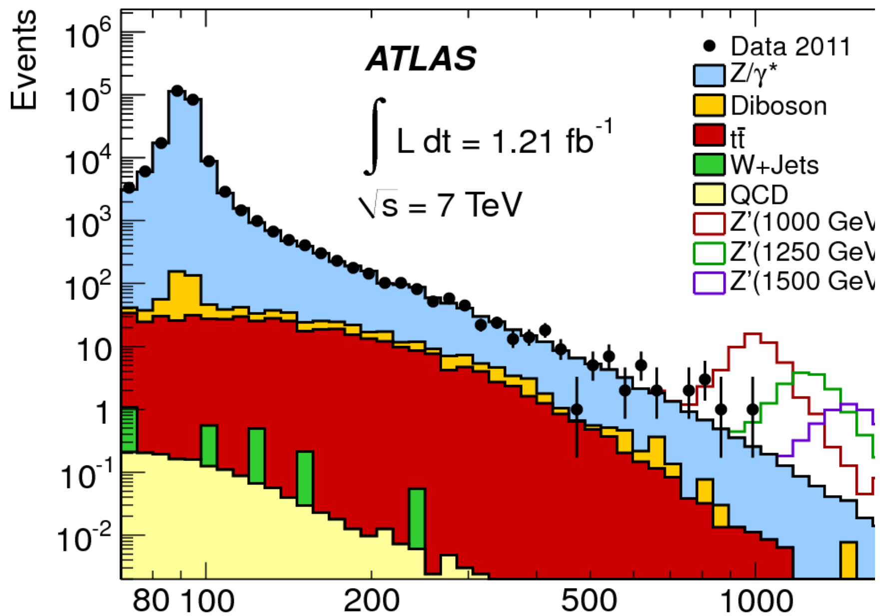


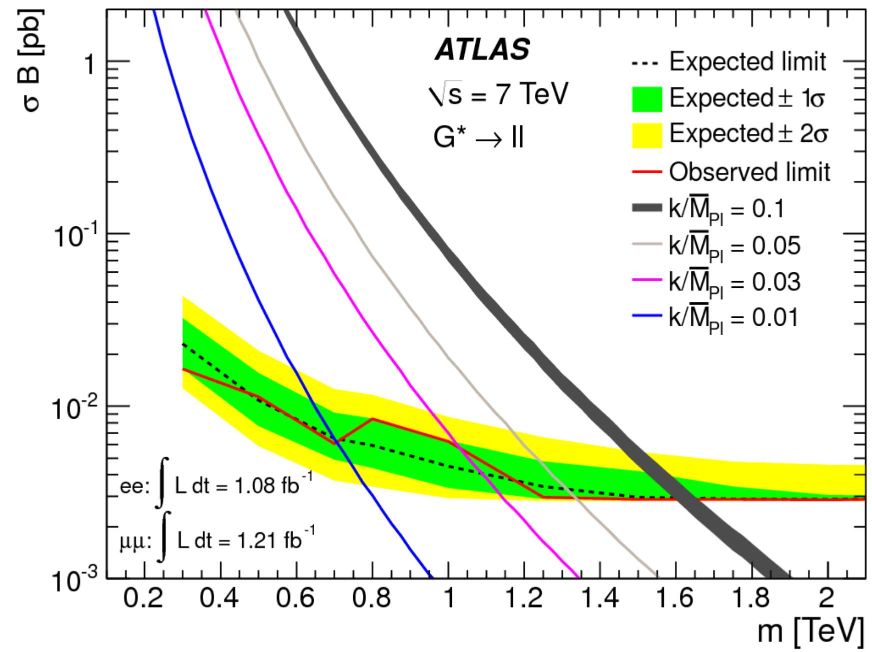
- Unlike mSUGRA, in GMSB SUSY is broken at the TeV scale in a hidden sector, and is propagated to the MSSM vaia gauge and gaugino interactions with MSSM particles.
- Gauge-Mediated SUSY Breaking:
  → LSP = Gravitino
  → NLSP = Neutralino (and Chargino)
  → NLSP → LSP + Photon or W or Z
- Inclusive search, jets may be present, bit not required in the selection
- Interpretation also in the context of UED
- Each SM particle has *n* KK excitations with *n*=1 accessible at the LHC
  KK produced in pairs and decay in cascade to excited photon with subsequent decay
  γ* → γ + G, with G escaping detector

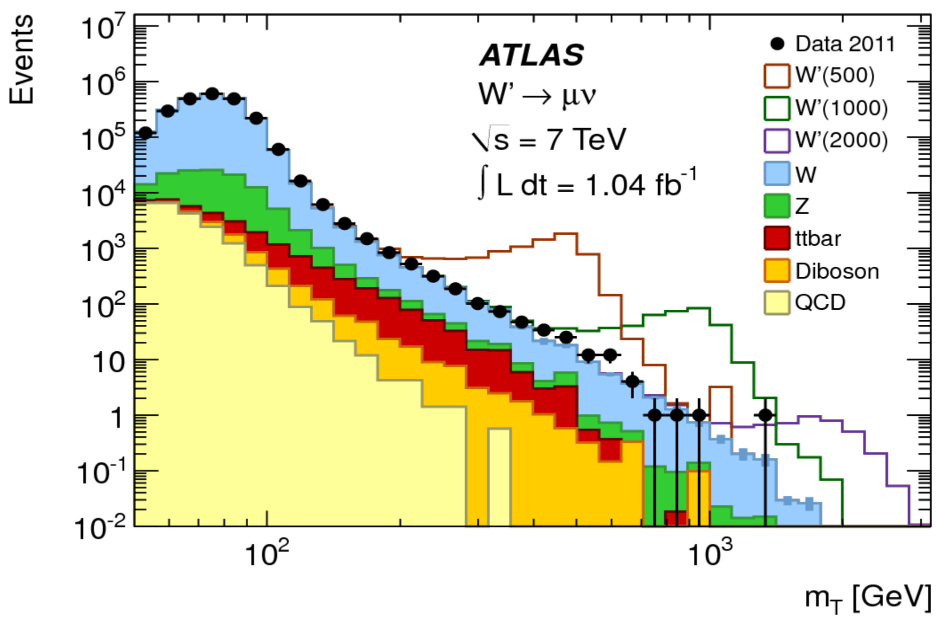
- No excess found in this spectra.
- Gluinos and neutralinos mass limits m>560 GeV
- 1/R <961 GeV

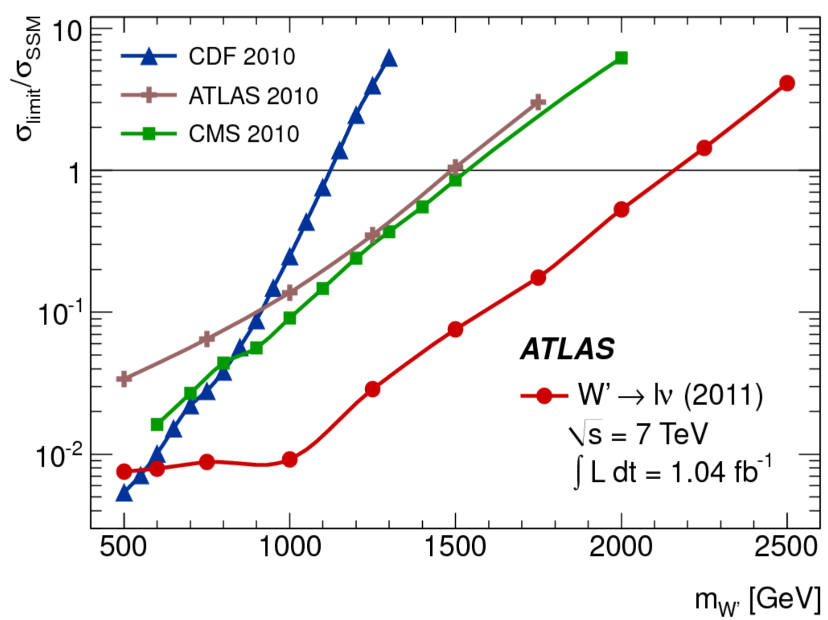
Heavy resonances

Lepton + X , X= another lepton or a neutrino

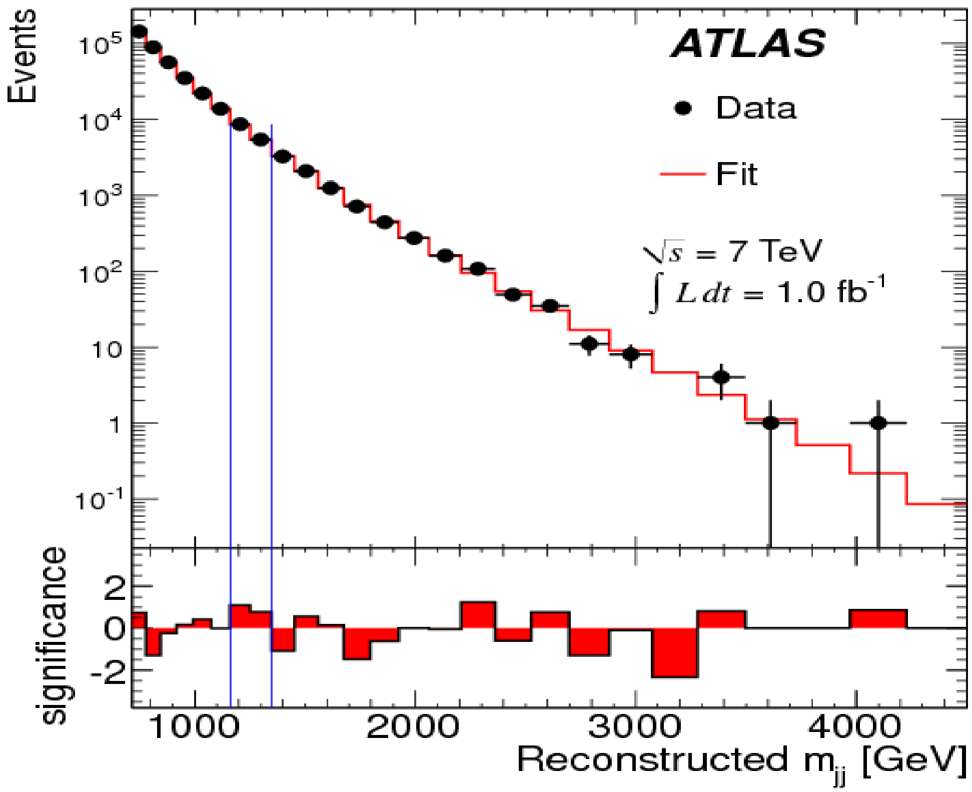


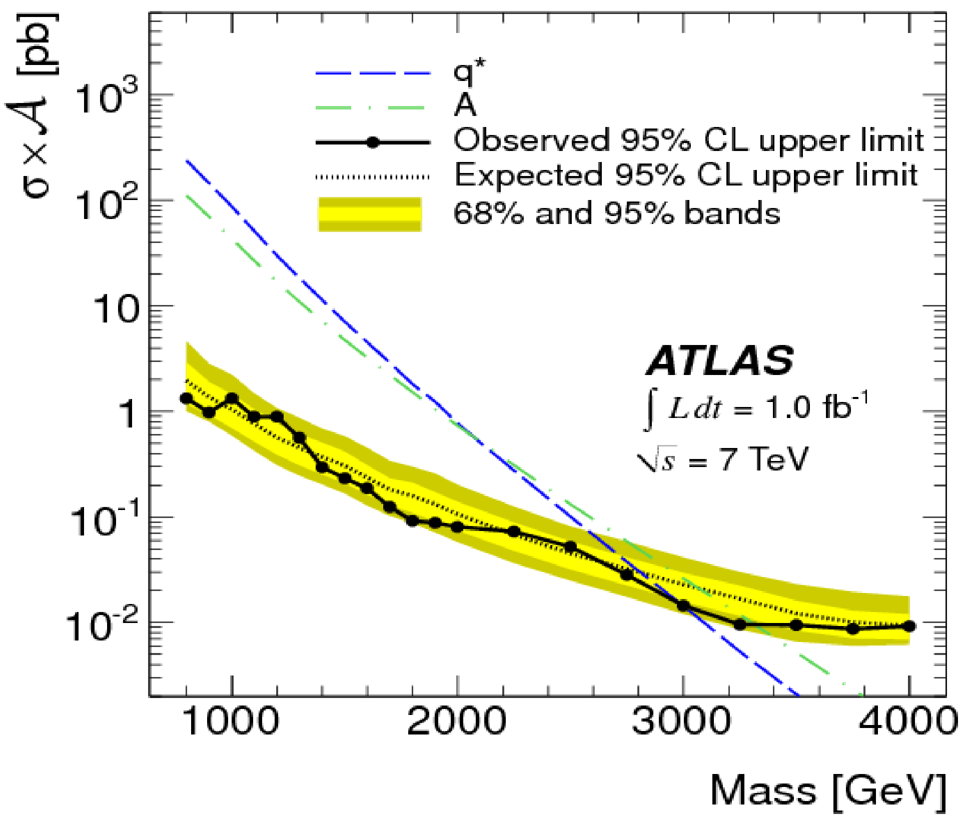






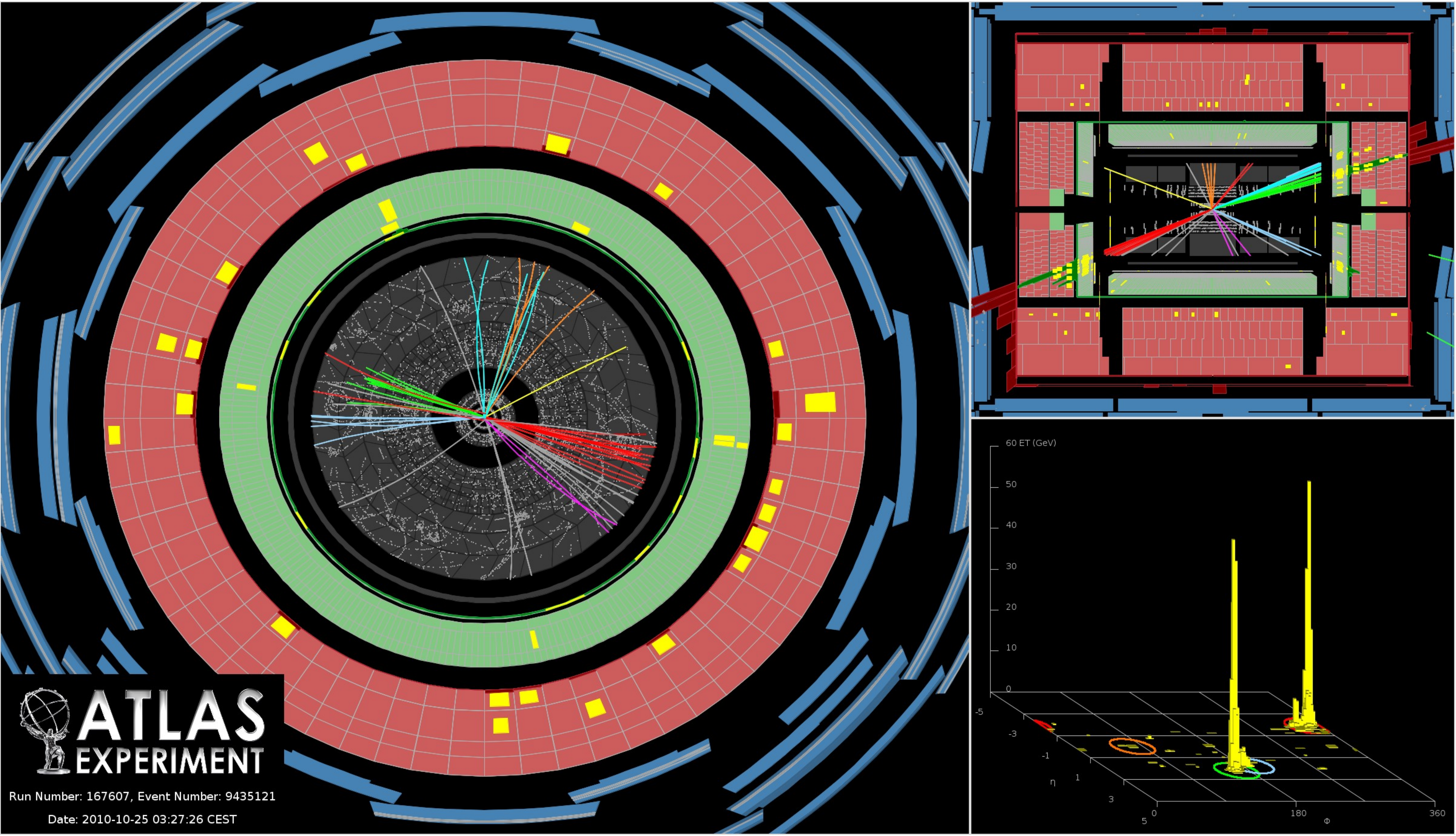
Dijet resonances





- Excited quarks, strong gravity, contact interaction
- Look for resonance above phenomenological fit of the data
- Probe quark structure at 4 TeV

Highest mass jj event



M(jj) ~ 4 TeV (impressive)   MissingEt ~100 GeV

Strong Gravity

Search for monojets

- Large Extra-D (ADD):
  → Brings the Plank scale down to the TeV scale:

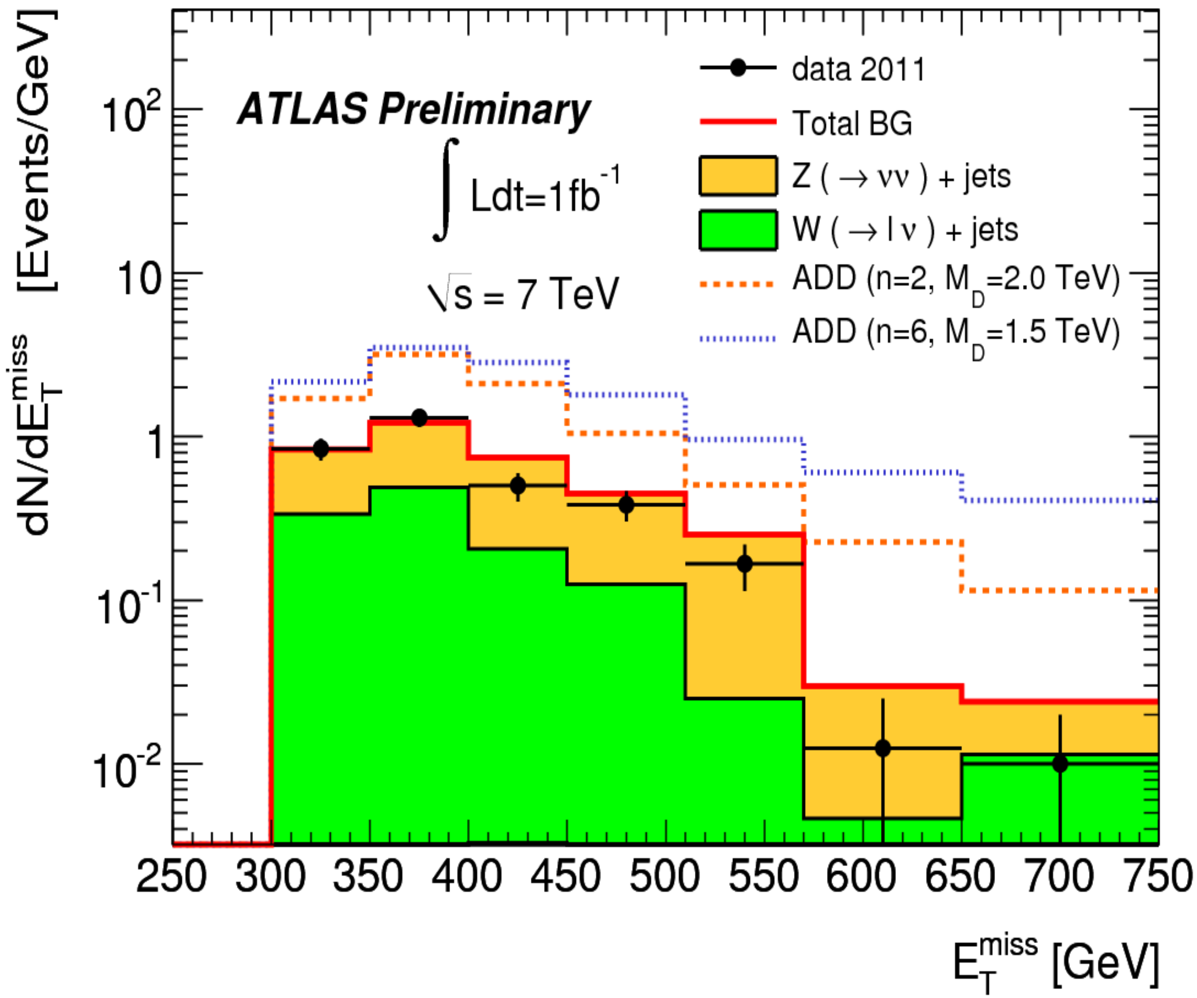
$$M_{Pl}{}^2 \sim M_D{}^{2+n} R^n$$

  → Graviton escapes detector
  Also Split SUSY

- KK massive graviton modes, produced in association with a jet

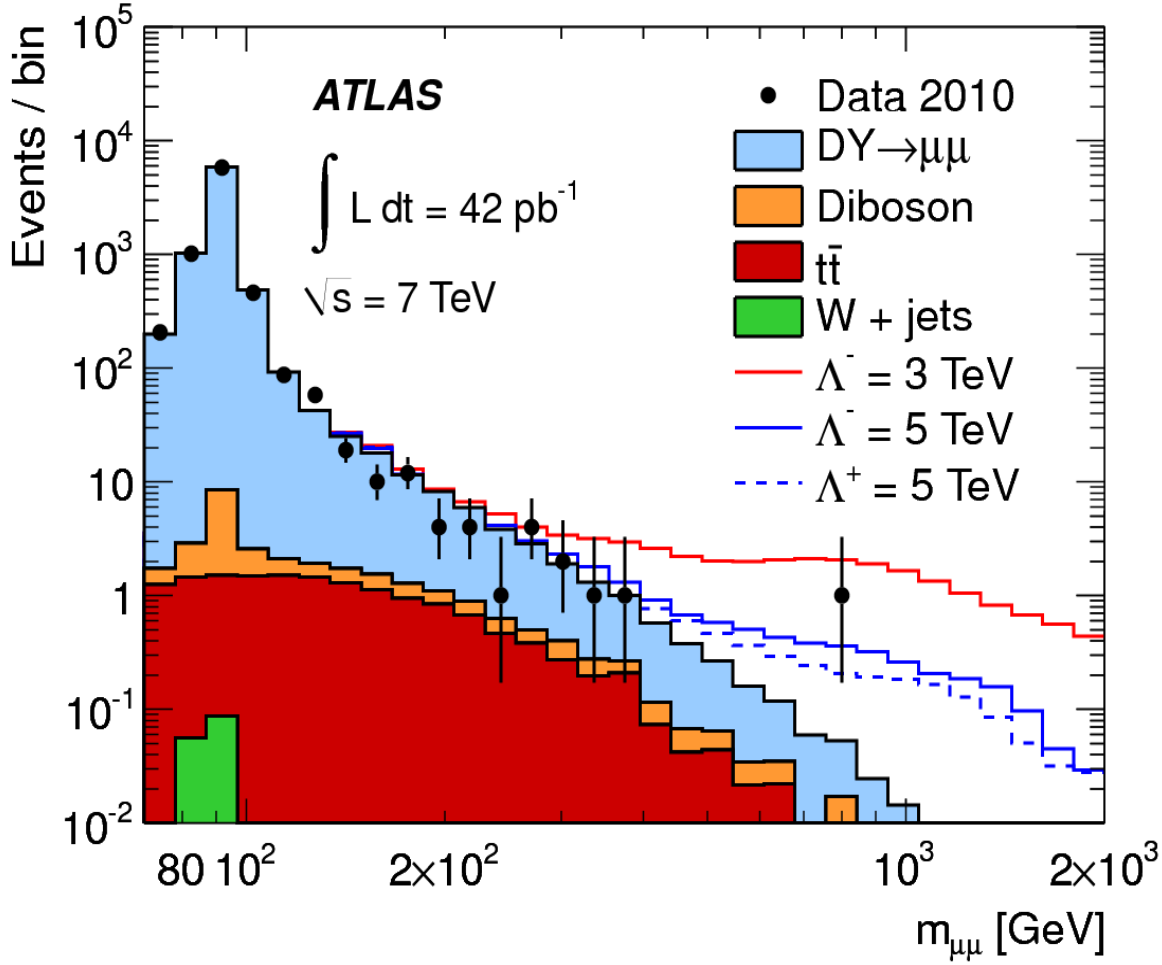
- Challenge:
  → Instrumental background
  → Understanding Z(→ νν) + jets

- M_D excluded in range 1.8 TeV-2.3 TeV, n=2-4



Contact interactions

- Phenomena BSM such as LED (in ADD model), or quark/lepton compositeness may be described as a four-fermion contact interaction
- Analogue to Fermi theory of β decay
- Experimentally interesting: no resonance peak, rather continuous change in shape. Good understanding of performance of very high-pt leptons
- Λ > 4.9(4.5) TeV excluded for constructive(destructive) interference

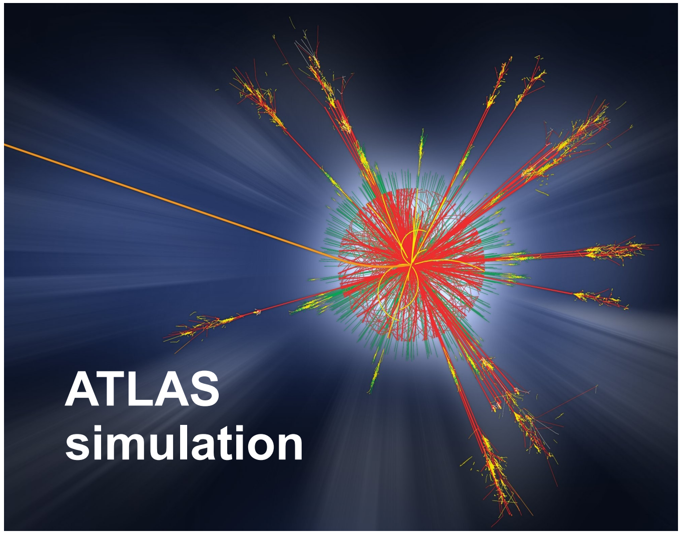


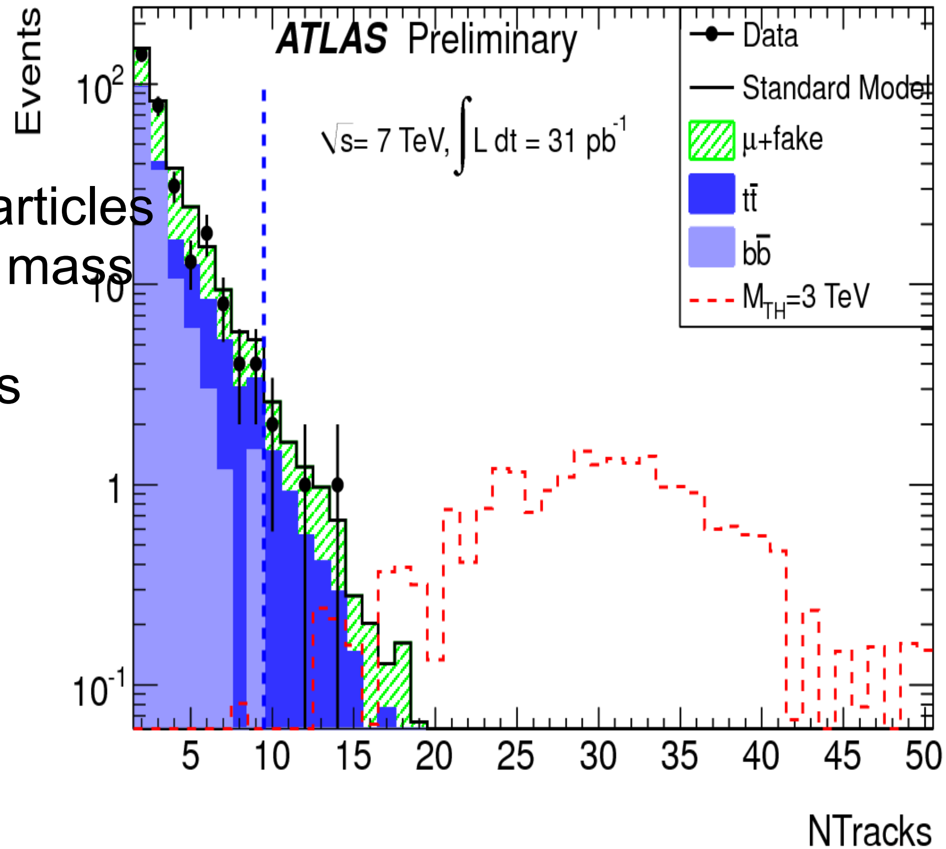
Inevitable black holes

- Microscopic black-holes decaying through Hawking radiation
- Large uncertainty on models due to our ignorance of quantum gravity
- Semi-classical models only for m(B.H.) >> m(threshold)
- A safe bet: decay is democratic and isotropic. Likely large multiplicity of particles → look or (many) jets and leptons at high mass
- Inclusive search: sum energy of all objects (e, μ, jets)

→ Can also select peculiar events, e.g. same-sign dilepton with very large track multiplicity

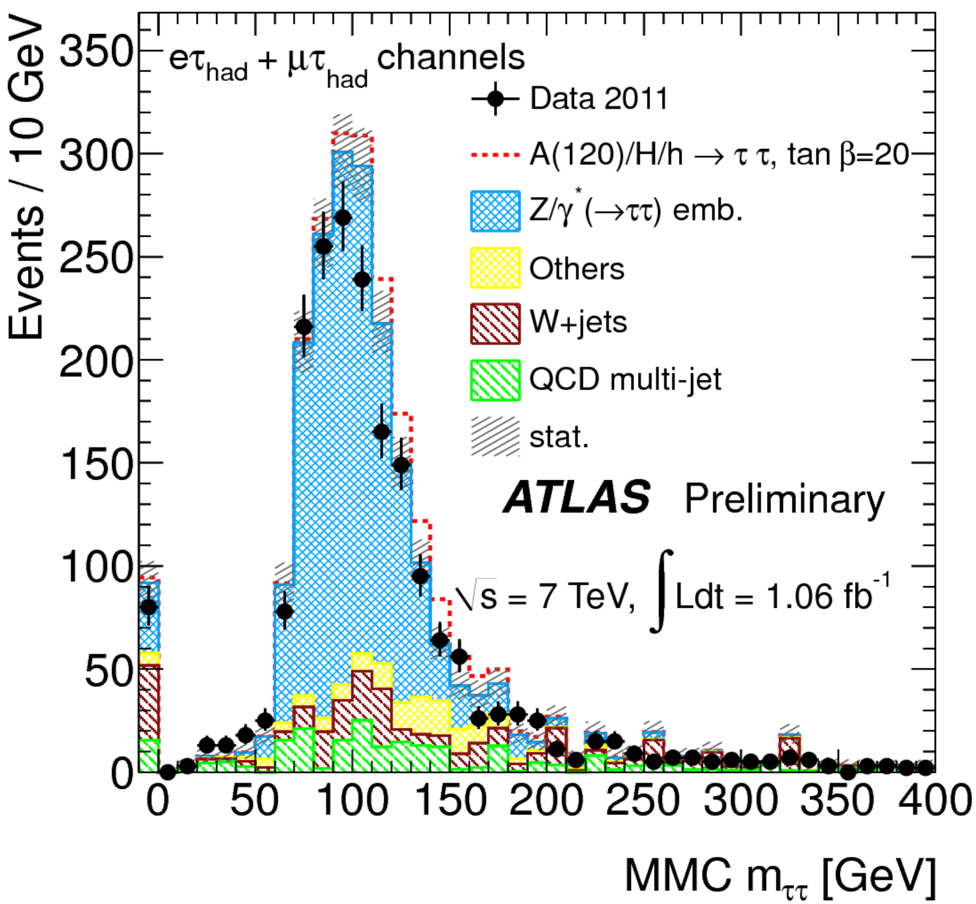
- No deviation from SM

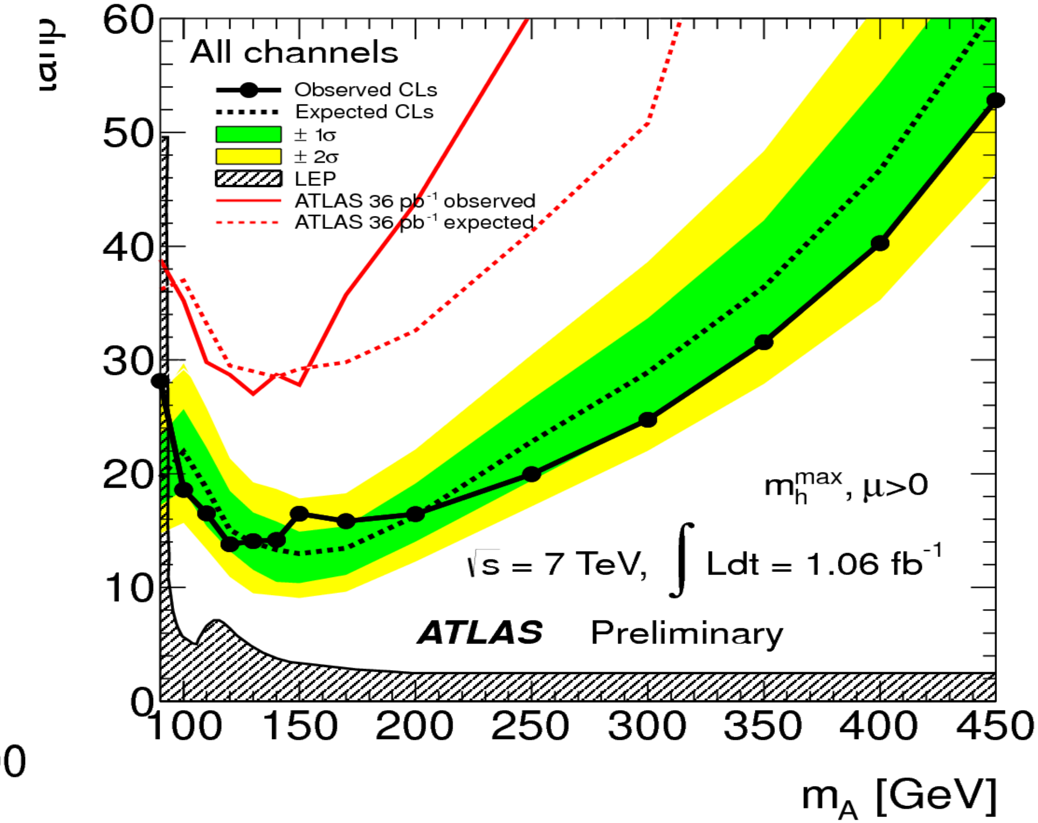




Non-SM Higgs

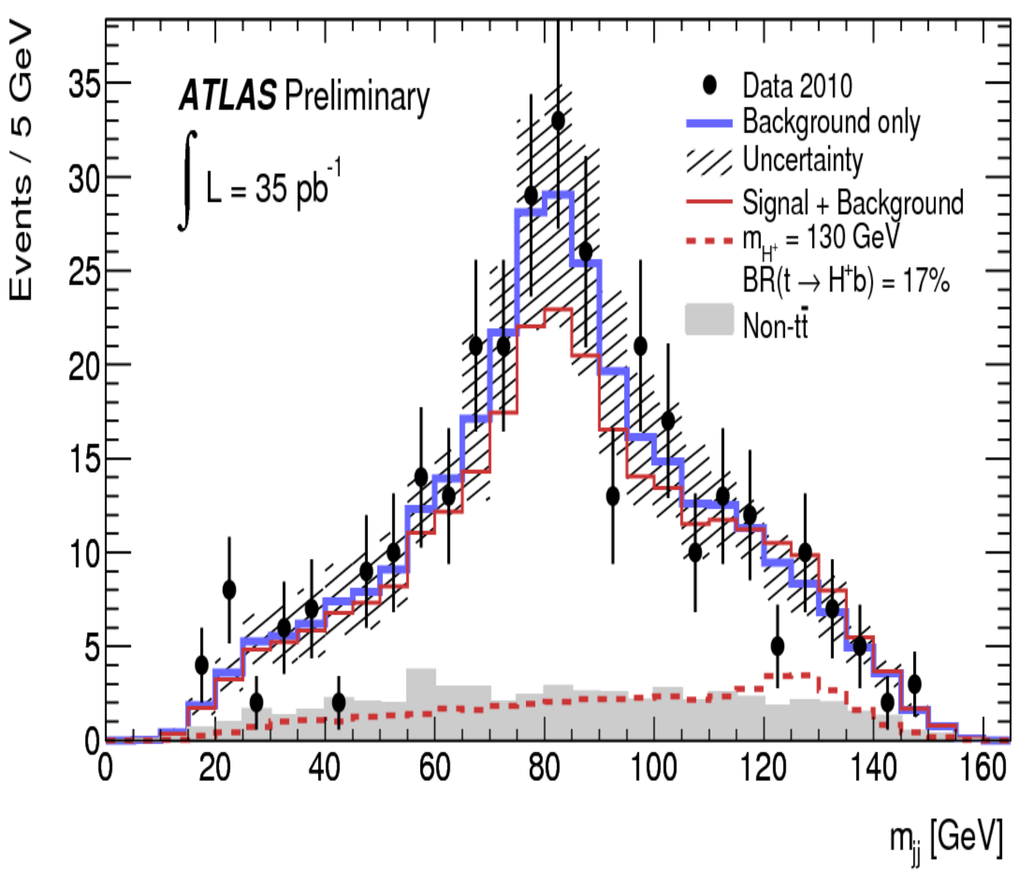
MSSM H/A → ττ

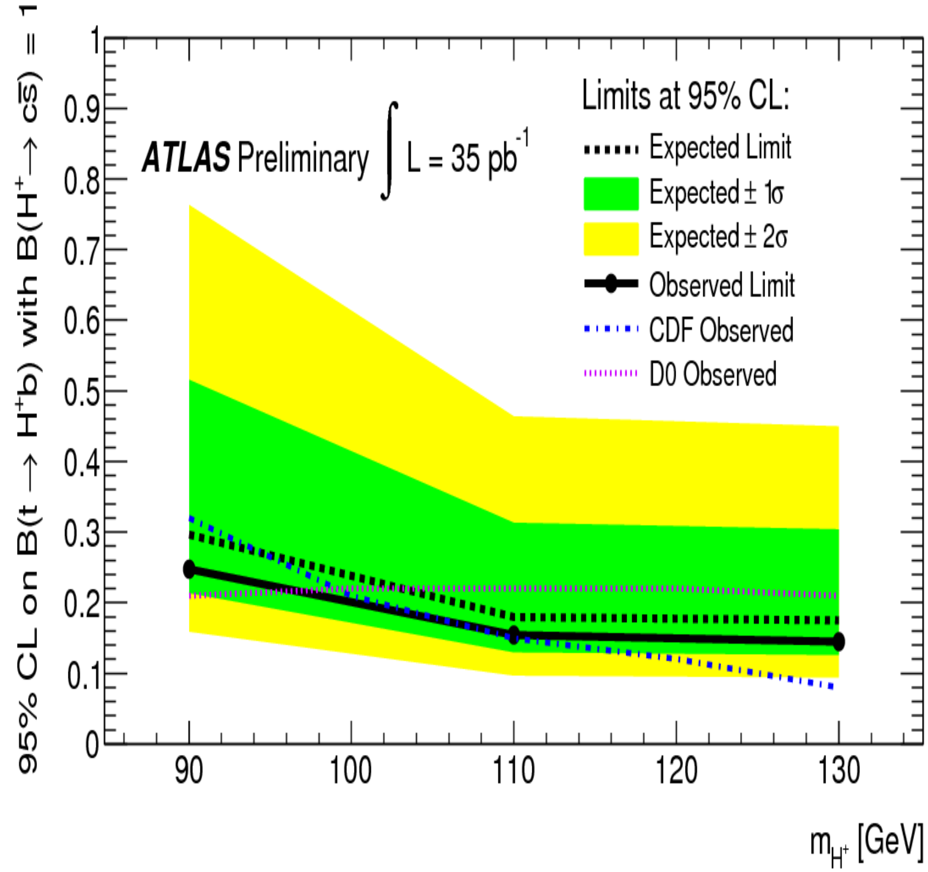




- Candidates for A/H/h->tautau decays are selected in the four final states eμ, ehad, μhad and hadhad.
- No evidence for a Higgs boson signal is observed. Exclusion limits on both the cross section for the production of a generic Higgs boson as a function of its mass and on MSSM Higgs boson production A/H/h as a function of m_A and tanβ , are derived.
- Regions of parameters space beyond the existing limits from LEP and Tevatron.

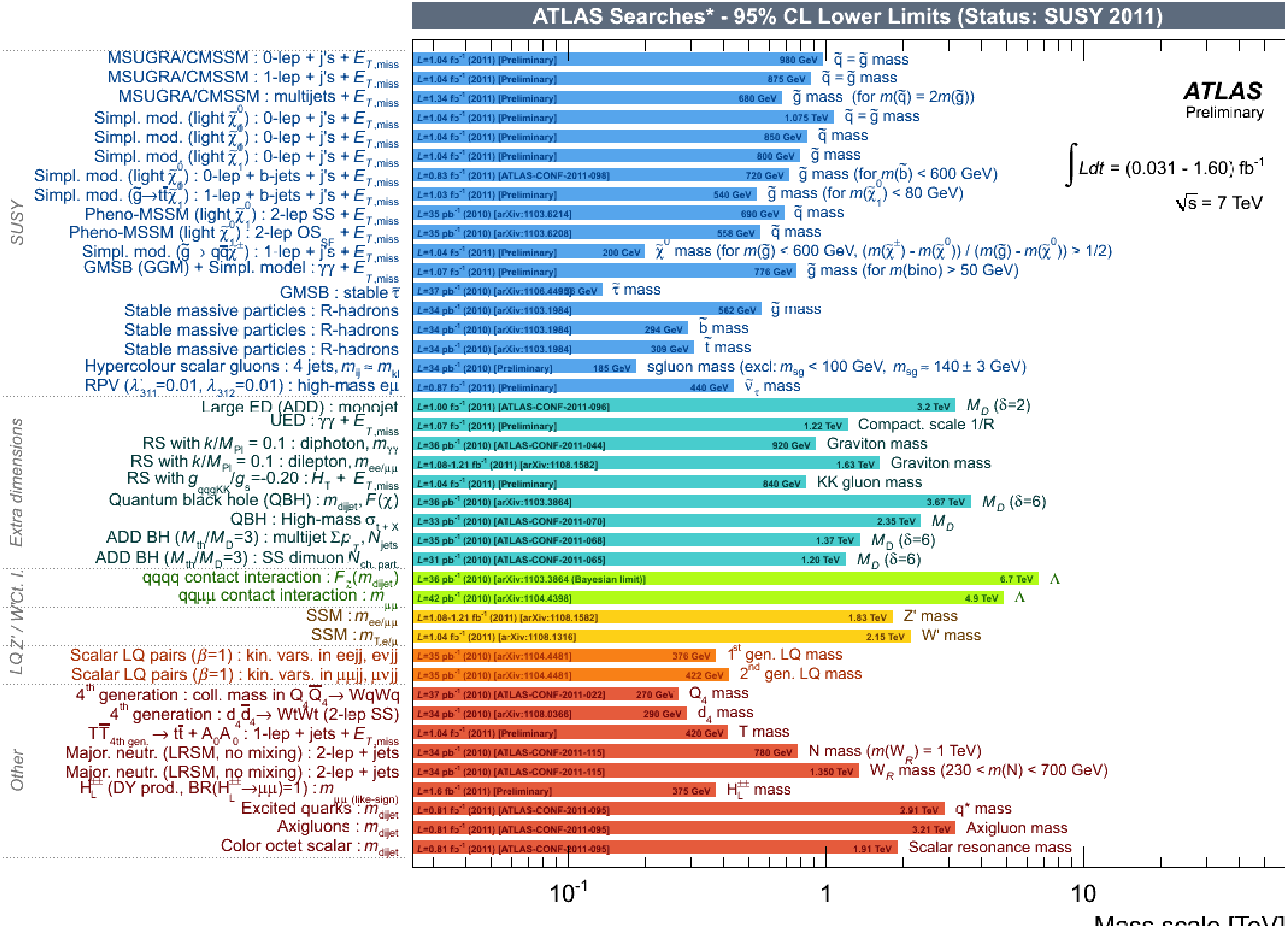
Charged Higgs



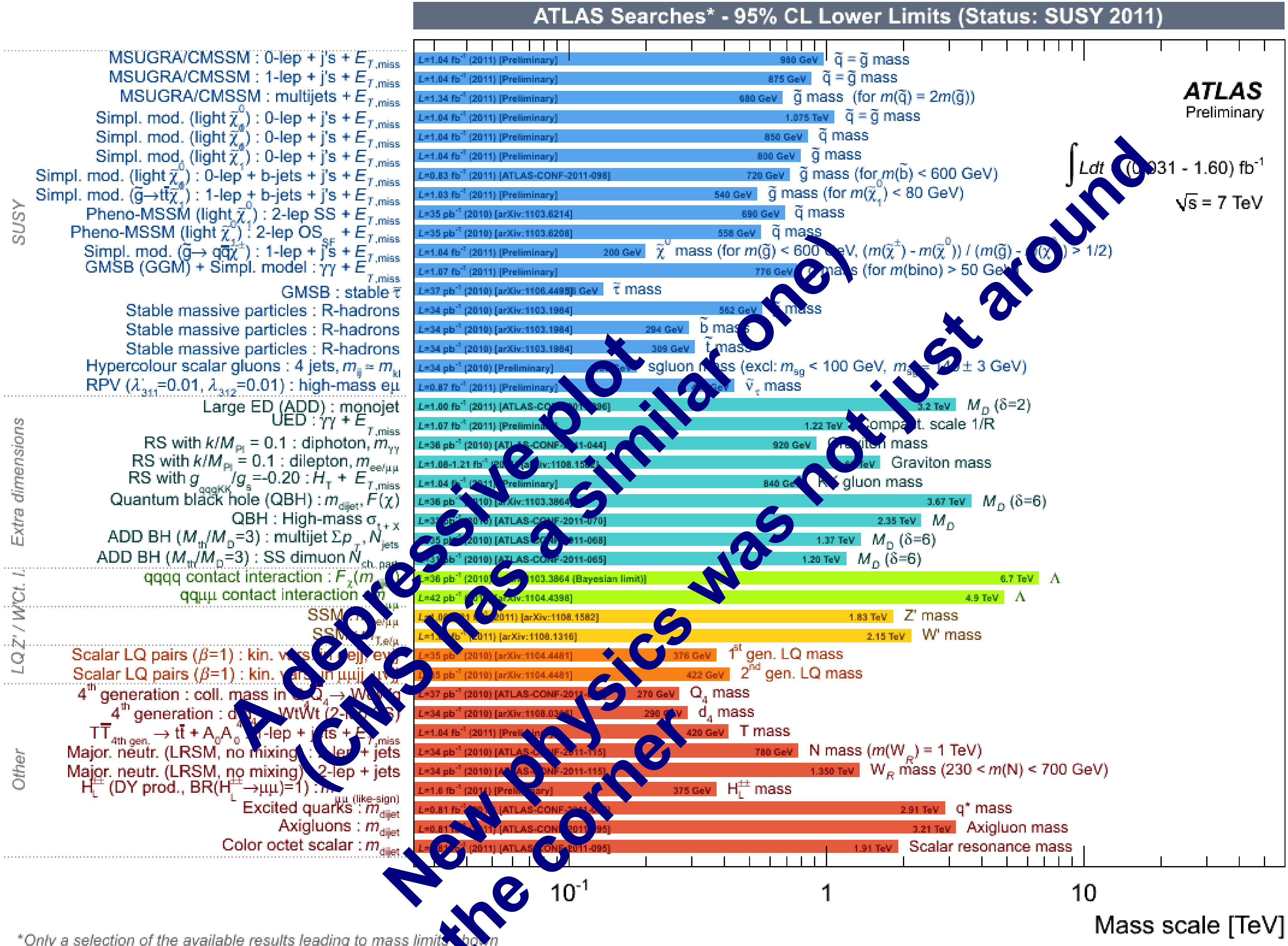


- Charged Higgs in jj chanel studied.
- Assuming 100% BR to charm-strange pairs
- Limits are comparable to the results from the Tevatron.

Summary

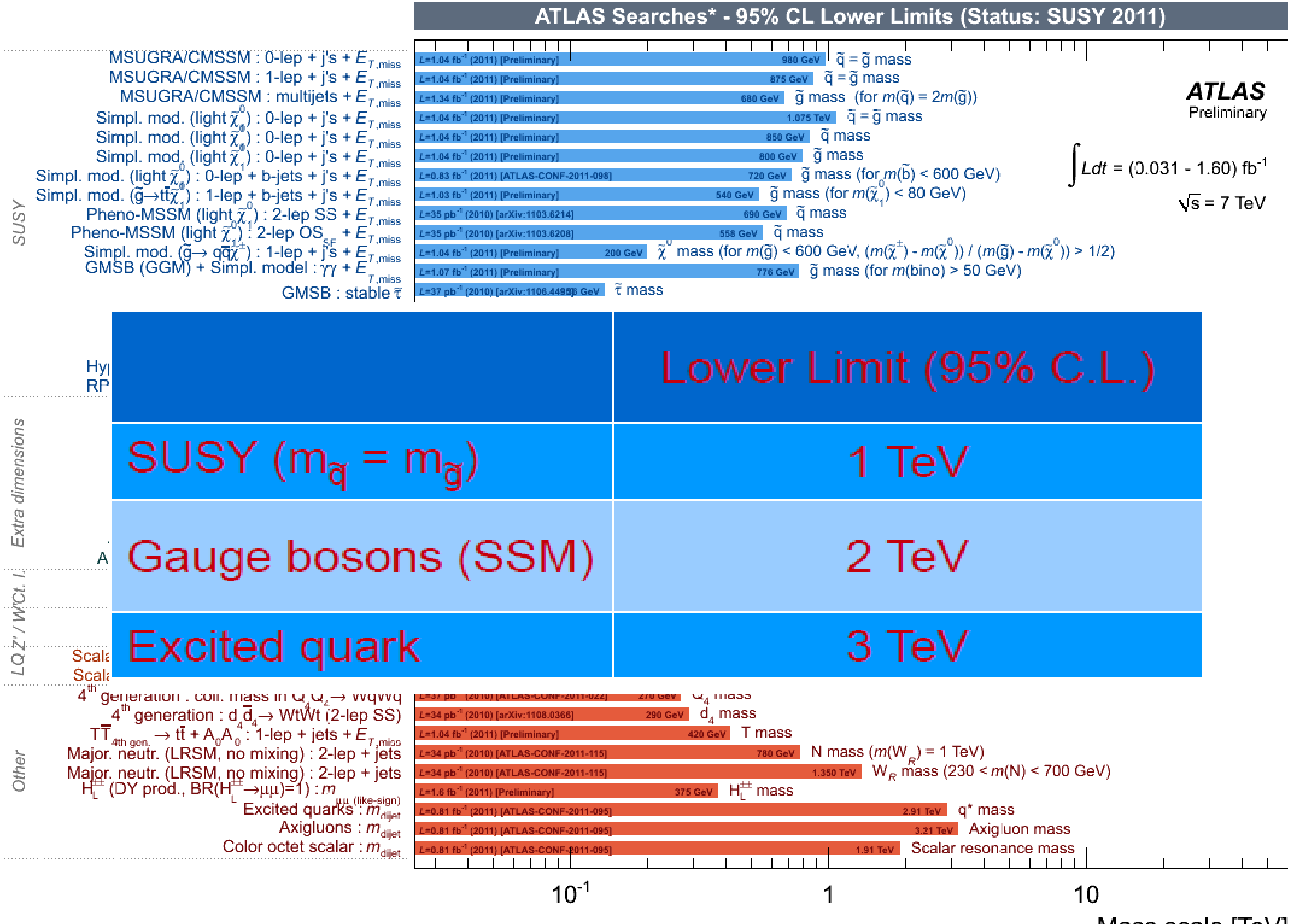


*Only a selection of the available results leading to mass limits shown



A depressive plot (CMS has a similar one)

New physics was not just around the corner



	Lower Limit (95% C.L.)
SUSY ($m_{\tilde{q}} = m_{\tilde{g}}$)	1 TeV
Gauge bosons (SSM)	2 TeV
Excited quark	3 TeV

*Only a selection of the available results leading to mass limits shown

Few general and personal comments

- SUSY in its most-hoped-for-incarnation on pressure (life support some say)
→ Of course ATLAS will continue looking and increasing the reach

- What if SUSY were hiding? (e.g. no Missing ET)
→ "Split", "low-MET", "squashed", "mashed?"
→ Even if very soft cascade at tree level, Initial State Radiation still creates MET, but this needs to be studied further

- With >1 fb-1, other SUSY production mechanisms open up
  → exclusive chargino/neutralino and 3rd generation production

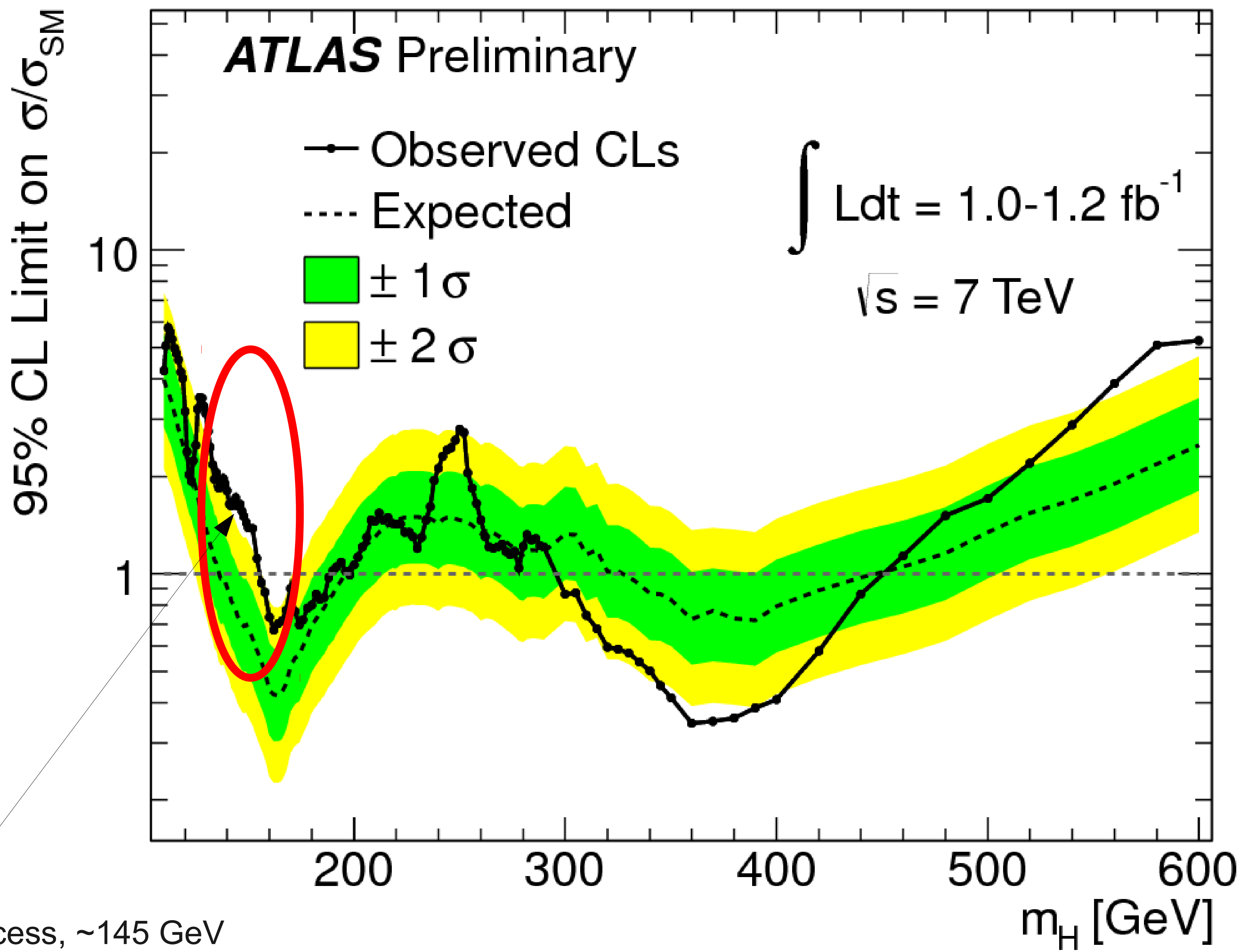
- Experimental challenges as we enter further the Multi-TeV: understanding very energetic leptons and jets...

- However, *this is only the beginning.*

- The moto of this conference is "New Ideas for (old) unsolved problems".
  So, this is also fun time for theorists and phenomenologists for new ideas: maybe something is missed in the LHC data!

THANK YOU!

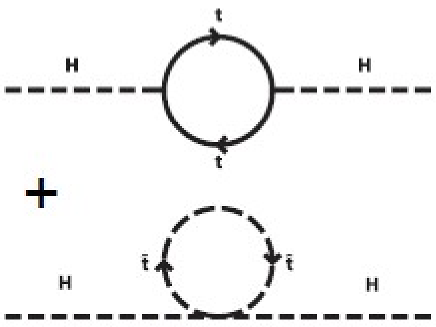
Backup



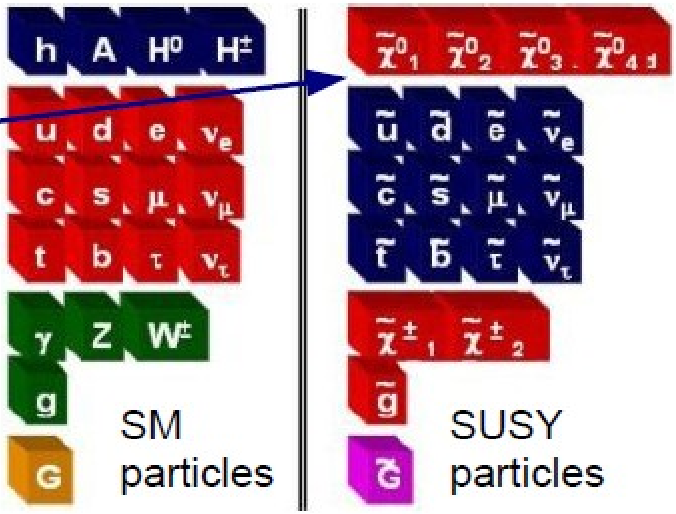
Excess, ~145 GeV

Supersymmetry

- Extension of the Poincaré algebra
- Fermion ↔ Boson symmetry
- Solves many problems of the SM, esp. stabilizes Higgs sector
- If R-parity ($R = (-1)^{3(B-L)+2s}$) is conserved, Lightest SUSY Particle (LSP) is an excellent Dark Matter candidate
- Phenomenology is **very** diverse



≈ 0 (if $\tilde{t}$ is light)



Wjj a la Tevatron

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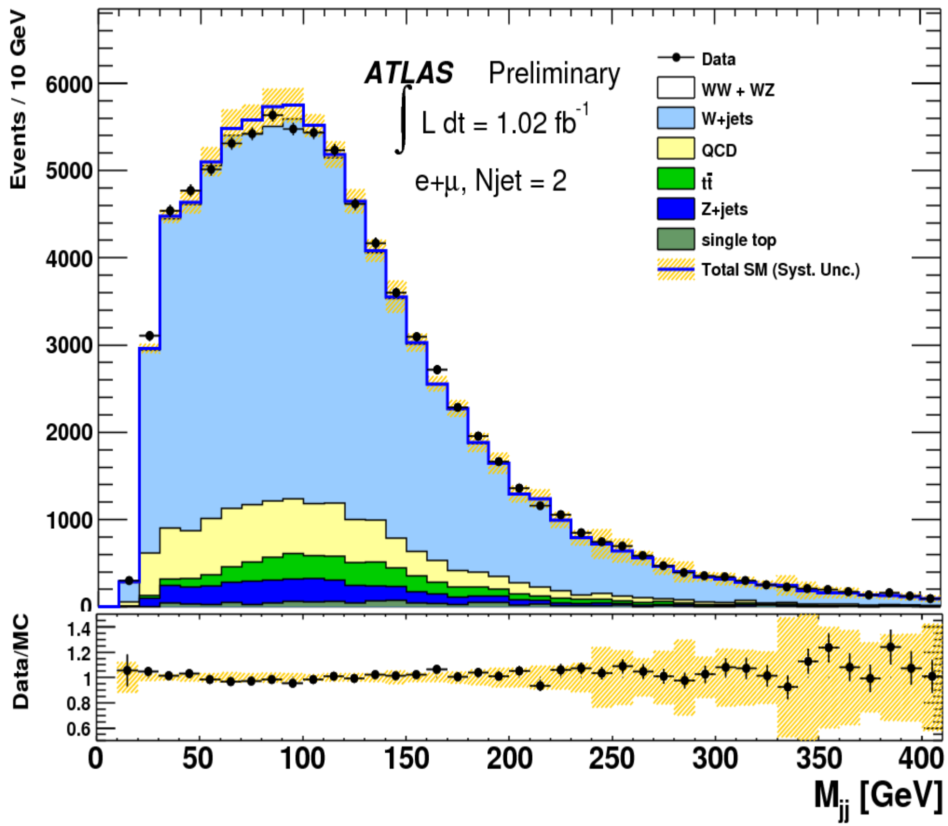

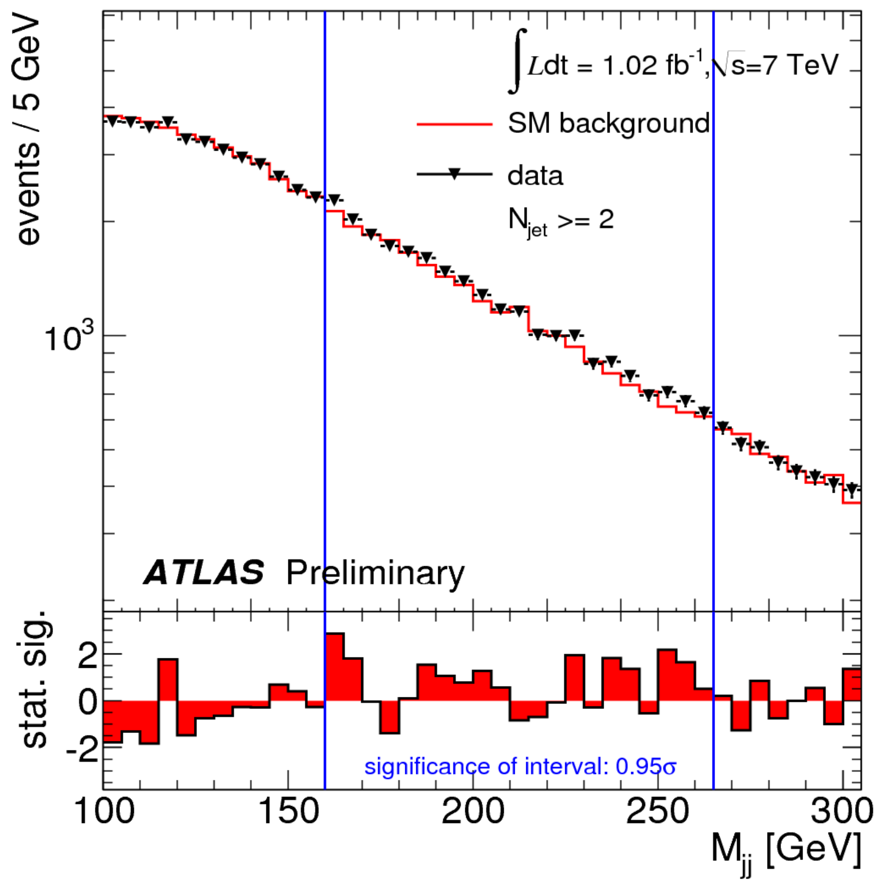

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Supersymmetric Models to Study

- Gravity-mediated:
  - NUHM2
    - as below, $m_{hu} \neq m_{hd}$
  - NUHM1
    - as below, common $m_h \neq m_0$
  - CMSSM
    - m_0, $m_{1/2}$, tan β (B_0), A_0
  - VCMSSM
    - as above, & $A_0 = B_0 + m_0$
  - mSUGRA
    - as above, & $m_{3/2} = m_0$
  - RPV CMSSM

Also studied in global fits

Most studied in global fits

Some Global fits

- Other SUSY models:
  - Gauge-mediated
  - Anomaly-mediated
  - Mixed modulus-anomaly-mediated
  - Phenomenological 19-parameter MSSM
  - NMSSM

Less studied in global fits

If model has N parameters, sample 100 values/parameter: 10^{2N} points, e.g., 10^8 in CMSSM

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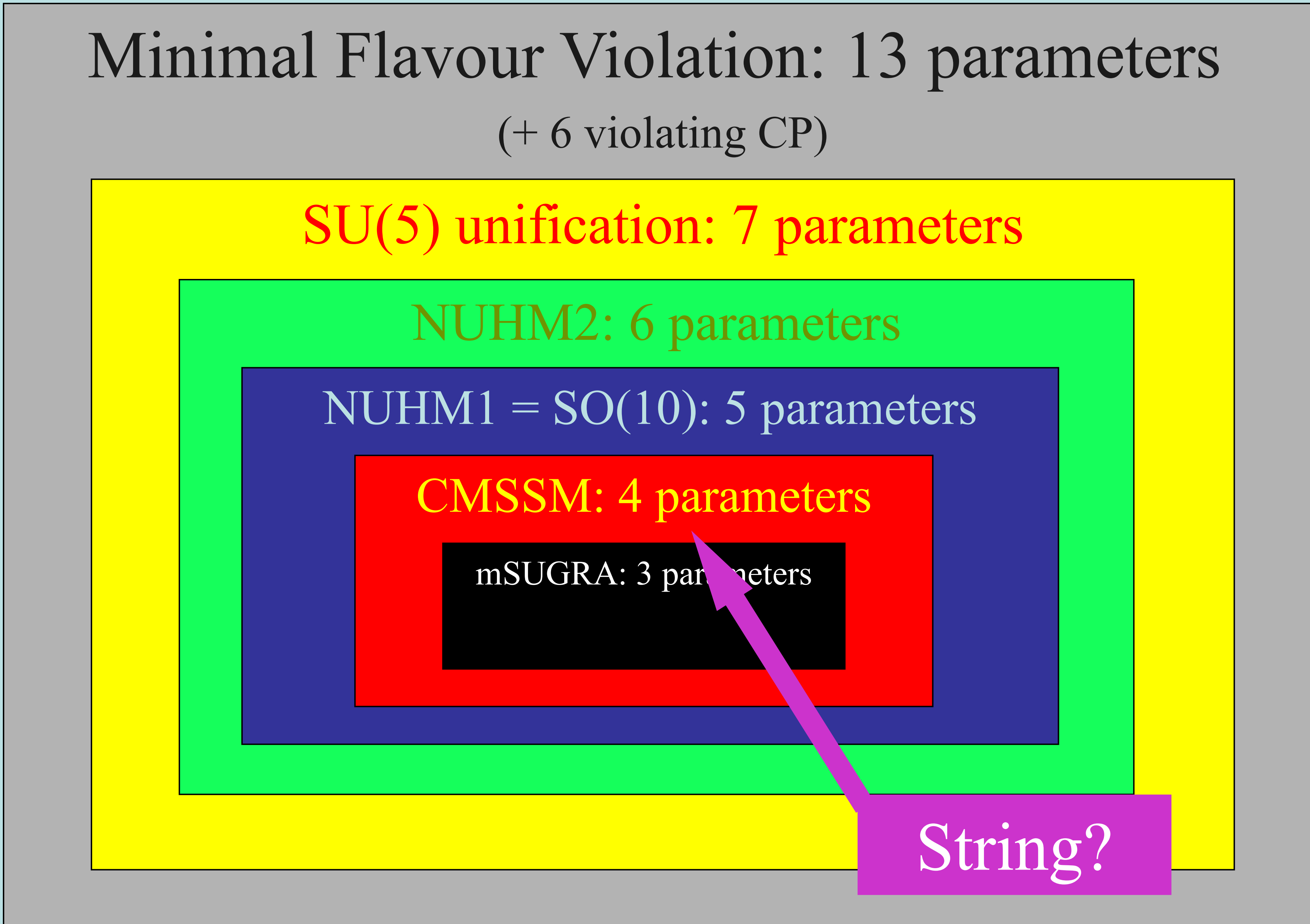
MSSM: > 100 parameters



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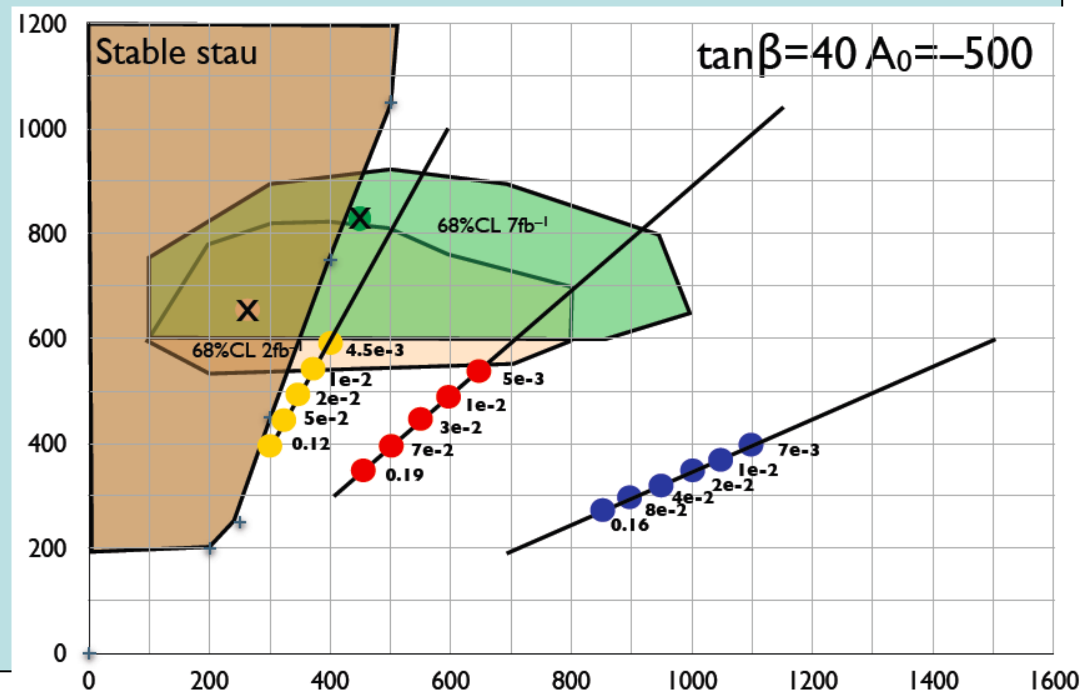
Sustainable Benchmarks

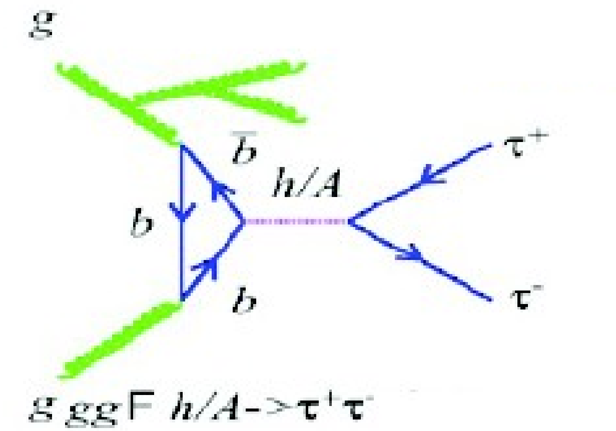
- Many models:
  - CMSSM, NUHM1, RPV-CMSSM, mGMSB, mAMSB, MM-AMSB and pMSSM
- Benchmark planes, lines & points, e.g., CMSSM
  - Varied signatures
  - Similar along lines
  - **Move to next point if/as needed**

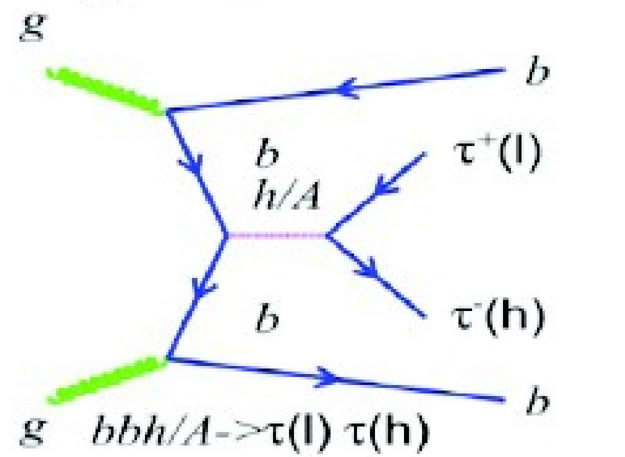


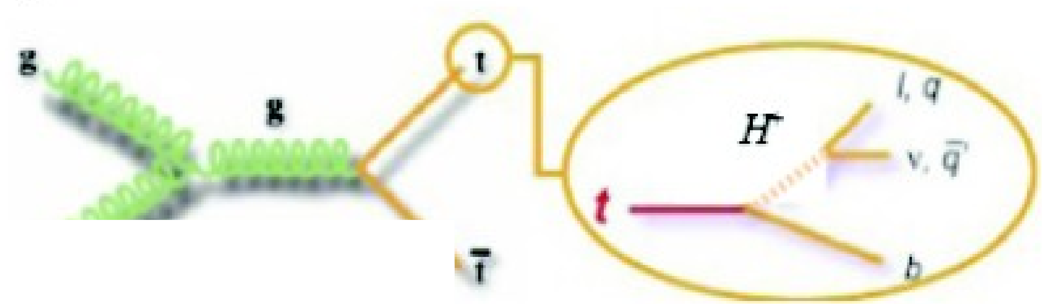
AbdusSalam, Allanach, Dreiner, Ellis, Heinemeyer, Krämer, Mangano, Olive, Rogerson, Roszkowski, Weiglein

MSSM Higgs(es)

- MSSM Higgs sector
  - 5 bosons h/H/A, H+, H-
  - Higgs sector: determined by two parameters; at tree level: tan β and m_A (or m_{H+})
- Major production modes:
  - h/H/A: gg-fusion, b-associated
  - Light H+: top quark decays
  - *[Heavy H+: gg/gb-fusion]*
- Dominant decay modes
  - h/H/A → ττ
  - H+ → τν, for small tan β: $H^+ \rightarrow cs$

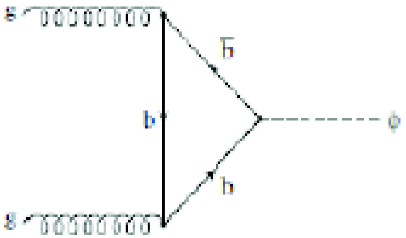


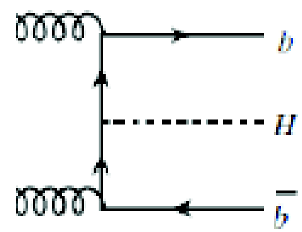




MSSM H/A → ττ

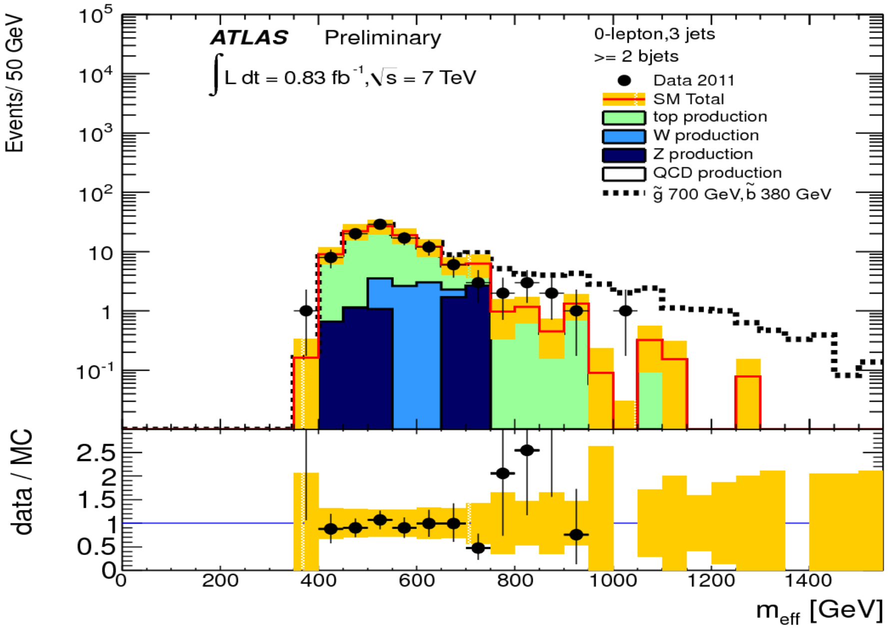
- In MSSM the decay of neutral Higgs(es) to tau-lepton pairs strongly enhanced for large regions of the parameter space: → H/A/h→ττ is one of the most promising channels for Higgs searches at the LHC
- Production: gg→A/H/h and associated bbA/H/h
- Study the final states:
  - H→eμ4ν
  - H→eτ_{had}3ν, μτ_{had}3ν
  - H→$\tau_{had}\tau_{had}$2ν
- Event selection: ask high-p_T, isolated leptons, large E_t^{miss}, good quality high-pT hadronic taus
  - More sophisticated method than the collinear approximation to evaluate the $m_{\tau\tau}$ mass is used for lτ_{had} final states

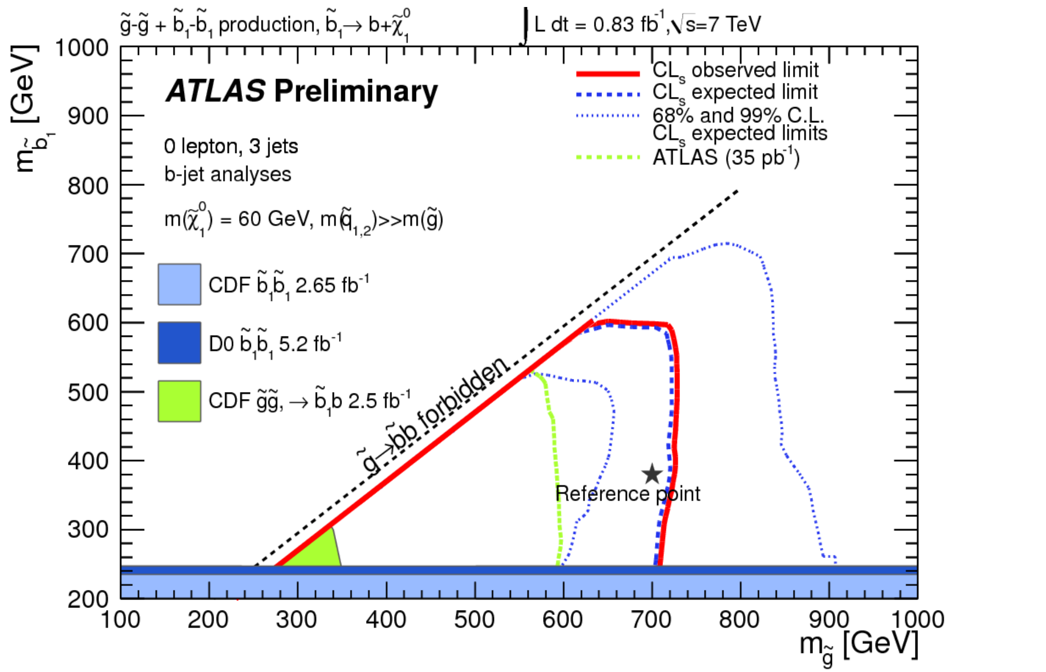




$gg \to b\bar{b}H$

b-jets, 0 lepton, 0.83/fb





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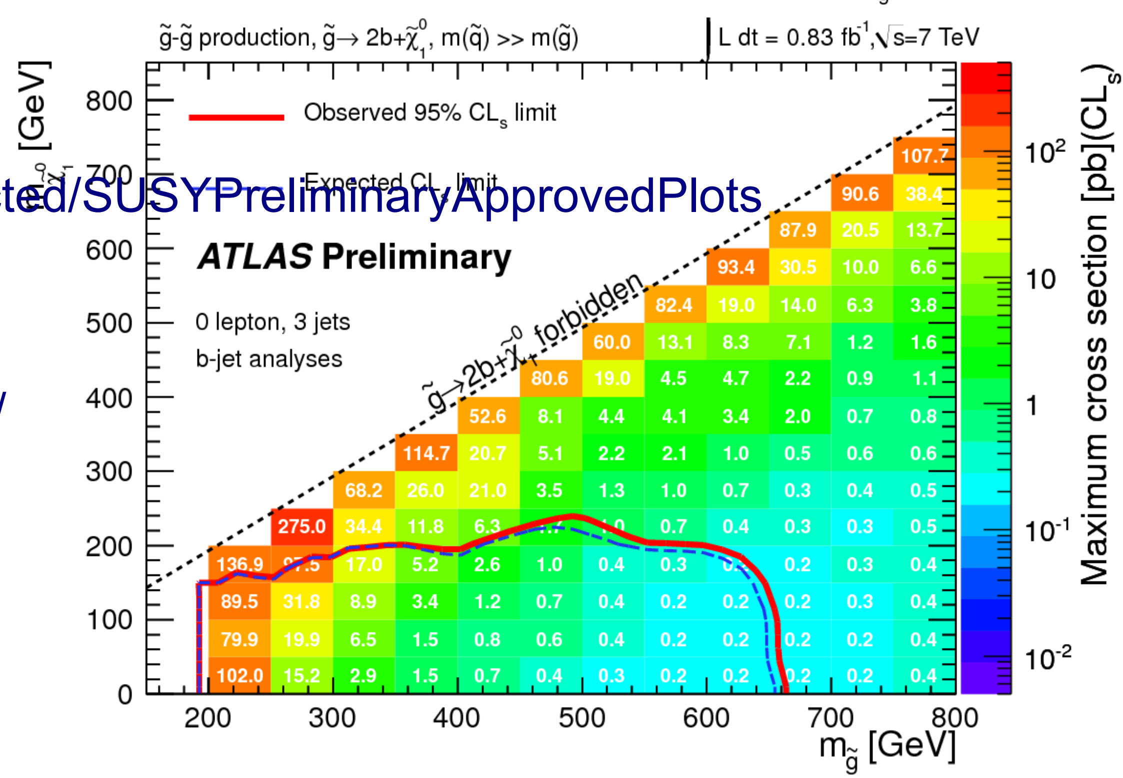

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults