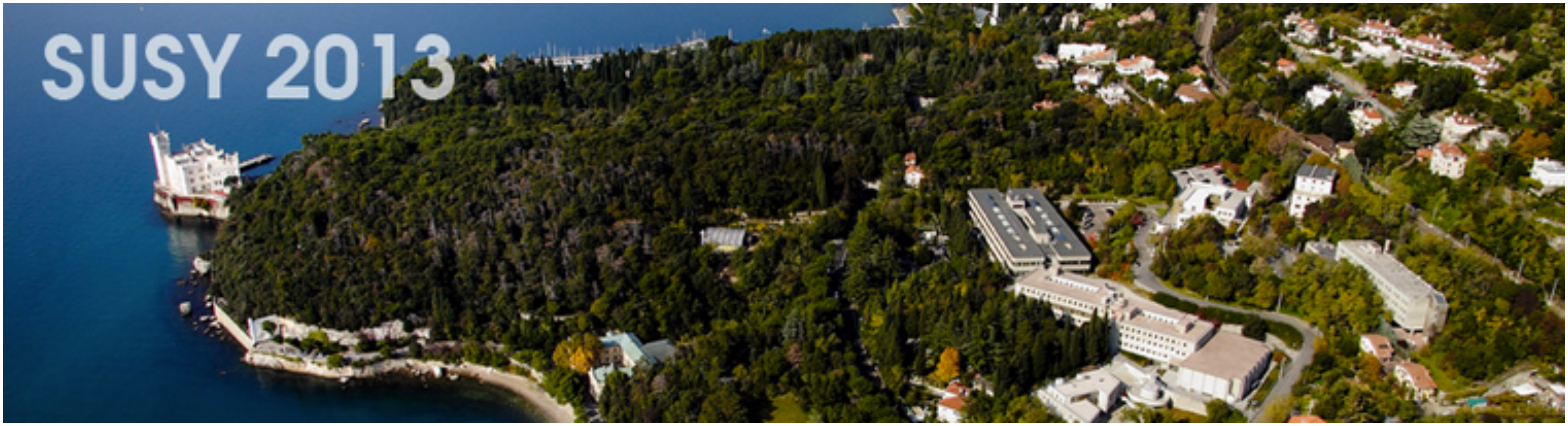

Searches for supersymmetry in resonance production and R-parity violating signatures with the ATLAS detector.

Nick Barlow

University of Cambridge

Contents

- Introduction to R-Parity violating SUSY.
- Multi-jet resonance searches.
  - Resolved jets (*ATLAS-CONF-2013-091*).
  - Boosted jets (*JHEP 1212 (2012) 086*).
- Multi-lepton search (*ATLAS-CONF-2013-036*).
- e/mu/tau resonance search (*Phys.Lett. B723 (2013) 15-32*).

R-Parity violation

- R-Parity is defined as $P_R = (-1)^{3(B-L)+2S}$.
  - B, L, S are Baryon number, Lepton number, and Spin respectively.
  - All SM particles have $P_R = 1$, all SUSY particles have $P_R = -1$.
- Many SUSY models assume R-Parity conservation.
  - Stable LSP is a good dark matter candidate!
- BUT no reason to assert this a priori.
- Can introduce R-Parity Violating terms into superpotential:

$$\lambda_{ijk} L^i L^j \overline{E}^k + \lambda'_{ijk} L^i Q^j \overline{D}^k + \lambda''_{ijk} \overline{U}^i \overline{D}^j \overline{D}^k + \epsilon_i L_i H_2$$

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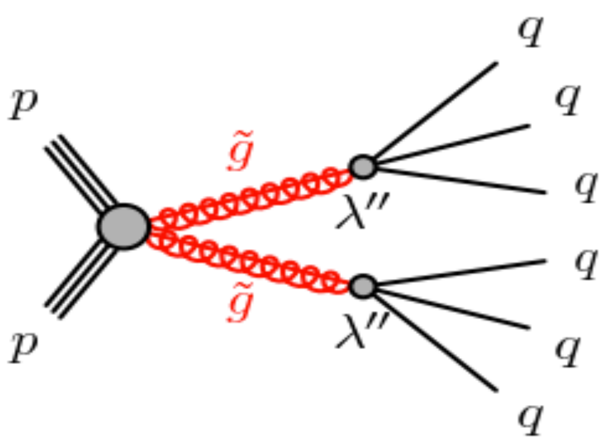
i,j,k are generation indices

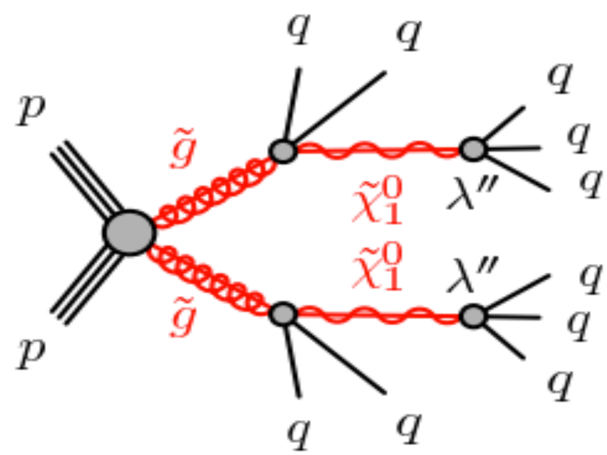
Constraints on RPV couplings

- Non-observation of proton decay effectively excludes processes that violate both lepton and baryon number.
  - Many RPV models assume "single coupling dominance", i.e. turn-on one coupling, leave the others as zero.
- CKM unitarity, τ decays, limits on neutrino masses, give upper limits on λ couplings
  - (arXiv:0910.4980, arXiv:1005.3309).
- Stringent limits on λ''_{11k} from neutron oscillation.
- But, only relatively weak constraints on third-generation λ'' couplings!
- Note that non-zero but small values of couplings would lead to long-lived signatures, e.g. displaced vertices.
  - Lifetime is proportional to $1/(\text{coupling})^2$.
  - See talk by Nimrod Taiblum for an example of ATLAS search for displaced vertices arising from small λ' coupling.

Multi-jet search

- If RPV couplings are small, R-Parity Conserving pair-production of sparticles will dominate, RPV couplings give rise to decay of LSP.
- Non-zero λ'' coupling can give rise to final states with high jet multiplicity.





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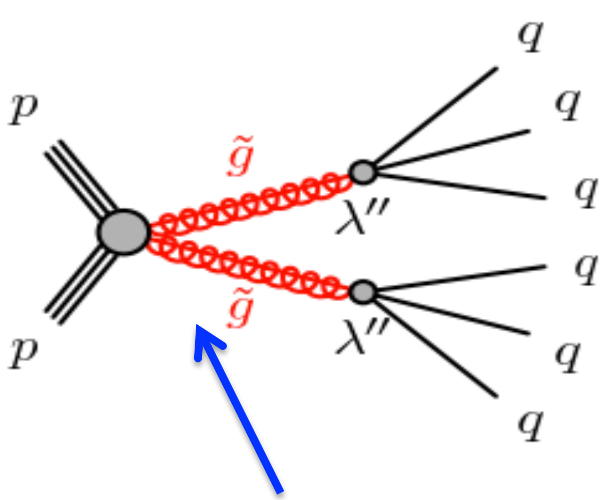
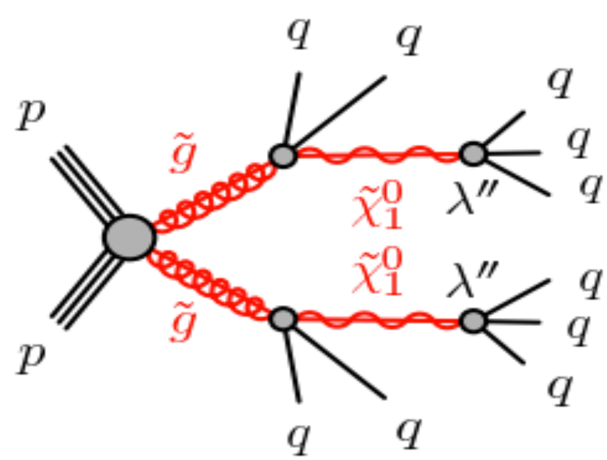


"6-jet model"



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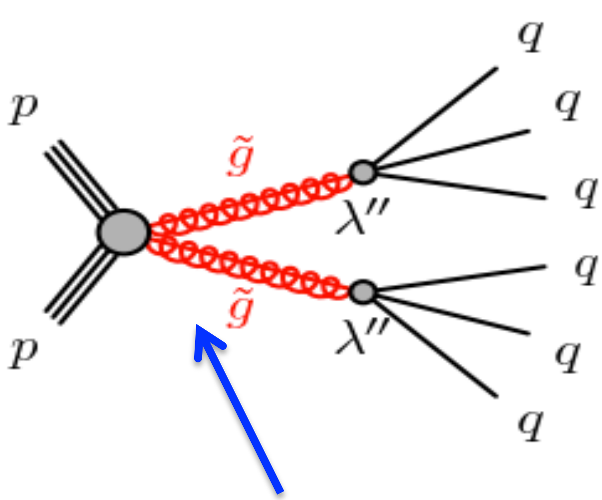

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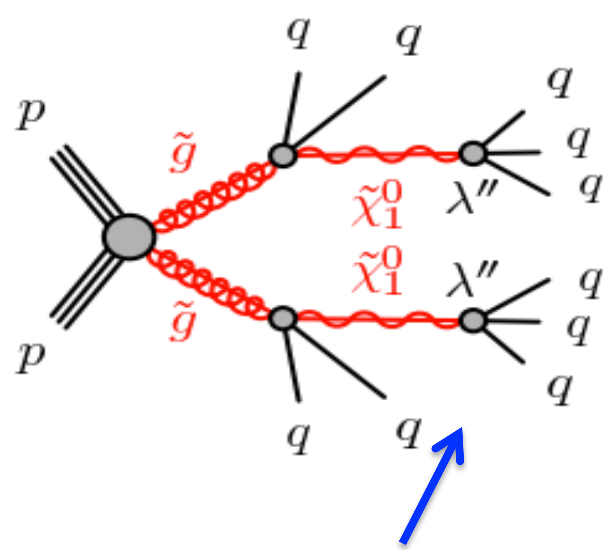

"10-jet model"

Multi-jet search

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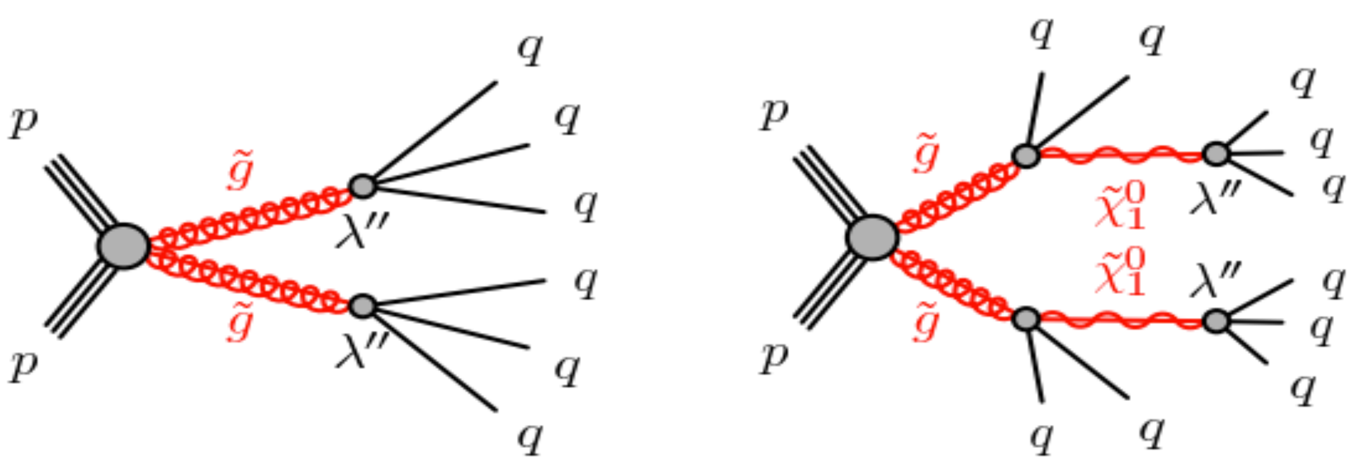

- Huge number of possible jet combinations (even just in signal events) precludes measurement of a resonance "peak".
- Instead, look for an excess of events with large number of high-pT jets.

Multi-jet search: selection and background

- Previous analysis on 2011 data (arXiv:1210.4813)
- New feature – use *b*-tagging info to estimate branching ratios of RPV decays to different flavours.
  - Each RPV decay going via λ''_{ijk} will give rise to one up-type quark, and two down-type quarks of different flavours.
  - BR(t) + BR(c) ≤ 1, and at most one b-quark per event.
- Optimize signal regions for different BR hypotheses and different gluino masses, for 6-quark and 10-quark models, by varying N(jet)≥6 or N(jet)≥7, minimum jet p_T cut, and number of *b*-tagged jets.

- Dominant source of background is from multi-jet events.
  - Estimate by projecting from lower-jet-multiplicity bins.

$$N^{data}_{n-jet} = \left(N^{data}_{m-jet} - N^{MC}_{m-jet,\ OtherBGs}\right) \times \left(\frac{N^{MC}_{n-jet}}{N^{MC}_{m-jet}}\right) + N^{MC}_{n-jet,\ OtherBGs}$$

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ttbar, Single top W+jets

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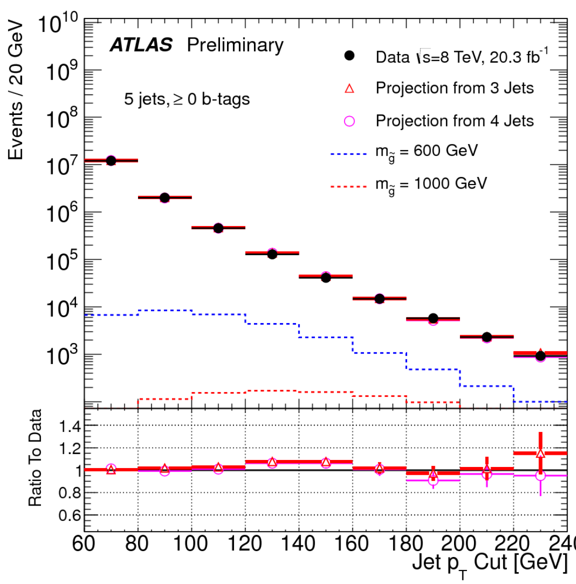
Projection factor derived from MC

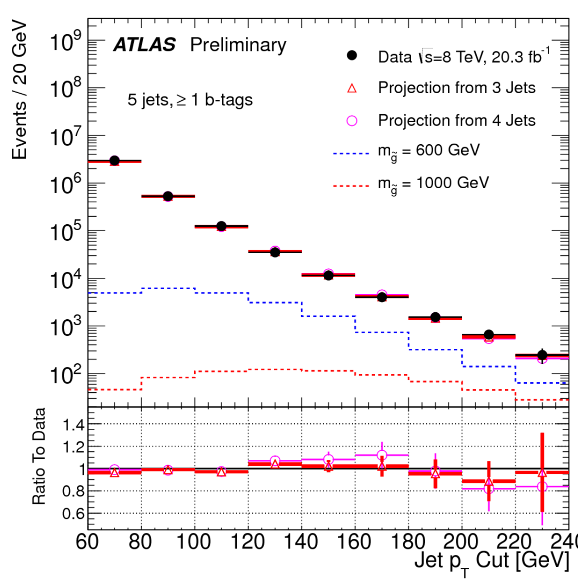
$$N^{data}_{n-jet} = \left(N^{data}_{m-jet} - N^{MC}_{m-jet,\ OtherBGs}\right) \times \left(\frac{N^{MC}_{n-jet}}{N^{MC}_{m-jet}}\right) + N^{MC}_{n-jet,\ OtherBGs}$$

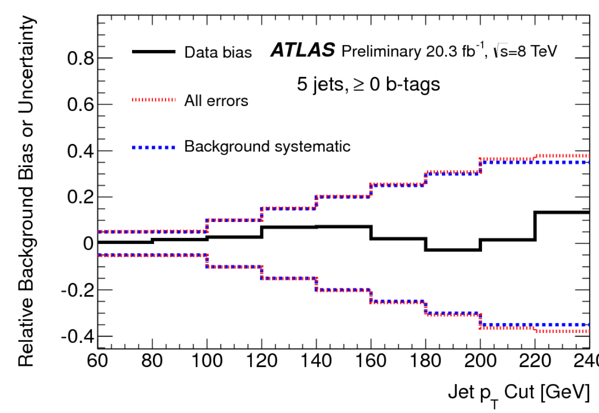
Multijet search – validation of background method

- Projection method is "calibrated" using the data.
- Baseline projection is from (N-2)-jets to N-jets, with same p_T cut and number of b-tags.
  - Also validate with projection from (N-1) jets.
  - For large N, look at low p_T or large η to avoid signal contamination.

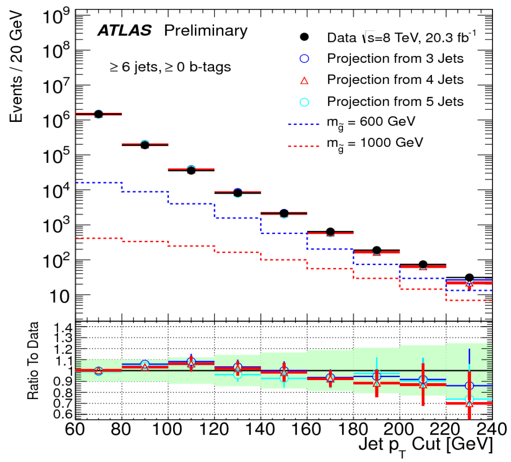
Use worst-case discrepancies from all projections to derive systematic uncertainties.



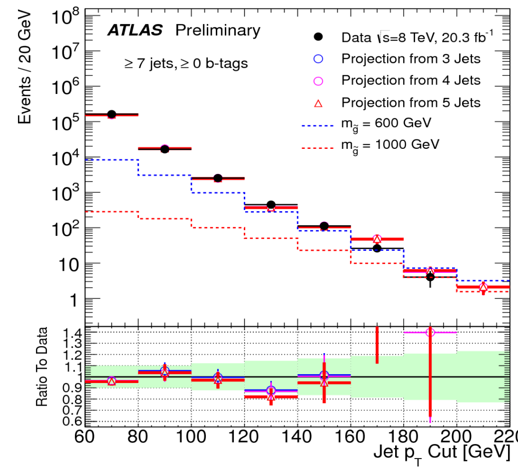




Multi-jet search: results



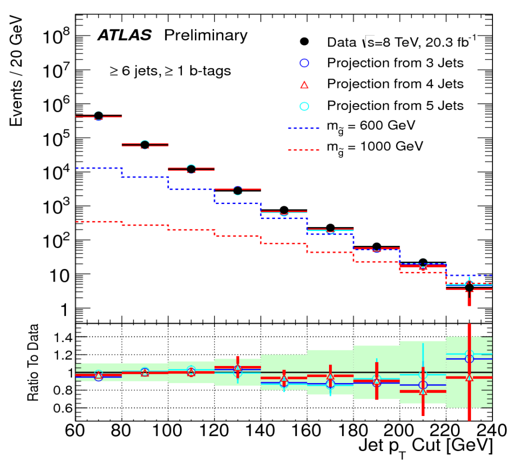
0 b-tagged jets



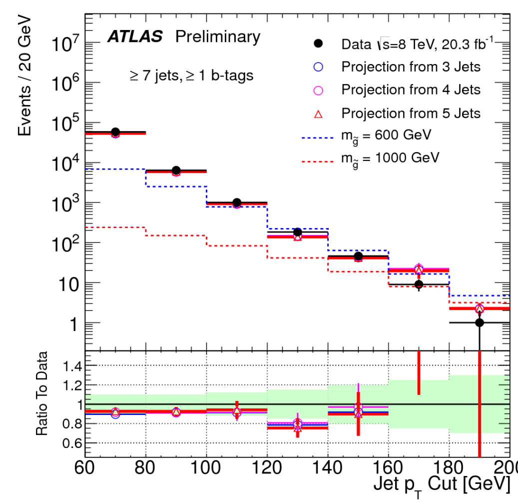
≥6 jets

Using full ATLAS 2012 dataset (20.3 fb^{-1}), no significant excess observed in any signal region.

≥7 jets

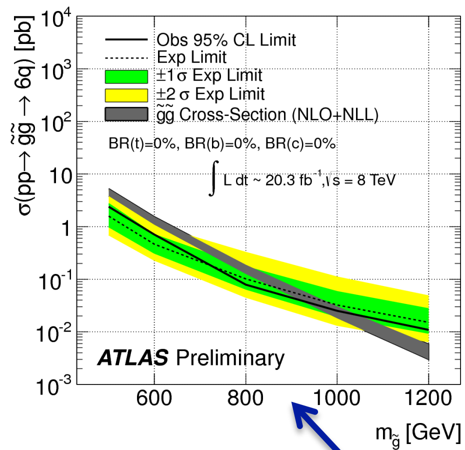


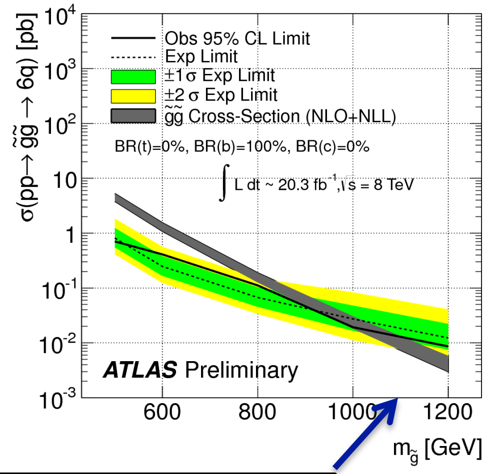
1 b-tagged jet



Multi-jet search: cross-section limits

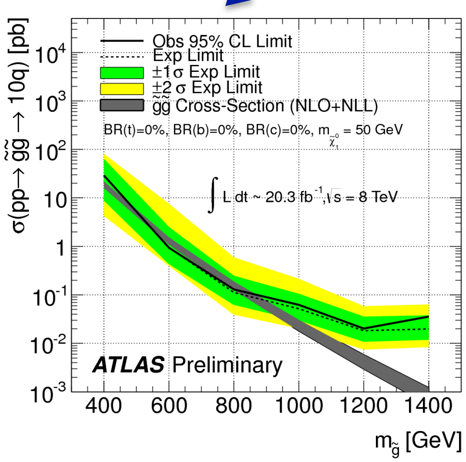
Set 95% CL upper limits on cross-section, for 6- and 10-quark models, and different assumed branching ratios.

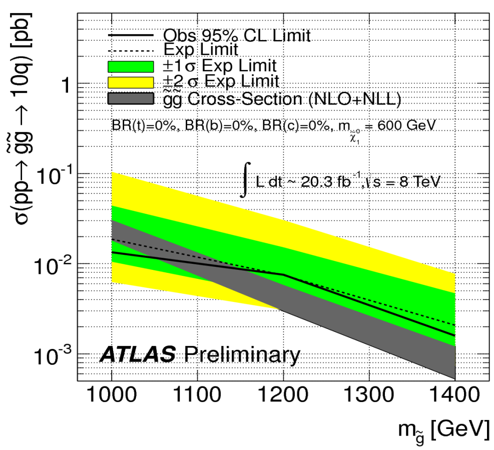




6-quark model

10-quark model





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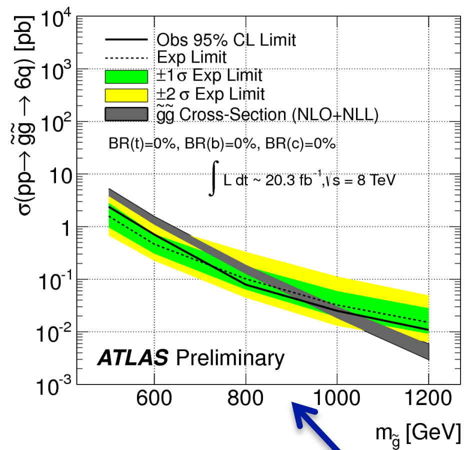

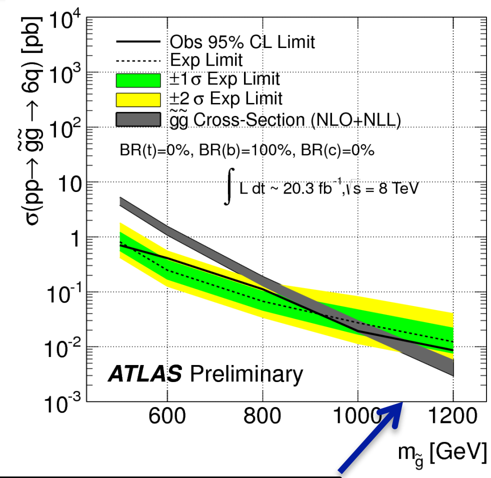

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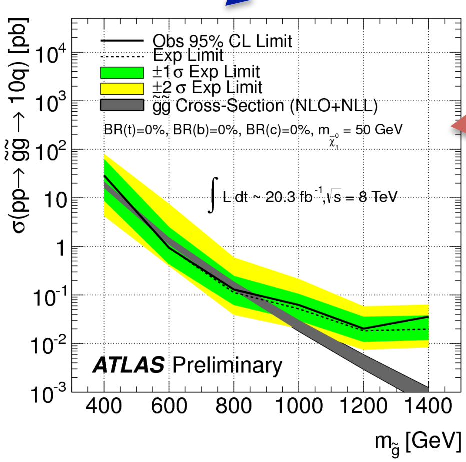
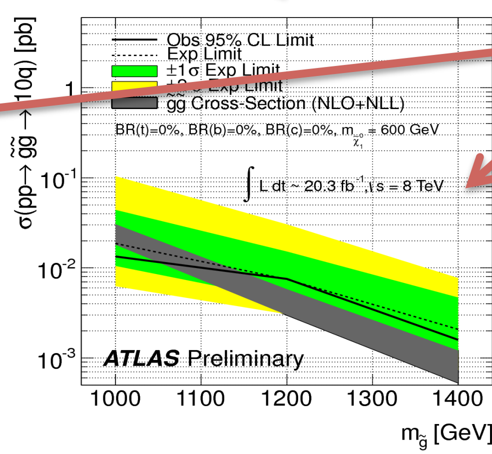
No heavy flavour BR





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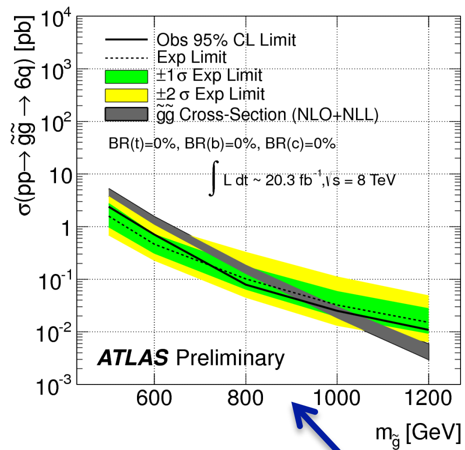

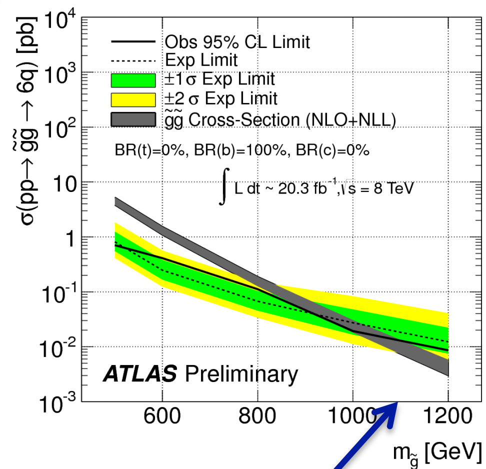

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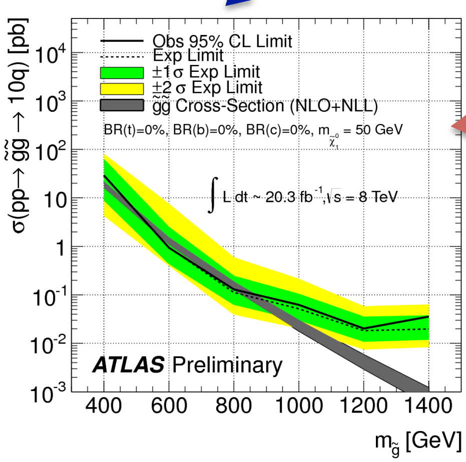
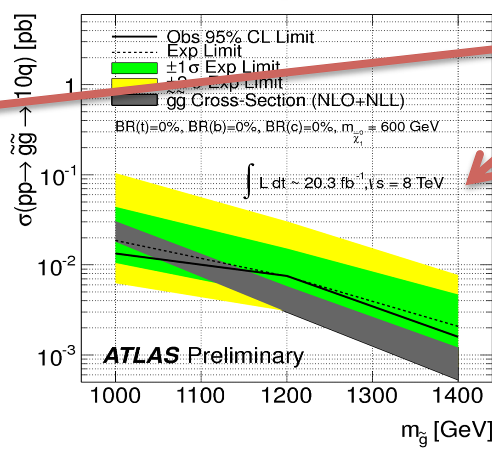
Every gluino decay contains b-quark





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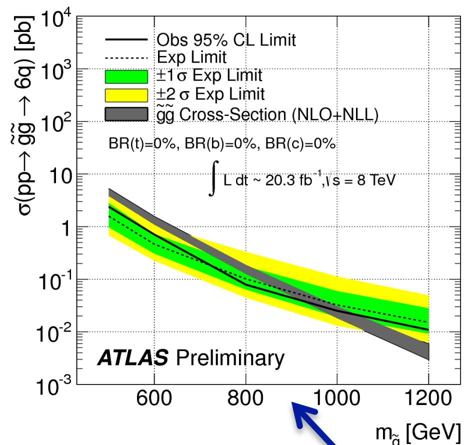

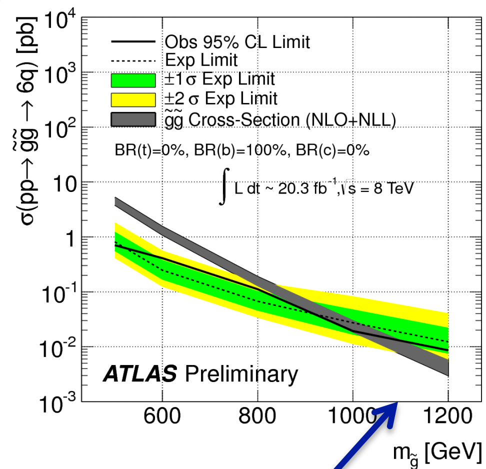

10-quark model

6-quark model

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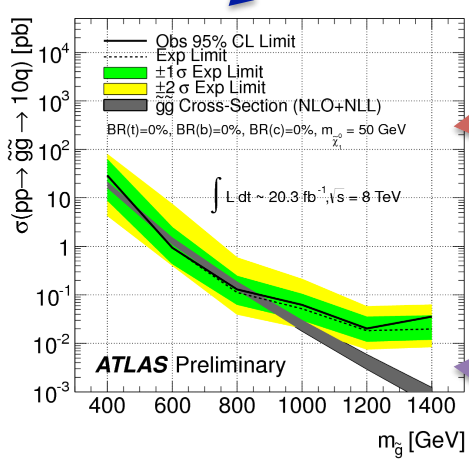
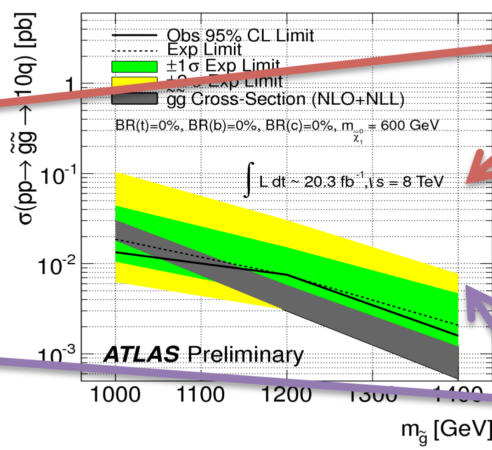
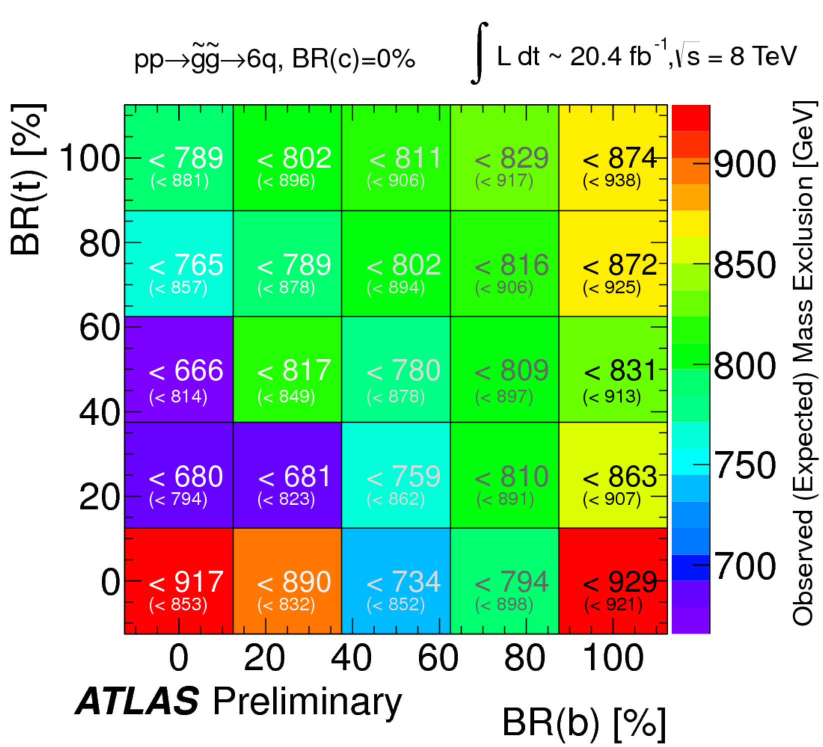
Different neutralino masses

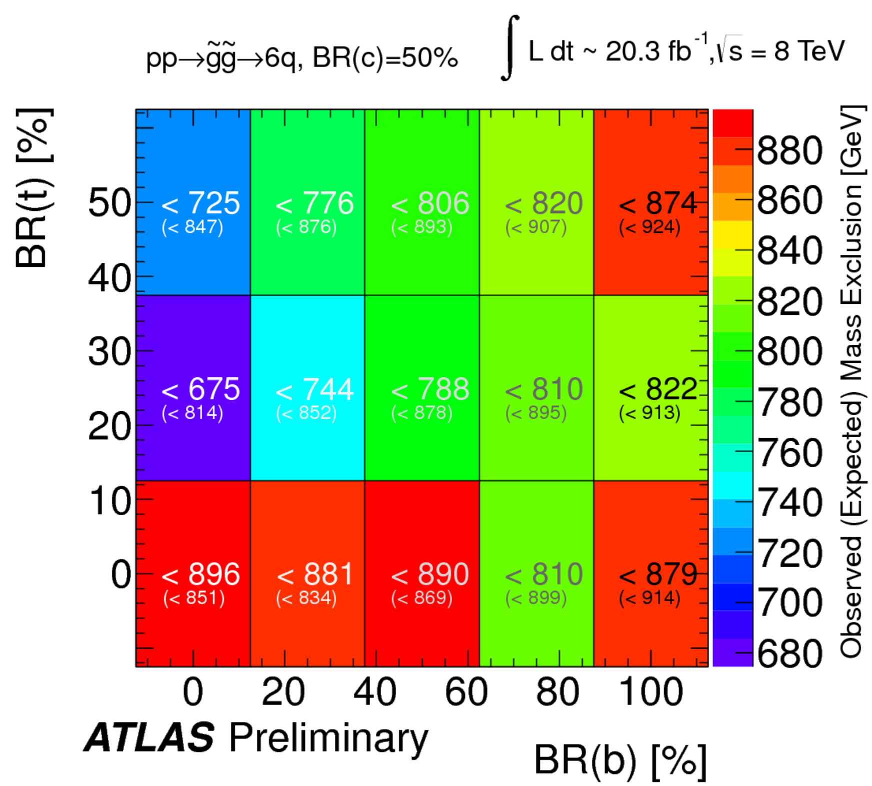




Multi-jet search: branching fractions

Plot excluded gluino masses as a function of Branching Ratios into heavy flavour:





Boosted multijet search

- Combinatorics problem is avoided if gluinos are highly boosted.
  - Decay products are all combined in one "fat" jet.
  - Use "N-subjettiness" substructure variables as discriminant:

$$\tau_N = \frac{1}{d_0}\sum_k p_{\mathrm{T}k} \times \min(\delta R_{1k}, \delta R_{2k}, ..., \delta R_{Nk}) \ , \quad \text{with} \quad d_0 \equiv \sum_k p_{\mathrm{T}k} \times R$$

where N is number of subjets, R is jet radius parameter in jet algorithm, and δR_{ik} is the distance between subjet *i* and constituent *k*.

  - Small value of $\tau_{32} = \tau_3 / \tau_2$ means jet is better described by three subjets than two.
    - Require $\tau_{32} < 0.7$.
  - Also use number N_{jet}^{R4} of small-radius (R=0.4) jets in the event, and jet mass m^{jet} of large-R jet.
  - Use "ABCD" method to estimate backgrounds.

Region	Jet (J_1) selections	Jet (J_2) selections	Description
CR-A	$m^{\text{jet}} < M_{\text{threshold}}$	$m^{\text{jet}} < M_{\text{threshold}}$	Low-mass jets, to validate τ_{32} shape
CR-B	$m^{\text{jet}} > M_{\text{threshold}}$ $\tau_{32} < 0.7$	$m^{\text{jet}} < M_{\text{threshold}}$	Signal-like leading jet, to validate m^{jet}
CR-C	$m^{\text{jet}} < M_{\text{threshold}}$	$m^{\text{jet}} > M_{\text{threshold}}$ $\tau_{32} < 0.7$	Signal-like subleading jet, to validate m^{jet}

$$N_{SR} = N_{\text{CR}-C} \times \left(\frac{N_{\text{CR}-B}}{N_{\text{CR}-A}}\right) \times \alpha$$

Correlation factor α derived from MC.

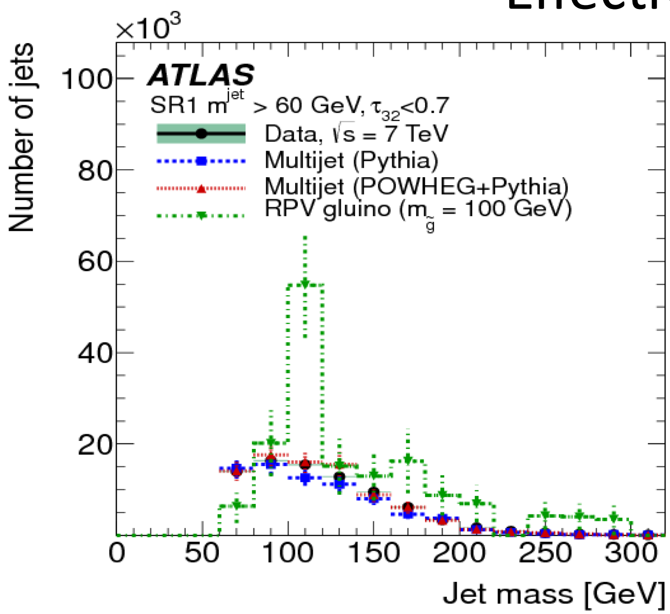
Boosted multi-jet search

Using 2011 dataset

(4.6 fb^{-1})

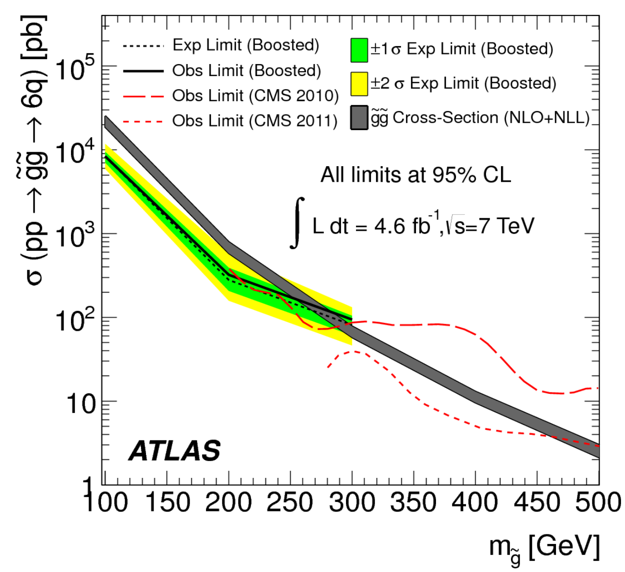
Model (m_{gluino})	$M_{threshold}$	Expected signal	Expected bkg	Data
100 GeV	60 GeV	77900 ± 16000	42400 ± 9700	40683
200 GeV	140 GeV	2400 ± 670	860 ± 460	1059
300 GeV	140 GeV	590 ± 55	860 ± 460	1059

Effectively looking for a peak in jet mass spectrum.



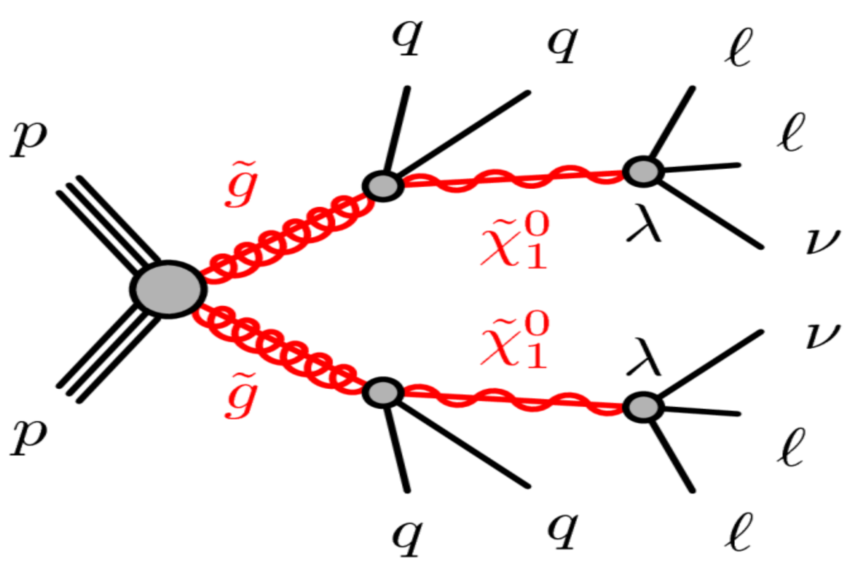
No significant excess observed.

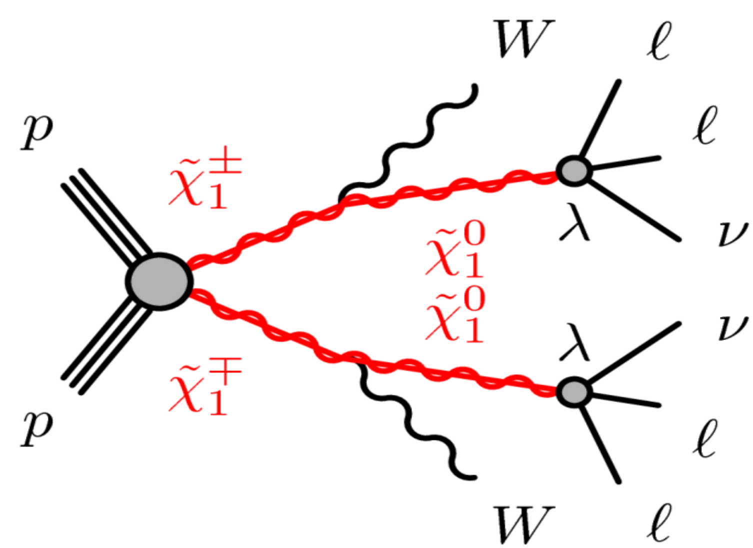
Set 95% CL upper limits on cross-section as function of gluino mass.



Multi-lepton analysis - motivation

- Again, assume RPV couplings are sufficiently small that they are only important for LSP decay.
  - But sufficiently large that LSP decay is prompt!
- Non-zero λ couplings lead to final states with high lepton multiplicity.
  - Neutrinos can also give substantial missing E_T





Multi-lepton search: selection

- Look for events containing at least 4 charged leptons, of which at least 3 are "light" (i.e. electrons or muons).
  - Identify hadronically decaying taus using BDT.
  - Combination of single/double electron and muon triggers is 90-100% efficient.
  - Veto events with SFOS lepton pair with mass < 12 GeV, or close to the Z-boson mass.
- 2 signal regions optimized for RPV search:

SR0noZb

At least 4 light leptons, no requirement on number of taus.

MET > 75 GeV OR m_{eff} > 600 GeV

SR1noZ

Exactly3 light leptons, at least 1 tau.

MET > 100 GeV OR m_{eff} > 400 GeV

(m_{eff} is scalar sum of MET, lepton, and jet p_T)

Multi-lepton search: background

Irreducible background:

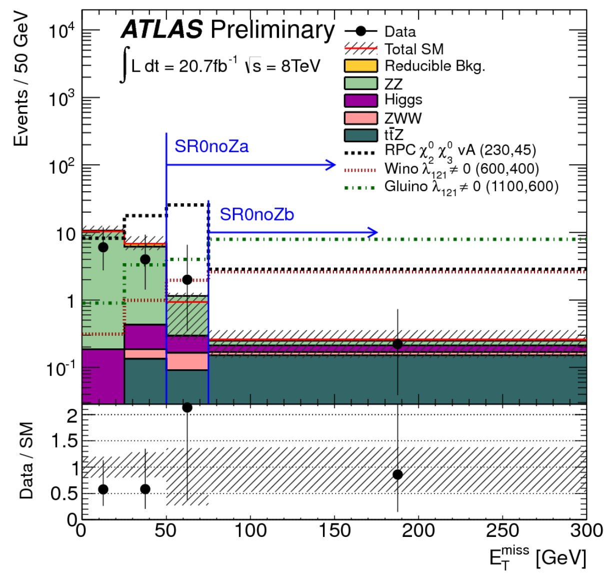
- contains four real leptons. e.g. ZZ, ZWW, ZZZ, tt+Z, tt+WW, tt+Higgs, Z +Higgs,W +Higgs (gauge bosons can be off-shell).
- Estimate using MC, applying corrections to accoung for data/ MC differences.
- Validate in regions with different kinematic requirements such that these contributions are enhanced.

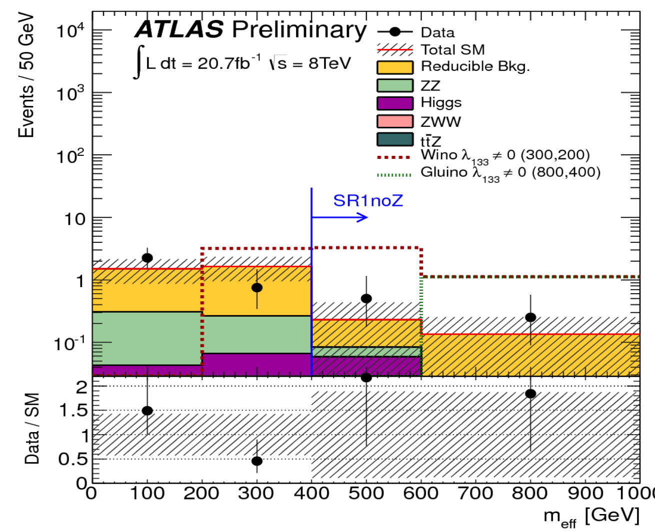
Reducible background:

- contains one or more "fake" leptons (either from semileptonic b or c decay, photon conversions, or jets misidentified as leptons).
- e.g. WZ, tt, tt+W, WW, single top.
- Estimate using semi-data-driven "weighting method":

Multi-lepton search: Results

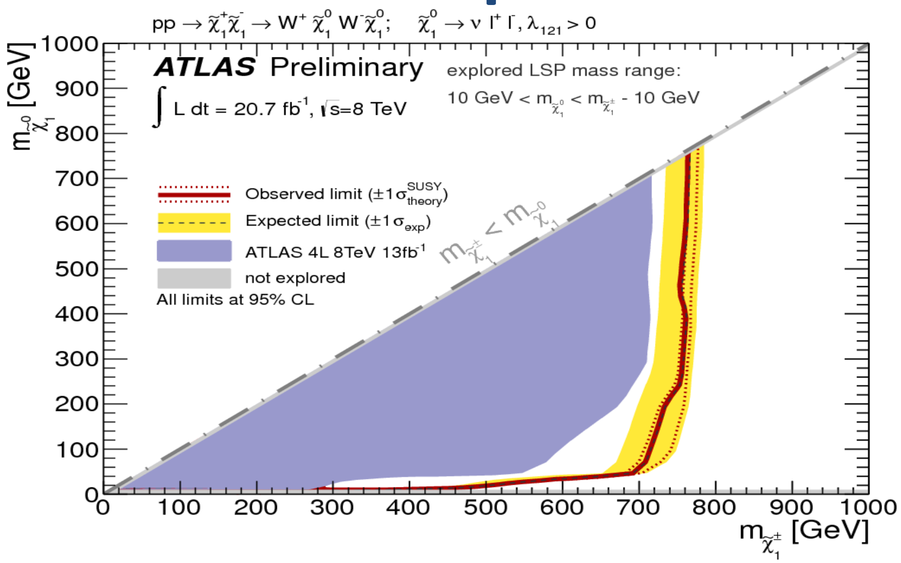
Using full ATLAS 2012 dataset (20.3 fb^{-1})

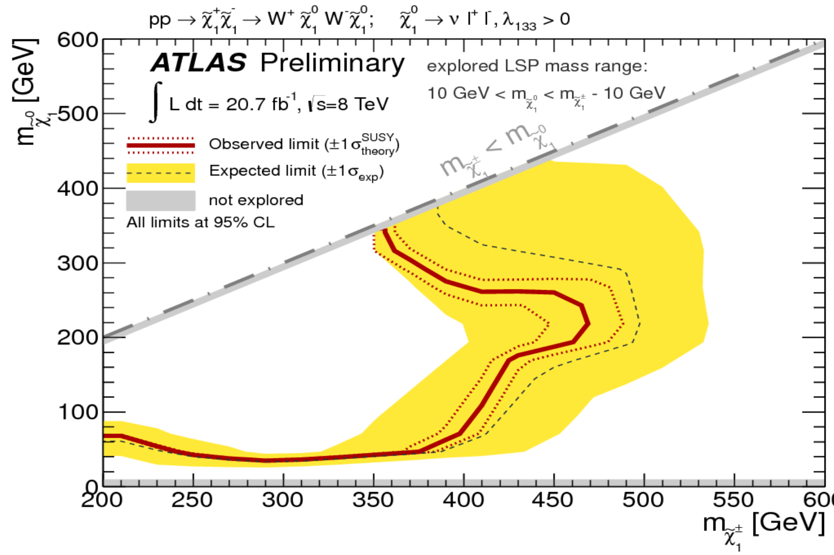


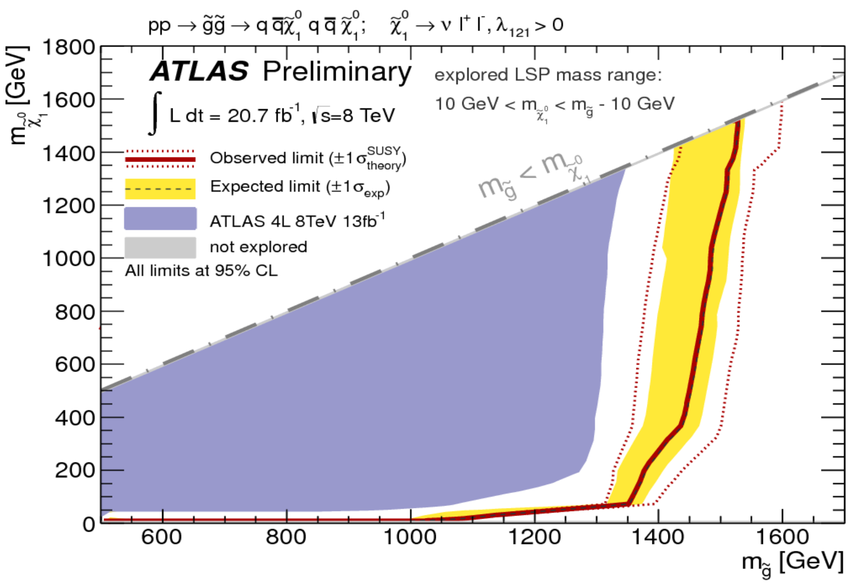


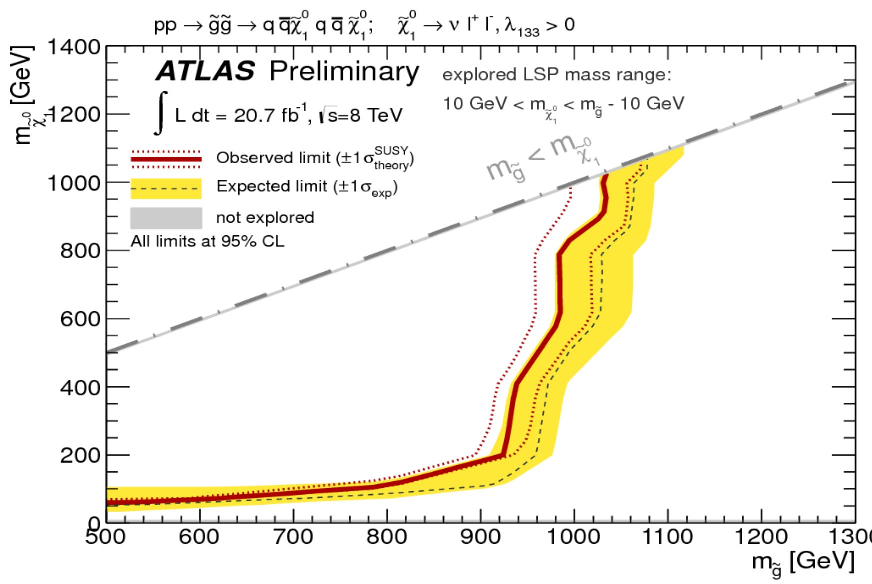
Signal Region	Irreducible Bkg	Reducible Bkg	Data	p-value	σ_{vis} (exp) [fb]	σ_{vis} (obs) [fb]
SR0noZb	1.6 ± 0.6	$0.05^{+0.14}_{-0.05}$	1	0.5	0.17	0.18
SR1noZ	0.62 ± 0.21	1.4 ± 1.3	4	0.15	0.26	0.36

Multi-lepton search: interpretation

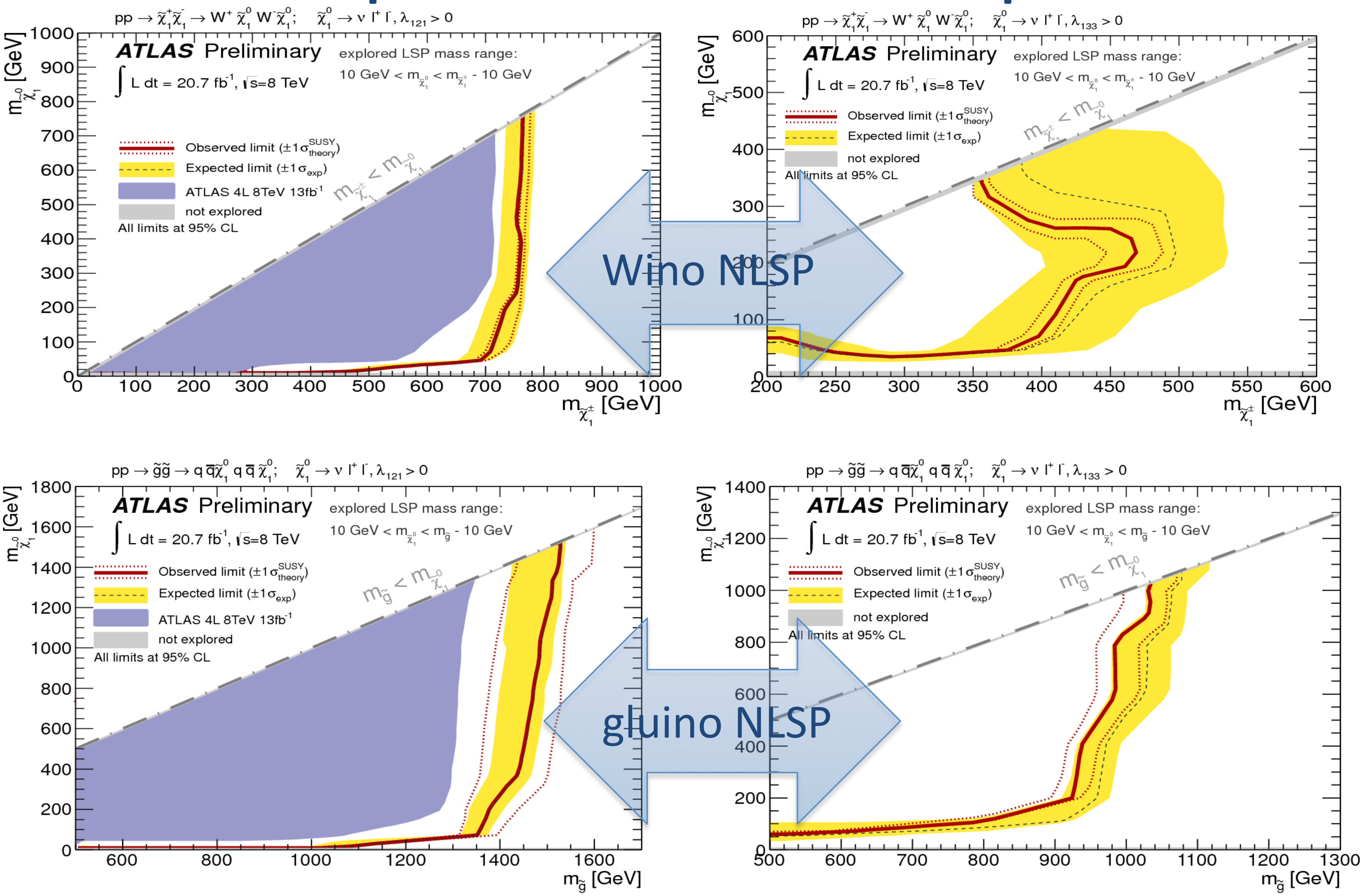




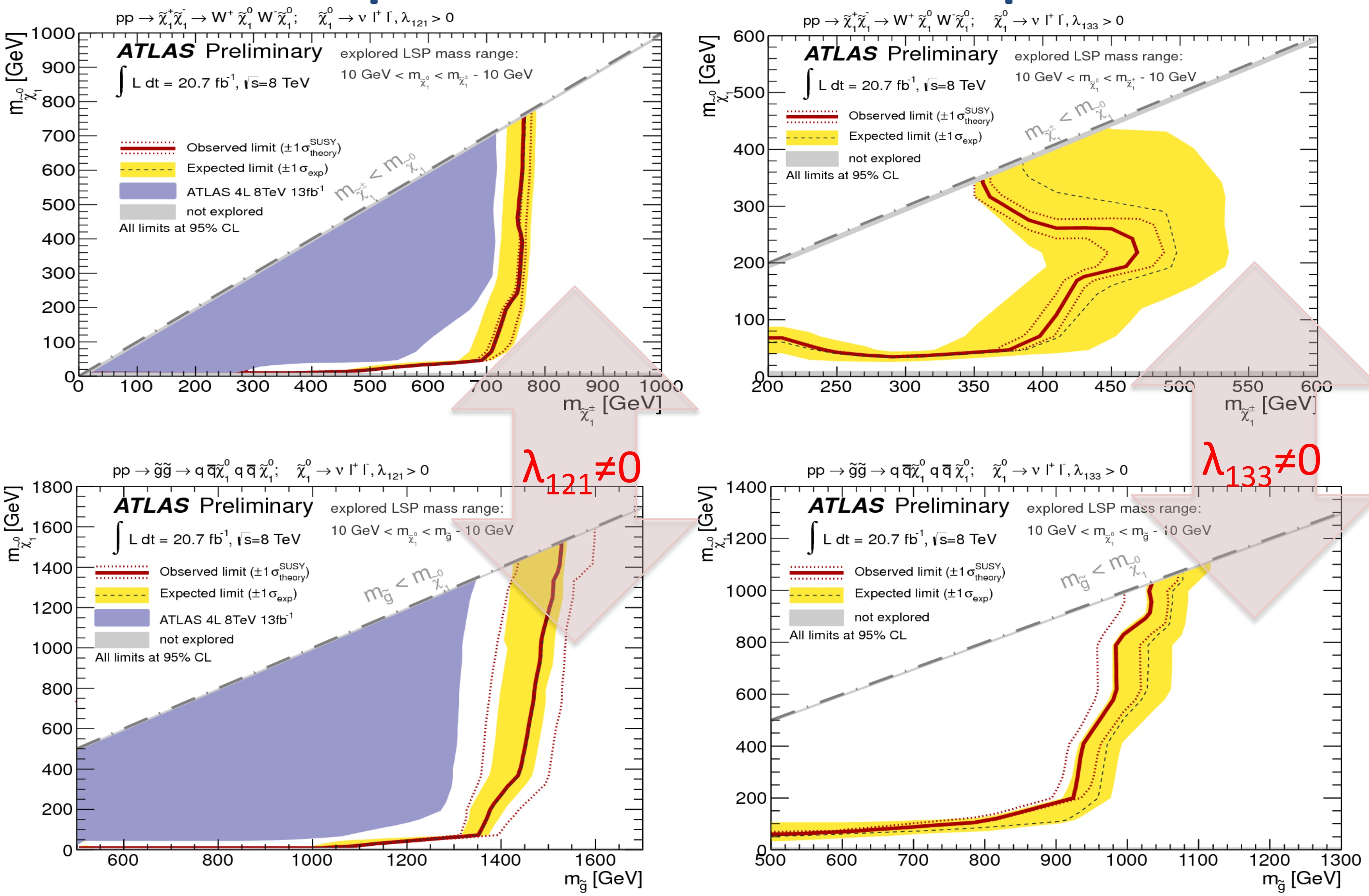




Multi-lepton search: interpretation

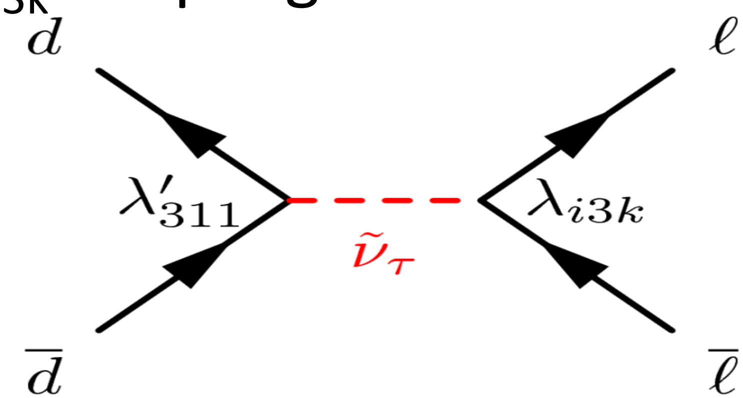


Multi-lepton search: interpretation



e/mu/tau resonance search

- Look for lepton-flavour-violating decays that take place via λ coupling.
  - e.g. decay of a tau-sneutrino to different-flavour leptons $\tilde{\nu}_\tau \rightarrow e^\pm\mu^\mp, e^\pm\tau^\mp, \mu^\pm\tau^\mp$
  - sneutrino can be produced via dd annihilation with the λ'_{311} coupling, and then decay to lepton pair via λ_{i3k} coupling .



e/mu/tau resonance search: selection and backgrounds.

- Use single electron trigger for eμ and eτ searches
- Single muon trigger for μτ searches.
- Electron or muon candidates must be isolated, and have p_T > 25 GeV.
- tau candidates must have p_T>20 GeV.
- BDT discriminator used for tau ID.
- 2 leptons required to have different flavour, opposite charge, and be back-to-back in aximuthal angle, Δϕ>2.7.

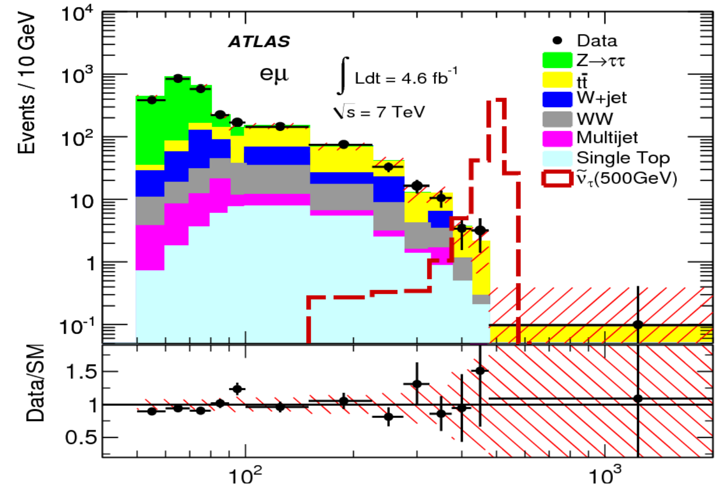
- "Direct lepton backgrounds", e.g. ttbar, *Z, WW, ZZ, WZ, Wt*, estimated using MC.
- Semi-data-driven methods used to estimate "jet backgrounds" , where one or both lepton candidates is a misidentified jet.
  - Mainly W+jets, multi-jet.

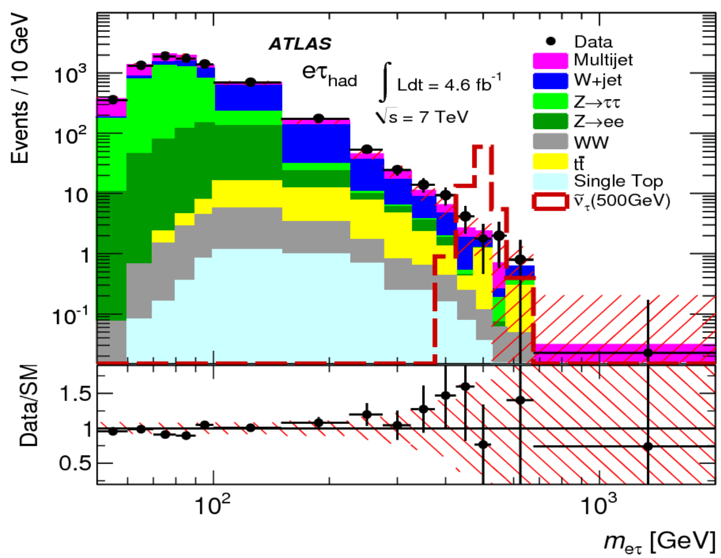
Use m(ll)<200 GeV as a control region for background estimation, m(ll)>200 GeV as signal region.

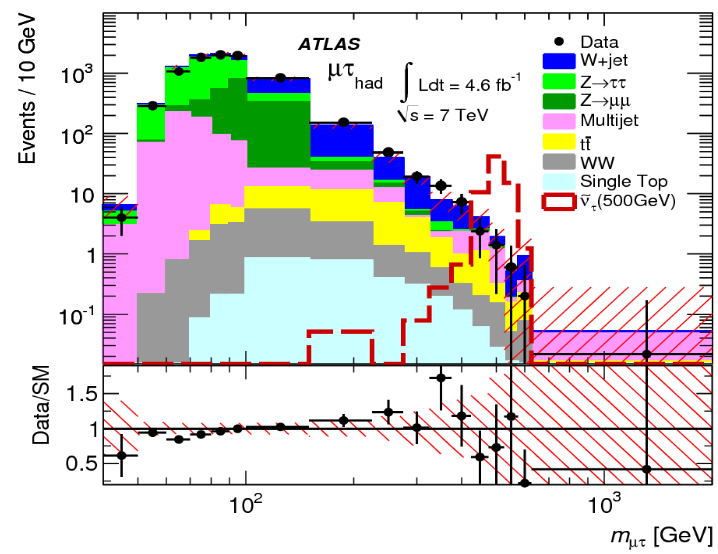
e/mu/tau resonance search: results

Using 2011 dataset (4.6 fb^{-1})

M(ll)>200 GeV	N(emu)	N(etau)	N(mutau)
Expected bkg	460 ± 60	720 ± 80	650 ± 90
Data	498	795	699



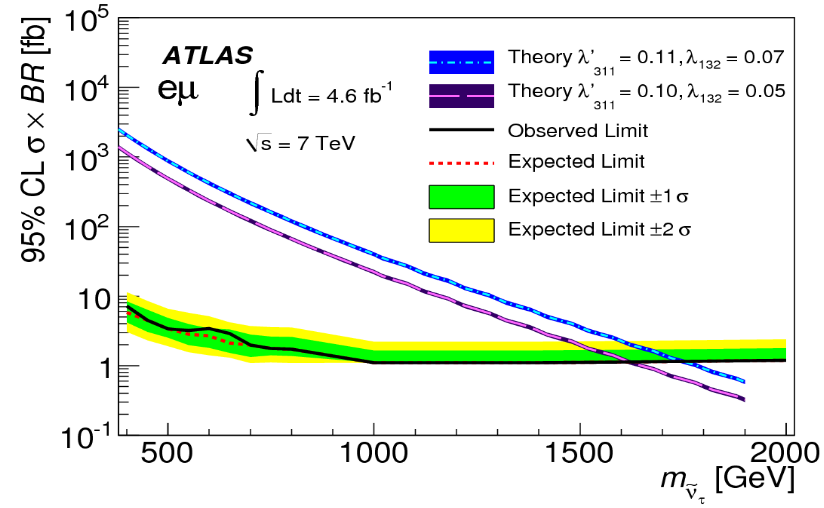


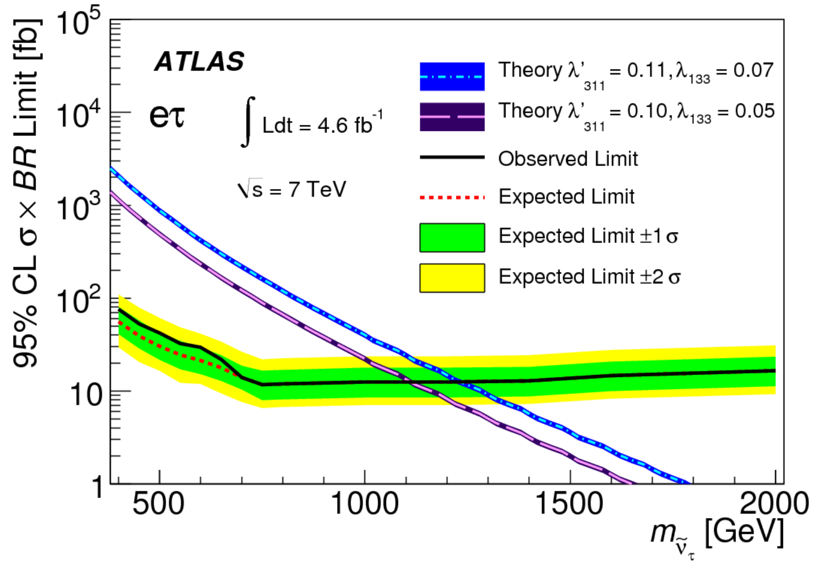


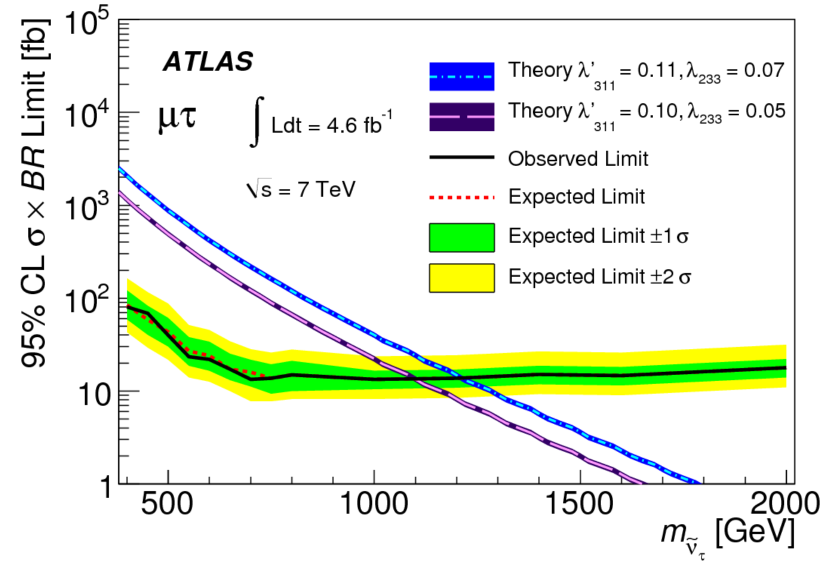
e/mu/tau resonance search: cross-section limits

Using 2011 dataset (4.6 fb^{-1})

Set 95% CL upper limits on cross-section*BR.



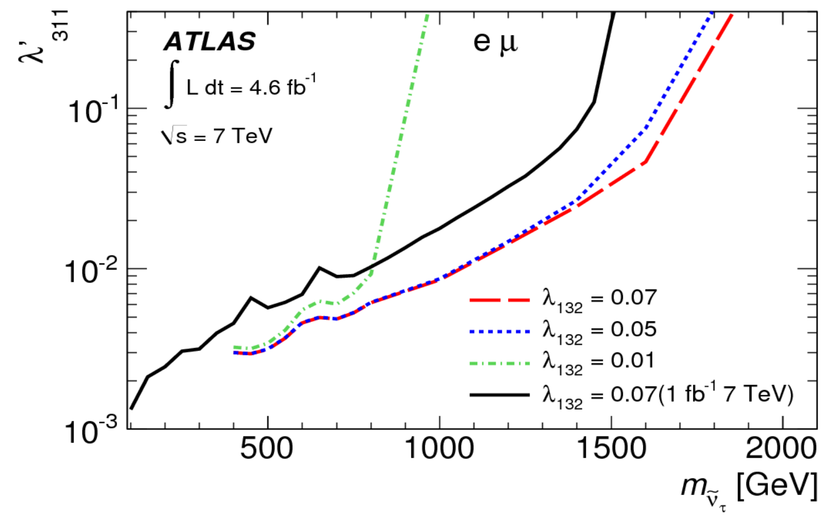


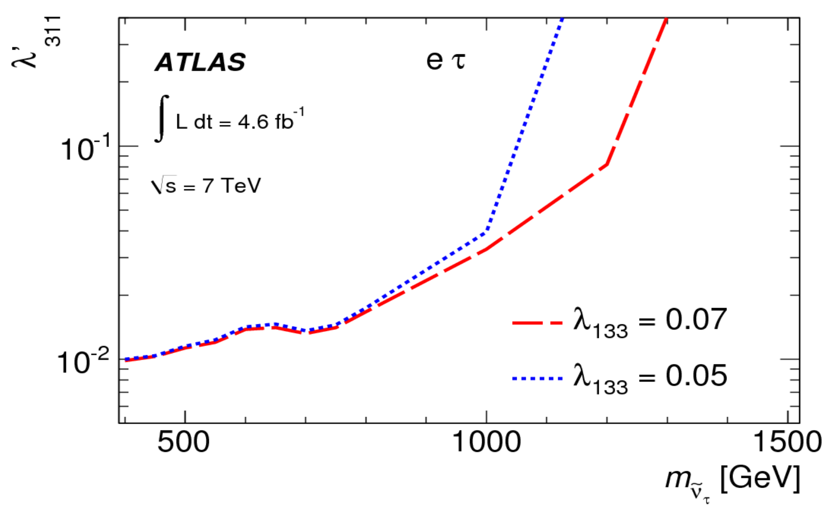


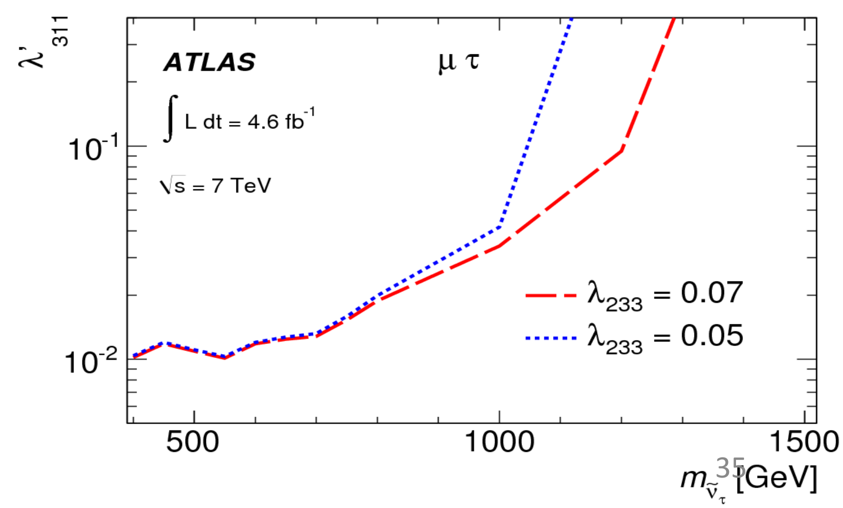
e/mu/tau resonance search: coupling limits

Using 2011 dataset (4.6 fb^{-1})

Set limits on coupling strength vs sneutrino mass.

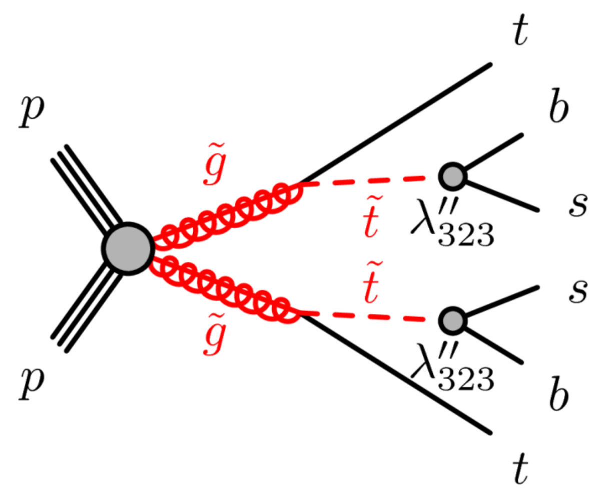






Conclusions and outlook

- Many interesting searches, covering wide variety of signatures.
- Increasingly, many ATLAS SUSY searches have both RPC and RPV interpretations, e.g.
    - Same-sign dilepton search (ATLAS-CONF-2013-007)
    - 7-10 jets plus missing E_T (arXiv:1308.1841)
    - Gluino masses < 900 GeV excluded for stop masses from 400-1000 TeV



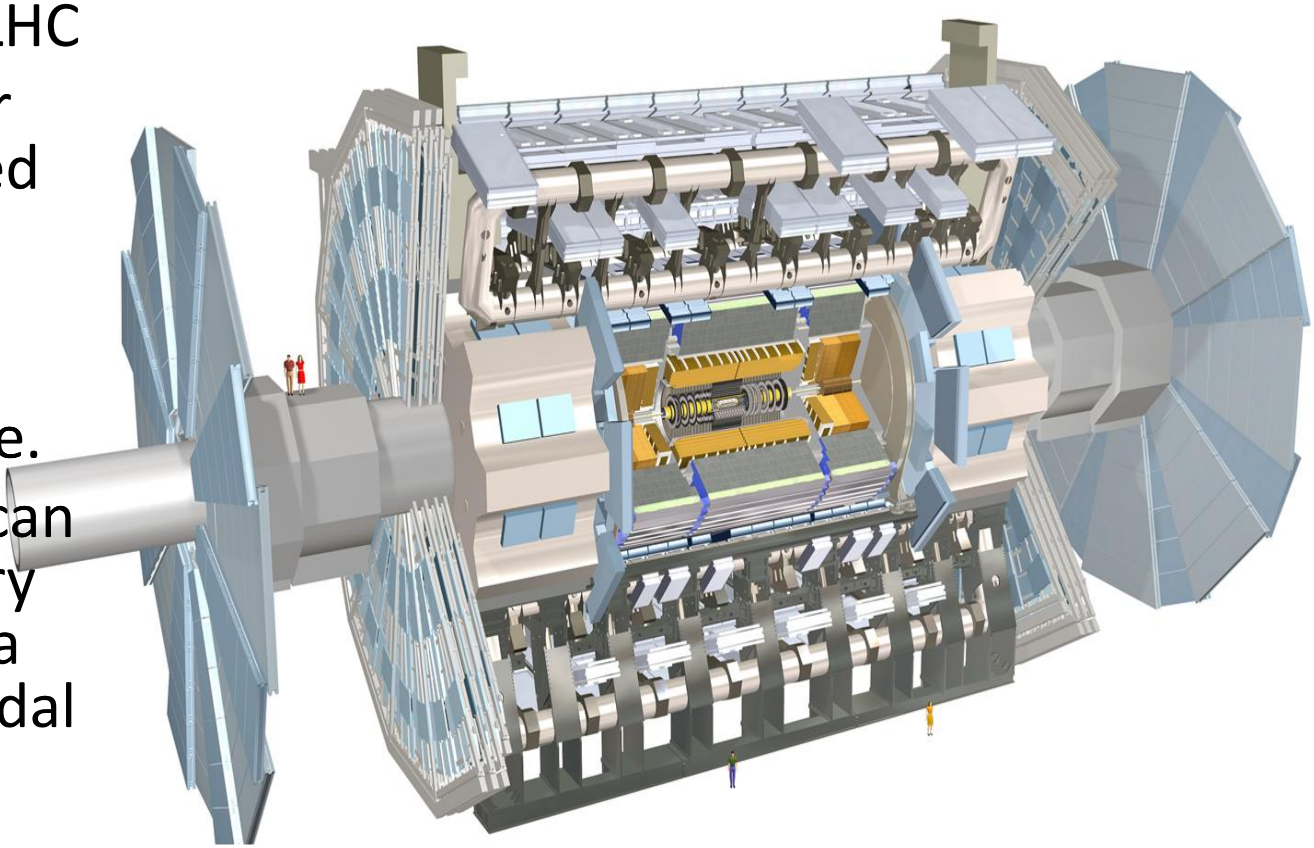
See talk by Marcello Barisonzi!

- No sign of new physics yet..
    - But, several results still to be updated to full 2012 dataset – updates coming soon!

Backup

The ATLAS detector

- One of the two large General Purpose Detectors at the LHC
- Inner Detector for measuring charged particle tracks
- EM and hadronic calorimetry, with hermetic coverage.
- Muon chambers can measure even very high-pT muons via curvature in toroidal B-field.



e/mu/tau resonance search

	$m_{\ell\ell'} < 200$ GeV			$m_{\ell\ell'} > 200$ GeV		
Process	$N_{e\mu}$	$N_{e\tau_{\text{had}}}$	$N_{\mu\tau_{\text{had}}}$	$N_{e\mu}$	$N_{e\tau_{\text{had}}}$	$N_{\mu\tau_{\text{had}}}$
$Z/\gamma^* \to \tau\tau$	1880 ± 150	4300 ± 600	5300 ± 600	8 ± 1	24 ± 3	28 ± 4
$Z/\gamma^* \to ee$		1050 ± 80			44 ± 3	
$Z/\gamma^* \to \mu\mu$			3030 ± 290			29 ± 3
$t\bar{t}$	760 ± 110	96 ± 18	94 ± 14	251 ± 30	90 ± 15	70 ± 13
Diboson	260 ± 27	57 ± 8	60 ± 7	71 ± 8	26 ± 3	24 ± 3
Single top quark	87 ± 8	11 ± 2	9 ± 1	39 ± 4	10 ± 2	8 ± 1
W+jets	420 ± 260	3500 ± 700	3200 ± 600	90 ± 40	370 ± 80	470 ± 110
multijet	37 ± 13	2200 ± 700	730 ± 230	6 ± 2	150 ± 50	24 ± 18
Total background	3440 ± 300	11200 ± 900	12400 ± 800	460 ± 60	720 ± 80	650 ± 90
Data	3345	11212	12285	498	795	699

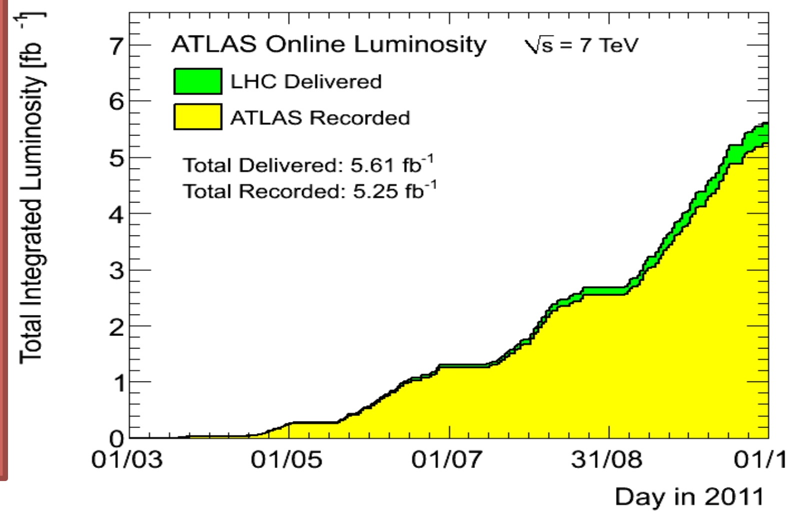
Multi-lepton analysis

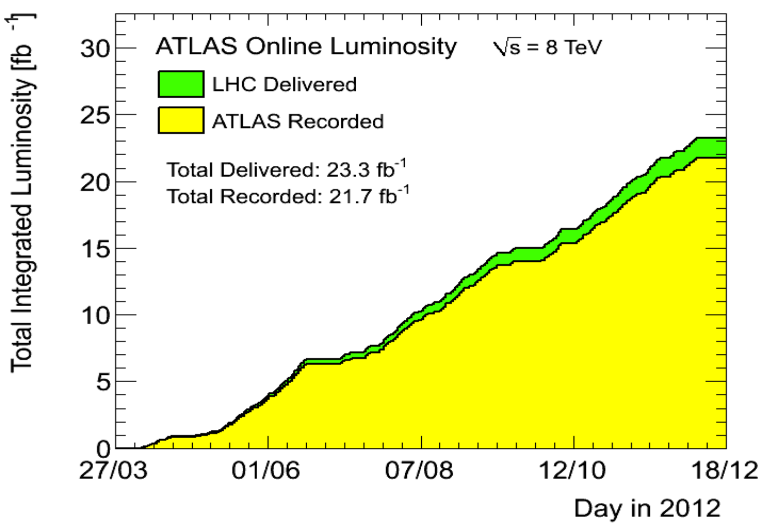
Sample	SR0noZa	SR0noZb	SR1noZ	SR0Z	SR1Z
ZZ	0.6 ± 0.5	0.50 ± 0.26	0.19 ± 0.05	1.2 ± 0.4	0.49 ± 0.10
ZWW	0.12 ± 0.12	0.08 ± 0.08	0.05 ± 0.05	0.6 ± 0.6	0.13 ± 0.13
$t\bar{t}Z$	0.73 ± 0.34	0.75 ± 0.35	0.16 ± 0.12	2.3 ± 0.9	0.29 ± 0.24
Higgs	0.26 ± 0.07	0.22 ± 0.07	0.23 ± 0.06	0.58 ± 0.15	0.14 ± 0.05
Irreducible Bkg.	1.7 ± 0.8	1.6 ± 0.6	0.62 ± 0.21	4.8 ± 1.8	1.1 ± 0.4
Reducible Bkg.	$0^{+0.16}_{-0}$	$0.05^{+0.14}_{-0.05}$	1.4 ± 1.3	$0^{+0.14}_{-0}$	$0.3^{+1.0}_{-0.3}$
Total Bkg.	1.7 ± 0.8	1.6 ± 0.6	2.0 ± 1.3	4.8 ± 1.8	$1.3^{+1.0}_{-0.5}$
Data	2	1	4	8	3
p_0-value	0.29	0.5	0.15	0.08	0.13
N_{signal} Excluded (exp)	3.9	3.6	5.3	6.7	4.5
N_{signal} Excluded (obs)	4.7	3.7	7.5	10.4	6.5
$\sigma_{\mathrm{visible}}$ Excluded (exp) [fb]	0.19	0.17	0.26	0.32	0.22
$\sigma_{\mathrm{visible}}$ Excluded (obs) [fb]	0.23	0.18	0.36	0.50	0.31

ATLAS 2011 and 2012 data

2011

7 TeV centre-of-mass energy
4.6fb^{-1} with all good data quality.
Average num. interactions/BC about 10.

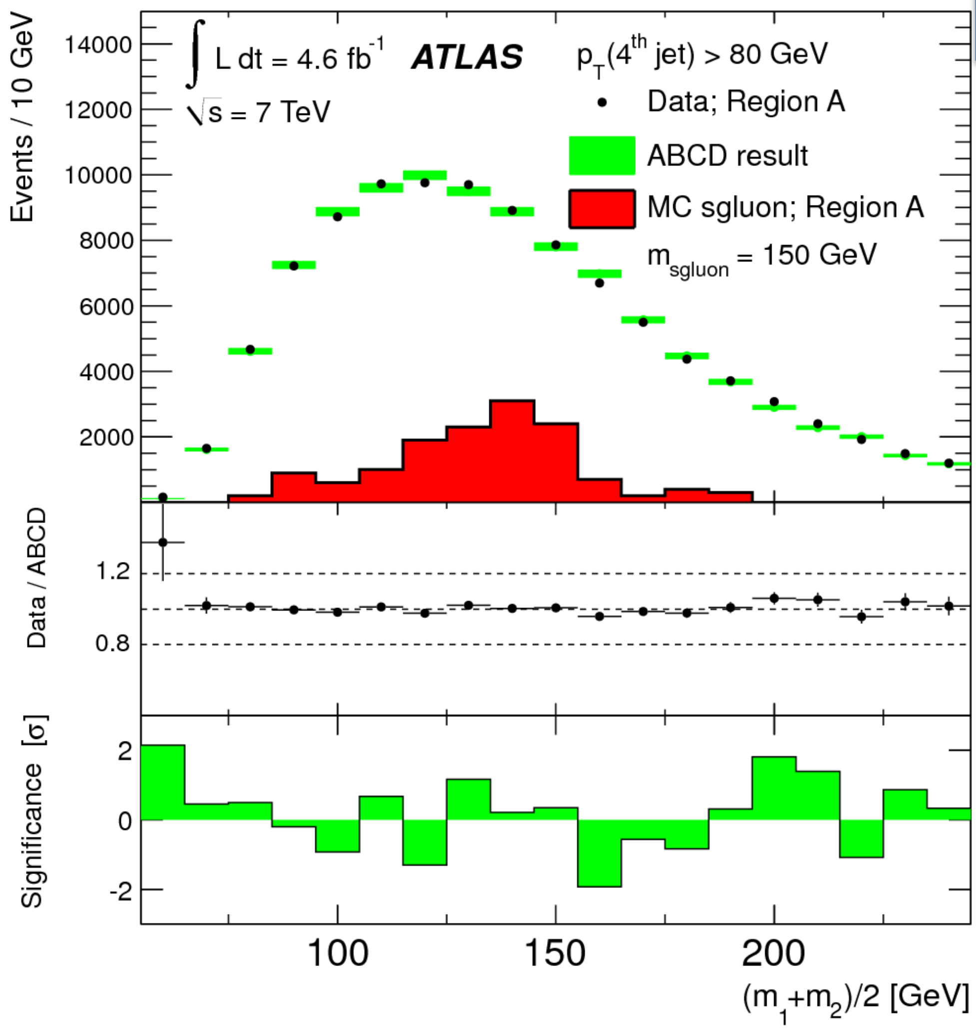




2012

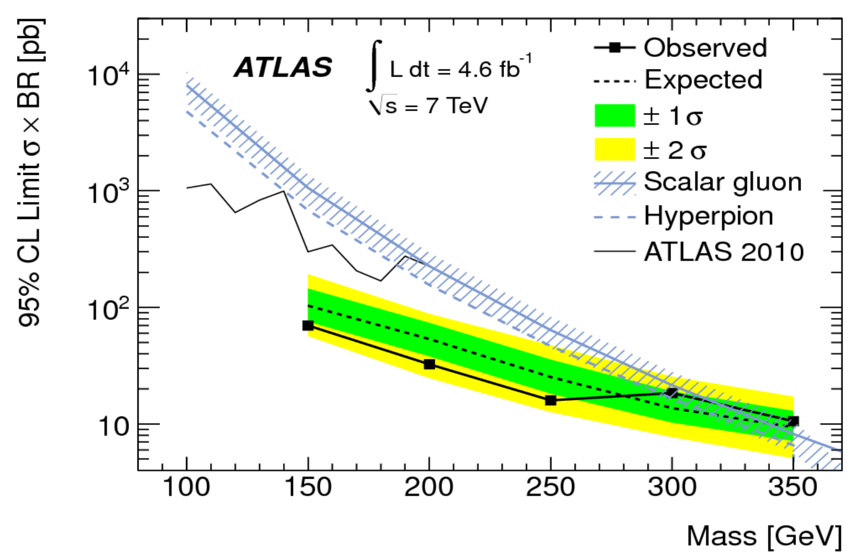
8 TeV centre-of-mass energy
20.3fb^{-1} with all good data quality.
Average num. interactions/BC about 20.

Sgluon search: results



Using 2011 dataset (4.6 fb^{-1})

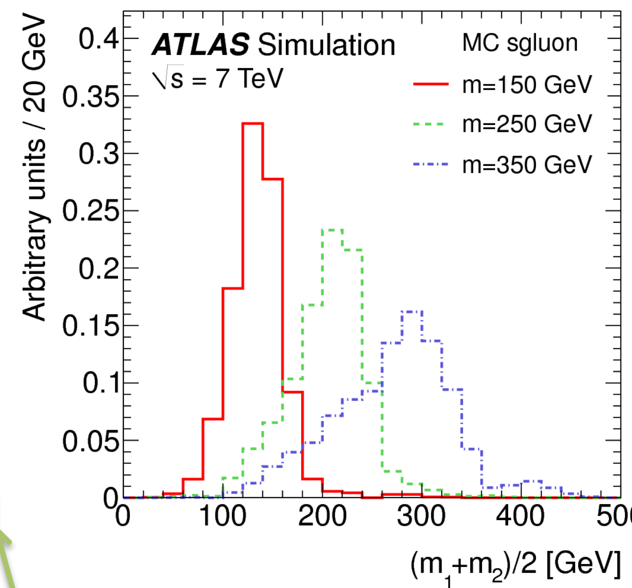
- No excess above background expectation.
- Set 95% CL upper limit on sgluon production cross-section multplied by Branching Ratio of decay to jets, as a function of sgluon mass.



Scalar gluon (sgluon) search

- Scalar partners of Dirac gluino occur in several extended SUSY models, e.g.
  - $\mathcal{N}$=1/$\mathcal{N}$=2 hybrid model (arXiv:0812.3586),
  - R-symmetric MSSM (arXiv:0712.2039).
- Such particles could be pair-produced, and each decay to a pair of gluons, leading to a 4-jet final state.

- Select events using multijet trigger.
- Require 4 jets with $|\eta|<1.4$, separated by $\Delta R>0.6$.
- Require 4th jet $p_T > \max(80\text{ GeV}, m_{sgluon}*0.3 + 30\text{ GeV})$
- Pair jets by minimising $|\Delta R_{pair1}-1|+|\Delta R_{pair2}-1|$.
- Define m_1 and m_2 as invariant masses of two pairs.
- Define $\cos(\theta^*)$ as cosine of angle between candidate flight direction and momentum.



Use "ABCD" method to estimate background

Region	$\lvert\cos(\theta^*)\rvert$	$\lvert m_1 - m_2\rvert/(m_1+m_2)$
A	< 0.5	< 0.15
B	> 0.5	< 0.15
C	< 0.5	> 0.15
D	> 0.5	> 0.15

Signal region

Multi-lepton search: background

Irreducible background:

- contains four real leptons. e.g. ZZ, ZWW, ZZZ, tt+Z, tt+WW, tt+Higgs, Z+Higgs,W +Higgs (gauge bosons can be off-shell).
- Estimate using MC, applying corrections to accoung for data/MC differences.
- Validate in regions with different kinematic requirements such that these contributions are enhanced.

Reducible background:

- contains one or more "fake" leptons (either from semileptonic b or c decay, photon conversions, or jets misidentified as leptons).
- e.g. WZ, tt, tt+W, WW, single top.
- Estimate using semi-data-driven "weighting method":

Define l_S and l_L as leptons passing all signal criteria, or loosened criteria, respectively.
Reducible bkg estimate is

$[N_{data}(3l_S+l_L)-N_{MC,irr}(3l_S+l_L)]*F(l_L) + [N_{data}(2l_S+l_{L1}+l_{L2}) - N_{MC,irr}(2l_S+l_{L1}+l_{L2})]*F(l_{L1})*F(l_{L2})$

Where $N_{MC,irr}$ is irreducible background contribution, and $F(l_L)$ is fake ratio, determined from MC and validated in data control regions.

Constraints on RPV couplings

- Non-observation of proton decay effectively excludes processes that violate both lepton and baryon number.
  - Many RPV models assume "single coupling dominance", i.e. turn-on one coupling, leave the others as zero.
- CKM unitarity, and τ decays, give upper limits of order 0.05 on λ couplings (arXiv:0910.4980).
- Neutrino masses constrain λ_{122} λ_{133} λ_{232} λ_{233} to be smaller than about $5*10^{-4}$ (arXiv:1005.3309)
- Limits on neutron oscillation imply $\lambda''_{11k} < 10^{-8}$.
- Very weak constraints on third-generation λ'' couplings!
- Note that non-zero but small values of couplings would lead to long-lived signatures, e.g. displaced vertices.
  - Lifetime is proportional to $1/(\text{coupling})^2$.
  - See talk by Nimrod Taiblum for an example of ATLAS search for displaced vertices arising from small λ' coupling.

e/mu/tau resonance search: selection and backgrounds.

- Use single electron trigger for eμ and eτ searches
- Single muon trigger for μτ searches.
- Electron or muon candidates must be isolated, and have p_T > 25 GeV.
- tau candidates must have p_T>20 GeV.
- BDT discriminator used for tau ID.
- 2 leptons required to have different flavour, opposite charge, and be back-to-back in aximuthal angle, Δφ>2.7.

- "Direct lepton backgrounds", e.g. ttbar*, Z, WW, ZZ, WZ, Wt*, estimated using MC.
- Semi-data-driven methods used to estimate "jet backgrounds" , where one or both lepton candidates is a misidentified jet.
  - Main bkg is W+jets.
  - Estimate contribution using control sample with MET>30 GeV.
  - Estimate multi-jet background using "same sign" selection, since prob. of identifying a jet as a lepton is independent of charge.

Use m(ll)<200 GeV as a control region for background estimation, m(ll)>200 GeV as signal region.