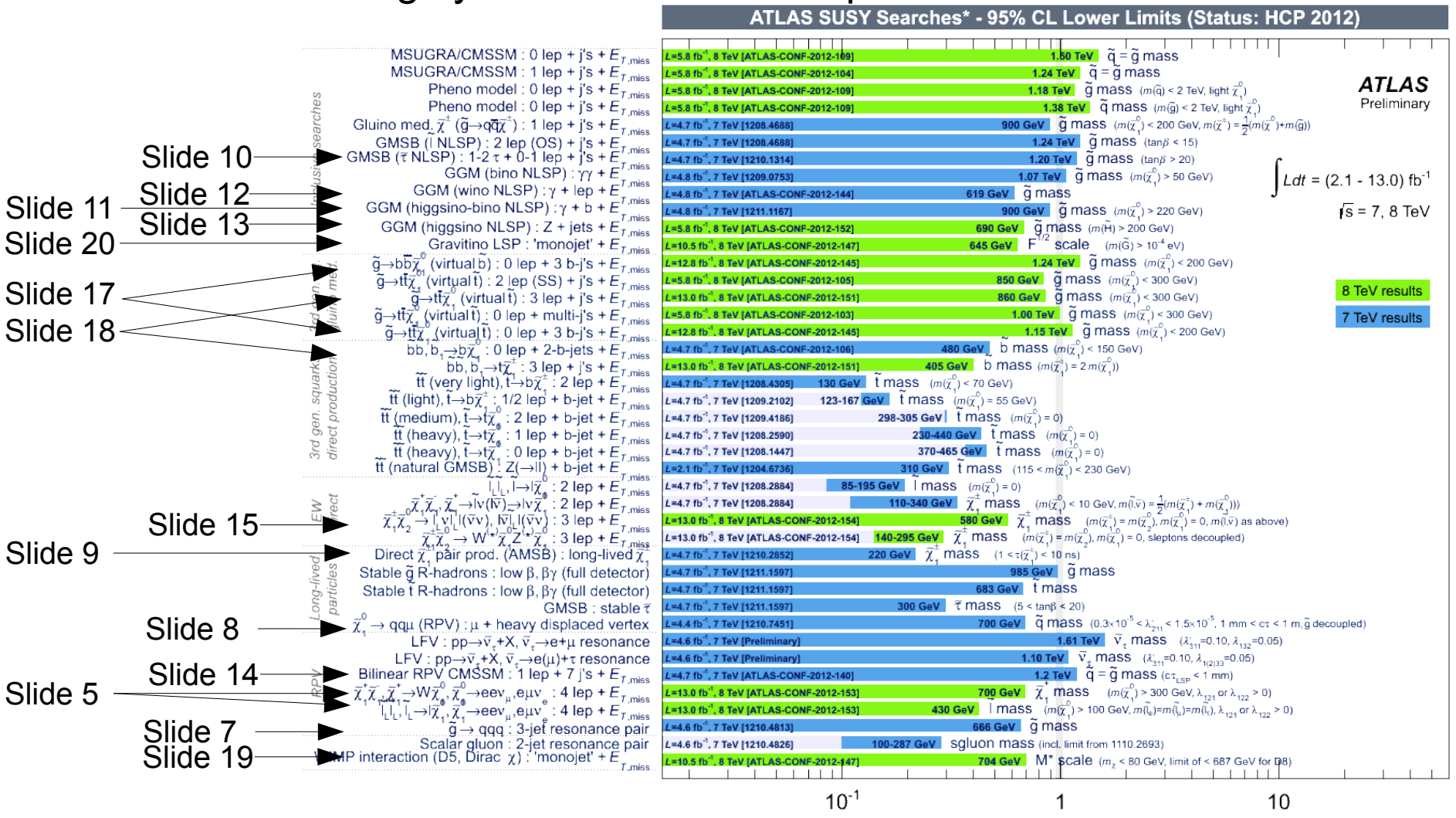
Searches Beyond the Standard Model at ATLAS

LHC on the March
November 20-22, 2012

Nathan Triplett – On behalf of the ATLAS collaboration

Outline

- ATLAS Exotics and SUSY searches have been extensive
- Most new models tested with limits at or above 1 TeV
- This talk will focus largely on results from the past two months



*Only a selection of the available mass limits on new states or phenomena shown.

All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

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- Most new models tested with limits at or above 1 TeV
- This talk will focus largely on results from the past two months

Slide 19 →
Slide 22 → Slide 21 →
Slide 29 →
Slide 24 → Slide 23 →
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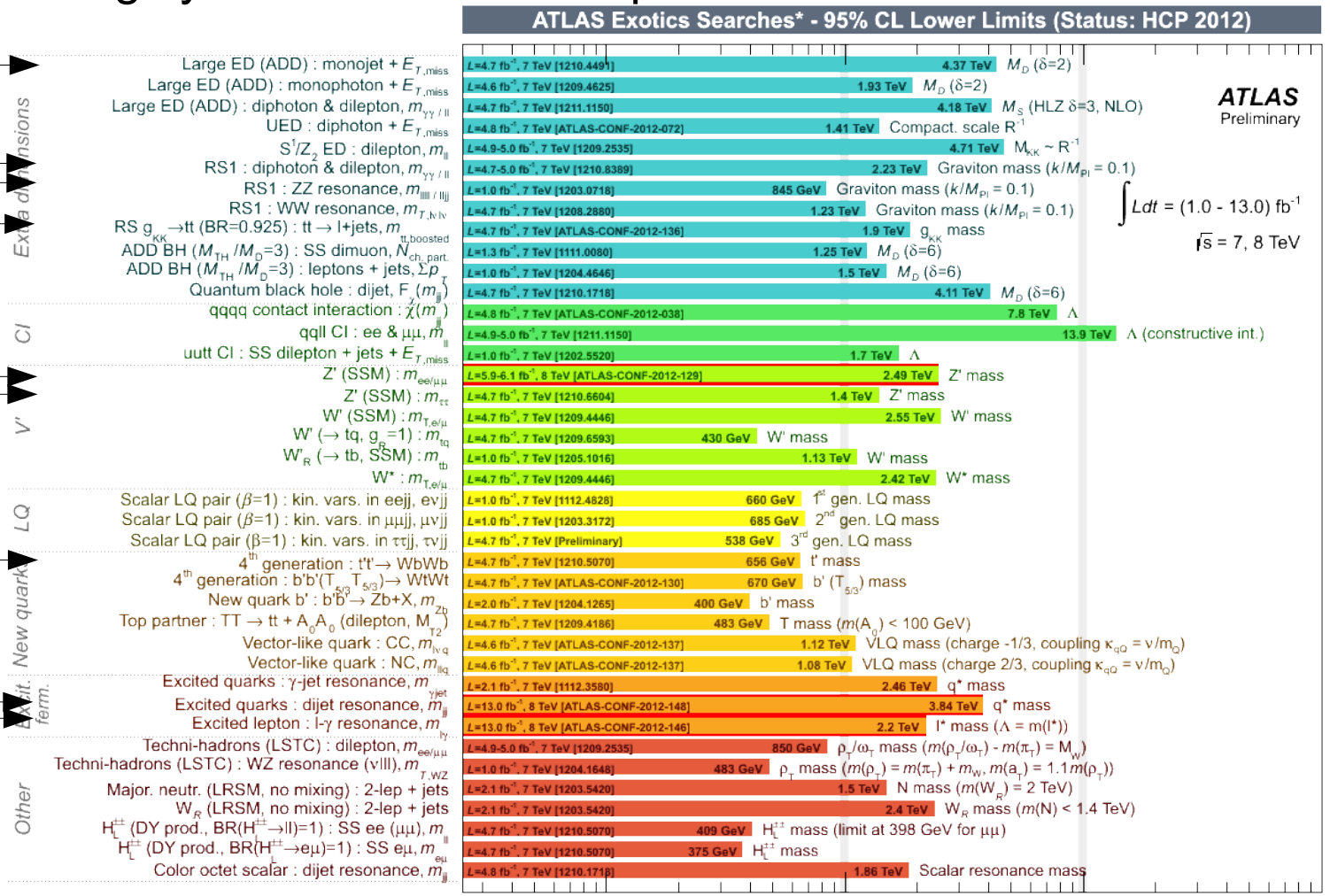

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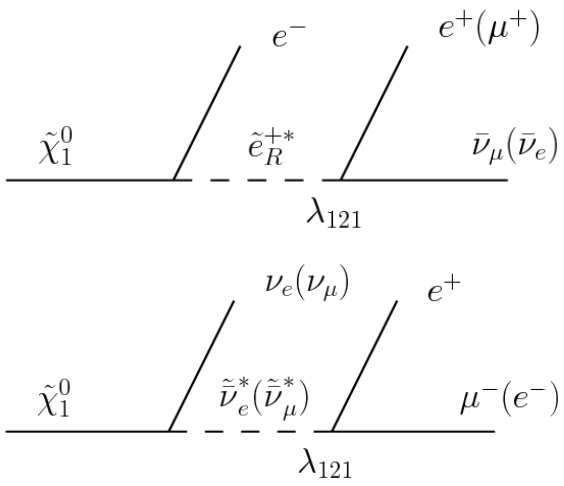
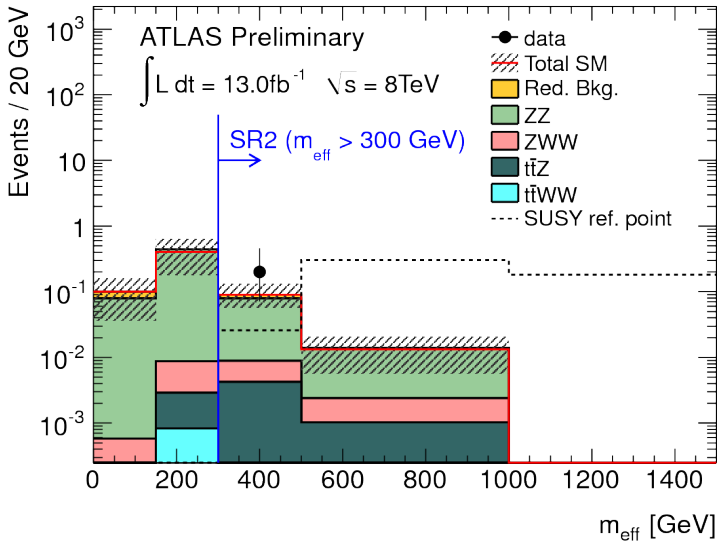
Some BSM models in this talk

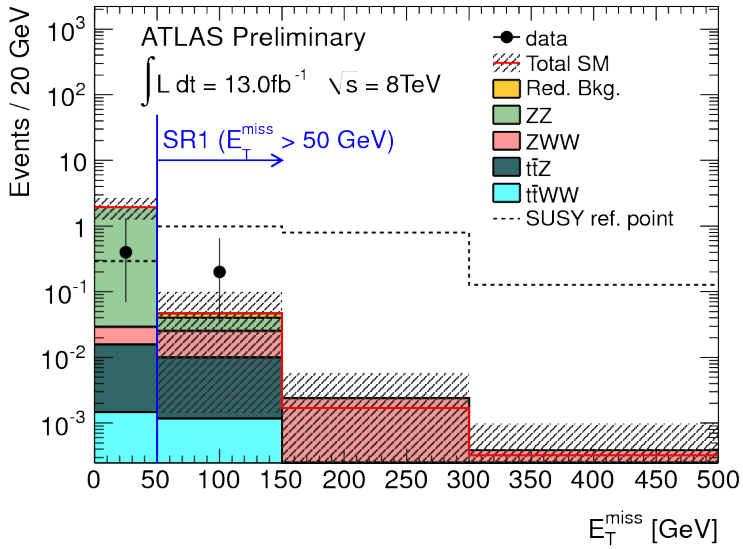
- R-parity violating (RPV) SUSY
  - $P_R = (-1)^{2S+3B+L}$
  - Lightest SUSY particle is stable if P_R is conserved
- Anomaly-mediated SUSY breaking (AMSB)
  - Soft SUSY breaking via loop effects
  - Can cause nearly degenerate particle masses
- Gauge-mediated SUSY breaking (GMSB)
  - Gravitino is the LSP
  - Look for decays of NLSP → Gravitino
- General Gauge Mediation (GGM)
  - Generalizes GMSB
  - Allows squarks/gluinos below 1 TeV
- Large Extra Dimensions
  - Look for gravaton decays into photons
- New "SM like" particles
  - 4^{th} Generation quarks
  - New Z-like boson
- Compositeness
  - Look for substructure inside quarks and leptons

RPV SUSY: 4 lepton channel (1)

- 8 TeV analysis
- Pair produced LSP → 4 leptons + neutrinos



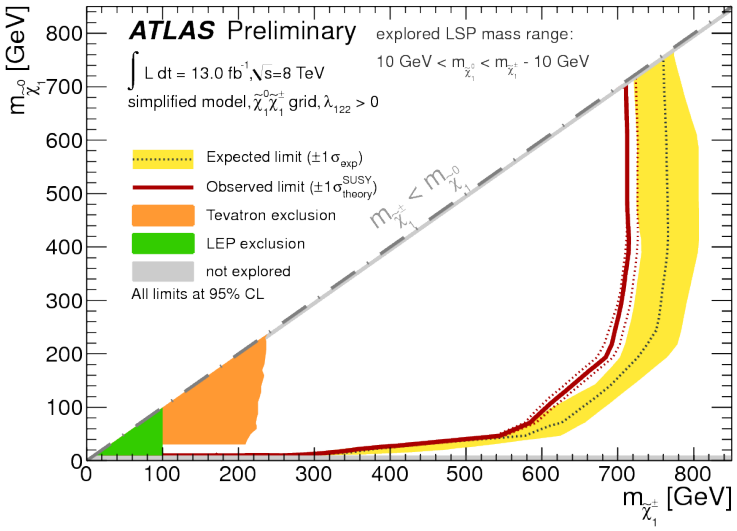


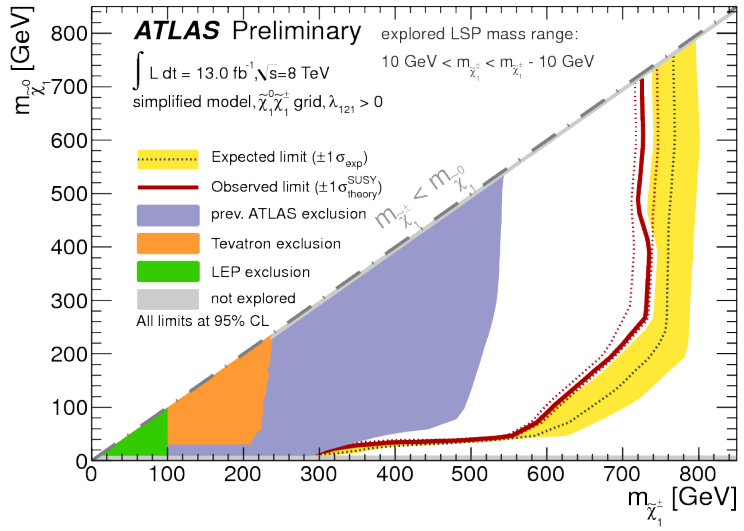


- Choice of NLSP affects limits
  - 4 models tested
- Selection:
  - 4 electrons/muons
  - Large MET or Meff
- 2 signal regions

Selection	SR1	SR2
Number of leptons	≥ 4	≥ 4
SFOS pair	–	–
Z-candidate	Z-veto	Z-veto
E_T^{miss}/GeV	> 50	–
m_{eff}/GeV	–	> 300

RPV Wino simplified model

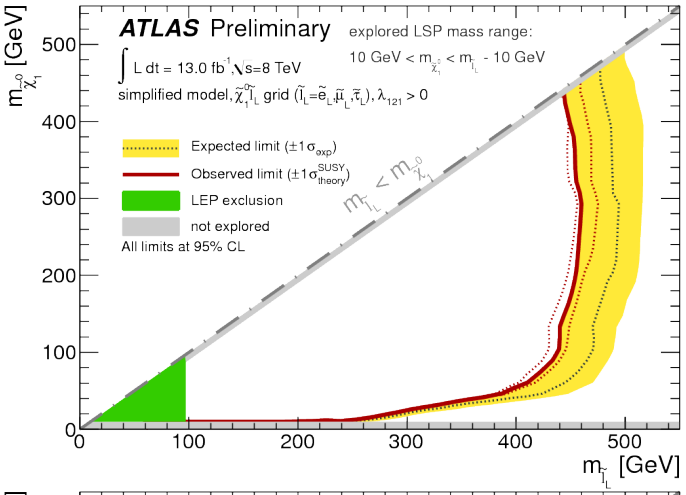


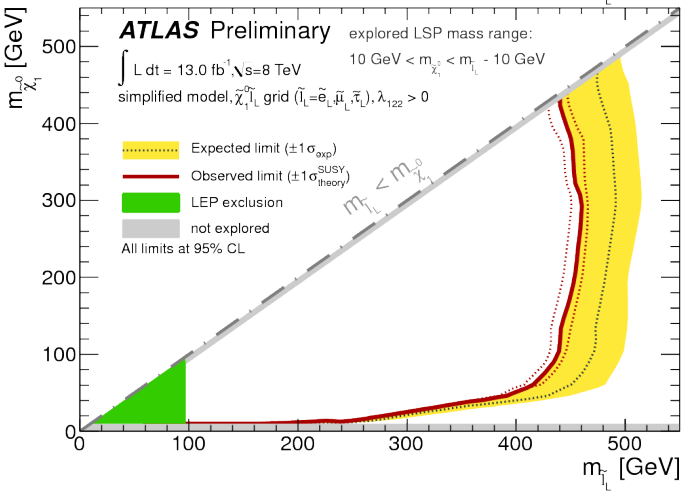


RPV SUSY: 4 lepton channel (2)

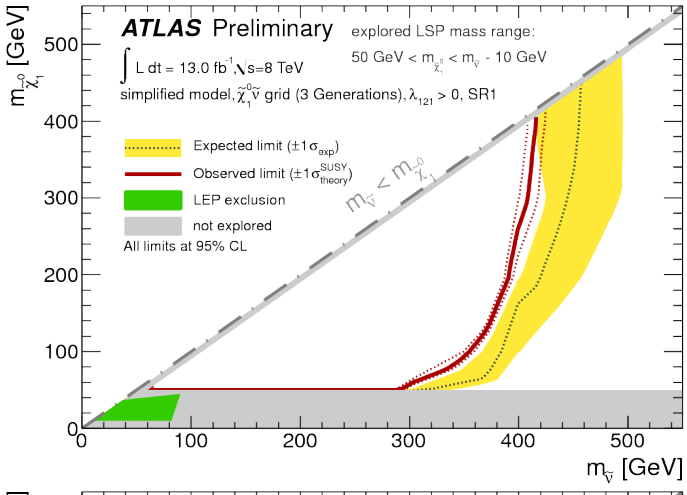
Each set of limits assumes a different NLSP as listed below

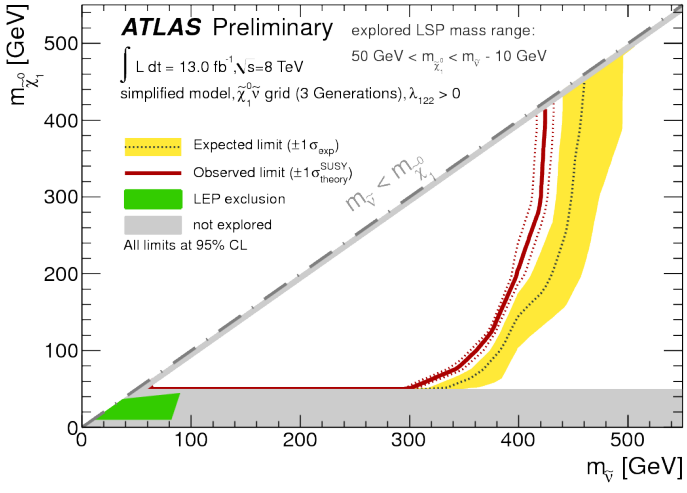
RPV L-slepton Simplified models



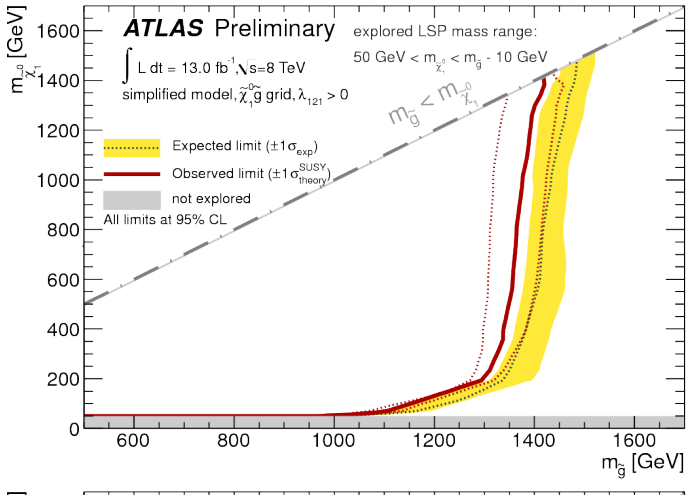


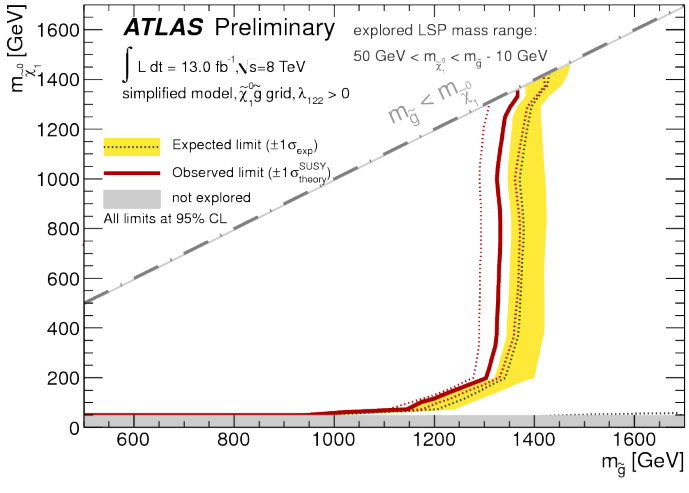
RPV sneutrino Simplified models





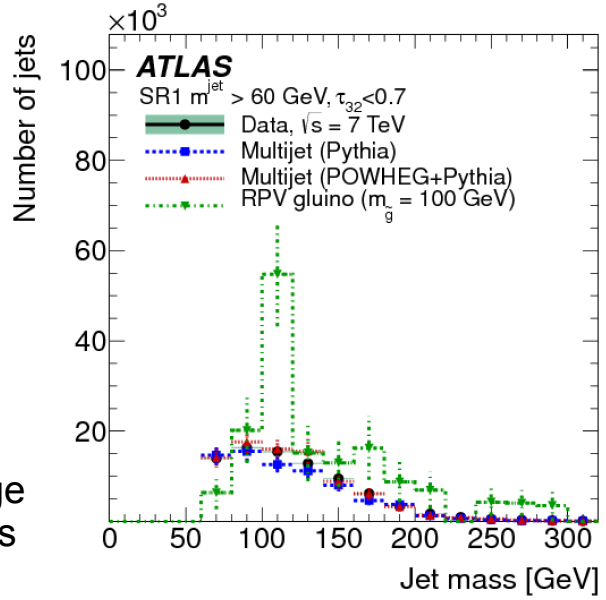
RPV gluino Simplified models

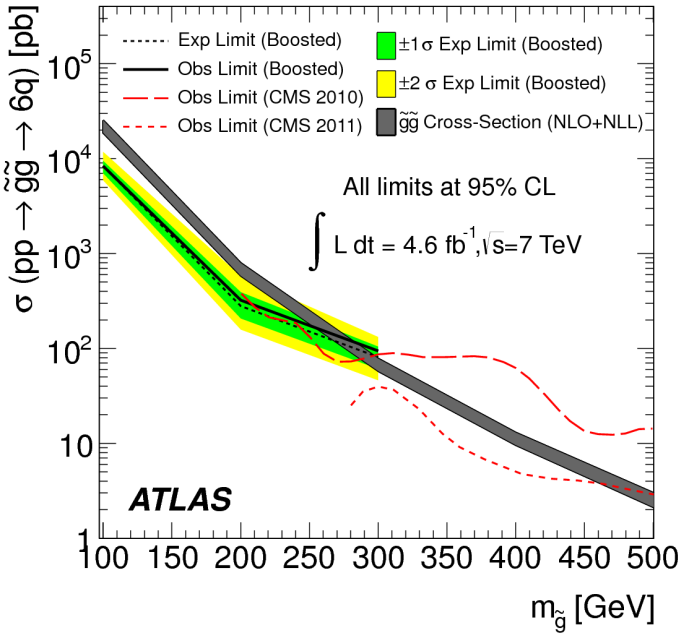


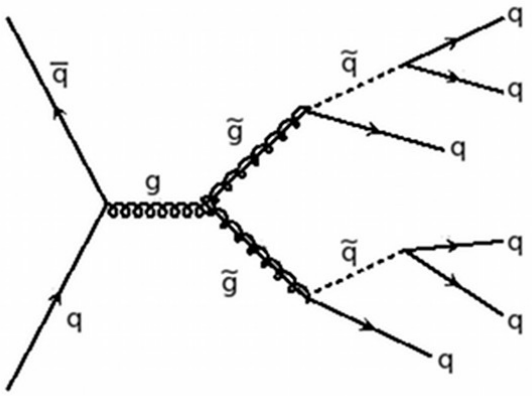


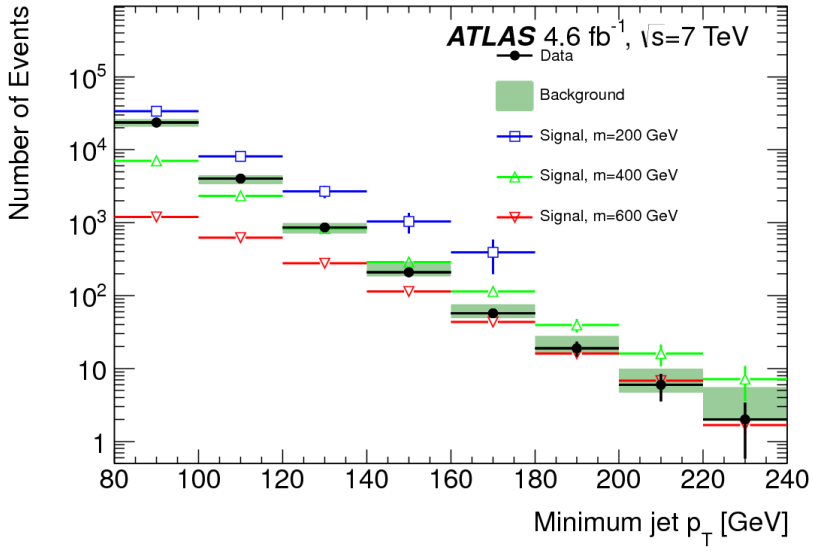
RPV SUSY: gluino → 3 quarks

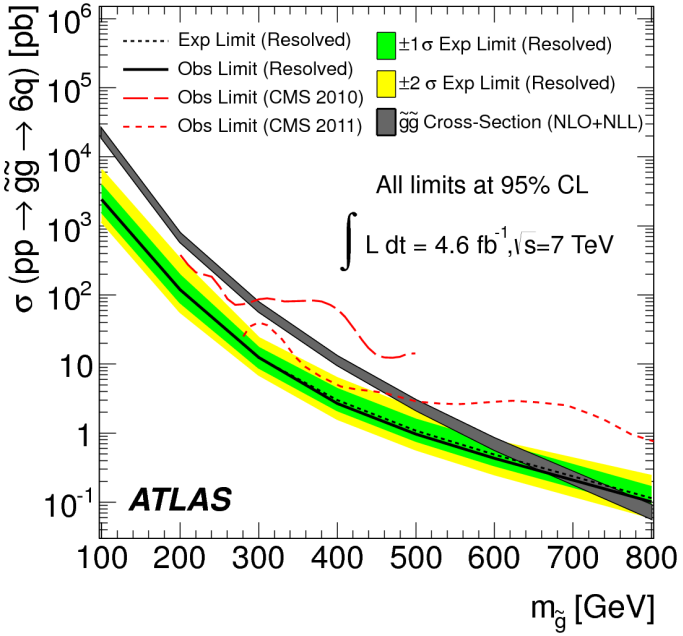
- Pair produced gluinos
  - Each decays to three quarks
- 2 analysis methods
  - Resolved analysis
    - Look for events with 6 high pT jets
    - pT of 6th jet is main kinematic discriminant
  - Boosted analysis
    - Look for events with two heavy, large radius jets and 4 normal (R=0.4) jets
    - Main discriminant are the large jets' substructure, mass, pT





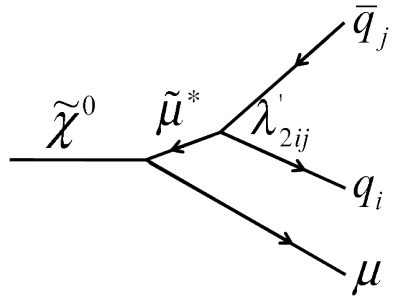




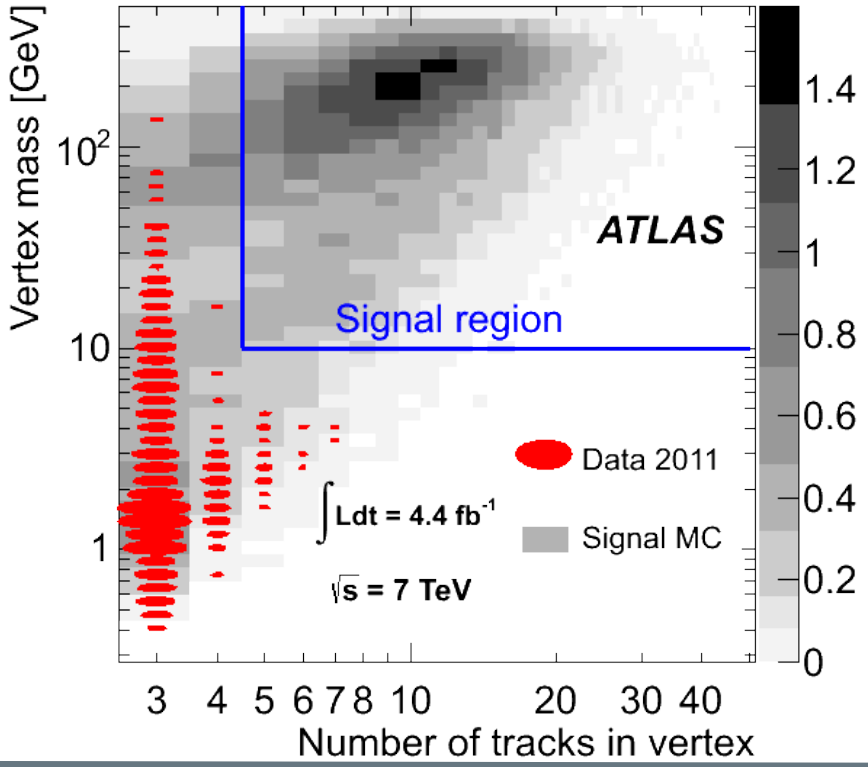


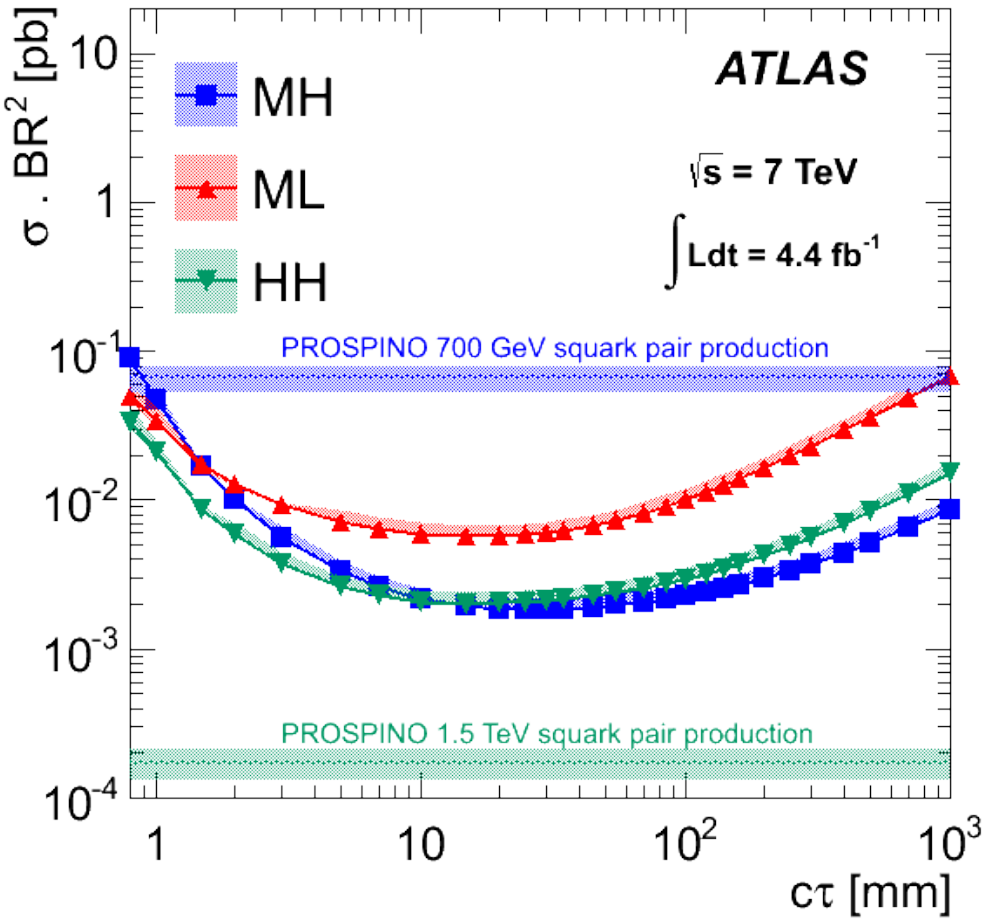
RPV SUSY: Displaced vertex

- Some models predict long lived neutralinos
  - Lifetime of picosecond to nanosecond
  - Decay length mm to many cm
- Look for events with a displaced vertex containing a muon and at least 5 tracks
  - Invariant mass of tracks in vertex required to be above 10 GeV
- Consider two different squark and neutralino masses in 3 combinations



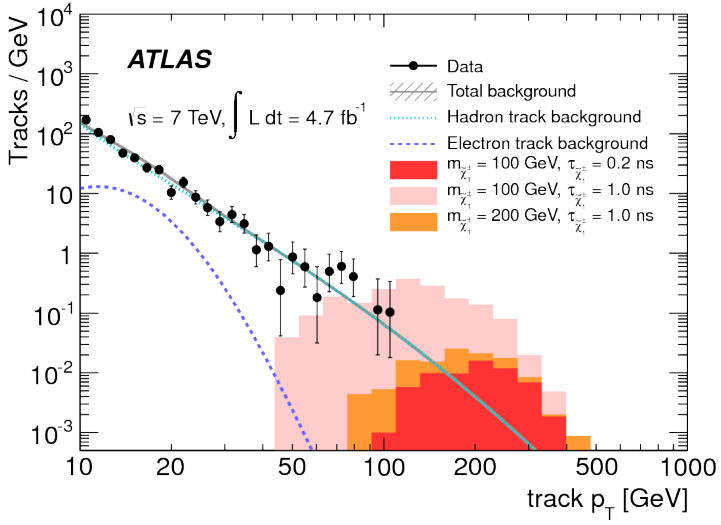
Sample	$m_{\tilde{q}}$ [GeV]	σ [fb]	$m_{\tilde{\chi}_1^0}$ [GeV]	$\langle\gamma\beta\rangle_{\tilde{\chi}_1^0}$	$c\tau_{\mathrm{MC}}$ [mm]	λ'_{211} $\times 10^{-5}$
MH	700	66.4	494	1.0	78	0.3
ML	700	66.4	108	3.1	101	1.5
HH	1500	0.2	494	1.9	82	1.5

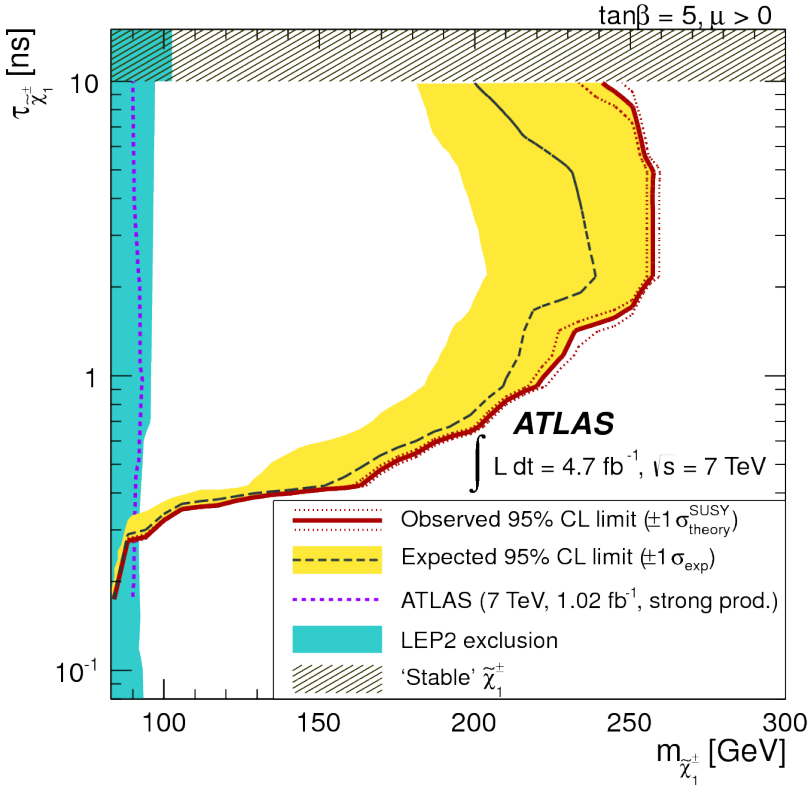


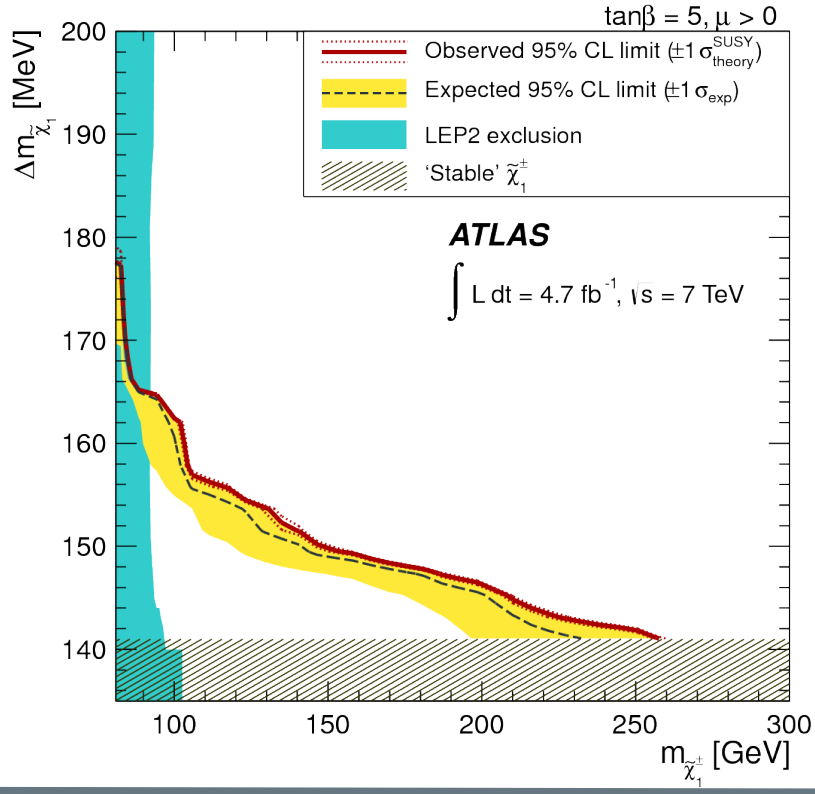


AMSB: Disappearing tracks

- Chargino and neutralino nearly degenerate
  - Very long lived particle
  - Look for a decay inside the tracking volume
- Signature:
  - Jet + MET + high pT disappearing track
  - Jet from ISR used for trigger
- Look for a good track with many good hits in the inner tracking volume but < 5 in the outer module

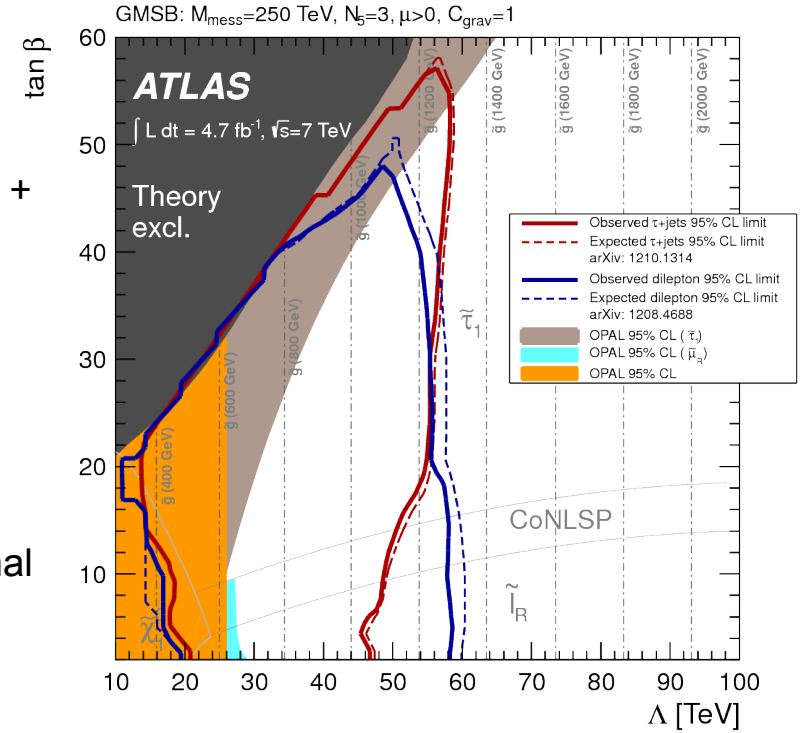




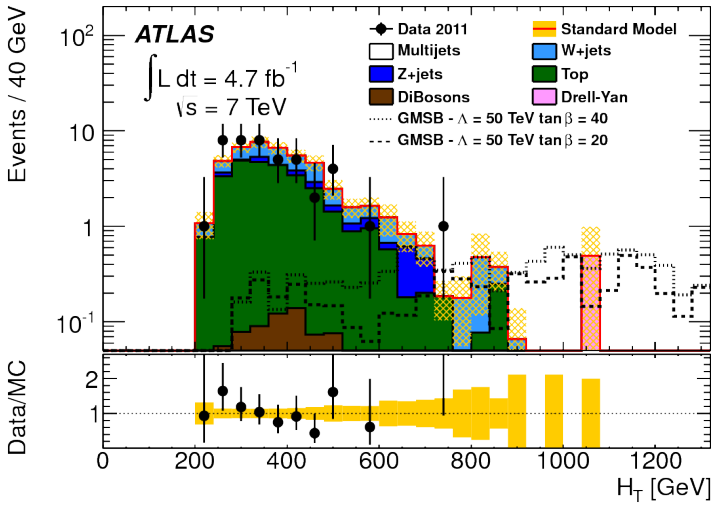


GMSB: MET + Jets + Tau

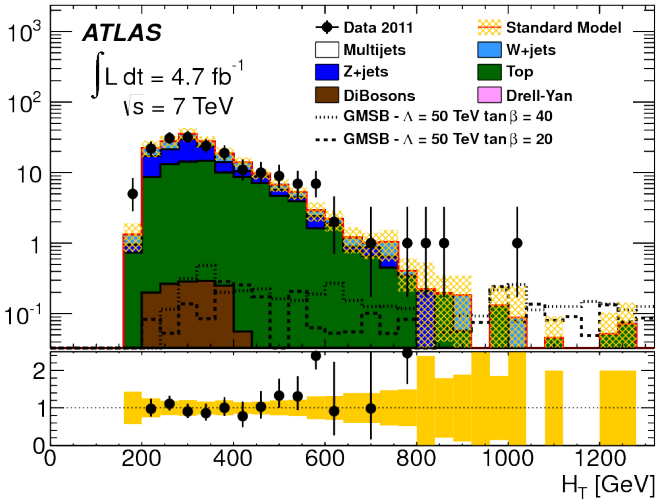
- This analysis assumes NLSP is a stau
  - Decays to gravitino + tau
- Look for events with a tau + leptons
- 4 signal regions
  - 1 tau
  - 2 taus
  - tau+muon
  - tau + electron
- Use MET, HT, and mT to discriminate between signal and background
  - Tune cuts for each signal region separately



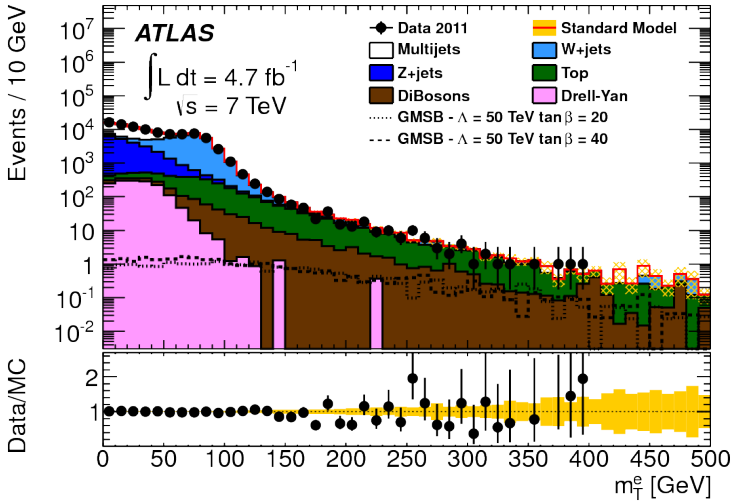
HT for 2 tau final state



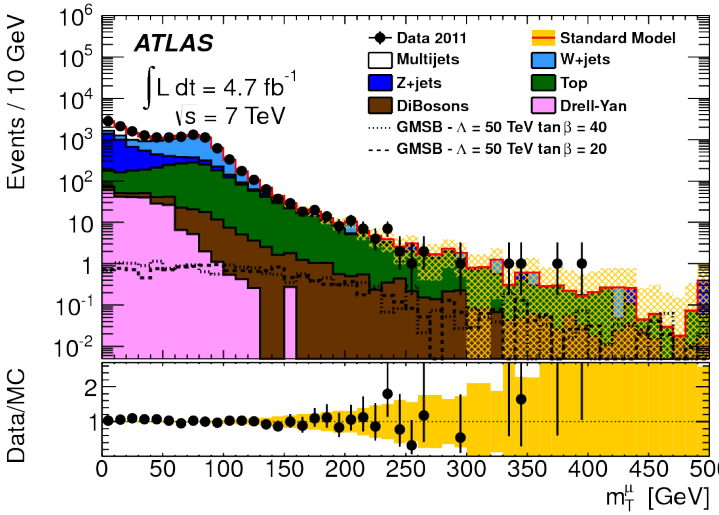
HT for 1 tau final state



mT in electron channel

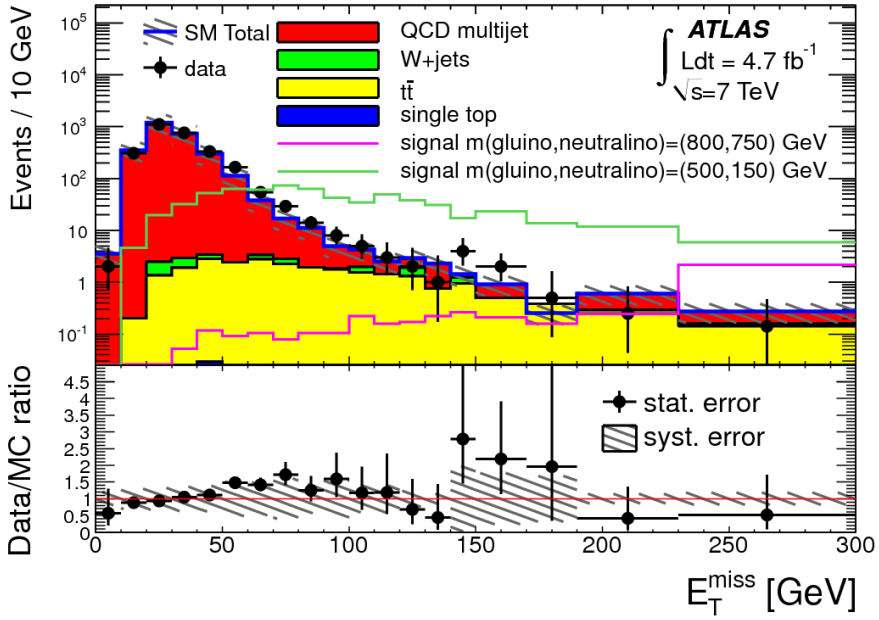


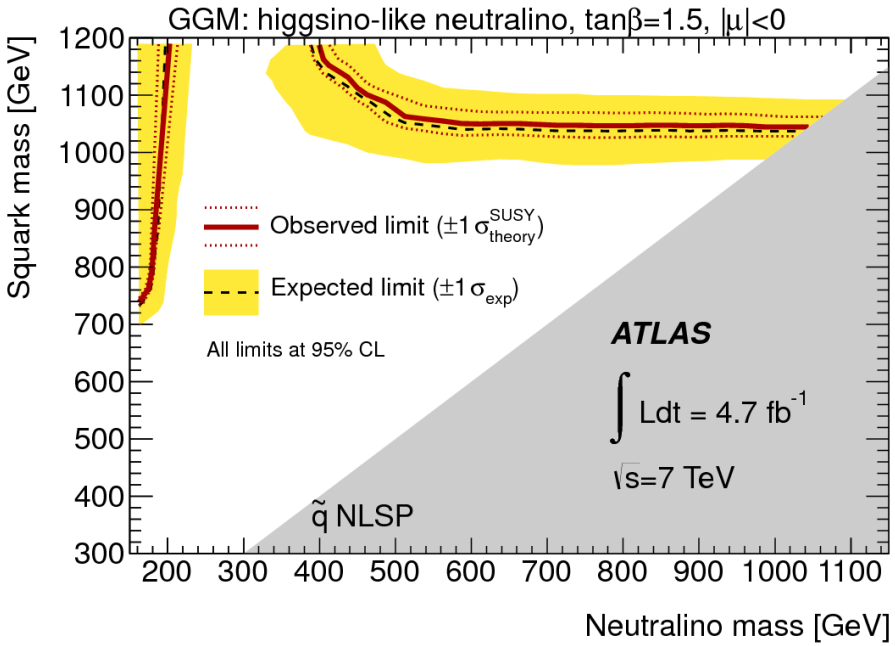
mT in muon channel

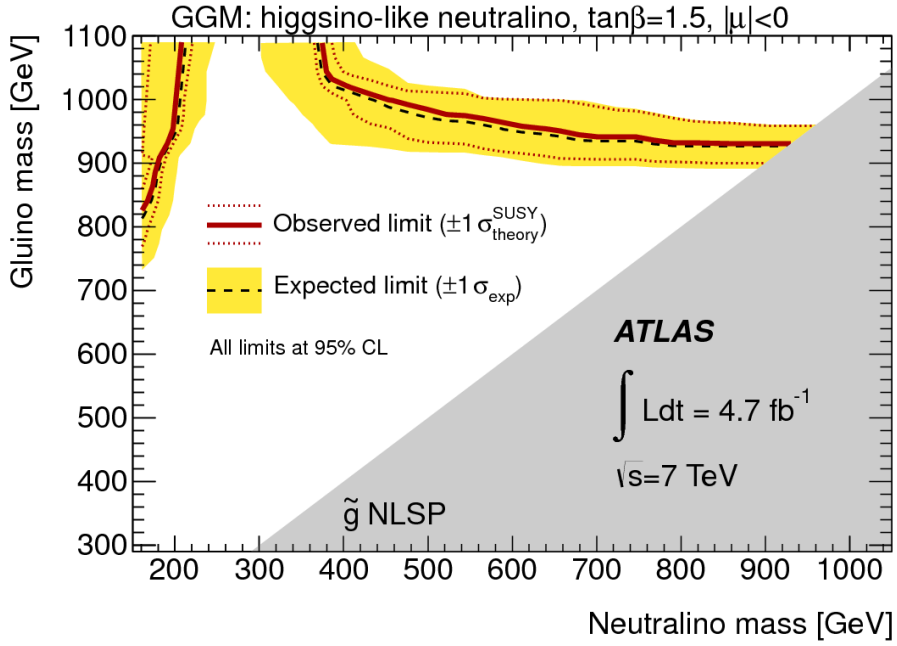


GGM: b-jets + photons + MET

- This analysis assumes NLSP is a neutralino
  - Can decay into photon + LSP
  - Can decay to Higgs → b-quarks
- Pair produced
  - Assume one decays in each channel
- Look for events with
  - Exactly 1 photon
  - 2 jets, at least one b-tagged
  - MET > 150 GeV
  - Photon + MET mT > 100 GeV

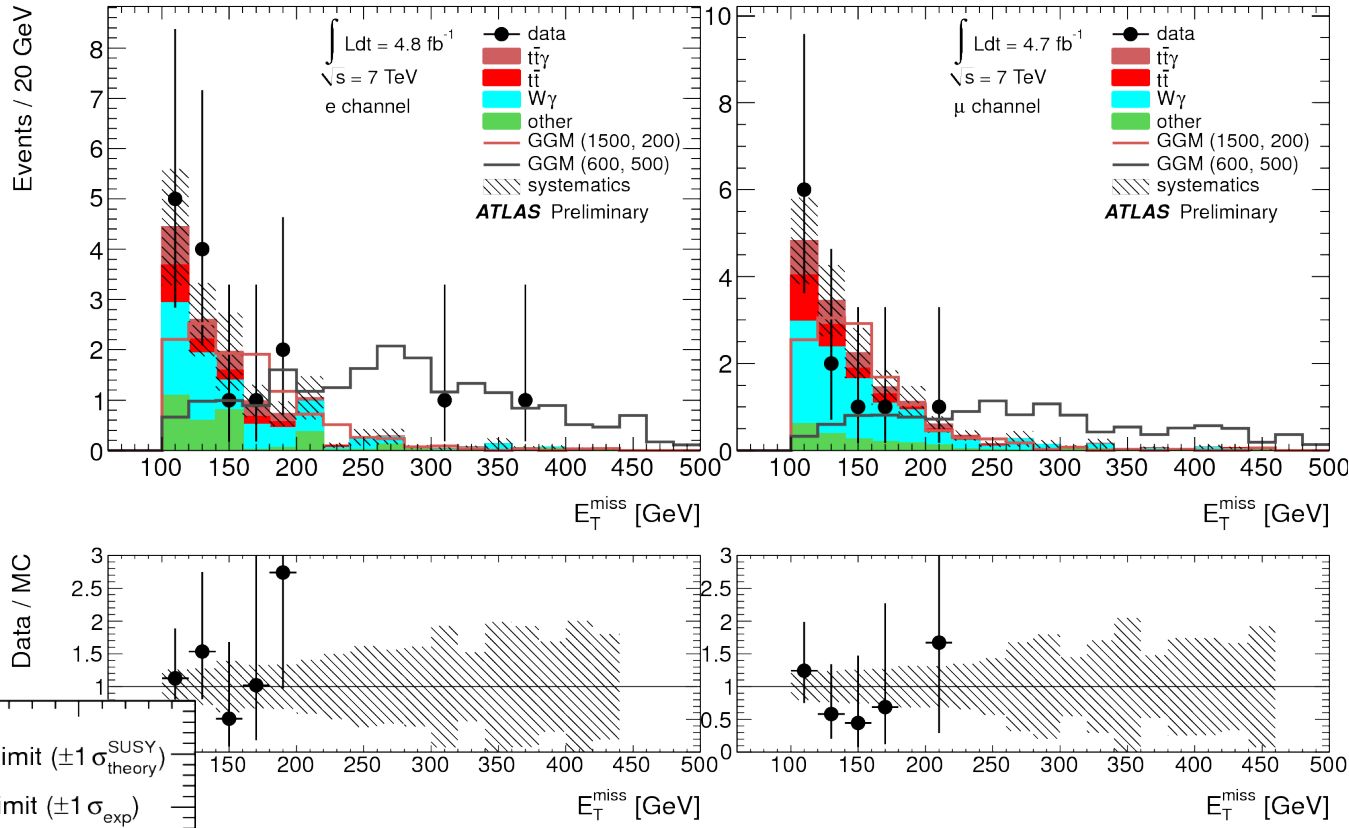


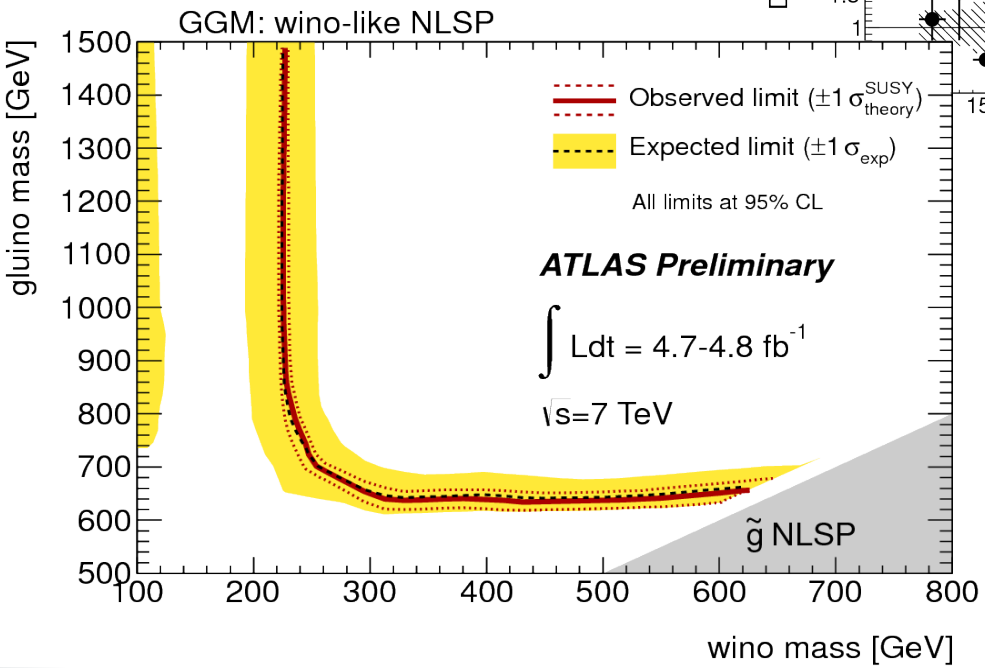


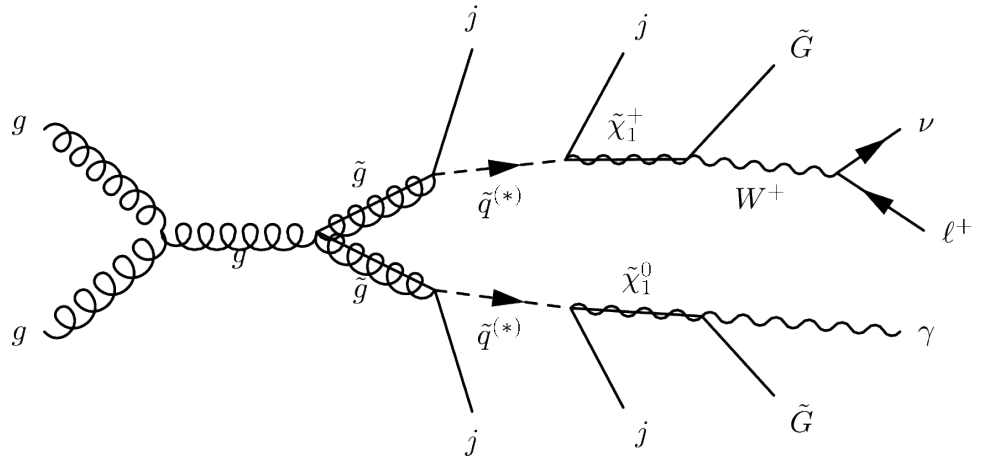


GGM: photon + lepton + MET

- Neutralino and charginos nearly degenerate
  - Chargino decays to gravitino + W
  - Neutralino decays to gravitino + photon (or Z)
- Look for events with a photon, and a W boson
  - mT lepton jet > 100 GeV
  - MET > 100 GeV

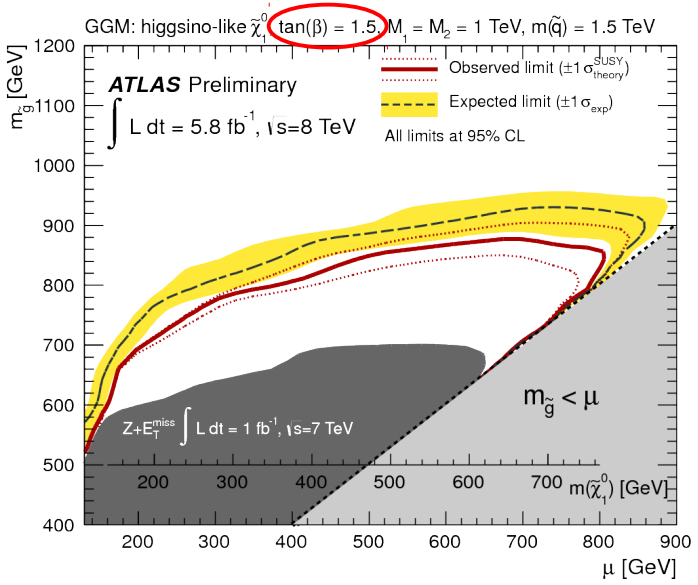


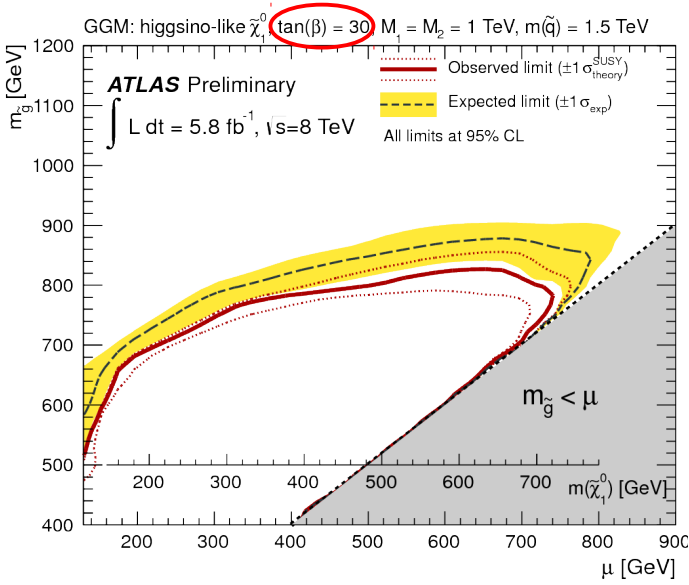


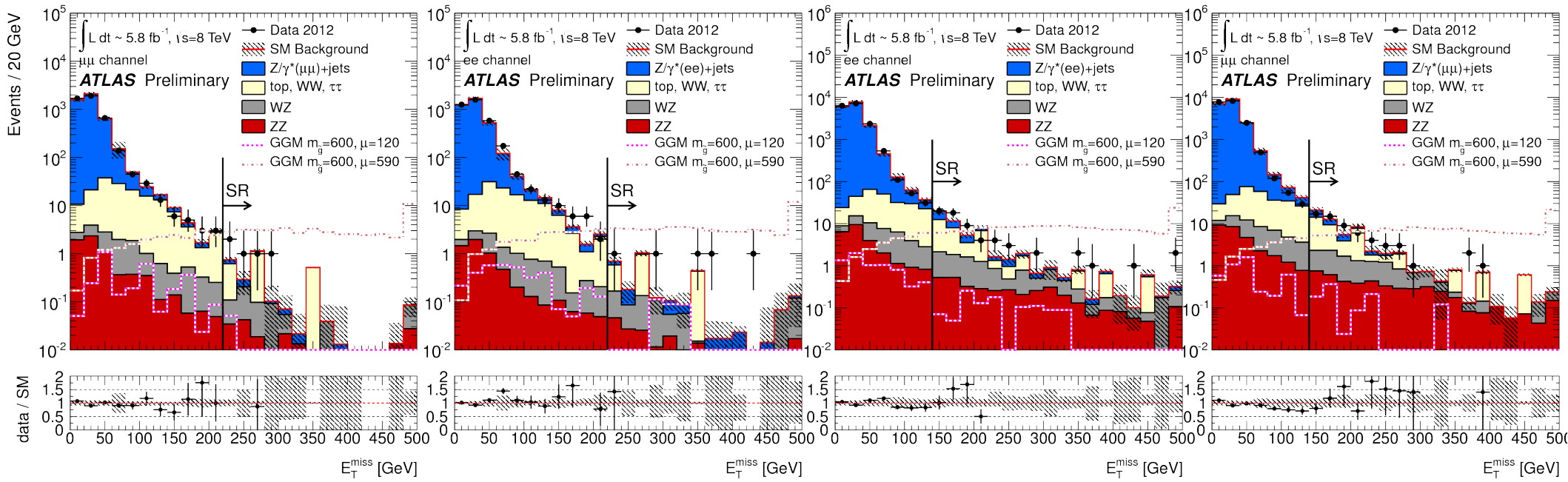


GGM: Z boson + jets + MET

- 8 TeV analysis
- If neutralino is higgsino-like it can decay to gravitino + Z
- 2 overlapping SR. Look for events with:
  - 3 jets (HT > 300)
  - MET > 220 (140)
  - Z boson





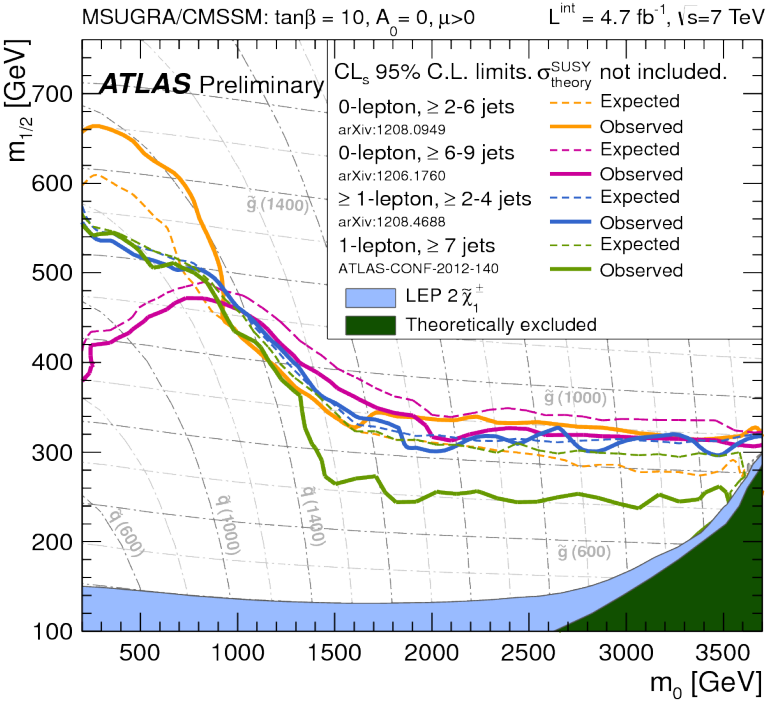


3 Jet signal region

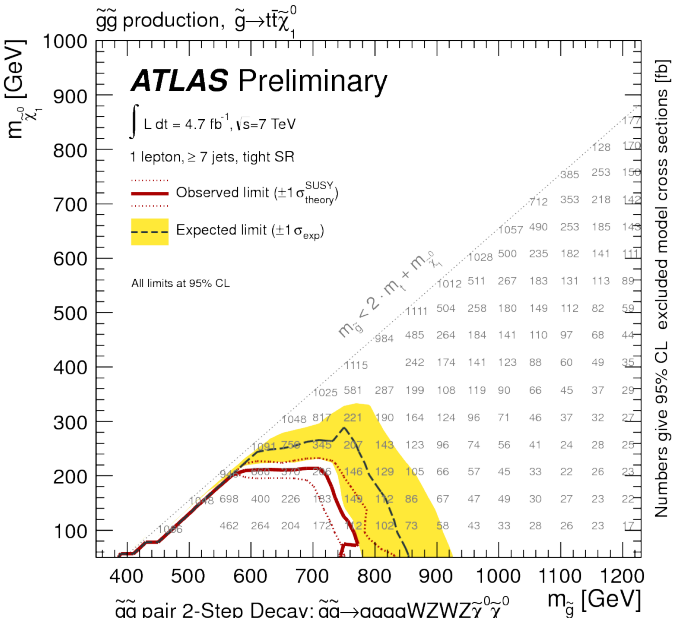
High HT signal region

SUSY: Multijet and lepton

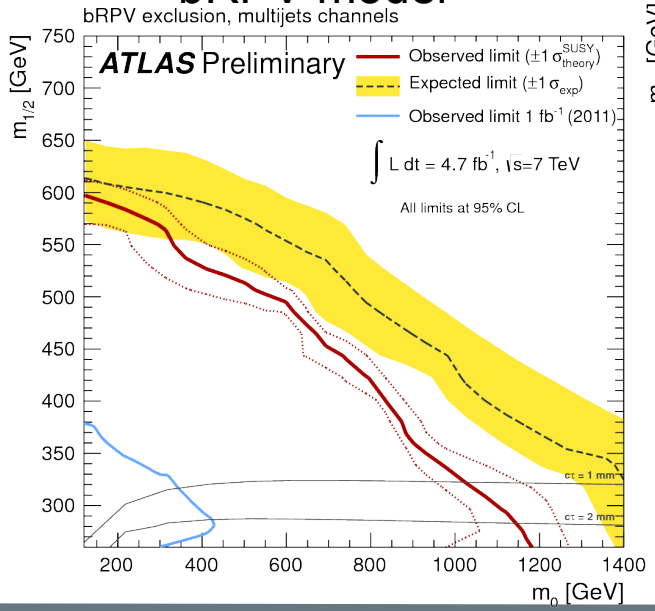
- Search uses MSUGRA/CMSSM/ and RPV models
  - SUSY particles decay via a cascade into the LSP
  - Final state has many jets + MET
- Require
  - At least 7 jets
  - MET > 180
  - Meff > 750
  - mT > 120
  - Exactly 1 lepton

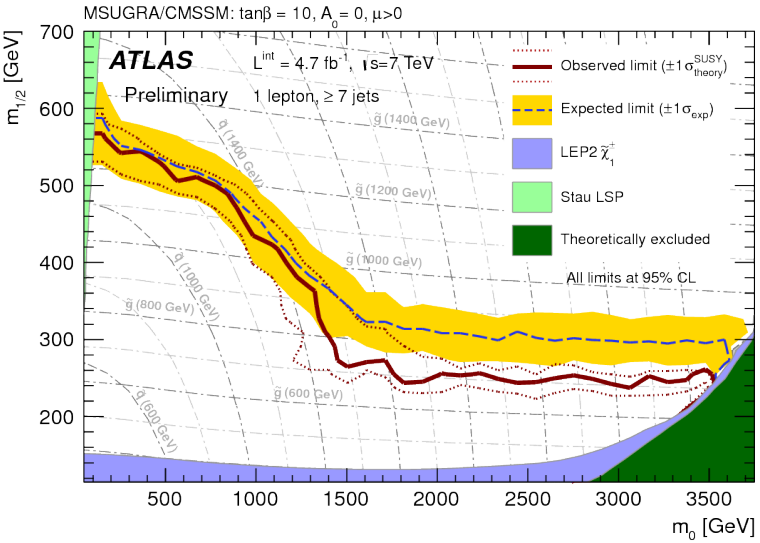


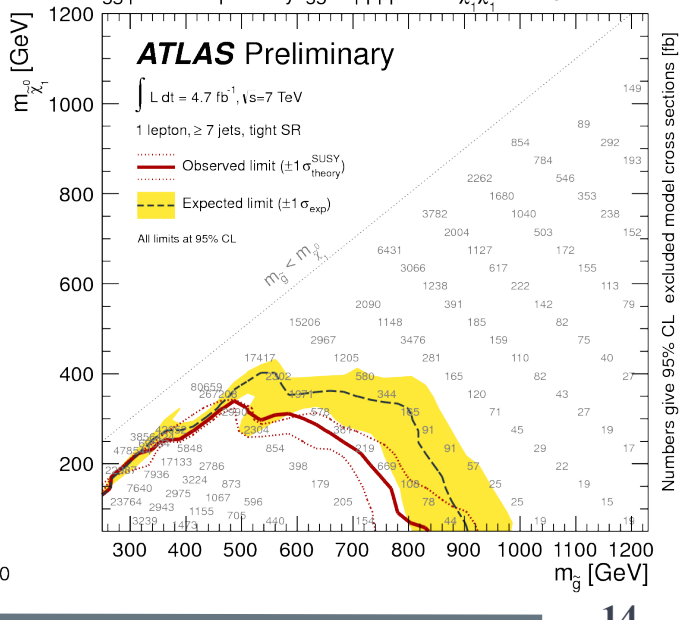
2 step simplified models



bRPV model



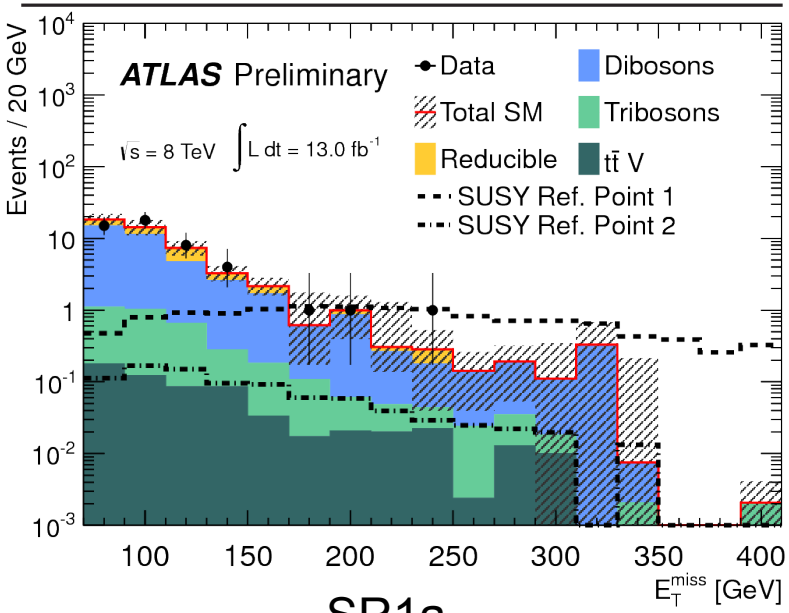




Electroweak SUSY production: 3 lepton channel (1)

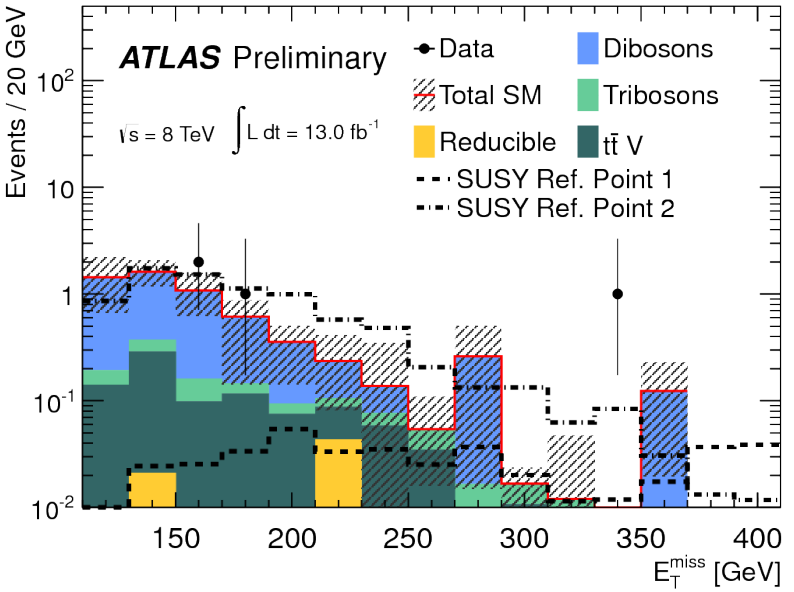
- 8 TeV analysis
- Direct production of charginos and neutralinos
  - Can decay to:
    - slepton or sneutrino+lepton
    - slepton + neutrino
    - W or Z + neutralinos
- Look for events with 3 leptons (e/mu)

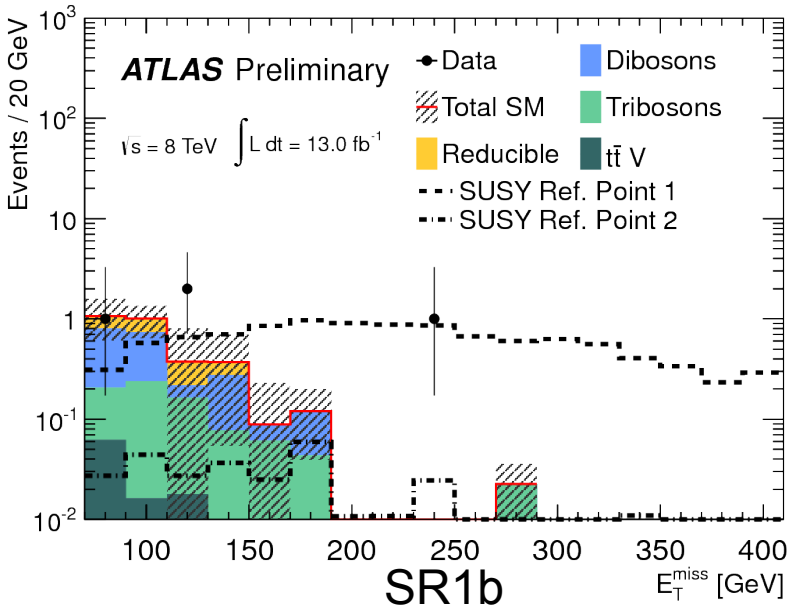
Selection	SR1a	SR1b	SR2
Targeted $\tilde{\chi}_2^0$ decay	$\tilde{l}^{(*)}$ or Z^*		on-shell Z
$\lvert m_{\mathrm{SFOS}} - m_Z \rvert$	> 10 GeV		< 10 GeV
Number of b-jets	0		any
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 75 GeV		> 120 GeV
m_{T}	any	> 110 GeV	> 110 GeV
p_{T} of leptons	> 10 GeV	> 30 GeV	> 10 GeV



SR1a

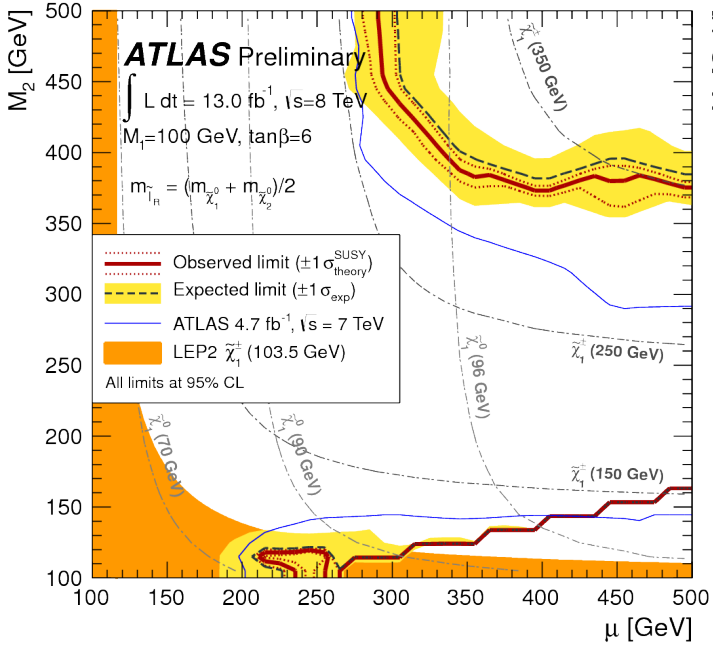
SR2

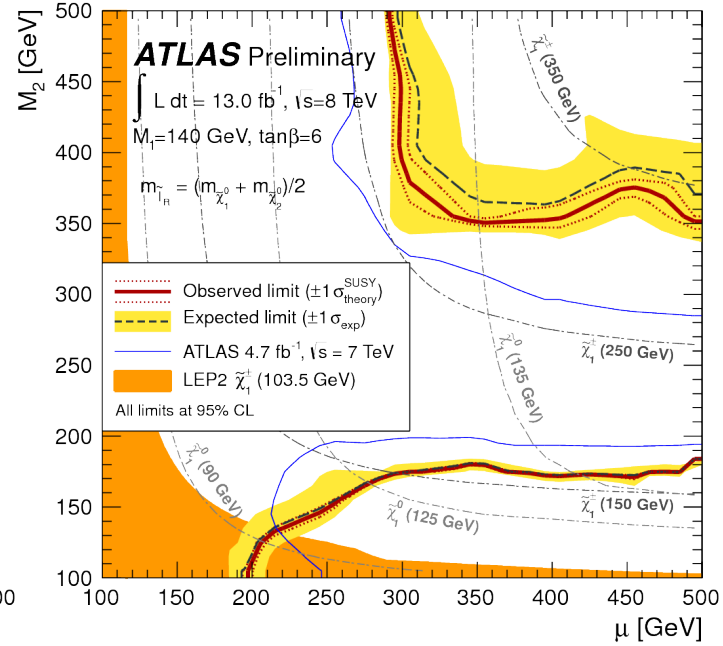


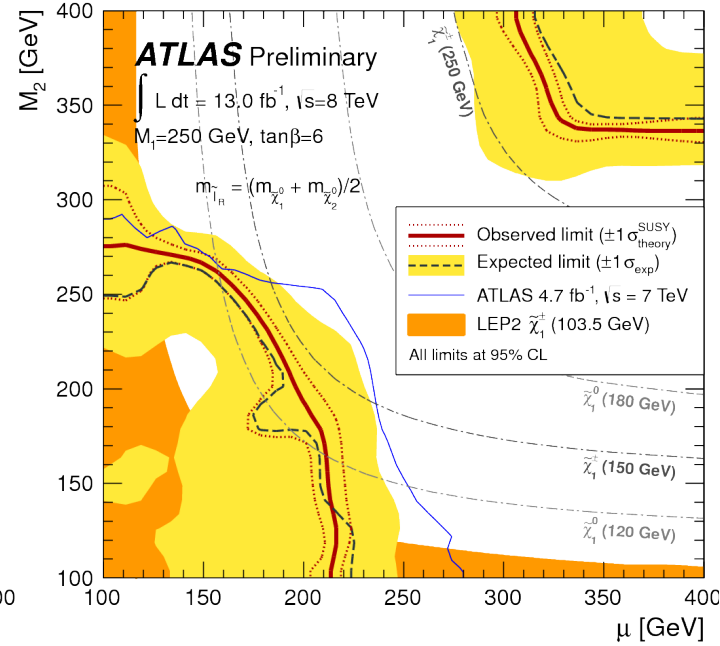


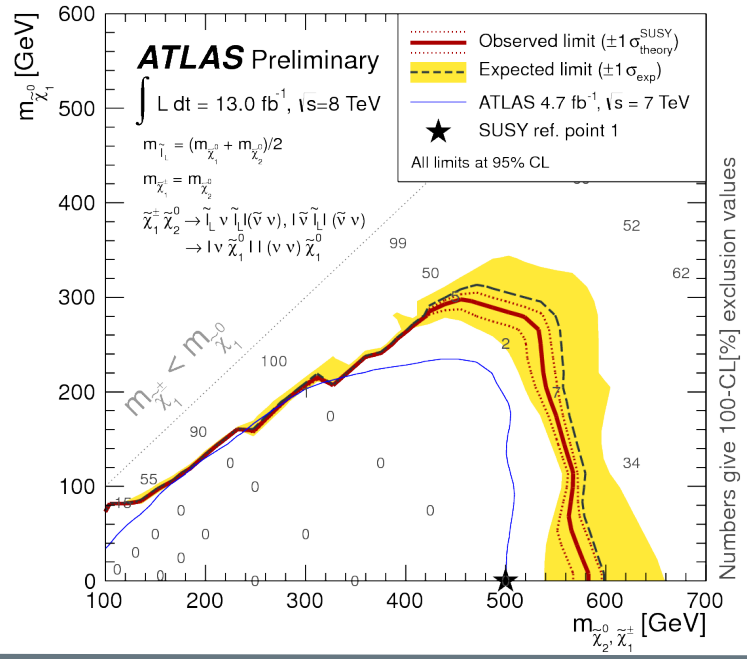
SR1b

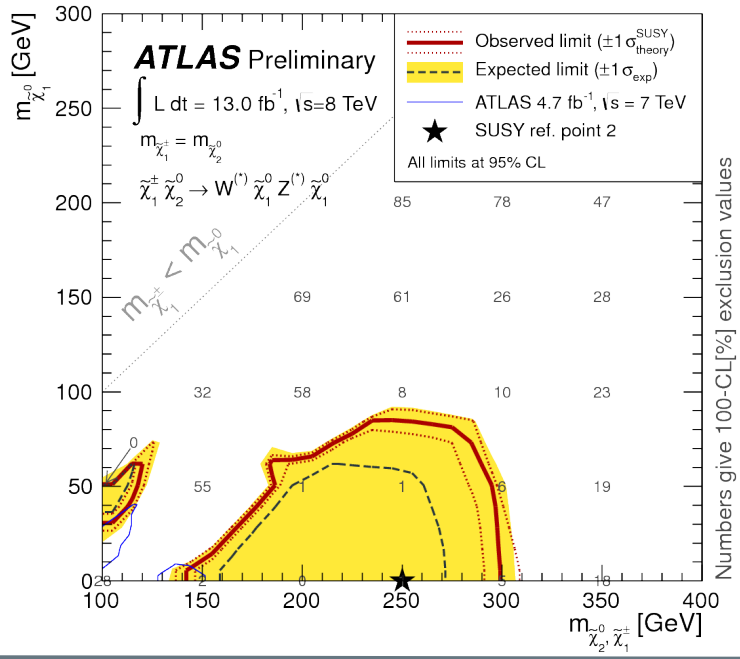
Electroweak SUSY production: 3 lepton channel (1)







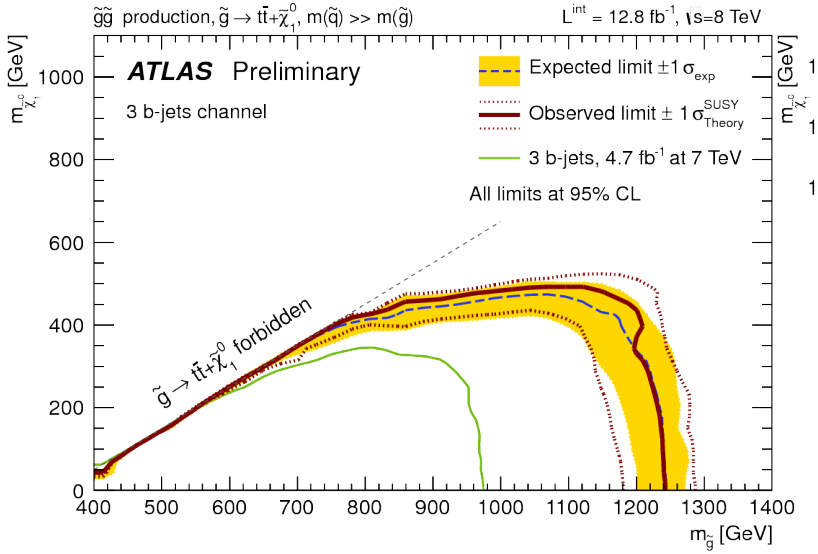


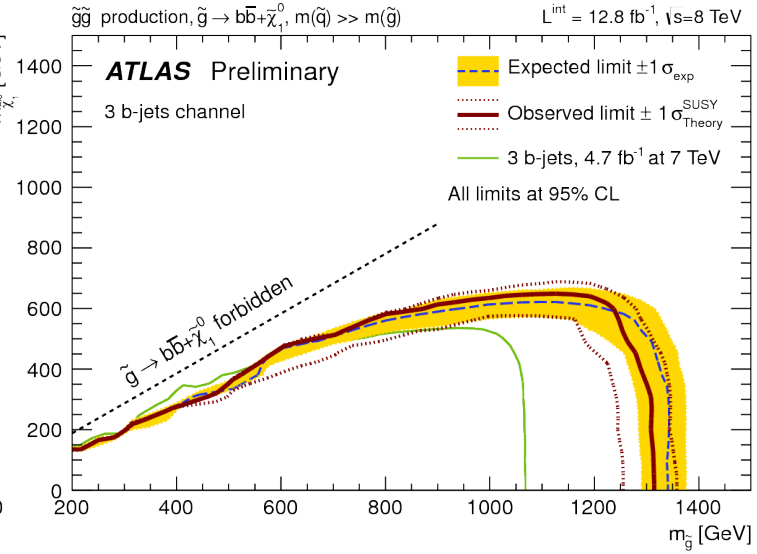


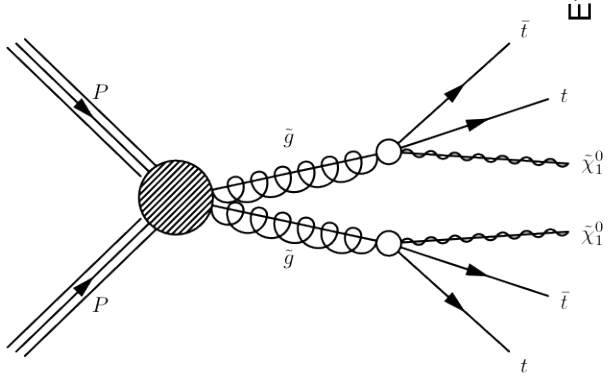
- Chargino & neutralino production in pMSSM (top)
  - M1=100 GeV (left)
  - M1=140 (center)
  - M1=250 (right)
- Chargino & neutralino production in simplified model (bottom)
  - Intermediate slepton decay (left)
  - Intermediate gauge boson decay (right)

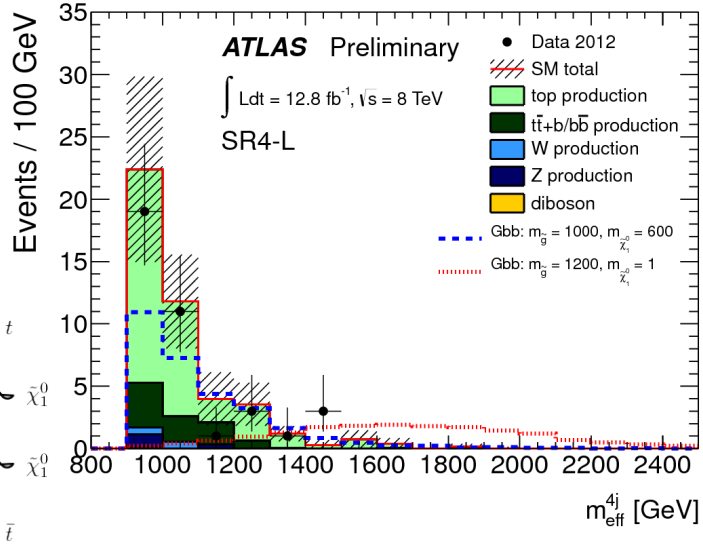
Gluino mediated stop and sbottom: 3 b-jets + MET

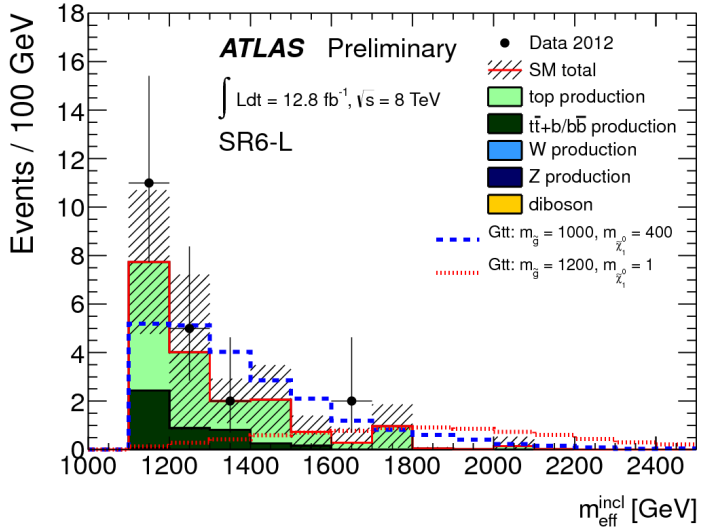
- 8 TeV analysis
- Pair produced gluinos
- Gluino decays either to:
  - top+stop+LSP
  - bottom+sbottom+LSP
- Look for events with
  - 3 b-jets
  - MET > 200 GeV
  - MET/Meff > 0.2
  - At least 4 jets and
    - B-jet pT > 50
    - Meff > 900/1100/1300
  - At least 6 jets and
    - B-jet pT > 30
    - Meff > 1100/1300/1500





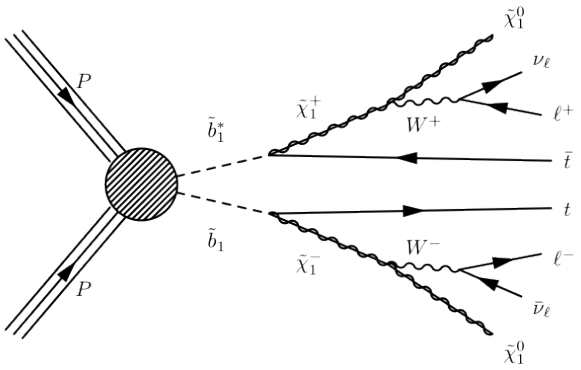


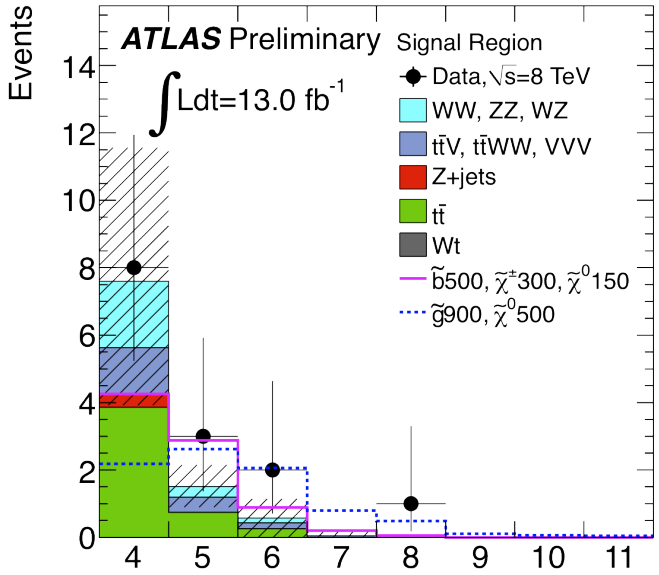


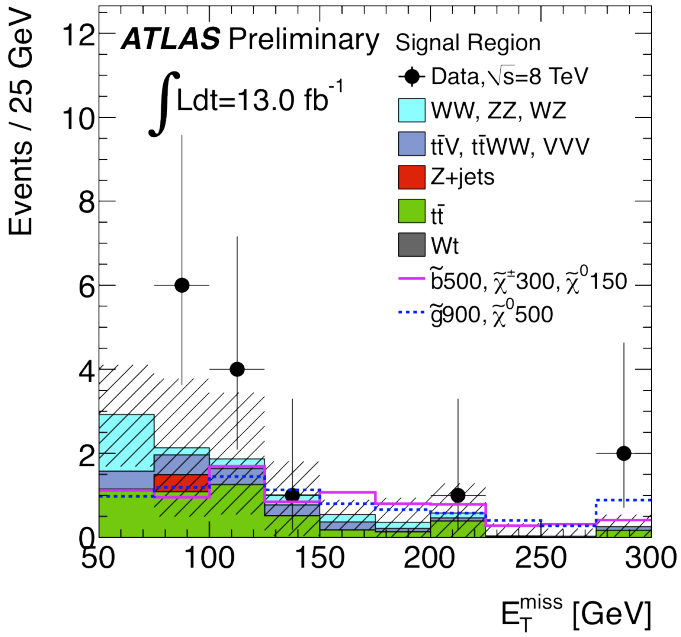


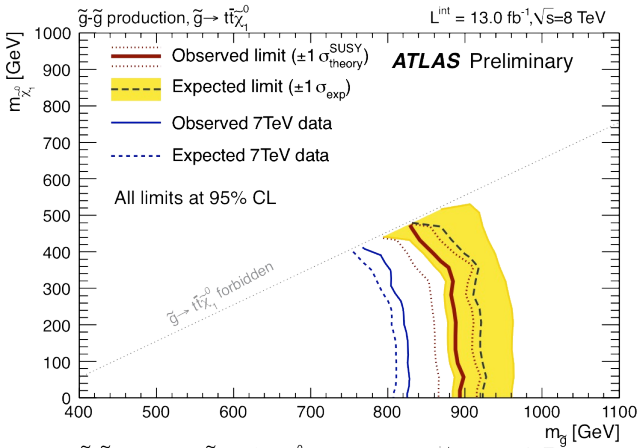
Gluino mediated stop, direct sbottom: 3 leptons + jets + MET

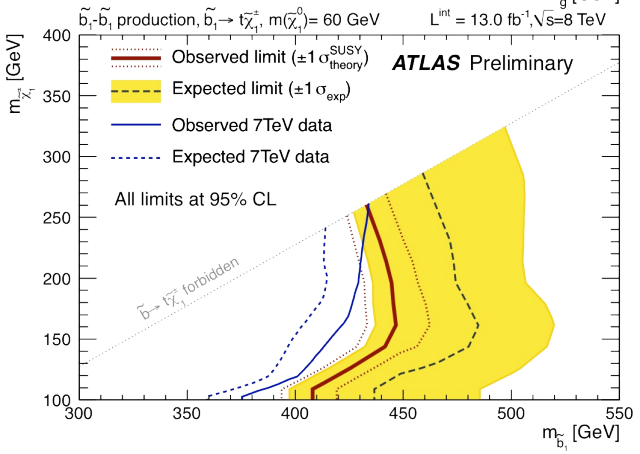
- 8 TeV analysis
- Pair produced gluinos
  - Decays to 4 tops + MET
- Pair produced sbottoms
  - Decays to 2 tops + 2 leptons + MET
- Look for events with
  - At least 3 leptons
  - At least 4 jets
  - MET > 50 GeV
  - No lepton pair consistent with J/Psi or Z boson decay

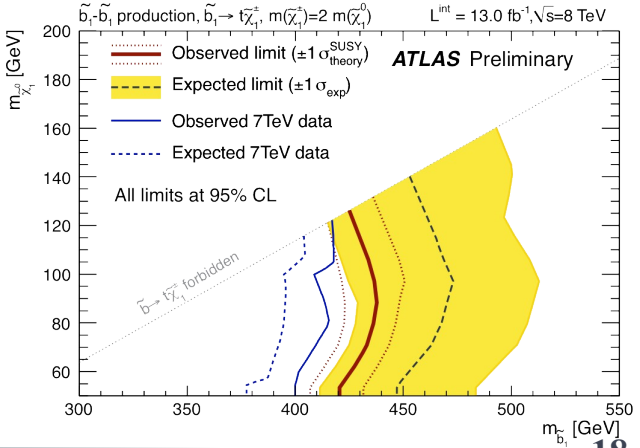










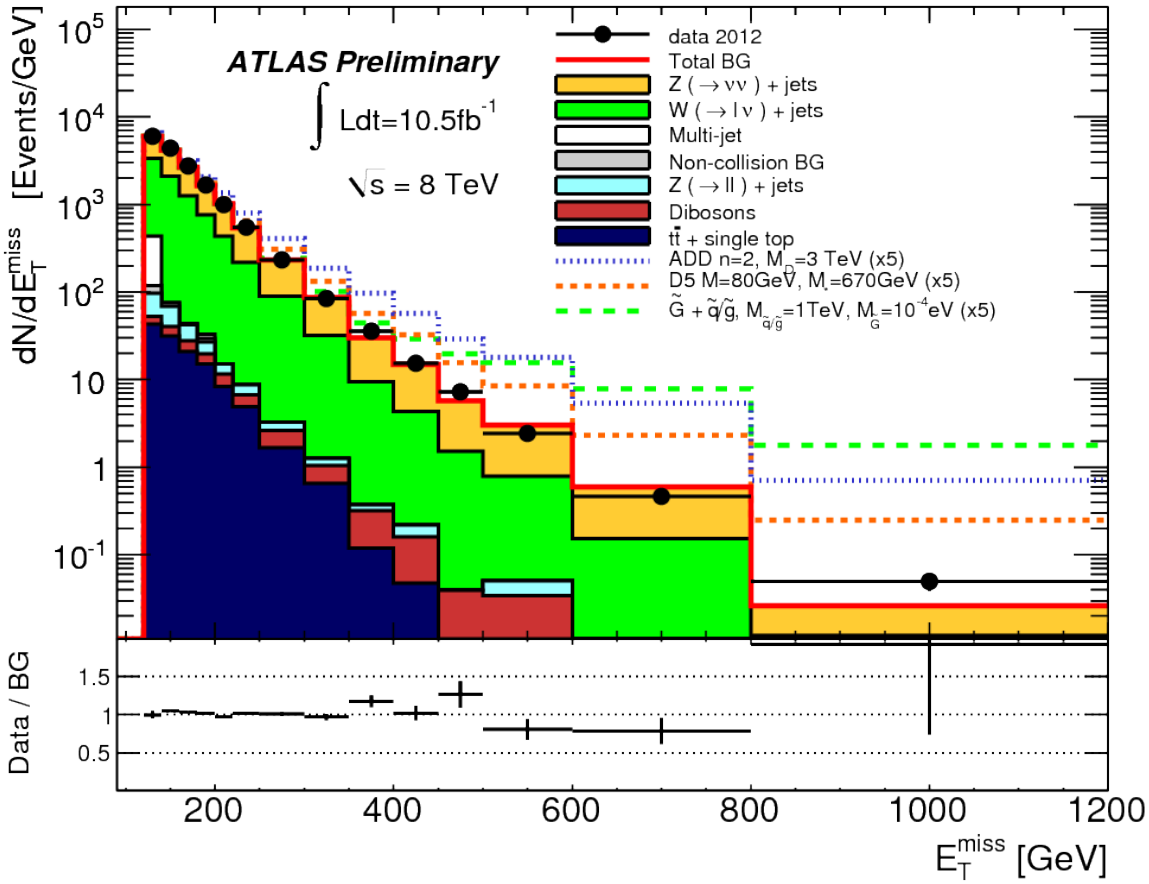


Monojets + MET (1)

- 8 TeV analysis
- Look for events with one high energy jet + large MET
- Veto on leptons and 3rd jet
- Require second jet to point away from MET
  - Reduces fake MET
- Models producing this signature
  - Large Extra Dimensions (LED)
    - Use model of Arkani-Hamed, Dimopoulos, and Davali (ADD)
  - Weakly interacting massive particle (WIMP)
    - Dark matter candidate
    - 3 possible couplings of WIMPs to SM particles considered (see below)
  - GMSB SUSY
    - Gravitino + squark/gluino production

Name	Initial state	Type	Operator
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

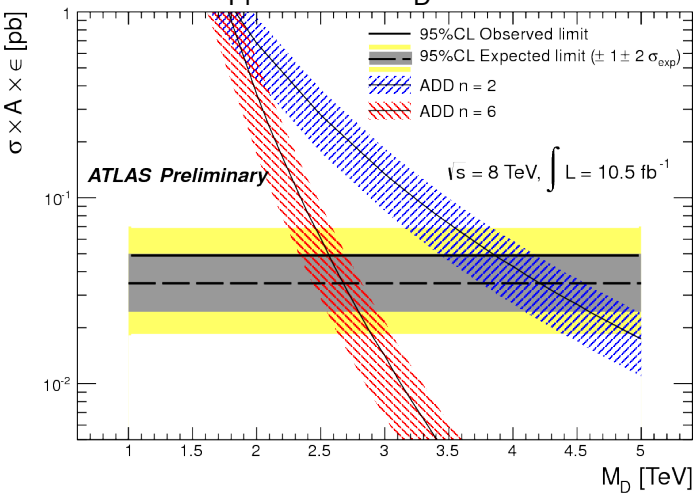
Signal regions	SR1	SR2	SR3	SR4
Common requirements	Data quality + trigger + vertex + jet quality + $\lvert\eta^{\text{jet1}}\rvert < 2.0$ + $\lvert\Delta\phi(\mathbf{p}_{\text{T}}^{\text{miss}}, \mathbf{p}_{\text{T}}^{\text{jet2}})\rvert > 0.5$ + $N_{\text{jets}} \leq 2$ + lepton veto			
$E_{\text{T}}^{\text{miss}}$, $p_{\text{T}}^{\text{jet1}} >$	120 GeV	220 GeV	350 GeV	500 GeV



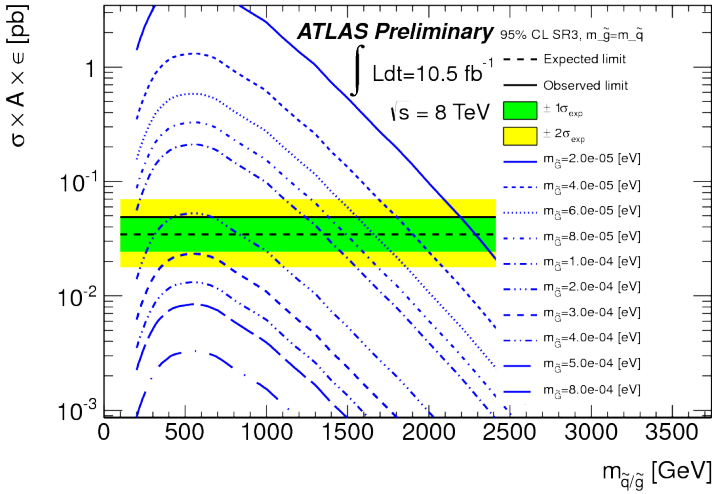
Monojets + MET (2)

Large Extra Dimensions

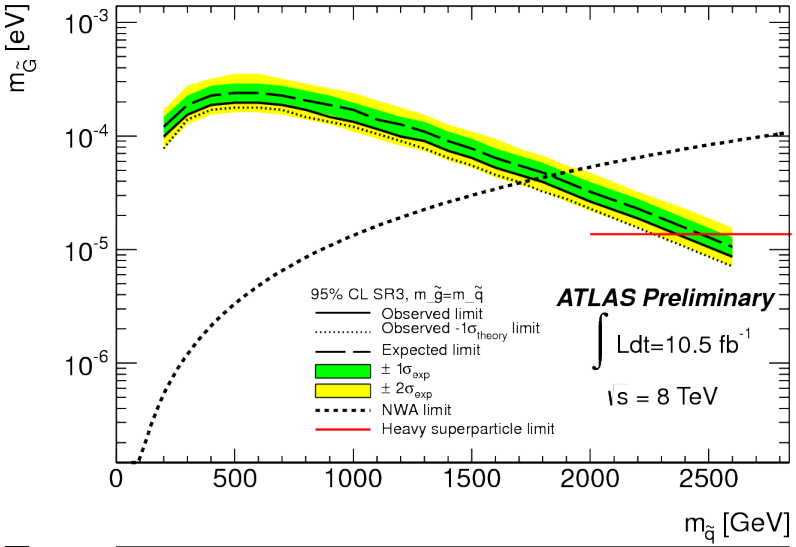
$M_{Pl}^2 = 8\pi M_D^{2+n} R^n$

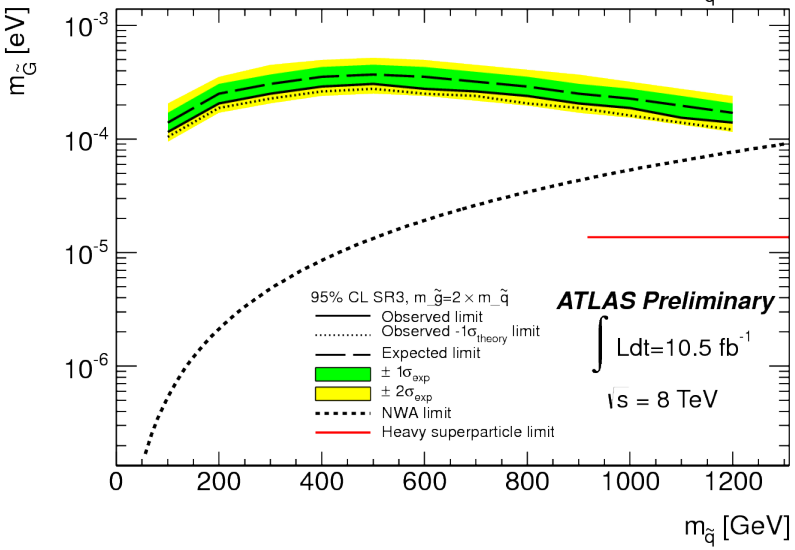


gravitino + squark/gluino production limit

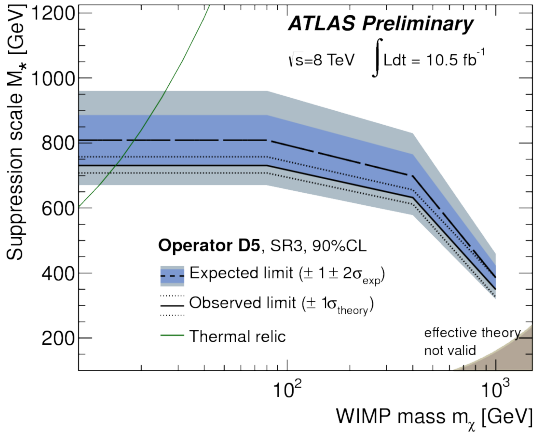


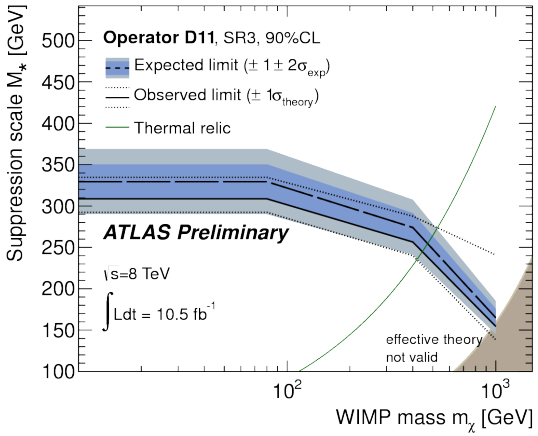
Gravitino mass vs squark mass

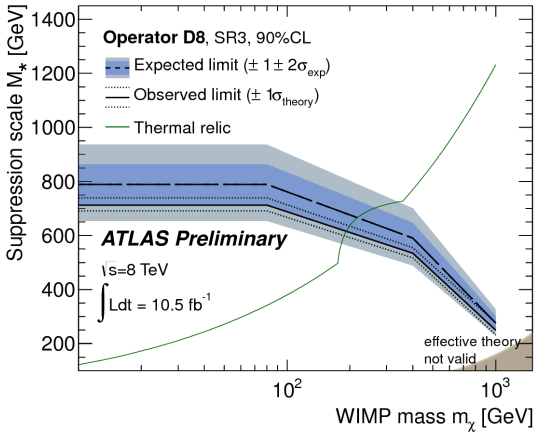




WIMPS Split by operator



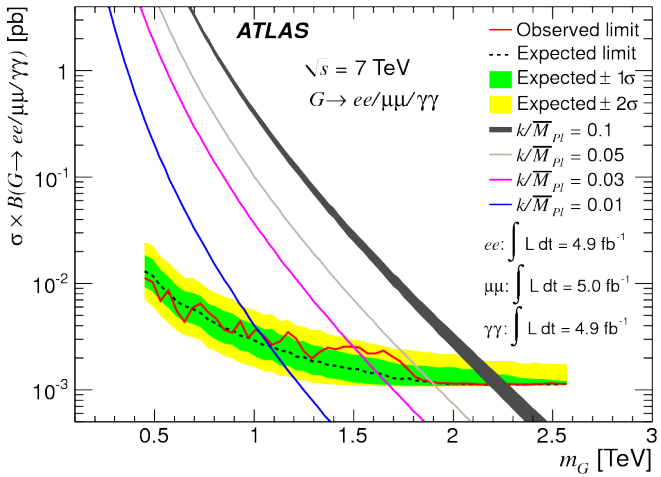


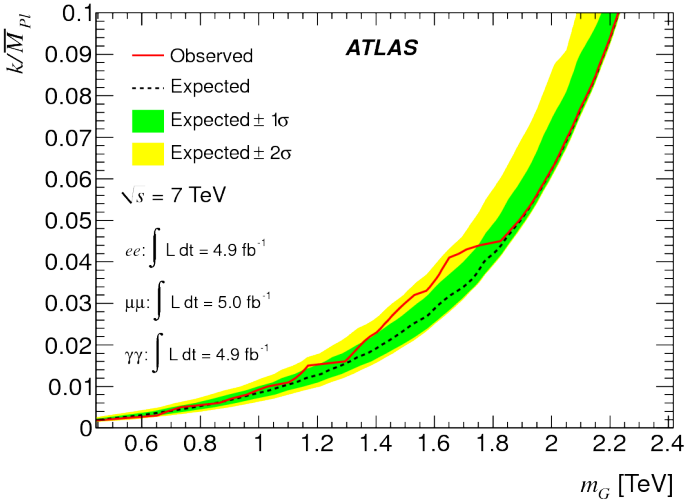


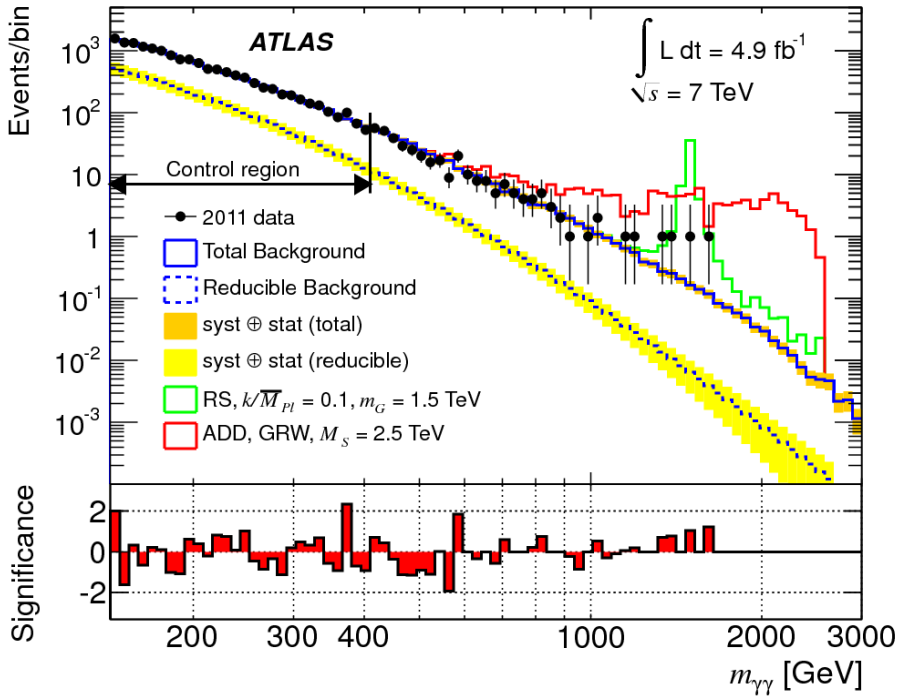
Extra Dimensions: Diphoton channel

- Two LED models considered here:
  - Randall-Sundrum (RS)
  - Arkani-Hamed, Dimopoulos, and Davali (ADD)
  - Both predict a graviton decaying to a pair of photons
- Pick events with a pair of high pT photons
  - Require both to be very cleanly identified
- Use BumpHunter to scan the diphoton invariant mass distribution

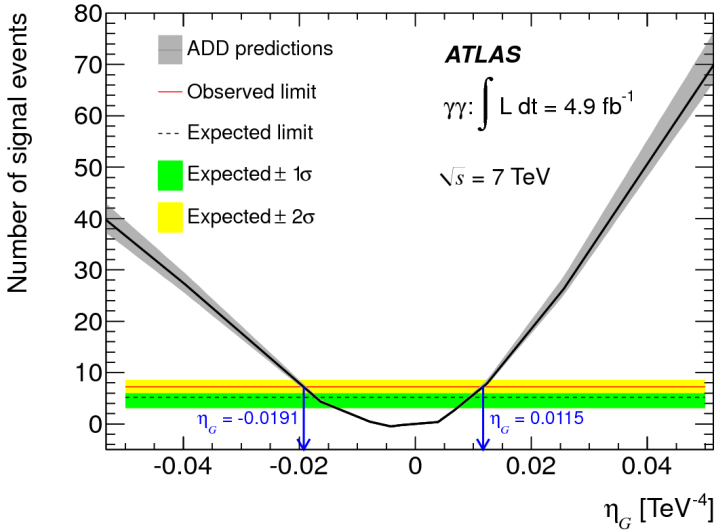
Graviton mass (m_G limits) in RS model





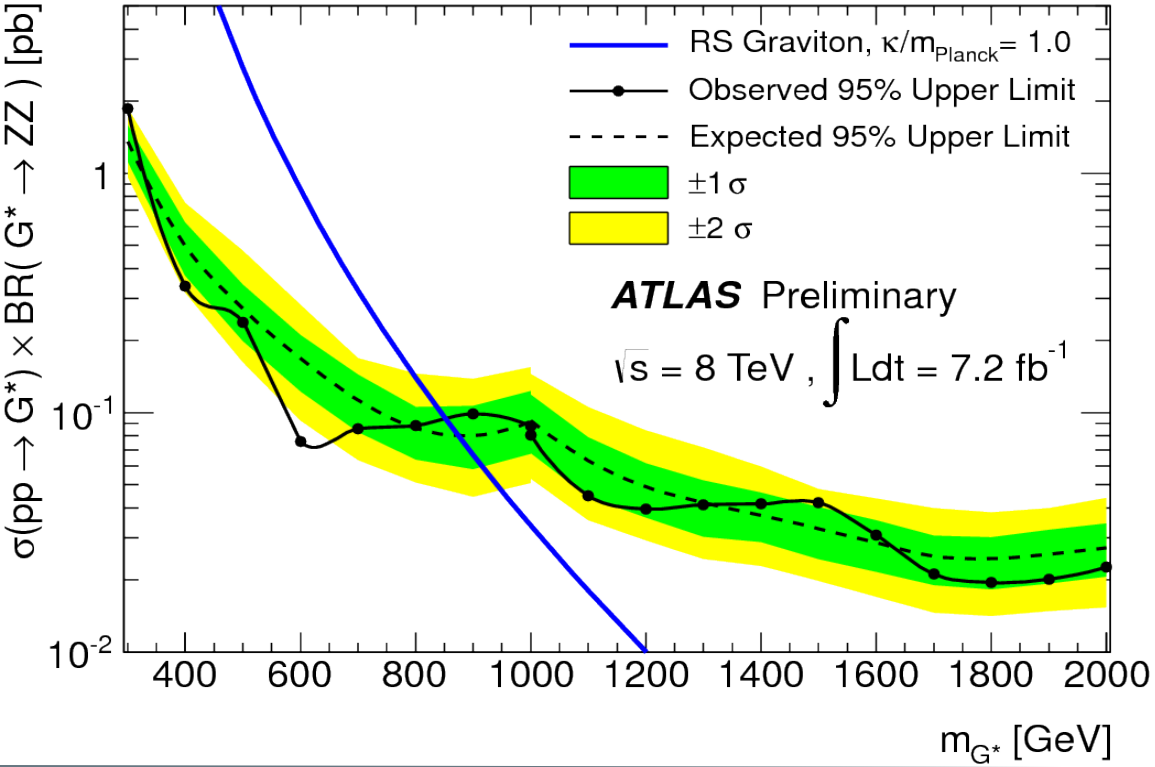


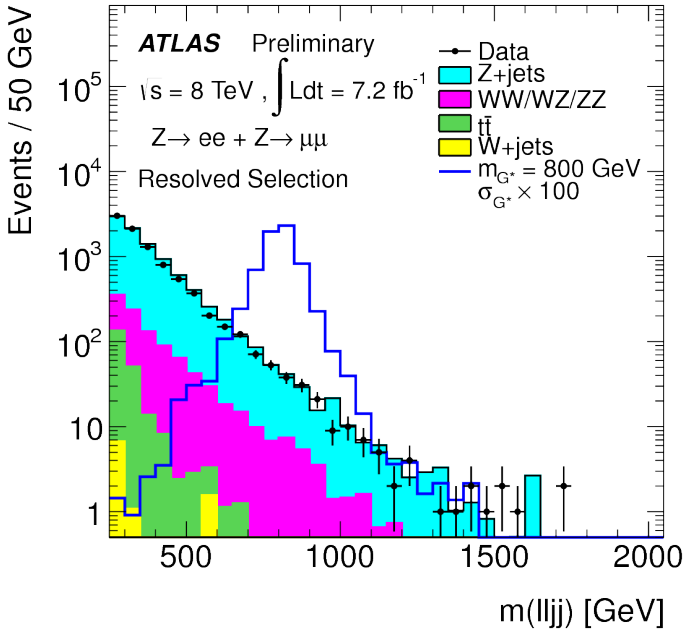
Strength of gravity (η_G) in ADD model

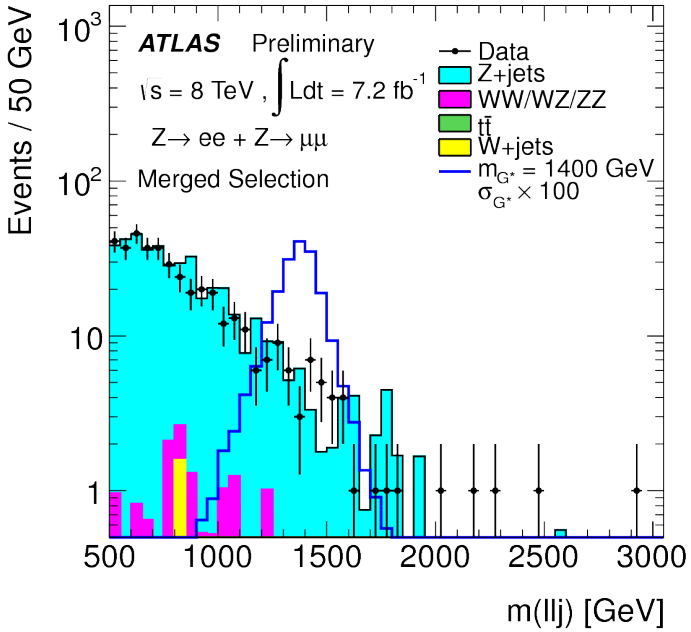


Extra Dimensions: Diboson channel

- 8 TeV analysis
- Look for RS graviton decaying to a ZZ pair
  - ZZ → llqq channel
- Look for events with:
  - 2 same flavor leptons
  - 1 (merged) or 2 (resolved) jets
    - 2 jets with a mass near the Z mass
    - 1 jet with mass > 40 GeV
- Form invariant mass of 2 leptons and jet(s)



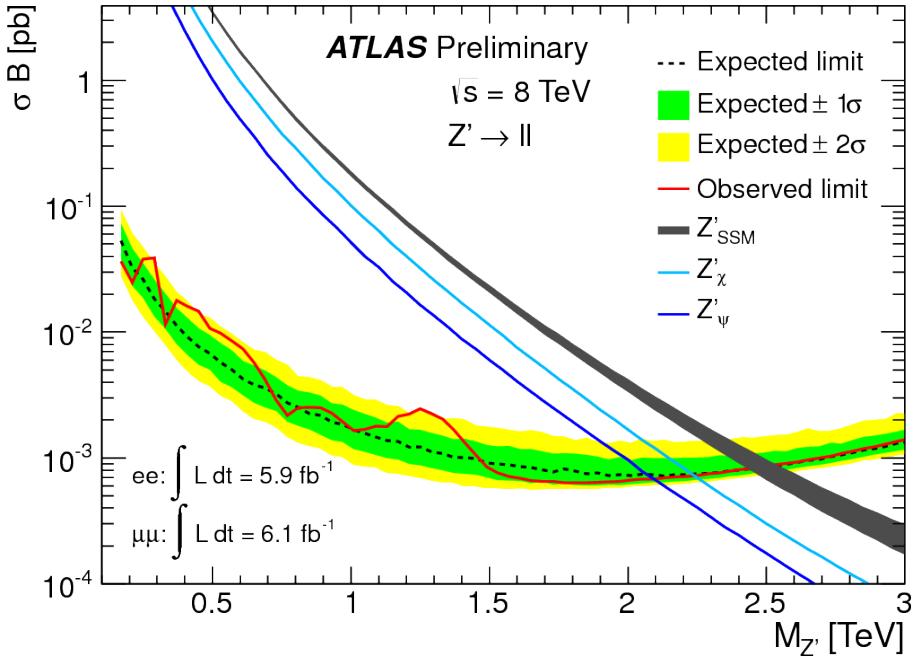


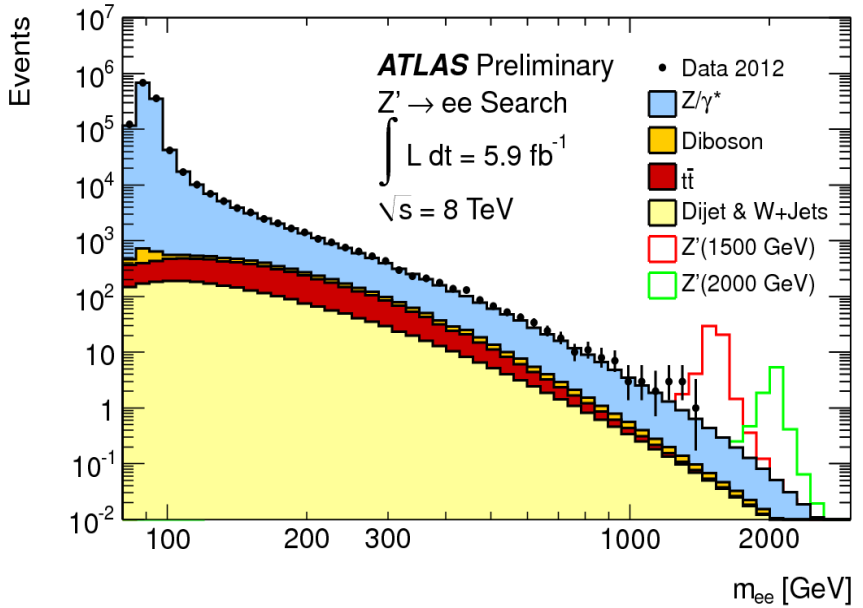


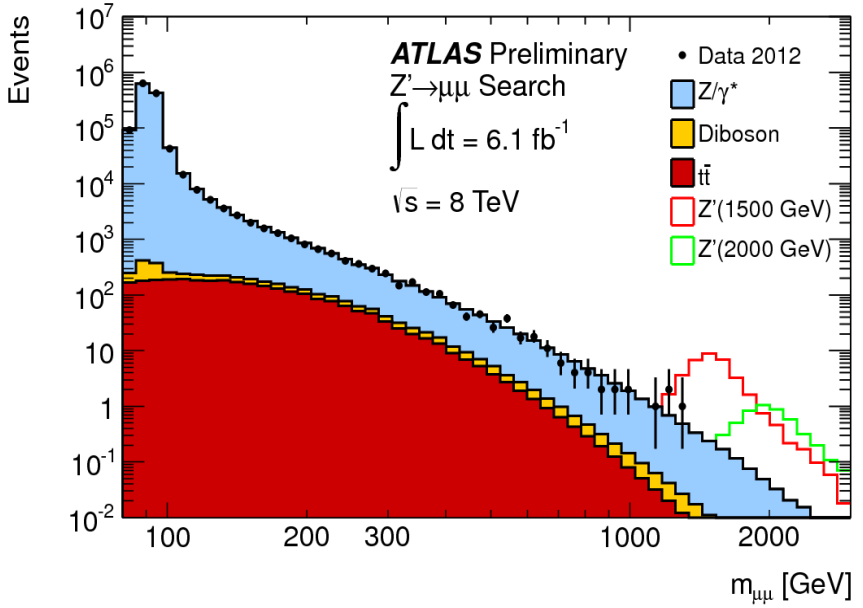
Z' Boson: electron/muon channel

- 8 TeV update
- Search for heavy Z-like boson
  - Look for Z' → ee or μμ decays
  - Select events with a pair of high pT electrons or muons
- Form dilepton invariant mass

m_{ee} [GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000
Z/γ^*	36200 ± 1500	4330 ± 180	412 ± 20	21.6 ± 1.5	3.03 ± 0.35
$t\bar{t}$	2190 ± 250	750 ± 130	53 ± 19	0.86 ± 0.18	0.041 ± 0.017
W + jets	470 ± 130	130 ± 40	10.6 ± 3.0	0.30 ± 0.09	0.026 ± 0.009
Diboson	482 ± 34	172 ± 22	21 ± 8	0.91 ± 0.05	0.117 ± 0.014
Dijet	720 ± 240	250 ± 120	34 ± 23	2.1 ± 2.0	0.4 ± 0.5
Total	40100 ± 1600	5620 ± 260	530 ± 40	25.8 ± 2.5	3.6 ± 0.6
Data	39875	5760	615	31	5

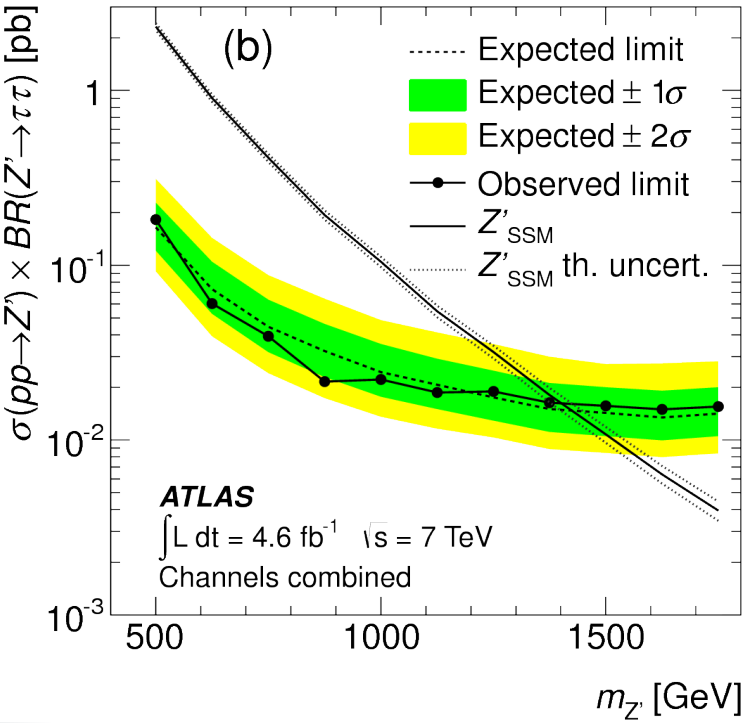


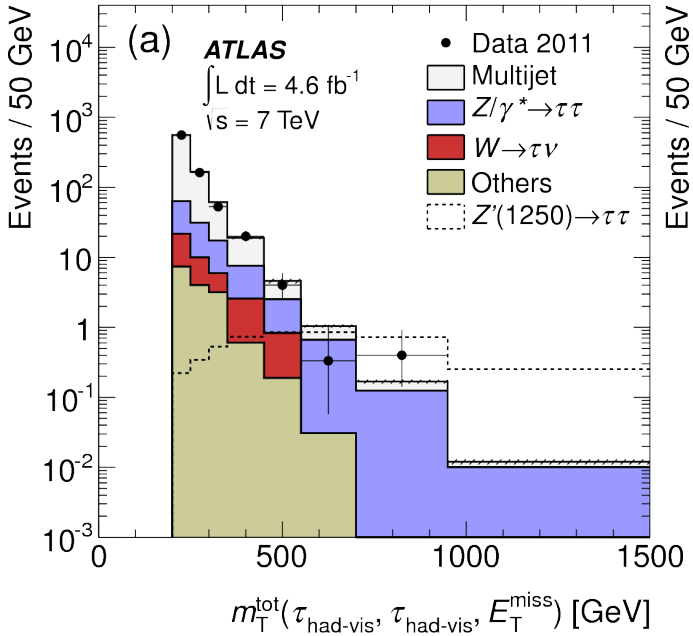


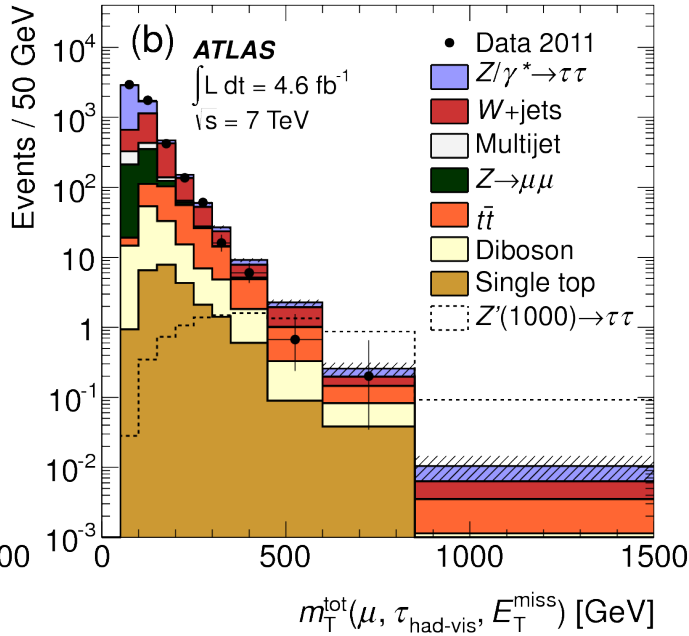


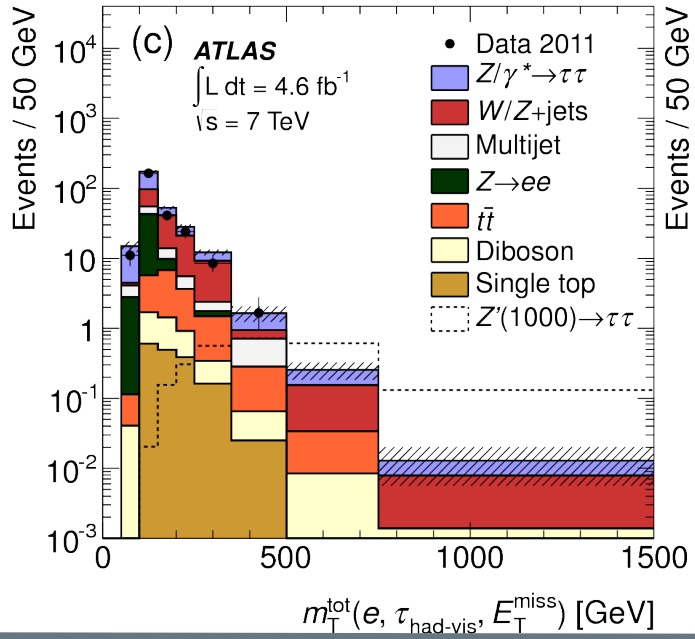
Z' Boson: tau channel

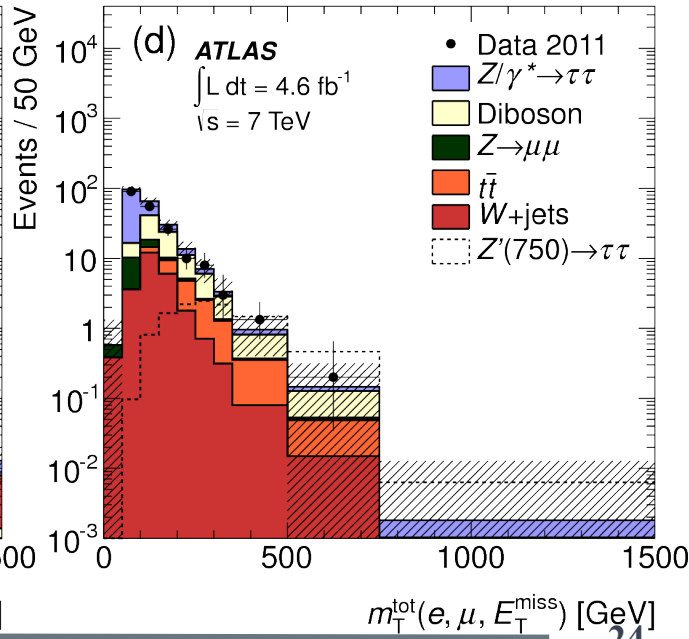
- Previous Z' search only looks in electron/muon channels
- If Z' decays predominantly to tau tau, dedicated search required
- Split by four tau decay channels:
  - Had-Had
  - Electron-Had
  - Muon-Had
  - Electron-Muon
- Additional MET, MT, and angular cuts to reject backgrounds





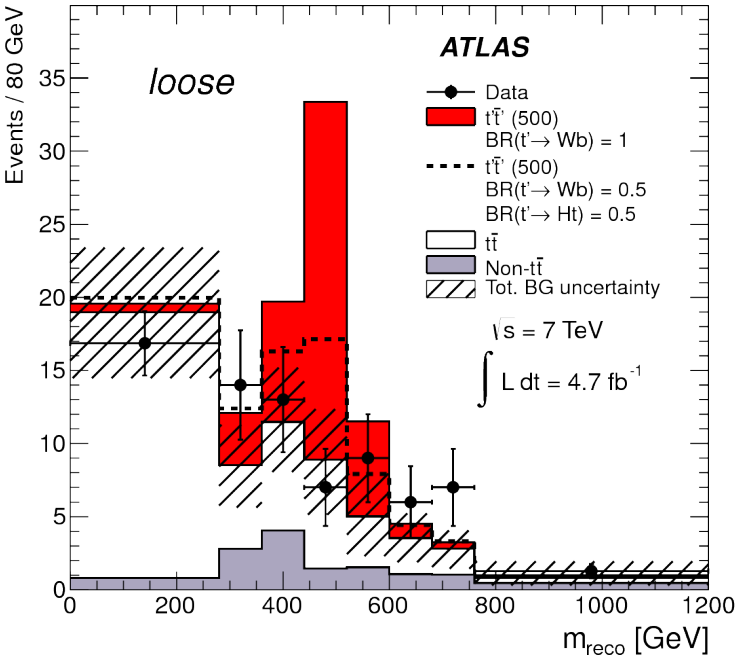


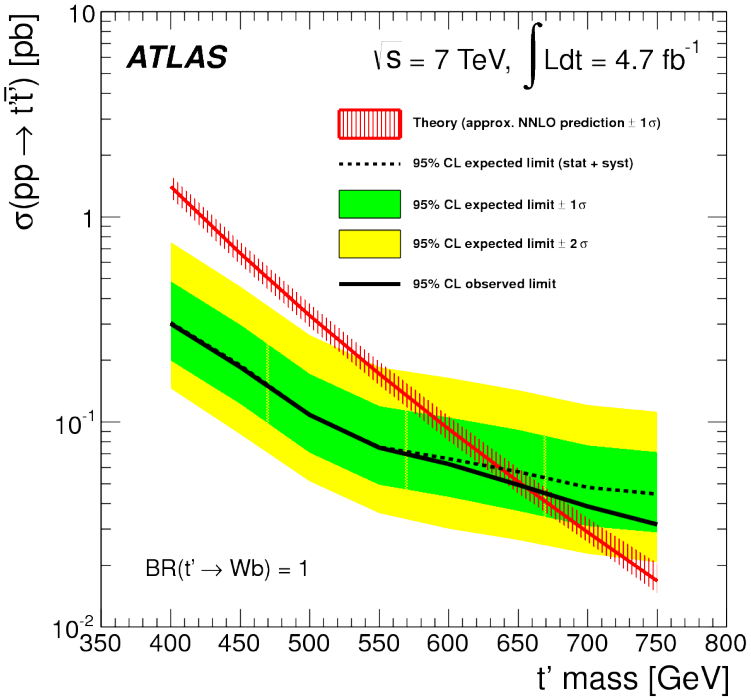


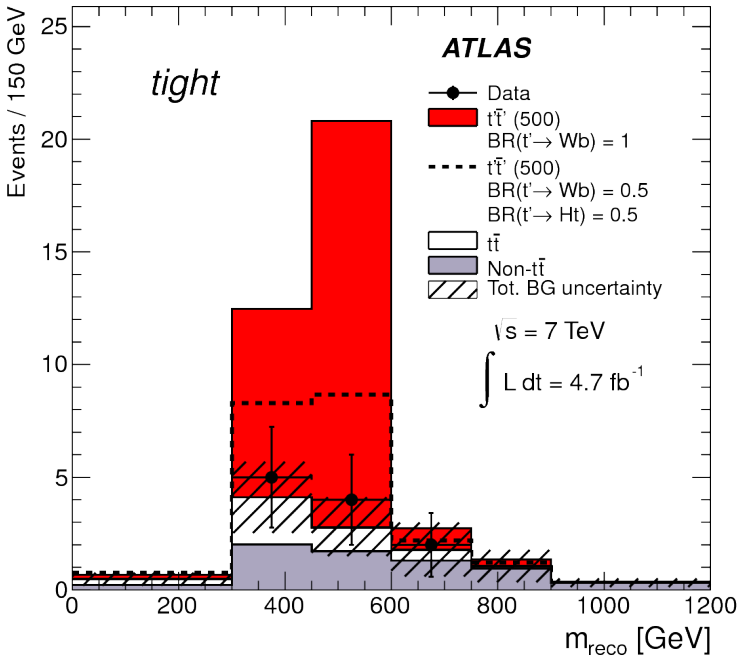


t' → Wb: lepton+jets channel

- High mass 4th generation top quark like particle
- Search for t't' → Wb+Wb decay
  - Assumes t' mass is close to b' mass
- Look for events with boosted W
  - W may merge into one jet
- Selection
  - 2 jets + boosted jet, or 4+ jets
  - H_T > 750 GeV
  - 1 or two b-tagged jets
  - Tagged jets must have ΔR >1.4 between W candidates and leptons (tight requirement)

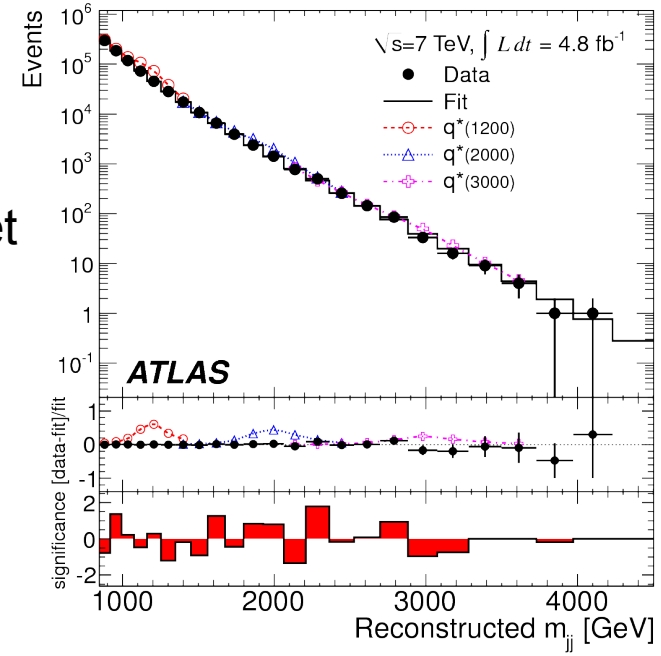


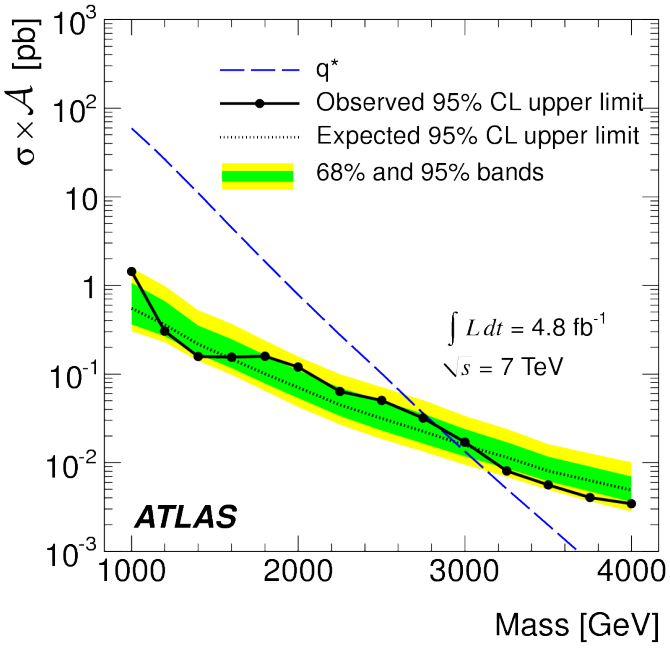


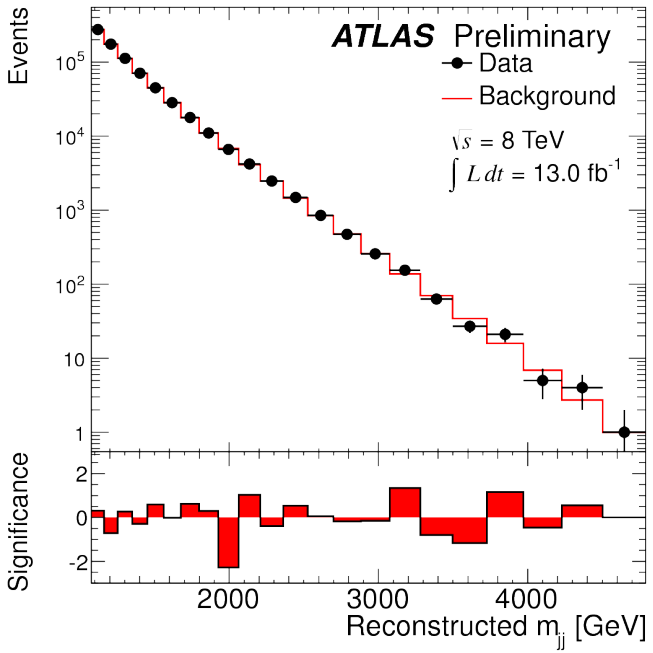


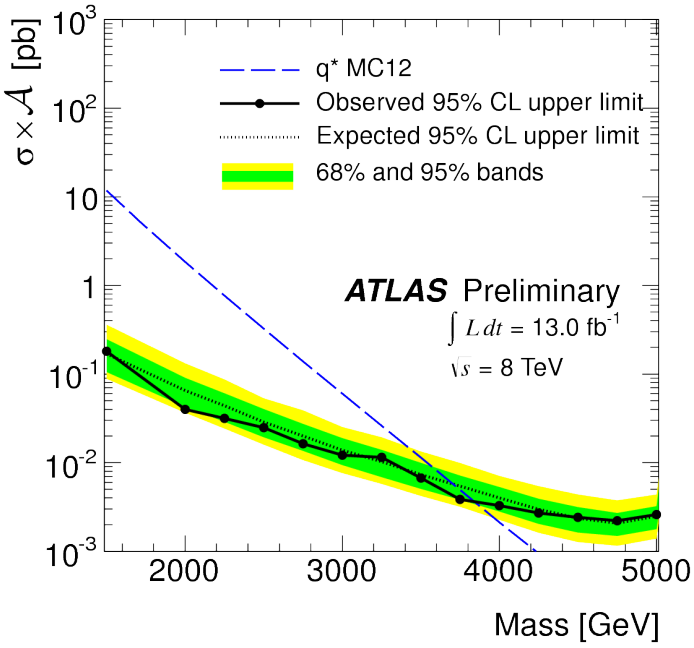
Dijet mass and angular distributions (1)

- 7 and 8 TeV analyses
- New physics can show up in the dijet invariant mass distribution or in the angular jet distributions
- Very inclusive type of search
  - Excited quarks
  - Colour octet scalars
  - Heavy W bosons
  - String resonances
  - Quantum black holes
  - Composite quarks
- Select events with two very high pT jets
- Compare shape of dijet distributions and angular variables
  - X = exp(|y1 - y2|)



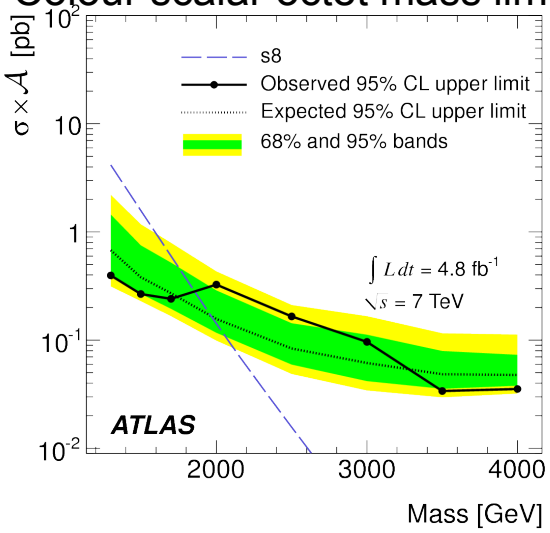




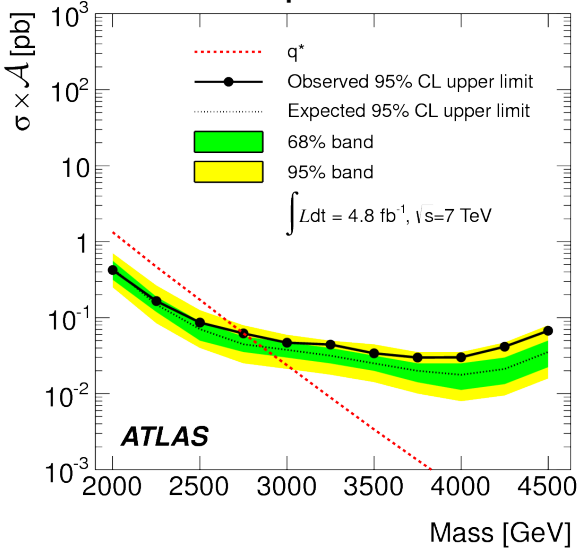


Dijet angular distributions (2)

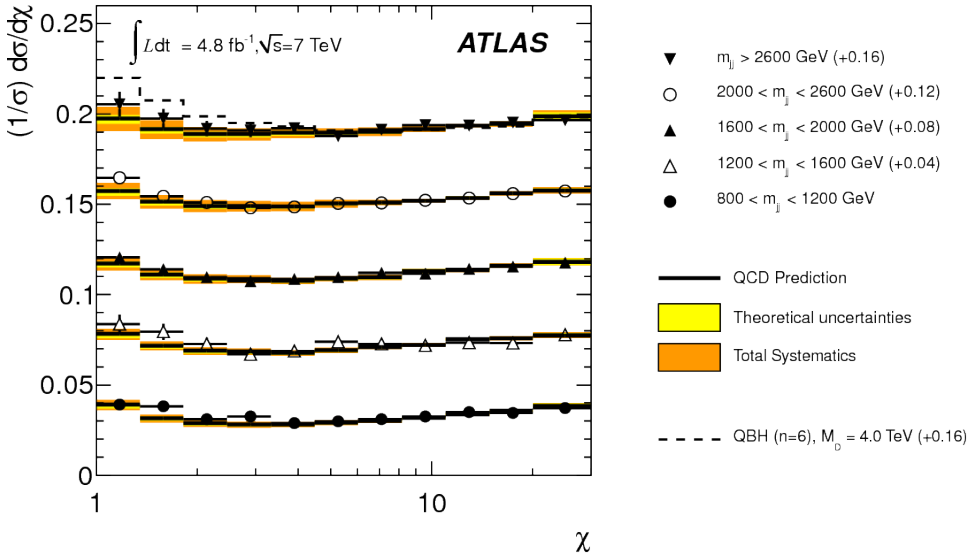
Colour scalar octet mass limit



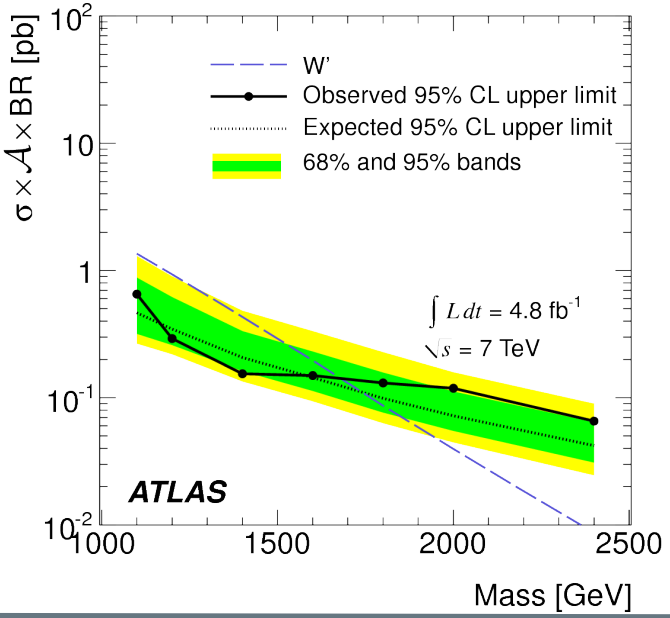
Excited quark mass limit



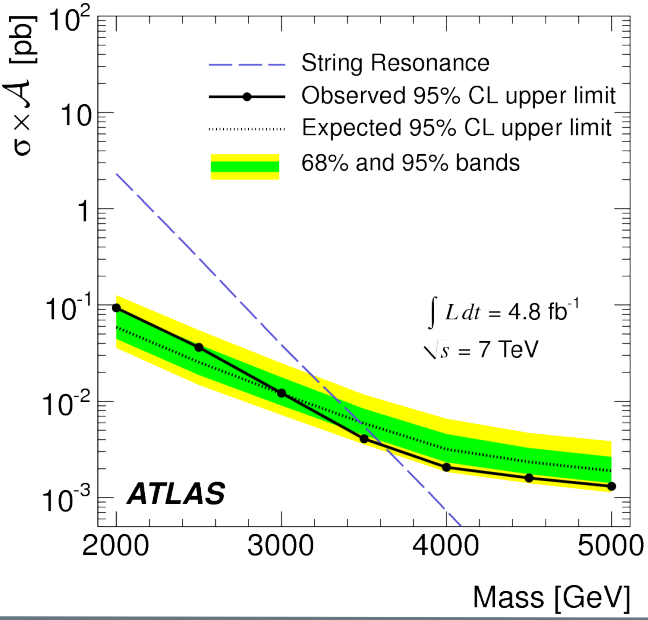
X distributions



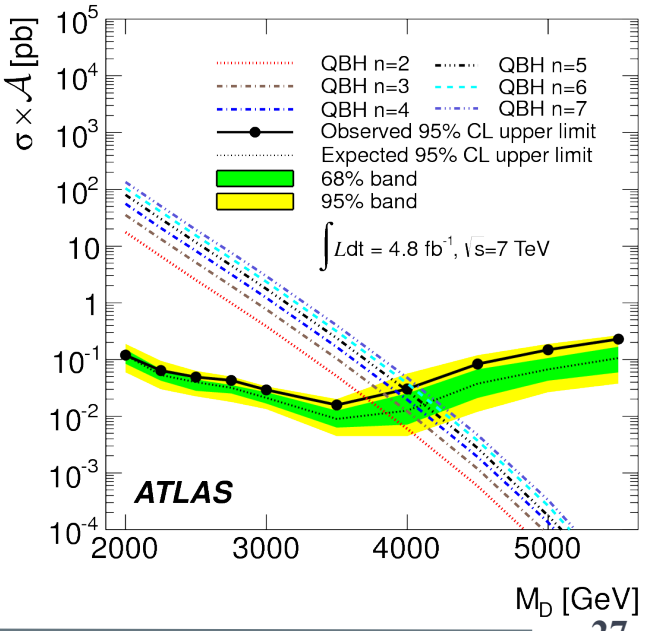
Heavy W' boson mass limit



String resonance mass limit

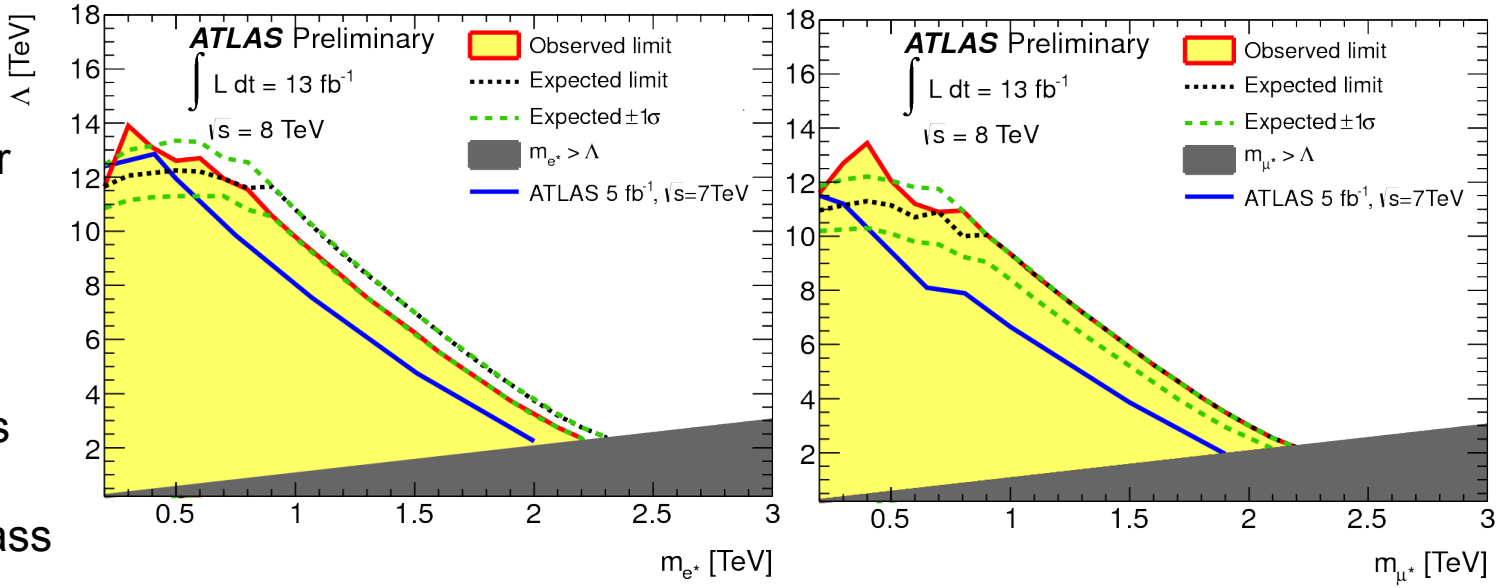


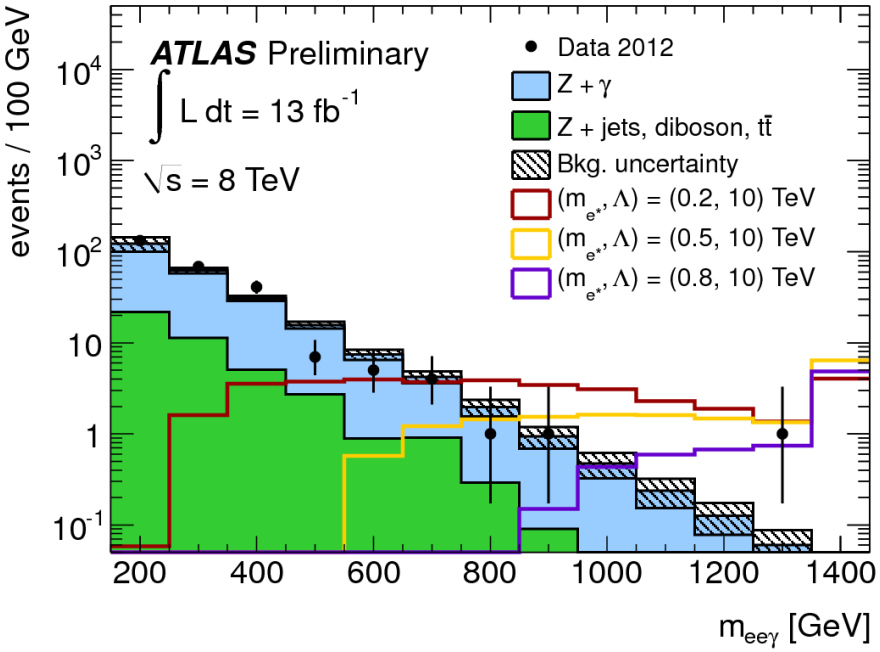
Reduced plank mass limit

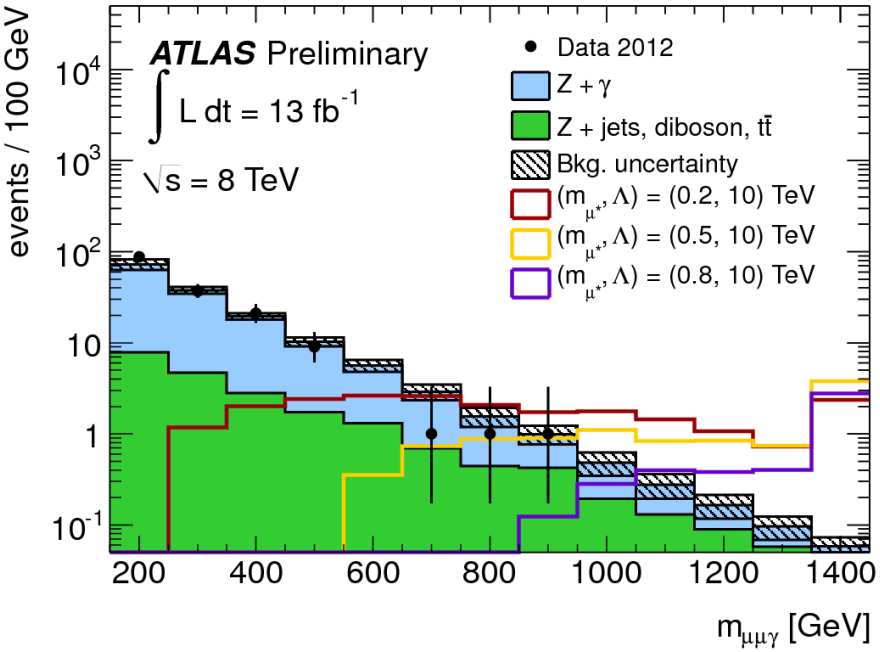


Excited leptons

- 8 TeV analysis
- Look for excited leptons decaying into a lepton pair plus photon
- Signature of composite leptons
- Look at invariant mass distribution of both leptons and photon
- Limit on excited lepton mass vs compositeness scale

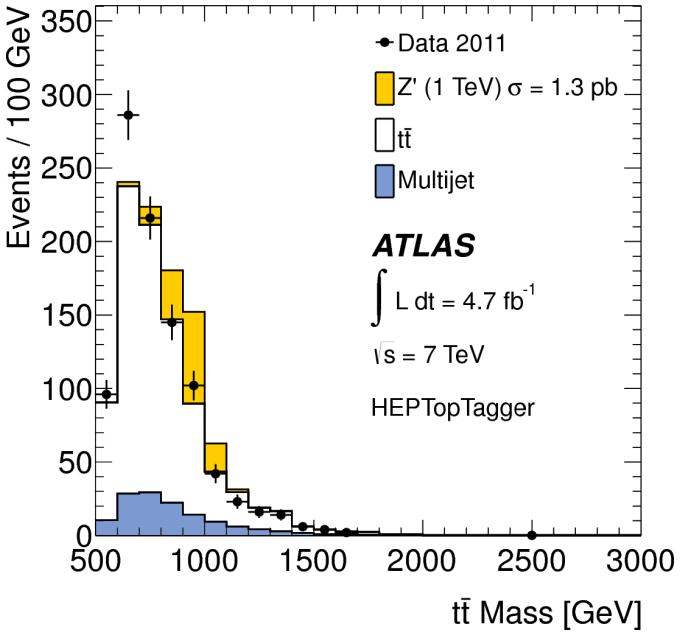


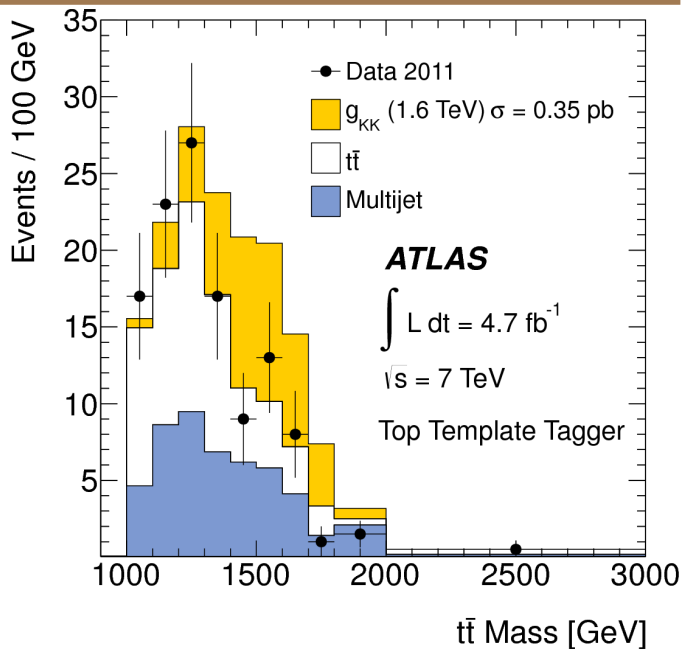


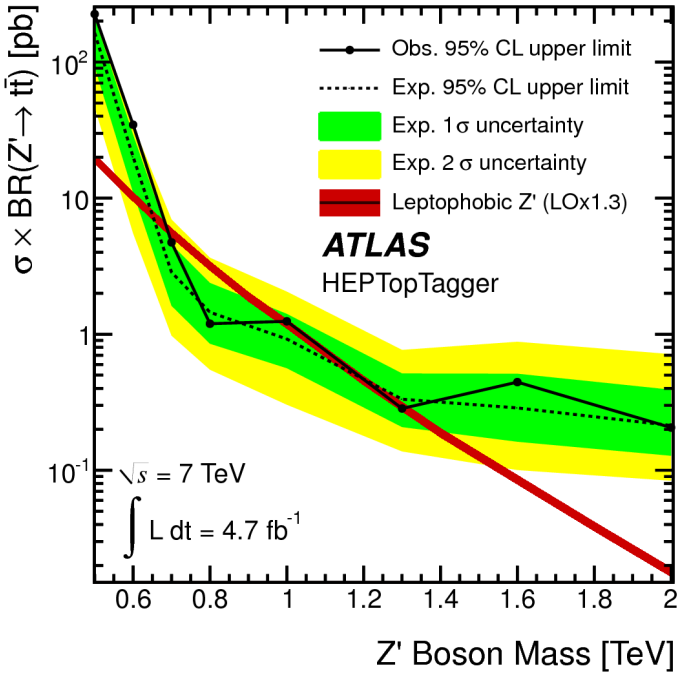


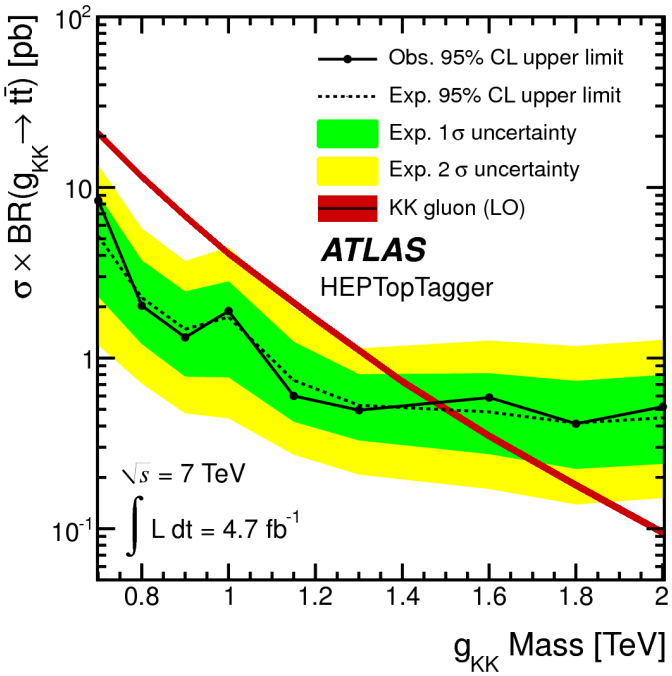
Top quark pair resonances

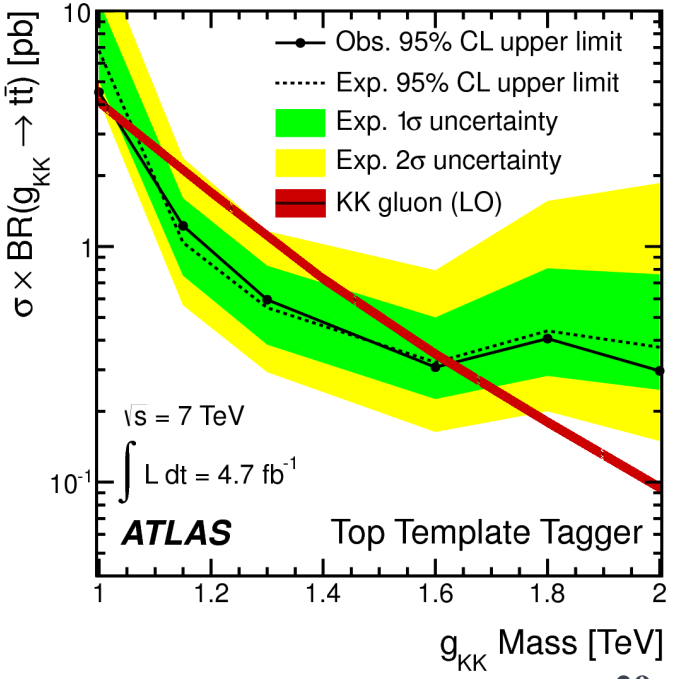
- Leptophobic Z' or KK gluons can decay into ttbar pairs
- Look for events with 2 high pT jets and 2 b-tagged jets
- Use jet substructure information
  - HEPTopTagger
    - For top pT > 200 GeV
    - R=1.5 jets
  - Top Template Tagger
    - For top pT > 450 GeV
    - R=1.0 jets





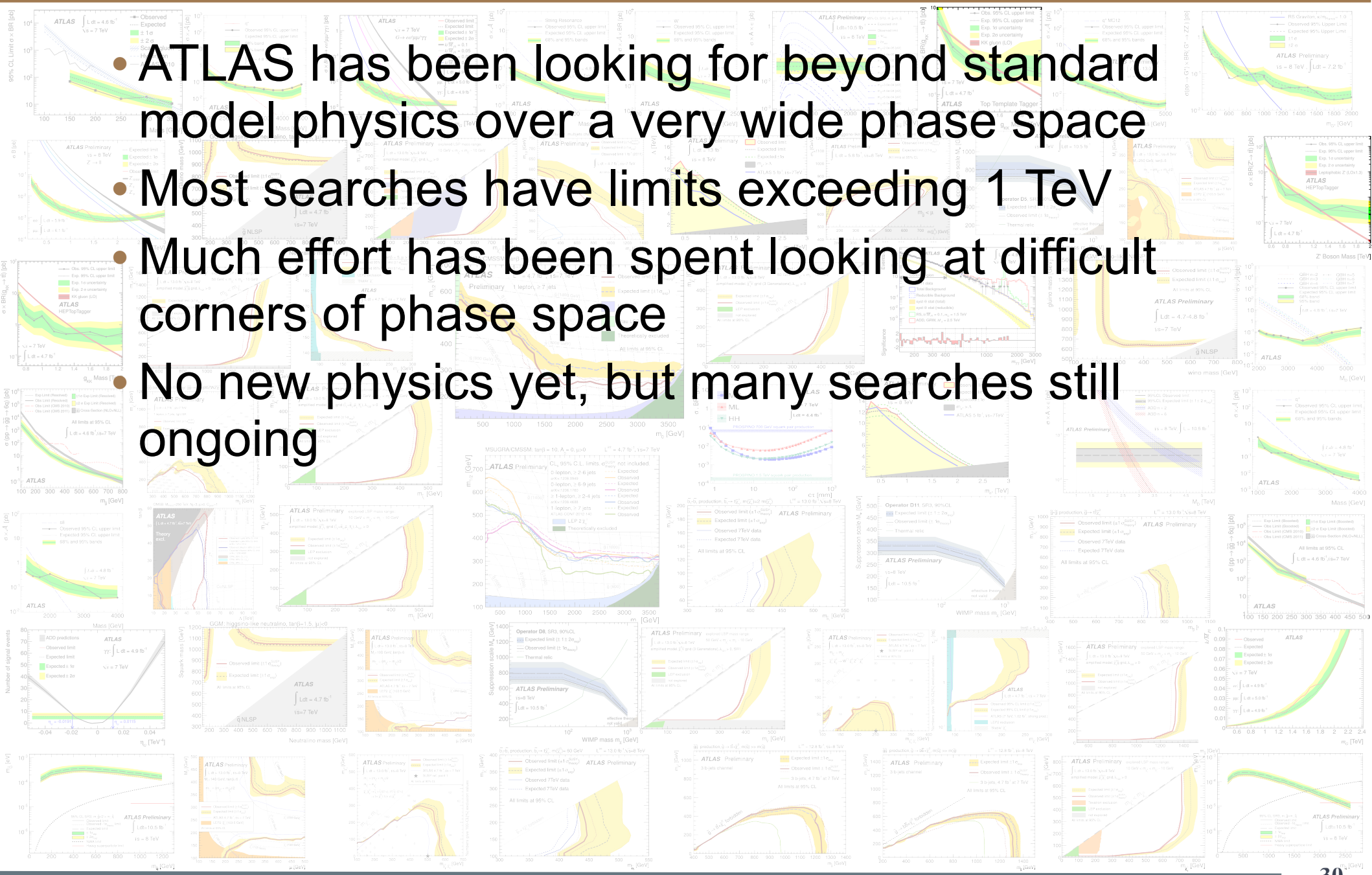




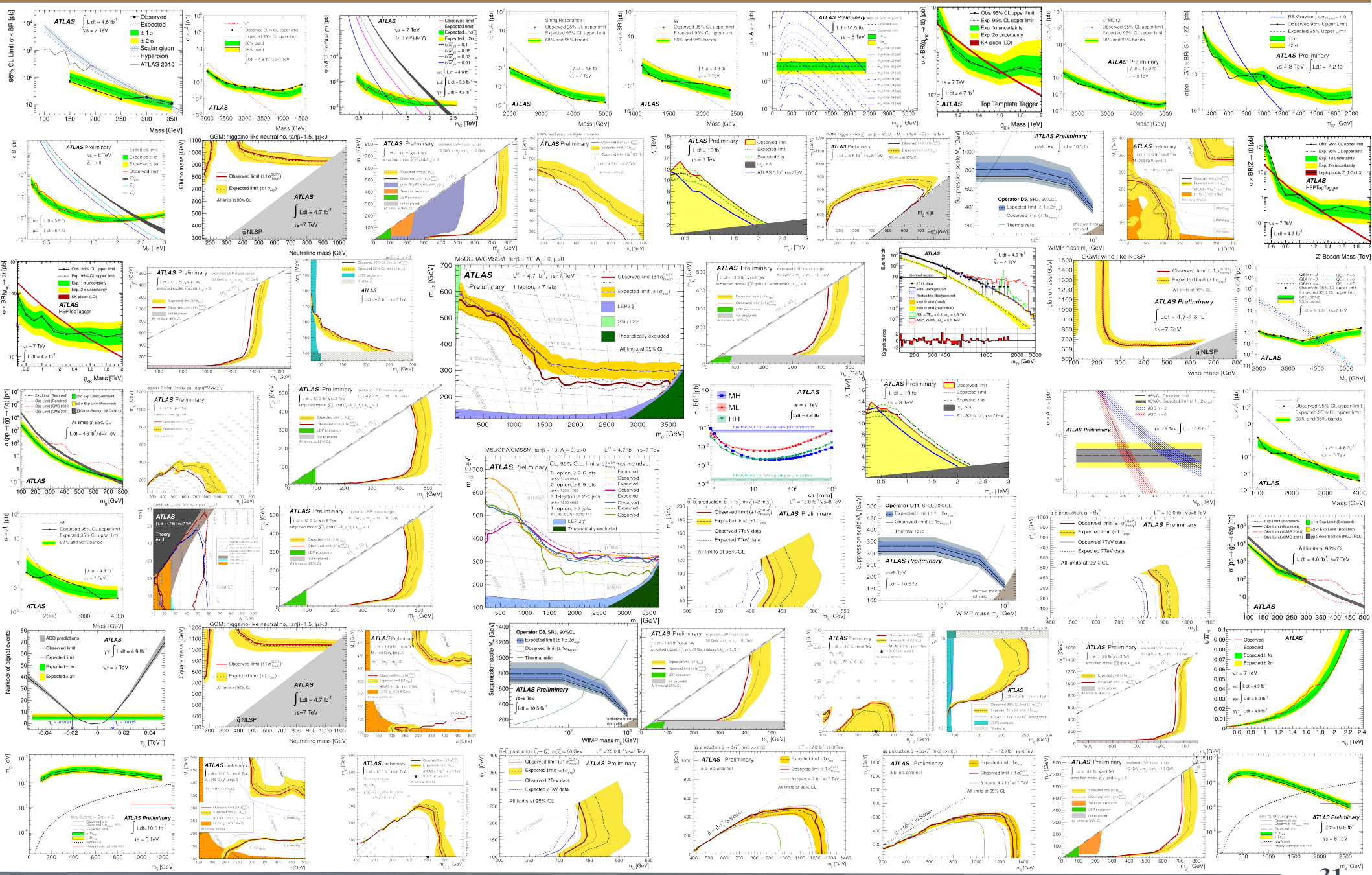


Summary

- ATLAS has been looking for beyond standard model physics over a very wide phase space
- Most searches have limits exceeding 1 TeV
- Much effort has been spent looking at difficult corners of phase space
- No new physics yet, but many searches still ongoing



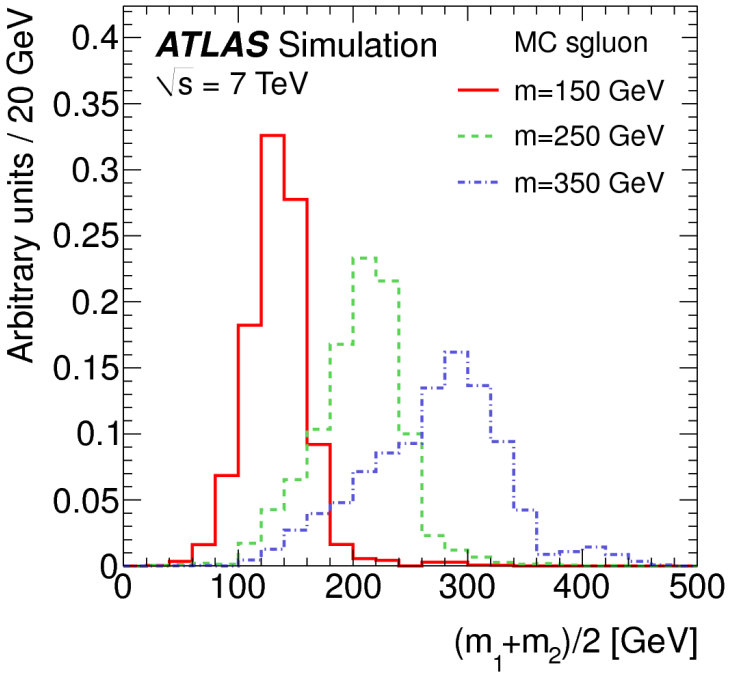
Thank you

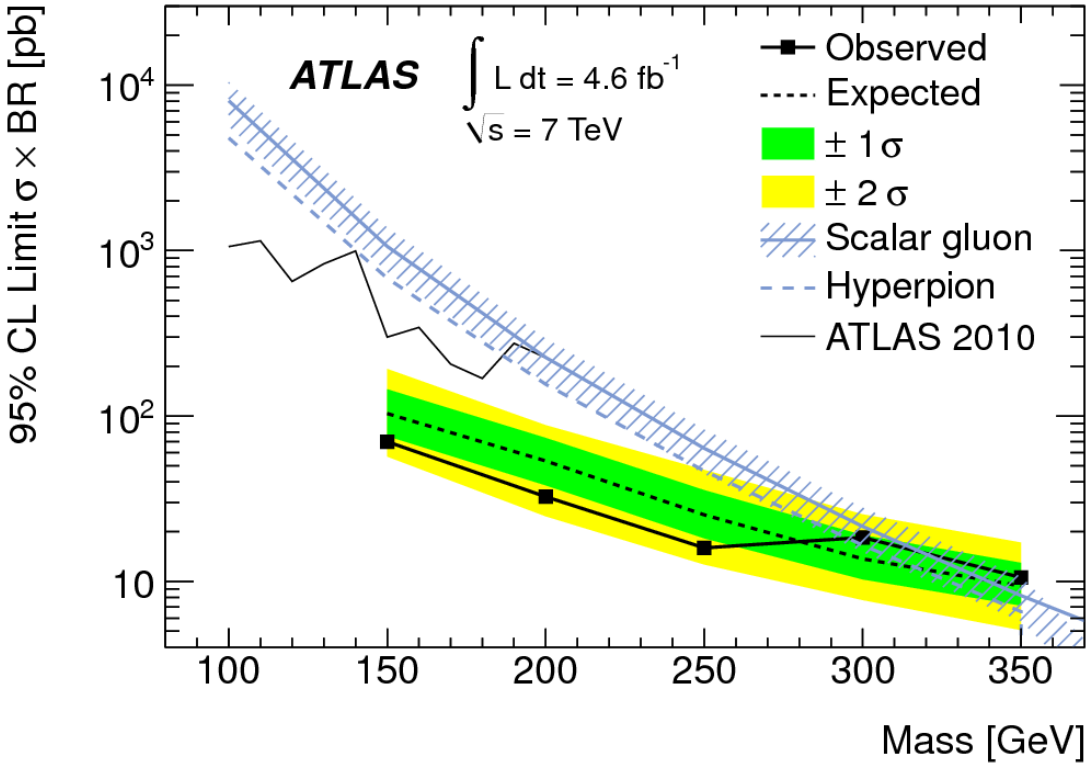


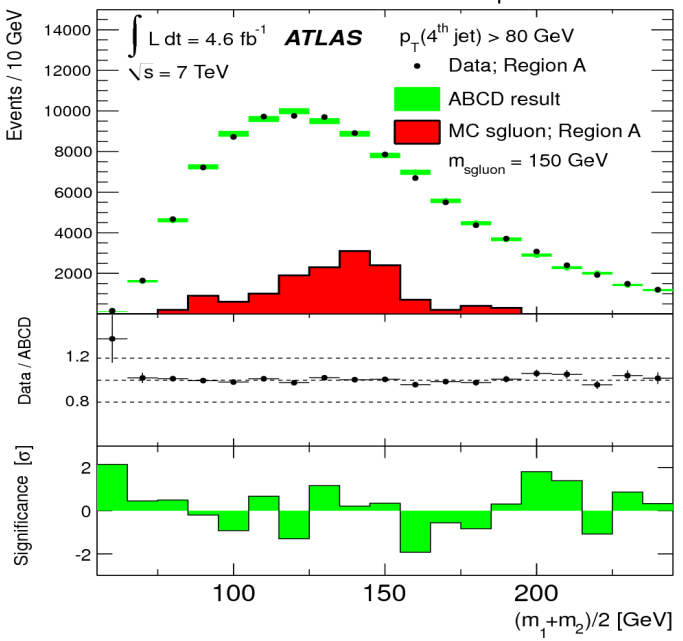
Backup Slides

Scalar gluons: four jet channel

- Pair produced scalar gluons
  - Each decays into a pair of jets
- Reconstruct events with 4 jets into two pairs
  - Minimize $|\Delta R_{pair1} - 1| + |\Delta R_{pair2} - 1|$
  - Mass of each pair should be within 30% of each other
  - Require |cos(scattering angle)| < 0.15





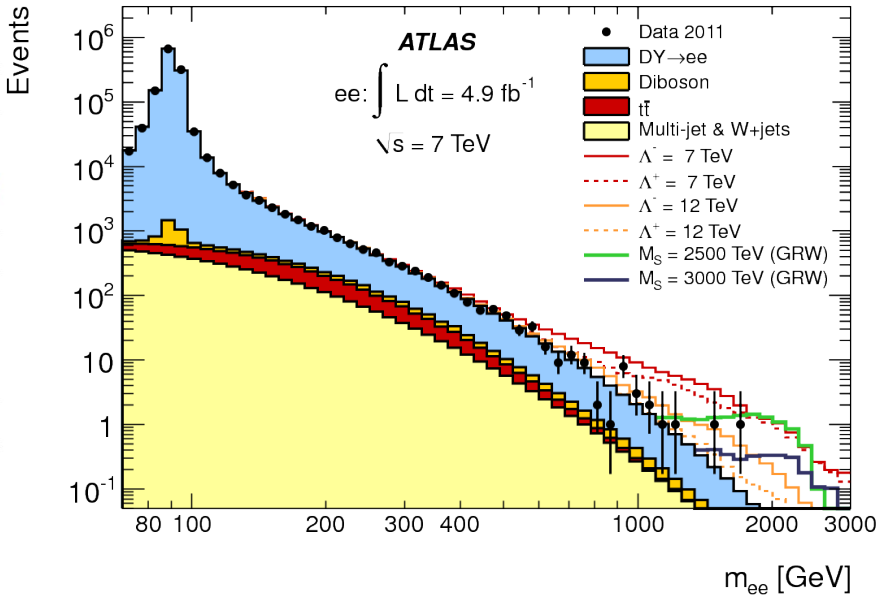


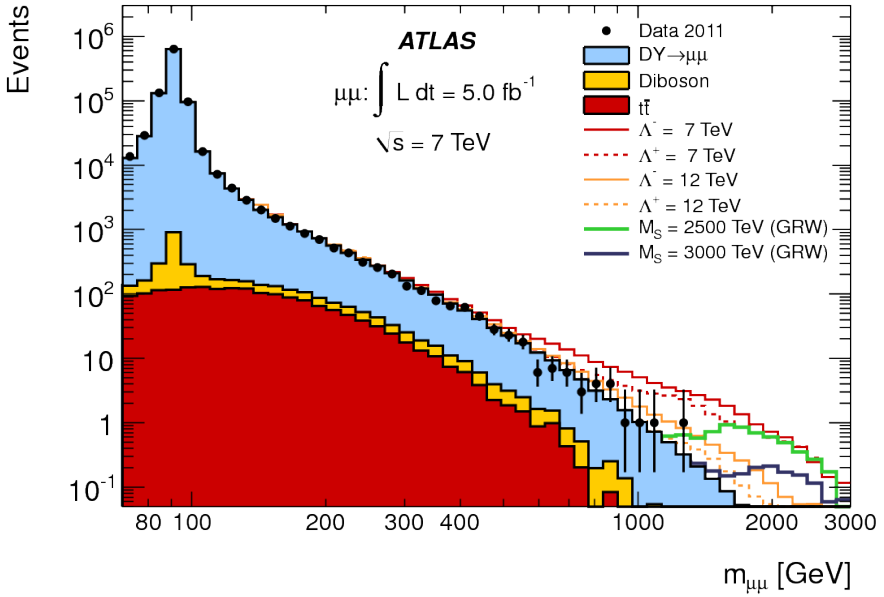
Extra Dimensions & Composite Particles: Dilepton channel

- New physics can change the dilepton invariant mass distribution
  - Gravitons/Extra dimensions
    - ADD model
  - Contact interactions
    - Composite quarks/leptons
- Select events with a pair of high pT electrons or muons
  - Well reconstructed and isolated leptons
- Use binned likelihood to compare data to different models

Events with m_{ll} > 1.3 TeV

Process	ee	$\mu\mu$
DY	0.89 ± 0.21	0.54 ± 0.16
$t\bar{t}$	< 0.01	< 0.01
Diboson	0.075 ± 0.005	0.059 ± 0.010
Multi-jet/W+jets	0.16 ± 0.20	–
Total background	1.13 ± 0.29	0.60 ± 0.16
$M_S = 1.5$ TeV	72 ± 5	47 ± 9
$M_S = 2.0$ TeV	40.2 ± 2.6	22 ± 4
$M_S = 2.5$ TeV	11.7 ± 0.9	6.3 ± 1.1
$M_S = 3.0$ TeV	4.2 ± 0.4	2.3 ± 0.4
Data	2	0





Limits on M_S (TeV) in various ADD models

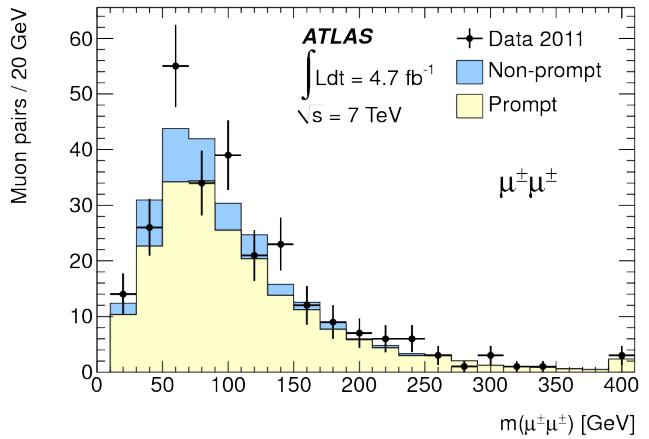
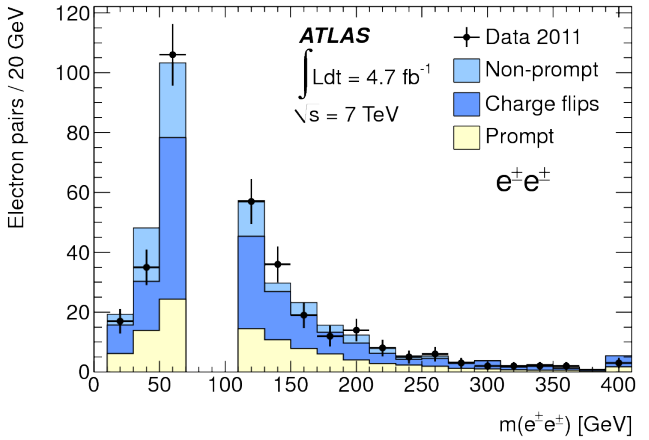
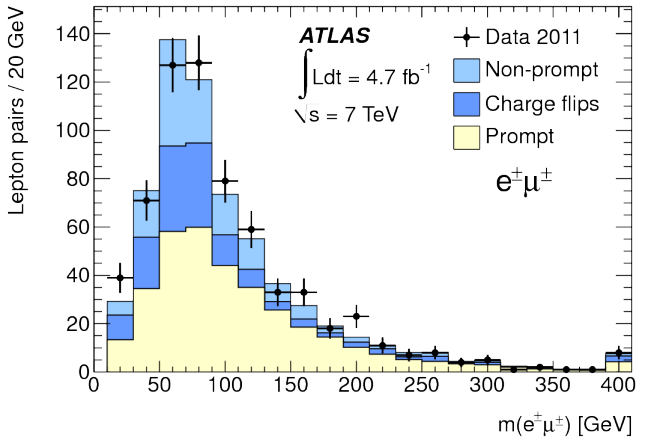
Channel	Prior	GRW	Hewett	HLZ n=3	HLZ n=4	HLZ n=5	HLZ n=6	HLZ n=7
ee	$1/M_S^4$	2.95	2.63	3.51	2.95	2.66	2.48	2.34
	$1/M_S^8$	2.82	2.67	3.08	2.82	2.68	2.59	2.52
$\mu\mu$	$1/M_S^4$	3.07	2.74	3.65	3.07	2.77	2.58	2.44
	$1/M_S^8$	2.82	2.67	3.08	2.82	2.68	2.59	2.52
$ee + \mu\mu$	$1/M_S^4$	3.27	2.92	3.88	3.27	2.95	2.75	2.60
	$1/M_S^8$	3.09	2.92	3.37	3.09	2.94	2.84	2.76
$ee + \mu\mu$	$1/M_S^4$	3.51	3.14	4.18	3.51	3.17	2.95	2.79
$+\gamma\gamma$	$1/M_S^8$	3.39	3.20	3.69	3.39	3.22	3.11	3.02

Limits on contact interaction scale

Channel	Prior	Expected limit [TeV] Constr.	Expected limit [TeV] Destr.	Observed limit [TeV] Constr.	Observed limit [TeV] Destr.
ee	$1/\Lambda^2$	13.8	10.4	12.1	9.5
	$1/\Lambda^4$	12.5	9.8	11.4	9.1
$\mu\mu$	$1/\Lambda^2$	12.7	9.9	12.9	9.6
	$1/\Lambda^4$	11.6	9.1	11.7	9.0
$ee + \mu\mu$	$1/\Lambda^2$	15.0	11.3	13.9	10.2
	$1/\Lambda^4$	13.8	10.5	12.9	9.8

Inclusive search: Same sign leptons

- Standard model same sign lepton production is rare
- Select events with two well identified, isolated leptons with the same sign
- Can be produced in many BSM models
  - Left-right symmetric
  - Higgs triplet
  - Little Higgs
  - 4th quark family
  - SUSY
  - Extra dimensions
- Main backgrounds:
  - Mis-identification
  - Photon conversion
  - Diboson production
  - Non-prompt leptons
- Form invariant mass
  - Look for resonance

Mass range	95% C.L. upper limit [fb]					
	expected	observed	expected	observed	expected	observed
	$e^{\pm}e^{\pm}$		$e^{\pm}\mu^{\pm}$		$\mu^{\pm}\mu^{\pm}$	
$m > 15$ GeV	46^{+15}_{-12}	42	56^{+23}_{-15}	64	$24.0^{+8.9}_{-6.0}$	29.8
$m > 100$ GeV	$24.1^{+8.9}_{-6.2}$	23.4	$23.0^{+9.1}_{-6.7}$	31.2	$12.2^{+4.5}_{-3.0}$	15.0
$m > 200$ GeV	$8.8^{+3.4}_{-2.1}$	7.5	$8.4^{+3.4}_{-1.7}$	9.8	$4.3^{+1.8}_{-1.1}$	6.7
$m > 300$ GeV	$4.5^{+1.8}_{-1.3}$	3.9	$4.1^{+1.8}_{-0.9}$	4.6	$2.4^{+0.9}_{-0.7}$	2.6
$m > 400$ GeV	$2.9^{+1.1}_{-0.8}$	2.4	$3.0^{+1.0}_{-0.8}$	3.1	$1.7^{+0.6}_{-0.5}$	1.7
	$e^{+}e^{+}$		$e^{+}\mu^{+}$		$\mu^{+}\mu^{+}$	
$m > 15$ GeV	$29.1^{+10.2}_{-8.6}$	22.8	$34.9^{+12.2}_{-8.6}$	34.1	$15.0^{+6.1}_{-3.3}$	15.2
$m > 100$ GeV	$16.1^{+5.9}_{-4.3}$	12.0	$15.4^{+5.9}_{-4.1}$	18.0	$8.4^{+3.2}_{-2.4}$	7.9
$m > 200$ GeV	$7.0^{+2.9}_{-2.2}$	6.1	$6.6^{+3.5}_{-1.8}$	8.8	$3.5^{+1.6}_{-0.7}$	4.3
$m > 300$ GeV	$3.7^{+1.4}_{-1.0}$	2.9	$3.2^{+1.2}_{-0.9}$	3.2	$2.0^{+0.8}_{-0.5}$	2.1
$m > 400$ GeV	$2.3^{+1.1}_{-0.6}$	1.7	$2.4^{+0.9}_{-0.6}$	2.5	$1.5^{+0.6}_{-0.3}$	1.8
	$e^{-}e^{-}$		$e^{-}\mu^{-}$		$\mu^{-}\mu^{-}$	
$m > 15$ GeV	$23.2^{+8.6}_{-5.8}$	25.7	$26.2^{+10.6}_{-7.6}$	34.4	$12.1^{+4.5}_{-3.5}$	18.5
$m > 100$ GeV	$12.0^{+5.3}_{-2.8}$	18.7	$11.5^{+4.2}_{-3.5}$	16.9	$6.0^{+2.3}_{-1.9}$	10.1
$m > 200$ GeV	$4.9^{+1.9}_{-1.2}$	4.0	$4.6^{+2.1}_{-1.2}$	4.5	$2.7^{+1.1}_{-0.7}$	4.4
$m > 300$ GeV	$2.9^{+1.0}_{-0.6}$	2.7	$2.7^{+1.1}_{-0.6}$	3.5	$1.5^{+0.8}_{-0.3}$	1.7
$m > 400$ GeV	$1.8^{+0.8}_{-0.4}$	2.3	$2.3^{+0.8}_{-0.5}$	2.5	$1.2^{+0.4}_{-0.0}$	1.2

Upper limit on fiducial cross section