Searches for New Physics with ATLAS detector at LHC

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Stony Brook University
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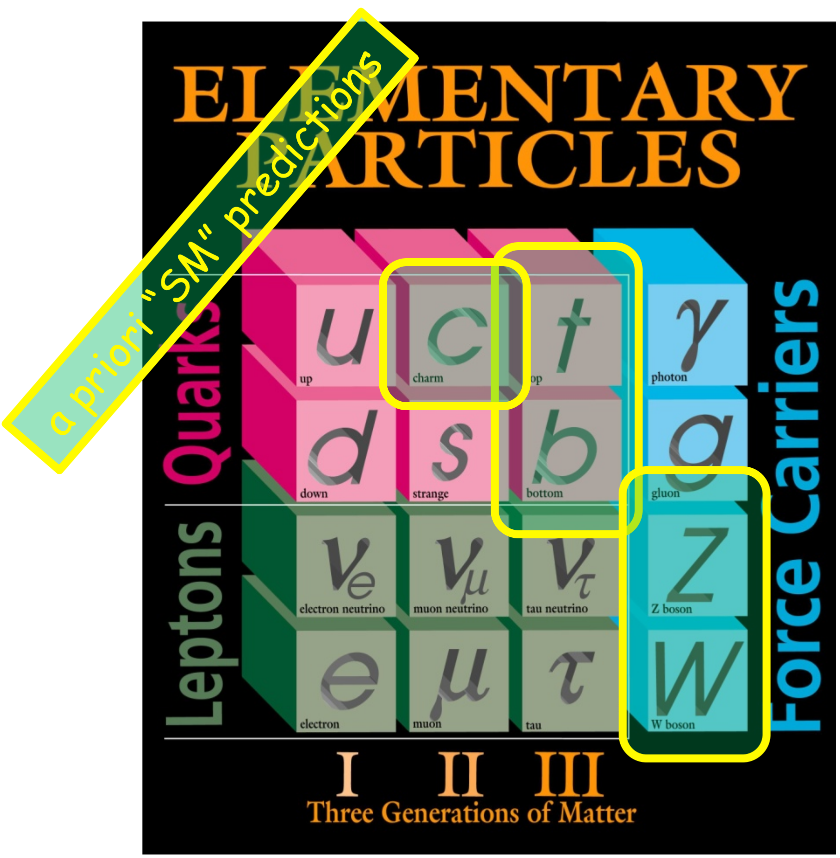
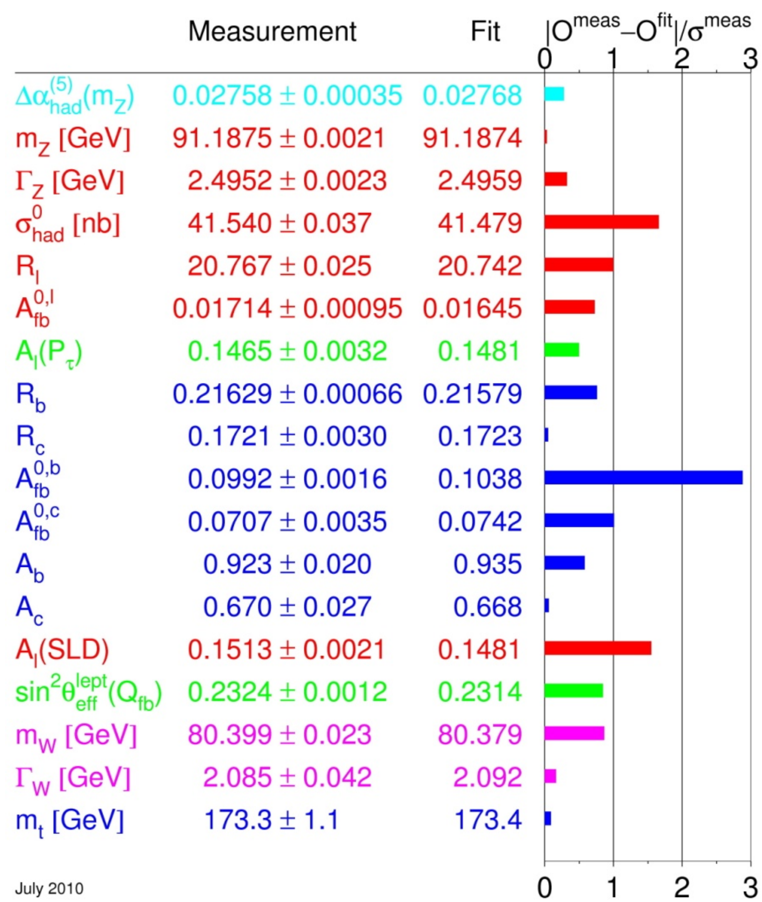
Outline

- Introduction
- LHC and ATLAS experiment
- SUSY searches
  - Squarks and Gluinos in Jets + MET signatures
  - Stable long lived particles
  - Lepton-jets
- Exotica
  - Searches in di-jet events
  - New heavy gauge boson searches
  - LED
- Summary

Introduction

The Standard Model (SM) provides an excellent description of experiments and is predictive

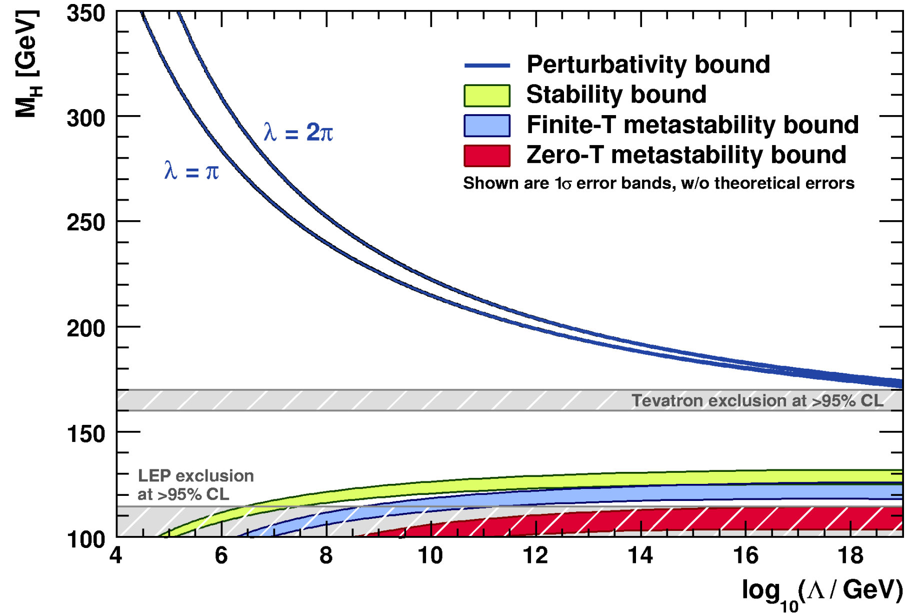


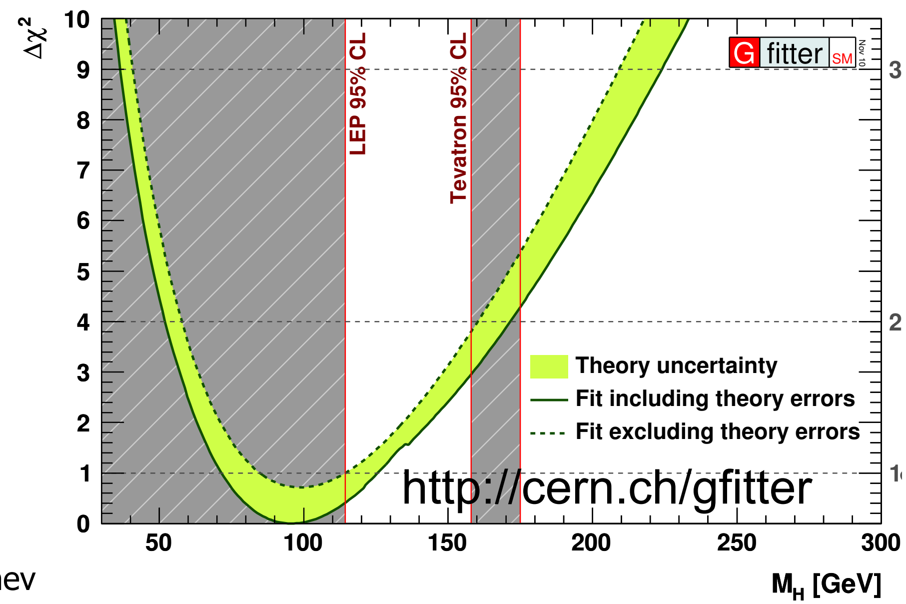


$|\chi|$ contributions to fits assuming SM

EW Symmetry Breaking

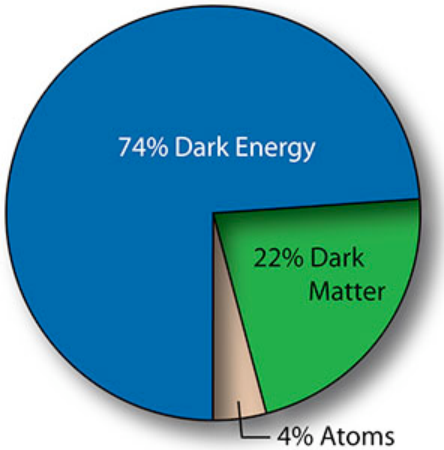
- Simplest form of (local) gauge invariance requires massless force carriers
  - Photon (and gluon), m=0. OK…
  - M_W = 80 and M_Z = 91 GeV
- SM and the Higgs mechanism
  - Permits non-zero boson mass & gauge invariance together
  - Requires a Higgs boson

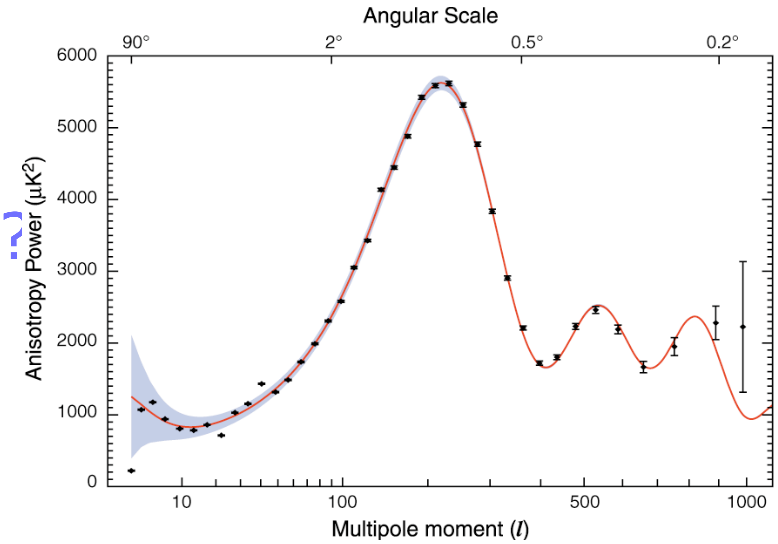




Motivation for Physics Beyond the SM

- Some pieces of SM to work on
  - Electroweak symmetry breaking unproven
  - Precision flavor studies
  - Stability: fine tuning issues
- SM doesn't answer some big questions
  - Fermion mass spectrum, 3 generations?
  - Dark matter?
  - Matter/antimatter asymmetry?
  - Ultimately EW + strong unification?





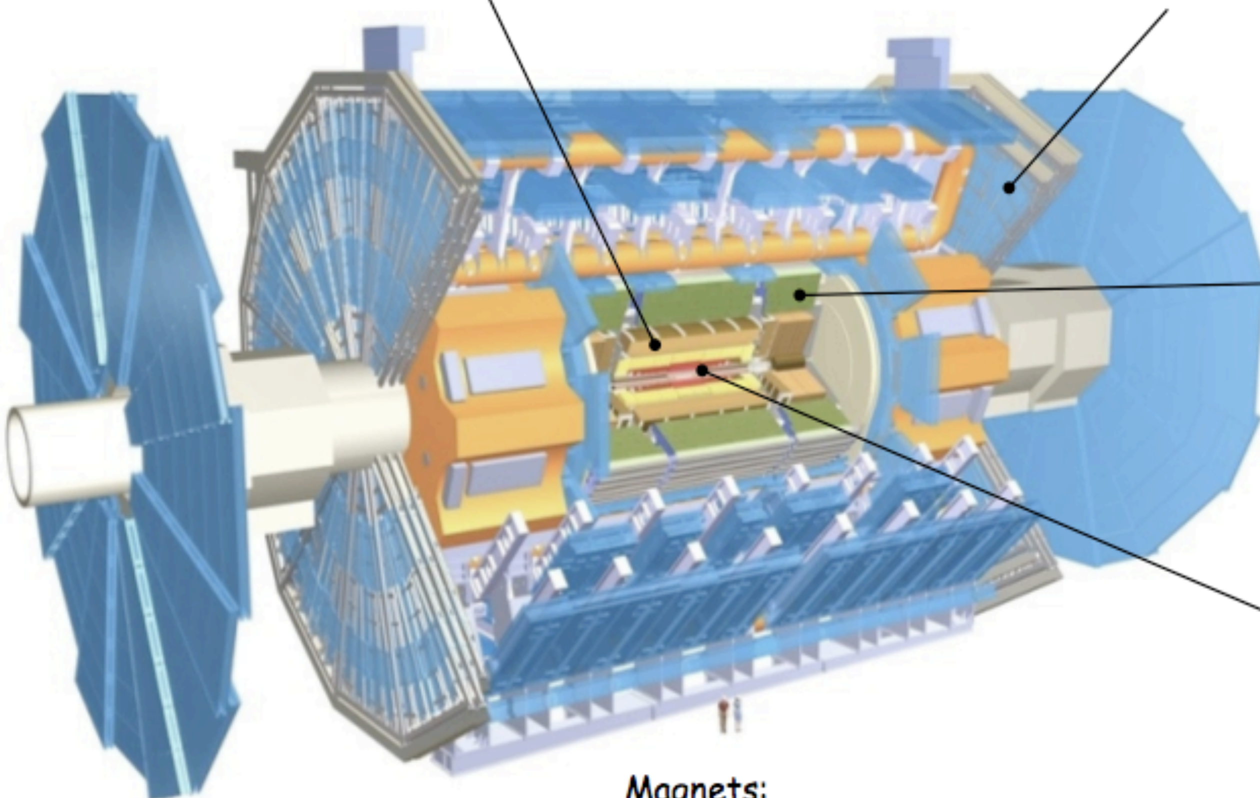
LHC Physics Motivation

- Tests of proposed solutions to SM shortcomings have led to lower mass bounds on new physics, but not yet direct observation
  - The space of new physics possibilities is large. Will not discuss specifics further…
- How to proceed?
  - Indirect tests through precision measurements
  - Direct searches for higher mass particles
- *High mass means higher energy, thus the LHC*

ATLAS Detector

EM Calorimeters: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$
excellent e/γ identification
good energy resolution

Prescision Muon Spectrometer: $\sigma/p_T \approx 10\%$ @ 1 TeV
fast trigger response
good momentum resolution

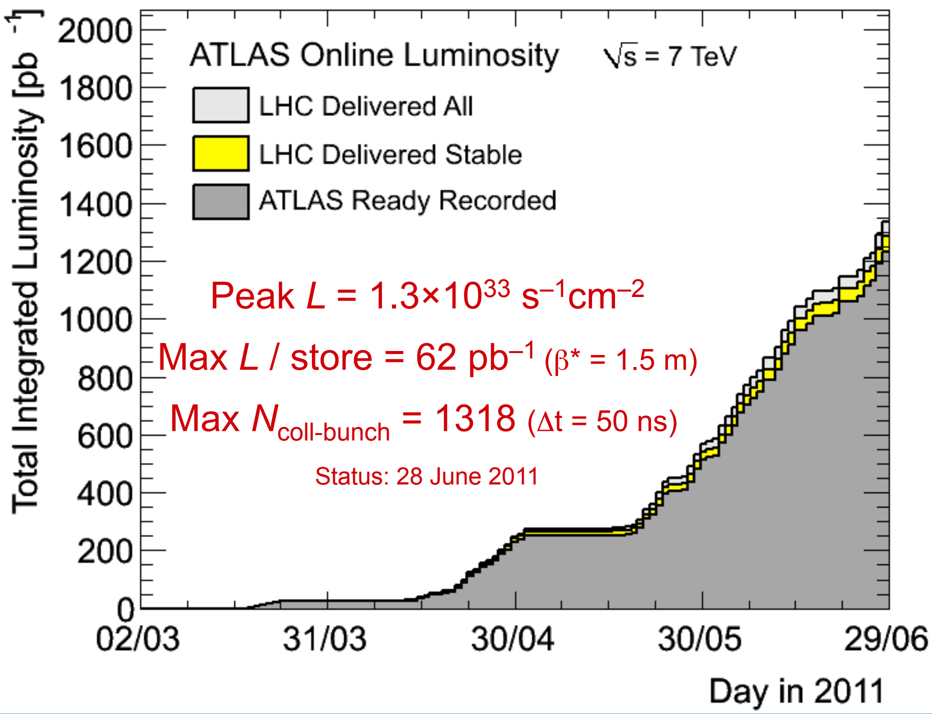


Hadron Calorimeter:
$\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$
good jet resolution
good missing E_T resolution

Inner Detector:
Si Pixel & strips; TRT
$\sigma/p_T \approx 5 \cdot 10^{-4}\, p_T \oplus 0.001$
good impact parameter res., i.e.
$\sigma(d_0) \approx 15\ \mu m$ @ 20 GeV

Magnets:
Solenoid (inner detector): 2 T
Toroid (muon spectrometer): 0.5 T

LHC and Data Taking

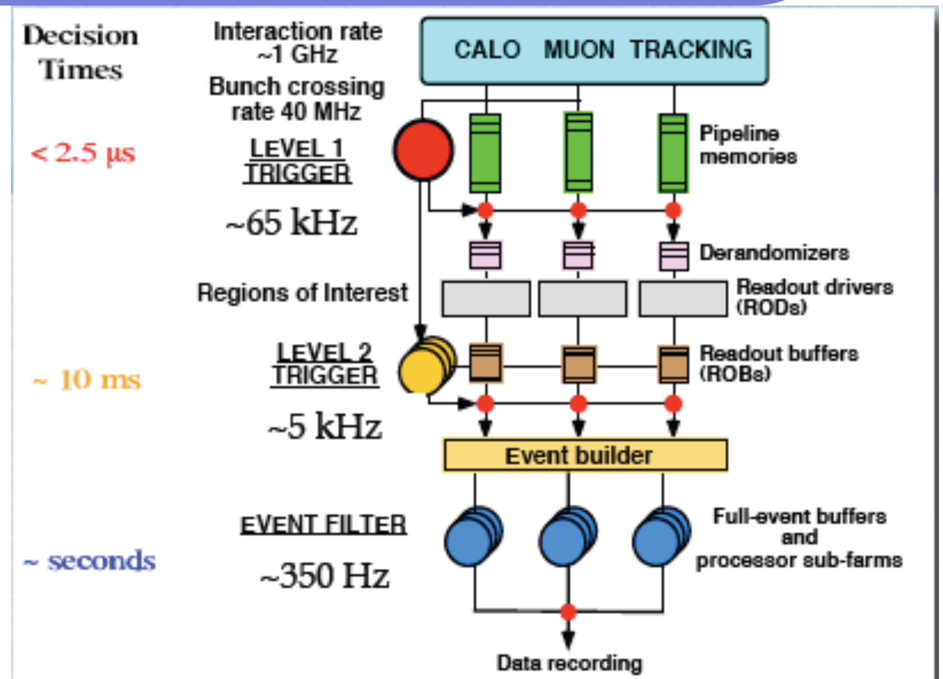


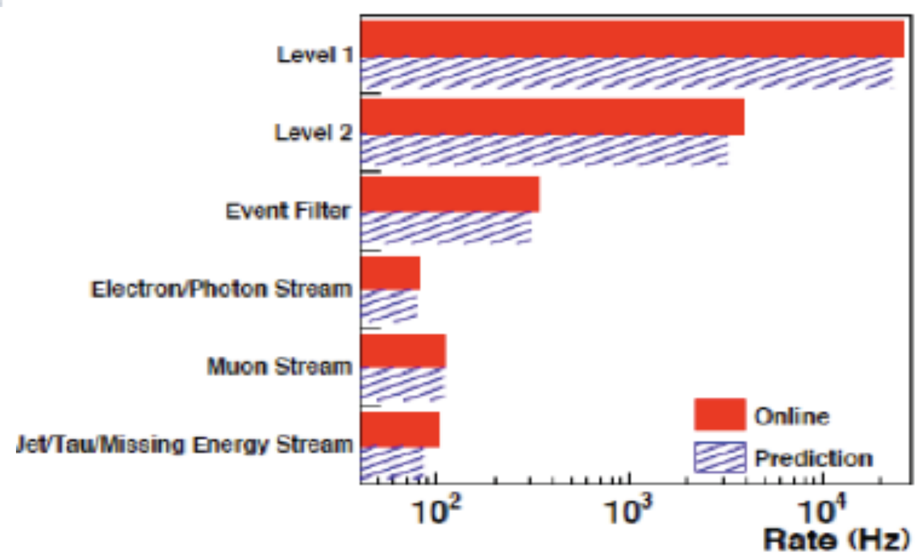
Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.5	100	89.3	92.7	94.3	99.5	100	99.5	100	99.9	98.5	97.9

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and June 6th (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future. The magnets were not operational for a 3-day period at the start of the data taking.

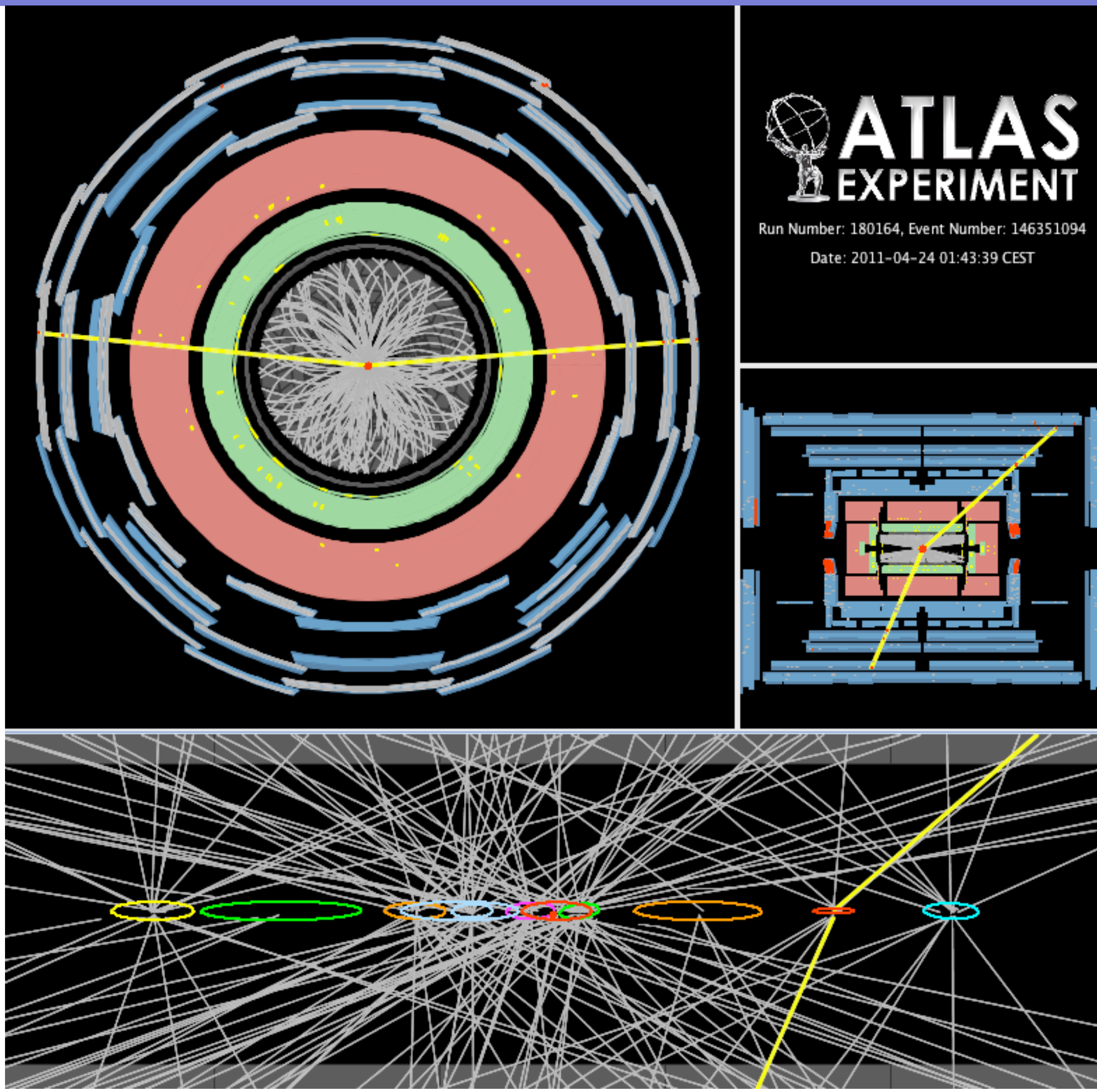
Trigger

- Online event selection
- Level-1 :
  - Hardware
  - muon spectrometers and calorimeters with coarse granularity e/γ, μ, π, τ, jet candidate selection
  - Define regions of interest (ROIs)
- Level-2 :
  - Software, seeded by level-1 ROIs, full granularity
  - Inner Detector – Calo track matching
- Event Filter:
  - Software, offline-like algorithms for physics signatures with full precision
  - Refine LV2 decision
  - Full event building





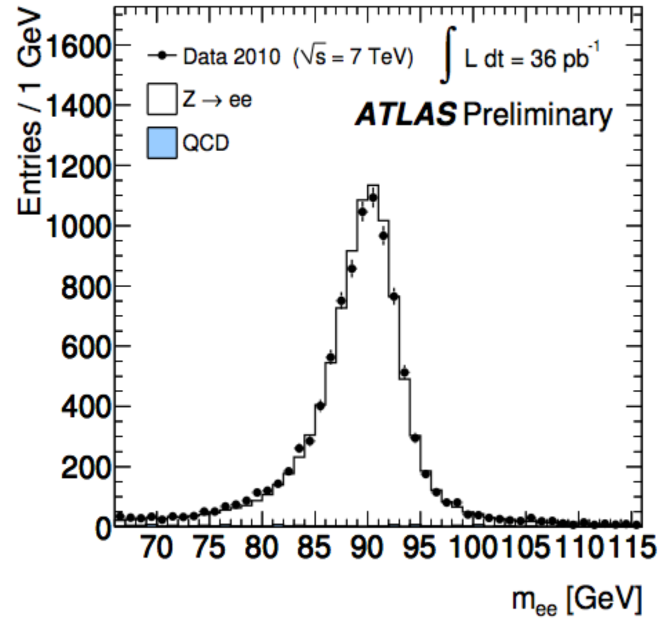
Challenging Experimental Environment

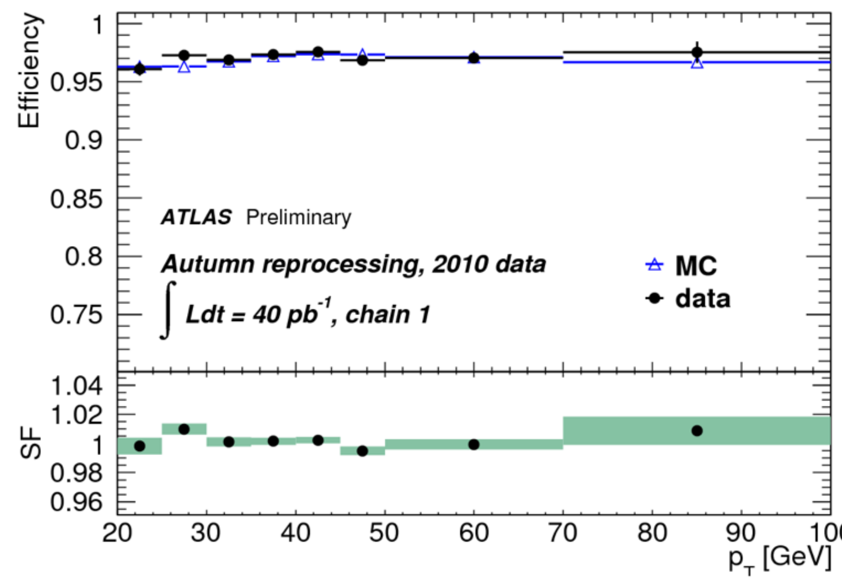


- Z(μμ) event with 11 interactions

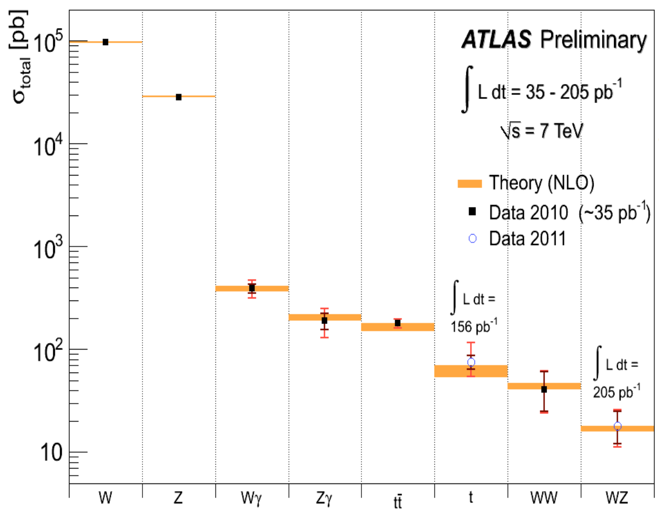
Understanding ATLAS Detector

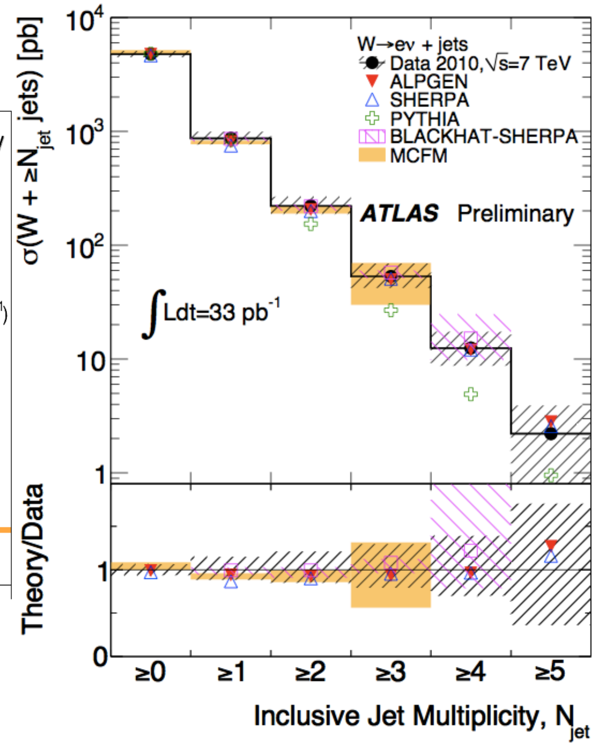
- Searches for new physics require a detailed understanding of the detector
  - 2010 allowed to understand the detector using data-driven techniques (J/Psi, W-, Z- bosons)
- Improvements in efficiencies, p_T scales and resolutions of our main analysis objects expected with much larger 2011 dataset
- Electron performance
  - Identification efficiency known at 1% level
  - Energy scale uncertainty <1%
- Muon performance
  - Reconstruction efficiency uncertainty 0.2-0.4%
  - Momentum scale uncertainty <1%
- Jets performance
  - Jet energy scale known at ~5% level
  - Jet energy resolution known to ~10%

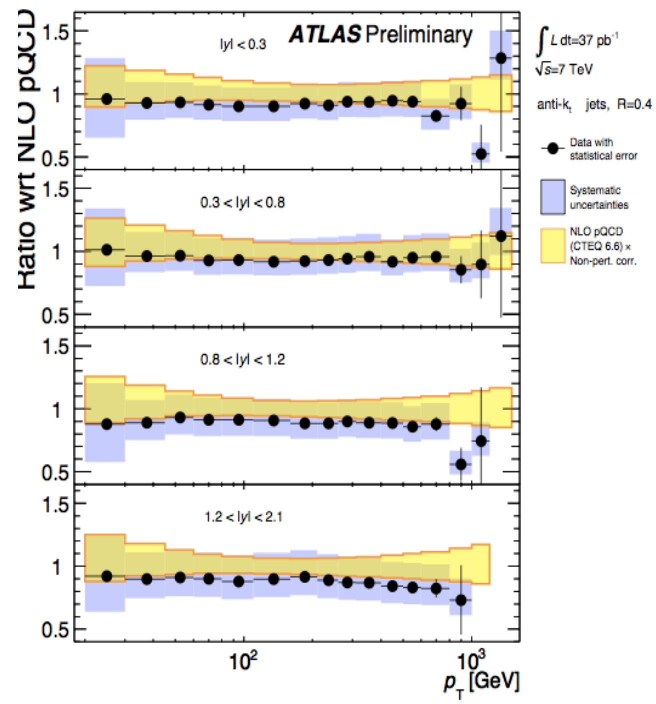




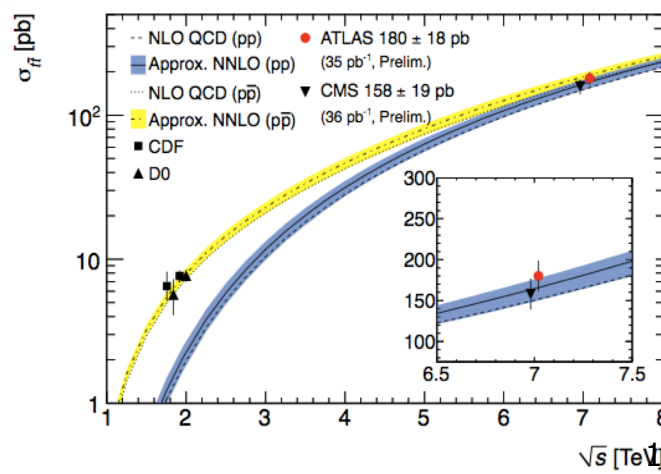
Standard Candles



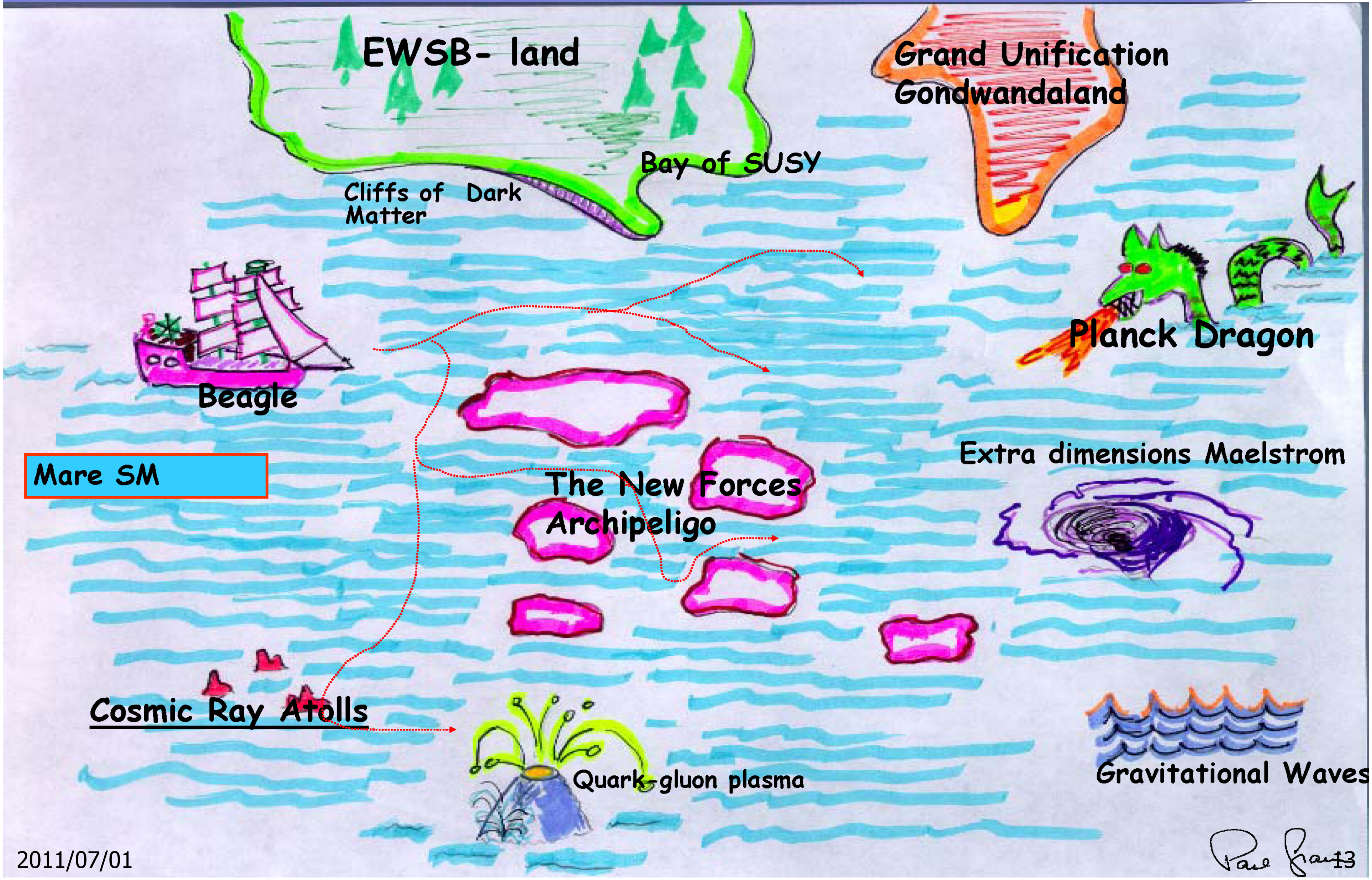




* Measurements of SM processes are important in understanding theoretical predictions, as those processes are dominant backgrounds to new physics searches

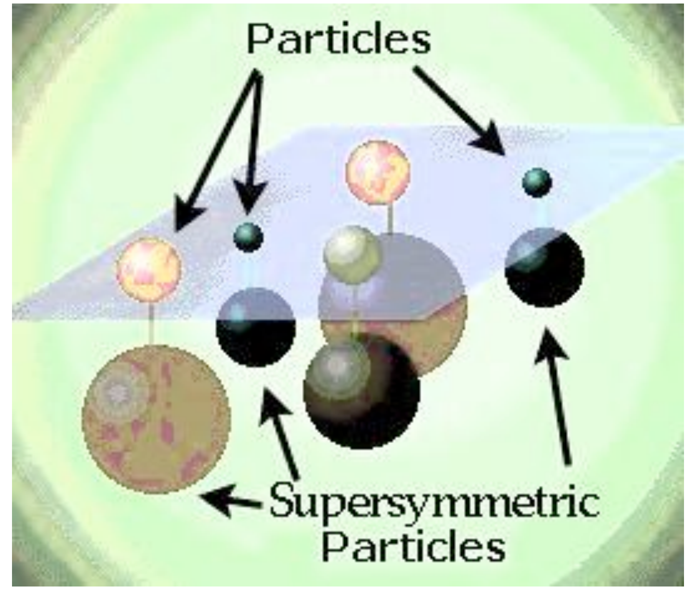


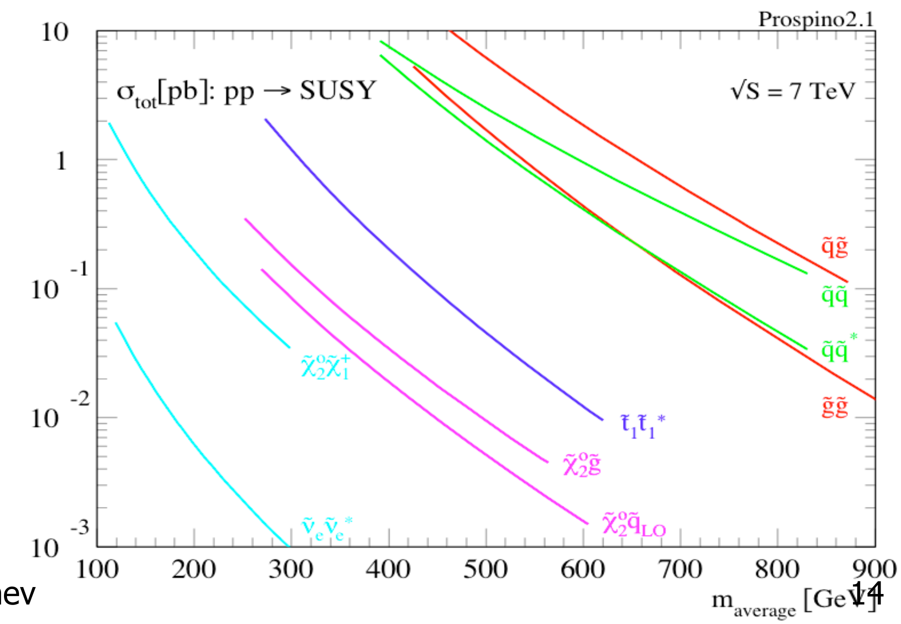
Where to?


EWSB- land
Grand Unification
Gondwandaland
Bay of SUSY
Cliffs of Dark Matter
Planck Dragon
Beagle
Extra dimensions Maelstrom
Mare SM
The New Forces Archipeligo
Cosmic Ray Atolls
Quark-gluon plasma
Gravitational Waves

Supersymmetry

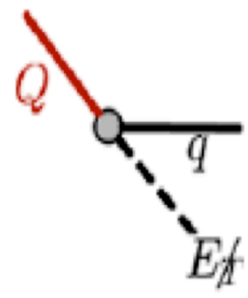
- SM has far too little dark matter (ν's).
- Fine tuning: SM values must be within a part in 10^{32} for stability.
- Supersymmetry is a possible solution to both:
  - Predicts new particles whose multiplicity is determined by SM particle content
  - Couplings of supersymmetric particles equal to couplings of Standard Model ones.
  - Includes a dark matter candidate.
  - Removes fine-tuning by cancellation and leads to m_H < 135 GeV?
  - Two Higgs doublets necessary. Ratio of vacuum expectation values denoted by $\tan\beta$
- But no direct experimental evidence, only bounds

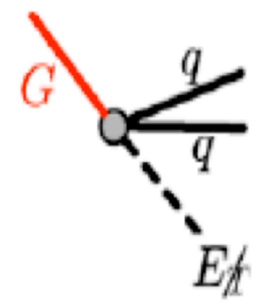




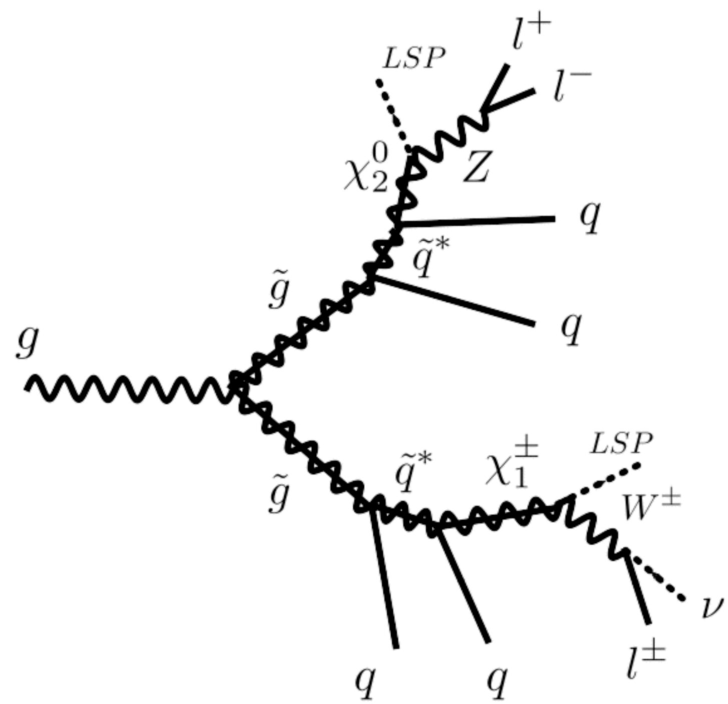
SUSY Signatures

- Complex (and model-dependent) supersymmetric particle cascade decays due to unknown mass spectrum result in multiple final states
- Focus on signatures covering large classes of models while strongly rejecting SM background
  - Large missing ET
  - High transverse momentum jets
  - Leptons
    - Perform separate analyses with and without lepton veto (0, 1, 2-leptons)
  - b-jets: to enhance sensitivity to third generation squarks



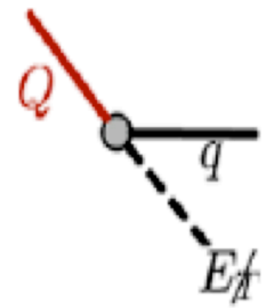


$\tilde{q} \rightarrow q\tilde{\chi}_1^0$ $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$

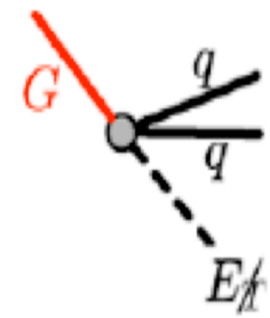


SUSY MET + Jets Searches

- Search for squarks and gluinos produced in pairs (R-parity conserving models) decaying in purely hadronic final states + MET
  - 2, 3, 4 Jets + MET
  - Squark → $q\chi^0_1$,
  - Gluino→ $qq\chi^0_1$ (χ^0_1 produces MET)
- Use MET and $M_{eff} = \Sigma|p_T^{jet}| +$ MET to setup 3 signal regions
- MC based transfer functions to predict number of background events in SR based on control regions



$$\tilde{q} \to q\tilde{\chi}_1^0$$



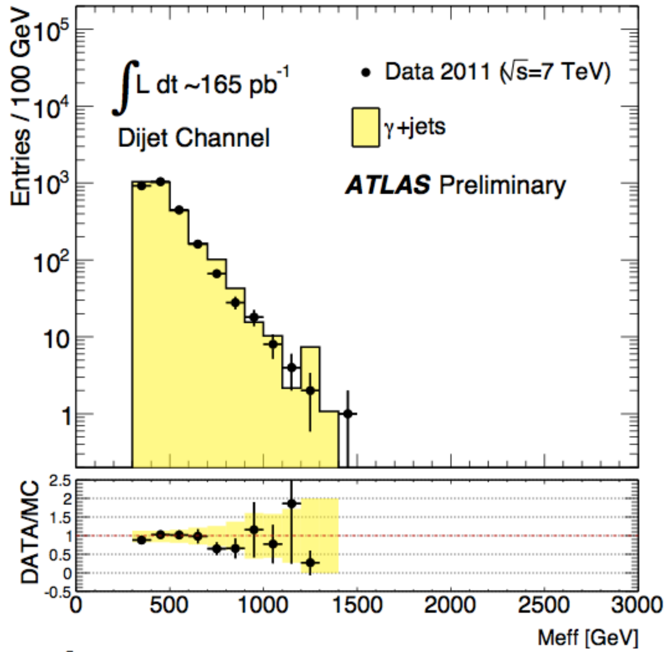
$$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$$

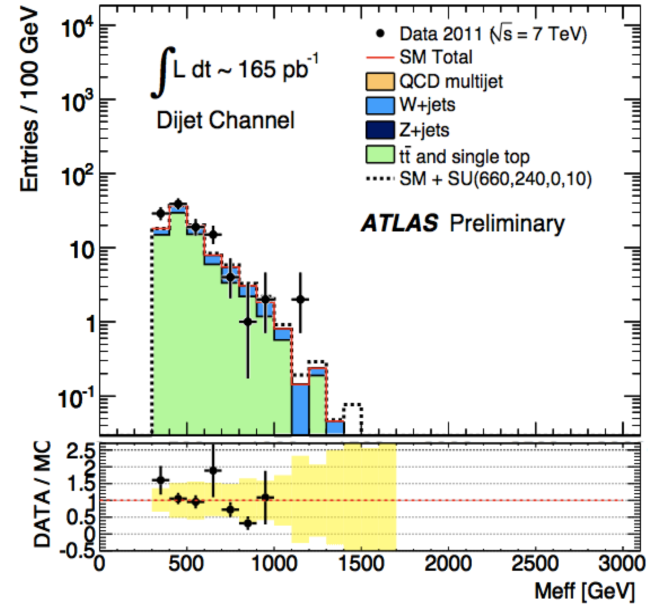
Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets
E_T^{miss} [GeV]	> 130	> 130	> 130
Leading jet p_T [GeV]	> 130	> 130	> 130
Second jet p_T [GeV]	> 40	> 40	> 40
Third jet p_T [GeV]	–	> 40	> 40
Fourth jet p_T [GeV]	–	–	> 40
$\Delta\phi(\text{jet}_i, E_T^{miss})_{min}$ $(i = 1,2,3)$	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25
m_{eff} [GeV]	> 1000	> 1000	> 1000

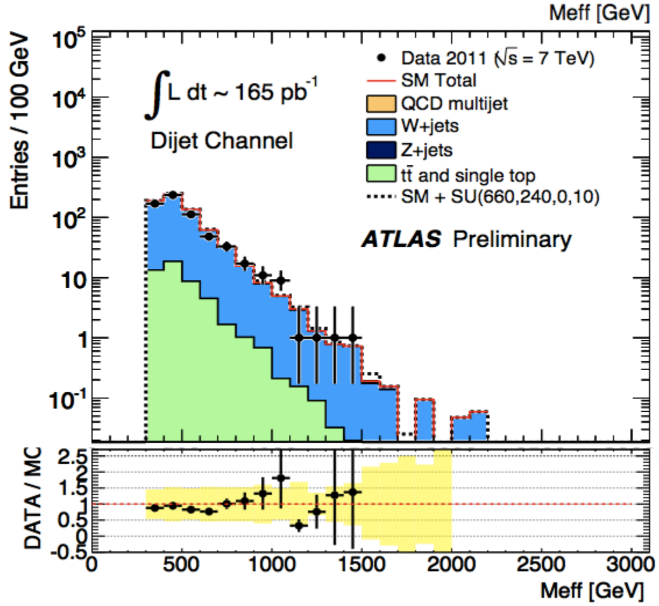
Background Estimation

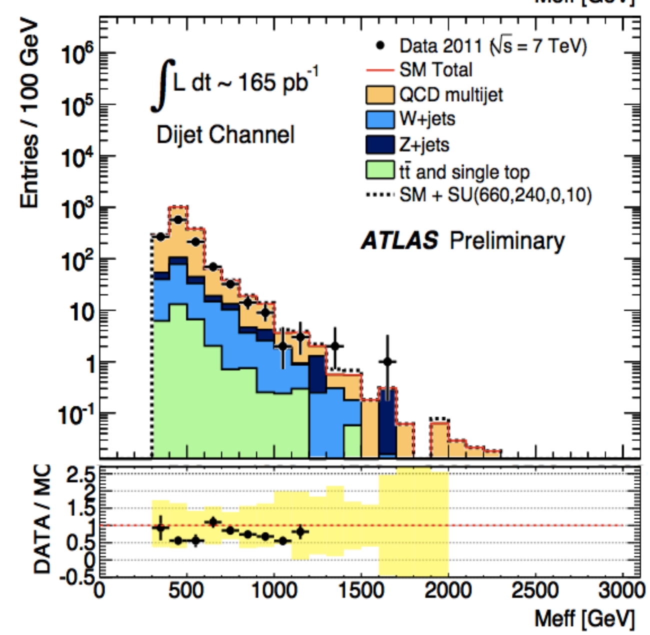
- Setup 5 control regions for each Signal region targeting specific background source
- Z + jets: irreducible $Z\nu\nu$ +jets,
  - fully data driven with γ+jets sample
  - control measurements Zee and Zmumu,
- W+jets : $W\tau\nu$ and $Wl\nu$ where l is not reconstructed
  - Control measurement via $We\nu$ and $W\mu\nu$ defined in MET vs m_T plane with veto on b-jets
- Top pairs and single top:
  - Hadronic τ decays in ttbb $\tau\nu$qq and single top control measurement defined in MET vs m_T plane with b-jet requirement
- QCD multi jet:
  - misreconstruction leads to fake MET, neutrino production in heavy flavor quark decays
  - control region with inverted angular separation cuts
  - fully data-driven TF by measuring detector response

Background in Control Regions





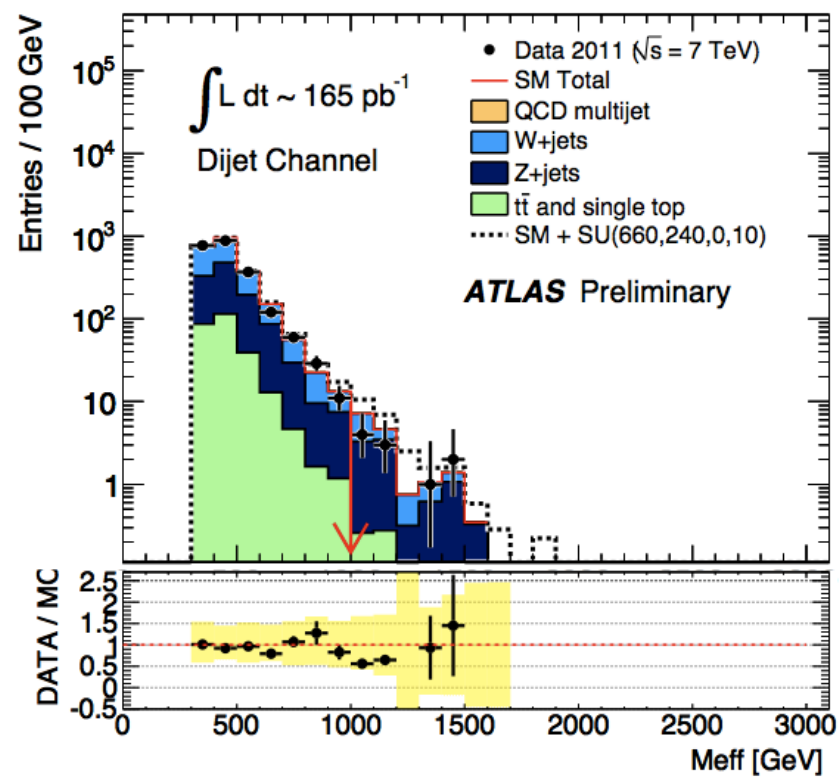




SUSY MET + Jets Search Results

Process	Signal Region		
	≥ 2 jets	≥ 3 jets	≥ 4 jets
$Z \to (\nu\nu)$+jets	5.6 ± 2.1	4.4 ± 1.6	3.0 ± 1.3
$W \to (\ell\nu)$+jets	6.2 ± 1.8	4.5 ± 1.6	2.7 ± 1.3
$t\bar{t}$+ single top	0.2 ± 0.3	1.0 ± 0.9	1.4 ± 0.9
QCD jets	0.05 ± 0.04	0.21 ± 0.07	0.16 ± 0.11
Total	12.1 ± 2.8	10.1 ± 2.3	7.3 ± 1.7
Observed	10	8	7

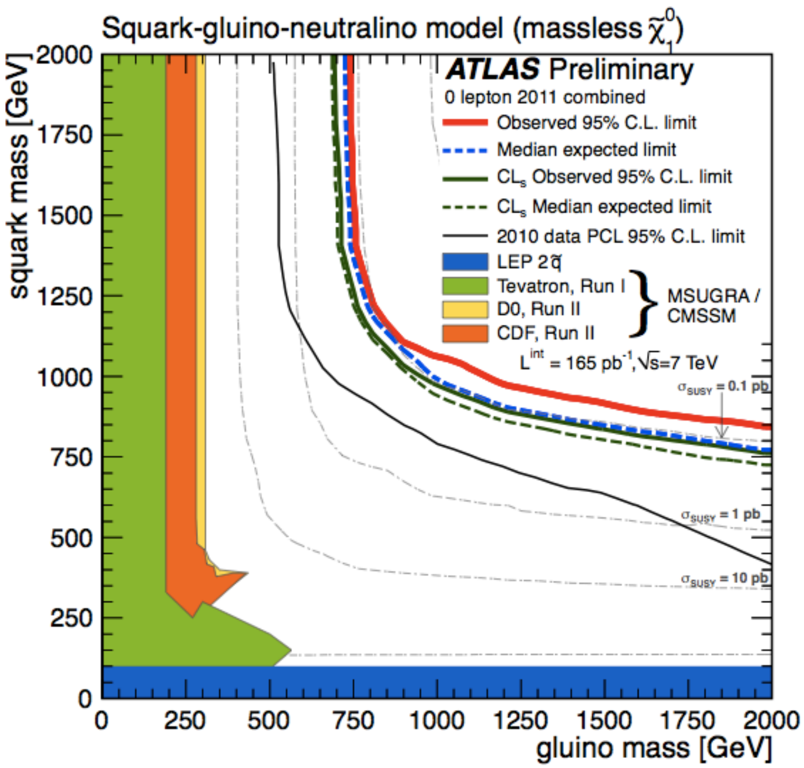
- Extract number of background events from CR through simultaneous log-likelihood fit
- Uncertainties ~30% dominated by jet energy scale, resolution, shapes of MC predictions

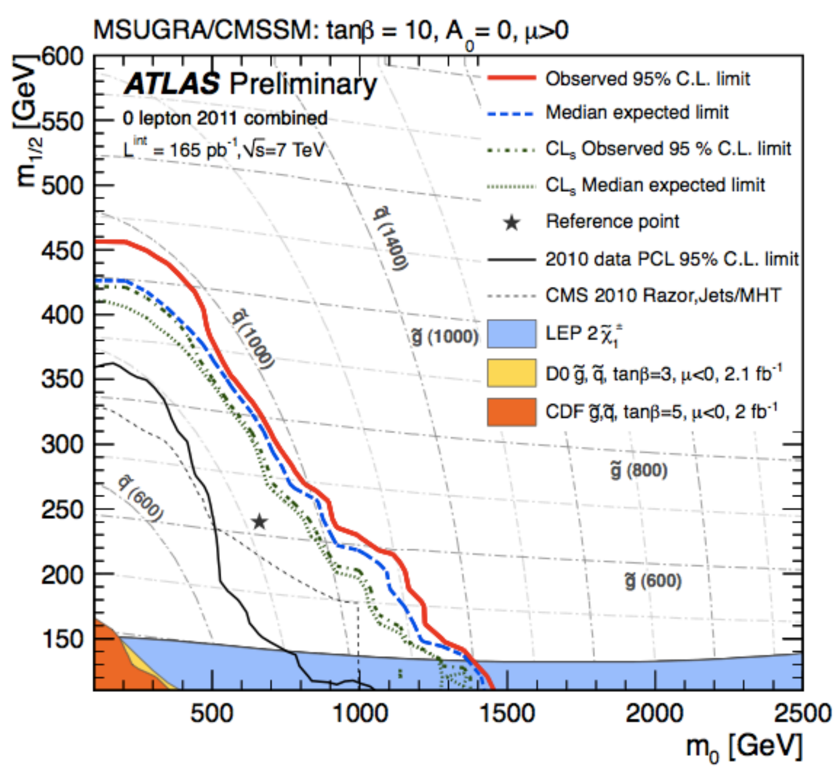


- All distributions for 3 signal regions are found to be consistent with expectations from background sources

SUSY MET + Jets Search Results

- The 2, 3, 4 inclusive jet signal regions considered
  - For exclusion use signal region with best expected sensitivity
- Exclude non-SM cross sections within acceptance of 35, 30 and 35 fb respectively at 95% CL.



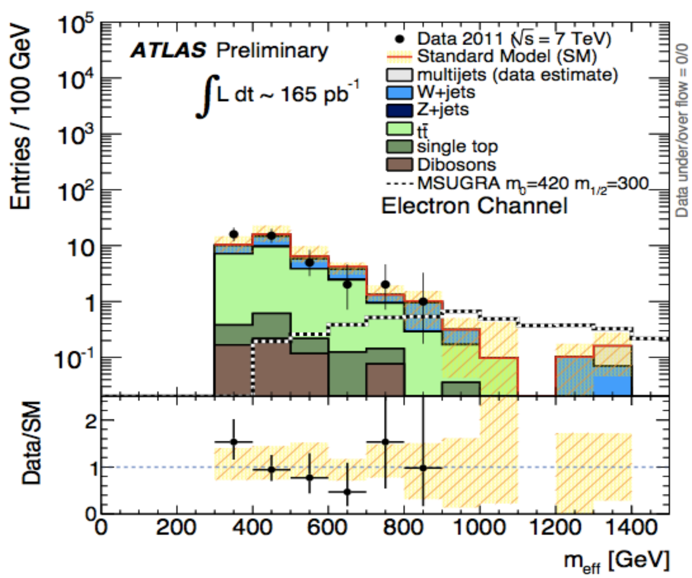


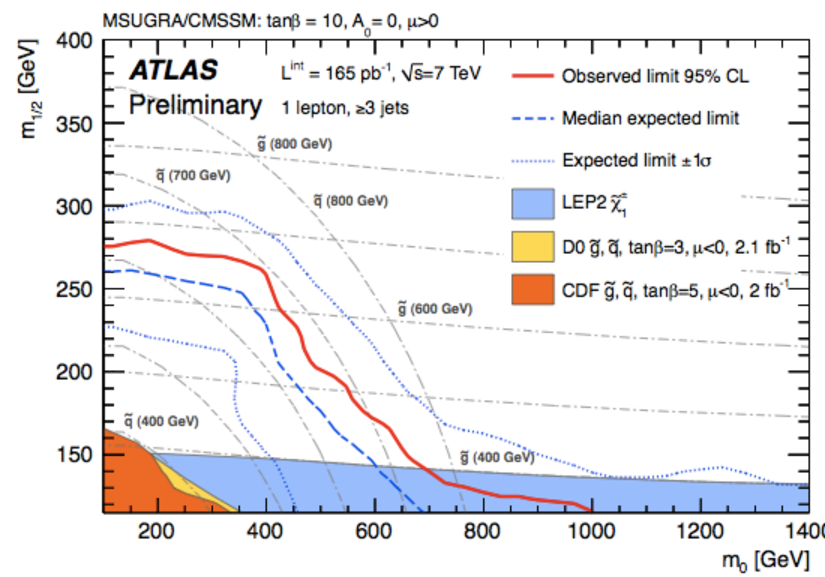
SUSY MET + Jets + 1 Lepton Search

- Complimentary analysis to MET + Jets
  - Require exactly one muon (electron) with p_T>20 (25) GeV
  - 3 jets with p_T>60, 25, 25 GeV
  - Signal selection m_{eff}= H_T+MET > 500 GeV; MET/m_{eff}>0.2

	muon	electron
Predict :	12.2 ± 3.8	14.5 ± 5.2
Observe:	12	10
Exclude :	53 fb	41 fb

Earlier SUSY results:
https://twiki.cern.ch/twiki/bin/view
/AtlasPublic/SupersymmetryPublicResults





Stable Long Lived Particle Searches

- Look for long lived bound states of squarks and gluinos
- Signature is slow (v < c) moving object loosing energy mainly through ionization
- Use β (tile) and $\beta\gamma$ (pixel) to get mass estimate:
  - $m = p/\beta\gamma$

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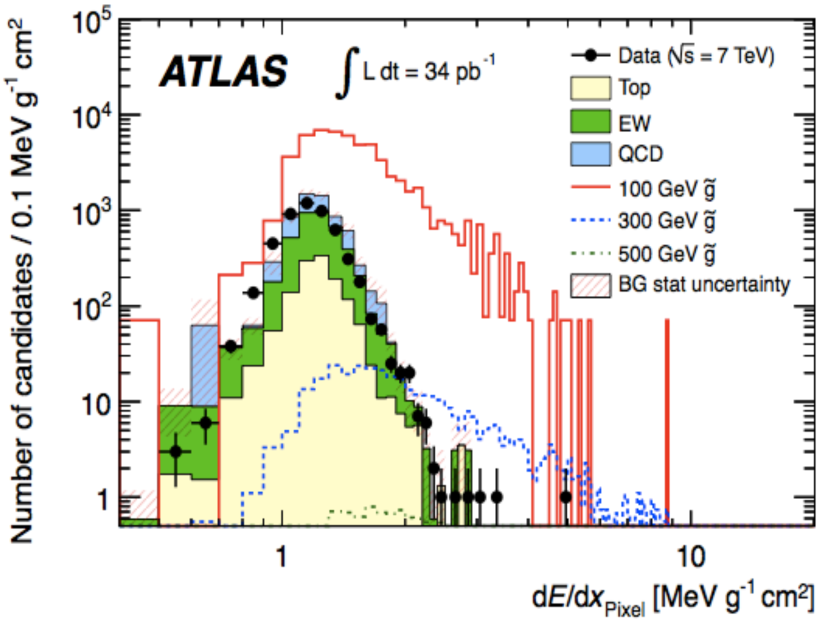
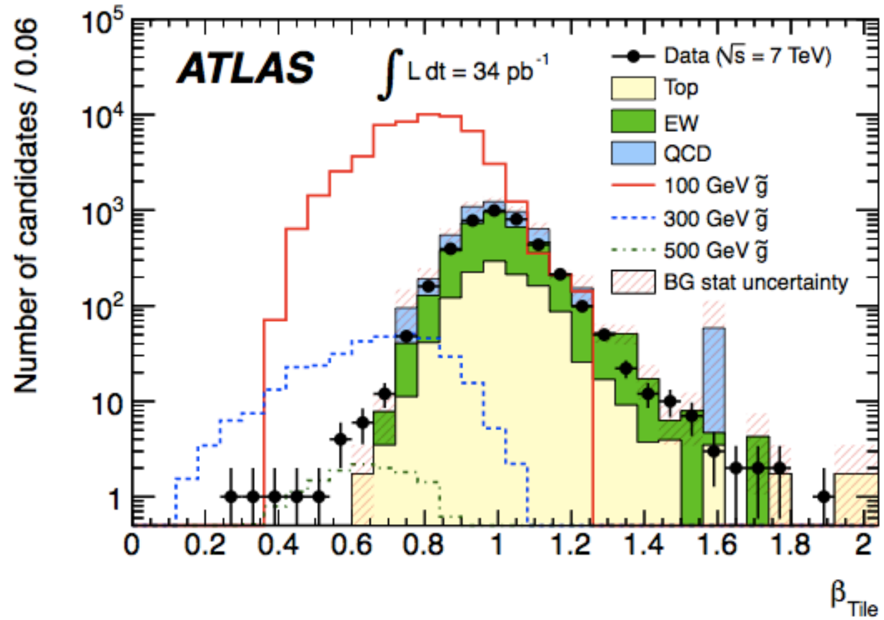
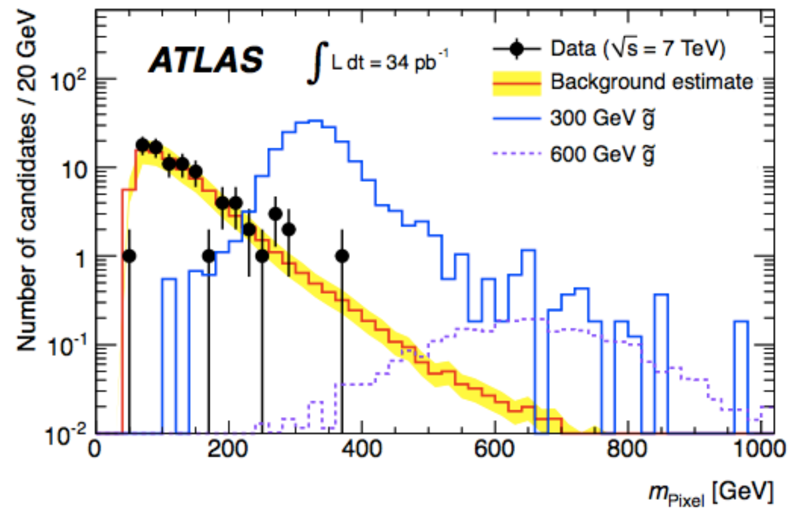
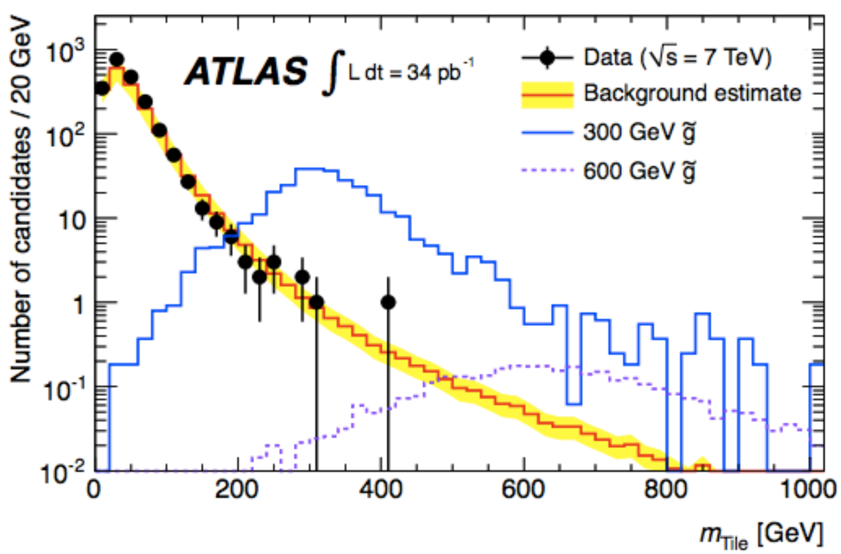


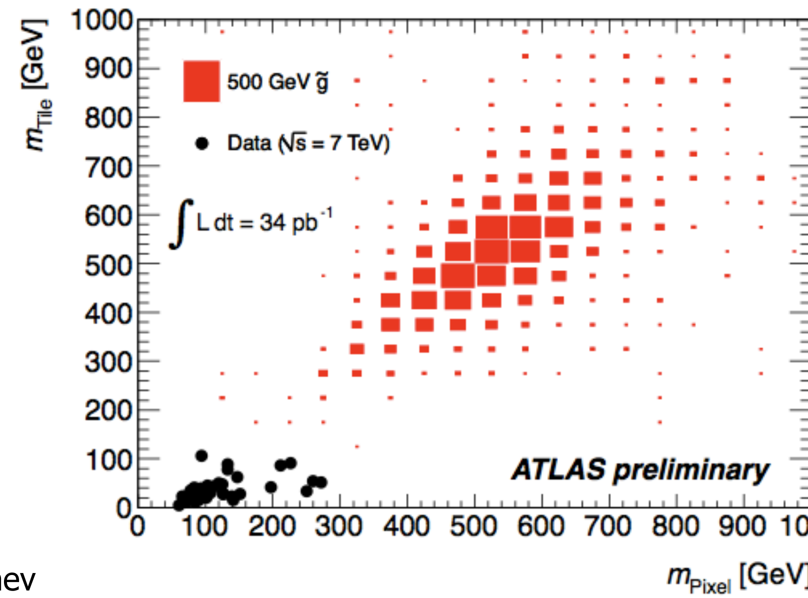


Stable Long Lived Particle Searches

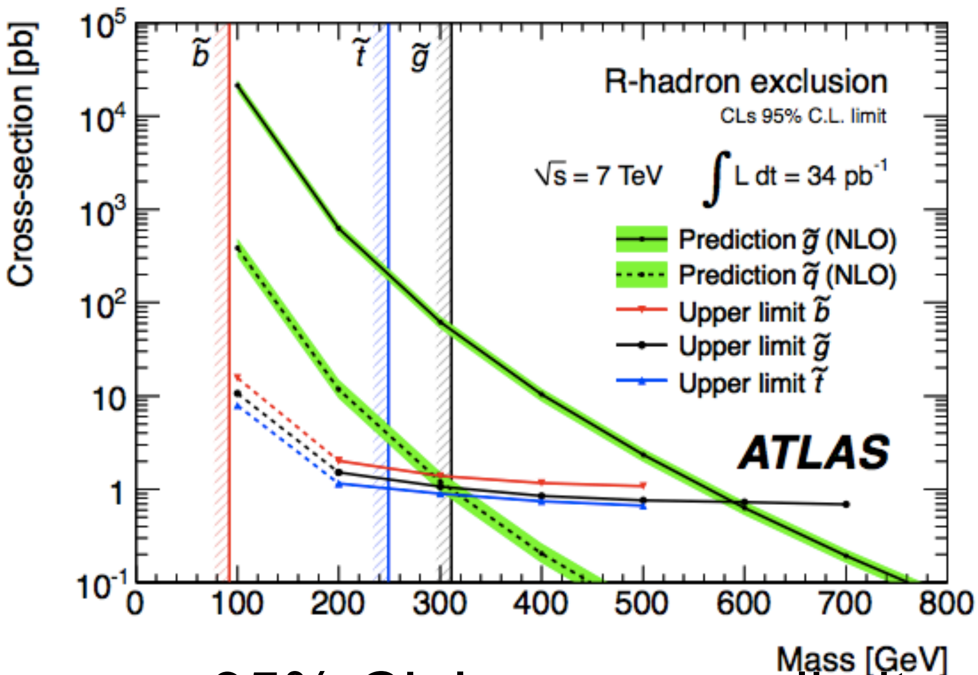
- Experimentally using two independent detectors greatly reduces backgrounds.







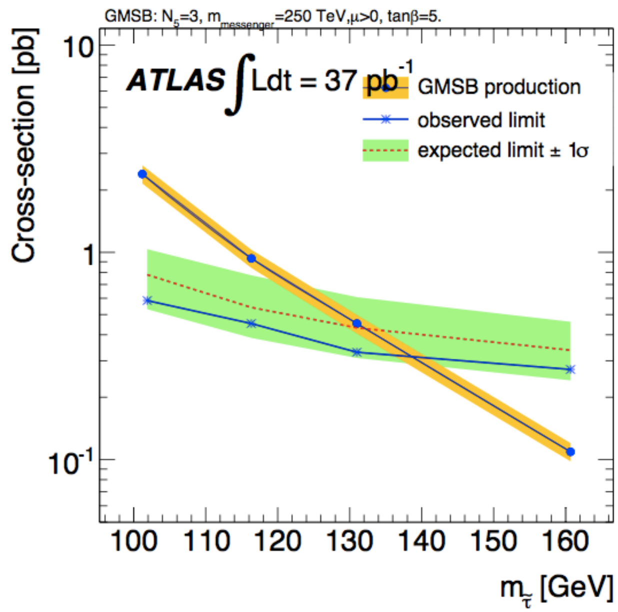
Stable Long Lived Particle Searches

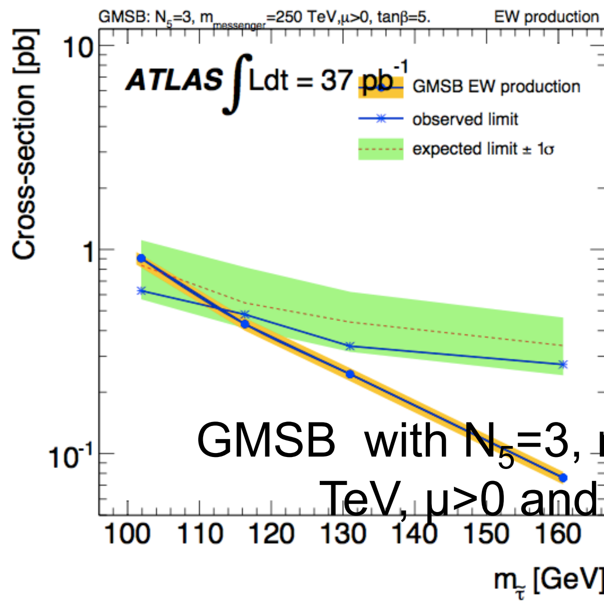


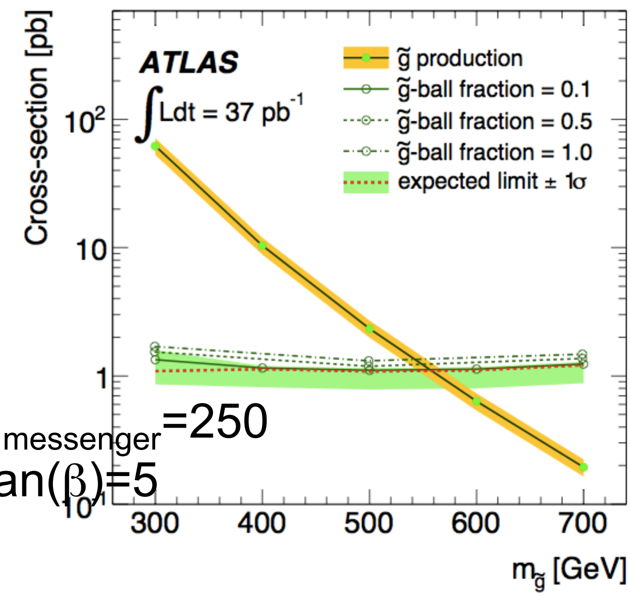
- 5 events observed for combined mass of 100 GeV, 5.4 expected
- 0 events for combined mass of 200 GeV

- 95% CL lower mass limits are 294GeV for sbottom R-hadrons, 309GeV for stop R-hadrons and 586 for GeV hadronising gluino.

Stable Long Lived Particle Searches







GMSB with N_5=3, $m_{messenger}$=250 TeV, μ>0 and tan(β)=5

- Look for sleptons in GMSB scenario and R-hadrons
  - R-hadrons may be neutral in ID, ionizing in later stage
  - Complimentary analysis
- Use muons chambers and tile calorimeter to estimate velocity
- Dedicated “muon” reconstruction since hits are expected to be late

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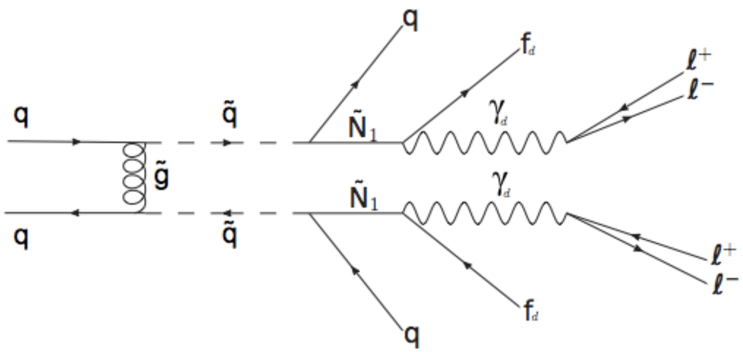
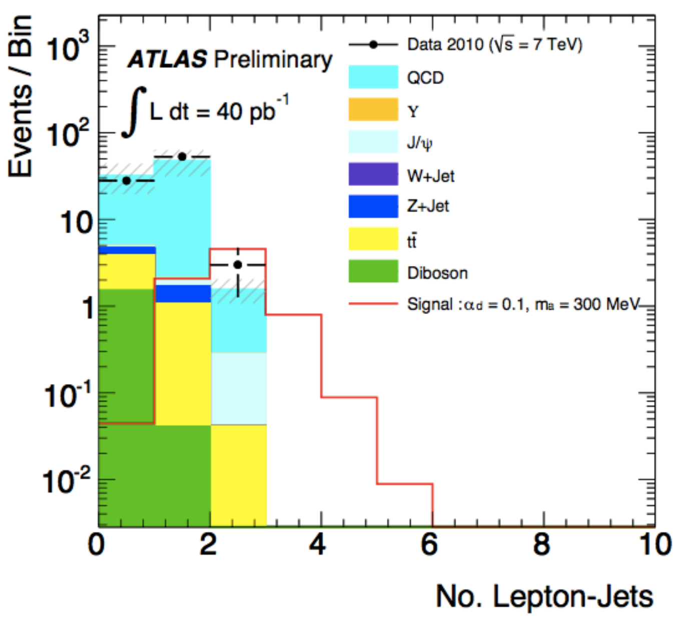
Search for Lepton Jets



Production of 2 lepton-jets from squark pairs

- dark photon g_d decays to lepton pairs
- dark fermion f_d ("darkino") escapes undetected



- Looking for light boosted bosons decaying into leptons
  - Dark photons in SUSY decays + hidden sector
- Search for two isolated "lepton jets", with ≥2 muons each
- No events observed
  - Estimated background 0.20 ± 0.19

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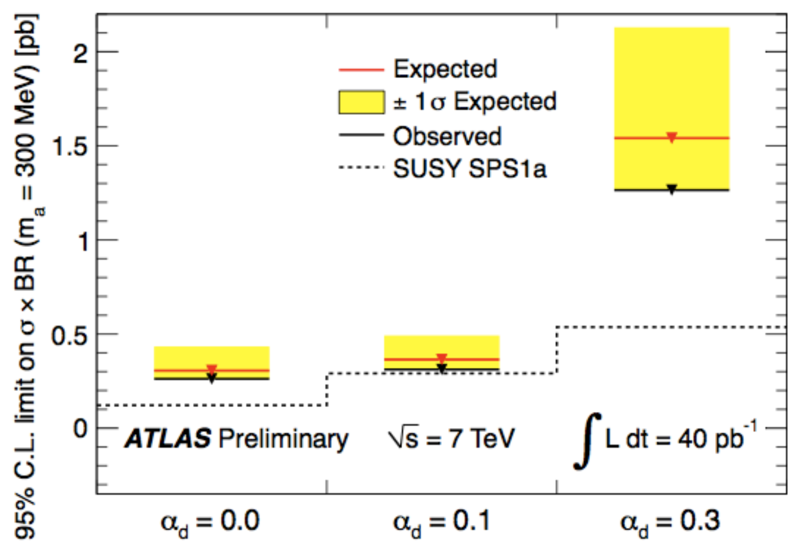
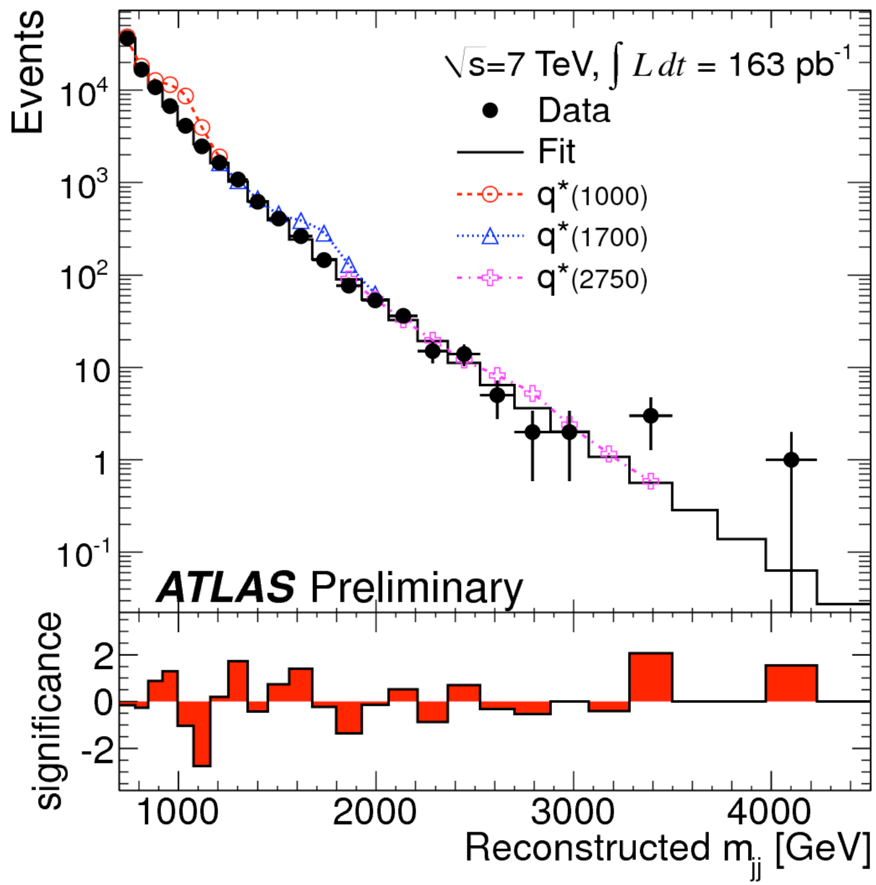


New Physics in Di-Jet Events

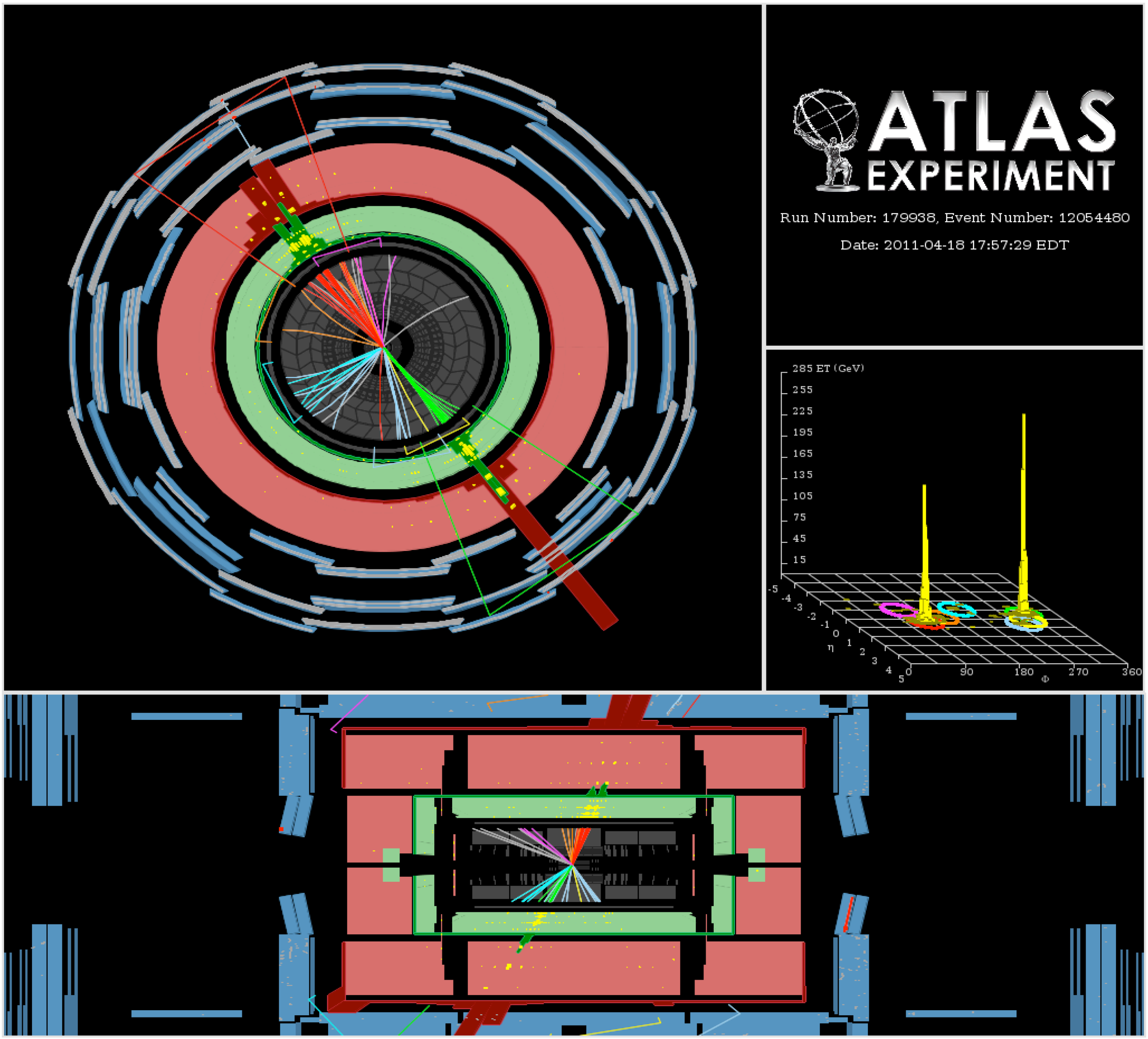
- Scattering processes well described within Standard Model (SM) by perturbative Quantum Chromodynamics (pQCD)
  - Deviation from expected behavior of di-jet process in pQCD would indicate new physics
- Additional contributions are possible due to new massive particles coupling to quarks or new forces appearing at higher CM energies
  - Compositeness, excited quarks, contact interactions, axigluons, quantum black holes [New J. Phys. 13 (2011) 053044]
- Thus look for
  - Bumps in di-jet invariant mass
  - Modified angular distributions

New Physics in the Dijet Mass Distribution



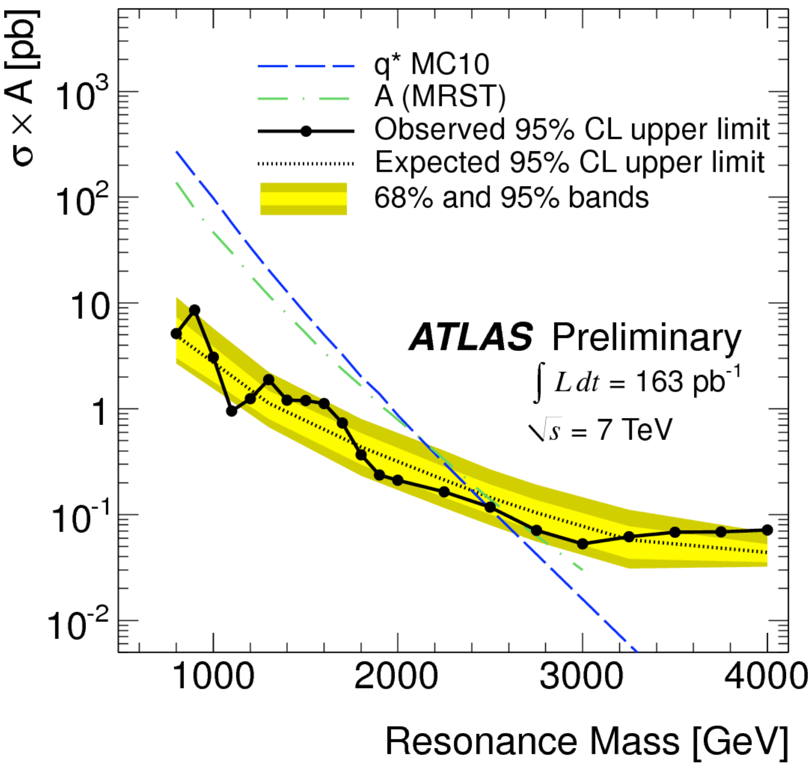
- Anti-kt jets with R = 0.6
- $|\eta_1 - \eta_2| < 1.3$ boost isotropic component, $|\eta_{1,2}| < 2.5$
- $m_{jj} > 700$ GeV
- Fit data to $f(x)=p_1(1-x)^{p2}\, x^{p3+p4 \ln x}$, where $x = m_{jj}/\sqrt{s}$
  - p–value of the fit to the data = 0.016
  - p–value of the fit without highest m_{jj} events = 0.26
- The predicted q* signals for excited -quark masses of 1000, 1700, and 2750 GeV are plotted on top of the background.
  - Bins with the discrepancy of a Poisson p-value of less than 0.5, show bin-by-bin significance of the data-background difference

Highest Di-Jet Event



- The di-jet mass is 4040 GeV
- 1st Jet (p_T, eta, phi, color) of (1850 GeV, 0.32, 2.2, red)
- 2nd Jet (1840 GeV, -0.53, -0.92, green)

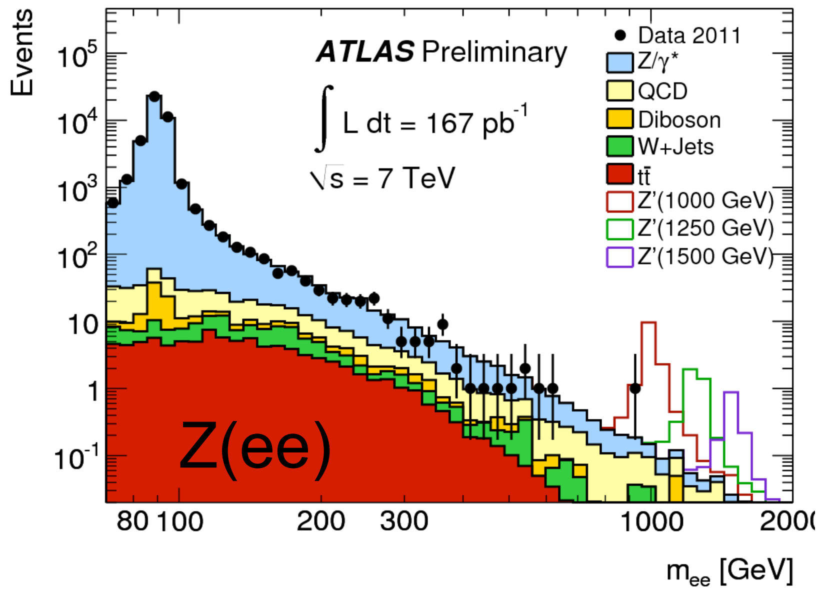
New Physics in the Dijet Mass Distribution

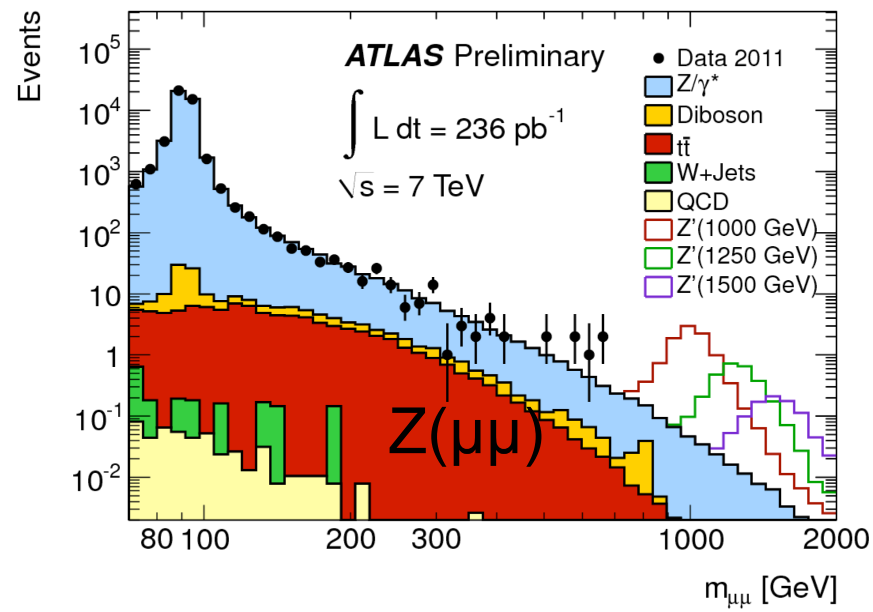


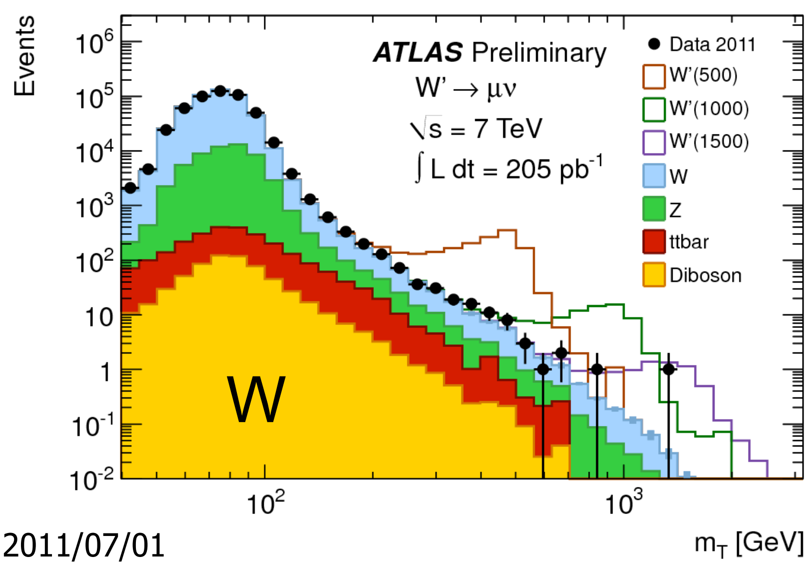
- BumpHunter systematically looks for "bumps"
- Signal window increased and shifted to include all bin intervals (up to half m_{jj} range)
- No evidence for a resonant signal is found

Benchmark model	Observed (expected) limit at 95% CL
Excited quarks	$m(q^*)$ > 2.49 (2.4) TeV
Axigluons	m > 2.67 (2.48) TeV
RM quantum black hole (δ = 6)	M_D > 3.67 (3.64) TeV
4-quark contact interactions	Λ > 6.7 (5.7) TeV

New Heavy Gauge Bosons

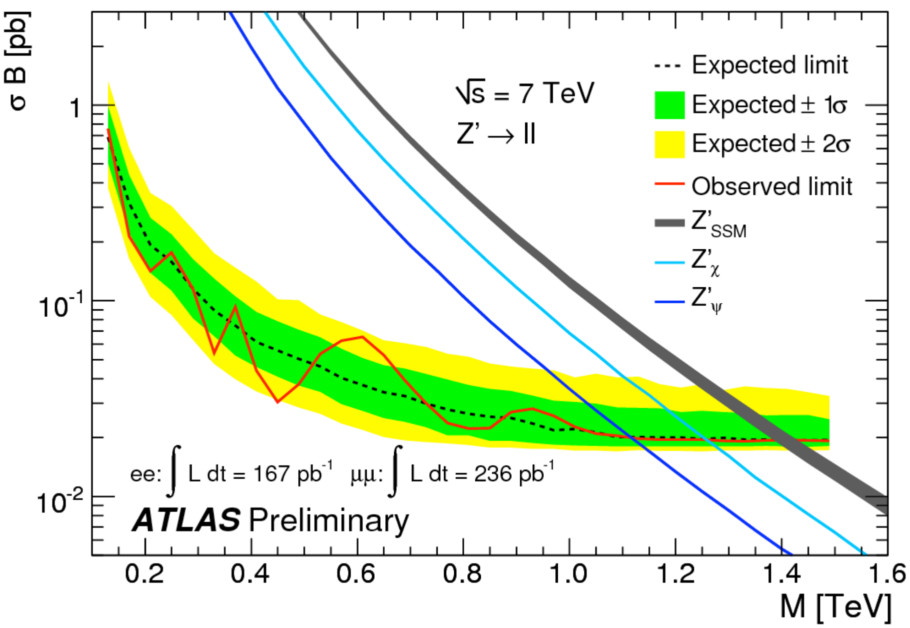


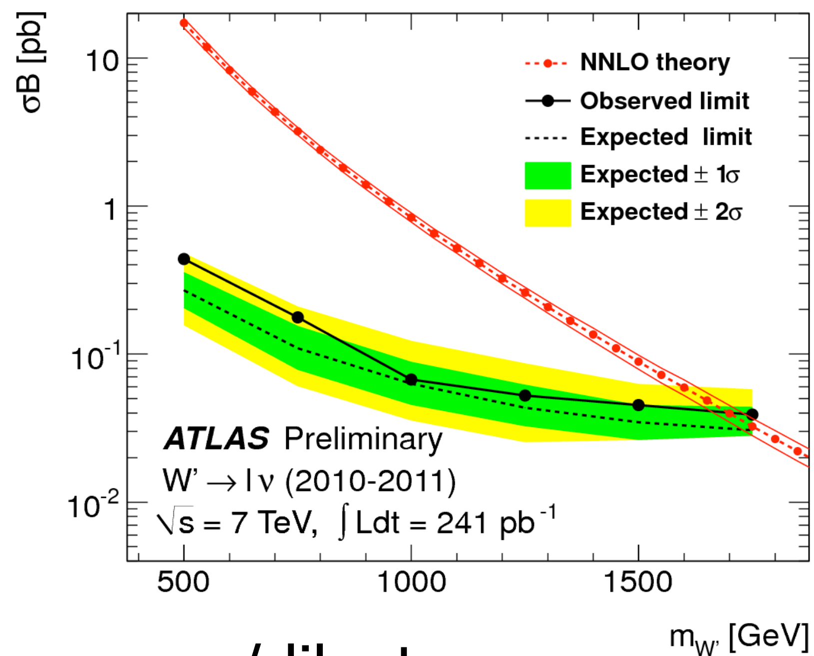




- New heavy gauge bosons are predicted in several extensions of the SM
- Benchmark model for these searches is the Sequential Standard Model
  - W', Z' have same leptonic couplings as SM W, Z
  - Widths scale linearly with mass
- For Z', also consider string theory -inspired E6 models

New Heavy Gauge Bosons

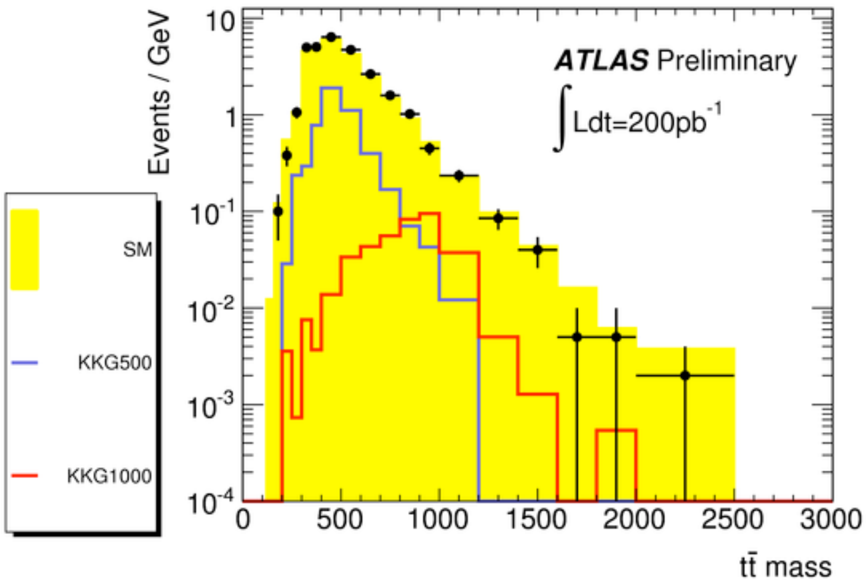




- No excess is observed in transverse/dilepton mass
  - Set limits on production cross section for benchmark models
  - Largest uncertainties due to MET modeling (W')
  - Background estimations (W', Z')
- For SSM m(W') > 1.7 TeV, m(Z') > 1.41 TeV @ 95% CL

Model	Z'_ψ	Z'_N	Z'_η	Z'_I	Z'_S	Z'_χ
Mass limit [TeV]	1.116	1.142	1.150	1.203	1.230	1.259

New Heavy Gauge Bosons in Top Pairs

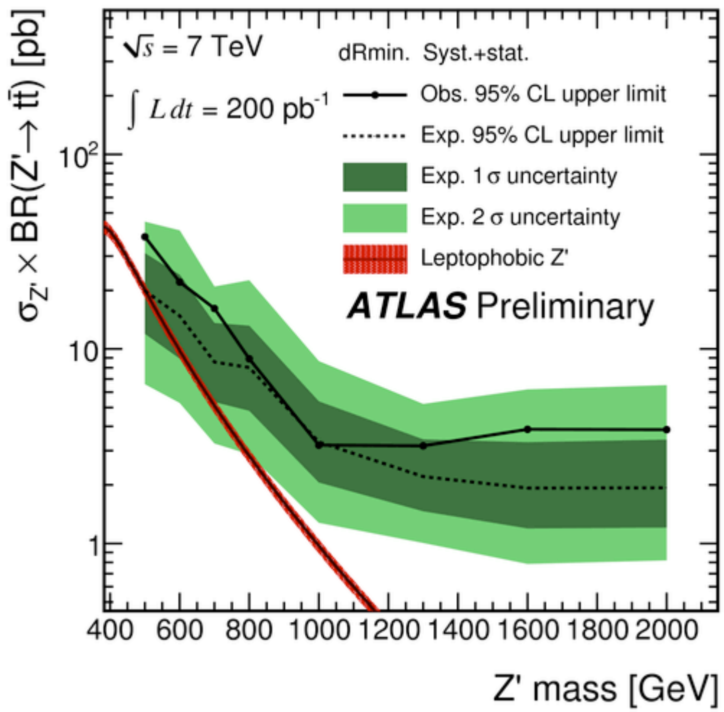


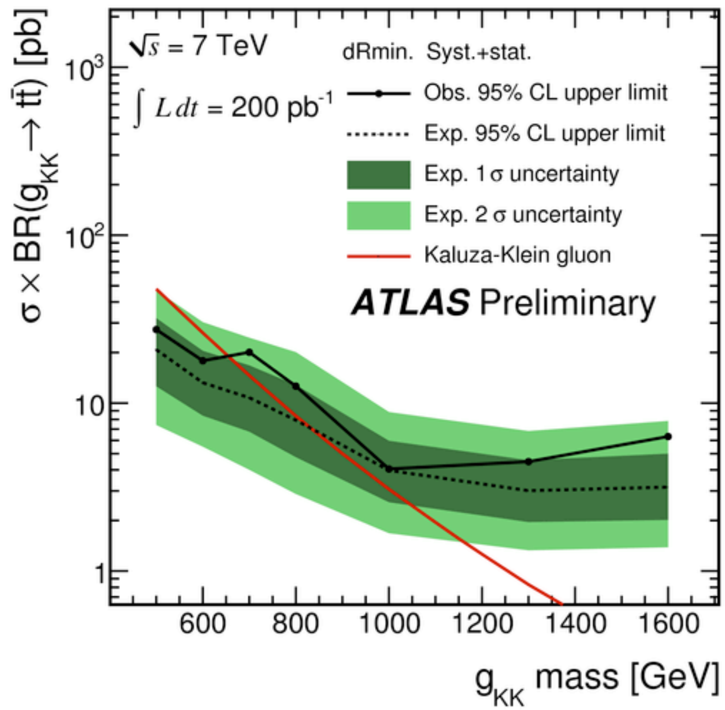
	Electron channel	Muon channel
$t\bar{t}$	724	988
Single top	36	50
W+jets	93	172
Z+jets	6	8
Diboson	2	2
Total MC Background	861	1220
QCD Background	35	105
Total Expected	896	1325
Data observed	935	1396
Z', $m = 500$ GeV	15	21
g_{KK}, $m = 700$ GeV	68	93

- Look for a resonance production of top pairs
- May arise in technicolor models, colored resonances
- Consider two benchmark scenarios
  - Narrow resonance: Leptophobic Z′ (Phys. Lett. B345 (1995) 483)
  - Wide resonance: Kaluza-Klein gluon from Randall-Sundrum warped extra dimension model (JHEP 09 (2007) 074)
- Study *tt* invariant mass spectrum in lepton + jets final states

ATLAS-CONF-2011-087

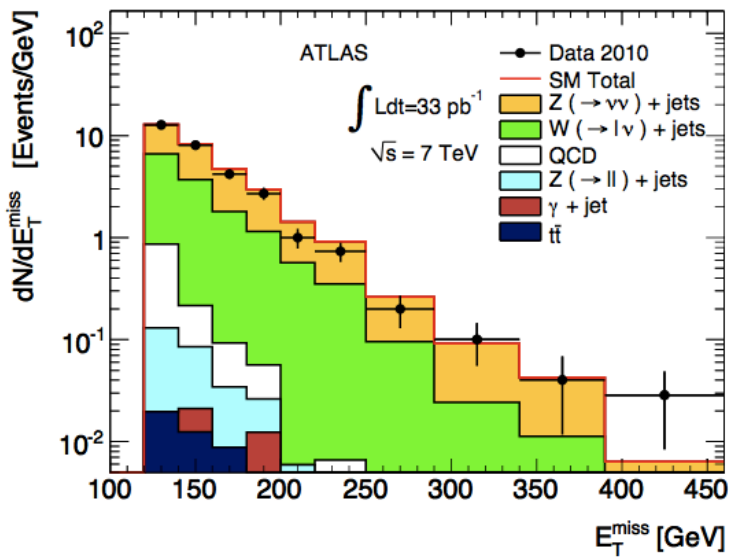
New Heavy Gauge Bosons in Top Pairs

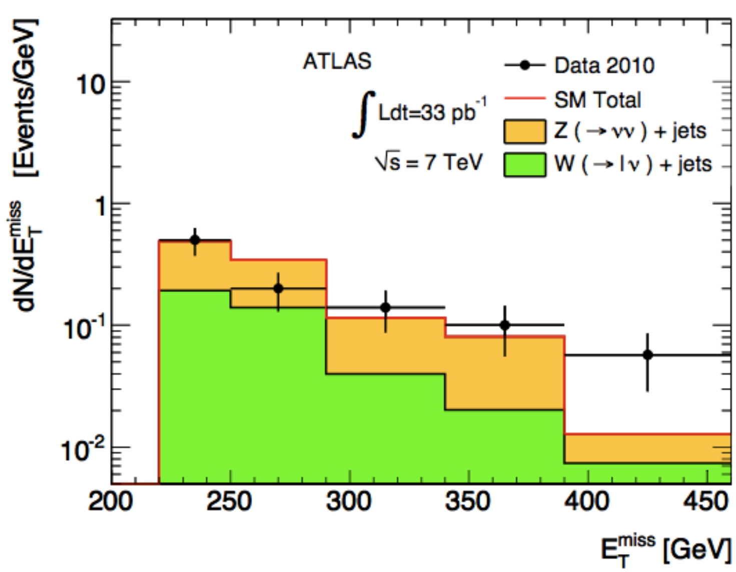




- Compare data to SM hypothesis using BumpHunter
  - Dominant systematics (35%) modeling of W+jets background
- Since no significant excess observed set limits

Monojet Searches





- Monojet may arise in models with Large Extra Dimensions (LED)
  - $M_{Pl}^2 \sim M_D^{2+n} R^n$, R size of extra dimensions n, M_D comparable to EW breaking scale
  - $qg \to qG$, $gg \to gG$, $qq \to gG$, G graviton escapes detection and source of MET
  - Two Kinematic regions (not optimized to retain sensitivity to different models)

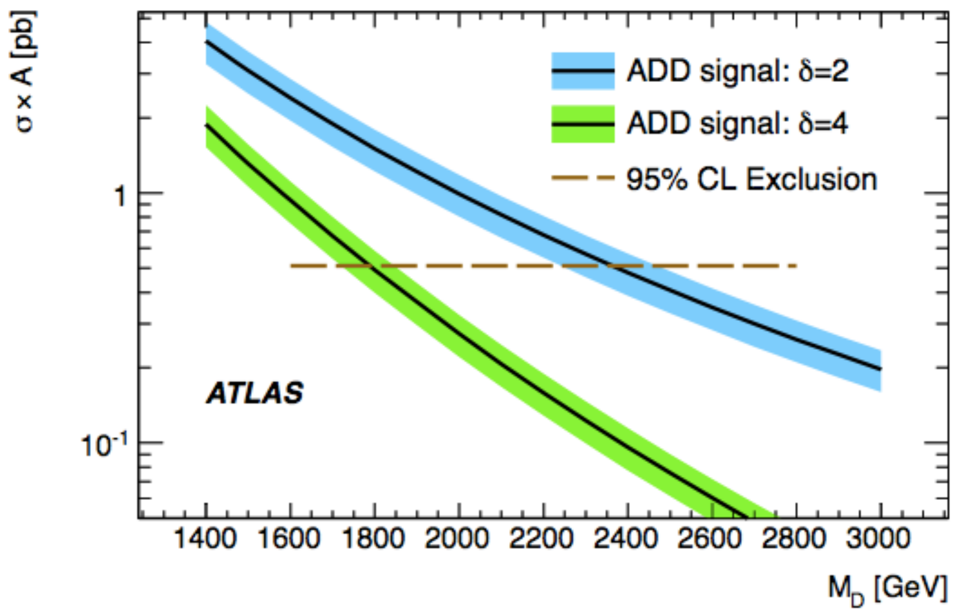
	LowPt	HighPt
MET	>120 GeV	>220 GeV
1st Jet ($\|\eta\|<2$)	>120 GeV	>250 GeV
2nd Jet ($\|\eta\|<4.5$)	<30 GeV	<60 GeV

$\phi(j_2, MET) > 0.5$

CERN-PH-EP-2011-090

Monojet Searches

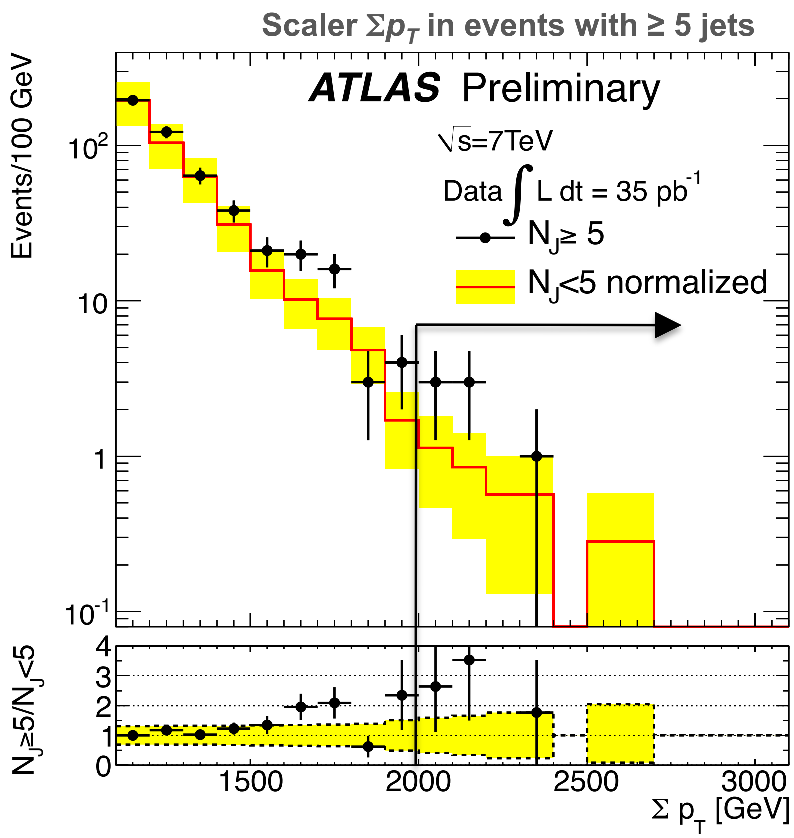
Background Predictions ± (stat.) ± (syst.)	LowPt Selection	HighPt Selection
$Z(\to \nu\bar{\nu})$+jets	$357 \pm 12 \pm 25$	$25.4 \pm 2.6 \pm 2.8$
$W(\to \tau\nu)$+jets	$139 \pm 5 \pm 36$	$7.8 \pm 1 \pm 2.3$
$W(\to \mu\nu)$+jets	$70 \pm 4 \pm 5$	$3.8 \pm 0.6 \pm 0.4$
$W(\to e\nu)$+jets	$59 \pm 3 \pm 15$	$3.0 \pm 0.7 \pm 0.9$
Multi-jets	$24 \pm 5 \pm 14$	–
$Z/\gamma^*(\to \tau^+\tau^-)$+jets	$2.6 \pm 0.5 \pm 0.7$	–
$Z/\gamma^*(\to \mu^+\mu^-)$+jets	$1.9 \pm 0.4 \pm 0.1$	–
top	$0.96 \pm 0.04 \pm 0.2$	–
γ+jets	$0.35 \pm 0.17 \pm 0.5$	–
$Z/\gamma^*(\to e^+e^-)$+jets	–	–
Non-collision Background	$2.4 \pm 0.5 \pm 1.1$	–
Total Background	$657 \pm 15 \pm 62$	$40 \pm 2.9 \pm 4.8$
Events in Data (33 pb^{-1})	611	39



- No excess observed
- Set 95%CL limits in context of ADD LED

Nucl. Phys. B544 (1999) 3

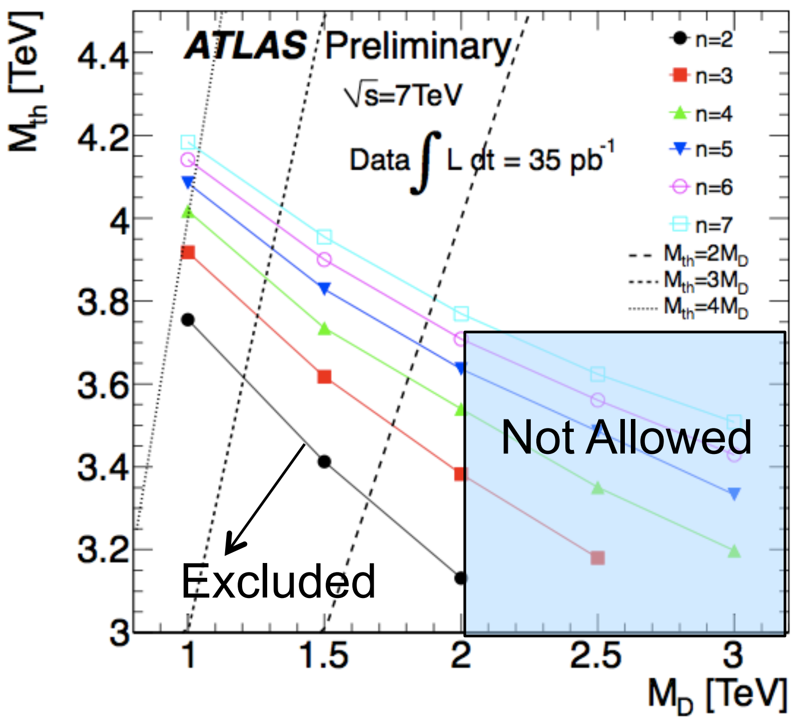
Microscopic Black Holes

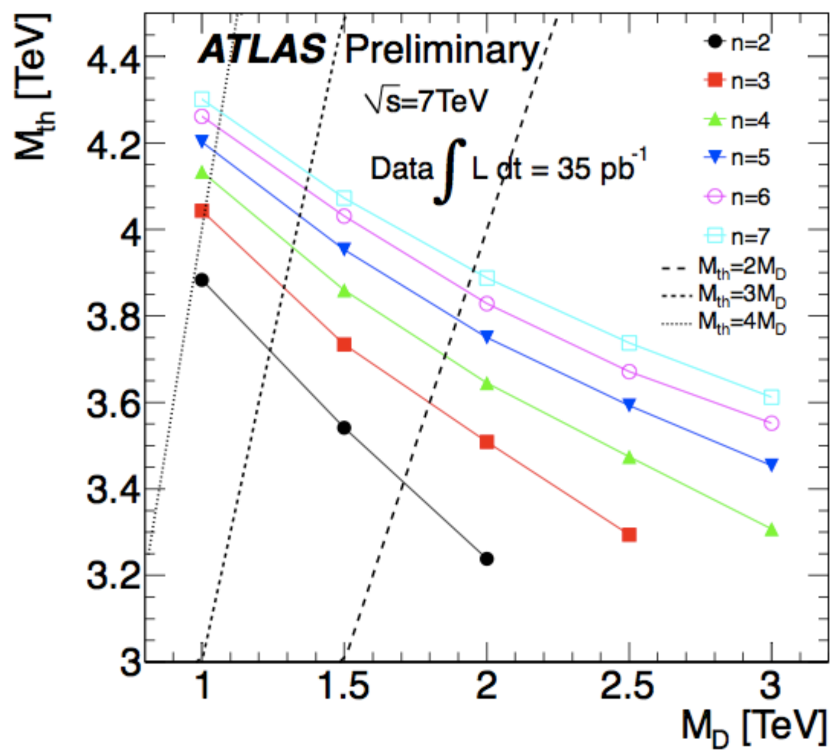


N_{obs} = 7
N_{exp} = 3.7 ± 1.5

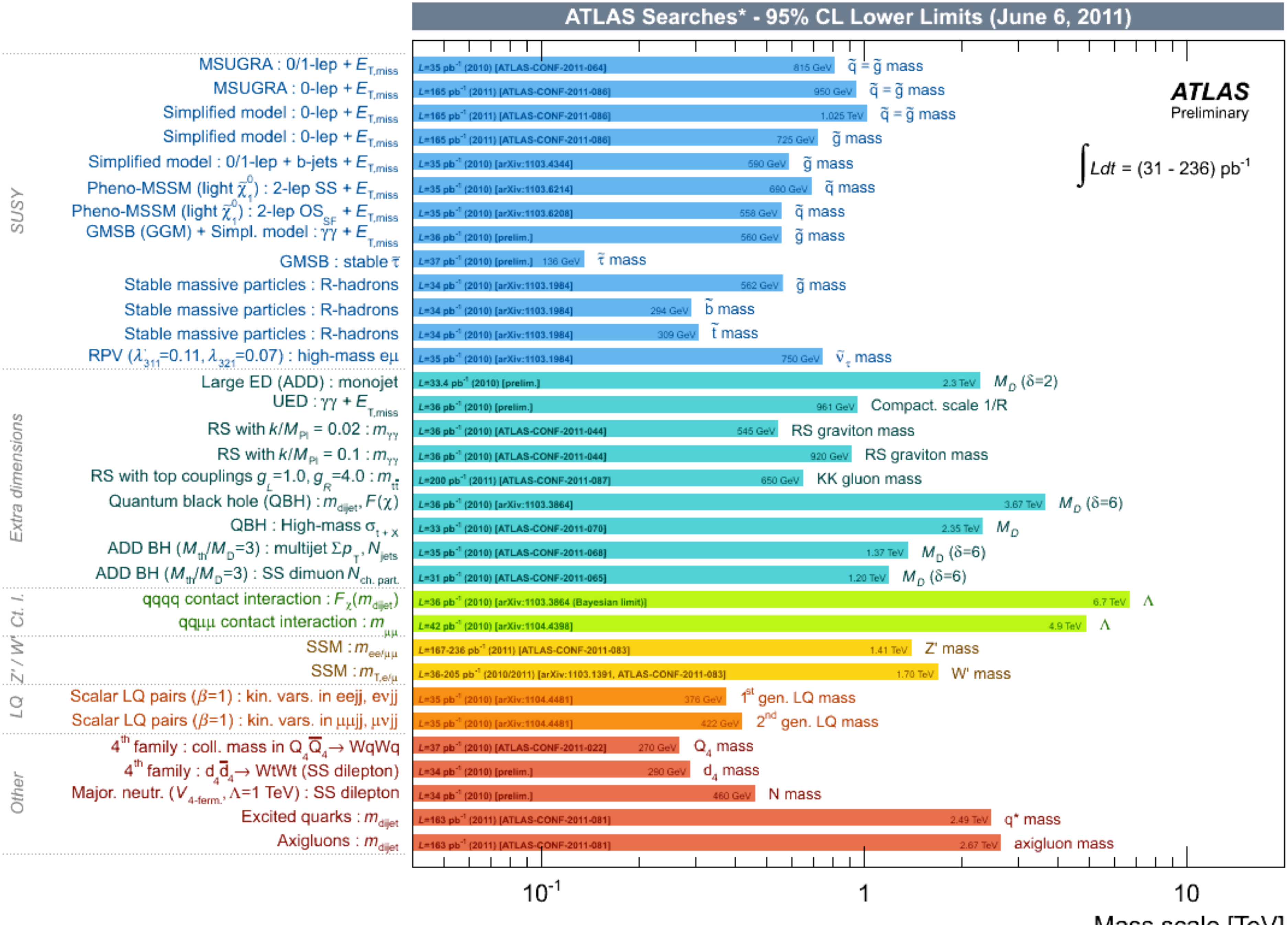
- Quantum black hole search in multijet final state
  - Formed when two colliding partons have impact parameter smaller than R_S, the Schwarzschild radius corresponding to their invariant mass M=√s.
- Use ADD LED models (Phys. Rev. D 59 (1999) 086004)
  - Classical approximation for production and decay works for M_{th}>M_D, use as a cut off
  - Decay through Hawkings radiation
- Select events with N_J ≥ 5 and Σp_T > 2 TeV

Microscopic Black Holes





- Upper limit on the cross-section times acceptance of 0.29 pb at the 95% CL is obtained
  - Strong dependence of BH production modeling on PDF sets
  - CTEQ6.6 vs MRST2007



*Only a selection of the available results shown

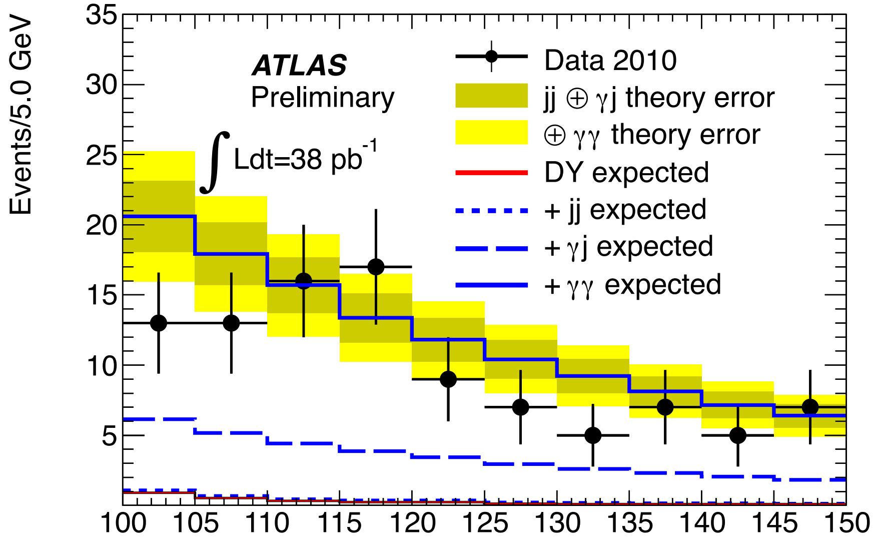
Summary and Outlook

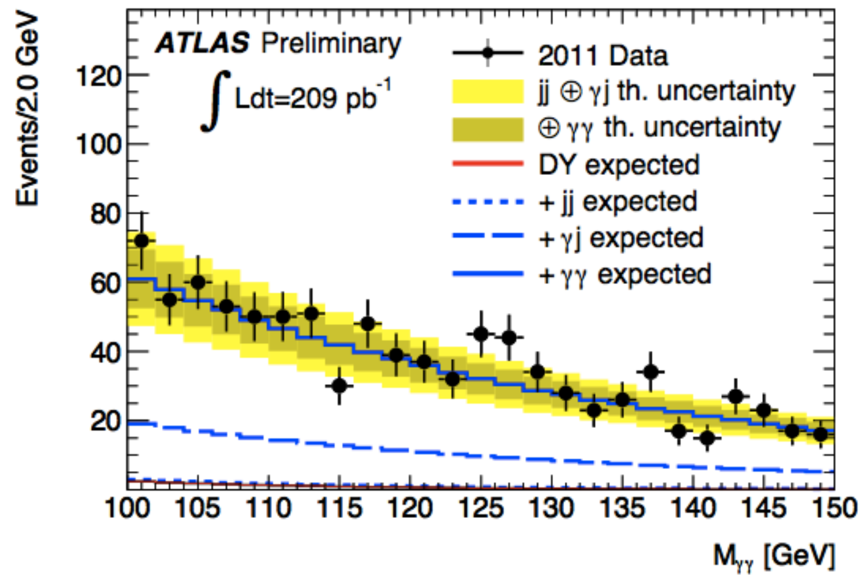
- LHC and ATLAS detector perform very well
- Wide range of searches for physics beyond the Standard Model covering many different final states and signatures
  - Have not seen large deviations yet
  - Derive limits on masses, cross sections
  - Pushing boundaries of the excluded parameter space
- Expect many more results this summer on data set O(1fb^{-1}) – stay tuned
- Official ATLAS Results:

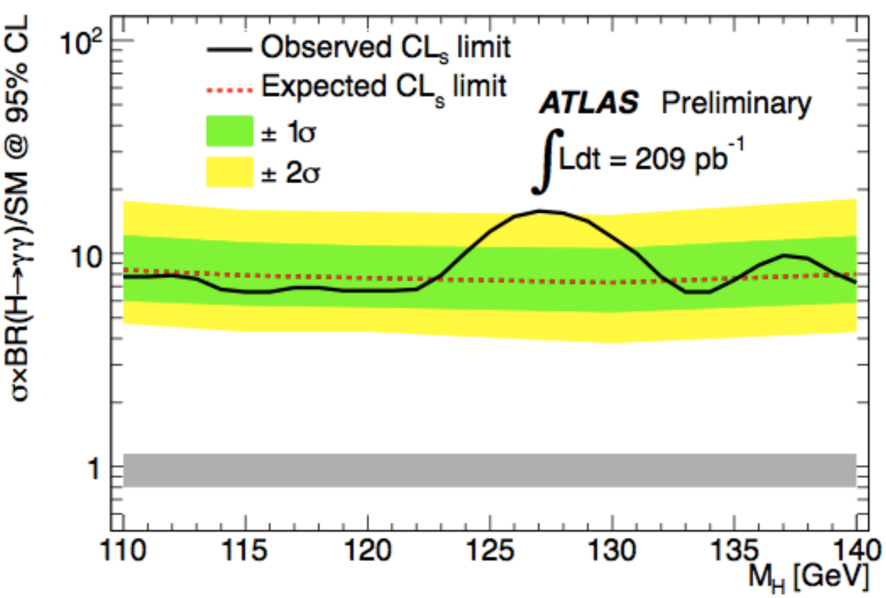
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic

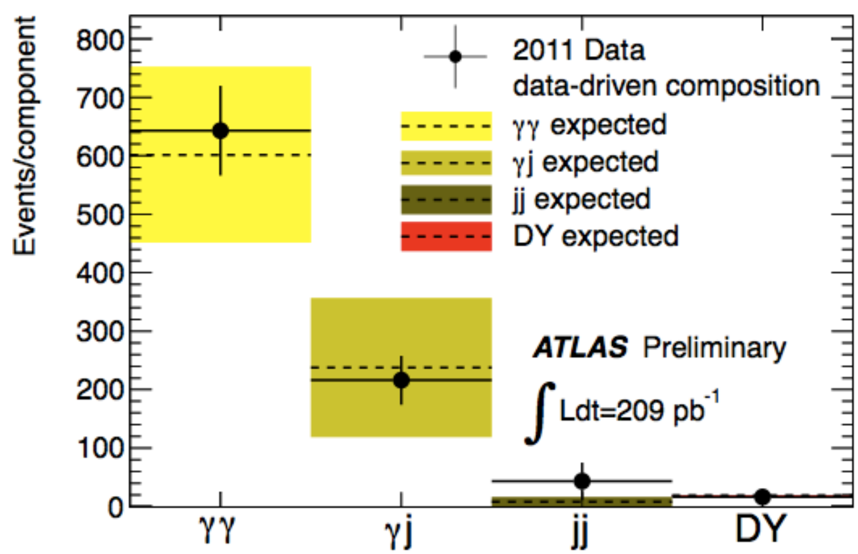
BACK UP

Higgs Boson in the Diphoton Channel

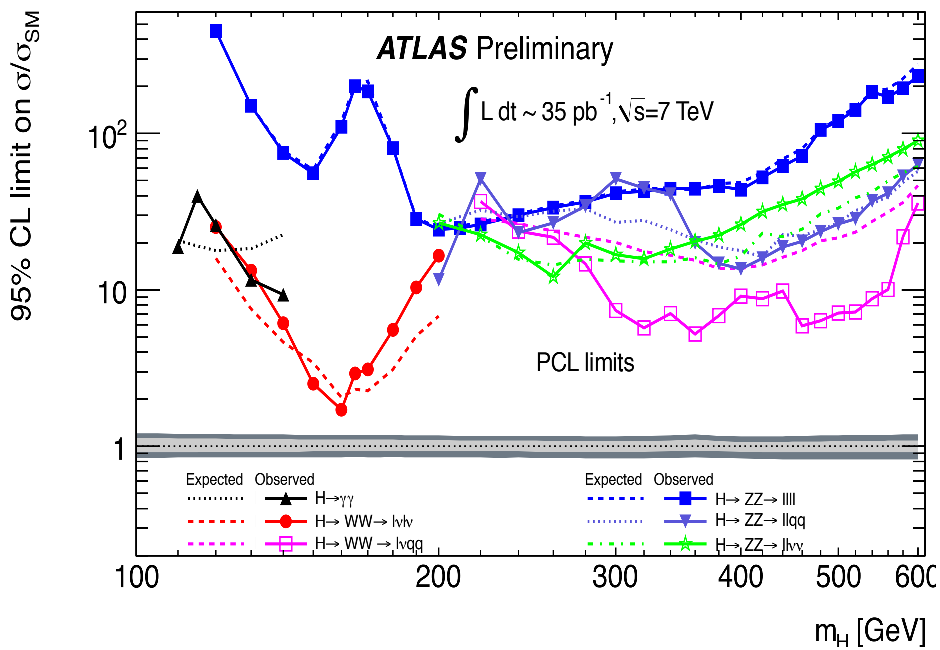


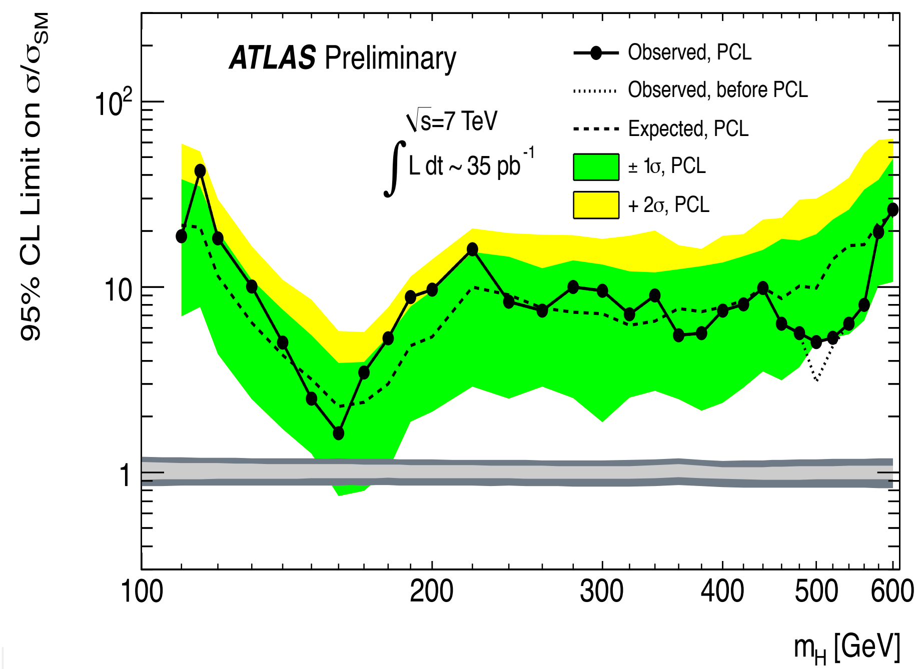


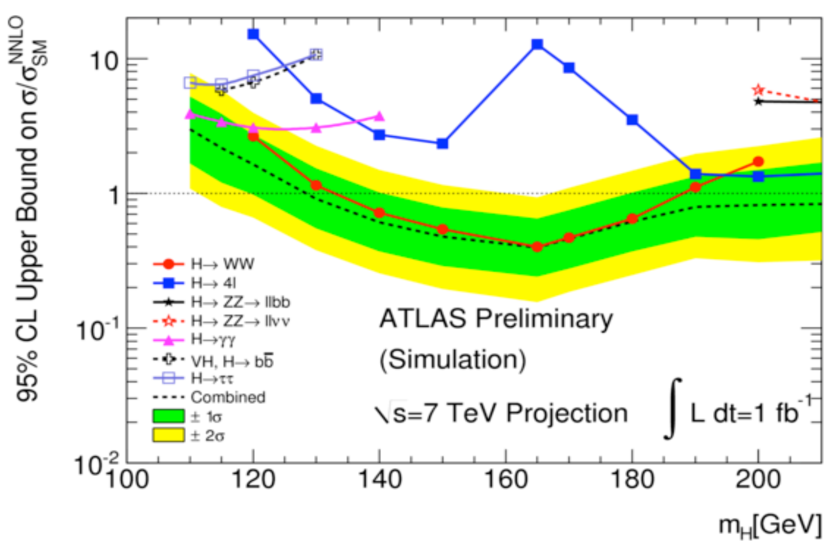


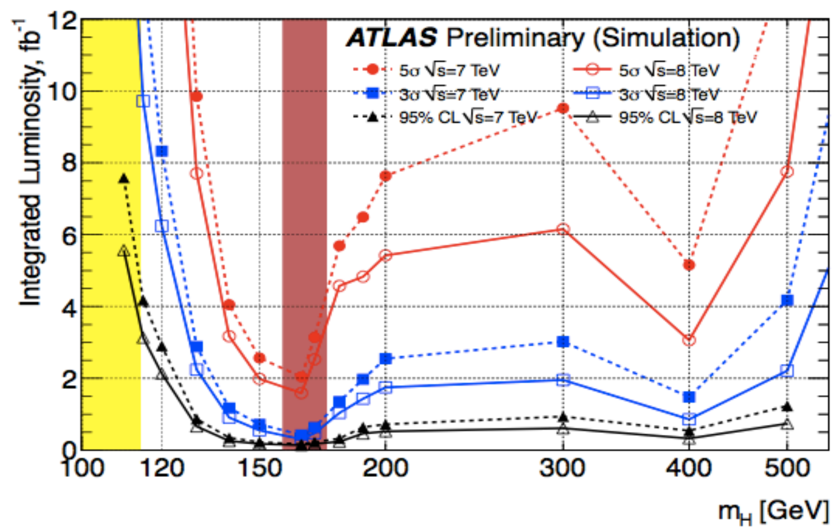


Higgs Boson


ATLAS Preliminary
∫L dt ~ 35 pb⁻¹, √s=7 TeV
PCL limits
95% CL limit on σ/σSM
Expected Observed
H→γγ
H→ WW→ lνlν
H→ WW → lνqq
H→ ZZ→ llll
H→ ZZ→ llqq
H→ ZZ→ llνν
mH [GeV]


ATLAS Preliminary
√s=7 TeV
∫L dt ~ 35 pb⁻¹
Observed, PCL
Observed, before PCL
Expected, PCL
± 1σ, PCL
+ 2σ, PCL
95% CL Limit on σ/σSM
mH [GeV]


ATLAS Preliminary
(Simulation)
√s=7 TeV Projection
∫L dt=1 fb⁻¹
H→ WW
H→ 4l
H→ ZZ→ llbb
H→ ZZ→ llνν
H→γγ
VH, H→ bb̄
H→ττ
Combined
± 1σ
± 2σ
95% CL Upper Bound on σ/σSM NNLO
mH[GeV]


ATLAS Preliminary (Simulation)
5σ √s=7 TeV
3σ √s=7 TeV
95% CL √s=7 TeV
5σ √s=8 TeV
3σ √s=8 TeV
95% CL √s=8 TeV
Integrated Luminosity, fb⁻¹
mH [GeV]