Searches for Physics Beyond the Standard Model with ATLAS

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XL International Symposium on Multiparticle Dynamics
(ISMD 2010, Antwerp)

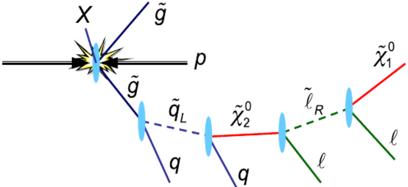
Overview

We will discuss some of results of early searches for new physics with the ATLAS experiment.

- SUSY :
  1. Prospects @ $\sqrt{s}$=7TeV
  2. 0Lepton + Jets + E_T^{miss}
  3. 1Lepton + Jets + E_T^{miss}
  4. b-Jets + E_T^{miss}
- Exotics (non-SUSY BSM) :
  1. Dijet resonance search
  2. Dijet angular distributions search
  3. High invariant mass, multi-object search
  4. Electron + E_T^{miss} (W')

SUSY

- In R-parity conserving SUSY scenarios :
  - Pair production of gluinos and squarks
  - Cascade decay
  - Several high-pt jets, letpons and E_T^{miss} in final state

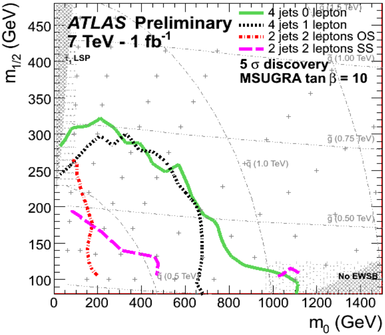


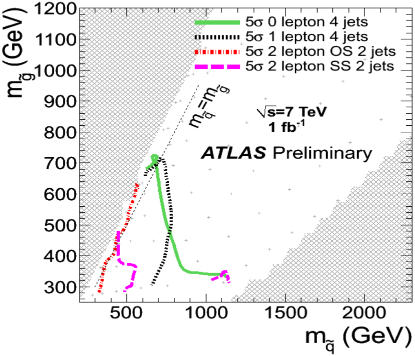
$$gg, q\bar{q}, qq, qg \rightarrow \widetilde{g}\widetilde{g}, \widetilde{q}\widetilde{q}, \widetilde{q}\widetilde{g}$$

- Early search, based on inclusive searches
- Loosen selection thresholds relative to the earlier MC studies
- Benchmark SUSY scenario : SU4 (LO 42.3pb, NLO 59.9pb)
  - m_0=200GeV, $m_{1/2}$=160GeV, A_0=-400GeV, tagβ=10 and u>0
  - Mass point above Tevatron limits : m(squarks, gluinos) $\sim$ 410-420GeV
  - Current limits from Tevatron : m(squark)>280GeV, m(gluino)>340GeV

SUSY : Prospects @ $\sqrt{s}$=7TeV

$$M_{\rm eff} = \sum P_T^{\rm jet,i} + \sum P_T^{\rm lep,i} + E_T^{\rm miss}$$





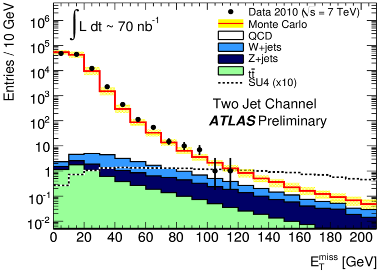
- Optimize $M_{\rm eff}$ cut to maximize the significance.
- Expected uncertainty ∼50%@1fb
- 4jet+0/1 lepton channels have the best discovery potential
- 5σ discovery potential for squarks and gluinos up to ∼700GeV

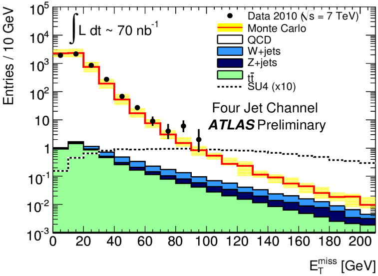
SUSY : 0Lepton + Jets + E_T^{miss}

4 channels : Veto events if there are any e/μ with pt$>$10GeV

Number of jets	Monojets	≥ 2 jets	≥ 3 jets	≥ 4 jets
Leading jet p_T (GeV) Subsequent jets p_T (GeV)	> 70 veto if > 30	> 70 > 30	> 70 > 30 (Jets 2 and 3)	> 70 > 30 (Jets 2 to 4)
E_T^{miss} $\Delta\phi(\text{jet}_i, \vec{E}_T^{miss})$	> 40 GeV no cut	> 40 GeV $[> 0.2, > 0.2]$	> 40 GeV $[> 0.2, > 0.2, > 0.2]$	> 40 GeV $[> 0.2, > 0.2, > 0.2, > 0]$
$E_T^{miss} > f \times M_{eff}$	no cut	$f = 0.3$	$f = 0.25$	$f = 0.2$

After preselection (70 nb^{-1})

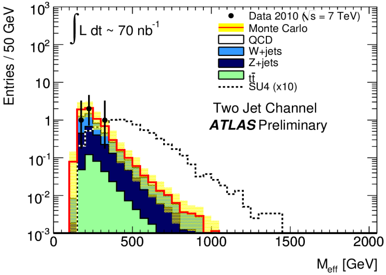


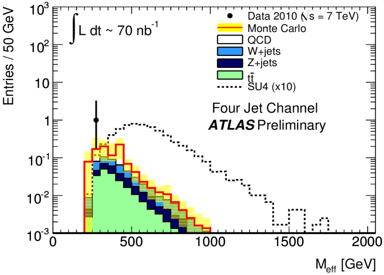


- MC normalized to data with number of events in Control region
- Good description of E_T^{miss} shape by MC (QCD)

SUSY : 0Lepton + Jets + E_T^{miss}

After final cuts (70 nb^{-1})





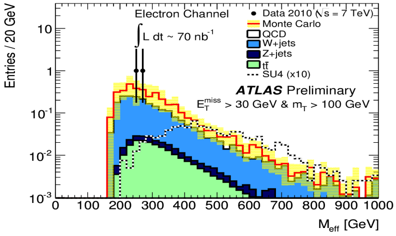
	Monojet		≥ 2 jets		≥ 3 jets		≥ 4 jets	
	Data	Monte Carlo	Data	Monte Carlo	Data	Monte Carlo	Data	Monte Carlo
After jet cuts	21 227	23000^{+7000}_{-6000}	108 239	$108\,000^{+31\,000}_{-25\,000}$	28 697	$31\,000^{+10000}_{-8000}$	5329	5600^{+2300}_{-1600}
$\cap\ E_T^{miss}$ cut	73	46^{+22}_{-14}	650	450^{+190}_{-120}	325	230^{+100}_{-70}	116	84^{+45}_{-30}
$\cap\ \Delta\phi$ and E_T^{miss} cuts	–	–	280	200^{+110}_{-65}	136	100^{+55}_{-30}	54	43^{+26}_{-16}
$\cap\ E_T^{miss}/M_{eff}$, $\Delta\phi$ and E_T^{miss} cuts	–	–	4	6.6 ± 3	0	1.9 ± 0.9	1	1.0 ± 0.6

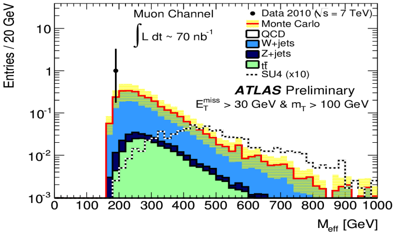
- Good description of E_T^{miss} and M_{eff} shapes by MC (QCD)
- The number of events are consistent bewteen data and MC prediction.

SUSY : 1Lepton + 2Jet + E_T^{miss}

- 1 isolated lepton with pt>20GeV, no further lepton with pt>10GeV 2Jets

After final cuts (70 nb^{-1})



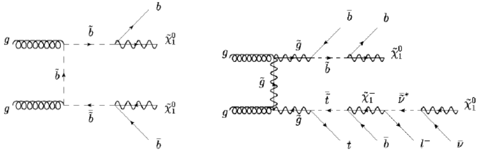


	Electron channel		Muon channel	
Selection	Data	Monte Carlo	Data	Monte Carlo
$p_T(\ell) > 20$ GeV $\cap$ ≥ 2 jets with $p_T > 30$ GeV	143	157 ± 85	40	37 ± 14
$\cap\ E_T^{miss} > 30$ GeV	13	16 ± 7	17	15 ± 7
$\cap\ m_T > 100$ GeV	2	3.6 ± 1.6	1	2.8 ± 1.2

- MC (QCD, W+Jets) normalized to data with different control regions
- Good description of shapes and event number by MC.
- The background can be controlled !

SUSY : b-jets + E_T^{miss}

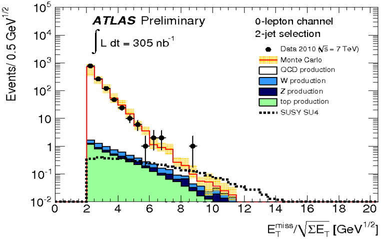
- In MSSM, the production of the third generation squarks could be favoured

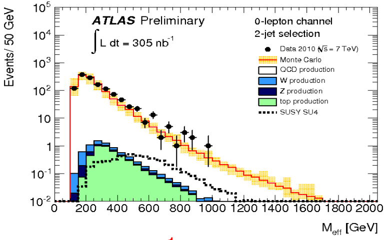


- b-jets are copiously produced and significant E_T^{miss}
  - Lifetime-base secondary vertex b-tagging algorithm
  - decay length significance : $L/\sigma > 6$, ε_{bjet} : 45 ∼50%, $\varepsilon_{light-jet}$: 1 ∼2%
- The presence of lepton depends on the sparticle mass spectrum.
- Performed analysis with lepton or w/o lepton

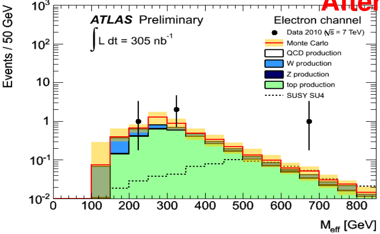
0-lepton	Electron	Muon
No lepton ($p_T > 10$ GeV)	≥ 1 electron ($p_T > 20$ GeV)	≥ 1 muon ($p_T > 20$ GeV)
2-jet: jet $p_T > (70, 30)$ GeV	jet $p_T > (30, 30)$ GeV	jet $p_T > (30, 30)$ GeV
3-jet: 3rd jet $p_T > 30$ GeV	-	-
$E_T^{miss}/\sqrt{\sum E_T} > 2$ GeV$^{1/2}$		
At least 1 b-tagged jet ($L/\sigma(L) > 6$, $p_T > 30$ GeV)		

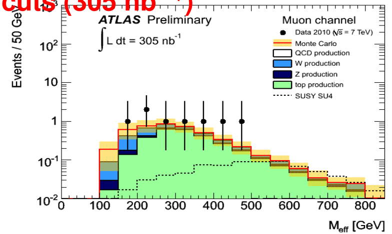
SUSY : b-jets + E_T^{miss}





After final cuts (305 nb^{-1})

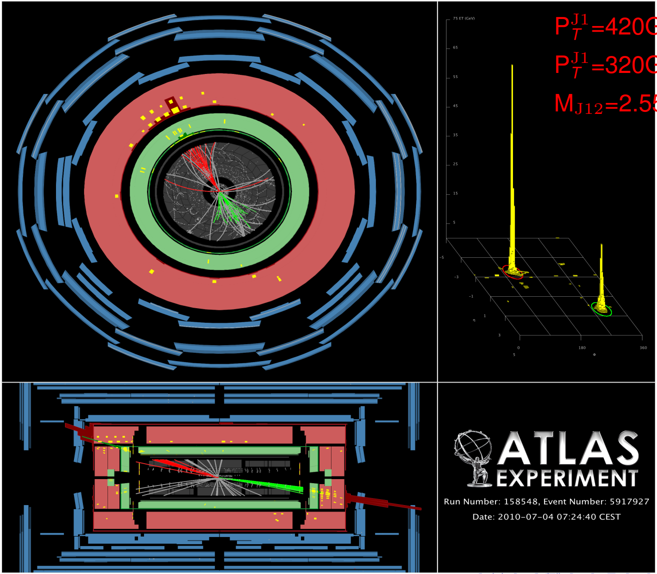




- MC normalized to data in the control region.
- The numbers of observed events are consistent with MC prediction.
- Distributions consistent with MC expectation.

Exotics Results

Exotics : Dijet resonance searches



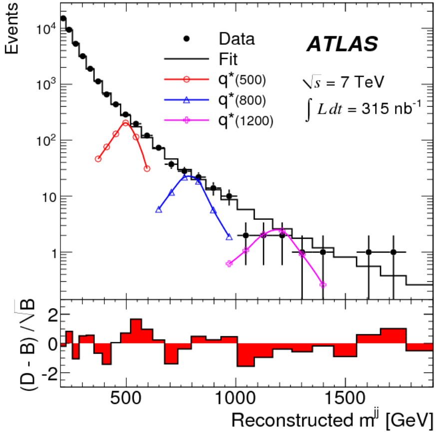
Exitocs : Dijet resonance searches

- Parton resonances decaying to dijet :
  - Excited Quarks
  - Axigluons
  - RS Gravitons
  - ...
- We study the inclusive dijet final state using dijet mass spectrum
  - provides a test of QCD
  - sensitivity to these new models.
- Observable :

$$m_{jj} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

- Benchmark signal : Excited quark q^*
  - Current Limit from Tevatron : $m_{q*} >$870GeV at 95% CL
    [CDF collaboration, PRD79 (2009) 112002]

Exotics : Dijet resonance searches



Fit the background shape with :

$$f(x) = p_0 \frac{(1-x)^{p_1}}{x^{p_2+p_3 \ln(x)}},$$

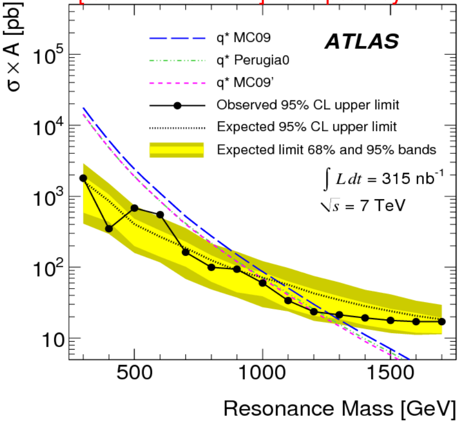
$$x = m_{jj}/\sqrt{s}$$

Also used in PRD 79 (2009) 112002.

- Data well described by smooth fit function
  - χ^2/NDF=22/22
  - Six statistical tests reveal no significant narrow resonance.
- Bayesian approach was employed to set limits on q^* mass at 95% CL.

Exotics : Dijet resonance searches

[arXiv:1008.2461] Accepted by PRL



Excluded with 95% CL :

- **0.4TeV$<m_{q^*}<$1.26TeV, ATLAS default MC settings with MRST2007 LO**
- **0.4TeV$<m_{q^*}<$1.20TeV, MC09' setting with CTEQ6L1**
- **First ATLAS search result that surpass world's best limit**

Exotics : Dijet angle distribution searches

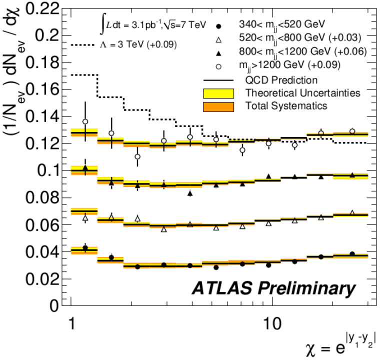
- Exotic physics processes : mainly *s*-channel
- QCD process : mainly *t*-channel
- Observables:

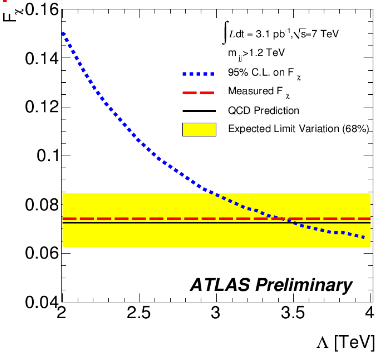
$$\chi = \exp(|\mathrm{y1} - \mathrm{y2}|), \quad \text{Centrality ration } \mathrm{R_C} = \frac{\mathrm{N}(|\eta_{1,2}| < 0.7)}{\mathrm{N}(0.7 < |\eta_{1,2}| < 1.3)}$$

- Both observables produce flat distributions for QCD
- New physics signals are expected to have :
  - an excess of events at low χ in bins of dijet mass, and
  - a rise in η ratio at high dijet masses.
- Benchmark signal : Quark contact interaction.

Exotics : χ angle distribution searches

Lumi = 3.1 pb^{-1}

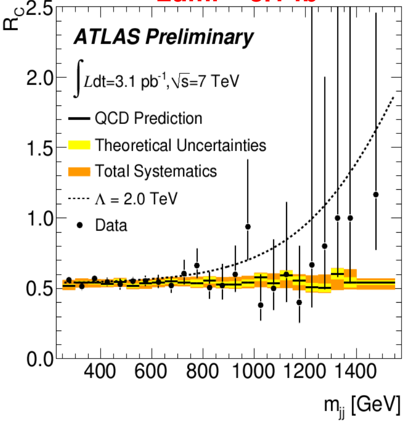




- Data well described by SM prediction, no significant new physics
- F_χ = The event number in the first four χ bin / The number in all χ bin
- Limit on compositeness scale Λ of 3.4TeV at 95% CL, corresponding to a distance scale of 6×10^{-6}fm
- Surpass the world's best limit 2.8TeV [D0 Collab., PRL 103:191803, 2009]

Exotics : Central ratio R_C distribution searches

Lumi = 3.1 fb^{-1}



Central ratio : $R_C = \frac{N(|j_{1,2}|<0.7)}{N(0.7<|j_{1,2}|<1.3)}$

Data shows good agreement with QCD predictions :

- χ^2/NDF=0.61

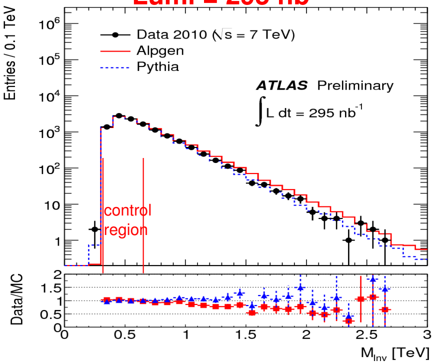
- Slightly favors a compositeness scale of 2.9TeV over pure QCD prediction, but not statistically significant.
- Limit on compositeness scale Λ of 2.0TeV at 95% CL

Exotics : High invariant mass, Multi-object search

- The fundamental scale of gravity M_D :
  - in TeV range in extra dimensions model
- Low-scale gravity models predict gravitational states :
  - Decay to all degrees of freedom in SM democratically
  - Several high-pt objects
  - Deviation from SM in the high invariant mass

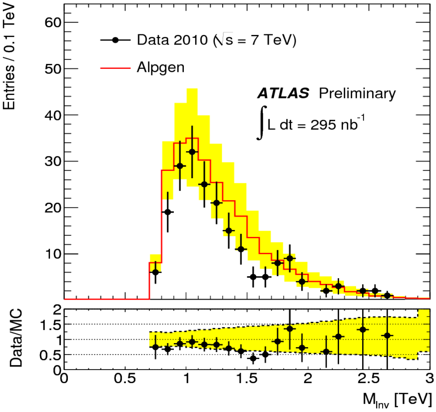
- Benchmark : TeV Gravity models (e.g. Black holes, string balls)
- Observables : nobj≥3
  - $M_{inv} = \sqrt{\sum E_i^2 - \sum \vec{P}_i^2}$
  - sumPt = $\sum P_{Ti}$
- Control region :
  - sumPt>300GeV
  - 300GeV$<M_{inv}<$700GeV

Lumi = 295 nb^{-1}



Exotics : High invariant mass, Multi-object search

Lumi = 295 nb^{-1}



Signal region :

- sumPt$>$ 700GeV
- $M_{\rm inv}$ $>$800GeV

Results :

- Observe 193 events in the SR
- Consistent with the estimated background 254$\pm$18$\pm$84
- An upper limit of 0.34nb on $\sigma \times A$ at 95%CL with Bayesian approach

This type of search was done for the first time !!!

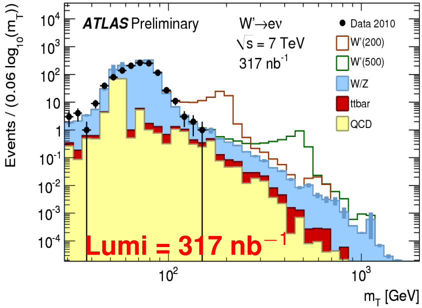
Exotics : Electron + E_T^{miss} Search

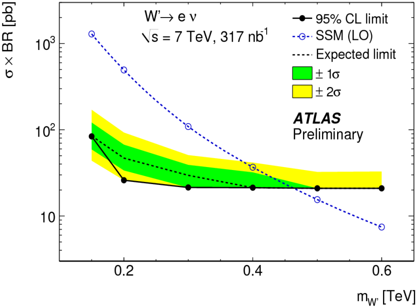
Benchmark signal : W' Boson

- High pt isolated lepton
- High E_T^{miss}

Observable :

$$M_T = \sqrt{2p_{Tl}E_T^{miss}(1 - \cos\Delta\phi_{l,E_T^{miss}})}$$





- Data is Consistent with SM predictions.
- Current limit that can be set (electrons) 465GeV for SSM W'.
- Expect to surpass the current best limits on W' (1TeV) with 10pb^{-1} data

Conclusions

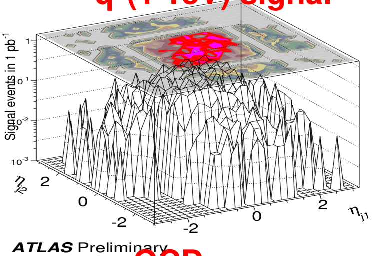
- ATLAS has started to explore physics in new territory!
  - Preliminary results show that data is consistent with SM predictions.
  - SUSY search with loose threshold :
    - The good level of understanding of the ATLAS performance
  - Dijet resonance search :
    - Exclude **0.4TeV**$<$**m**$_q^*$ $<$**1.26TeV**
    - Surpassed world's best limit, paper accepted by PRL.
  - Dijet angle distribution search :
    - Limit on **compositeness scale** Λ **3.4TeV**
    - Surpass the current best limit
  - Multi-object search :
    - **The upper limit of 0.34nb** with $\mathrm{M_{inv}} > 800 GeV$, sumPt>700GeV
    - First time!, sensitive to black hole, string ball search
  - Electron + $\mathrm{E_T^{miss}}$ search :
    - Limit on **SSM W' 465GeV**
    - Expect 10pb^{-1} to surpass the current best limit
- Important benchmark searches like Z',Supersymmetry etc ... are underway.
  - Searches use high-pt jets, muons, electrons, photons, b-tagging, $\mathrm{E_T^{miss}}$
  - More LHC data on the way, new exciting results are in the pipe-line.

Extra slides

Dijet resonance searches

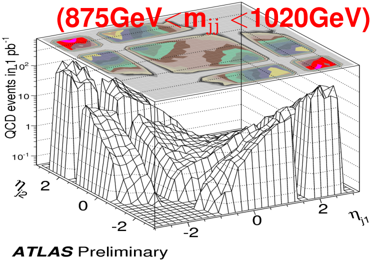
- Jet reconstruction algorithm : Anti-Kt with R=0.6
- Events accepted by single jet trigger
- Jet1 : $P_T > 80$GeV,
  Jet2 : $P_T > 30$GeV
- Remove event if leading or next leading jet in $1.3 < |\eta| < 1.8$
- Jet1 : $|\eta| < 2.5$
  Jet2 : $|\eta| < 2.5$
- $\Delta\eta < 1.3$,
  QCD jets are forward(large $|\Delta\eta|$), signal is more central

q^*(1 TeV) signal

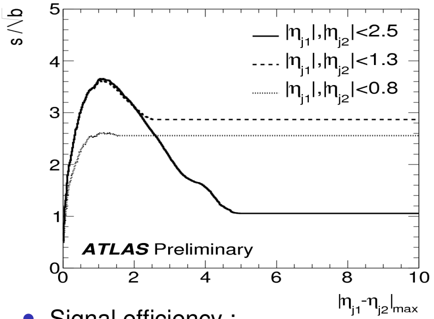


QCD

(875GeV$< m_{jj} <$1020GeV)



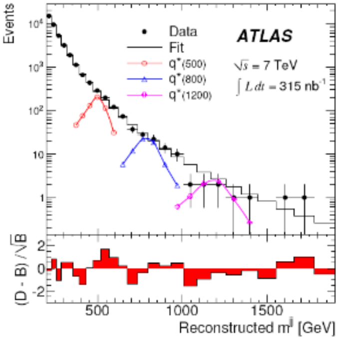
DiJet resonance search

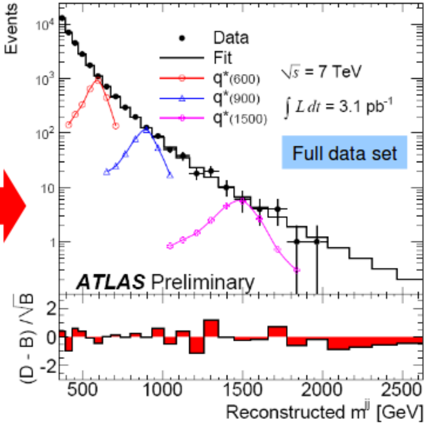


- Signal efficiency :
  - 36% $\sim$ 400GeV, 49%$\sim$ 1.5TeV
- Systematic Uncertainties :
  - Jet energy scale (dominant)
  - Background fit parameters
  - Integrated luminosity
  - Jet energy resolution (small)

- Six statical test :
  - BumpHunter
  - Jeffreys divergence
  - Kolmogoriv-Smirnov test
  - Likelihood
  - Pearson χ^2
  - TailHunter statistic
- The p-value of the backround only hypothesis is defined as the fracion of the pseudo-experiments that results in a value of given statistics greater than the value of the same statics found by the fit to the data.

DiJet resonance search



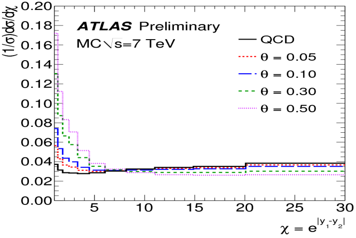


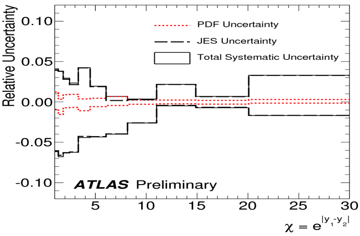
- With 10x as much data the expected limit moves from 1.06 TeV to 1.51 TeV and the observed limit moves from 1.26 TeV to 1.53 TeV.
  - We raised the jet requirement to $p_T(j_1)$ > 150 GeV to match the evolving trigger.

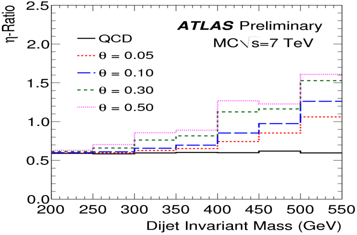
Dijet angle distribution searches

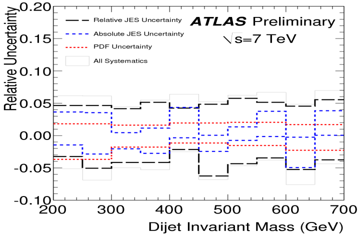
- Observables:
  - χ is boost invariant and relates to CM scattering angle θ^*
  - Observe dijet angle distribution binned in the χ variable and in dijet invariant mass $\mathrm{M_{jj}}$, η ratio distribution binned in $\mathrm{M_{jj}}$.
- Goal : Look for evidence of new physics from angle distribution deviations from the behavior expected from QCD.
  - benchmark : quark contact interations
- Further Events selections:
  - $|y_{1,2}| < |y|_{max}, \ |y|_{max} = 2.45$
  - $|y_1 - y_2| < 2|y_{max}|$-1.5, $\ |y_1 + y_2| < 1.5$

DiJet angle search







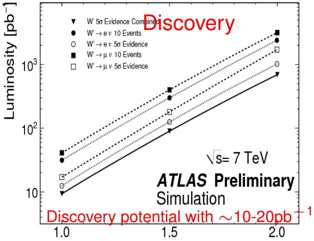


High invariant mass, Multi-object search

- In extra dimensions model, the fundamental scale of gravity, M_D is expected to be in TeV range.
  - Some low-scale gravity models predict a continuum production of mon-perturbative gravitational states above the new mass threshold.
  - Rely on a few basic assumptions for the behaviour of final states arising from gravity in the quantum regime, we expect deviation from the SM in the high invariant mass distribution of several high-pt objects.
  - Since gravity couples only to the energy-momentum content of matter, the decays of strong gravitational objects are approximately democratic to all degrees of freedom in the SM

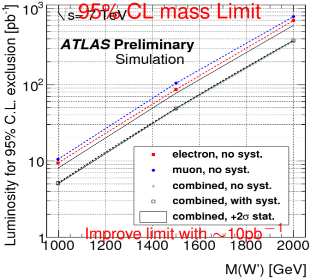
Lepton + MET Search

- Heavy gauge bosons are predicted by many extension theories of the SM



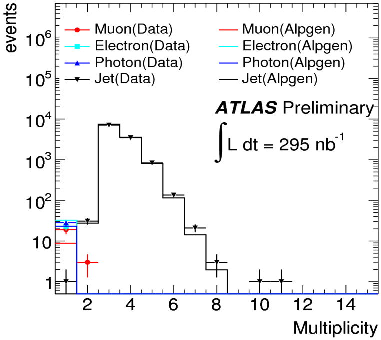
- Goals:
  - Discovery !!!
  - If no, set a limit on W' mass
  - Limit : $M_{W'} > 1.0$TeV at 95% CL.

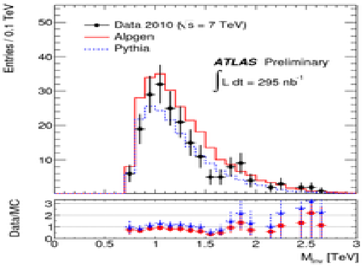
    D0 Collaboration, PRL. 100 (2008) 031804
- Event Selections
  - High p_T isolated lepton (>25GeV)
  - High E_TMiss (>25GeV)
- Background :
  - high M_T tail of SM W
  - ttbar, dijets, Drell-Yan

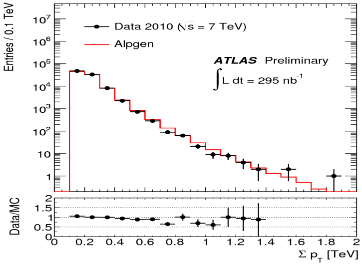


High invariant mass, Multi-object search

- Objects are :
  - certral jets (pt>40GeV)
  - e/γ (pt>20GeV)
  - μ (pt>20GeV)
  - MET, only used in M_{inv}

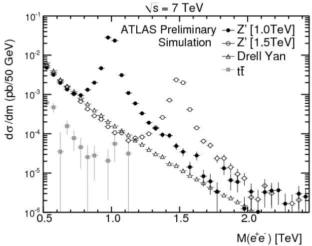






DiLepton Search

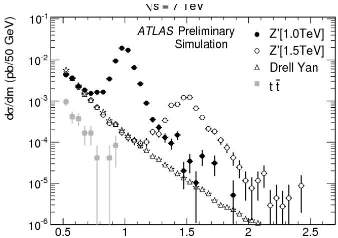
- Because of the historic importance, dilepton as a discovery channel, and the simplicity of the final status, the channel is be very important to study with early ATLAS data.



- Benchmark signal: Z' Boson
  - Current limit from CDF $M_{Z'} > 1$TeV
- Observable : Invariant mass

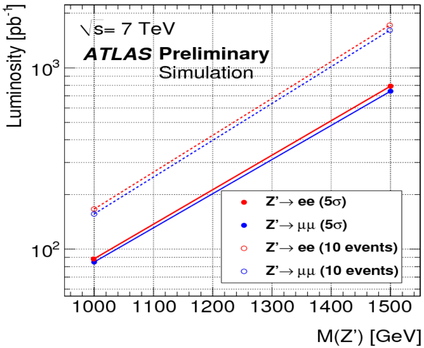
$$M_{l^+l^-} = \sqrt{(E_{l^+} + E_{l^-})^2 - (\tilde{P}_{l^+} + \tilde{P}_{l^-})^2}$$

- Event selections :
  - Two high-pt isolated leptons (pt>20GeV)
  - Lepton $|\eta| < 2.5$
  - Different change
- Main background :
  - High mass Drell-Yan

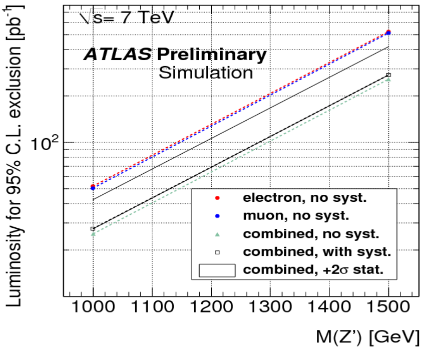


DiLepton Search

Discovery



95% CL mass Limit



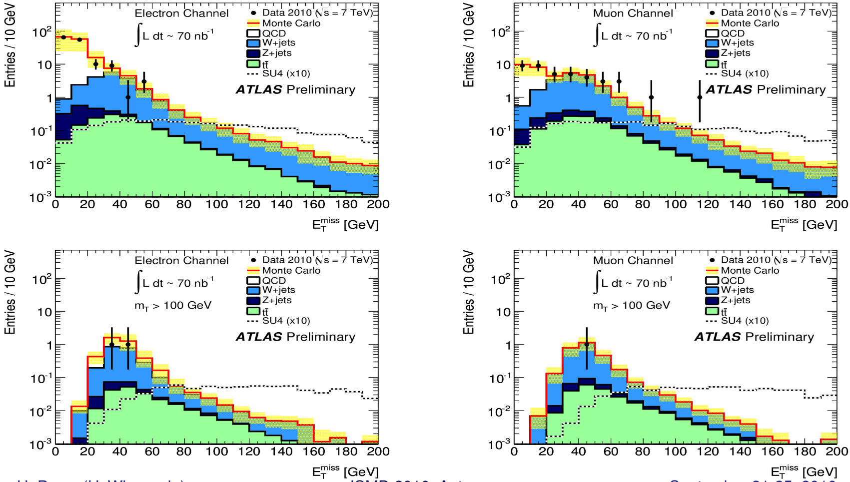
Discovery potential with $\sim$100pb^{-1}(2011)

Improve limit with $\sim$30pb^{-1}

SUSY : 1Lep + 2Jet + E_T^{miss}

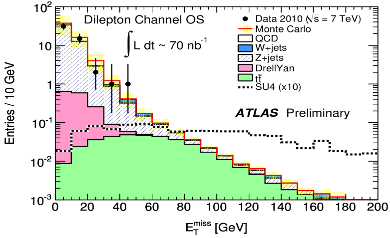
Control Regions :

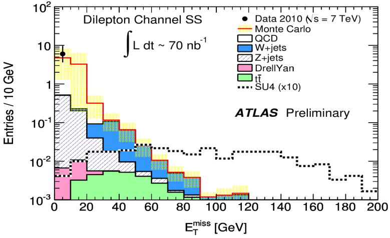
- QCD : m_T <40GeV, E_T^{miss} < 40GeV
- W+Jet : 30GeV< E_T^{miss} < 50GeV, 40< m_T <80GeV



SUSY : 2Lep + E_T^{miss}

- Data (70nb^{-1})
- Exactly 2 isolate lep with pt1$>$ 20GeV, pt2$>$ 10GeV
- Control Regions :
  - QCD : 5$<m_{ll}$ $<$15GeV, E_T^{miss} $<$ 15GeV
  - W+Jet : 30GeV$<$ E_T^{miss} $<$ 50GeV, 40$<m_T$ $<$80GeV
- 2 Event with different sign pass the cuts with lepton and E_T^{miss} $>$30GeV, consistent with expectation 2.0$\pm$0.8 from SM
- 0 Event with same sign pass cuts.





SUSY : b-jet + 0lep + E_T^{miss}

- Normalization of QCD background :
  - Control region : events pass dijet cuts, and MetSig$<$2GeV$^{1/2}$

Selection	data	QCD	data/QCD
MetSig < 2 GeV$^{1/2}$ (inclusive)	463180	752913	0.61
MetSig < 2 GeV$^{1/2}$ (≥ 1 b-tag jet)	28638	42562	0.67

- expected events in 2Jets:

2-jet selection	data	Standard Model expectation	SU4
Jets $p_T > (70, 30)$ GeV	474243	$(4.7^{+2.1}_{-1.9}) \cdot 10^5$	9.95$\pm$0.06
MetSig > 2 GeV$^{1/2}$	11190	$(1.1^{+0.5}_{-0.6}) \cdot 10^4$	8.71$\pm$0.06
At least 1 b-tagged jet	1253	1190 ± 430	4.23$\pm$0.04

2-jet selection	QCD	W+jets	Z+jets	top
Jets $p_T > (70, 30)$ GeV	$(4.72 \pm 0.01) \cdot 10^5$	71.1 ± 0.3	28.6 ± 0.2	26.4 ± 0.07
MetSig > 2 GeV$^{1/2}$	$(1.11 \pm 0.02) \cdot 10^4$	47.4 ± 0.2	19.3 ± 0.2	6.73 ± 0.02
At least 1 b-tagged jet	1181 ± 36	2.18 ± 0.04	0.74 ± 0.03	4.51 ± 0.02

- After 3 Jets : data 429 events; MC : 400$\pm$160

SUSY : b-jet + 1 Lepton + E_T^{miss}

- Normalization of QCD background :
  - Control region : events pass 1lepton + 2 jet cuts, MetSig$<$2GeV$^{1/2}$, M$_T$ $<$40GeV

Selection	data	QCD	non-QCD	(data – non-QCD) /QCD
Electron channel	353	1070$\pm$170	7.23$\pm$0.07	0.32 $\pm$0.05
Electron channel after b-tagging	15	70$\pm$20	0.65$\pm$0.01	0.21 $\pm$ 0.08
Muon channel	70	143$\pm$5	5.07$\pm$0.06	0.45$\pm$0.05
Muon channel after b-tagging	9	29$\pm$2	0.55$\pm$0.01	0.30$\pm$ 0.10

- Expected events in electron channel :

Electron channel	data	Standard Model	SU4
$\geq$ 1 electron and 2 jets $p_T > (30, 30)$ GeV	557	520^{+360}_{-330}	1.65 $\pm$ 0.02
MetSig $>$ 2 GeV$^{1/2}$	31	39^{+28}_{-20}	1.40 $\pm$ 0.02
At least 1 b-tagged jet	4	$4.8^{+1.7}_{-1.5}$	0.81 $\pm$ 0.02

Electron channel	QCD	W+jets	Z+jets	top
$\geq$ 1 electron and 2 jets $p_T > (30, 30)$ GeV	470 $\pm$ 57	38.3 $\pm$ 0.2	8.42 $\pm$ 0.08	7.22 $\pm$ 0.02
MetSig $>$ 2 GeV$^{1/2}$	8.0 $\pm$ 1.0	25.4 $\pm$ 0.1	1.20 $\pm$ 0.03	4.67 $\pm$ 0.01
At least 1 b-tagged jet	0.78 $\pm$ 0.31	1.00 $\pm$ 0.03	0.10 $\pm$ 0.01	2.95 $\pm$ 0.01

SUSY : b-jet + 1 Lepton + E_T^{miss}

- Expected events in muon channel :

Muon channel	data	Standard Model	SU4
≥ 1 muon and 2 jets $p_T > (30, 30)$ GeV	138	130^{+70}_{-60}	1.58 ± 0.02
MetSig > 2 GeV$^{1/2}$	40	37^{+28}_{-19}	1.34 ± 0.02
At least 1 b-tagged jet	8	$4.7^{+1.7}_{-1.5}$	0.80 ± 0.02

Muon channel	QCD	W+jets	Z+jets	top
≥ 1 muon and 2 jets $p_T > (30, 30)$ GeV	74.4 ± 2.3	38.5 ± 0.2	7.14 ± 0.07	6.77 ± 0.02
MetSig > 2 GeV$^{1/2}$	1.7 ± 0.3	27.9 ± 0.1	2.83 ± 0.05	4.60 ± 0.01
At least 1 b-tagged jet	0.49 ± 0.14	1.09 ± 0.03	0.20 ± 0.01	2.93 ± 0.01