A search for Supersymmetric Particles in events with two leptons and Etmiss with the ATLAS experiment at the LHC

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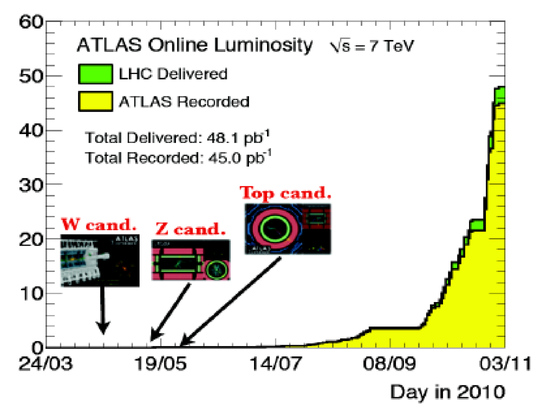
Introduction

The two-lepton signature is a very promising venue for the discovery and measurement of Supersymmetry. Many studies have been devoted to this signature in the last fifteen years. The channels characterized by the presence of two leptons in the final state are the best channels for the measurement of SUSY particle properties. The two-lepton signature typically suffers from lower statistics than the zero lepton and one lepton analyses. On the other hand, there are advantages due to the reduced Standard Model background.

The 2010 ATLAS pp data



2010 was a great year!

- Calibrating ATLAS
- "Rediscovering" the SM: W, Z and top candidates

The road to the discovery of Supersymmetry is started...(if SUSY exists)!

The analyses are based on 34.3 pb^{-1}

Standard Model background

SM dilepton sources are:
- Z/γ -> ll + jets [partially data-driven estimate]
- ttbar (fully dileptonic) [partially data-driven estimate]
- Di-bosons WW, WZ, ZZ [only MC]
- Fakes (one or both leptons not from heavy objects: W, QCD, semi-leptonic ttbar) [fully data-driven estimate]
- Cosmics [fully data-driven estimate]

SS channel
- Fakes dominate ee and co-dominates eμ, μμ (in particular semi-leptonic ttbar where the second lepton comes from a *b*.)
- WZ/ZZ can produce SS when 1/2 leptons are lost
- Charge-flip (of e) mainly in di-leptonic ttbar

OS channel
- ttbar dominates, has real MET
- (Z important in ee)

Flavour-subtracted OS channel
- ttbar subtracts to 0 (but large statistical uncertainty)
- Z/γ^*, WZ, fakes and ttbar similar size at this luminosity

Background determination: ttbar

Contransverse mass tagger

- For two identical decays of heavy particles δ into two invisible particles (or -aggregates) α, and visible particles χ_i, as in

$$t\bar{t} \to (W^+b)(W^-\bar{b}) \to (\ell^+\nu_\ell b)(\ell^-\bar{\nu}_\ell\bar{b})$$

the contransverse mass m_{CT} is defined by

$$m_{CT}^2(\chi_1,\chi_2) = [E_T(\chi_1)+E_T(\chi_2)]^2 - [\vec{p}_T(\chi_1)+\vec{p}_T(\chi_2)]^2$$

where χ_i can then be a lepton, a jet or a lepton-jet combination, giving three m_{CT} variables (per leg assignment):

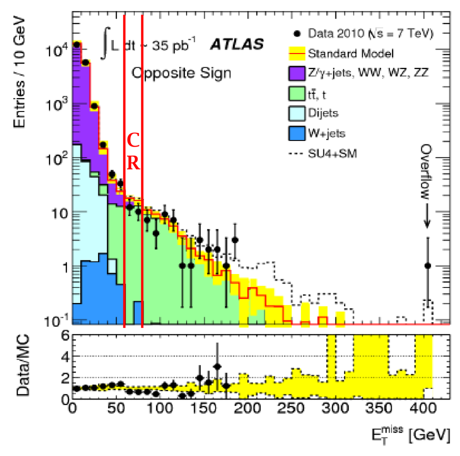
$$m_{CT}(\ell,\ell),\ \ m_{CT}(j,j),\ \ m_{CT}(j\ell,j\ell)$$

- The values are then compared to appropriate distributions and the various leg assignments are rejected or accepted as compatible with dileptonic ttbar
- If at least one leg fulfills this condition, the event is top-tagged

Estimation procedure

- Define a ttbar-dominated CR region
  - Based on the contransverse mass tagger
  - 60 GeV < MET < 80 GeV
- Estimate non-top background in the CR region
- Apply MC to find the ratio of ttbar events in the SR and the CR region
- Get estimated number of ttbar events in SR from simple scaling, e.g. for ee

$$(N_{tt})_{SRee} = \left((N^{tag}_{data})_{CR} - (N^{tag}_{non-tt,MC})_{CR}\right)\frac{(N_{top,MC})_{SRee}}{(N^{tag}_{top,MC})_{CR}}$$



Results

MC dileptonic ttbar has a top-tagging efficiency of 83% both for CR and for SR

Data CR: 15 top-tagged events
MC CR: 21.3±3.8 (18.8 from ttbar)

The estimation in SR (MET>100GeV) gives:

Data SR: 13.8 + 5.6 – 5.3
MC SR: 20.5 ± 4.8

And for MET>150GeV:

Data SR: 2.8 + 1.4 – 1.3
MC SR: 4.2 ± 1.2

In presence of low-mass SUSY the ttbar background is overestimated by 10-15% reducing the significance for signal discovery

Background determination: fakes

Estimation done for 6 combinations:
(SS, OS) x (*ee, μμ, eμ*)
- SS: fake contribution dominant. Well described.
- OS: fake contribution less important

Matrix method

- Define two lepton definitions/qualities, one "loose" (L), the other "tight" (T).
- Define a "real" region where leptons (R) are expected to be real (from Z, W)
- Define a "fake" region where leptons (F) are expected to be from jets
- Find the probability that a real/fake lepton also passes the tight definition. This gives the real and fake efficiency ("rate"), r and f.
- Then count the number of TT, TL, LT and LL in the Signal Region of the analysis
- Invert the matrix and get the number of RR, RF, FR and FF events in the SR.

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} rr & rf & fr & ff \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

The method is validated with collision data, in a control region where one of the two electrons has E_T between 10 GeV and 20 GeV and the other still has E_T above 20 GeV.

- For MET>100 GeV, no event is observed; the estimation is 0.05 ± 0.05(stat) ± 0.02(sys) events

Background determination: cosmic muons

Cosmic muons enter the analysis in:
- eμ, if a cosmic muons is incident with a collision event
- $\mu^+\mu^-$ if both incoming and outgoing is reconstructed within the same event

Estimation method

- Use the transverse impact parameter in an additional "quality" cut to select cosmic muons; "cosmic-loose" and "cosmic-tight" (passing this new cut)
- obtain cosmic and collider efficiencies for "cosmic-loose" to also be "cosmic-tight" from calo-stream and MC
- The number of cosmic events in SR are estimated for the eμ and μμ channels using matrix methods.

Results

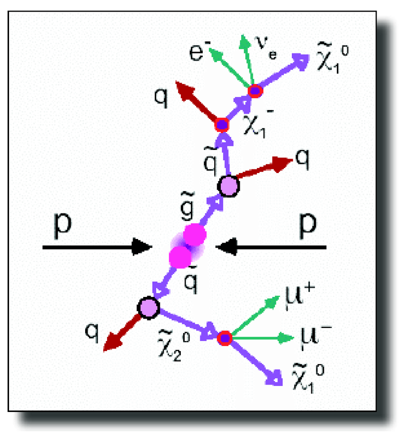
- Consistent with zero, but considerable uncertainty
- Upper bound: N_{cos} < 1.32 at 68% CL, N_{cos} < 3.45 at 95% CL

Cuts	Data	Estimated cosmics
OS $e\mu$	131	-3.14 ± 3.34
$E_T^{miss} > 100GeV$	13	0.42 ± 1.07
$E_T^{miss} > 150GeV$	4	-0.20 ± 1.18
SS $e\mu$	5	0.69 ± 1.04
$E_T^{miss} > 80GeV$	0	0 ± 1.17
$E_T^{miss} > 100GeV$	0	0 ± 1.17

Cuts	Data	2 cosmics	1 cosmic
OS $\mu\mu$	12772	9.39 ± 3.19	86.63 ± 11.49
$E_T^{miss} > 100GeV$	13	0.03 ± 1.20	-1.39 ± 1.43
$E_T^{miss} > 150GeV$	4	0.01 ± 1.20	-0.43 ± 1.27
SS $\mu\mu$	3	2.12 ± 1.50	-0.29 ± 1.29
$E_T^{miss} > 80GeV$	0	0 ± 1.20	0 ± 1.24
$E_T^{miss} > 100GeV$	0	0 ± 1.20	0 ± 1.24

Supersymmetry signature

- Inclusive SUSY search strategy relies on fairly general features:
  - SUSY production at collider dominated by squark and gluino production
  - In many model gluinos/squarks are the heaviest and decay through complex cascades involving charginos and neutralinos
  - gluino/squark decays give rise to (high pt) jets
  - neutralinos/charginos often decay via emission of leptons
  - if the conservation of R-parity is assumed, sparticles are produced in couples and LSP is stable, neutral and escaping detector.
- Generic signature, covering a large classe of models and with a good rejection of SM background, is:
  - transverse momentum **jets**
  - possibly some **leptons**
  - large **missing transverse energy**



The main source of dilepton events is the decay of neutralinos and charginos

a) $\tilde{\chi}_i^0 \to \ell^\pm \nu \tilde{\chi}_j^\mp$

b) $\tilde{\chi}_i^\pm \to \ell^\pm \nu \tilde{\chi}_j^0$

c) $\tilde{\chi}_i^0 \to \ell^\pm \ell^\mp \tilde{\chi}_j^0$

d) $\tilde{\chi}_i^\pm \to \ell^\pm \ell^\mp \tilde{\chi}_j^\pm$

- A two-lepton event can be obtained either through decays c) and d) on a single leg or decays a) and b) on both legs.
- The two final state leptons can have equal or opposite sign, and equal or different flavour, thus yielding four possible configurations.

This feature has been exploited by developing three independent analyses:

1) One analysis searches for same-sign lepton pairs (SS)

2) The second analysis searches for inclusive opposite-sign leptons (OS)

3) A 'flavour subtraction' analysis searching an excess of same-flavour over different-flavour events with two OS leptons

Limit setting

- For quantifying the agreement between observed data and the prediction from Standard Model physics or specific SUSY models we used a profile log likelihood ratio (LLR) test.
- A profile LLR is obtained from a likelihood defined for each specific analysis. Defined the signal enriched region (SR) as well as control regions (CRs) dominated by the various components of SM background that reach the SR, we can write a generic likelihood function as the product of a Poisson distribution for the SR, optional Poisson distributions for CRs, and of additional distributions that implement the constraints on systematic uncertainties.

$$L(\boldsymbol{n},\boldsymbol{\theta}^0|\mu,\boldsymbol{b},\boldsymbol{\theta}) = P_{SR} \times P_{CR} \times P_{Syst}$$

$$= P(n_S|\lambda_S(\mu,\boldsymbol{b},\boldsymbol{\theta})) \times \prod_{i\in CS} P(n_i|\lambda_i(\mu,\boldsymbol{b},\boldsymbol{\theta})) \times P_{Syst}(\boldsymbol{\theta}^0,\boldsymbol{\theta}).$$

where n_s and n_i are the number of observed events in the signal region and each control region i, λ_s and λ_i are the Poisson expectations depending on
- background normalization factors **b** for various sources such as QCD jets or W+jets
- nuisance parameters **θ** that parameterize systematic uncertainties
- a signal normalization factor μ, also called the signal strength. For μ = 0 the signal component is turned off, and for μ = 1 the signal expectation equals the nominal value of the model under consideration.

Systematic uncertainties are included using the probability density function $P_{Syst}(\boldsymbol{\theta}^0,\boldsymbol{\theta})$ where $\boldsymbol{\theta}^0$ are the nominal values around which **θ** can be varied.

- The statistical treatment is based on the profile LLR, defined as

$$\Lambda(\mu) \equiv \Lambda(\mu,\boldsymbol{n},\boldsymbol{\theta}^0) \equiv -2\left(\ln L\left(\boldsymbol{n},\boldsymbol{\theta}^0 \mid \mu,\hat{\hat{\boldsymbol{b}}},\hat{\hat{\boldsymbol{\theta}}}\right) - \ln L\left(\boldsymbol{n},\boldsymbol{\theta}^0 \mid \hat{\mu},\hat{\boldsymbol{b}},\hat{\boldsymbol{\theta}}\right)\right)$$

where $\hat{\mu},\hat{\boldsymbol{b}},\hat{\boldsymbol{\theta}}$ maximize the likelihood function, and $\hat{\hat{\boldsymbol{b}}},\hat{\hat{\boldsymbol{\theta}}}$ maximize the likelihood for the specific, fixed value of the signal strength μ, and the data $\mathbf{n}$, $\boldsymbol{\theta}^0$

Only signal hypotheses that lead to a positive number of observed events are considered, that is if $\hat{\mu} < 0$, a fit with fixed $\hat{\mu} = 0$ is used.

- Defining P_{χ^2} as giving the one-sided p value for a given χ^2, the test statistic for upper limits is defined as

$$q_\mu \equiv \begin{cases} P_{\chi^2}(\Lambda(\hat{\mu})) & \hat{\mu} \ge \mu \\ 1-P_{\chi^2}(\Lambda(\hat{\mu})) & \hat{\mu} < \mu \end{cases} \qquad q_0 \equiv \begin{cases} P_{\chi^2}(\Lambda(\hat{\mu})) & \hat{\mu} < 0 \\ 1-P_{\chi^2}(\Lambda(\hat{\mu})) & \hat{\mu} \ge 0 \end{cases}$$

for a signal SUSY hypothesis (left, generally μ=1) and SM hypothesis (right, μ=0).
- It is the approximate p-value for the agreement between the SUSY signal (Standard Model) and the experimental data
- Models with p-values smaller than 0.05 are said to be excluded with 95% confidence level.

Flavour subtraction (OS)

- At the base of this method there is the observation that the dominant SM OS dilepton mechanisms, ttbar, gives uncorrelated (OS) di-leptons and that the combinations come in equal rates, SF = DF.
- This gives opportunity to subtract one with the other.
- Useful if a signal is expected in SF
- So, we can estimate the excess of SF events after the "flavour subtraction" as

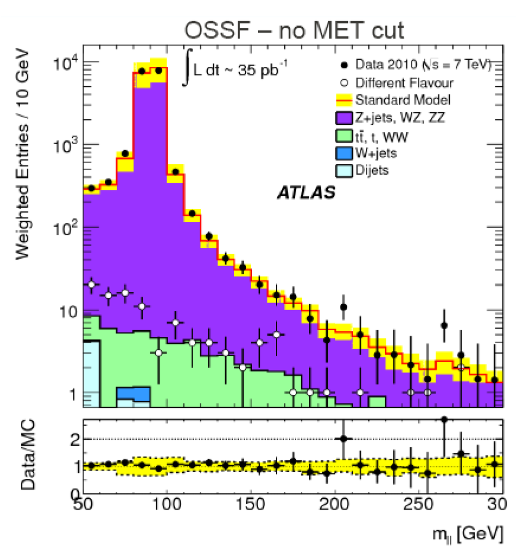
$$S = \frac{N(e^\pm e^\mp)}{\beta(1-(1-\tau_e)^2)} - \frac{N(e^\pm\mu^\mp)}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^\pm\mu^\mp)}{(1-(1-\tau_\mu)^2)}$$

which takes into account the differences in both reconstruction efficiencies ε $\left(\beta = \varepsilon_e/\varepsilon_\mu\right)$ and trigger efficiencies τ between muons and electrons.

For data we have:

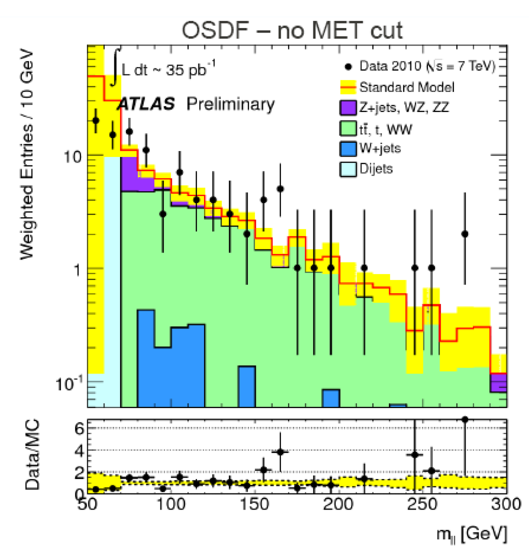
$$\beta = 0.69(\pm 0.3), \quad \tau_e = 98.5(\pm 1.1)\%, \quad \tau_\mu = 83.7(\pm 1.9)\%$$

OSSF – no MET cut



OSSF: Z totally dominates before MET cut

OSDF – no MET cut



OSDF: ttbar main background above certain m(ll)

Note the approximate equality between OSSF and OSDF ttbar
Events are appropriately weighted with β, τ_e and τ_μ

MC predictions (34.3 pb^{-1})

	$e^\pm e^\mp$	$e^\pm\mu^\mp$	$\mu^\pm\mu^\mp$
$t\bar{t}$	3.7±0.3	9.8±0.5	7.0±0.4
Dibosons	0.30±0.02	0.36±0.03	0.61±0.03
Drell Yan	0±0	0±0	0±0
Z+jets	0.4±0.2	0.4±0.2	1.0±0.3
W+jets	0±0	0±0	0±0
Dijets	0±0	0±0	0±0
Single Top	0±0	1±0	1±0
Total SM	4.5±0.4	11.3±0.6	9.2±0.6
MSSM27	13.8±1.2	4.5±0.7	16.2±1.3
Data	4+3.2-1.9	13+4.7-3.6	13+4.7-3.6

MET>100GeV

	$\mathcal{S}$	Total sys.	stat.
$t\bar{t}$	0.52	0.53	0.76
Dibosons	0.51	0.12	0.043
Drell Yan	0	0	0
Z+jets	0.89	0.54	0.35
W+jets	0	0	0
Dijets	0	0	0
Single Top	-0.096	0.081	0.23

$$\mathcal{S}_{MC} = 1.8 \pm 1.1(\text{sys.}) \pm 0.87(\text{stat.})$$

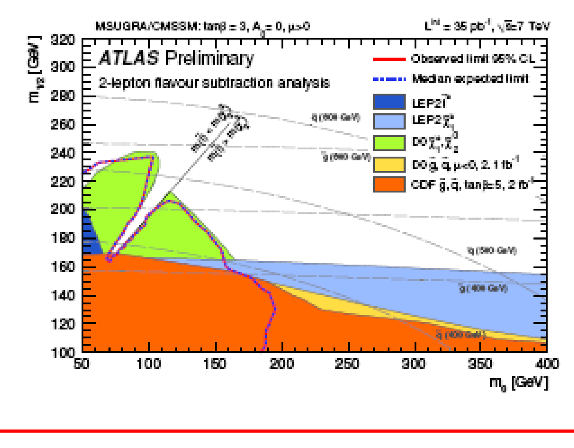
$$\mathcal{S}_{obs.} = 1.98 \pm 0.15(sys._\beta) \pm 0.02(sys._{\tau_e}) \pm 0.06(sys._{\tau\mu})$$

-ttbar: still some, but subtracts to zero

-Diboson: significant in all channels, also after flavour subtraction

- Others (including Z): nearly consistent with zero

- Some excess in data relative to SM estimation, eμ and μμ, not present after flavour-subtraction



Selections and signal region

The three dilepton analyses share common object definitions, a common set of event selection criteria and where appropriate they share common background estimation techniques. The only difference in event selection between the opposite-sign and same-sign analyses is the different charge requirements on the leptons in the pairs.

Primary vertex
- At least 1 good vertex with N_{tracks}>4

Jets
- anti-k_T, R=0.4
- p_T > 20 GeV, |η|<2.5
- Reject events compatible with noise or cosmics

Missing E_T
- Calculated from objects and clusters

Electrons
- p_T > 20 GeV, |η|<2.47
- reject events if electron candidates are in transition region (1.37<|η|<1.52)

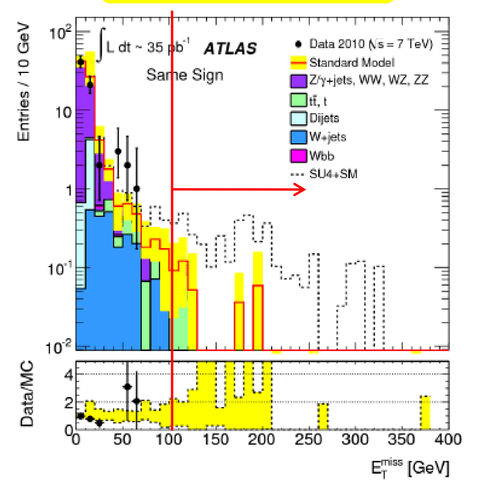
Muons
- p_T > 20 GeV, |η|<2.4
- combined/extrapolated info from ID and Muon spectrometer
- Sum p_T of tracks <1.8 GeV in ΔR<0.2

Remove overlapping objects
- If ΔR(jet,e)<0.2, remove jet
- If 0.2<ΔR(jet,e)<0.4, veto electron
- If ΔR(jet,μ)<0.4, veto muon

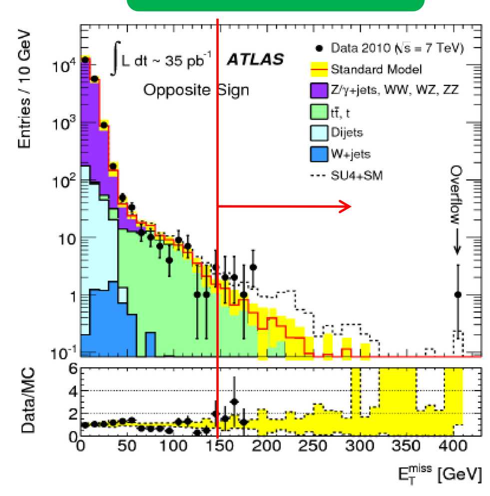
For selecting the interested topologies we request exactly 2 leptons with m(ll)>5GeV

The signals regions used in these analysis are all simple high missing transverse energy regions.

SS
MET > 100 GeV



OS
MET > 150 GeV

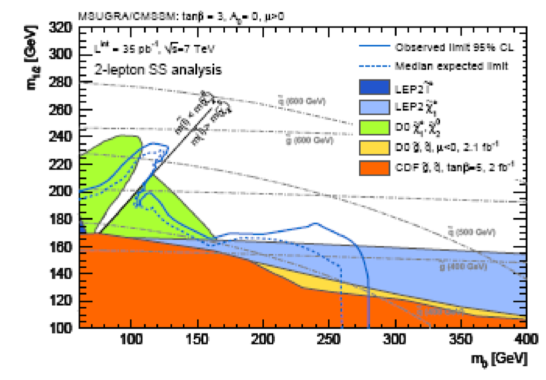


SS results

The number of observed and expected events for each SS channel in the MET > 100 GeV signal region at 34.3 pb^{-1} is shown in the table

	Data(Observed)	Fake background (estimated)	Diboson (expected)	$t\bar{t}$ (charge-flip)
$e^\pm e^\mp$	0	0.12±0.12±0.05	0.015±0.004 ±0.003	0.019 ± 0.001 ± 0.008
$\mu^\pm\mu^\pm$	0	0.014±0.01±0.005	0.035 ±0.005 ±0.011	0.0
$e^\pm\mu^\mp$	0	0.03±0.026±0.005(el)±0.009(μ)	0.021 ±0.0.004±0.0.008	0.026 ± 0.001 ± 0.011

None event expected and none event observed!
By comparing the SM expectations with the numbers of events observed in the SS channel, we put 95% confidence limits on the 'effective cross section' (cross section times branching ratio times acceptance) for new physics processes producing SS lepton pairs and MET of 0.07 pb.



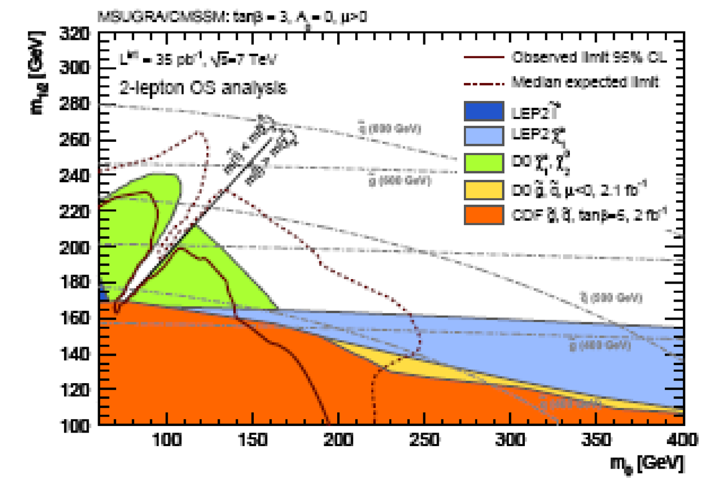
OS results

MET>100GeV	e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$
Data,	4	13	13
$t\bar{t}$	$2.50^{+1.03}_{-0.96}$	$6.61^{+2.72}_{-2.52}$	$4.71^{+1.87}_{-1.80}$
Z+jets	0.37 ± 0.15	0.36 ± 0.13	0.91 ± 0.26
fakes	0.31 ± 0.24	-0.15 ± 0.46	0.01 ± 0.01
single top	0.13 ± 0.08	0.70 ± 0.21	0.67 ± 0.20
WW+WZ+ZZ	0.30 ± 0.15	0.36 ± 0.18	0.61 ± 0.30
cosmics	0	0.42 ± 1.07	-1.39 ± 1.43
total	$3.56^{+1.24}_{-1.12}$(uncorr.)±0.36(corr.)	$8.23^{+3.21}_{-2.72}$(uncorr.)±0.94(corr.)	$6.82^{+2.57}_{-1.93}$(uncorr.)±0.67(corr.)

MET>150GeV	e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$
Data	1	4	4
$t\bar{t}$	$0.62^{+0.31}_{-0.28}$	$1.24^{+0.62}_{-0.56}$	$1.00^{+0.50}_{-0.45}$
Z+jets	0.19 ± 0.15	0.08 ± 0.08	$0.14^{+0.17}_{-0.14}$
fakes	-0.02 ± 0.02	-0.05 ± 0.04	0
single top	$0.03^{+0.05}_{-0.03}$	$0.06^{+0.08}_{-0.06}$	0.10 ± 0.07
WW+WZ+ZZ	0.09 ± 0.03	0.06 ± 0.03	0.15 ± 0.03
cosmics	0	-0.20 ± 0.18	-0.43 ± 1.27
total	$0.92^{+0.40}_{-0.34}$(uncorr.)±0.14(corr.)	$1.43^{+1.42}_{-0.48}$(uncorr.)±0.28(corr.)	$1.39^{+1.39}_{-0.48}$(uncorr.)±0.23(corr.)

Considering MET>150GeV, we observed 9 events when SM predicts 3.7 (+2.2 -0.9) events for 34.3 pb^{-1}. The excess is in eμ and μμ.
The probability for the SM background to exceed the number of observed events is 14% and 13% for eμ and μμ.

Limits can still be set on the existence of new physics which produces OS di-leptons (leptons with PT > 20 GeV and MET > 150 GeV) :
- ee: cross-section x BR x acceptance < 0.09 pb
- eμ: cross-section x BR x acceptance < 0.21 pb
- μμ: cross-section x BR x acceptance < 0.22 pb



Conclusions

I presented the details and results of three different searches for two-lepton, high missing transverse energy events. These three searches when carried out in parallel are sensitive to a variety of supersymmetric decays. These analyses observed no significant deviations from Standard Model predictions.
During the 2011 we hope to collect a fb^{-1} of data. In this way, we'll be able to extend the Tevatron limits on SUSY parameter space…

References

The ATLAS Collaboration, Search for an excess of events with an identical flavour lepton pair and significant missing transverse momentum in $\sqrt{s}$= 7 TeV proton-proton collisions with the ATLAS detector, ArXiv:1103.6208, submitted to EPJC

The ATLAS Collaboration, Search for supersymmetric particles in events with lepton pairs and large missing transverse momentum in $\sqrt{s}$= 7TeV proton-proton collisions at the ATLAS experiment , ArXiv:1103.6214, submitted to EPJC Letters

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