Search for supersymmetry in final states with multiple leptons and missing transverse energy with the ATLAS detector

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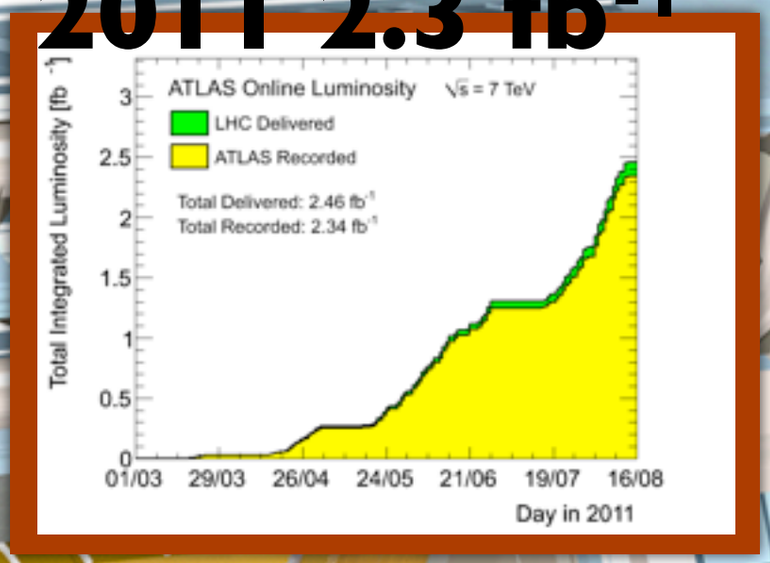
(University of Cambridge)
on behalf of the ATLAS Collaboration

SUSY'11
Fermilab, USA
28th August - 2nd September 2011

The ATLAS Experiment and the LHC

This year - 7 TeV proton-proton collisions at the LHC have already delivered more than 2 fb^{-1} of integrated luminosity!

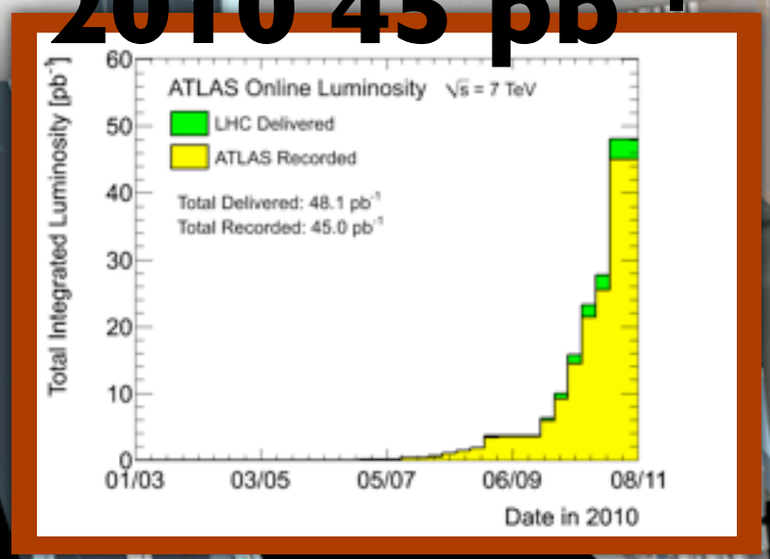
2011 2.3 fb^{-1}



The ATLAS Experiment has...

- an inner detector (composed of pixels, a silicon microstrip detector, and a transition radiation tracker)
- electromagnetic and hadronic calorimeters
- muon spectrometer
- an ambitious magnet system

2010 45 pb^{-1}



The ATLAS Experiment is designed to have...

- very good particle identification, jet resolution and missing energy resolution
- large coverage

Supersymmetry Search Results from ATLAS

Very many search results...

- analysis of 35 pb^{-1} of 2010 7 TeV collision data
- analysis of up to 1 fb^{-1} of 2011 7 TeV collision data

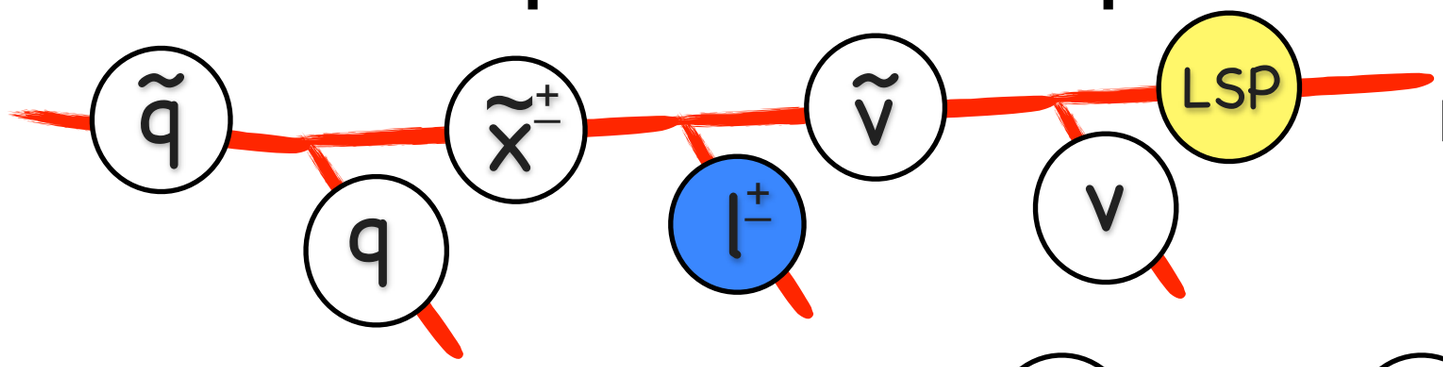
This talk focuses on multiple lepton searches in final states with missing transverse energy.

For all ATLAS supersymmetry search results see:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
(over 13 "CONF" notes and 9 papers)
and the many presentations this week.

Both R-parity conserving supersymmetry searches (like this), and R-parity violating supersymmetry searches

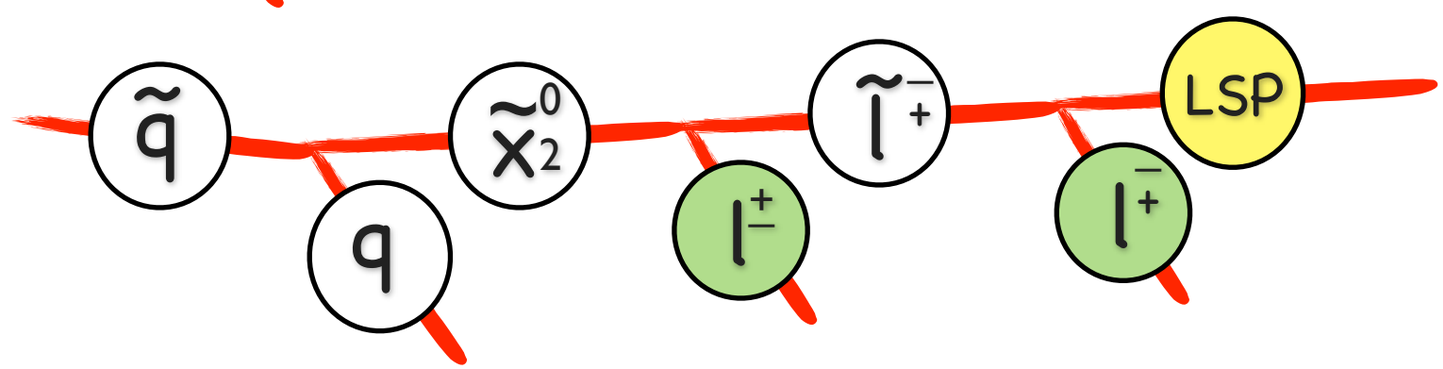
Multiple Lepton Search Results from ATLAS

Final state leptons can be produced in different ways...



LSP escapes undetected, giving rise to high missing transverse energy

- (a) $\tilde{\chi}_i^0 \to l^\pm \nu \tilde{\chi}_j^\mp$
- (b) $\tilde{\chi}_i^\pm \to l^\pm \nu \tilde{\chi}_j^0$
- (c) $\tilde{\chi}_i^0 \to l^\pm l^\mp \tilde{\chi}_j^0$
- (d) $\tilde{\chi}_i^\pm \to l^\pm l^\mp \tilde{\chi}_j^\pm$



(c) and (d) on a single-leg (opposite-sign)
(a) or (b) on both-legs (opposite-sign or same-sign)

Two categories of search in ATLAS...

NEW

Dilepton final states (opposite-sign and same-sign)

Multilepton final states (three or more leptons)

(electrons and muons)

Same-Sign Dilepton Search

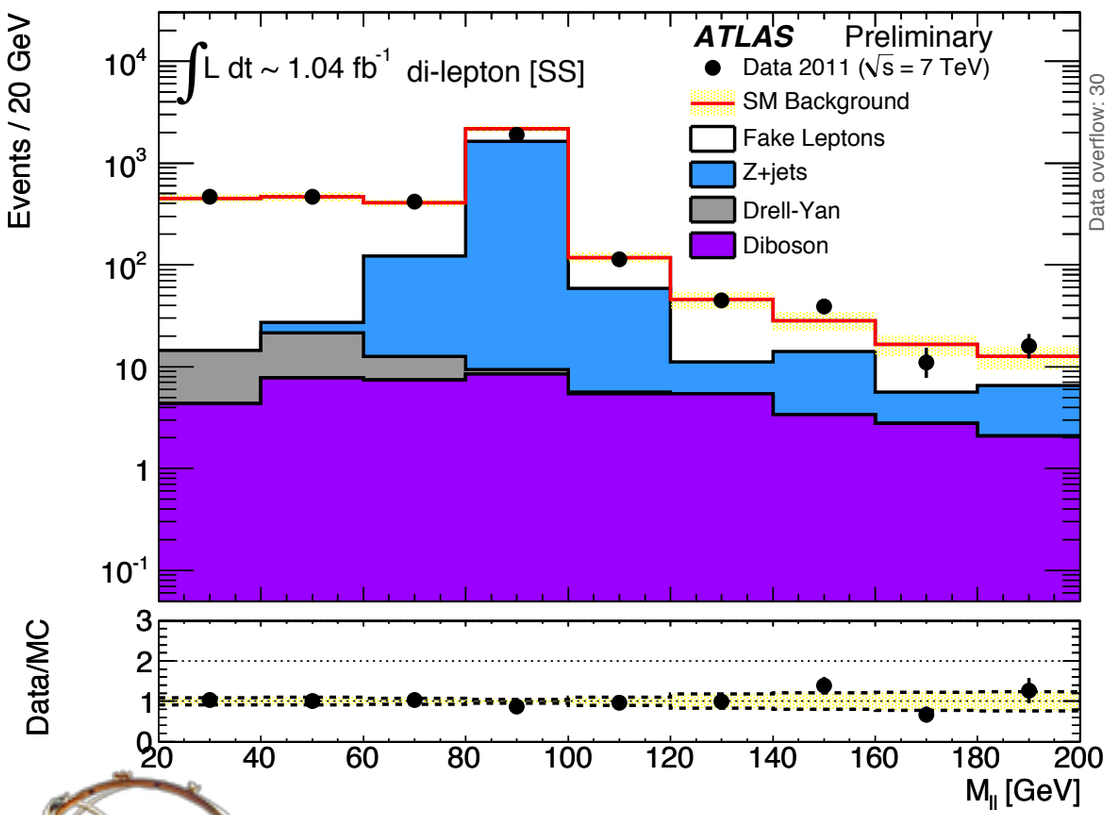
NEW

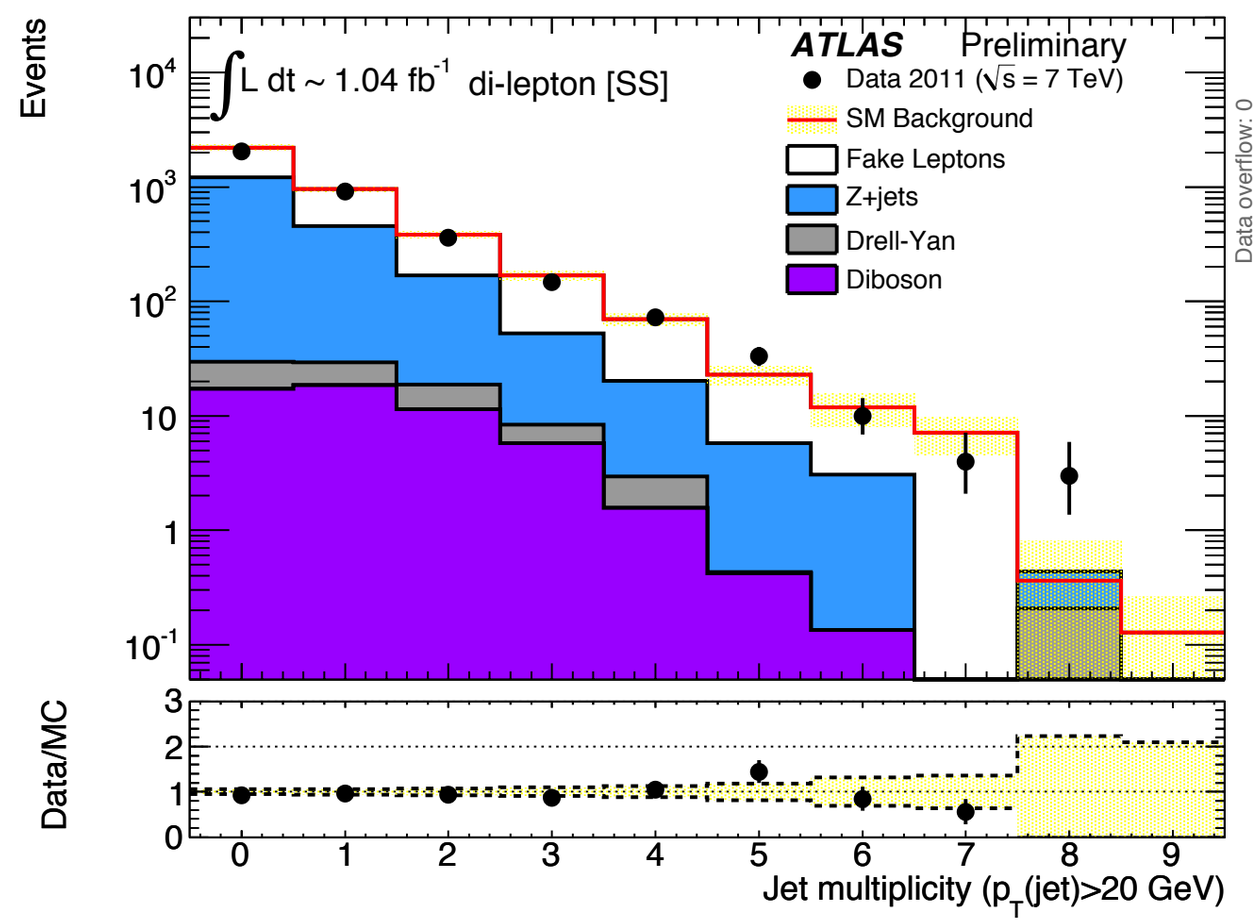
Latest 2011 Results 1.04 fb^{-1}

Search for exactly 2-leptons with same-sign and large missing transverse energy.

Electron p_T > 20 (25 if leading) GeV
Muon p_T > 10 (20 if leading) GeV
m_{ll} > 12 GeV

Events are triggered using the single electron and single muon triggers.





Good agreement between expectation and observation for a variety of event properties.

For 2010 Results, see:
EPJC 71 (2011) 1682

In figures:
All backgrounds MC normalised to luminosity x cross-section.
Except "Fake leptons" component, which is data-derived.

Same-Sign Dilepton Search

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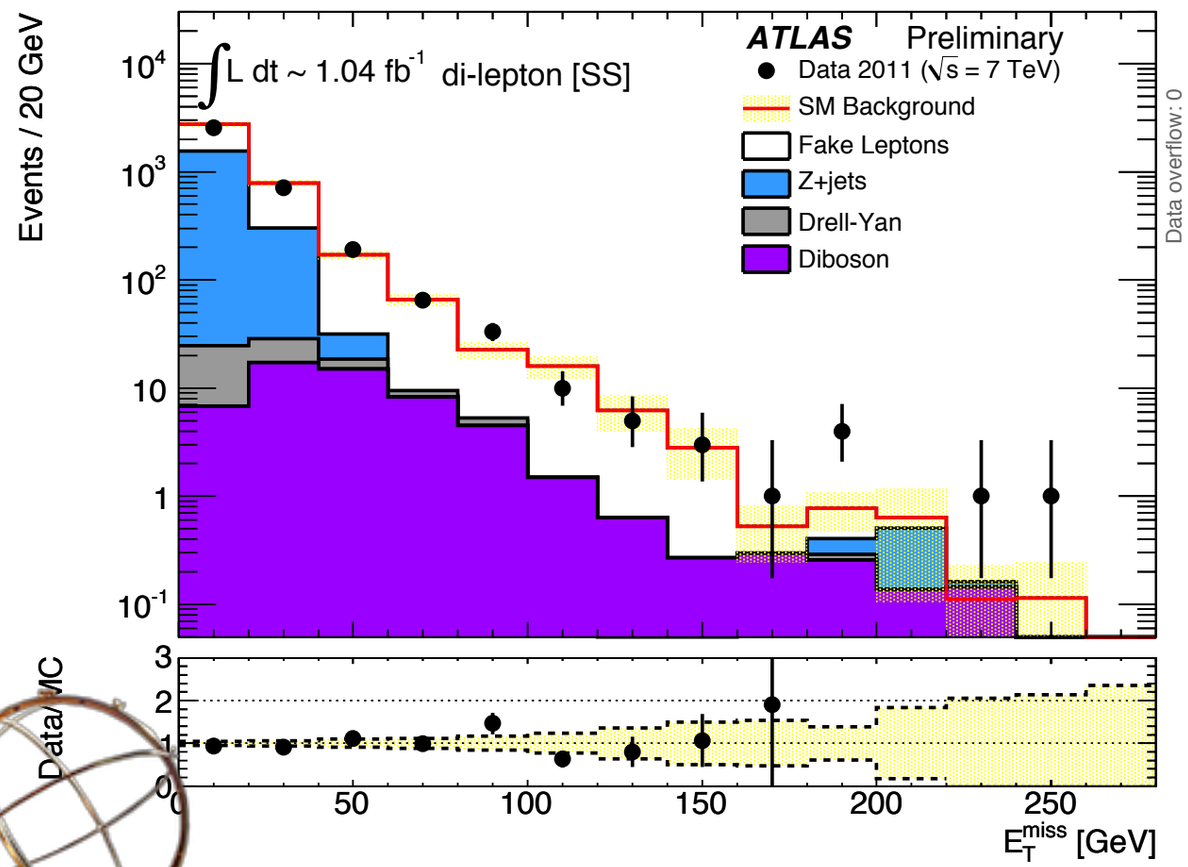
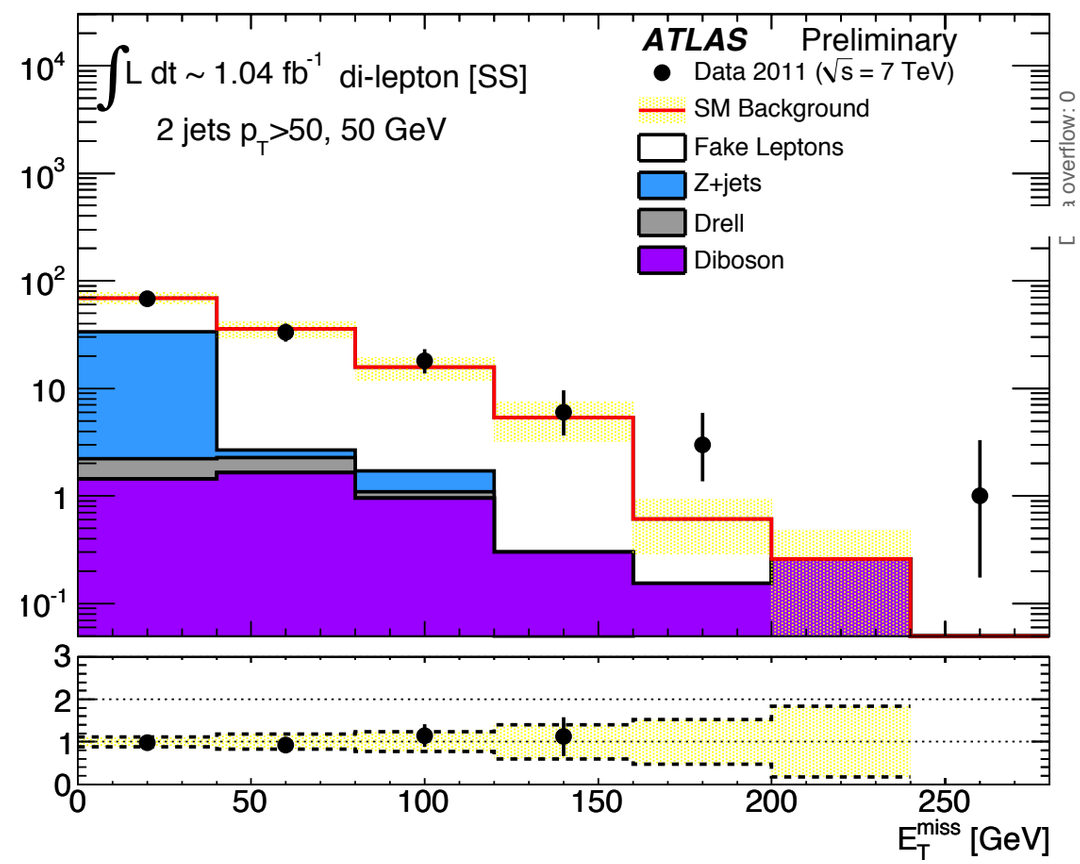
Latest 2011 Results 1.04 fb^{-1}

Two signal-regions...

1. $E_T^{miss} > 100$ GeV
2. $E_T^{miss} > 80$ GeV, 2 jets $p_T > 50,50$ GeV





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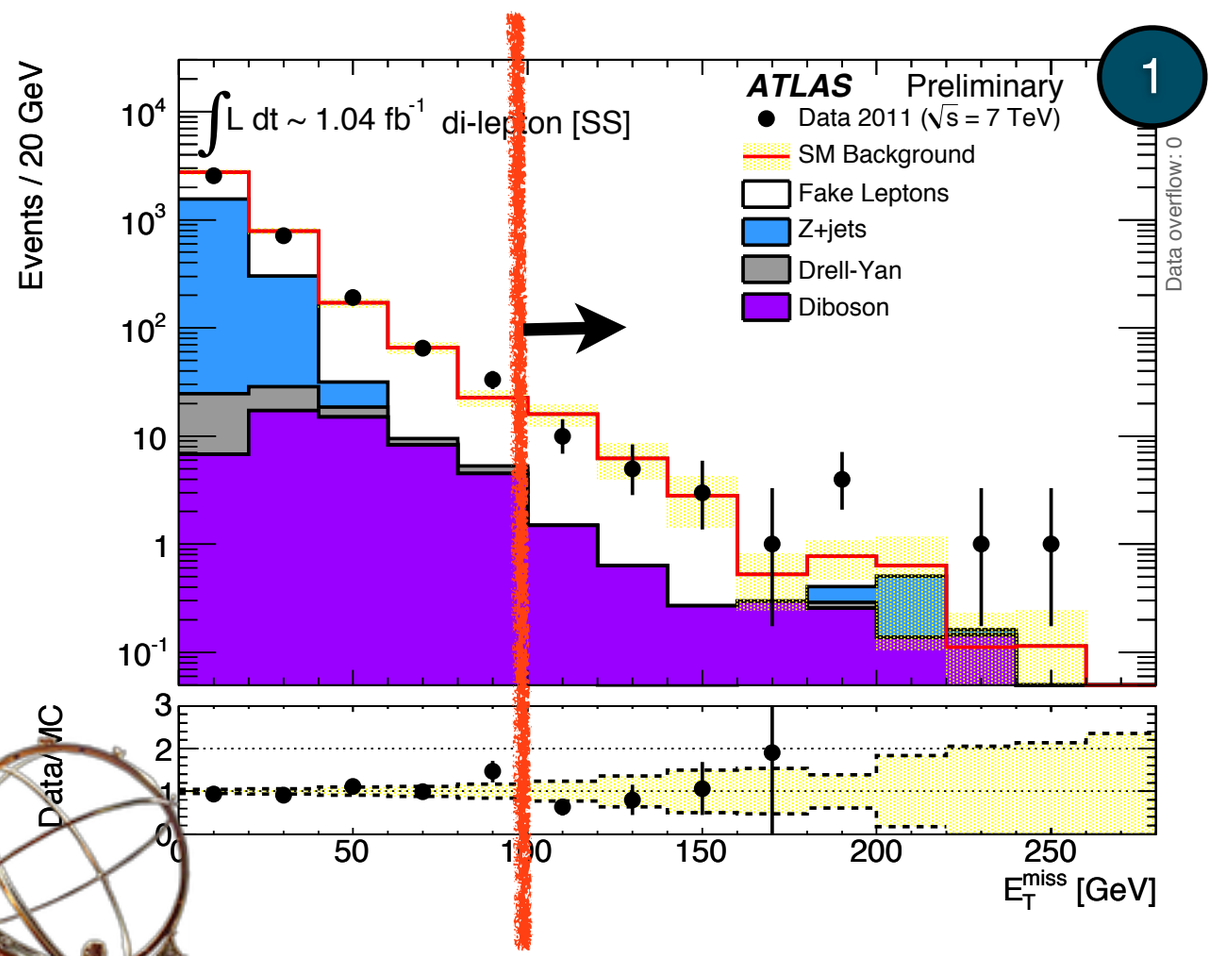

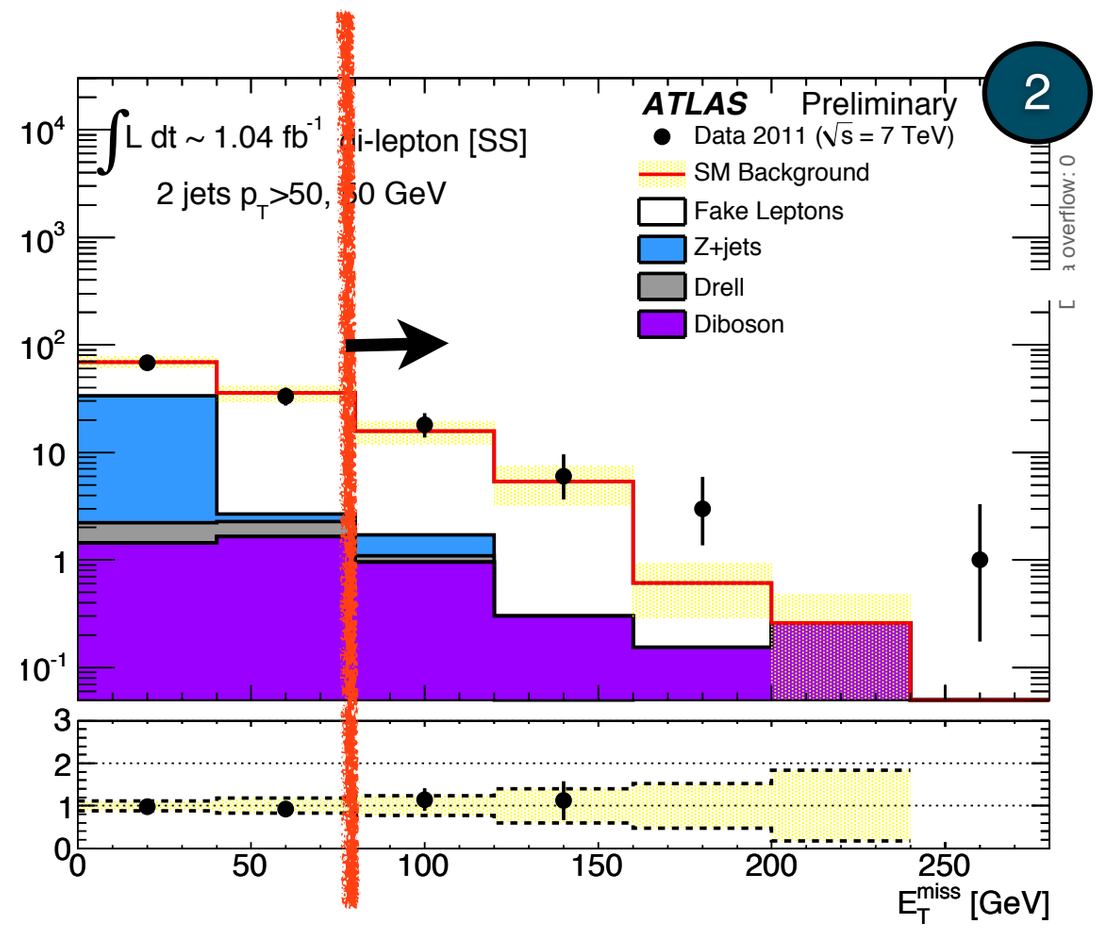

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Same-Sign Dilepton Search

NEW

Latest 2011 Results 1.04 fb^{-1}

Standard Model backgrounds -- events with fake leptons, charge misidentification and dibosons

- Background from fakes -- estimate using the "matrix-method"

  'N$_{FF}$' - light or heavy flavour jets

  'N$_{RF}$/N$_{FR}$' - $t\bar{t} \to b\ell\nu qq$, W+jets

  loosen lepton selection criteria, and call these leptons "loose" (signal leptons are "tight")
  measure 'r' (probability of real lepton R passing the "tight" reconstruction criteria)
  measure 'f' (probability of a fake lepton F passing the "tight" reconstruction criteria)
  count in the signal region the numbers of "loose-loose" (LL), "loose-tight" (LT), "tight-loose" (TL), "tight-tight" (TT) pairs

  invert this matrix to find N$_{RF}$+N$_{FR}$+N$_{FF}$ ("Fake lepton" background)

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

- Background from charge misidentification --

  calculate charge misidentification probability using Z Monte Carlo

  apply misidentification probabilities to $t\bar{t}$ Monte Carlo events

$$e^{\mp}_{\text{hard}} \to \gamma_{\text{hard}}\, e^{\mp}_{\text{soft}} \to e^{\mp}_{\text{soft}}\, e^{\mp}_{\text{soft}}\, e^{\pm}_{\text{hard}}$$

- Background from dibosons -- estimate using Monte Carlo

Same-Sign Dilepton Search

NEW

Latest 2011 Results 1.04 fb^{-1}

Limits on cross-section x A x e using CLs prescription

	Background	Obs.	95% C.L.
SS-SR1	$32.6 \pm 4.4 \pm 4.4$	25	10.2 fb
SS-SR2	$24.9 \pm 4.1 \pm 6.6$	28	20.3 fb

Same Sign [SS-SR1]	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Fake	$3.5\pm0.7\pm2.0$	$14.4\pm3.2\pm0.6$	$9.2\pm4.0\pm1.8$
Charge flip	$0.73\pm0.05\pm0.06$	$1.10\pm0.07\ \pm0.08$	*neg.*
Dibosons	$0.79\pm0.27\pm0.05$	$1.7\pm0.4\pm0.3$	$1.1\pm0.2\pm0.1$
Standard Model	$5.0\pm0.8\pm2.0$	$17.2\pm3.2\pm0.6$	$10.3\pm3.0\pm1.8$
Cosmics	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
Observed	6	14	5

Same Sign [SS-SR2]	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Fake	$1.5\pm0.5\pm2.0$	$13.4\pm3.2\pm2.7$	$6.7\pm2.5\pm1.8$
Charge flip	$0.59\pm0.04\pm0.04$	$1.36\pm0.05\pm0.06$	*neg.*
Dibosons	$0.25\pm0.06\pm0.13$	$0.9\pm0.2\pm0.2$	$0.64\pm0.05\pm0.02$
Standard Model	$2.4\pm0.5\pm2.0$	$15.6\pm3.2\pm2.7$	$6.9\pm2.5\pm1.8$
Cosmics	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
Observed	4	14	10

"Fake leptons" are the dominant background

(with small contributions from charge misidentification and dibosons)

Opposite-Sign Dilepton Search

NEW

Latest 2011 Results 1.04 fb^{-1}

Search for exactly 2-leptons with opposite-sign and large missing transverse energy.

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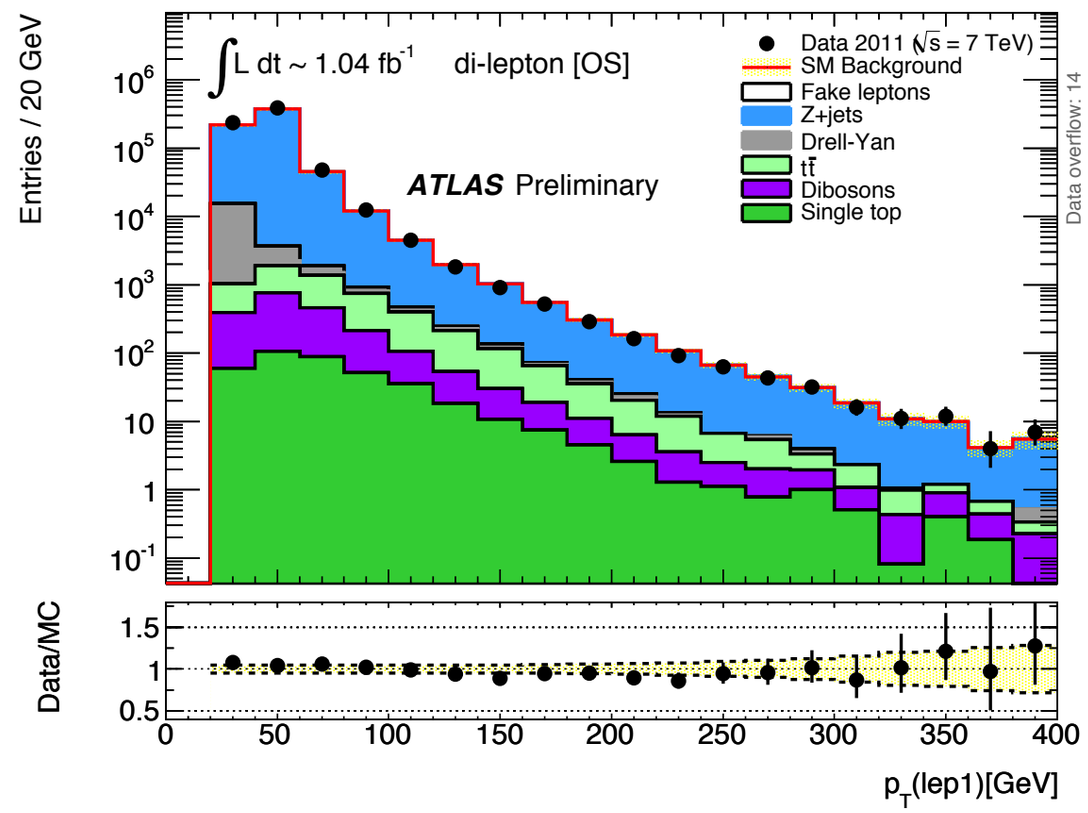

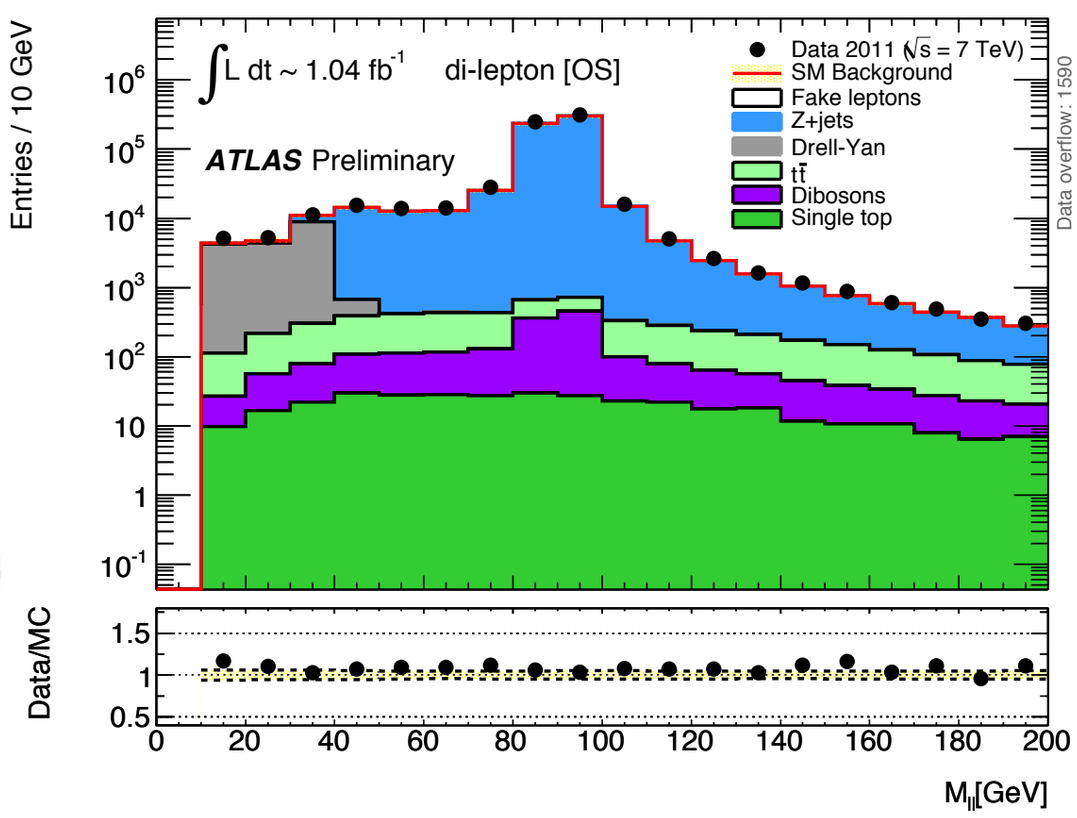

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Good agreement between expectation and observation for a variety of event properties.

For 2010 Results, see:
EPJC 71 (2011) 1682

Opposite-Sign Dilepton Search

NEW

Latest 2011 Results 1.04 fb^{-1}

Three signal-regions...

1. $E_T^{miss} > 250$ GeV
2. $E_T^{miss} > 220$ GeV, jet $p_T > 80,40,40$ GeV
3. $E_T^{miss} > 100$ GeV, jet $p_T > 100,70,70,70$ GeV

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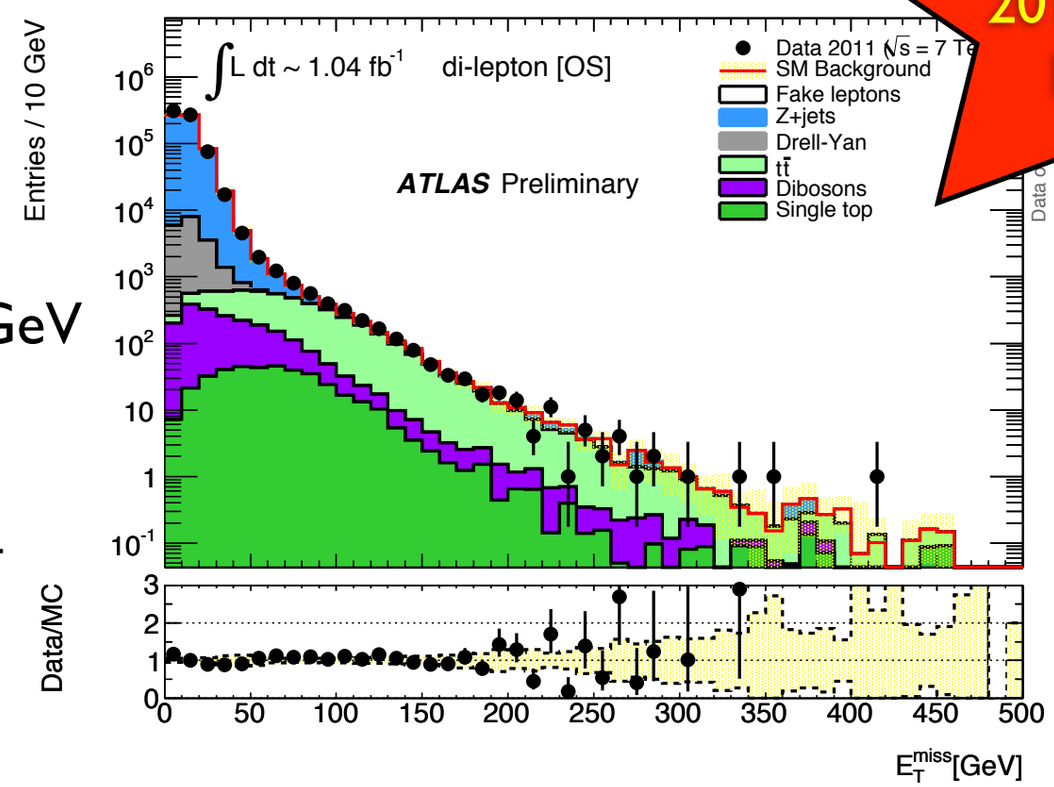

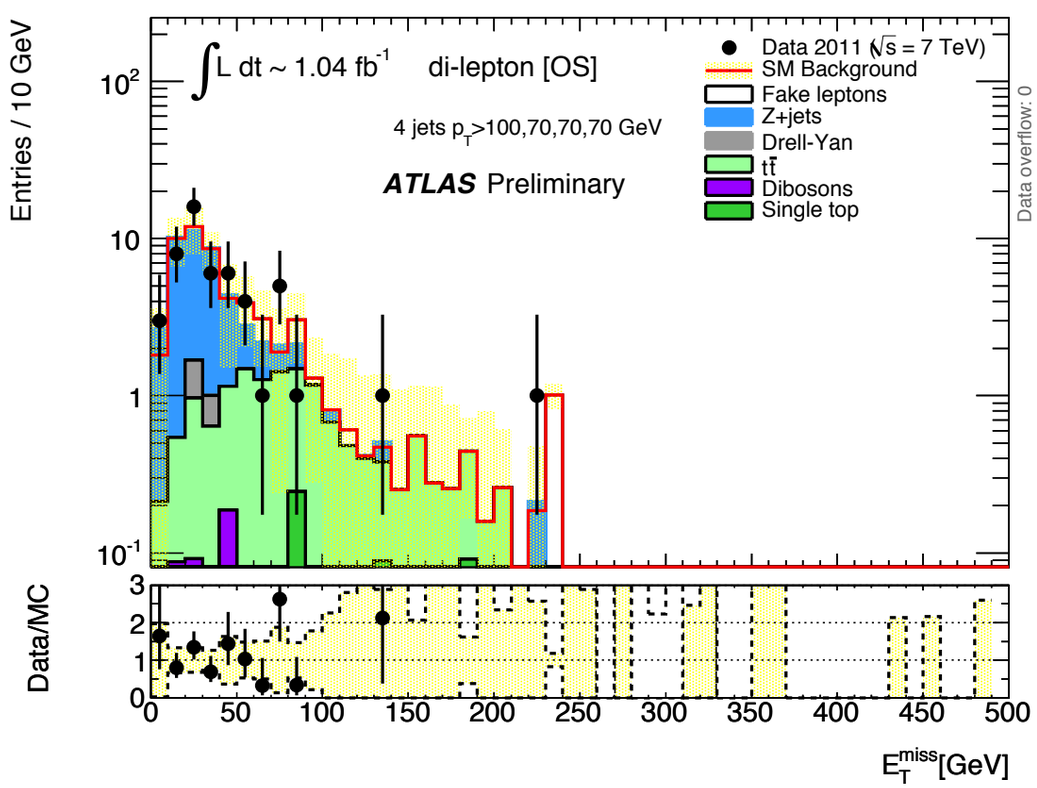

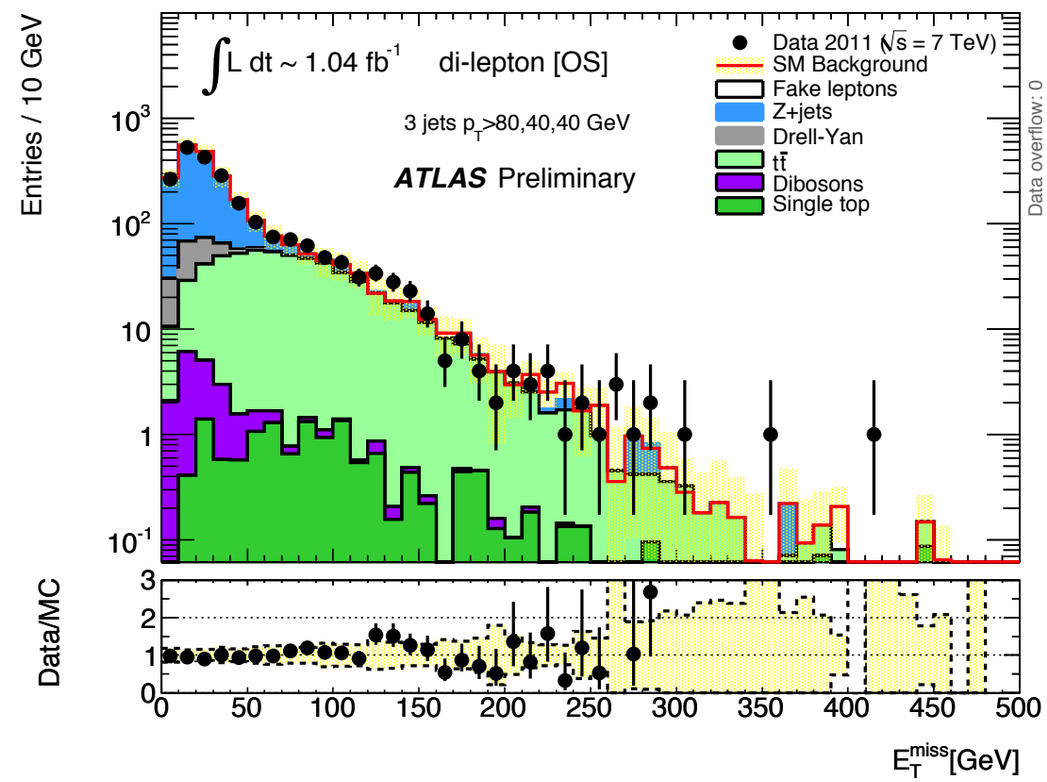

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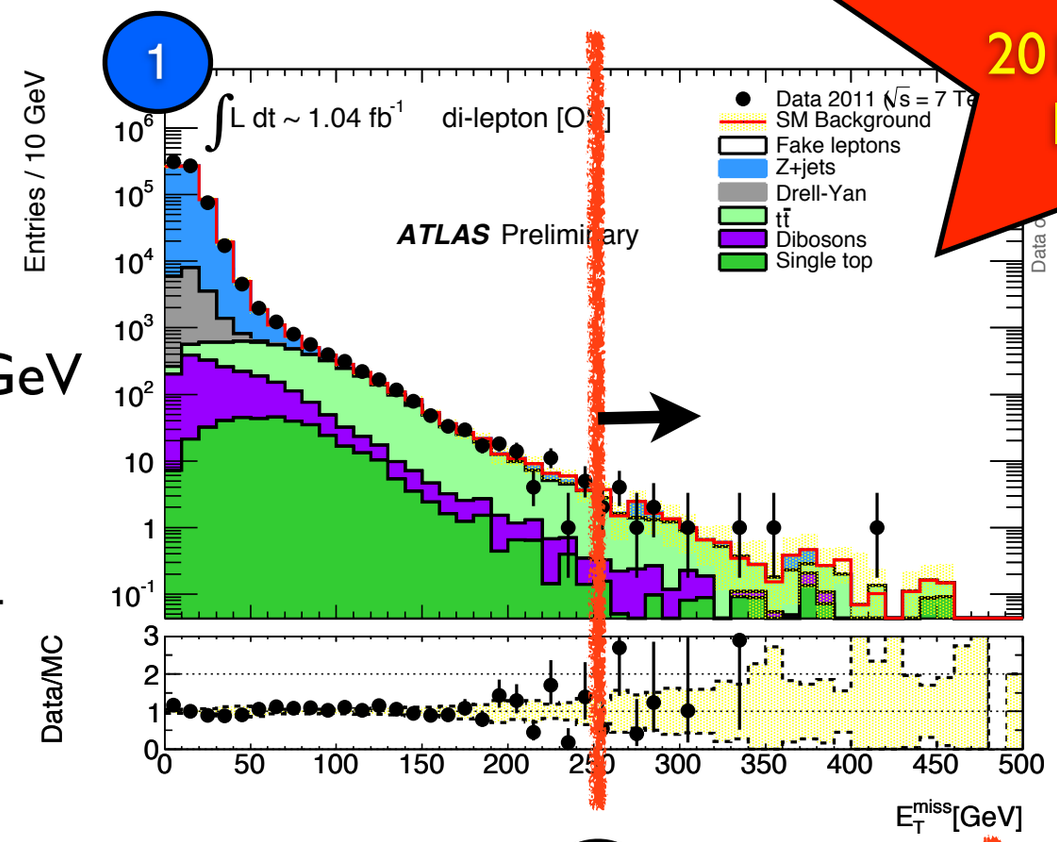
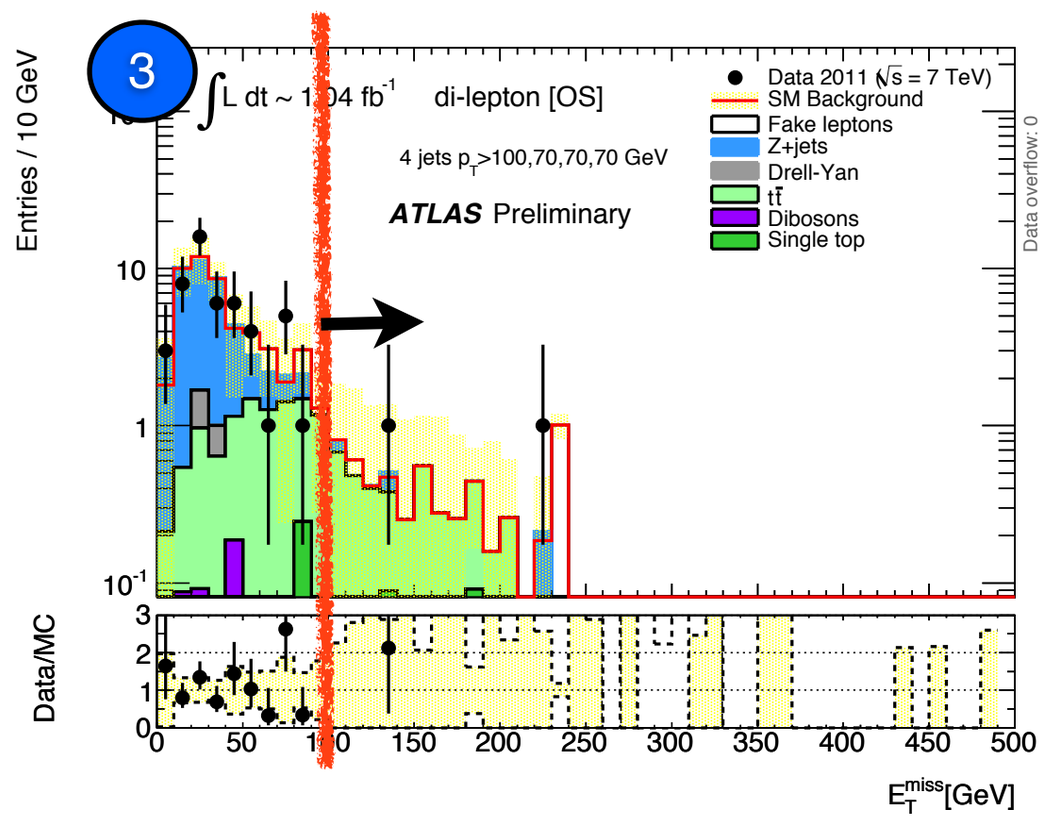
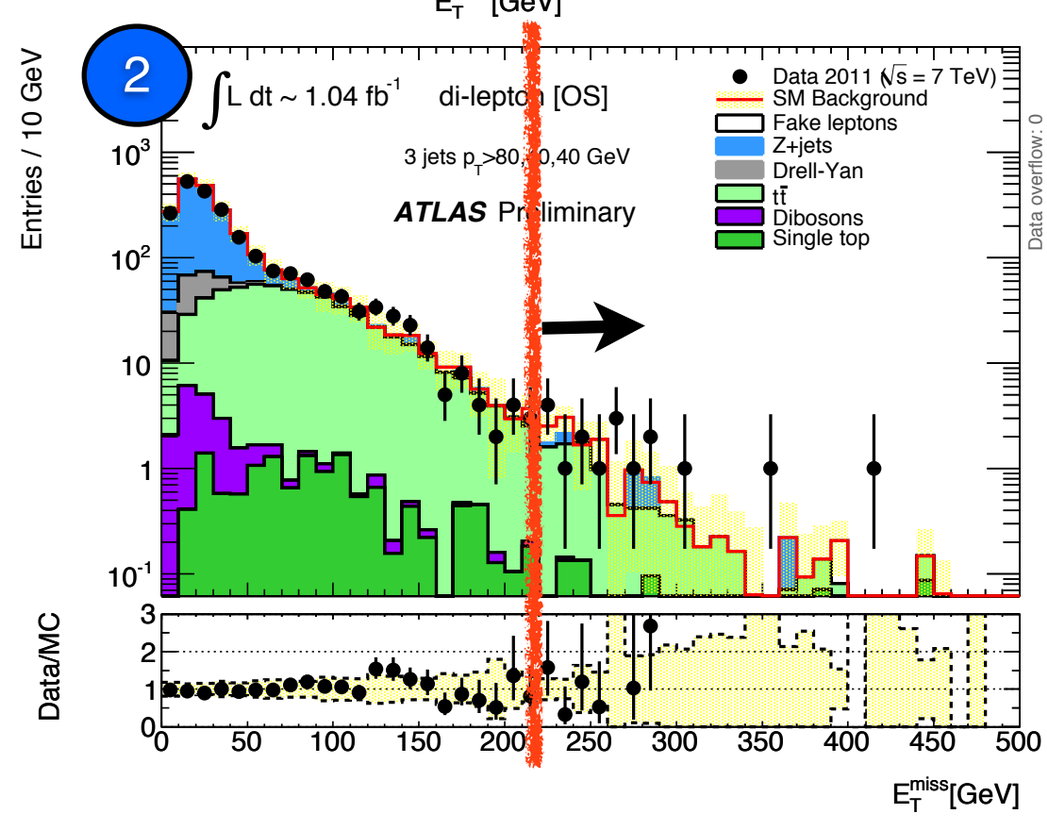






Opposite-Sign Dilepton Search

NEW

Latest 2011 Results 1.04 fb^{-1}

Standard Model backgrounds -- fully-leptonic $t\bar{t}$, Z+jets, WW, WZ, ZZ, single top and events with fake leptons

- $t\bar{t}$ and Z+jets -- normalise data to Monte Carlo using suitable control regions
  - $t\bar{t}$ - control region: "top-tag" events using the m_{CT} variable
  - Z+jets - control region: low E_T^{miss}, m_{ll} compatible with a Z boson
- WW, WZ, ZZ and single top -- event yields taken from Monte Carlo
- Background from fake leptons -- estimate using the "matrix-method"

m_{CT} exploits kinematics of $t\bar{t} \to \ell^+ \nu b \ell^- \nu b$ decay

Limits on cross-section x A x e using CLs prescription

	Background	Obs.	95% C.L.
OS-SR1	$15.5 \pm 1.2 \pm 4.4$	13	9.5 fb
OS-SR2	$13.0 \pm 1.8 \pm 4.1$	17	15.2 fb
OS-SR3	$5.7 \pm 1.1 \pm 3.5$	2	5.0 fb

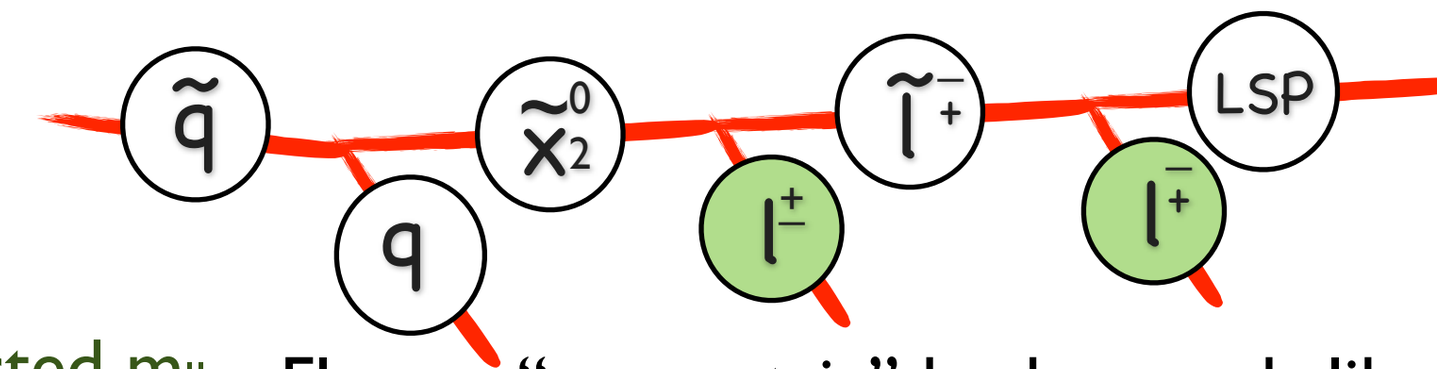
$t\bar{t}$ is the dominant background

(followed by Z+jets, then smaller contributions from the others)

Opposite-Sign "Flavour Subtraction" Search

Use the selected opposite-sign events to search for an excess of opposite-sign dileptons with identical-flavour, over those of different-flavour...

- these decay chains offer one of the best routes to the measurement of SUSY particle masses
- via edges in the flavour subtracted m_{ll} distribution



Flavour "symmetric" backgrounds like $t\bar{t} \to \ell^+\nu b \ell^-\nu b$ "cancel".

Quantify the identical-flavour excess using the variable "S"

ratio of electron to muon reconstruction efficiencies and acceptances

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

estimate the N using the same techniques used for the opposite-sign analysis

muon trigger efficiency

electron trigger efficiency

Opposite-Sign "Flavour Subtraction" Search

NEW

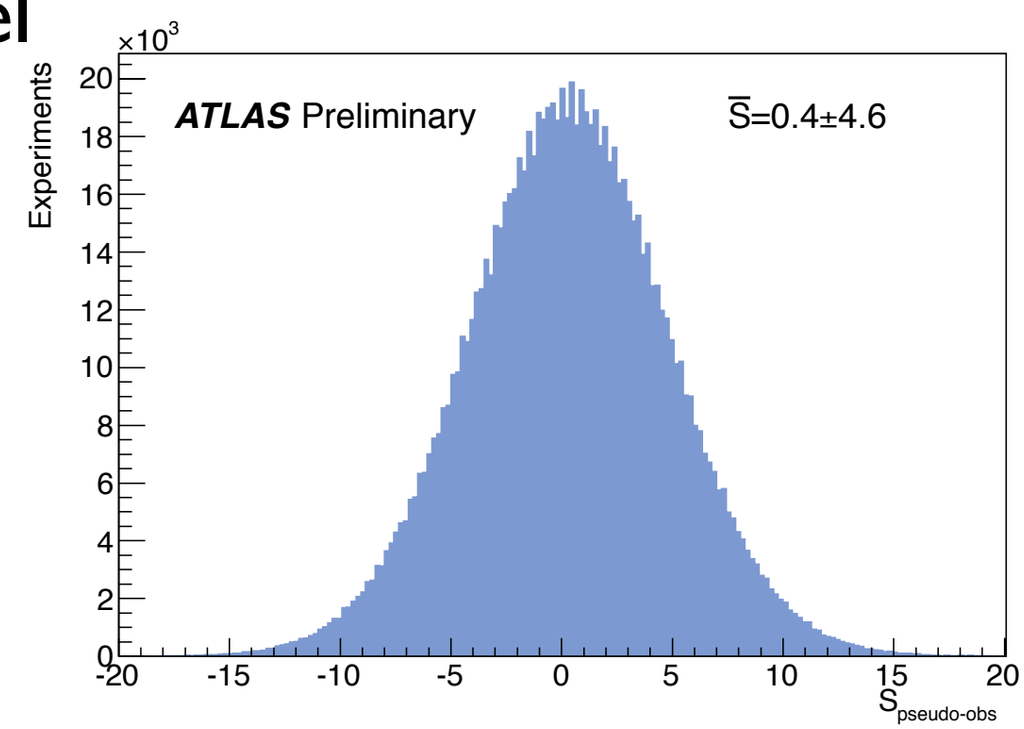
Latest 2011 Results 1.04 fb^{-1}

Signal Region $E_T^{miss} > 250$ GeV

Observe S_{obs} in data $S_{obs} = -3.1 +/- 0.003$

Check consistency of S_{obs} with the Standard Model using pseudo-experiments

- sample the mean number of background events expected in each channel (dielectron, electron-muon and dimuon)
- use sampled means to construct three Poisson distributions
- draw observed events in each channel from these and calculate $S_{pseudo-obs}$
- 77% of pseudo-experiments have recorded $S > S_{obs}$



For 2010 Results, see: EPJC 71 (2011) 1647

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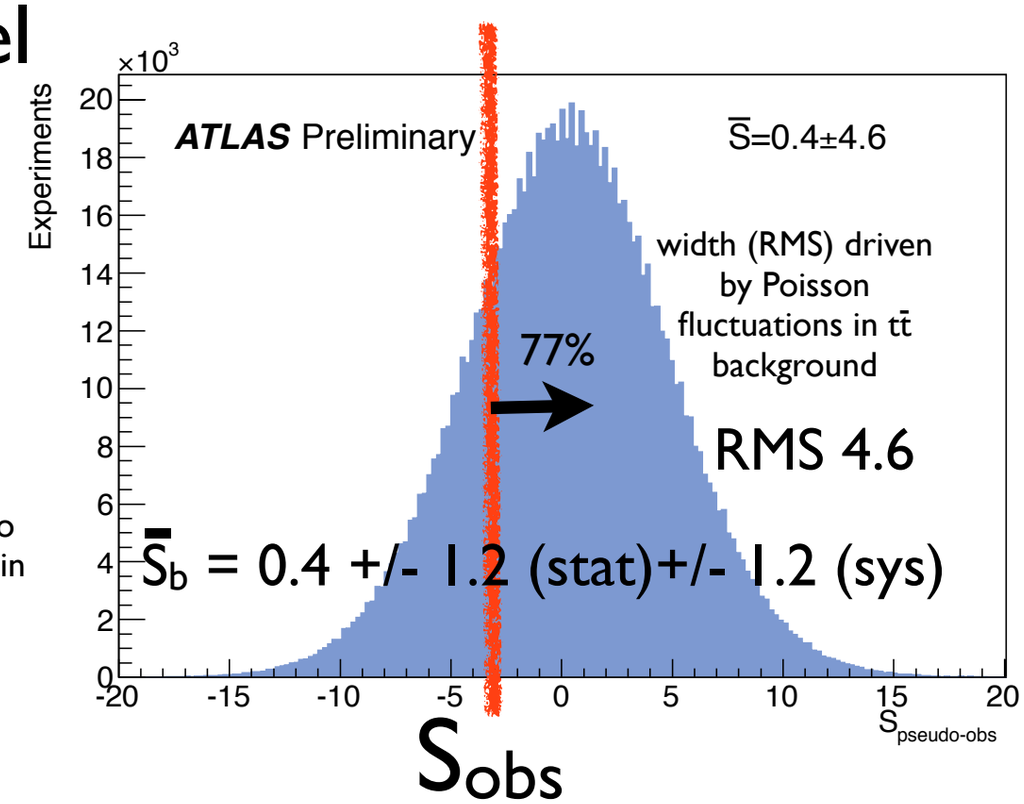


a deviation of $\bar{S}_b$ from zero would be due to Z events in signal region

For 2010 Results, see: EPJC 71 (2011) 1647

Opposite-Sign "Flavour Subtraction" Search

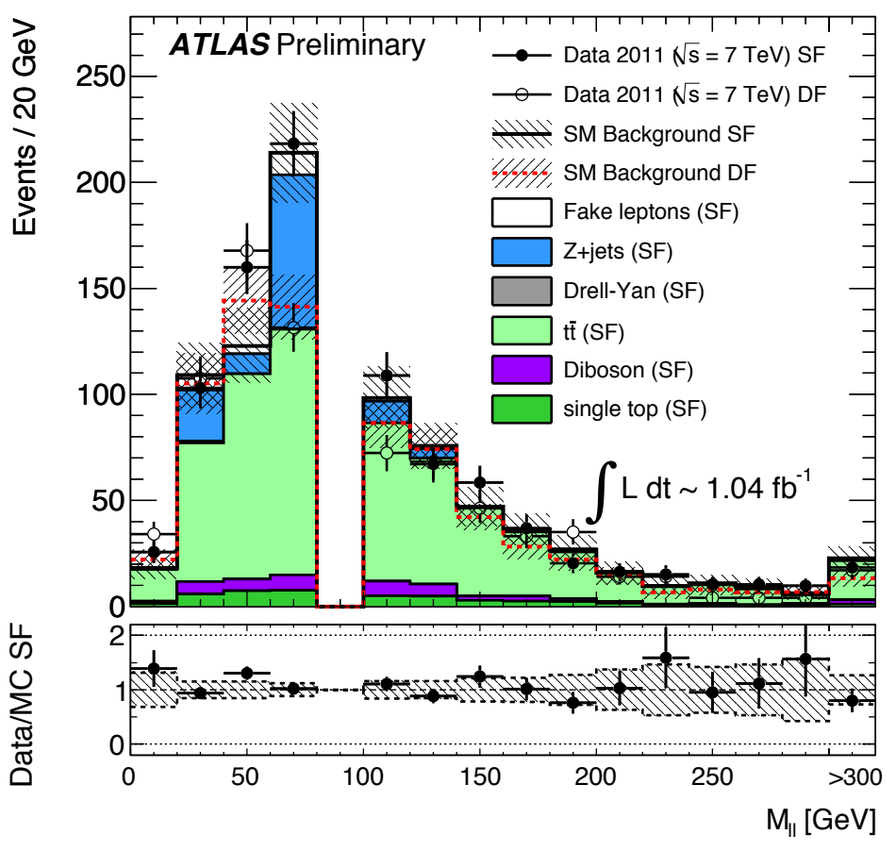
NEW

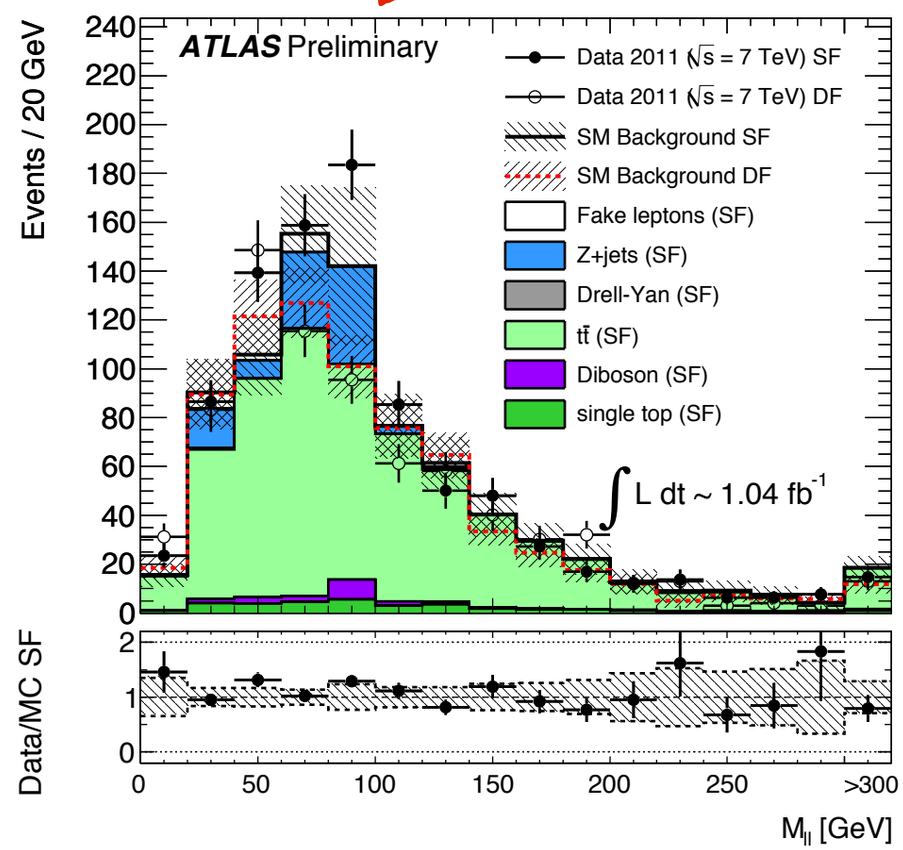
Latest 2011 Results 1.04 fb^{-1}

- Set limits on supersymmetry
- add hypothesised numbers of events in each channel from supersymmetry to the Standard Model counts
- sample as before
- set the contributions so that % S < S_{obs} is 5 %

Under assumption that for supersymmetry, BR(ll') = 0, Limit on $\overline{S}_s$ < 4.9 at 95 % C.L.

also observe no significant deviations from the Standard Model in alternative signal-regions:
E_T^{miss} > 80 GeV, at least 2 jets
E_T^{miss} > 80 GeV, "Z-veto"





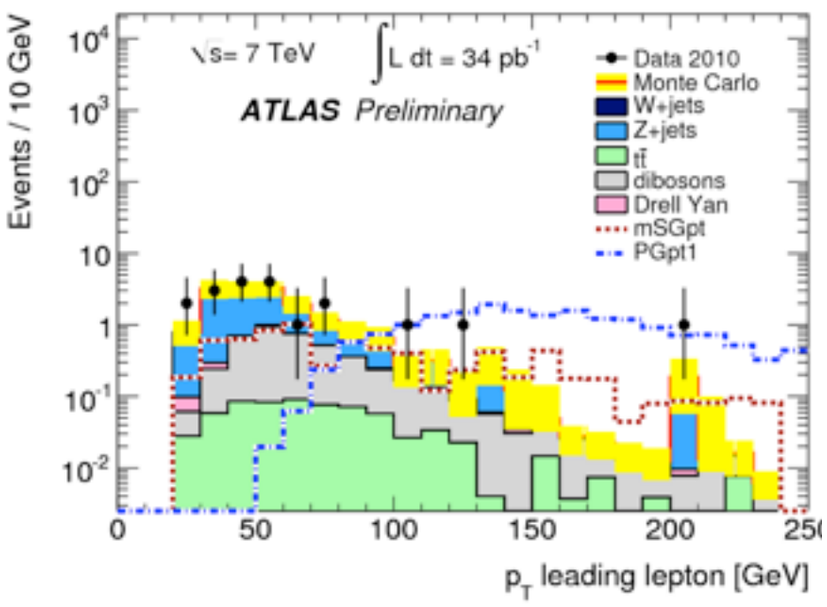
Multilepton Search

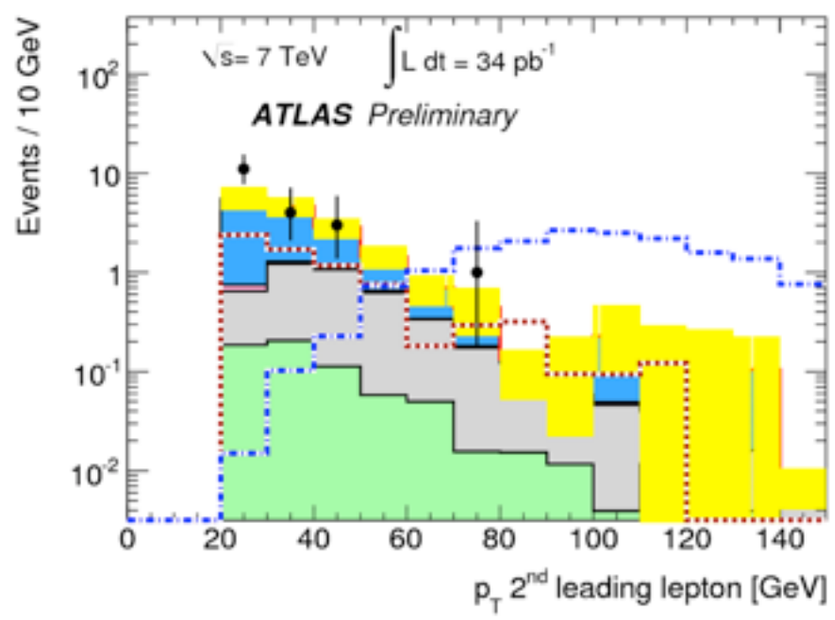
ATLAS-CONF-2011-039

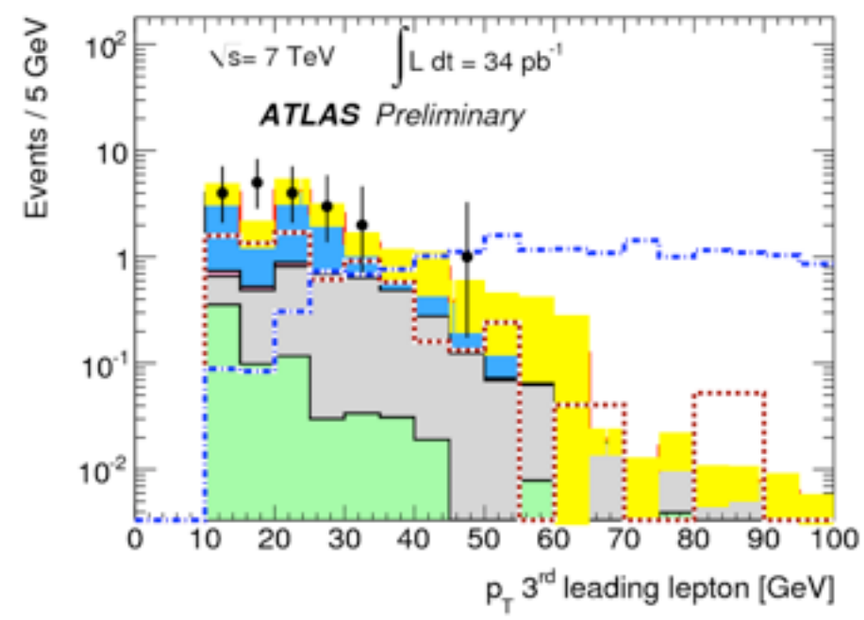
2010 Data

If $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{0}$ are copiously produced, expect final states with 3 or more leptons ("golden channel" for supersymmetry at the Tevatron).

Search for final states with 3 or more isolated leptons: p_T > 20, 20, 20 (10) GeV for electrons (muons)







Observe: 19 events
Predict: 16.6 +/- 1.3

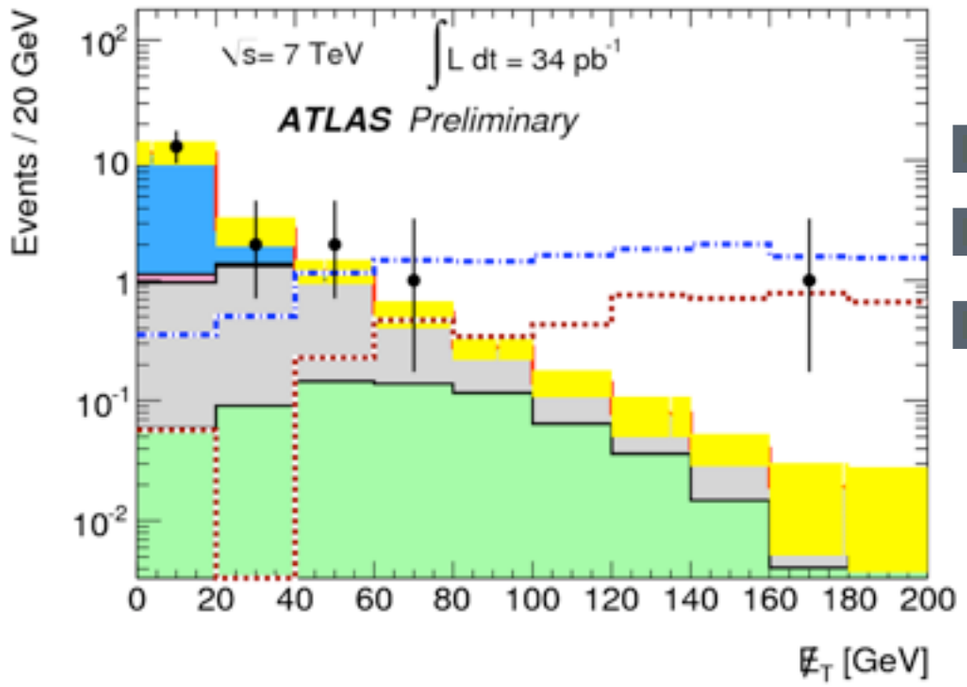
'mSGpt': mSUGRA point,
$(m_0\ m_{1/2}, A_0)$ = (80, 180, 0) GeV, $\tan\beta$= 3, μ> 0
'PGpt1': light LSP PhenoGrid point (see later)

(none of these candidates have four or more leptons with p_T above threshold)

Multilepton Search

ATLAS-CONF-2011-039

2010 Data

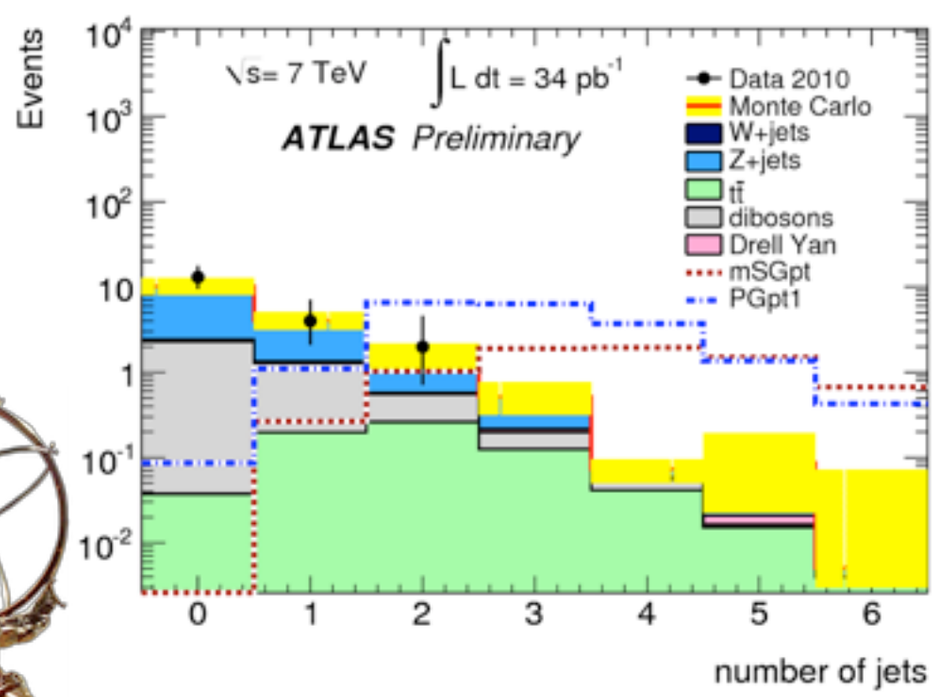


Further require --

- At least 2 jets with p_T > 50, 50 GeV
- E_T^{miss} > 50 GeV
- m_{ll} > 20 GeV for opposite-sign same-flavour pairs (but not within 5 GeV of the Z mass)

- No events are observed in data
- Monte Carlo predicts

$$0.109 \pm 0.023 \; {}^{+0.036}_{-0.025}$$



Virtually all $t\bar{t}$
(< 0.01 events from Z+jets)

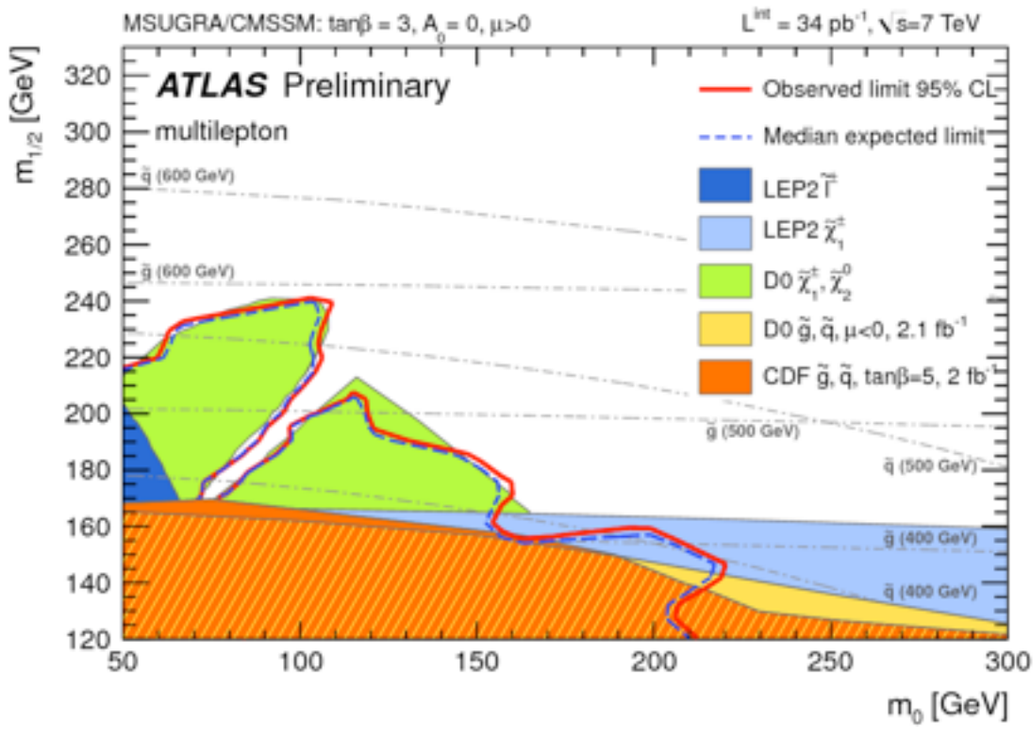
Dominant Systematic Uncertainties
jet energy scale (12%)
electron energy scale (20%)
electron energy resolution (10%)
pile-up (11%)
MC cross-sections (10%)

Multilepton Search

ATLAS-CONF-2011-039

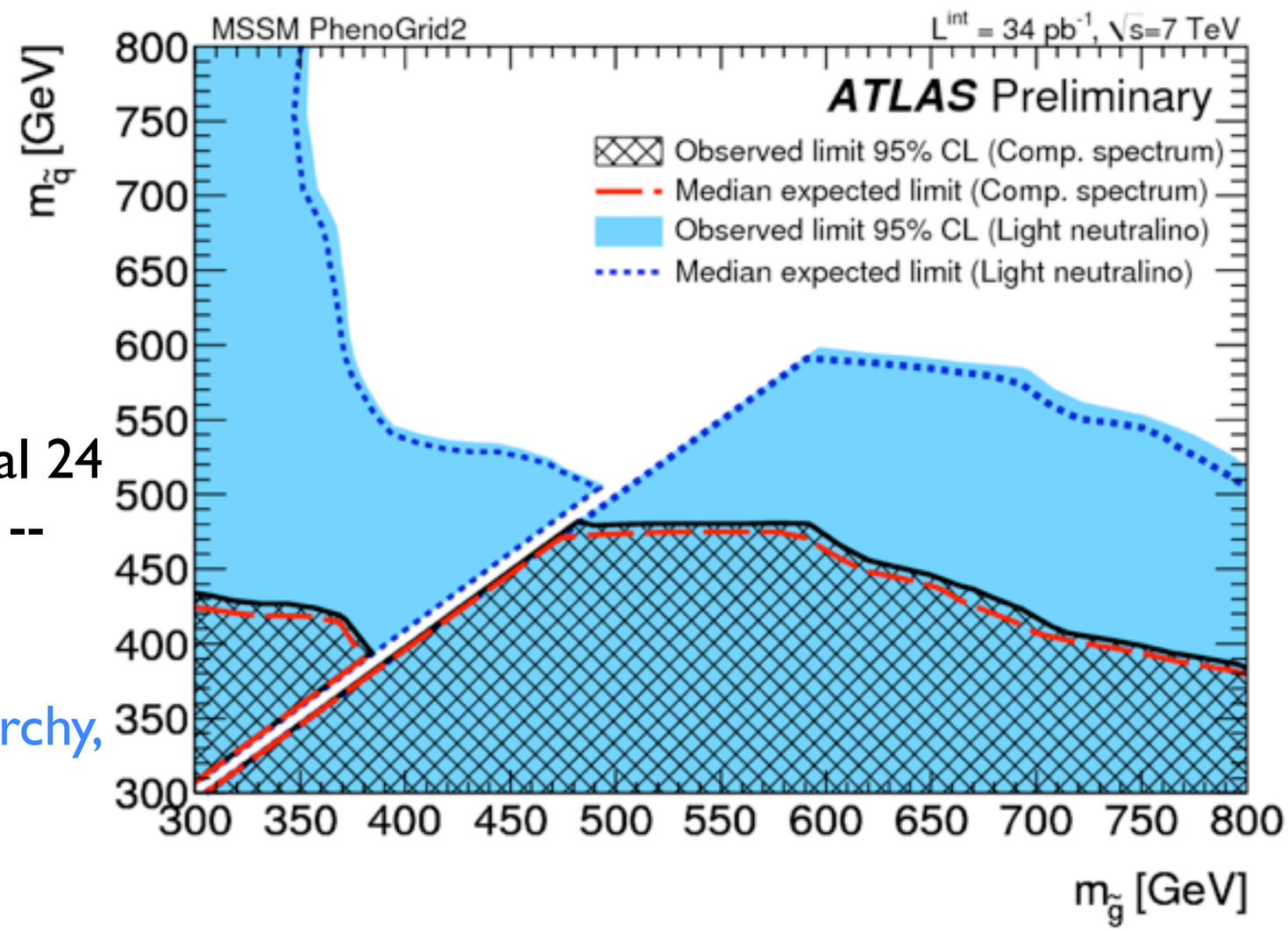
2010 Data

Set limit on cross-section x A x e -- 62 fb at 95% confidence



mSUGRA/CMSSM Exclusion
similar exclusion bound to the Tevatron

"PhenoGrid"



Interpretation in more general 24 parameter MSSM framework --

- **Compressed particle spectrum** → *softer leptons*
- More favourable mass hierarchy, light LSP → *harder leptons*

Summary

The LHC has delivered over 2 fb^{-1} of 7 TeV collision data (reaching the 1 fb^{-1} milestone in July)!

The ATLAS detector is performing very well and producing lots of new physics results.

This talk has summarised the latest search results for supersymmetry in final states with

- two leptons (opposite-sign, same-sign and "flavour subtraction")
- and three or more leptons

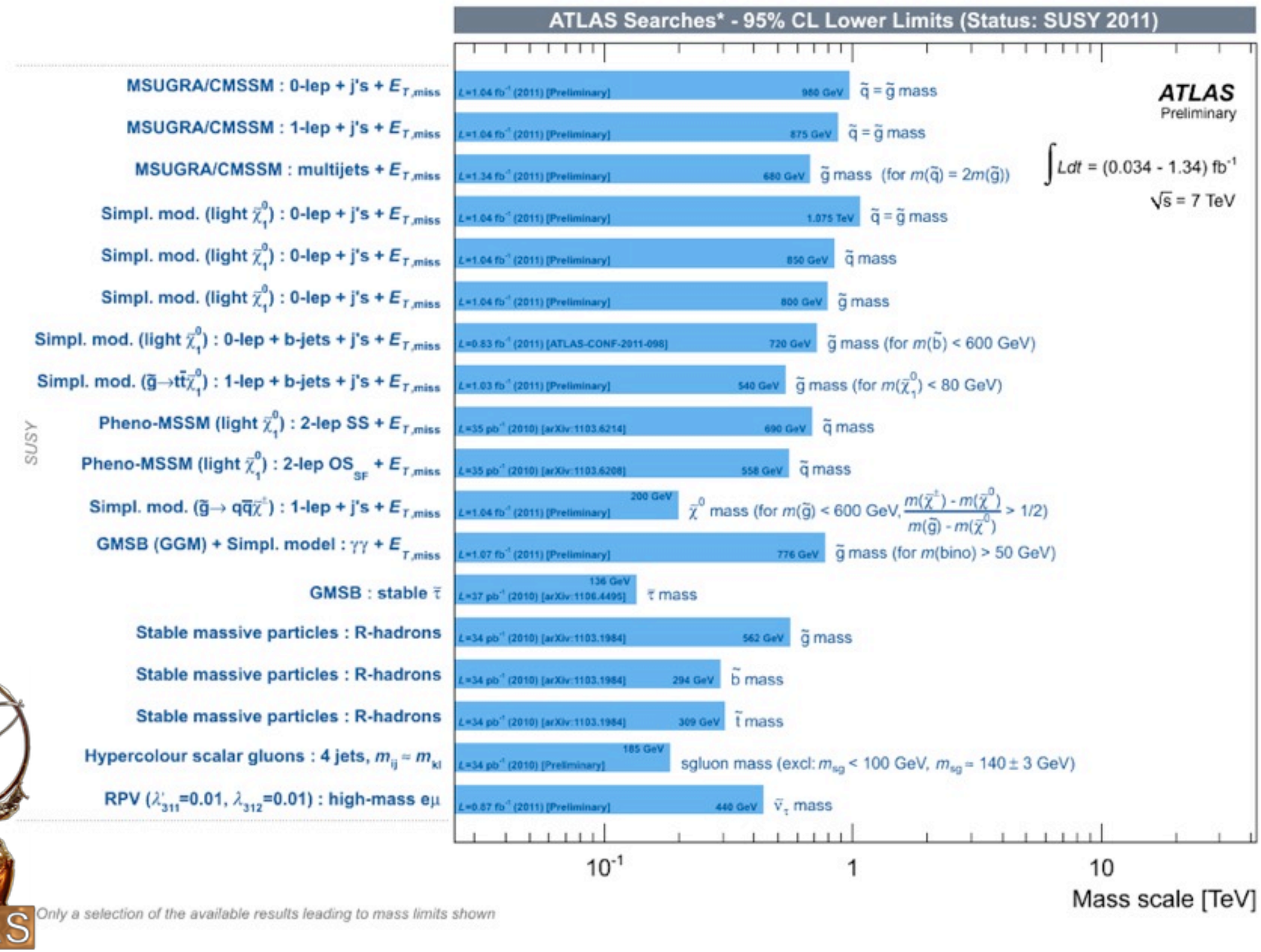
No deviations from the Standard Model expectation seen so far...

Keep an eye out for future "multiple lepton" search results from ATLAS

http://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

Back-up Slides

Summary of Supersymmetry Search Results



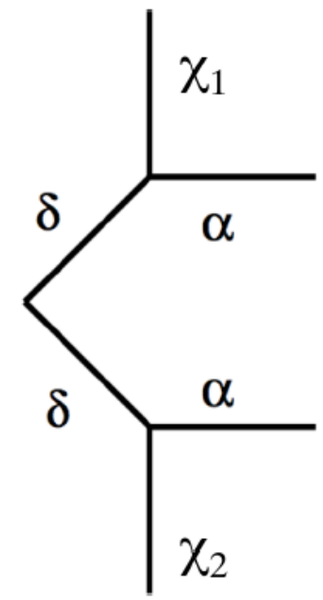
m_{CT} top-tagging

Contransverse mass variable proposed in Tovey, JHEP 0804 (2008) 034 and Polesello, Tovey, JHEP 1003 (2010) 030

Consider the decay of two pair-produced heavy states which both decay via:

$$\delta \rightarrow \alpha \chi_1$$

$$m^2_{CT}(\chi_1, \chi_2) = [E_T(\chi_1) + E_T(\chi_2)]^2 - [\mathbf{p_T}(\chi_1) - \mathbf{p_T}(\chi_2)]^2$$



The end-points in the m_{CT} distribution are determined by:

- the mass of α
- the mass of χ_1
- and the sum of the transverse momenta of all particles upstream of the system for which the variable is calculated (p_b)

For the $t\bar{t}$ system it is possible to calculate $m_{CT}(l,l)$, $m_{CT}(jl,jl)$, $m_{CT}(j,j)$

"Top-tagging" algorithm

The event should have at least 2 jets with $p_T > 20$ GeV
Consider all 2 jet permutations (j_1, j_2) such that the two jets have -
$p_T > 20$ GeV and $p_T(j_1) + p_T(j_2) + p_T(l_1) + p_T(l_2) > 100$ GeV
$m_{CT}(l_1,l_2)$ should be in the allowed area of the $(m_{CT}(l_1,l_2), p_b(l,l))$ plane
Build all pairs $((j_i, l_1)(j_j, l_2)$ such that $m(j_i, l_1) < 155$ GeV and $m(j_j, l_2) < 155$ GeV
There should be at least one combination with $m_{CT}(j,j)$ in the allowed area of the $m_{CT}(j,j)$,$p_b(j,j)$ plane.
For the combinations passing the previous cuts: m_{CT} (jl,jl) should be compatible with $t\bar{t}$

Opposite-Sign Dilepton Search

NEW

Latest 2011 Results 1.04 fb^{-1}

Opposite Sign [OS-SR1]	$e^{\pm}e^{\mp}$	$e^{\pm}\mu^{\mp}$	$\mu^{\pm}\mu^{\mp}$
$t\bar{t}$	1.84±0.07±0.49	5.09±0.19±1.35	3.34±0.13±0.88
Z/γ^{*}+jets	0.013±0.008±0.67	1.03±0.42±0.02	0.81±0.26±0.06
Fakes	0.17±0.19±0.36	0.92±0.96±1.15	-0.08±0.03±0.003
Dibosons	0.54±0.29±0.07	0.04±0.03±0.03	0.67±0.25±0.31
Single-top	0.11±0.11±0.05	0.47±0.16±0.16	0.48±0.17±0.09
Standard Model	2.67±0.37±1.29	7.55±1.07±2.13	5.30±0.42±1.29
Cosmics	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
Observed	2	8	3

Opposite Sign [OS-SR2]	$e^{\pm}e^{\mp}$	$e^{\pm}\mu^{\mp}$	$\mu^{\pm}\mu^{\mp}$
$t\bar{t}$	1.41±0.11±0.33	3.90±0.30±0.95	2.56±0.20±0.62
Z/γ^{*}+jets	0.45±0.23±0.44	0.84±0.59±0.32	0.27±0.14±0.27
Fakes	0.01±0.14±0.19	2.77±1.64±2.11	-0.13±0.04±0.01
Dibosons	*neg.*	0.03±0.03±0.03	0.24±0.21±0.02
Single-top	0.05±0.10±0.02	0.39±0.16±0.25	0.09±0.15±0.08
Standard Model	1.92±0.31±0.77	7.93±1.77±1.41	3.16±0.36±0.94
Cosmics	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
Observed	3	9	5

Opposite Sign [OS-SR3]	$e^{\pm}e^{\mp}$	$e^{\pm}\mu^{\mp}$	$\mu^{\pm}\mu^{\mp}$
$t\bar{t}$	0.77±0.14±0.51	2.14±0.38±1.41	1.40±0.25±0.92
Z/γ^{*}+jets	0.01±0.01±0.17	*neg.*	0.27±0.20±0.47
Fakes	0.13±0.13±0.03	0.91±0.94±0.04	-0.03±0.02±0.001
Single-top	*neg.*	0.0±0.0±0.02	0.10±0.10±0.05
Standard Model	0.91±0.19±0.67	3.05±1.01±1.43	1.77±0.34±1.41
Cosmics	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
Observed	0	1	1

ATLAS

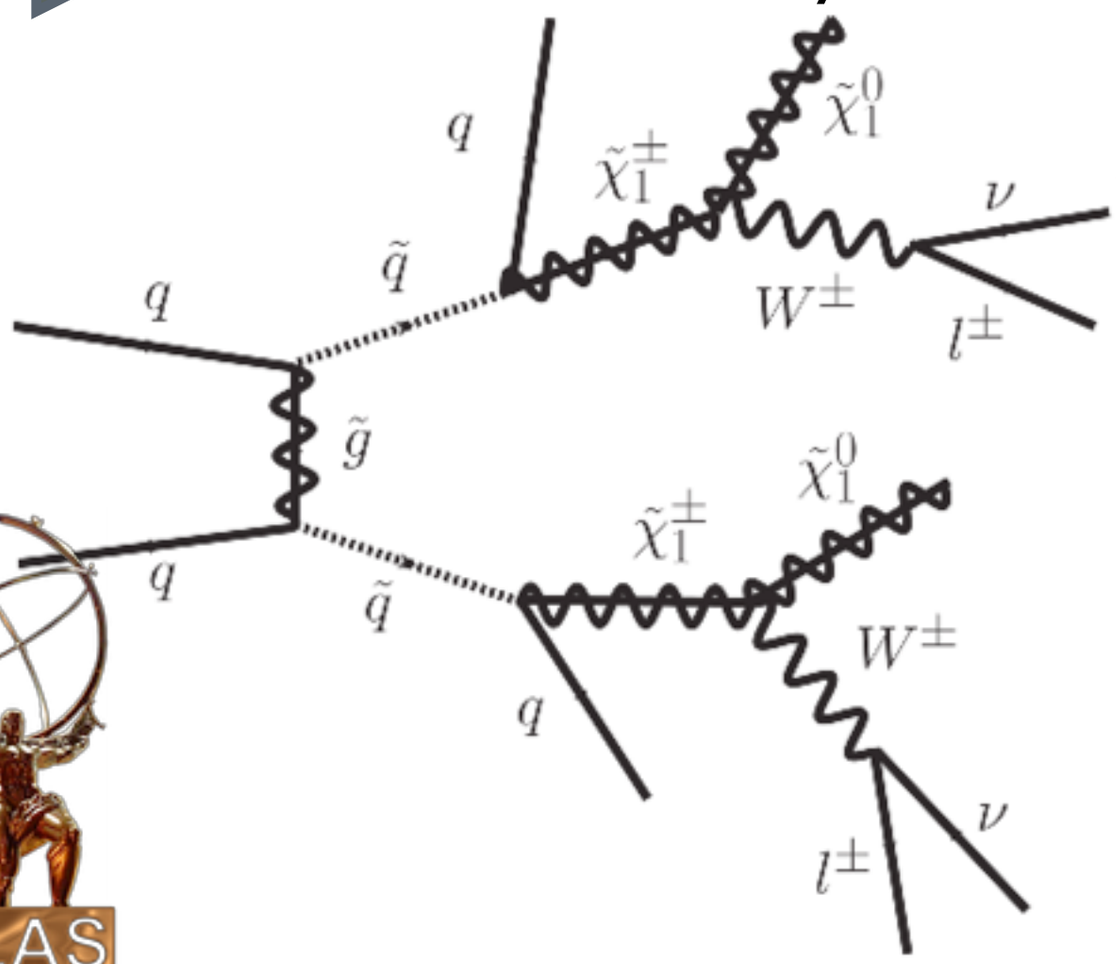
Simplified Models

ATLAS-CONF-2011-091

2010 Data

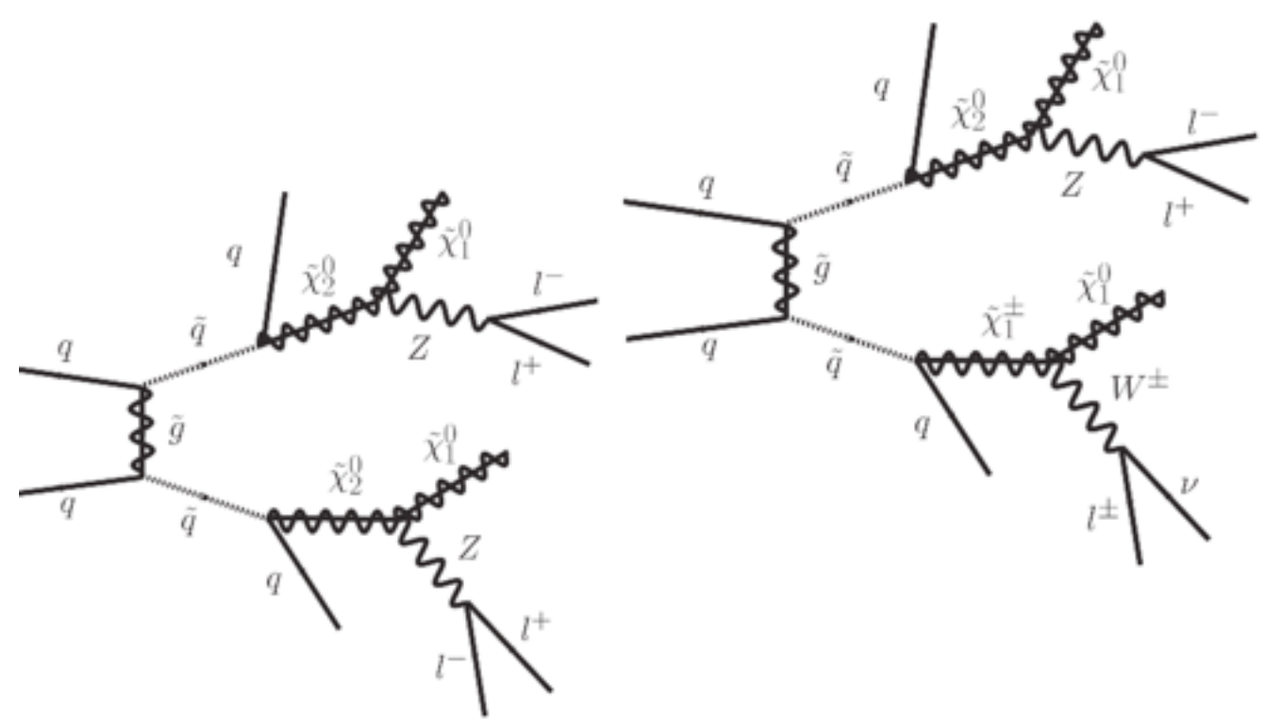
Search for same-sign dileptons - interpreted using a simplified SUSY model (complementary to results in EPJC 71 (2011) 1682))

- Simplified SUSY model built with the minimal particle content necessary to produce SUSY-like events in like-sign dilepton final states.
- Parameterised directly in terms of sparticle masses.



Dependent on three mass parameters:

LSP $\tilde{q}$ $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$



Simplified Models

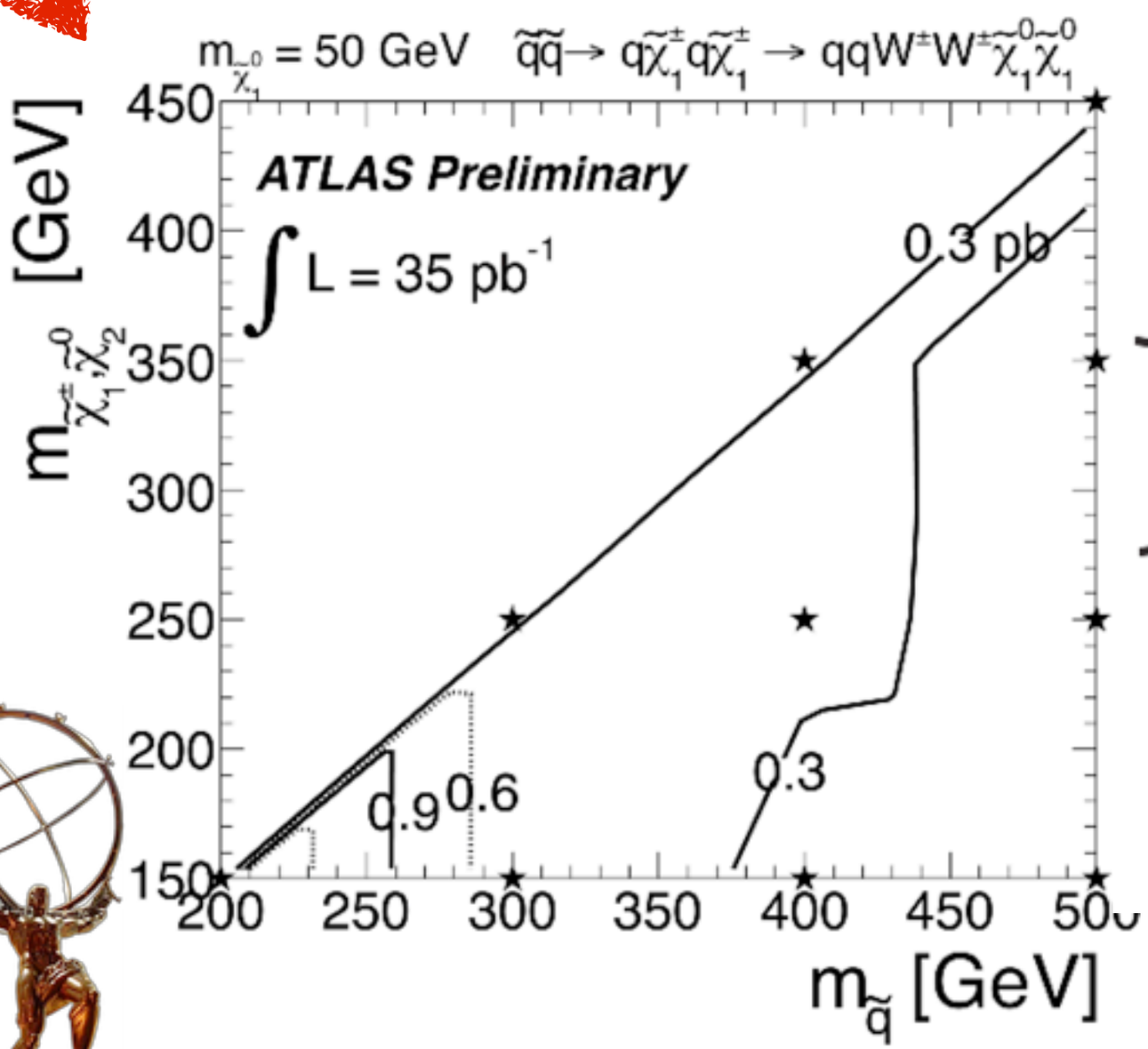
ATLAS-CONF-2011-091

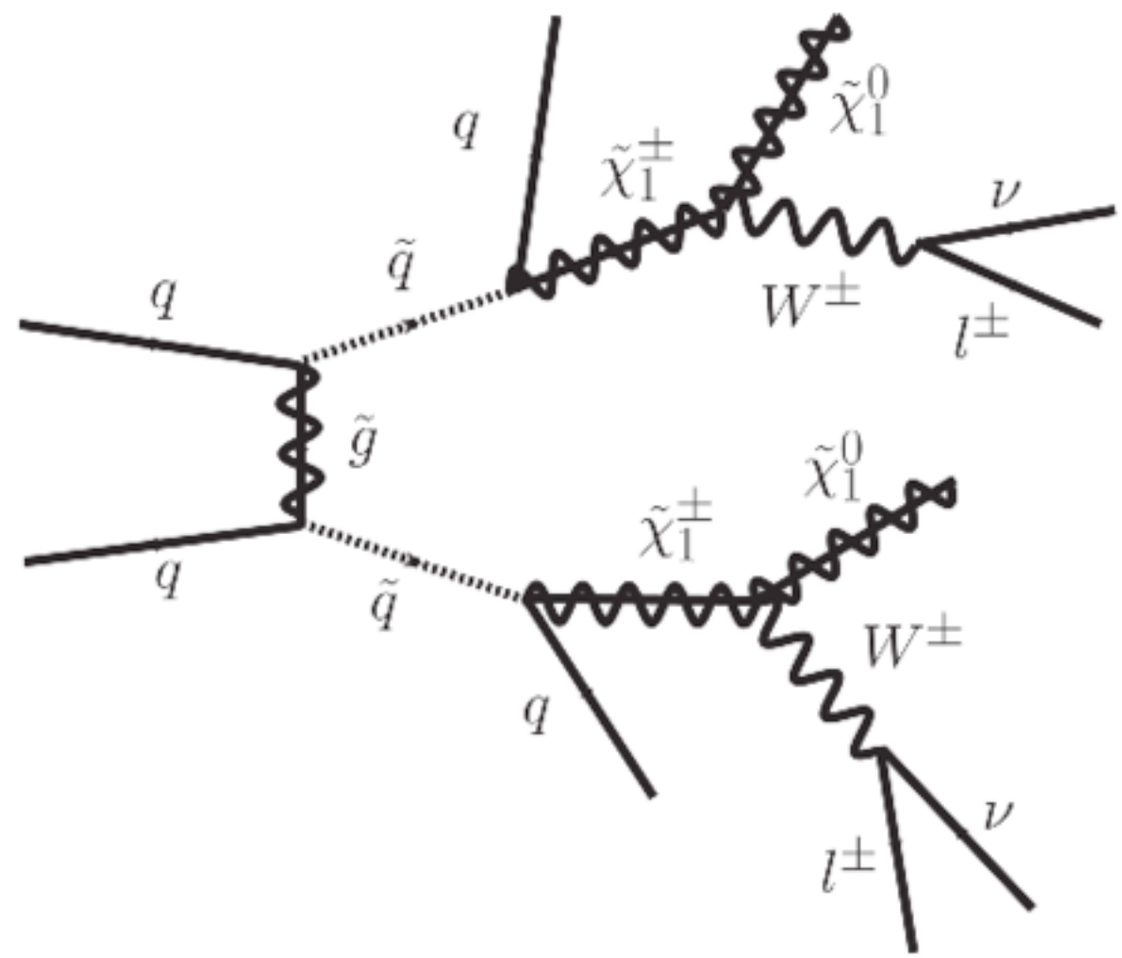
2010 Data

Signal region: two leptons with p_T > 20 GeV, E_T^{miss} > 100 GeV

selection identical to EPJC 71 (2011) 1682

e.g. m(LSP) = 50 GeV





Same-Sign Dilepton Search

EPJC 71 (2011) 1682

2010 Data

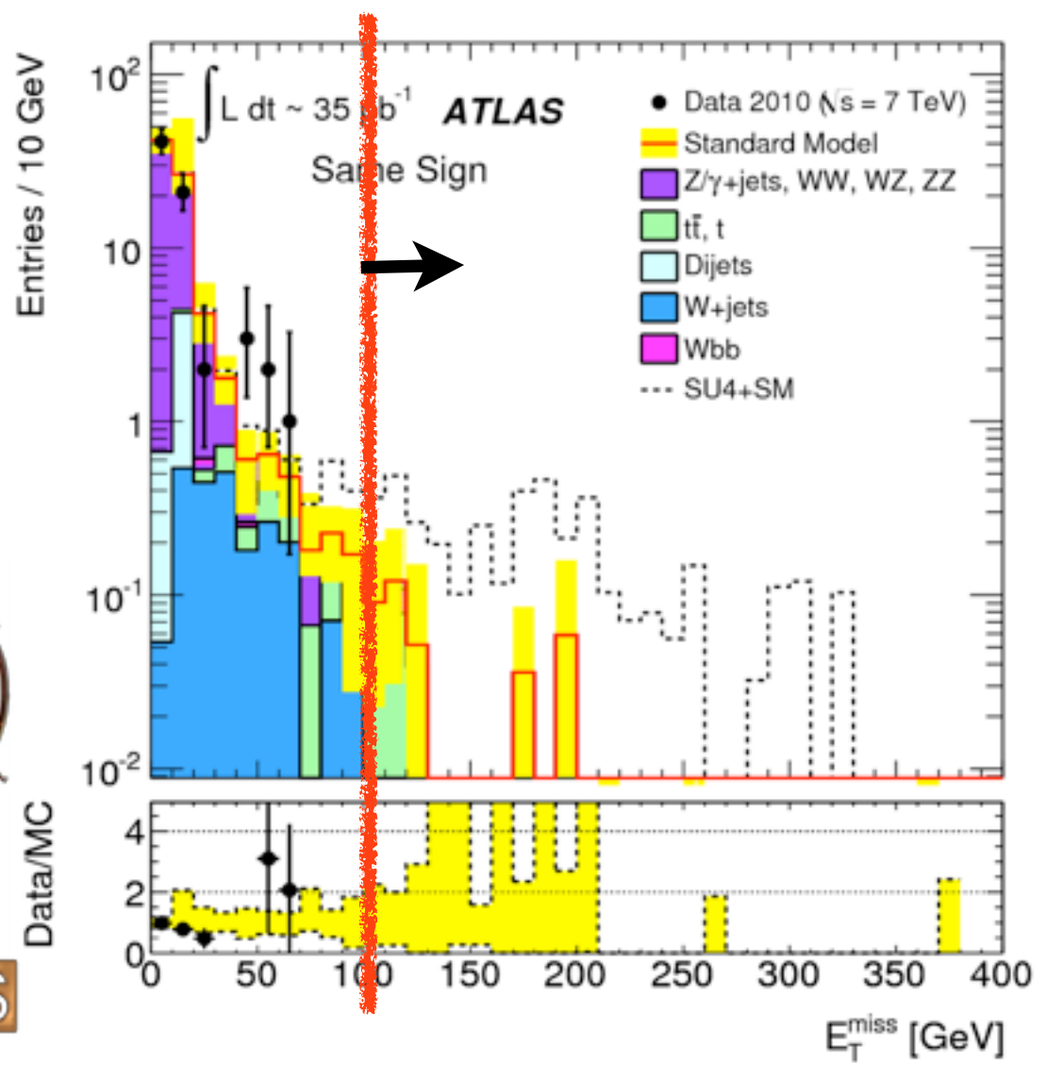
Search for exactly 2-leptons with same-sign and large missing transverse energy.

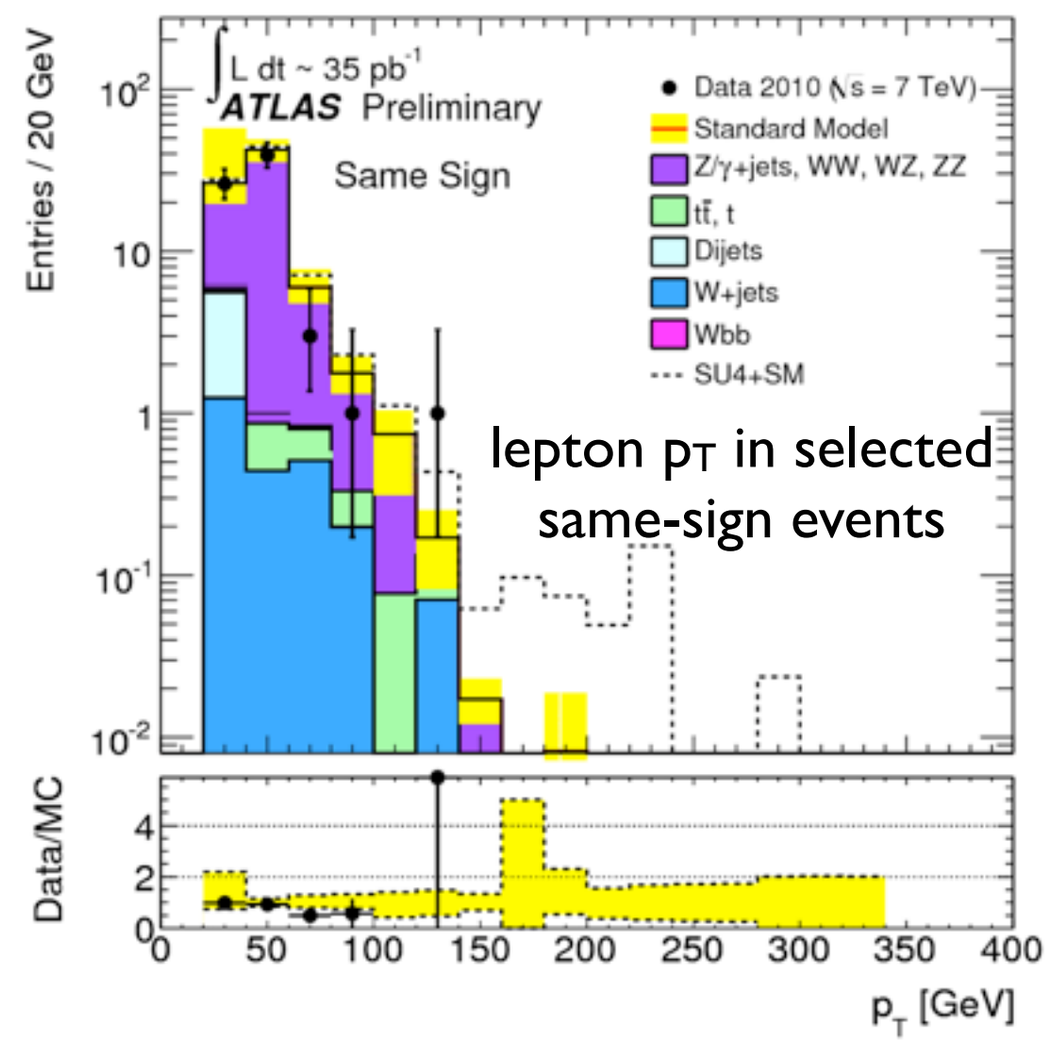
In figures:
All backgrounds MC normalised to luminosity x cross-section.

Signal-region selects events with...

$E_T^{miss} > 100$ GeV

Electron $p_T > 20$ GeV
Muon $p_T > 20$ GeV
$m_{ll} > 5$ GeV





lepton p_T in selected same-sign events

Same-Sign Dilepton Search

EPJC 71 (2011) 1682

2010 Data

Same Sign, $E_T^{miss} > 100$ GeV			
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
Data	0	0	0
Fakes	0.12 ± 0.13	0.030 ± 0.026	0.014 ± 0.010
Di-bosons	0.015 ± 0.005	0.035 ± 0.012	0.021 ± 0.009
Charge-flip	0.019 ± 0.008	0.026 ± 0.011	-
Cosmics	-	$0^{+1.17}_{-0}$	-
Total	0.15 ± 0.13	$0.09\ ^{+1.17}_{-0.03}$	0.04 ± 0.01

Observe good agreement between data and the Standard Model expectation

Combining the observations in each channel we set limits on new physics ...

Limits on cross-section x A x e using PCL prescription
0.07 pb

Opposite-Sign Dilepton Search

EPJC 71 (2011) 1682

2010 Data

Search for exactly 2-leptons with opposite-sign and large missing transverse energy.

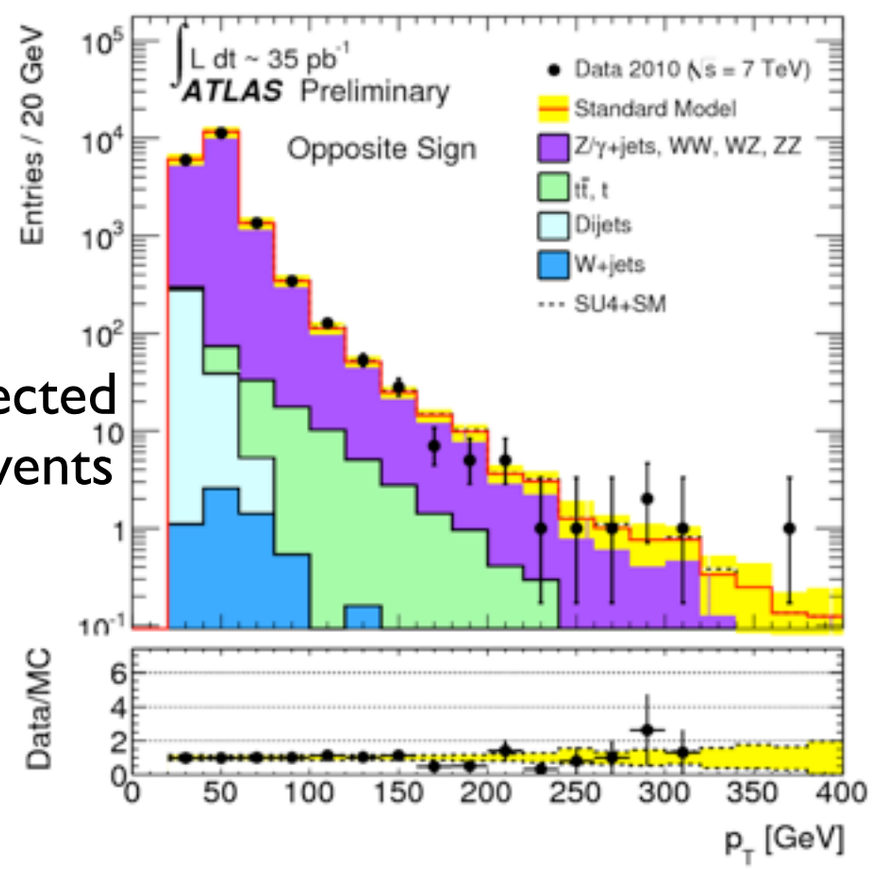
Signal-region selects events with...

$E_T^{miss} > 150$ GeV

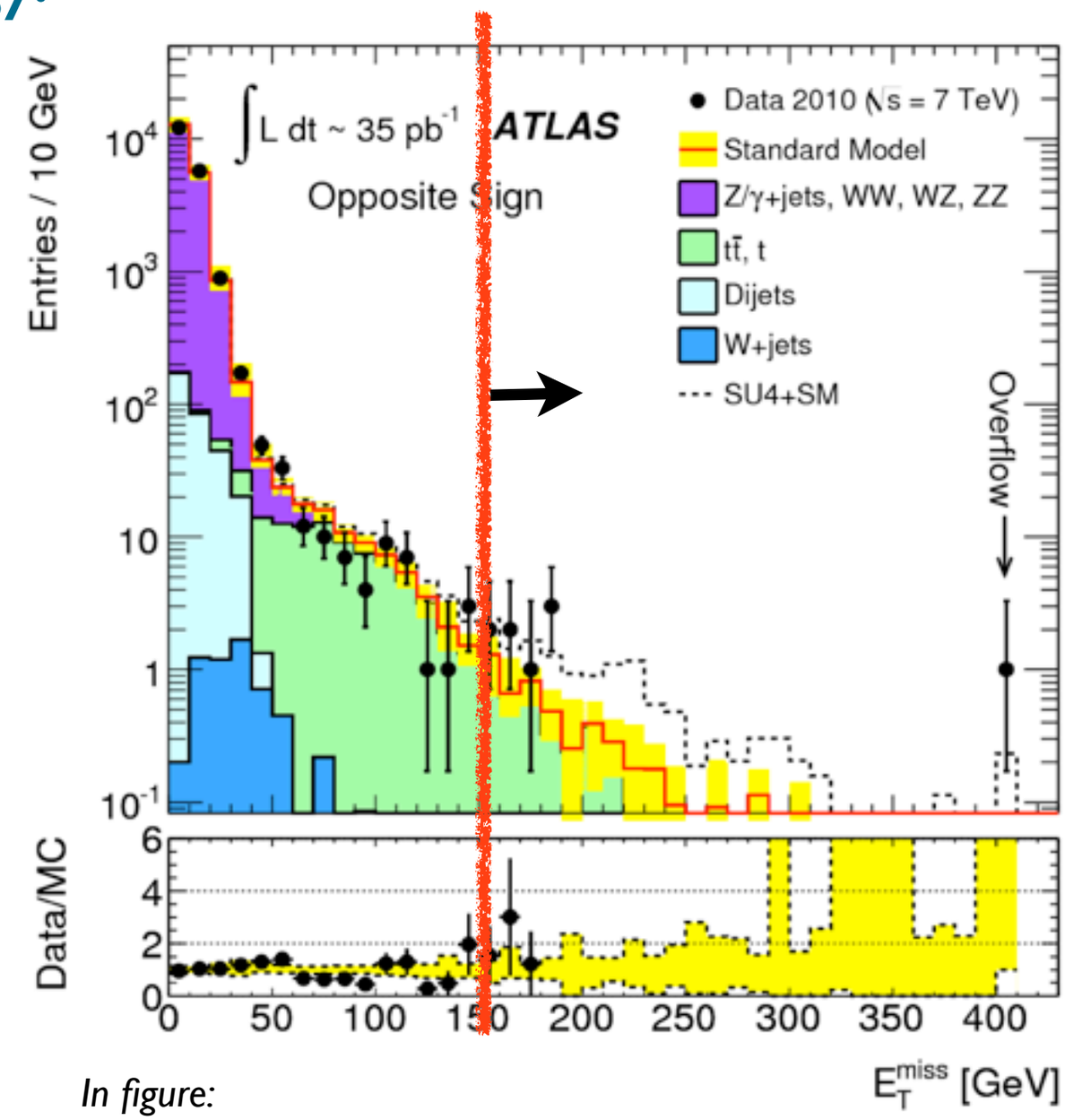
Electron $p_T > 20$ GeV

Muon $p_T > 20$ GeV

$m_{ll} > 5$ GeV



lepton p_T in selected opposite-sign events



In figure:
All backgrounds MC normalised to luminosity x cross-section.

Opposite-Sign Dilepton Search

EPJC 71 (2011) 1682

2010 Data

Opposite Sign, $E_T^{miss} > 150$ GeV			
	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
Fakes	-0.02 ± 0.02	-0.05 ± 0.04	-
Single top	0.03 ± 0.05	0.06 ± 0.08	0.10 ± 0.07
Di-bosons	0.09 ± 0.03	0.06 ± 0.03	0.15 ± 0.03
Cosmics	-	-0.2 ± 1.18	-0.43 ± 1.27
Total	$0.92^{+0.42}_{-0.40}$	$1.43^{+1.45}_{-0.59}$	$1.39^{+1.41}_{-0.53}$

Limits on cross-section x A x e using PCL prescription

Dielectron channel 0.09 pb
Electron-muon channel 0.22 pb
Dimuon channel 0.21 pb

Opposite-Sign "Flavour Subtraction" Search

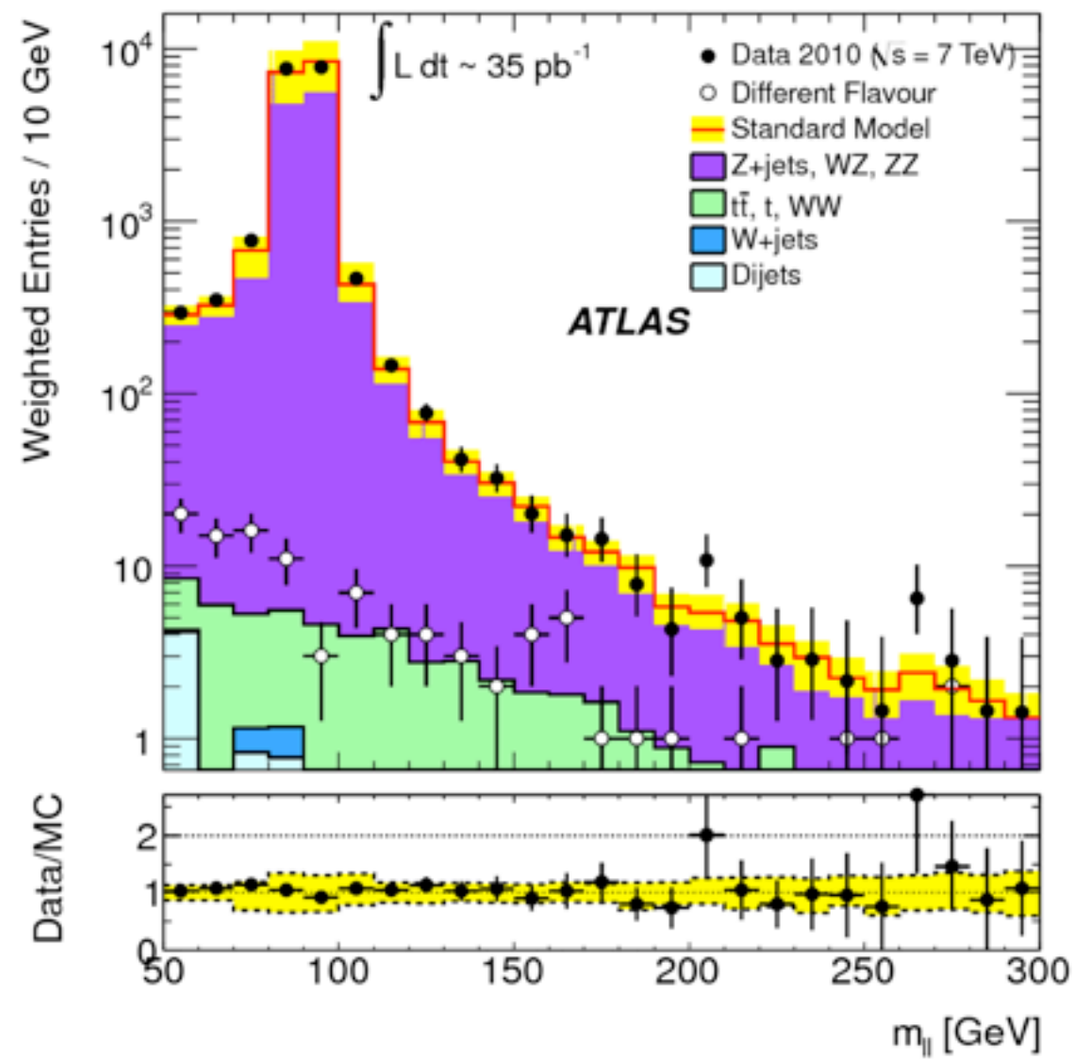
2010 Data

EPJC 71 (2011) 1647

Signal Region E_T^{miss} > 100 GeV

	$e^{\pm}e^{\mp}$	$e^{\pm}\mu^{\mp}$	$\mu^{\pm}\mu^{\mp}$
Data	4	13	13
Z/γ^*+jets	0.40±0.46	0.36±0.20	0.91±0.67
Dibosons	0.30±0.11	0.36±0.10	0.61±0.10
$t\bar{t}$	2.50±1.02	6.61±2.68	4.71±1.91
Single top	0.13±0.09	0.76±0.25	0.67±0.33
Fakes	0.31±0.21	-0.15±0.08	0.01±0.01
Total SM	3.64±1.24	8.08±2.78	6.91±2.20

Selected opposite-sign events, before missing transverse energy cut



Opposite-Sign "Flavour Subtraction" Search

2010 Data

EPJC 71 (2011) 1647

Signal Region E_T^{miss} > 100 GeV

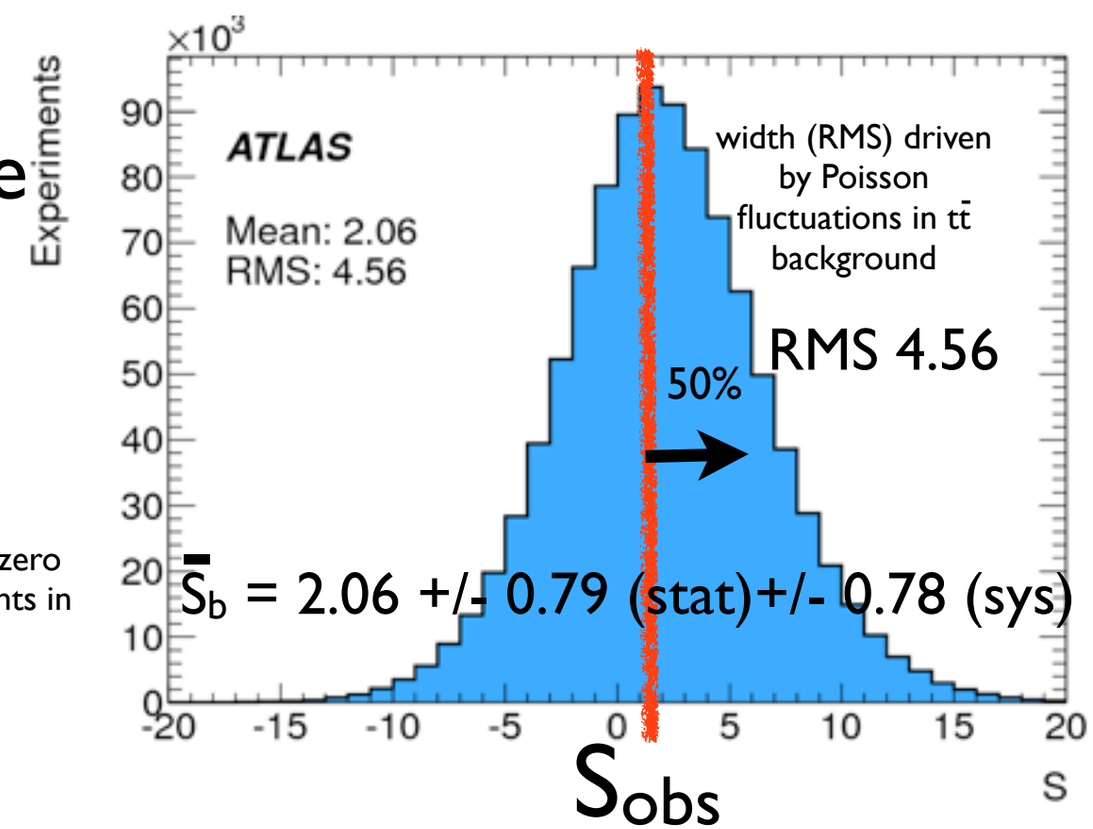
Observe S_{obs} in data

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

Check consistency of S_{obs} with the Standard Model using pseudo-experiments

- sample the mean number of background events expected in each channel (dielectron, electron-muon and dimuon)
- use resulting event numbers to construct three Poissons
  - draw observed events in each channel from these and calculate $S_{pseudo\text{-}obs}$
  - 49.7% of pseudo-experiments have record $S > S_{obs}$

a deviation of $\bar{S}_b$ from zero would be due to Z events in signal region



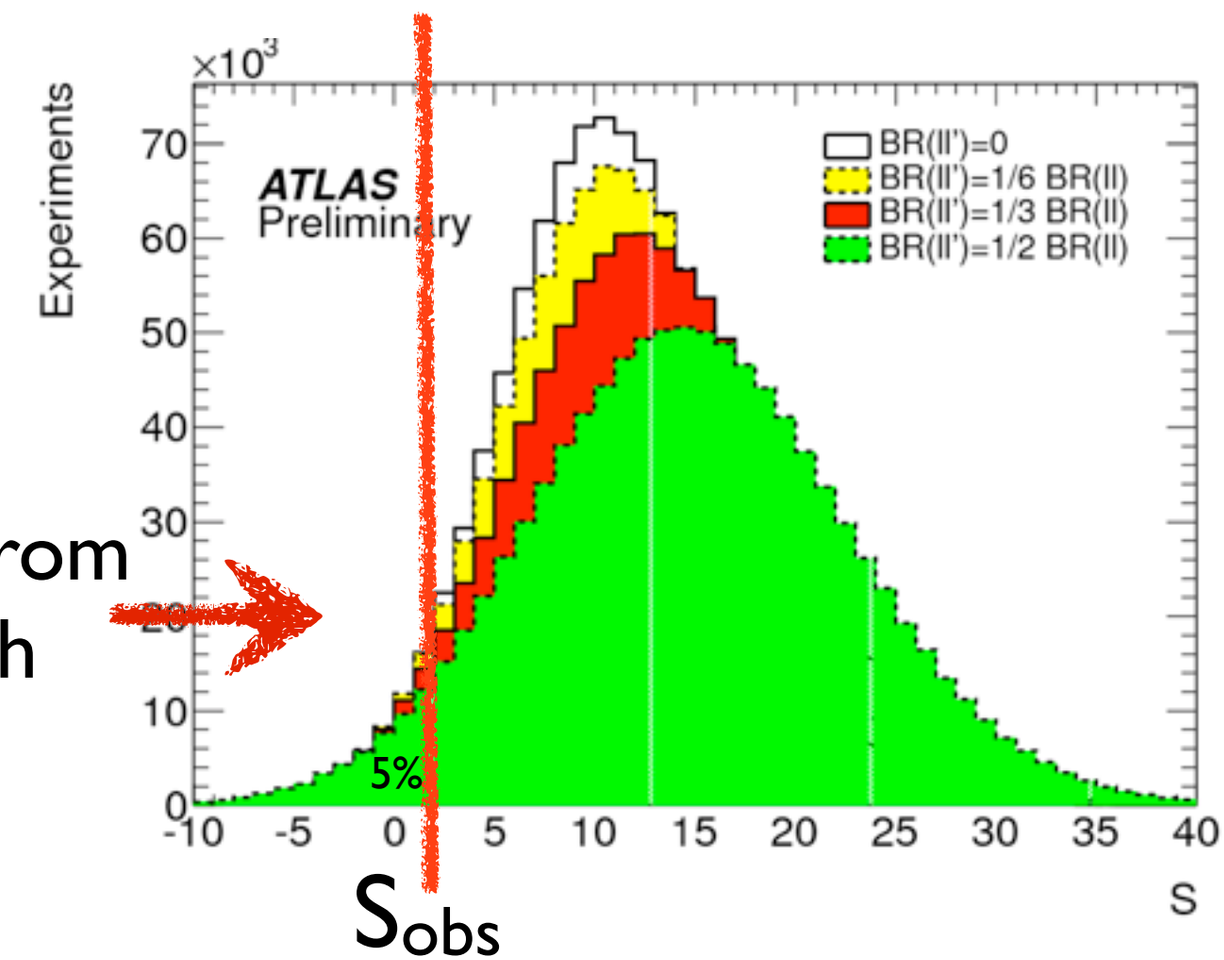
Opposite-Sign "Flavour Subtraction" Search

2010 Data

EPJC 71 (2011) 1647

- Set limits on supersymmetry
- Add hypothesised numbers of events in each channel from supersymmetry to the Standard Model counts
- Sample as before
- Set the contributions so that % $S < S_{obs}$ is 5 %

Under assumption that for supersymmetry, BR(ll') = 0
Limit on $\overline{S}_s < 8.8$ at 95 % C.L.



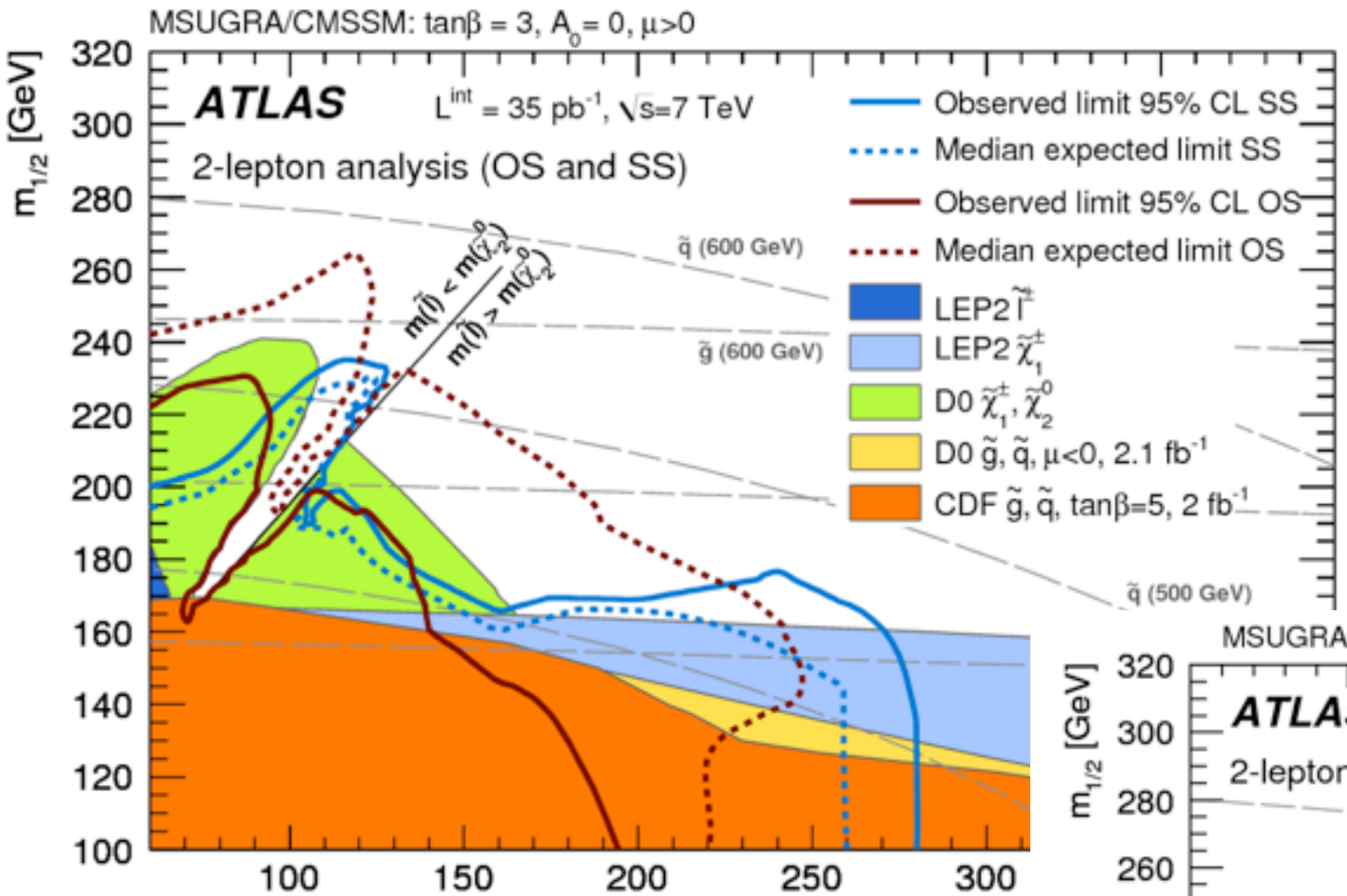
distribution of S values from pseudo-experiments with supersymmetry and the Standard Model

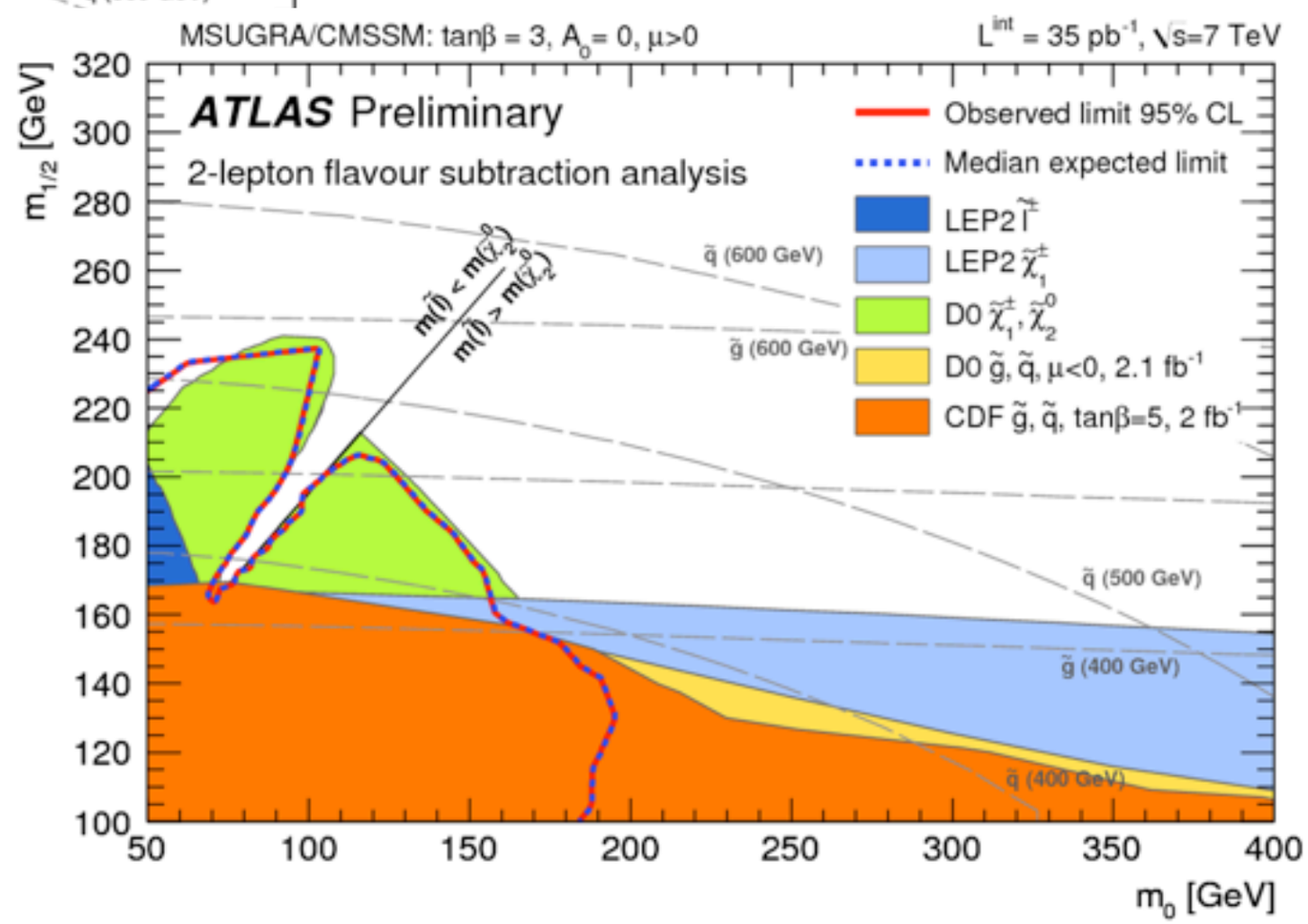
Dilepton mSUGRA/CMSSM Exclusions

2010 Data

EPJC 71 (2011) 1647

EPJC 71 (2011) 1682



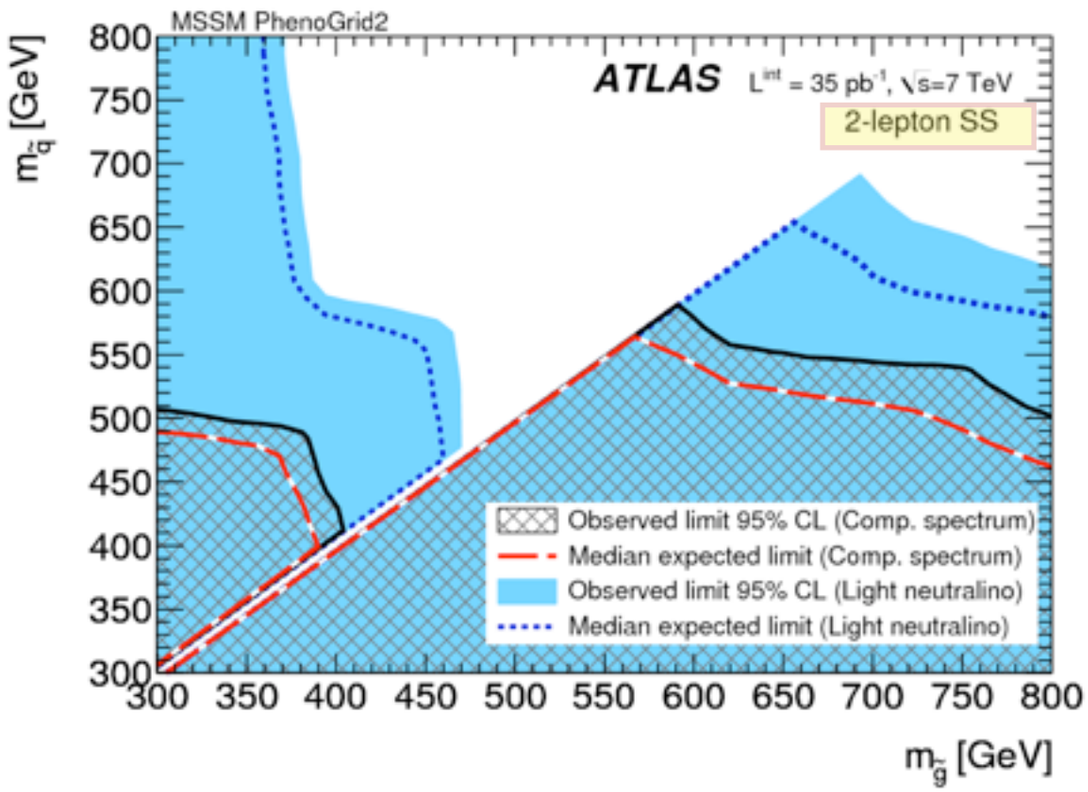


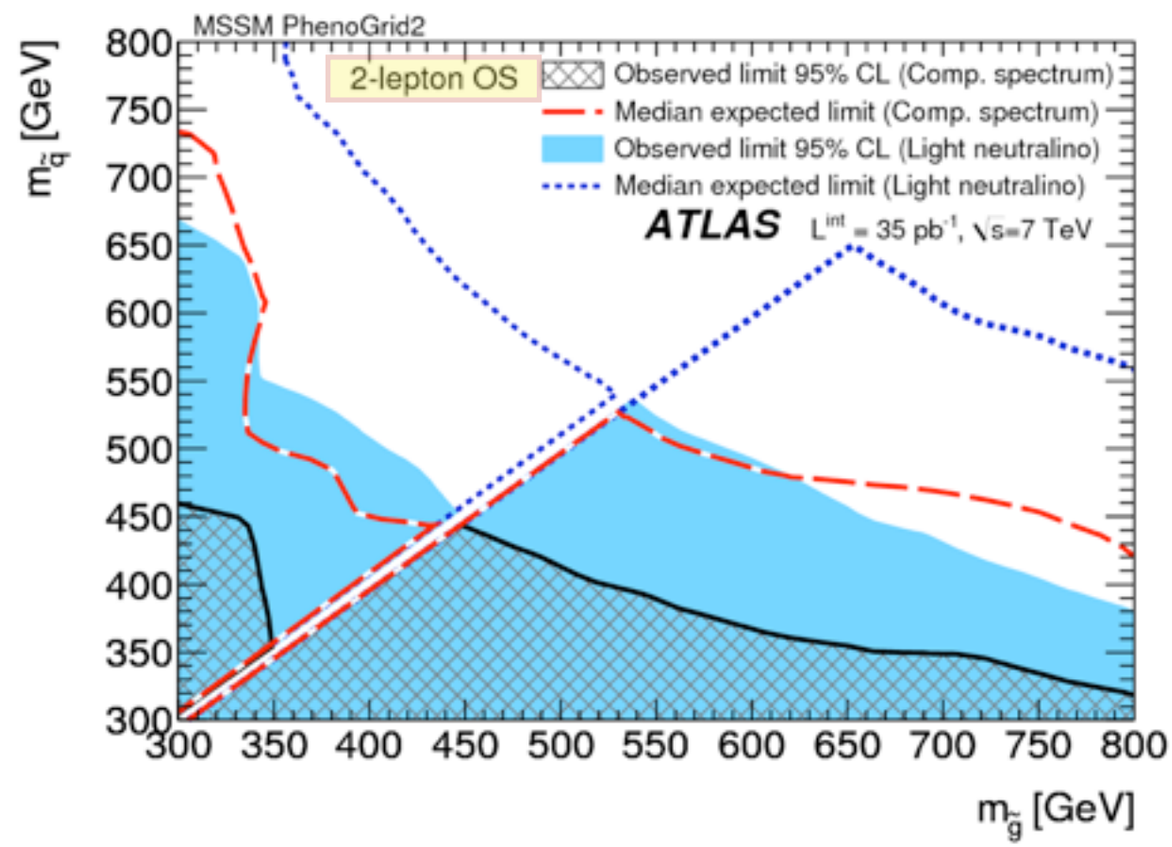
Dilepton PhenoGrid Exclusions

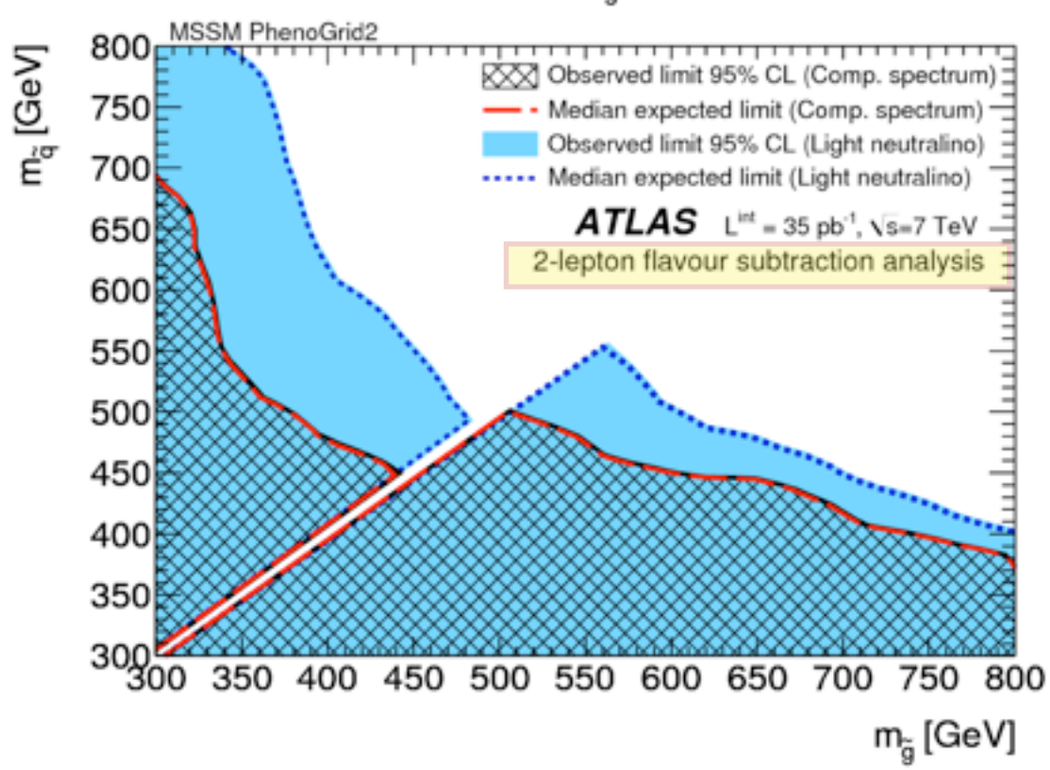
2010 Data

EPJC 71 (2011) 1647

EPJC 71 (2011) 1682







Masses of 3rd generation fermions = 2 TeV
Assume common squark mass and common slepton mass for 2nd generations
Free parameters: three gaugino masses, squark mass, slepton mass

$$m_A = 1000 \text{ GeV}, \mu = 1.5 \min(m_{\tilde{g}}, m_{\tilde{q}}), \tan\beta = 4, A_t = \mu/\tan\beta, A_b = \mu \tan\beta, \text{ and } A_l = \mu \tan\beta.$$