Search for Direct Stop

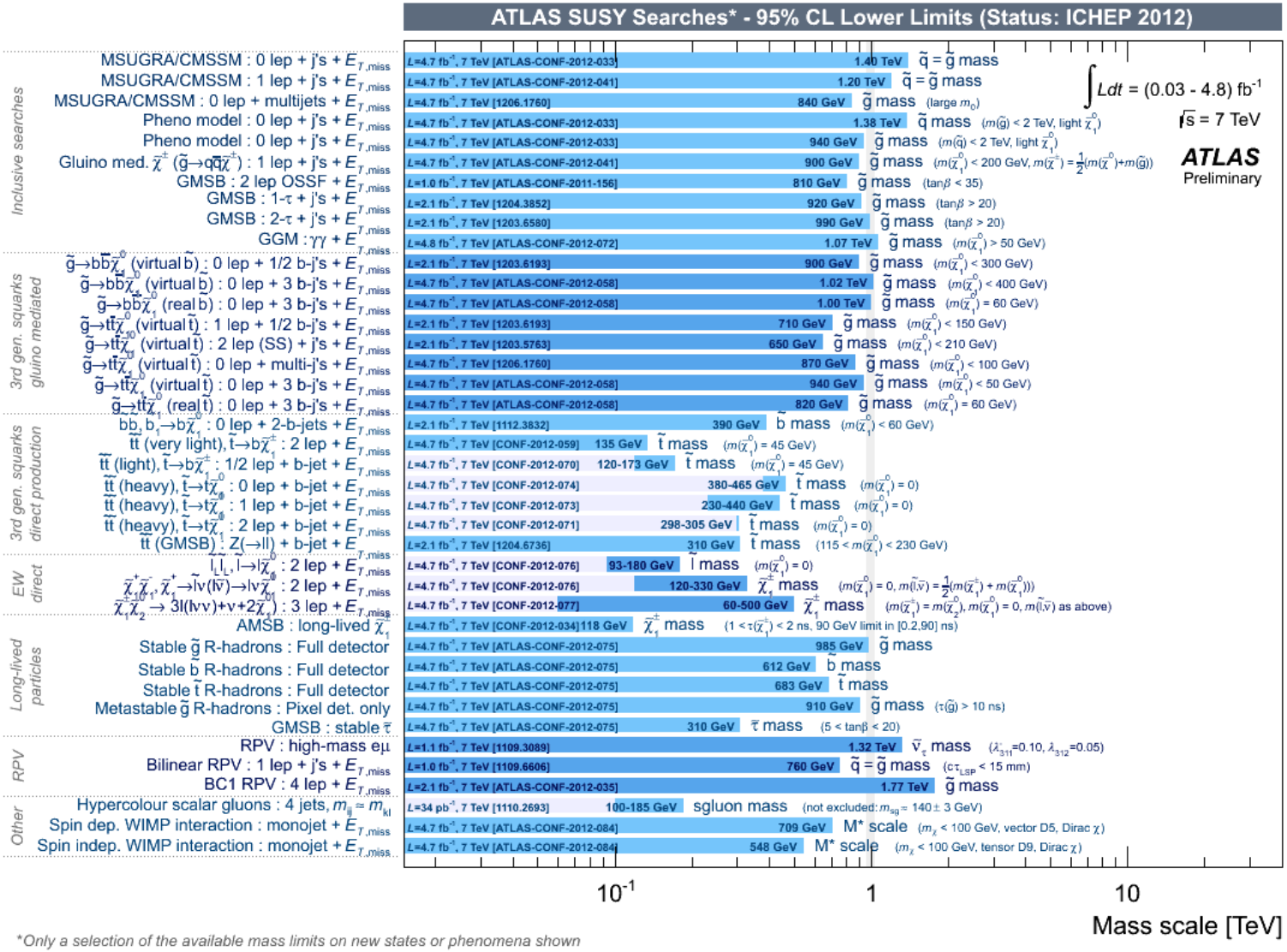
Particle Physics Seminar
Brookhaven National Laboratory
August 9th, 2012

Nathan Triplett (BNL)



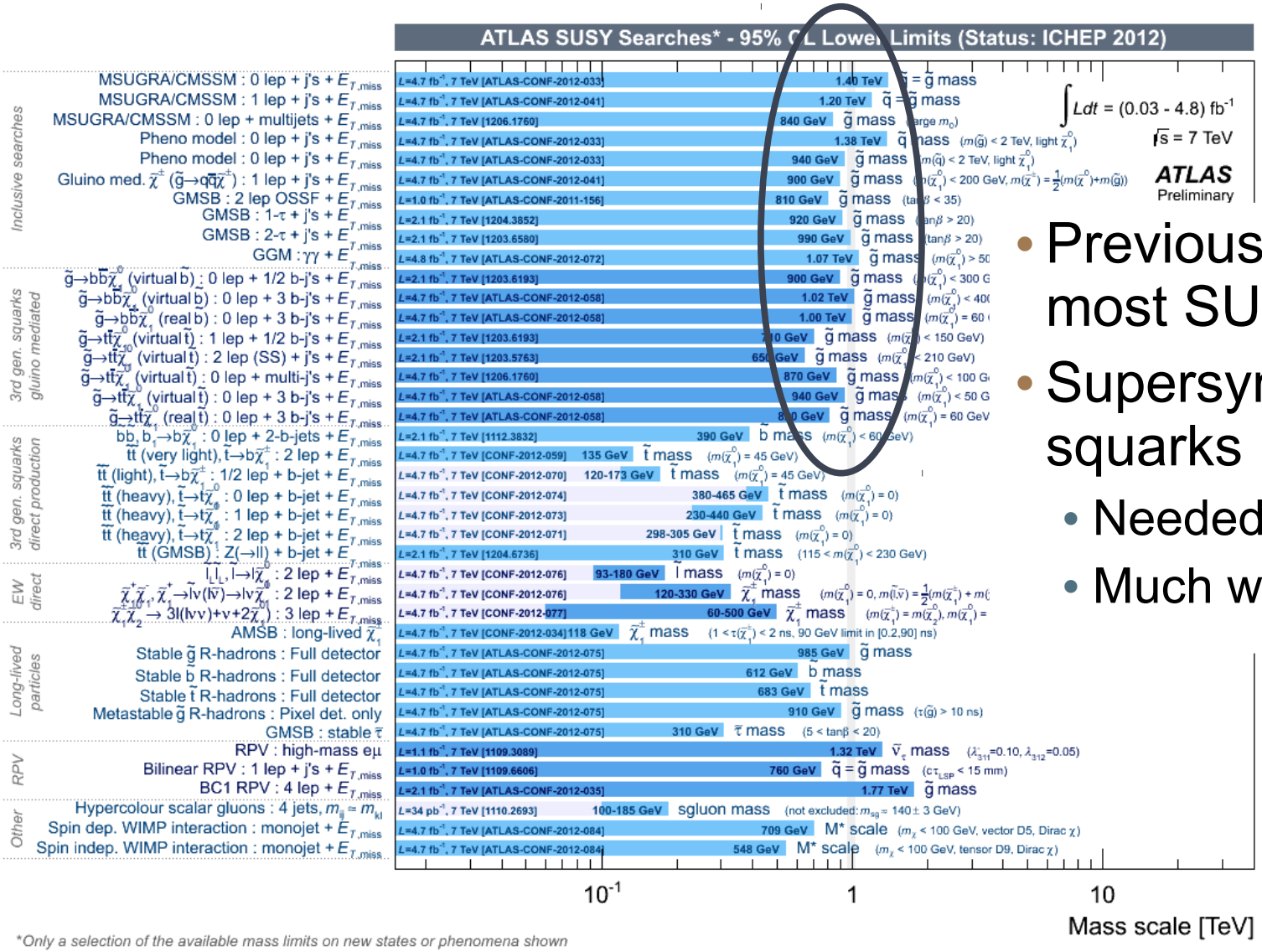


Introduction



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

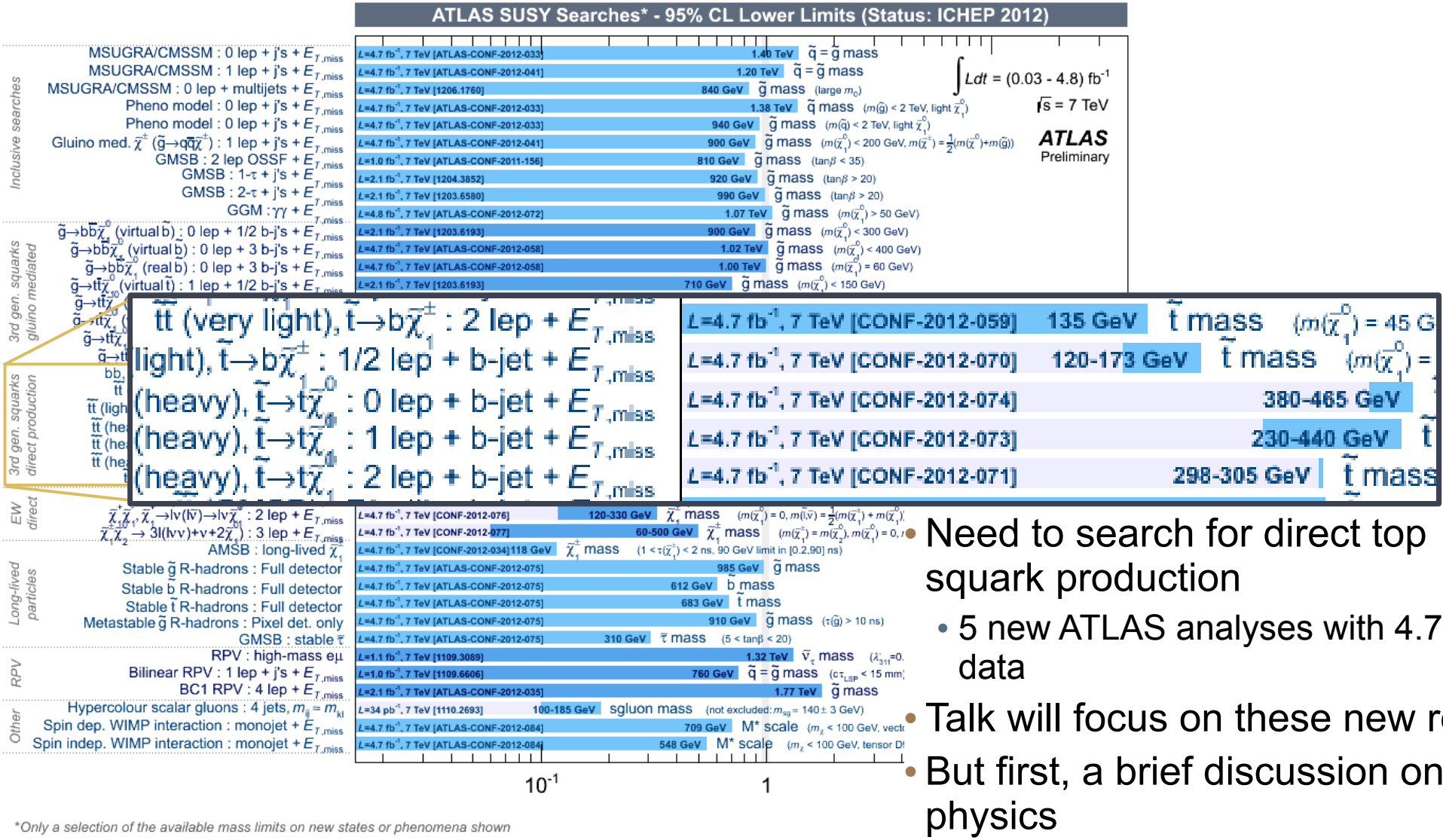
Introduction



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

- Previous mass limits on most SUSY particles ~TeV
- Supersymmetric top squarks may still be light
  - Needed for naturalness
  - Much weaker mass limits

Introduction

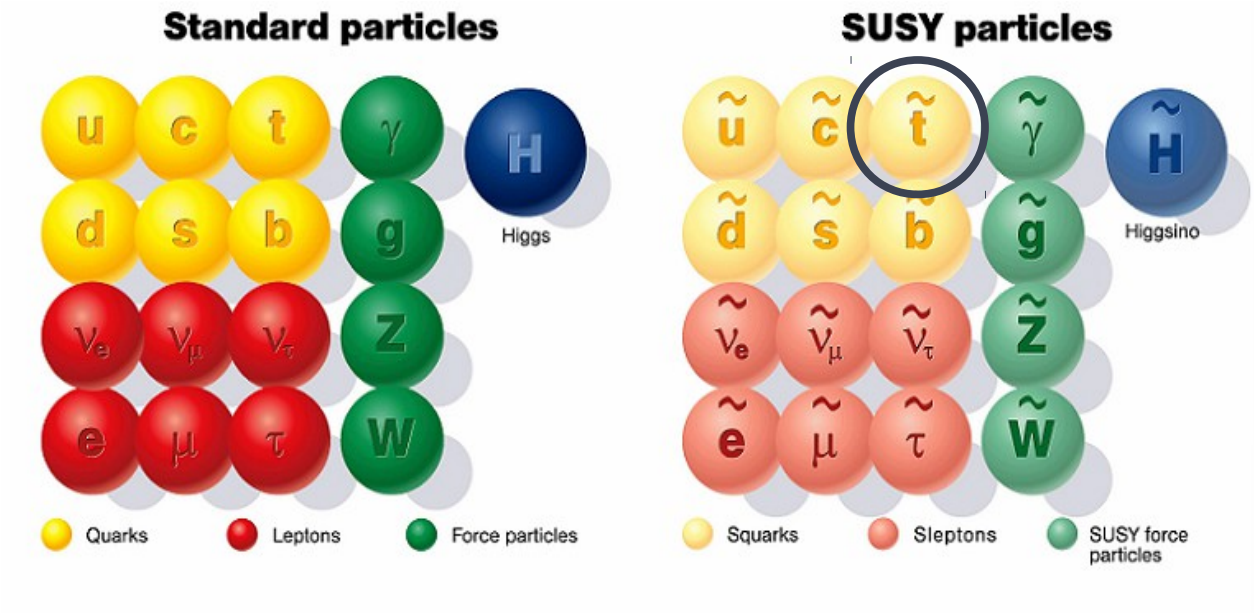


*Only a selection of the available mass limits on new states or phenomena shown

- Need to search for direct top squark production
  - 5 new ATLAS analyses with 4.7 fb^{-1} of data
- Talk will focus on these new results
- But first, a brief discussion on stop physics

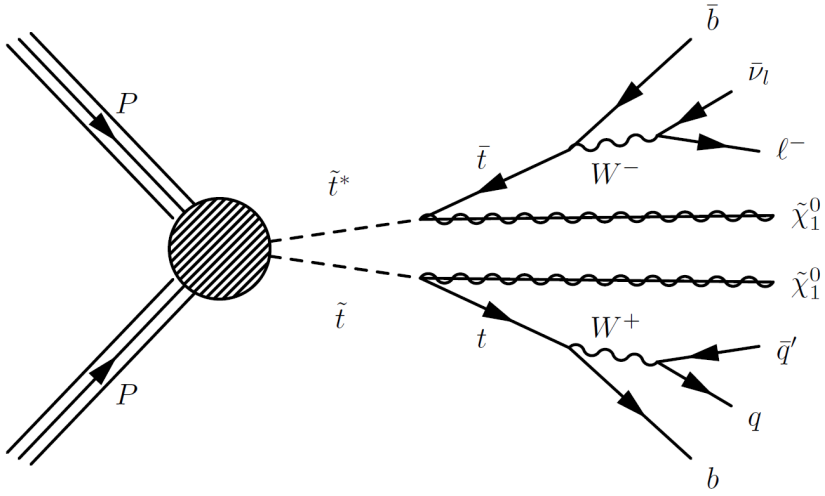
Supersymmetry (SUSY)

- SUSY postulates the existence of a partner particle for every existing particle
  - SM fermion ↔ SUSY boson
  - SM boson ↔ SUSY fermion
- Many new particles to search for
  - So far, no new particles found
- Many free parameters and different SUSY models
  - Each often needing its own analysis
- Mass of SUSY particles are unknown
  - A top squark (stop) mass under ~1 TeV is favored by naturalness arguments
  - A good place to start

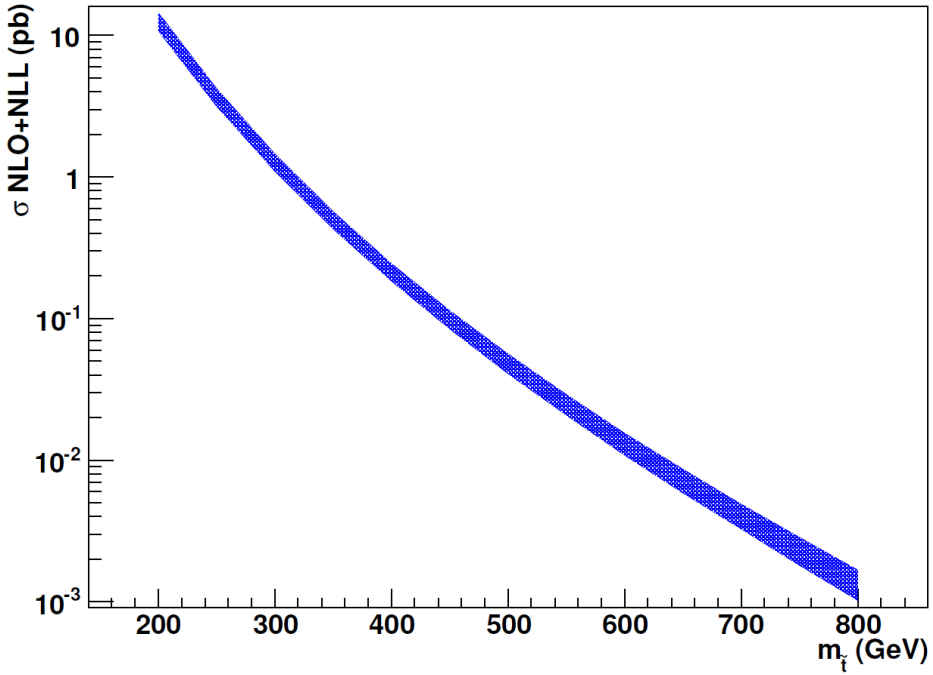


Direct Stop Production

- Several possible ways to produce stops
  - Many are very model dependent
- Pair produced “Direct” stop shown on right
- Cross section for direct stop production depends almost entirely on the stop mass
  - Search is therefore largely model independent
  - Cross section drops rapidly with increasing stop mass



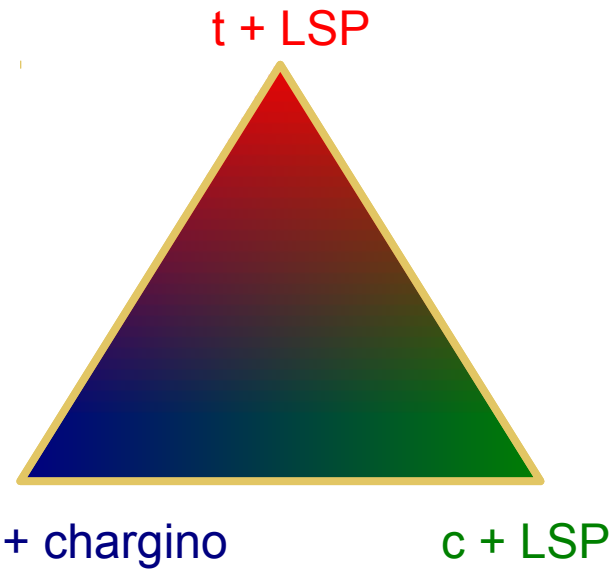
- High mass stop (Heavier than ~350 GeV)
  - Easy to discriminate between top/stop at high mass
  - Few events left
- Low mass stop (Lighter than ~200 GeV)
  - Larger cross section, many events
  - Harder to distinguish from ttbar
- Very low mass stop (Lighter than top)
  - Different kinematics entirely
- Different stop decay modes for different mass hierarchies
  - Need specialized analyses to cover the whole range of masses



Stop Decay Modes

- Decay of stop depends on mass hierarchy
- Stop lighter than top + LSP
  - Can decay into:
    - b + chargino
    - c + LSP
- Stop heavier than top + LSP
  - Can decay into:
    - b + chargino
    - c + LSP
    - t + LSP

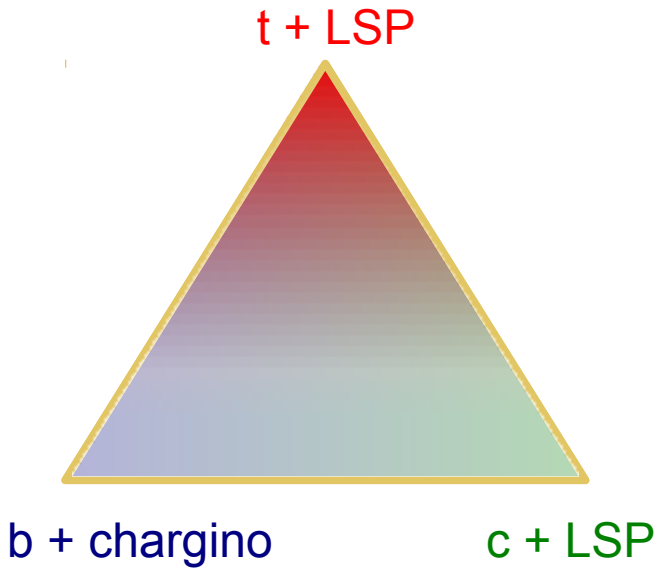




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- Stop heavier than top + LSP
  - Can decay into:
    - b + chargino
    - c + LSP
    - t + LSP
- Final states with charm are hard to identify
  - Start with t + LSP and b + chargino
- Branching fractions unknown
  - Assume 100% to a specific final state
  - Plan to study mixed scenarios in 2012 data





Stop Signal MC Samples

- Several choices in parameters left
- Three sets of samples (grids) created
- Light stop: two grids
  - For stop → b + chargino: three parameters to set
    - Stop, chargino, LSP masses
    - Other SUSY masses > 2 TeV
    - Vary stop and LSP masses to make a 2D grid of points
    - Fix chargino mass in one of two ways
      - Chargino = 106 GeV (just above exclusion limits)
      - Chargino = twice neutralino mass (gaugino universality)
- Heavy stop: one grid
  - For stop → t + LSP: two parameters
    - Stop and LSP masses
    - Other SUSY masses > 2 TeV
    - Stop mass 200-600 GeV
    - LSP mass < stop - top

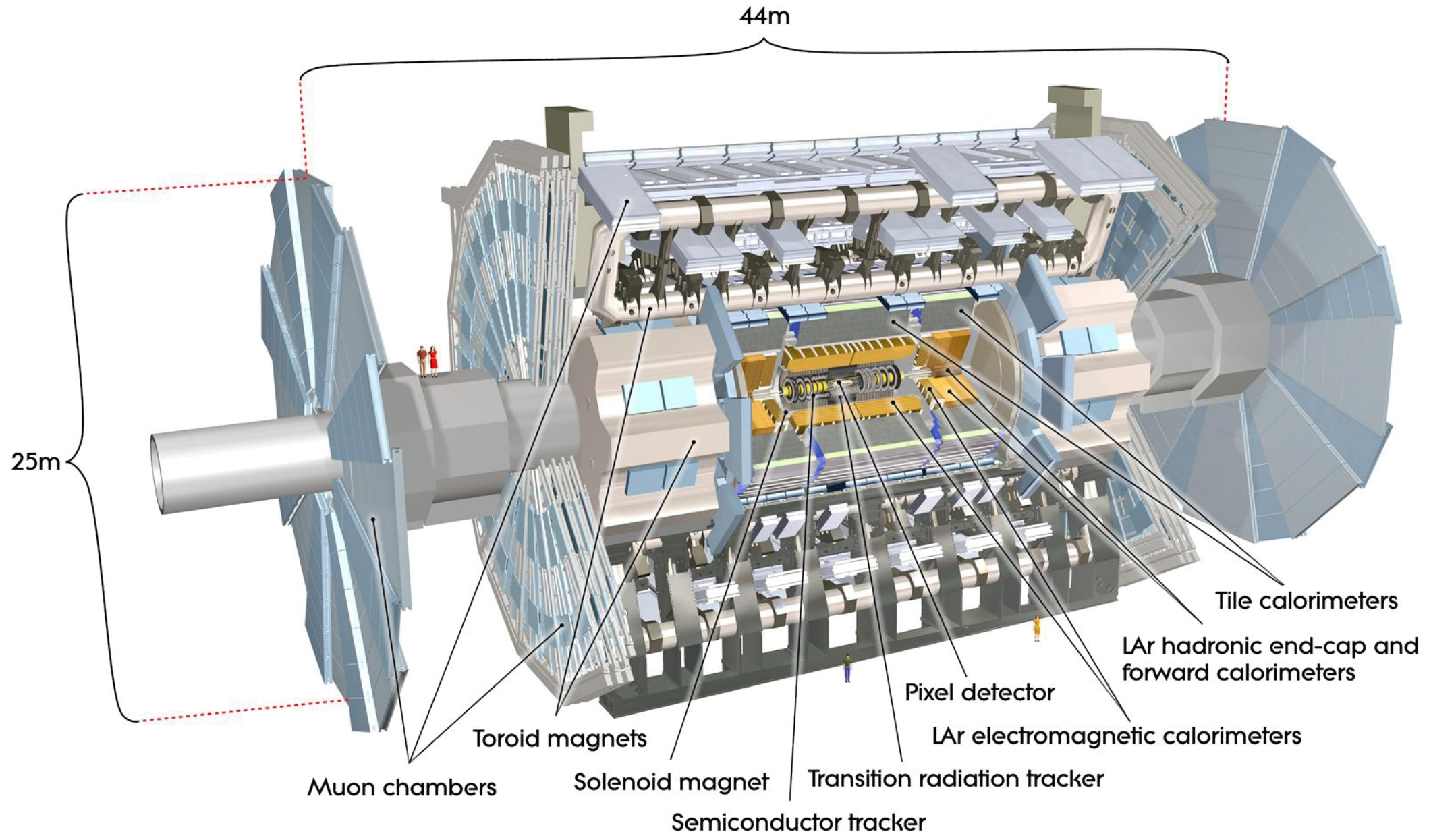
2011 Stop Analyses

- 5 new analyses to study these cases
  - CONF notes released for ICHEP
  - Papers in progress
- 2 analyses for b+chargino
  - One optimized for very light stop
  - One optimized for stop mass near top mass
- 3 analyses for t+LSP
  - Split by top decay modes: 0, 1, 2 leptons (e/mu)

Analysis	CONF note
$t_1 \rightarrow$ b+chargino: 2-lepton, light stop	*ATLAS-CONF-2012-059*
$t_1 \rightarrow$ b+chargino: 1-2 lepton	*ATLAS-CONF-2012-070*
$t_1 \rightarrow$ t+LSP: 0-lepton	*ATLAS-CONF-2012-074*
$t_1 \rightarrow$ t+LSP: 1-lepton	*ATLAS-CONF-2012-073*
$t_1 \rightarrow$ t+LSP: 2-lepton	*ATLAS-CONF-2012-071*

← Submitted to PRL
CERN-PH-EP-2012-201

Aside: the ATLAS Detector

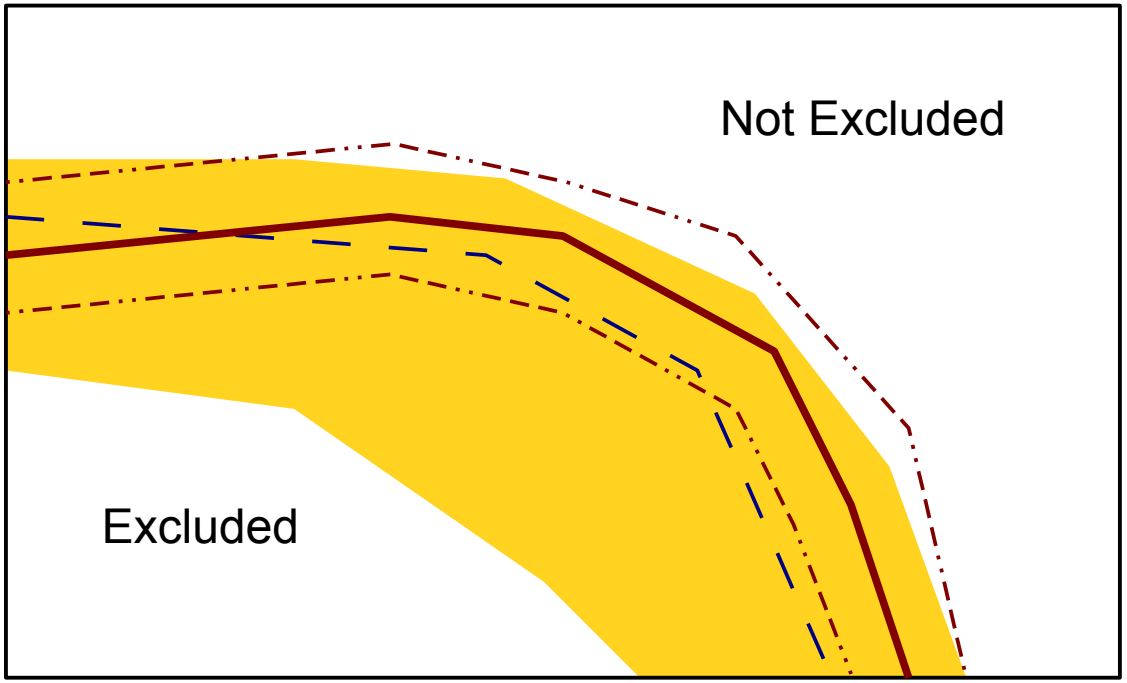


Aside: Leptons, Jets, EtMiss

- Stop decays into top + LSP
  - top decays into W+ b-quark
    - W decays into hadron pair or lepton+neutrino
- Look for events with:
  - Hadrons → Shower into “jets” which are measured by the calorimeter
  - b-quarks → Form b-hadrons and shower into jets
    - Can distinguish from other jets some fraction of the time (60-75%)
  - Leptons:
    - Electrons and muons are easily detectable by the EM-calorimeter and muon detectors
    - Taus are tricky when they decay into hadrons
      - Look very jet-like and are usually identified as such
  - Neutrinos/LSP
    - Don't interact with the detecter at all
    - Only visible as an imbalance in the total energy: “missing energy”
    - Can't distinguish between the two

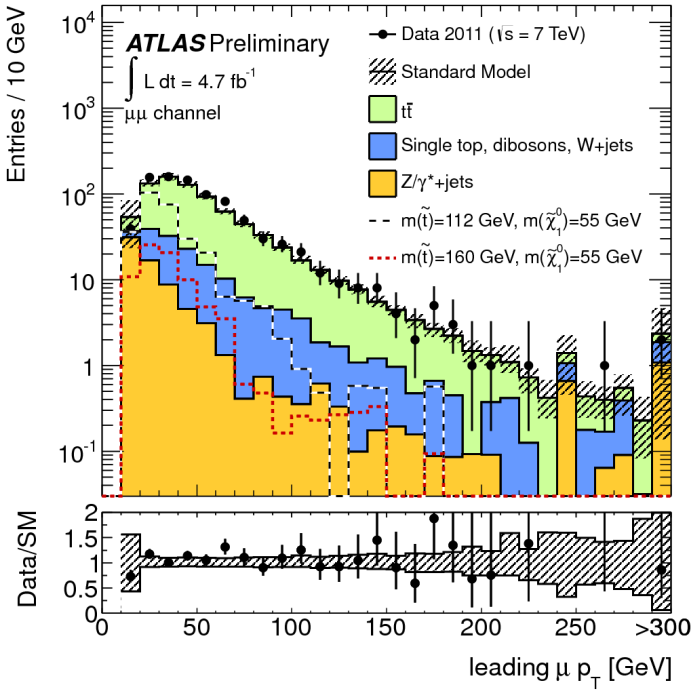
Aside: Limit Plots

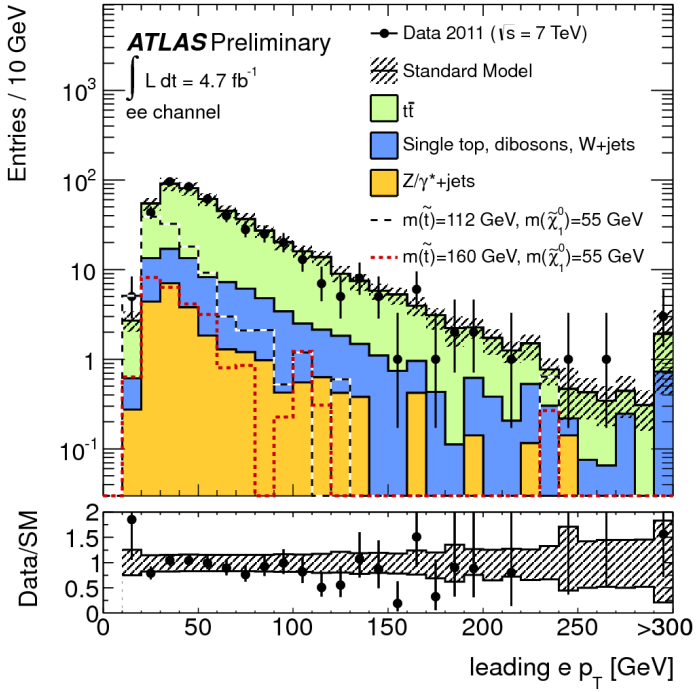
- SUSY limit plot legend:
  - **Navy blue line**: Expected result
  - Yellow band: +/- 1 sigma bands (experimental uncertainties only)
  - **Dark red line**: Observed limit
  - Red dashed lines: +/- 1 sigma signal theory uncertainty bands on observed limit
    - -1 sigma band is the limit quoted by ATLAS papers



Light Stop: 2-Lepton

- 2 leptons:
  - Electron p_T > 17 GeV and Muon p_T > 12 GeV
  - Lepton p_T < 30 GeV
  - Oppositely signed
- At least 1 jet: p_T > 25 GeV
- Di-lepton mass:
  - At least 20 GeV. Veto at Z-mass for same flavor
- EtMiss > 20 GeV. EtMiss significance > 7.5 $GeV^{1/2}$

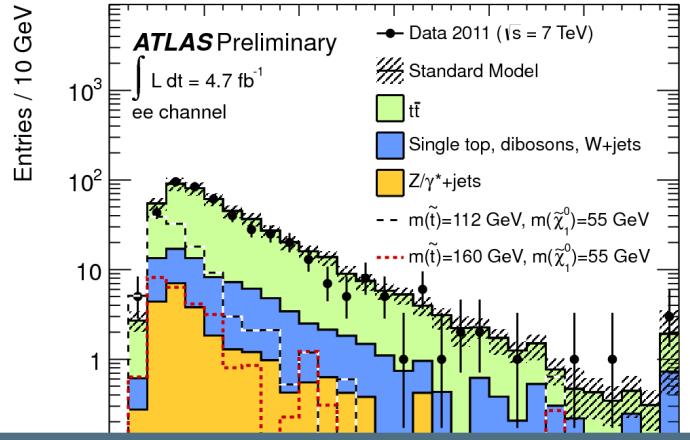


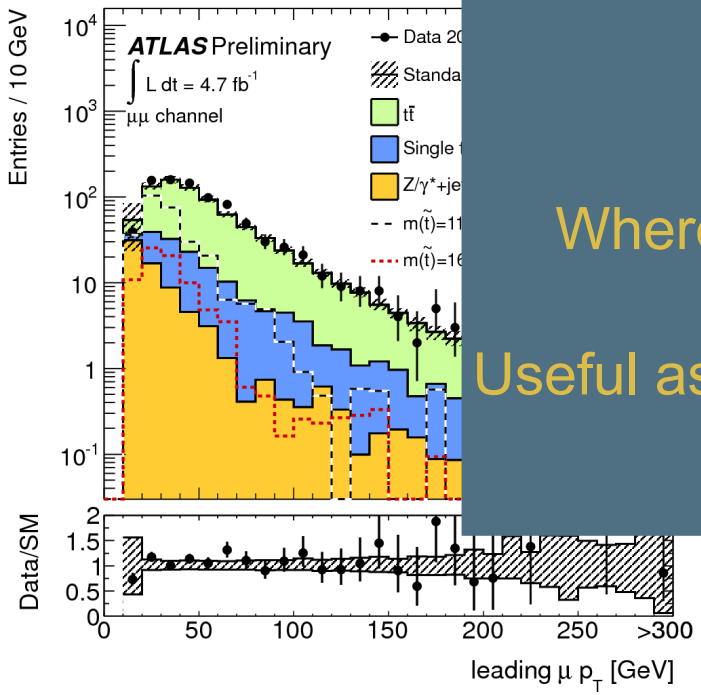


- No b-tagging: very inefficient for low p_T b-jets
- Main backgrounds:
  - ttbar → control region with 1 b-tagged jet
  - Z+jets → control region with z-mass veto reversed (81 < m_{ll} < 101 GeV)
- Minor backgrounds:
  - Single top, diboson, W+jets, Z→tau
  - Estimate from MC

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Missing ET Significance: EtMiss/Sqrt(H_T)

Where H_T is the total energy of all jets/leptons.

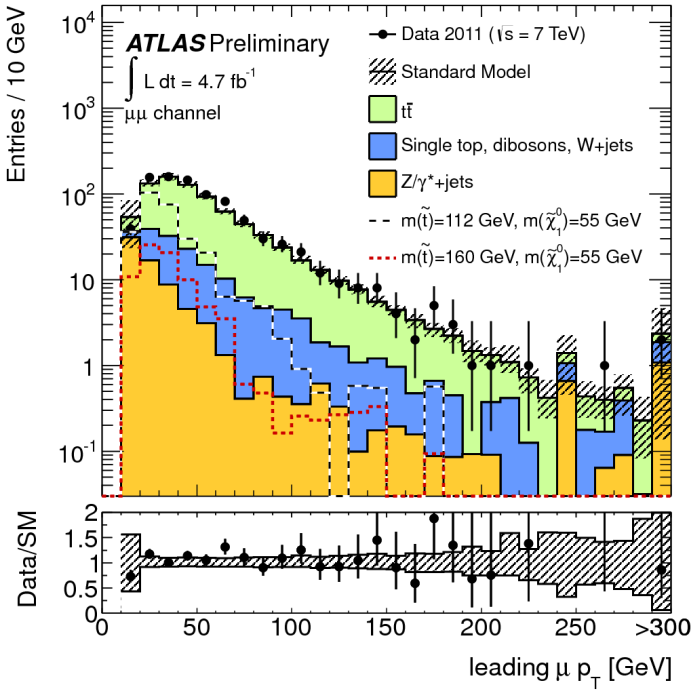
Useful as less sensitive to "fake" missing energy than EtMiss directly

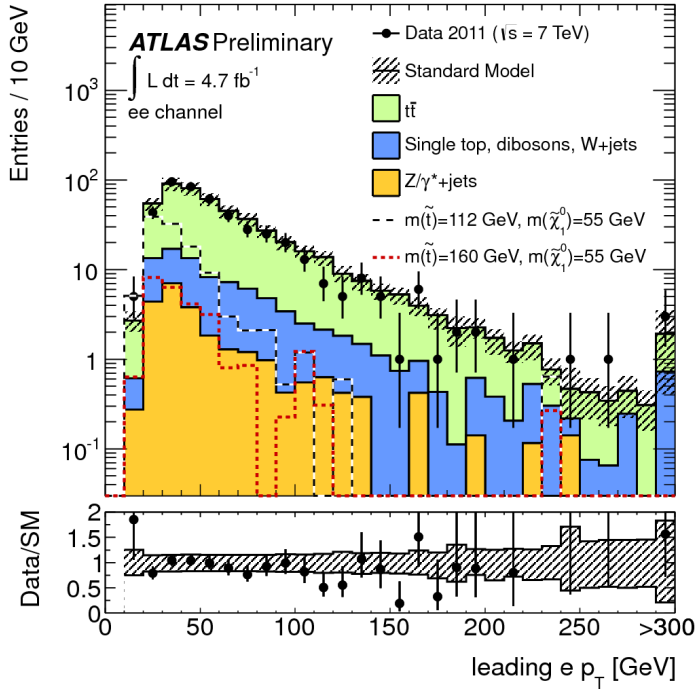
m_{ll} < 101 GeV)

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Light Stop: 2-Lepton

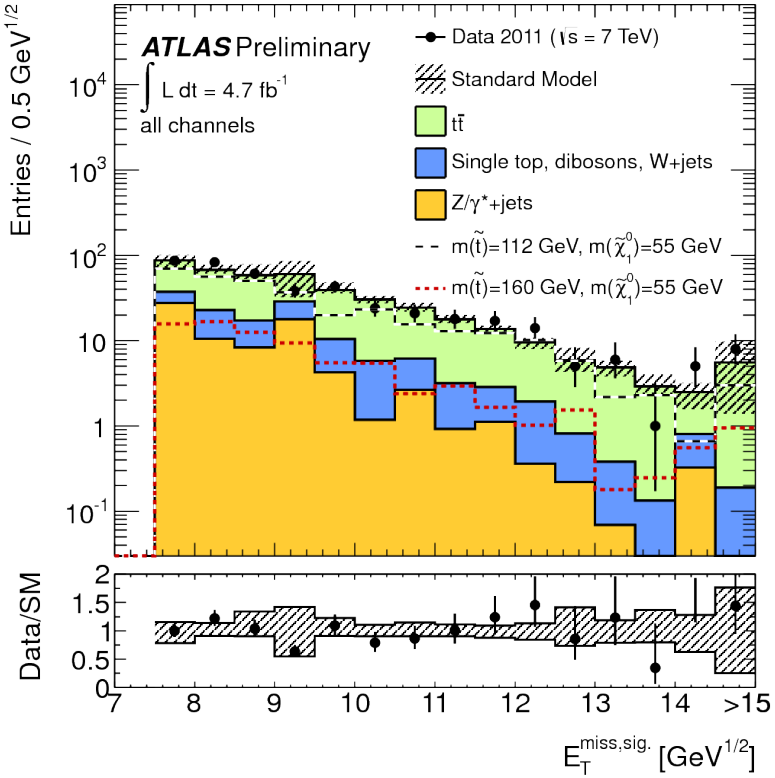
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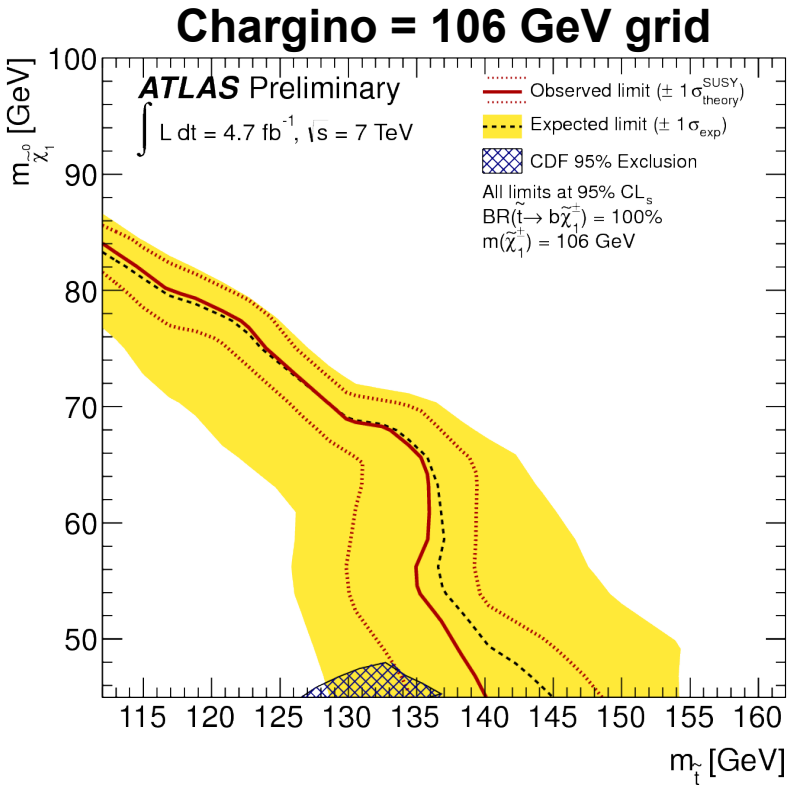




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Light Stop Results

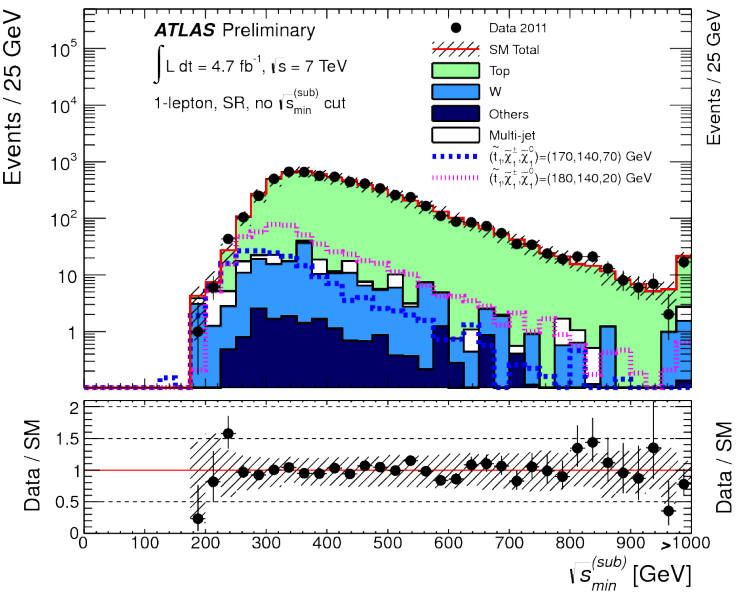


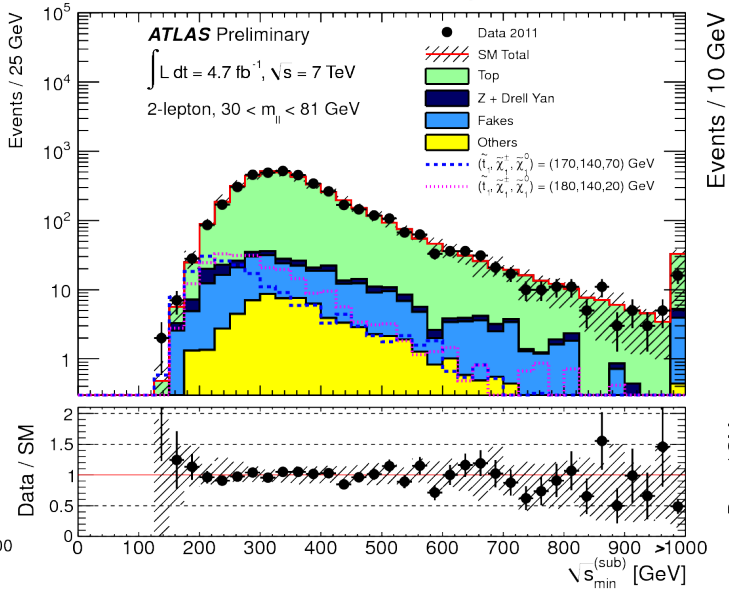


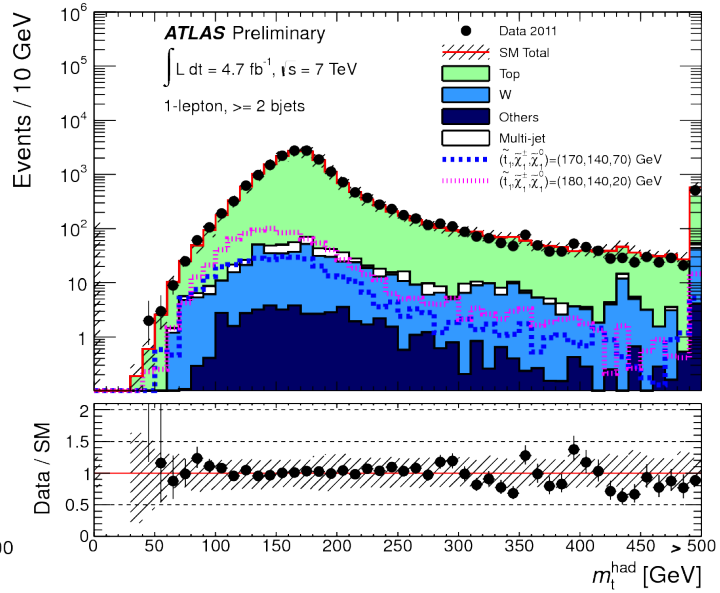
	ee	*eμ*	*μμ*	all
$t\bar{t}$	44 ± 4 ± 5	139 ± 7 ± 22	111 ± 8 ± 10	293 ± 12 ± 34
Z/γ^*+jets	5 ± 1 ± 2	23 ± 2 ± 8	48 ± 16 ± 27	76 ± 16 ± 27
Single top	3 ± 0.5 ± 1	12 ± 1 ± 2	12 ± 1 ± 2	28 ± 2 ± 5
W+jets	3 ± 3 ± 3	5 ± 2 ± 1	6 ± 2 ± 1	13 ± 3 ± 3
Diboson	4 ± 0.4 ± 0.5	9 ± 0.7 ± 2	10 ± 0.7 ± 1	22 ± 1 ± 3
multijet	$2.9\ ^{+3.2}_{-2.9}$ ± 2.2	2.0 ± 1.4 ± 0.3	3.0 ± 2.8 ± 0.3	8.0 ± 3.7 ± 2.3
Total	61 ± 6 ± 6	189 ± 8 ± 21	190 ± 19 ± 31	440 ± 21 ± 43
Data	48	188	195	431
σ_{vis} (exp. limit) [fb]	4.9	11.1	16.2	22.0
σ_{vis} (obs. limit) [fb]	3.3	10.9	16.9	21.0
$m(\tilde{t}, \tilde{\chi}_1^0) = (112, 55)$ GeV	44.1 ± 4.8	137 ± 8	140 ± 8	322 ± 13
$m(\tilde{t}, \tilde{\chi}_1^0) = (160, 55)$ GeV	8.8 ± 1.5	31.4 ± 2.7	36.5 ± 2.9	76.6 ± 4.3

Stop Mass ~ Top Mass (1,2-Leptons)

$$\sqrt{s}_{min}^{(sub)} = \left\{ \left(\sqrt{m_{(sub)}^2 + p_{T(sub)}^2} + \sqrt{(m^{miss})^2 + (E_T^{miss})^2} \right)^2 - \left(\mathbf{p}_{T(sub)} + \mathbf{p}_T^{miss} \right)^2 \right\}^{\frac{1}{2}}$$







1 lepton selection

- Electron (pT > 25 GeV) OR muon (pT > 20 GeV)
- mT(lepton, EtMiss) > 30 GeV
- At least 4 jets (pT > 20 GeV)
  - At least 2 of which are b-tagged
- EtMiss > 40 GeV
- Upper cut on hadronic top mass
- $\sqrt{S}_{min}^{(sub)}$ < 250 GeV

2 lepton selection

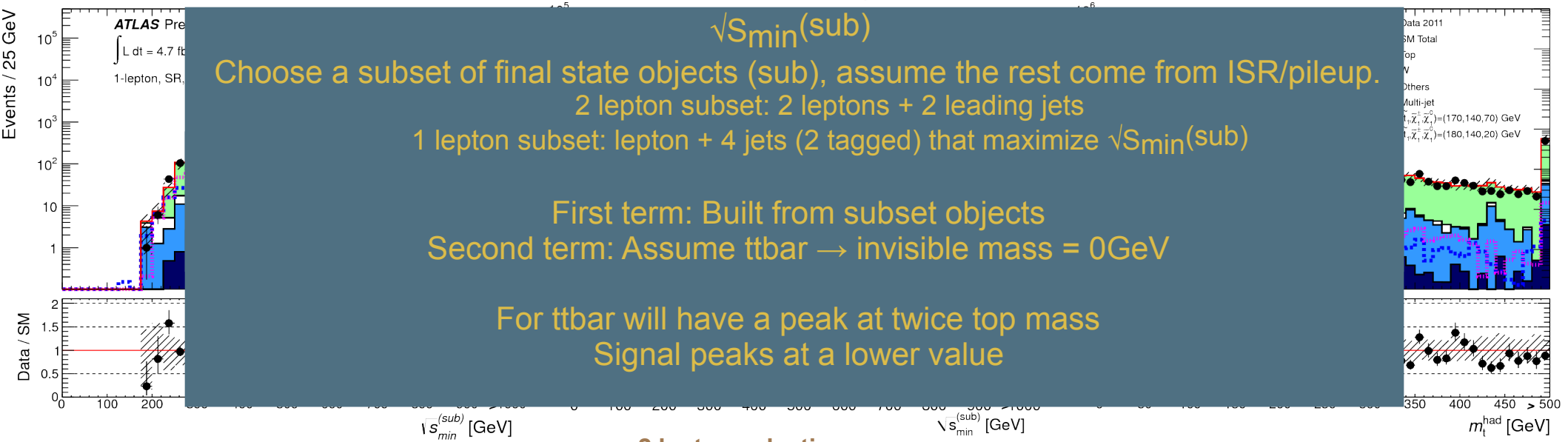
- Exactly 2 opposite-sign leptons
- 30 GeV < m_{ll} < 81 GeV
- At least 2 jets (pT > 20 GeV)
  - At least 1 of which is b-tagged
- EtMiss > 40 GeV
- Upper cut on hadronic top mass
- $\sqrt{S}_{min}^{(sub)}$ < 225 GeV (SR1)
- $\sqrt{S}_{min}^{(sub)}$ < 235 GeV and m_{lljj} < 140 GeV (SR2)

Control Regions

- Top pair production
  - Select on top mass window and relax $\sqrt{S}_{min}^{(sub)}$ cut
- W+Jets (1 lepton)
  - Select top mass > 250 GeV and m_{bb} < 50 GeV
- Z+Jets (2 lepton)
  - Select for 81 < mll < 101 GeV

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$\sqrt{S}_{min}^{(sub)}$

Choose a subset of final state objects (sub), assume the rest come from ISR/pileup.

2 lepton subset: 2 leptons + 2 leading jets

1 lepton subset: lepton + 4 jets (2 tagged) that maximize $\sqrt{S}_{min}^{(sub)}$

First term: Built from subset objects

Second term: Assume ttbar → invisible mass = 0GeV

For ttbar will have a peak at twice top mass

Signal peaks at a lower value

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2 lepton selection

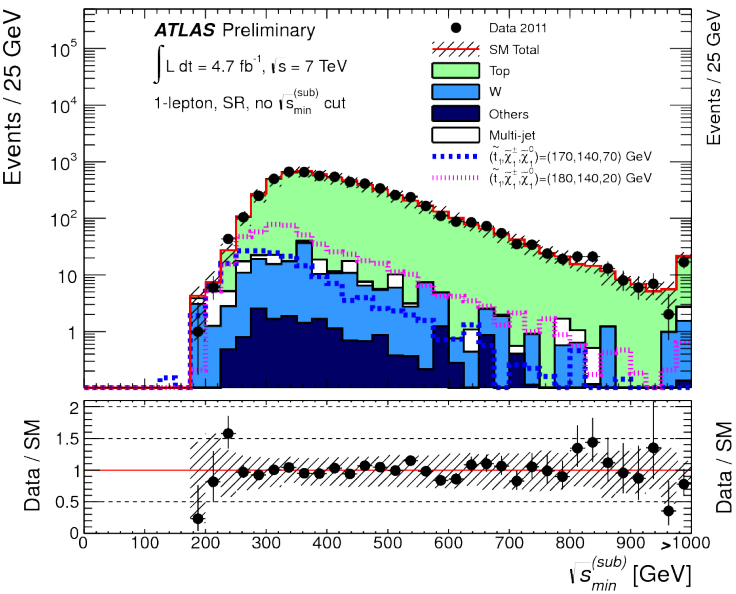
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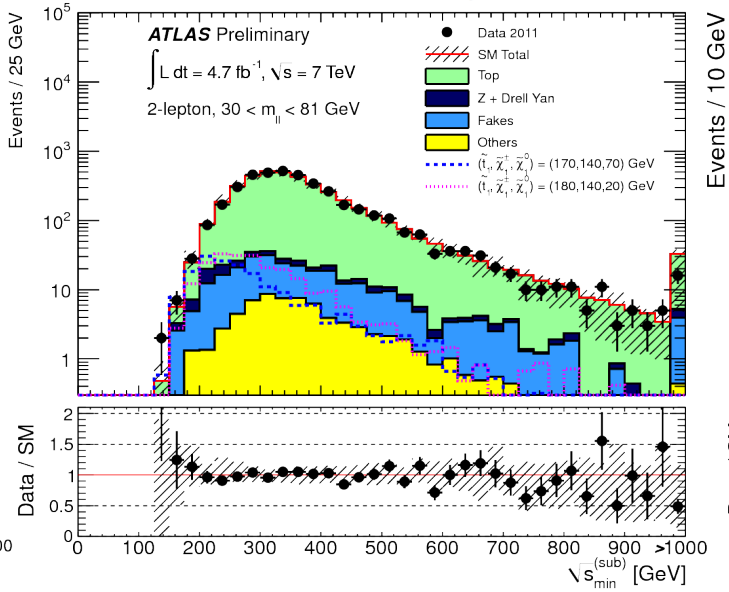
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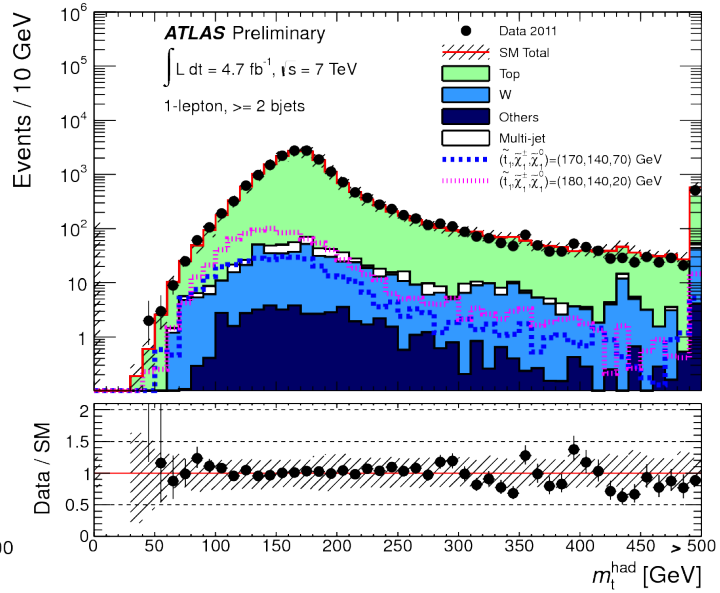
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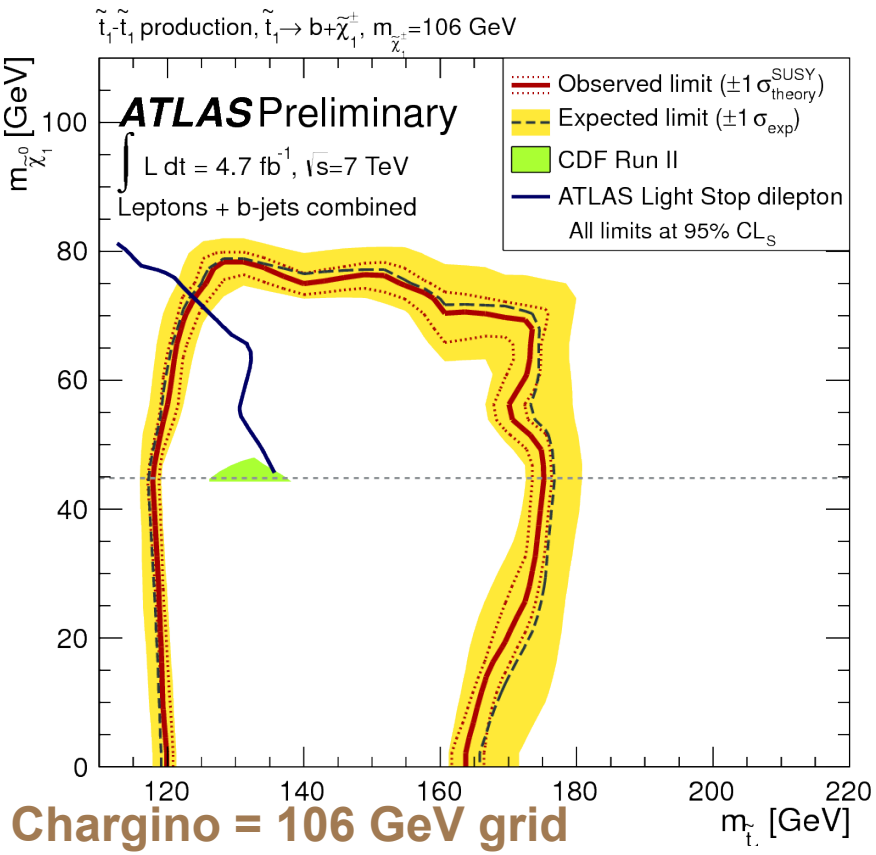
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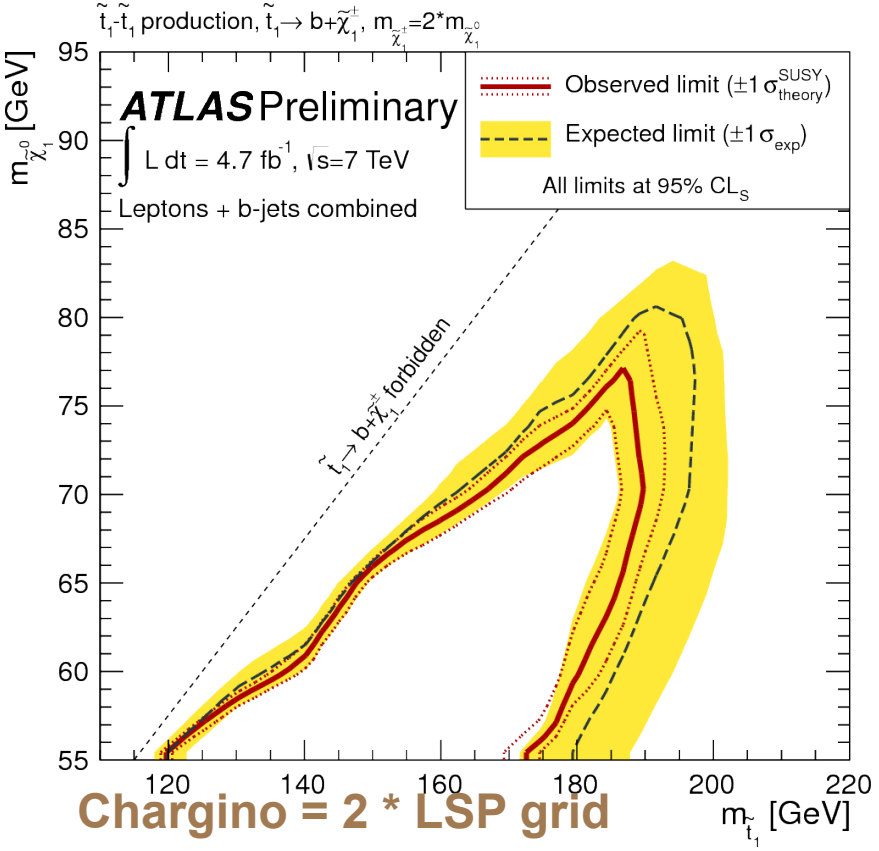
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Results



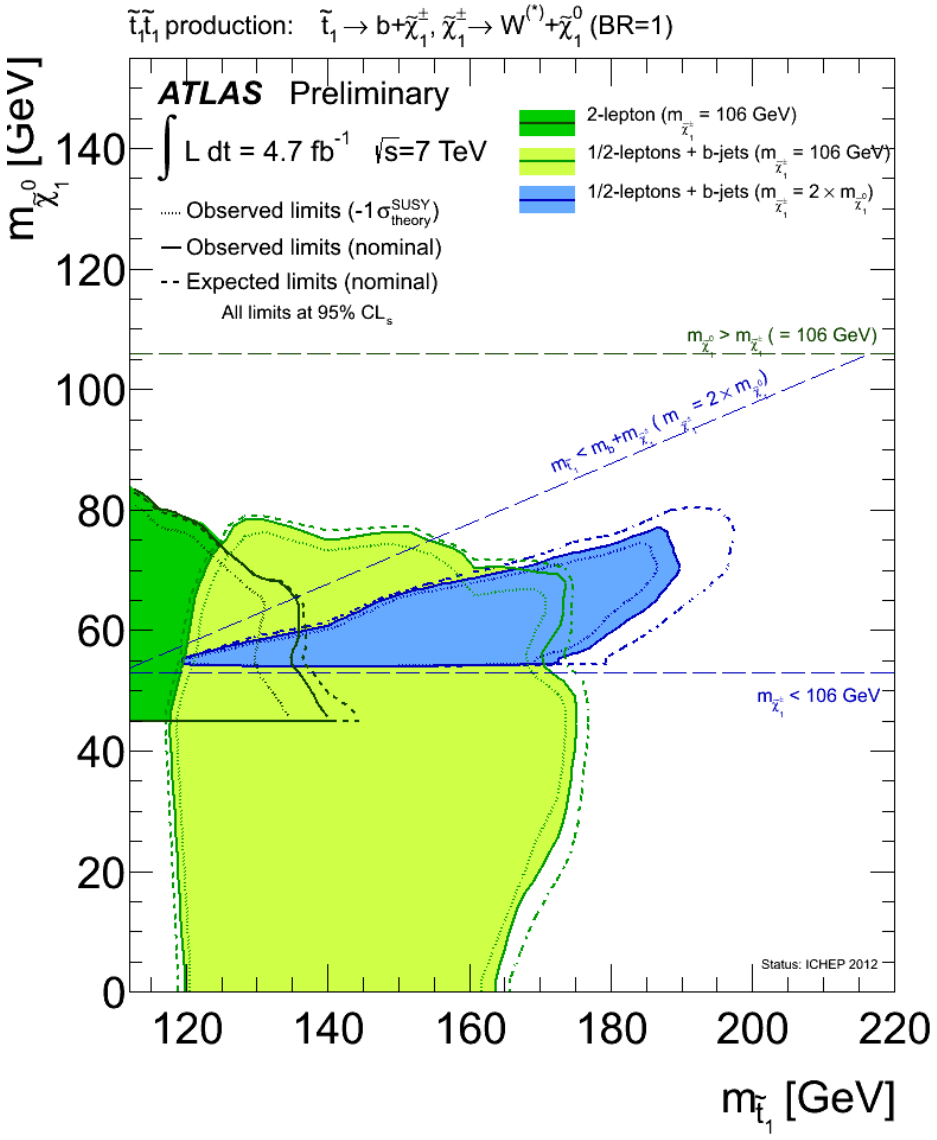
Chargino = 106 GeV grid



Chargino = 2 * LSP grid

	Number of events		
Process	1LSR	2LSR1	2LSR2
Top	$24 \pm 3 \pm 5$	$89 \pm 6 \pm 10$	$36 \pm 2 \pm 5$
W+jets	$6 \pm 1 \pm 2$	n/a	n/a
Z+jets	$0.5 \pm 0.3 \pm 0.3$	$11 \pm 4 \pm 3$	$3 \pm 1 \pm 1$
Fake leptons	$7 \pm 1 \pm 2$	$12 \pm 5 \pm 11$	$6 \pm 4 \pm 4$
Others	$0.3 \pm 0.1 \pm 0.1$	$2.7 \pm 0.9 \pm 0.7$	$0.9 \pm 0.2 \pm 0.5$
Total SM	$38 \pm 3 \pm 7$	$115 \pm 8 \pm 15$	$46 \pm 4 \pm 7$
Data	50	123	47
$m_{\tilde{t}_1} = 170$ GeV, $m_{\tilde{\chi}_1^0} = 70$ GeV	$26 \pm 2 \pm 6$	$57 \pm 3 \pm 6$	$36 \pm 2 \pm 4$
$m_{\tilde{t}_1} = 180$ GeV, $m_{\tilde{\chi}_1^0} = 20$ GeV	$20 \pm 2 \pm 4$	$41 \pm 3 \pm 5$	$27 \pm 2 \pm 3$

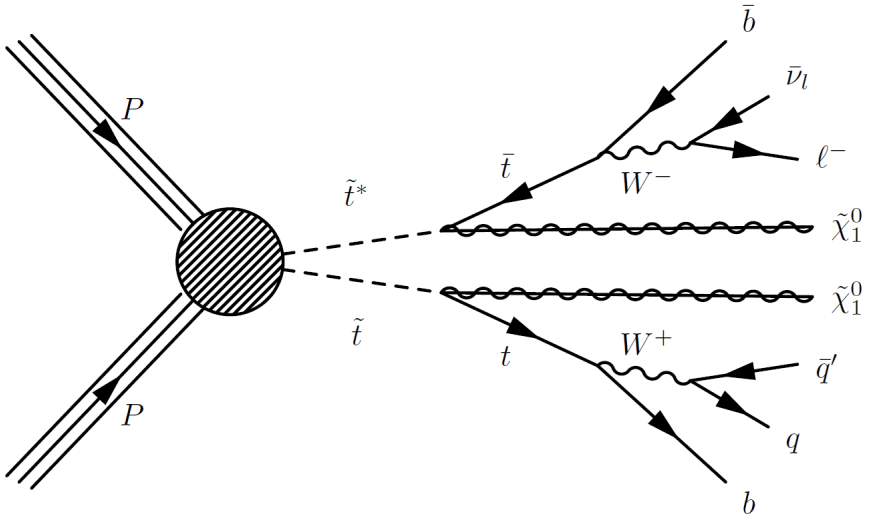
Light Stop Summary



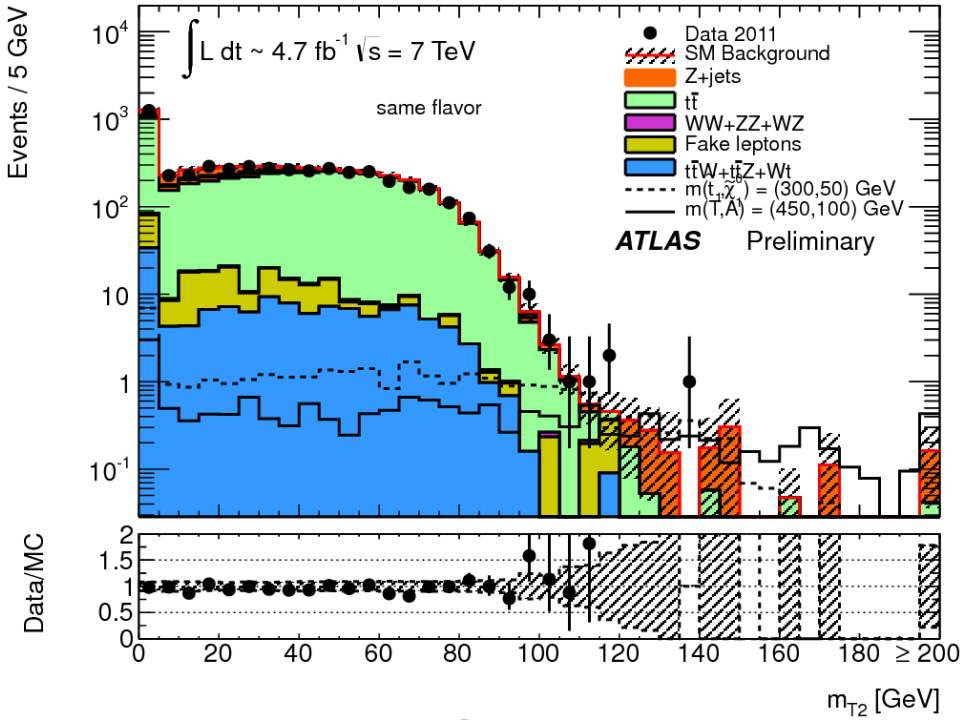
Heavy Stop

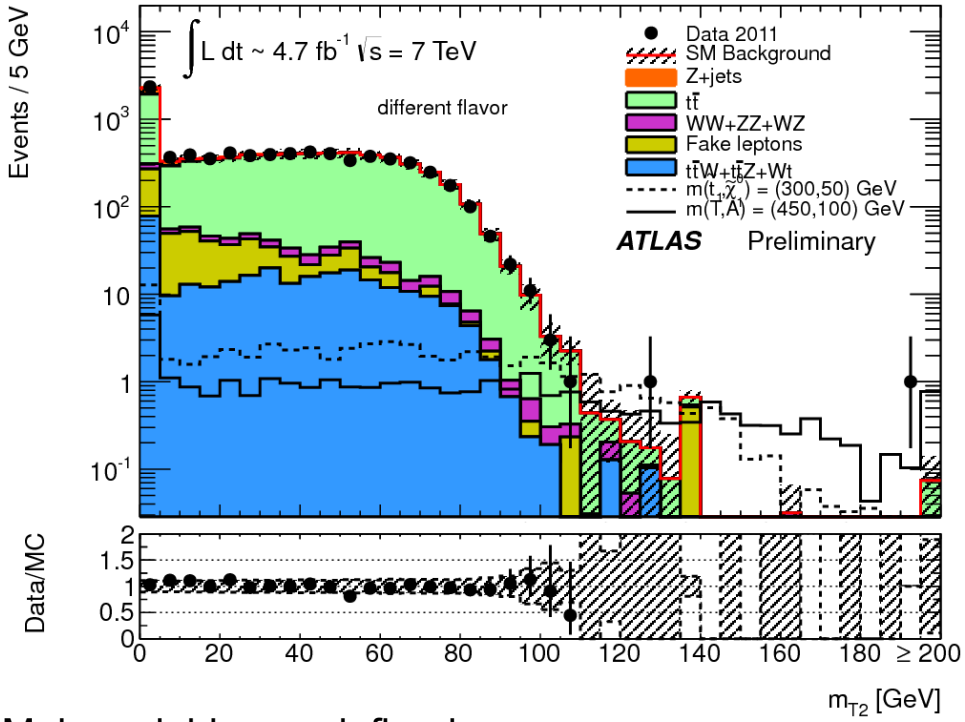
- Three analyses to look at decay chain:
  Stop → LSP + top → LSP + W + b

- Minimum stop mass ~200 GeV
- Split into three orthogonal searches depending on number of final state leptons
  - Consider lepton to be only e/mu in splitting final states
  - Very different kinematics, need separate optimization for each final state
  - Plan to combine results at some point



2-Lepton





Event Selection

- Exactly 2 opposite sign leptons
- m_{ll} > 20 GeV
- Same flavor leptons: m_{ll} < 71 GeV or m_{ll} > 111 GeV
- At least 2 jets with p_T 50/25 GeV
  - Same flavor leptons: at lest 1 b-tagged jet
- Value of m_{T2} > 120 GeV

- Main variable $\mathbf{m_{T2}}$ defined as:

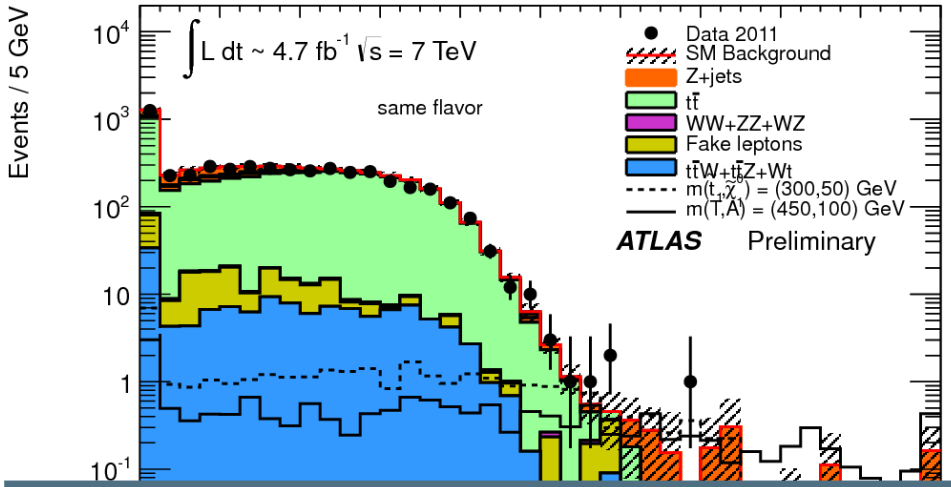
$$m_{T2}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{miss}) = \min_{\mathbf{q}_T+\mathbf{r}_T=\mathbf{p}_T^{miss}} \left\{ \max[\, m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{r}_T)\,] \right\}$$

- Minimization over all decompositions of pTMiss
- For ttbar, mT2 has a sharp endpoint at the W mass

Control Regions

- Control region for ttbar
  - Select for 85 < m_{T2} < 100 GeV
- Control region for Z+Jets
  - Select events with 71 < m_{ll} < 111 GeV

2-Lepton

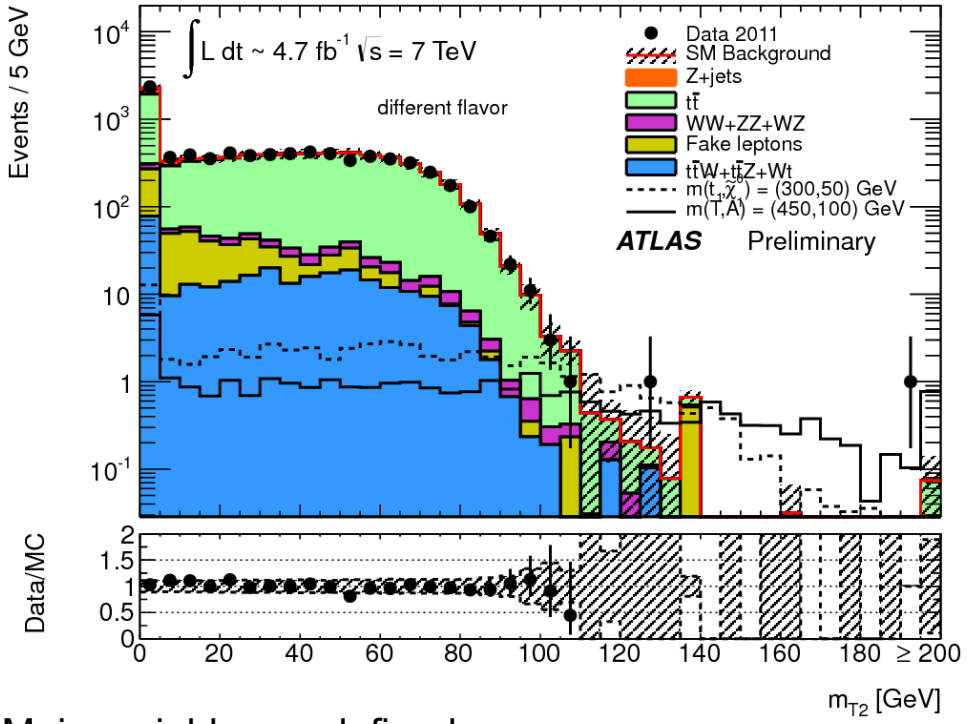


m_{T2}

For ttbar decaying into a pair of leptons and neutrinos, try to un-entangle each neutrino's pT

Take all q_T+r_T combinations and pick the one that minimizes m_{T2} (numerically)

For ttbar, there is a very sharp endpoint at the W mass. Much flatter for stop.



- Main variable $\mathbf{m_{T2}}$ defined as:

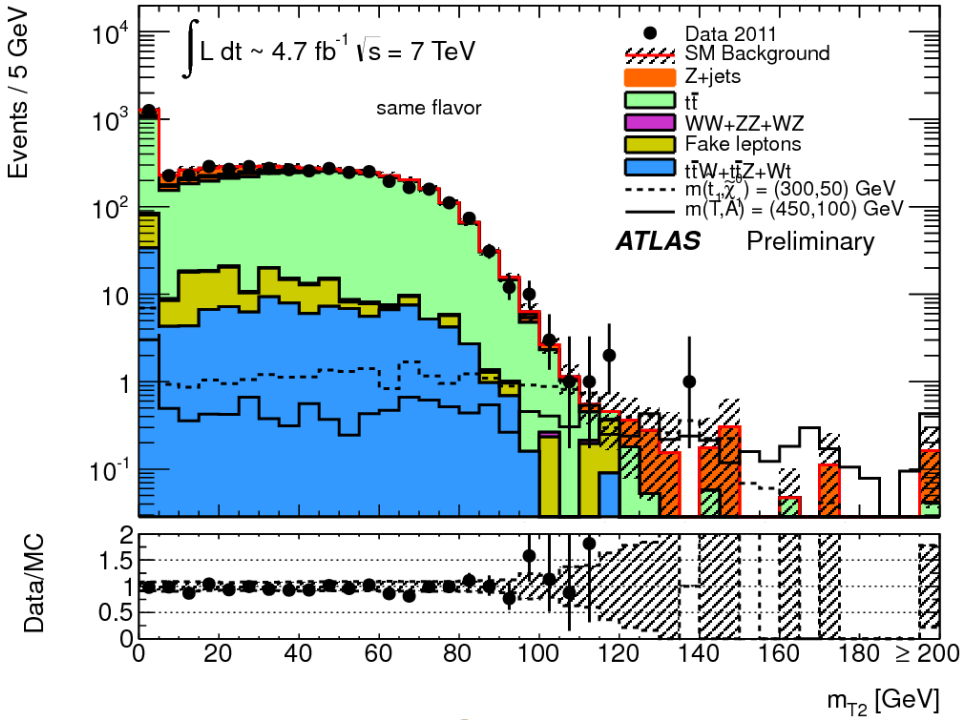
$$m_{T2}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{\text{miss}}) = \min_{\mathbf{q}_T+\mathbf{r}_T=\mathbf{p}_T^{\text{miss}}} \left\{ \max[\, m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{r}_T) \,] \right\}$$

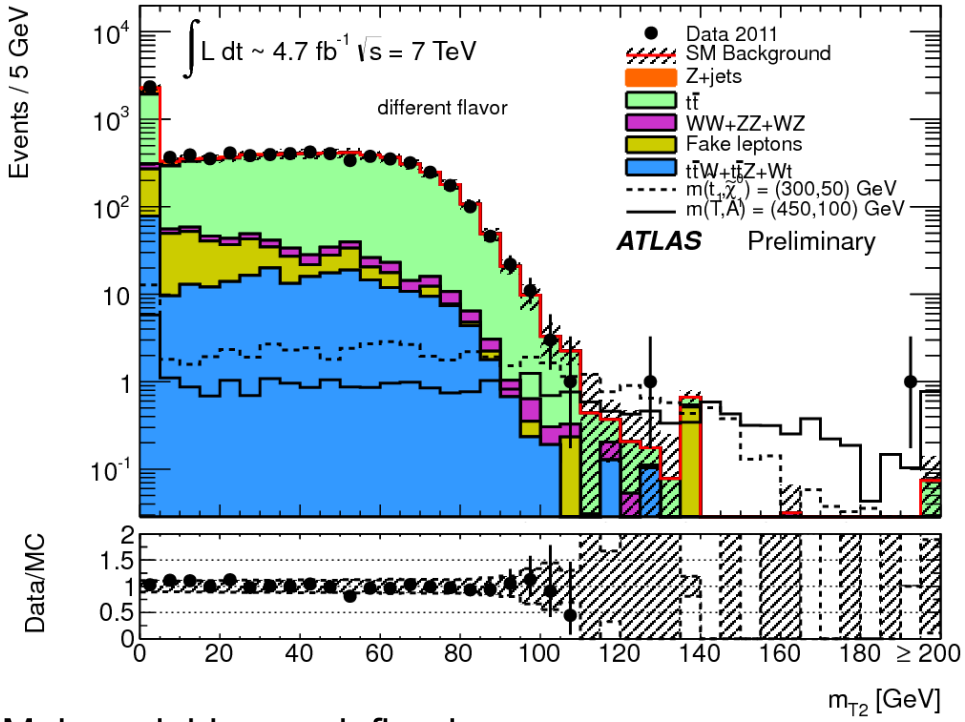
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- For ttbar, mT2 has a sharp endpoint at the W mass

Control Regions

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- Control region for Z+Jets
  - Select events with $71 < m_{ll} < 111$ GeV

2-Lepton





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$$m_{T2}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{miss}) = \min_{\mathbf{q}_T+\mathbf{r}_T=\mathbf{p}_T^{miss}} \left\{ \max[\, m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{r}_T)\,] \right\}$$

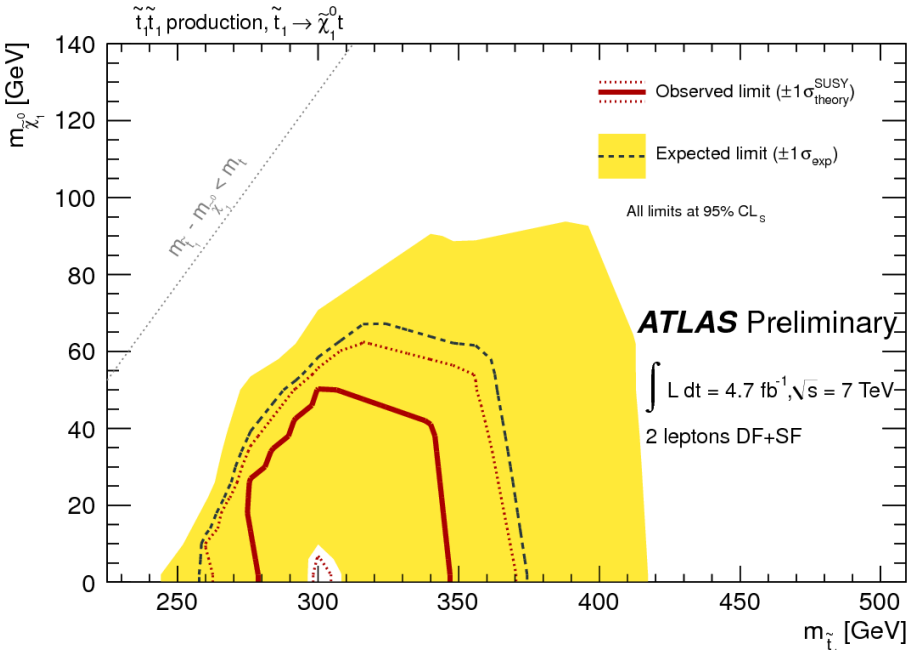
- Minimization over all decompositions of pTMiss
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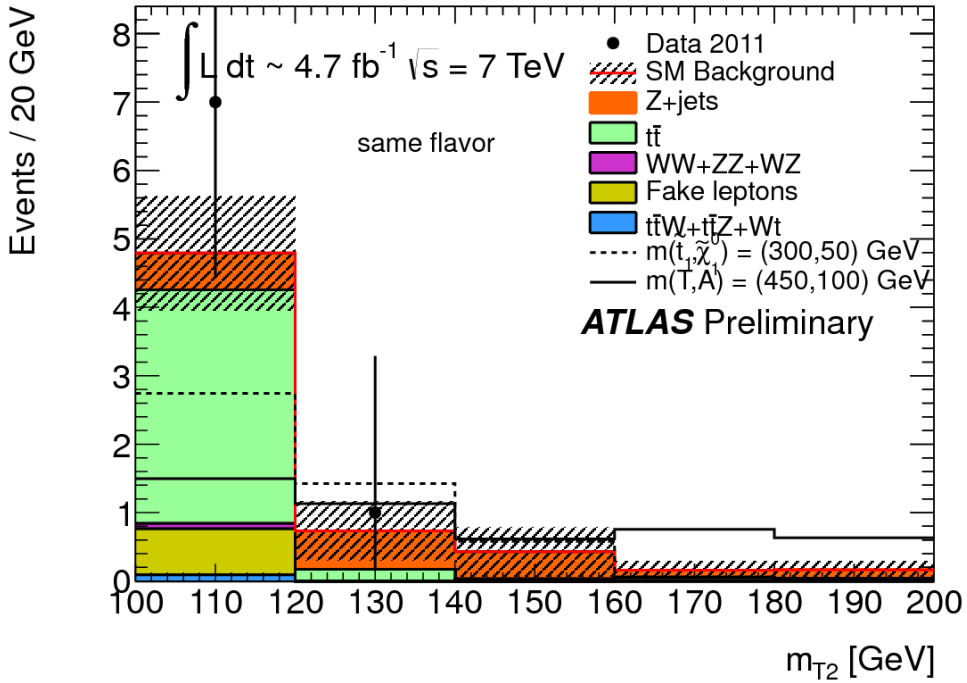
Control Regions

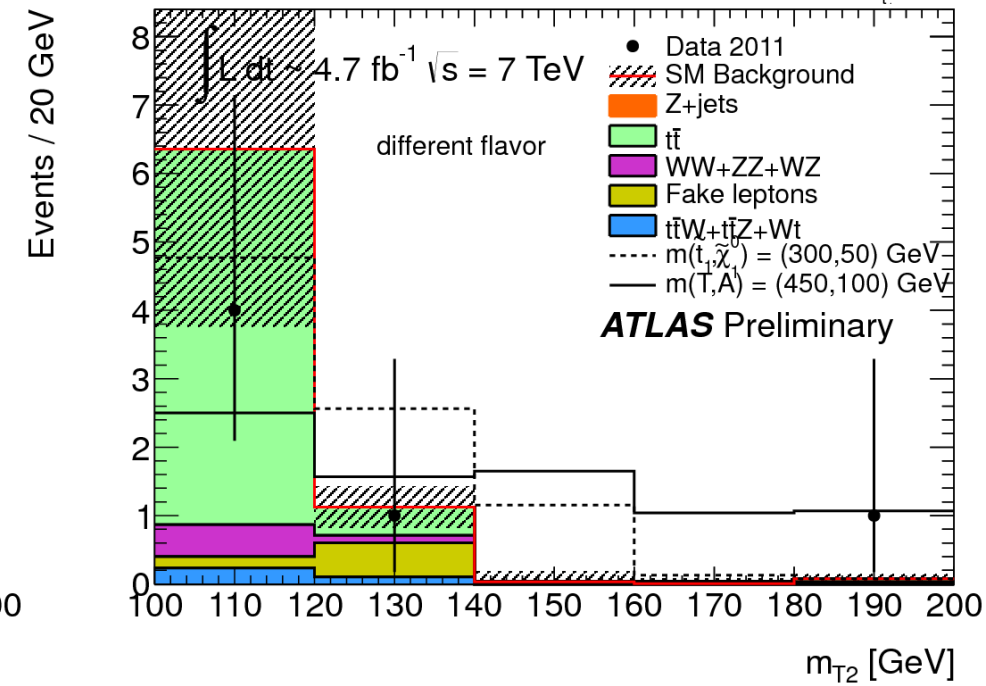
- Control region for ttbar
  - Select for 85 < m_{T2} < 100 GeV
- Control region for Z+Jets
  - Select events with 71 < m_{ll} < 111 GeV

2-Lepton Results

	SF	DF
$Z/\gamma^\star$+jets	1.2 ± 0.5	-
($Z/\gamma^\star$+jets scale factor)	(1.27)	-
$t\bar{t}$	0.23 ± 0.23	0.4 ± 0.3
($t\bar{t}$ scale factor)	(1.21)	(1.10)
$t\bar{t}W + t\bar{t}Z$	0.11 ± 0.07	0.19 ± 0.12
WW	$0.01^{+0.02}_{-0.01}$	0.19 ± 0.18
$WZ + ZZ$	0.05 ± 0.05	0.03 ± 0.03
Wt	$0.00^{+0.17}_{-0.00}$	$0.10^{+0.18}_{-0.10}$
Fake leptons	$0.00^{+0.14}_{-0.00}$	$0.00^{+0.09}_{-0.00}$
Total SM	1.6 ± 0.6	0.9 ± 0.6
Signal, m($\tilde{t}_1$) = 300 GeV, m($\tilde{\chi}^0_1$)= 50 GeV	2.15	3.73
Signal, m(T) = 450 GeV, m(A_0)= 100 GeV	3.10	5.78
Observed	1	2







1-Lepton

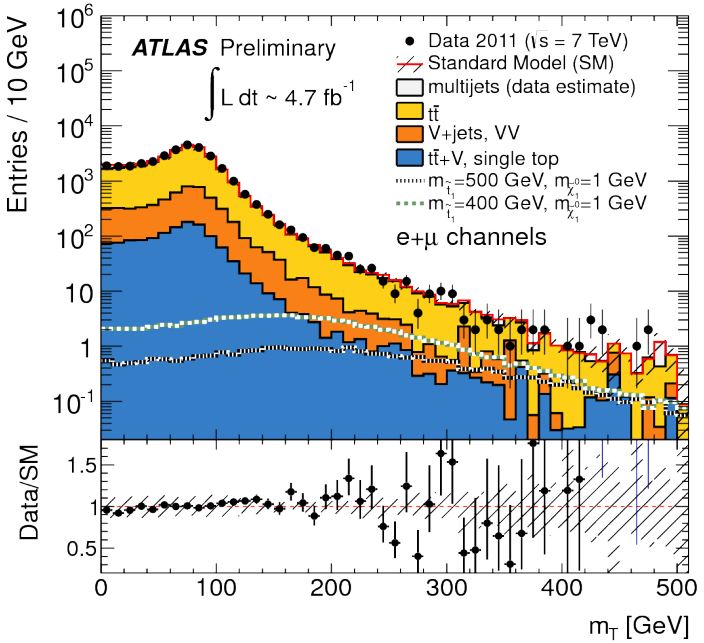
Event Selection

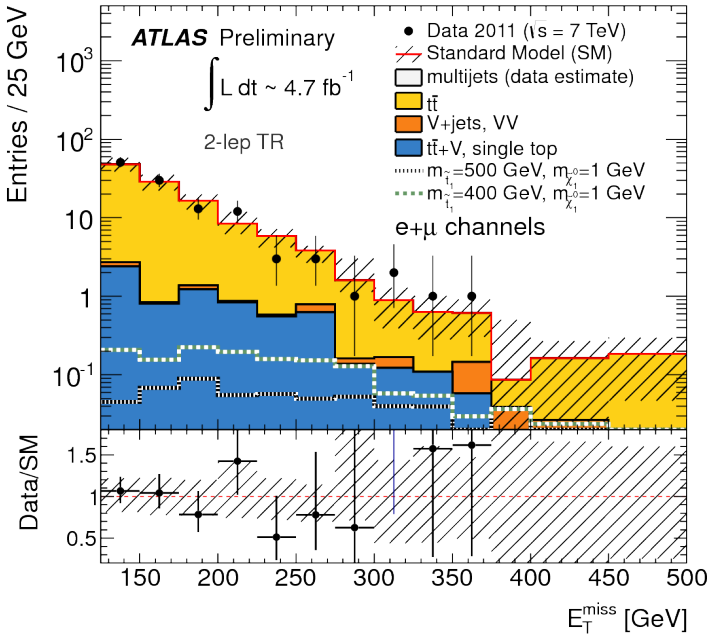
- Exactly 1 lepton
- At least 4 Jets with pT 80/60/40/25 GeV
  - At least 1 of which is b-tagged
- ΔΦ(2 leading jets, EtMiss) > 0.8 radians
- Hadronic top: m_{jjj} formed by picking 3 closest jets
  - Require 2 jet pair mass > 60 GeV
  - 130 < m_{jjj} < 205 GeV
- 5 Signal regions defined with 3 additional cuts:

Requirement	SR A	SR B	SR C	SR D	SR E
E_T^{miss} [GeV] >	150	150	150	225	275
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >	7	9	11	11	11
m_T [GeV] >	120	120	120	130	140

Control Regions

- Di-lepton ttbar control region
  - Exactly 2 leptons
  - No EtMissSig or mT cut. EtMiss > 125 GeV
  - No mjj cut
- Single lepton ttbar
  - Same as SR A except 60 < m_T < 90 GeV
- W+Jets control region
  - Same as SR A except 60 < m_T < 90 GeV and b-jet veto





1-Lepton

Event Selection

Transverse mass: m_T

$m_T = 2\ p_T^{Lep} * E_T miss * (1-\cos(\Delta\Phi))$

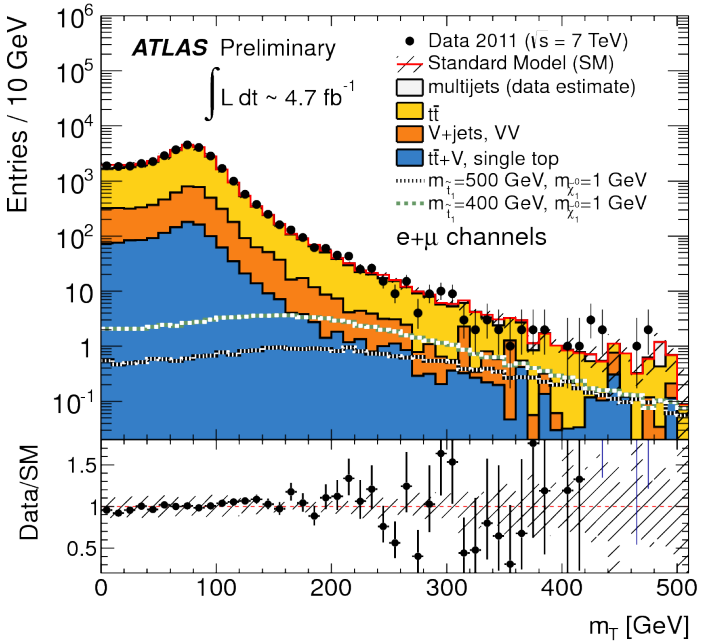
Assumes massless neutrino

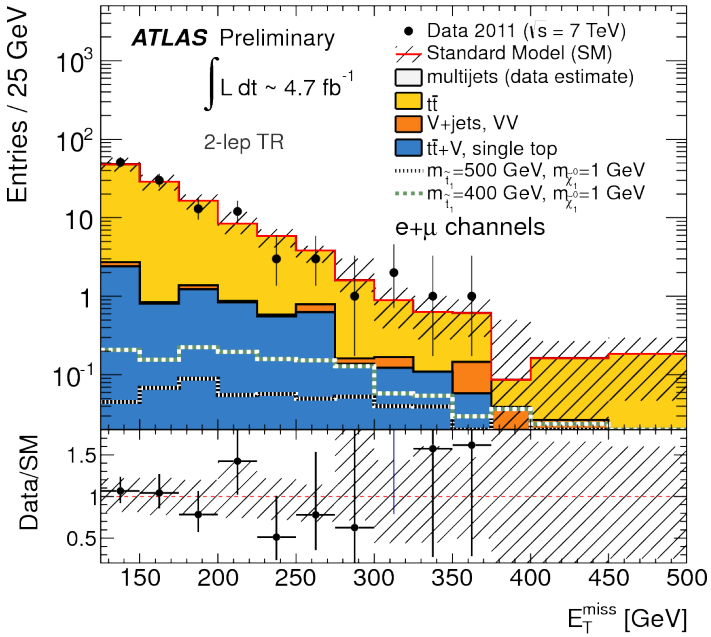
For ttbar, peak at W mass

Requirement	SR A	SR B	SR C	SR D	SR E
E_T^{miss} [GeV] >	150	150	150	225	275
$E_T^{miss} / \sqrt{H_T}$ [GeV$^{1/2}$] >	7	9	11	11	11
m_T [GeV] >	120	120	120	130	140

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1-Lepton

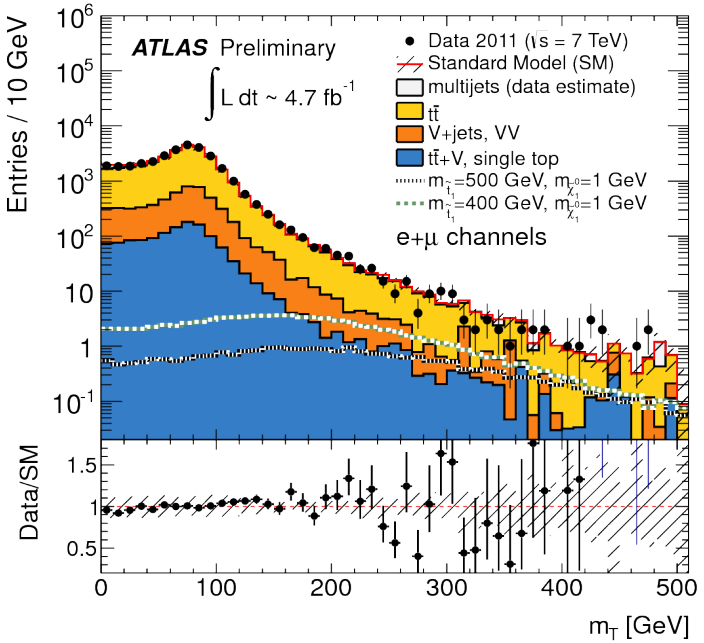
Event Selection

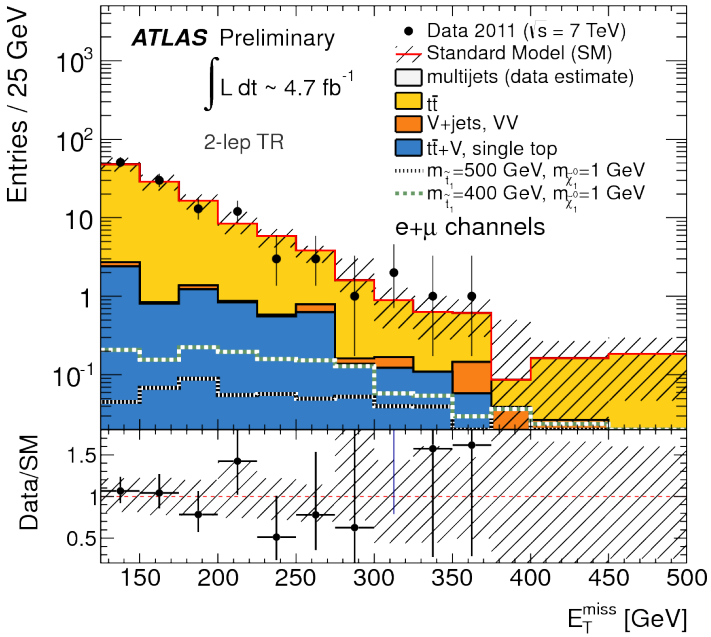
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Control Regions

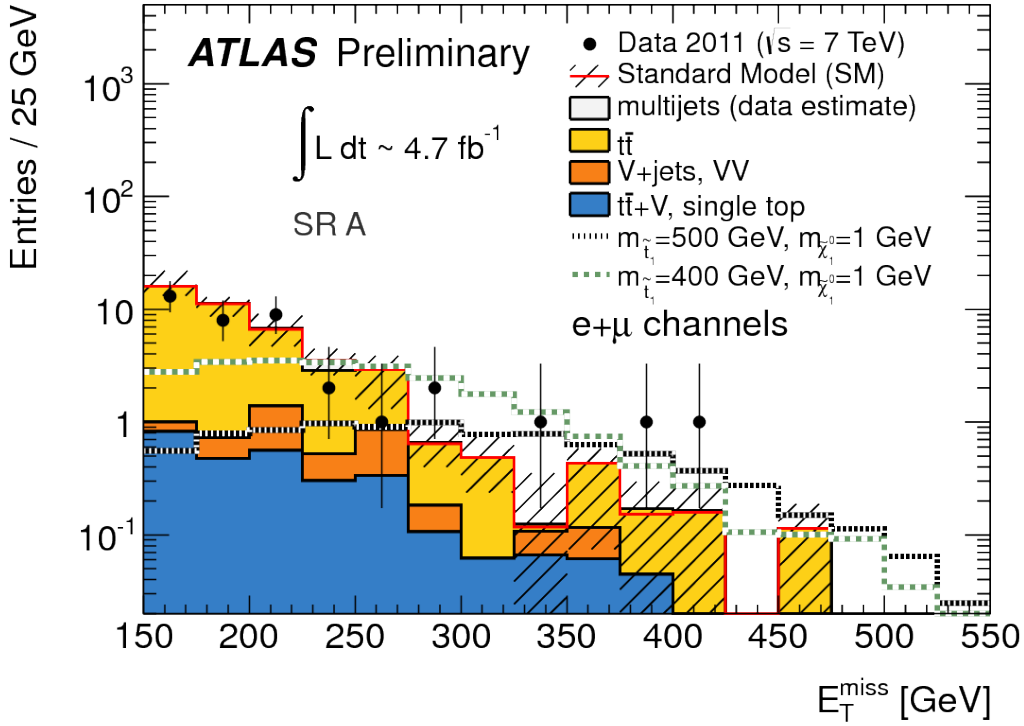
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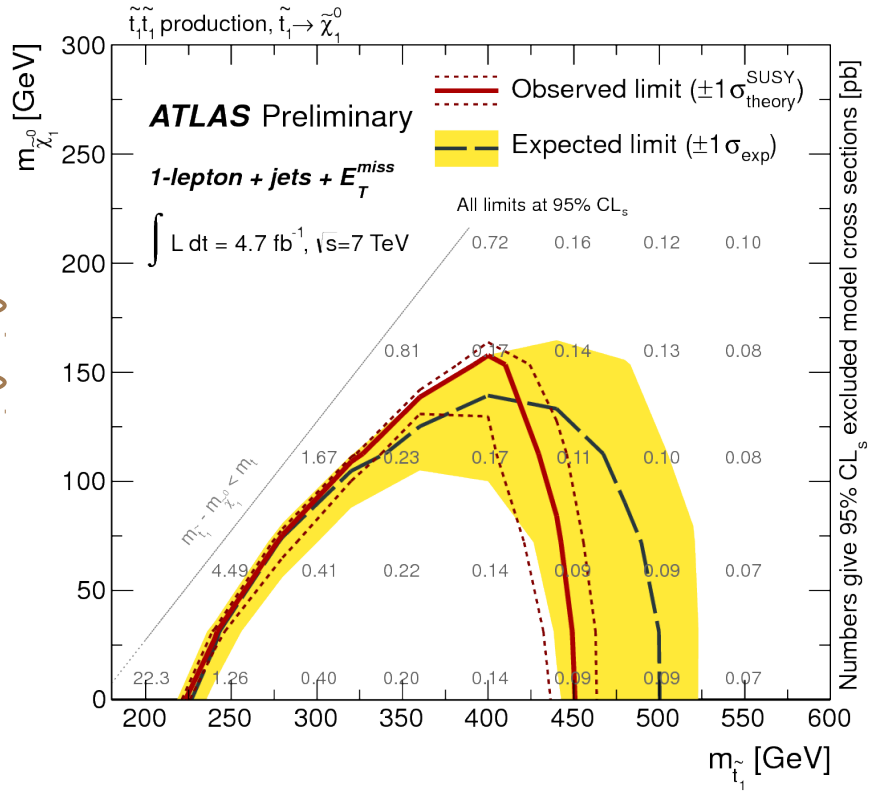


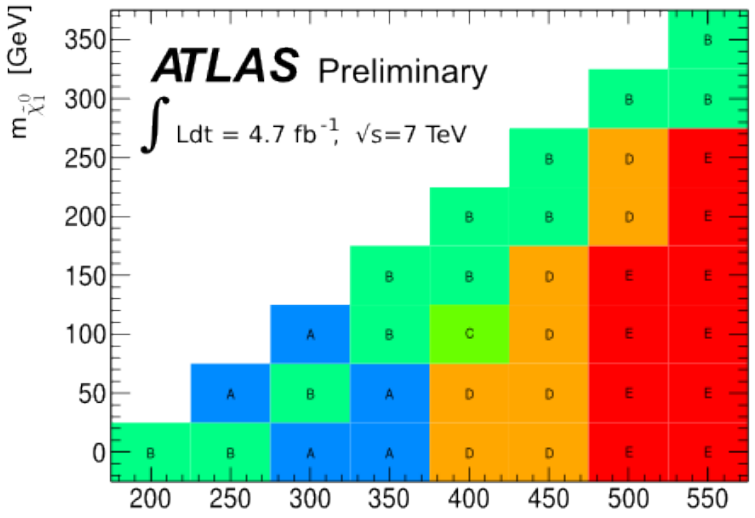


1-Lepton Results

Regions	SR A	SR B	SR C	SR D	SR E
$t\bar{t}$	36 ± 5	27 ± 4	11 ± 2	4.9 ± 1.3	1.3 ± 0.6
$t\bar{t}+V$, single top	2.9 ± 0.7	2.5 ± 0.6	1.6 ± 0.3	0.9 ± 0.3	0.4 ± 0.1
V+jets, VV	2.5 ± 1.3	1.7 ± 0.8	0.4 ± 0.1	0.3 ± 0.1	0.1 ± 0.1
Multijet	$0.4^{+0.4}_{-0.4}$	$0.3^{+0.3}_{-0.3}$	$0.3^{+0.3}_{-0.3}$	$0.3^{+0.3}_{-0.3}$	$0.0^{+0.3}_{-0.0}$
Total background	42 ± 6	31 ± 4	13 ± 2	6.4 ± 1.4	1.8 ± 0.7
Signal benchmark 1 (2)	25.6 (8.8)	23.0 (8.1)	17.5 (6.9)	13.5 (6.2)	7.1 (4.5)
Observed events	38	25	15	8	5
p_0-values	0.5	0.5	0.32	0.24	0.015
Obs. (exp.) $N_{\text{beyond-SM}}$ <	15.1 (17.2)	10.1 (13.8)	10.8 (9.2)	8.4 (7.0)	8.2 (4.6)





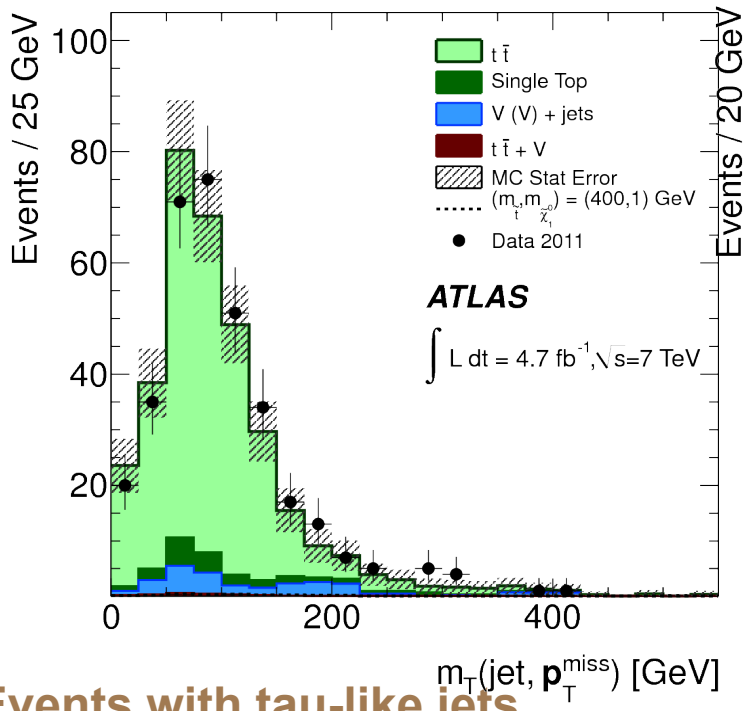


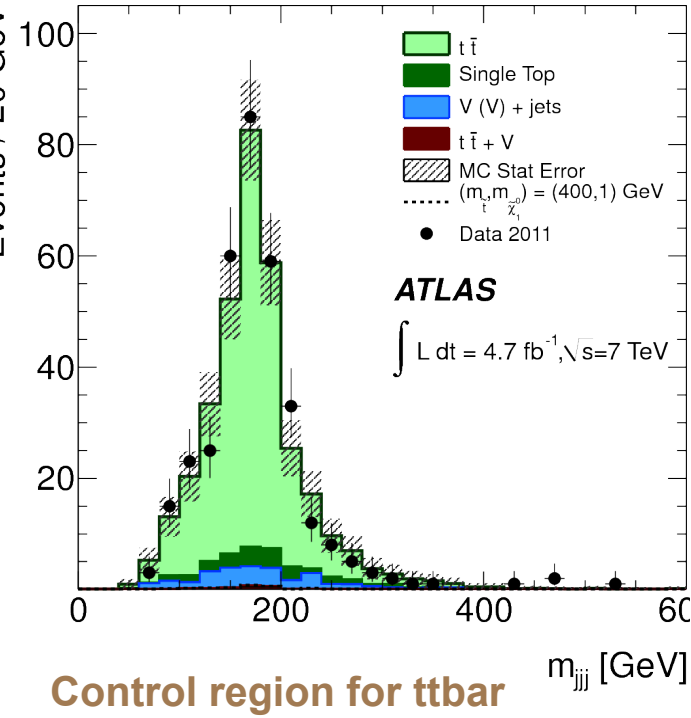
0-Lepton

Event Selection

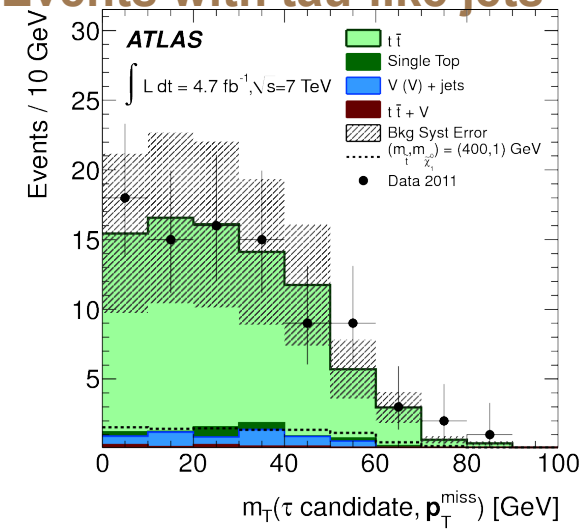
- Lepton veto
- EtMiss > 150 (260) GeV for SR1 (SR2)
- At least 6 jets with p_T > 30 GeV
  - Leading jet p_T > 130 GeV
  - At least 1 b-tagged jet
- ΔΦ(leading 3 jets, EtMiss) > π/5 radians
- $EtMiss_{Track}$ > 30 GeV
- $\Delta\Phi(EtMiss_{Track}, EtMiss) < \pi/3$ radians
- Reconstruct two hadronic top quarks
  - Add 3 closest jets → each top quark
  - 80 GeV < m_{jjj} < 270 GeV for each
- Veto on tau-like jet
- m_T(jet,EtMiss) > 175 GeV
  - One tag case: use jet from leading 4 that minimizes m_T
  - Two tag case: use b-jet that minimizes m_T

Distributions in ttbar control region





Events with tau-like jets



Control region for ttbar

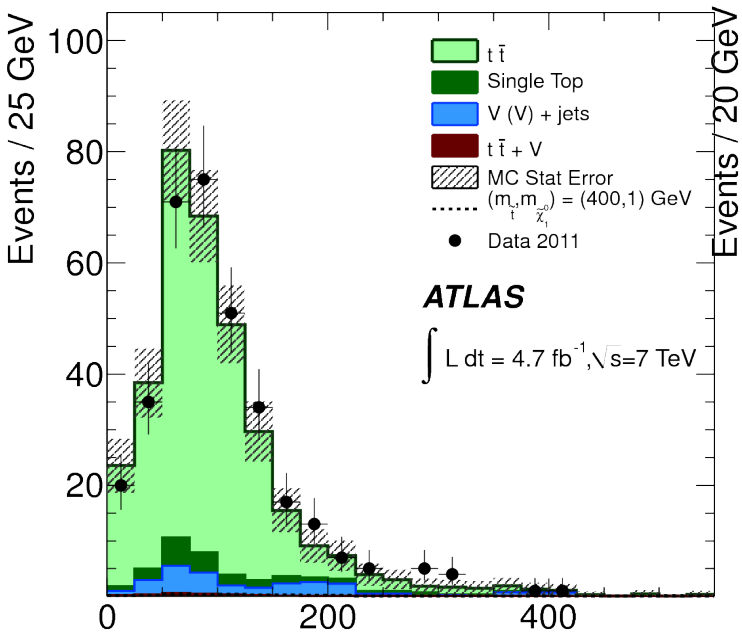
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- Select events with exactly 1 lepton
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- Same selection as SR except for cuts to remove ttbar
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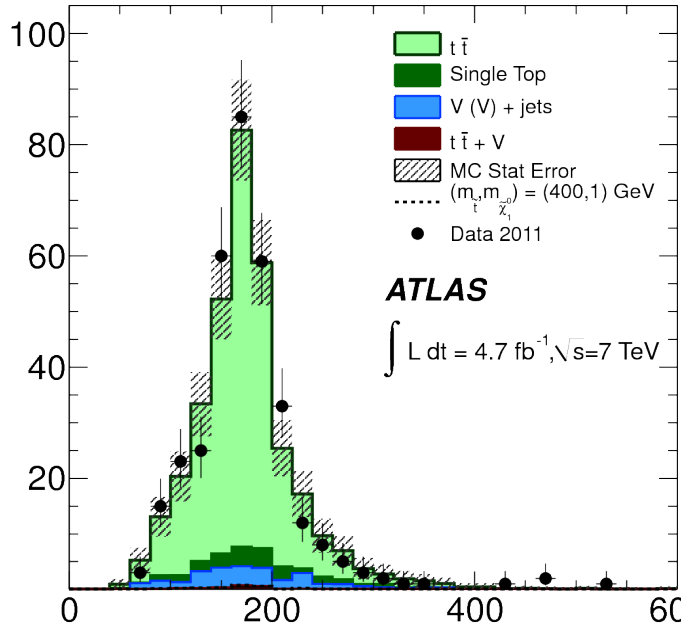
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Distributions in ttbar control region





Transverse mass: m_T

$$m_T = 2\, p_T^{Jet} * E_T miss * (1-\cos(\Delta\Phi))$$

Assumes massless neutrino

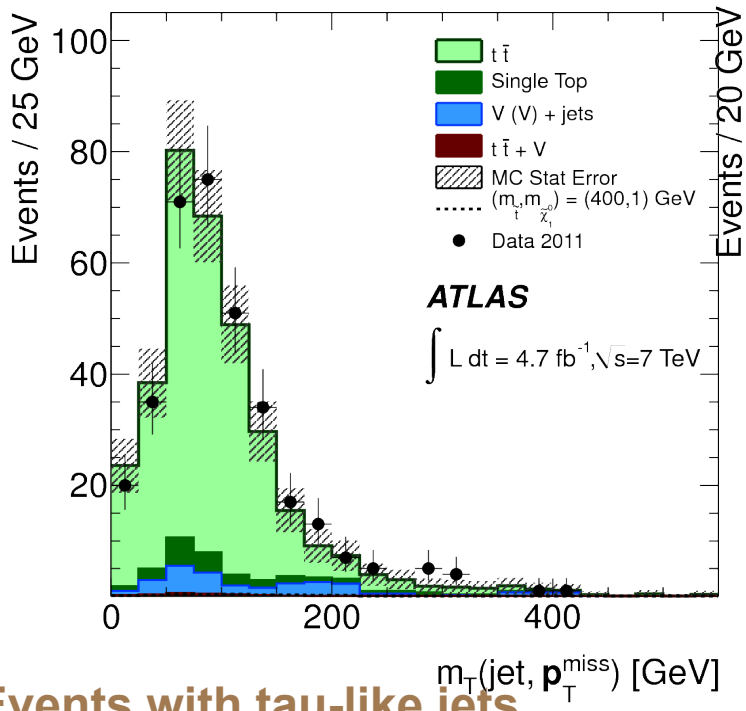
Want to pick b-jet associated with top decay
For ttbar, endpoint at top mass
Require m_T > 175 to reject ttbar

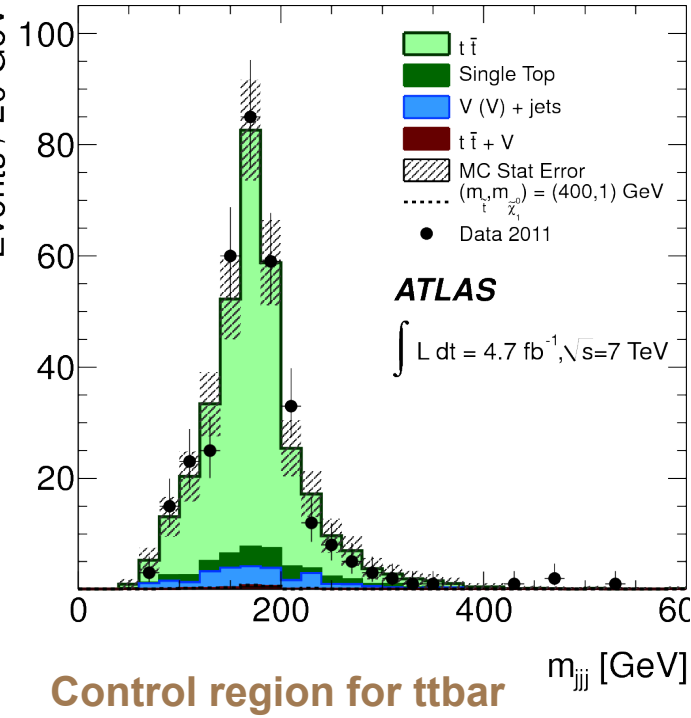
0-Lepton

Event Selection

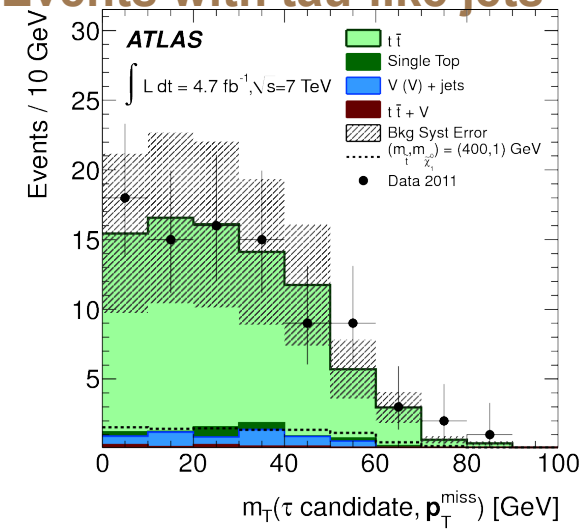
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Distributions in ttbar control region





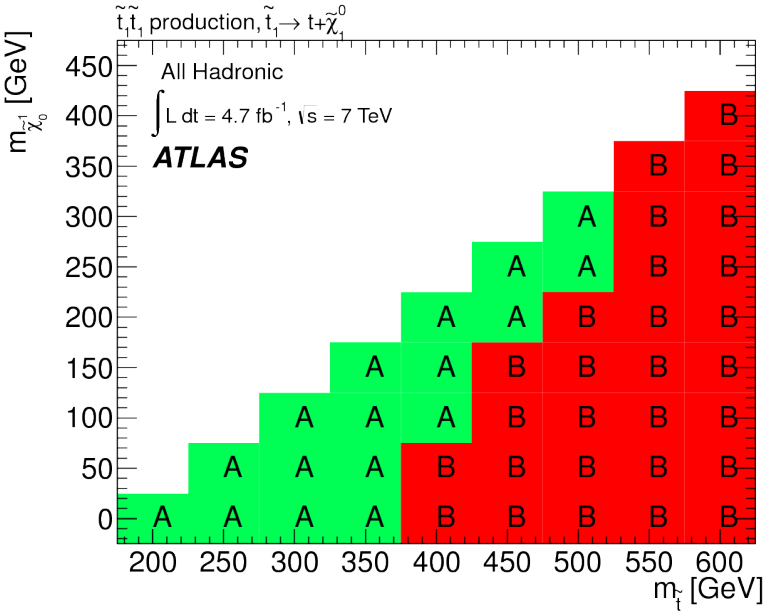
Events with tau-like jets



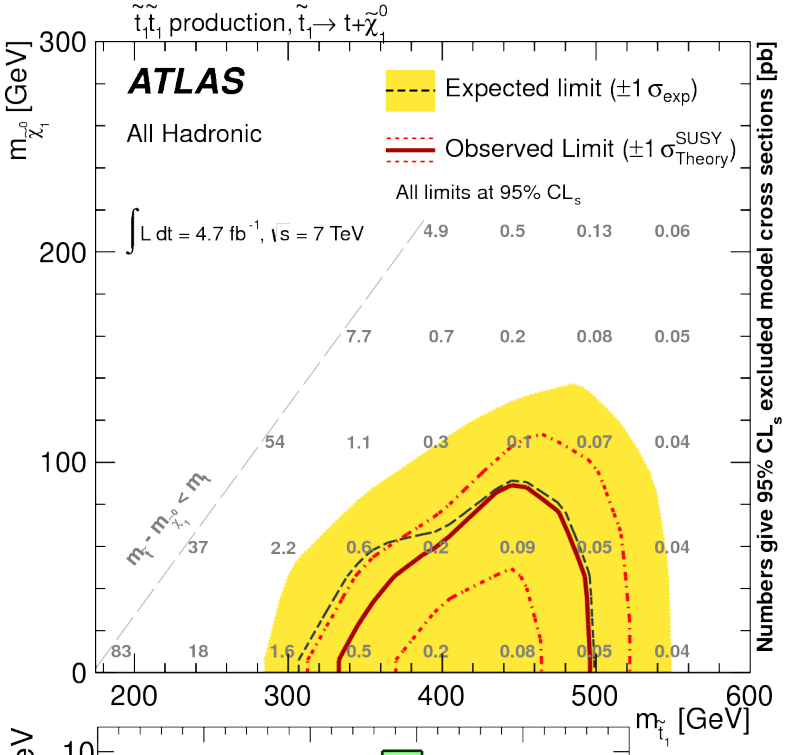
Control region for ttbar

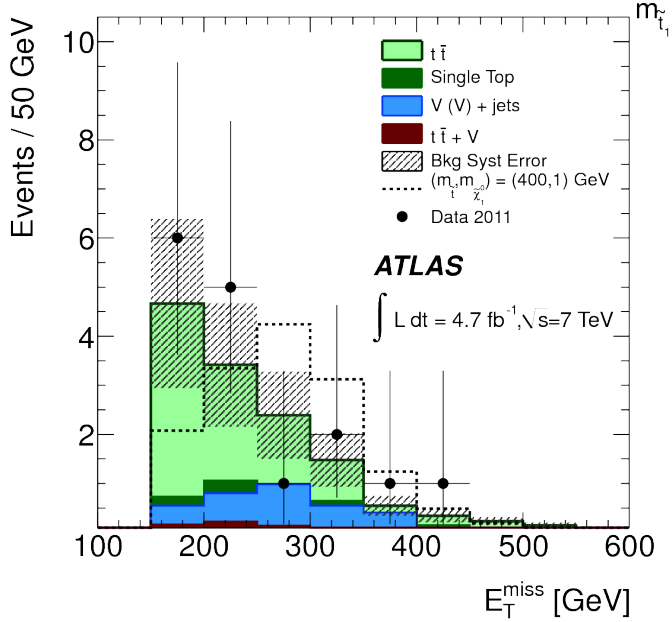
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    - Orthogonal to 1-lepton analysis
  - Treat that lepton as a jet for all subsequent cuts
- Same selection as SR except for cuts to remove ttbar
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0-Lepton Results

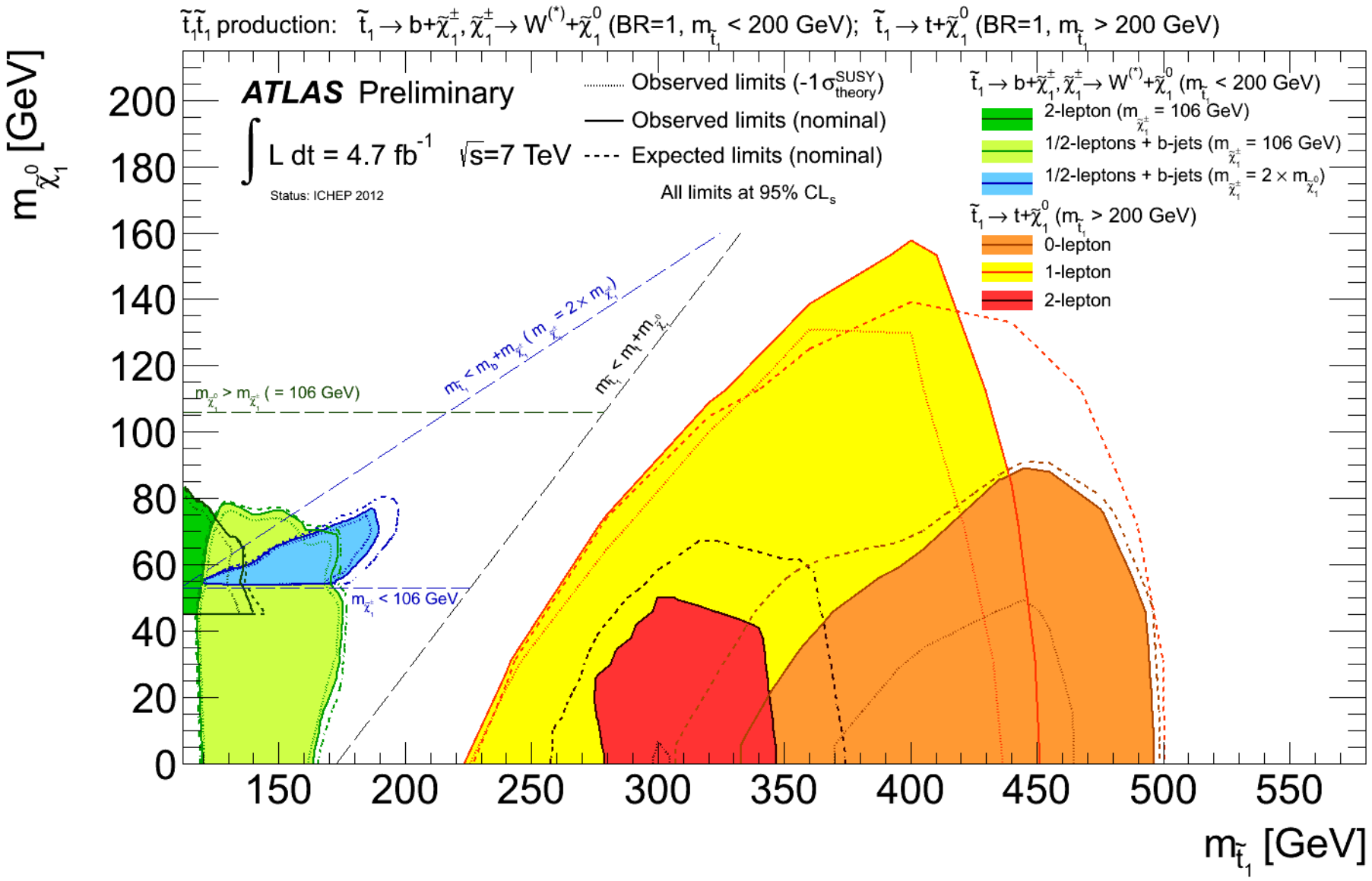


	SRA	SRB
	$E_{\mathrm{T}}^{\mathrm{miss}}$ > 150 GeV	> 260 GeV
$t\bar{t}$	9.2 ± 2.7	2.3 ± 0.6
$t\bar{t} + W/Z$	0.8 ± 0.2	0.4 ± 0.1
Single top	0.7 ± 0.4	$0.2 \,^{+\,0.3}_{-\,0.2}$
Z+jets	$1.3 \,^{+\,1.1}_{-\,1.0}$	$0.9 \,^{+\,0.8}_{-\,0.7}$
W+jets	$1.2 \,^{+\,1.4}_{-\,1.0}$	0.5 ± 0.4
Diboson	$0.1 \,^{+\,0.2}_{-\,0.1}$	$0.1 \,^{+\,0.2}_{-\,0.1}$
Multi-jets	0.2 ± 0.2	0.02 ± 0.02
Total SM	$13.5 \,^{+\,3.7}_{-\,3.6}$	$4.4 \,^{+\,1.7}_{-\,1.3}$
SUSY $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = (400, 1)$ GeV	14.8 ± 4.0	8.9 ± 3.1
Data (observed)	16	4





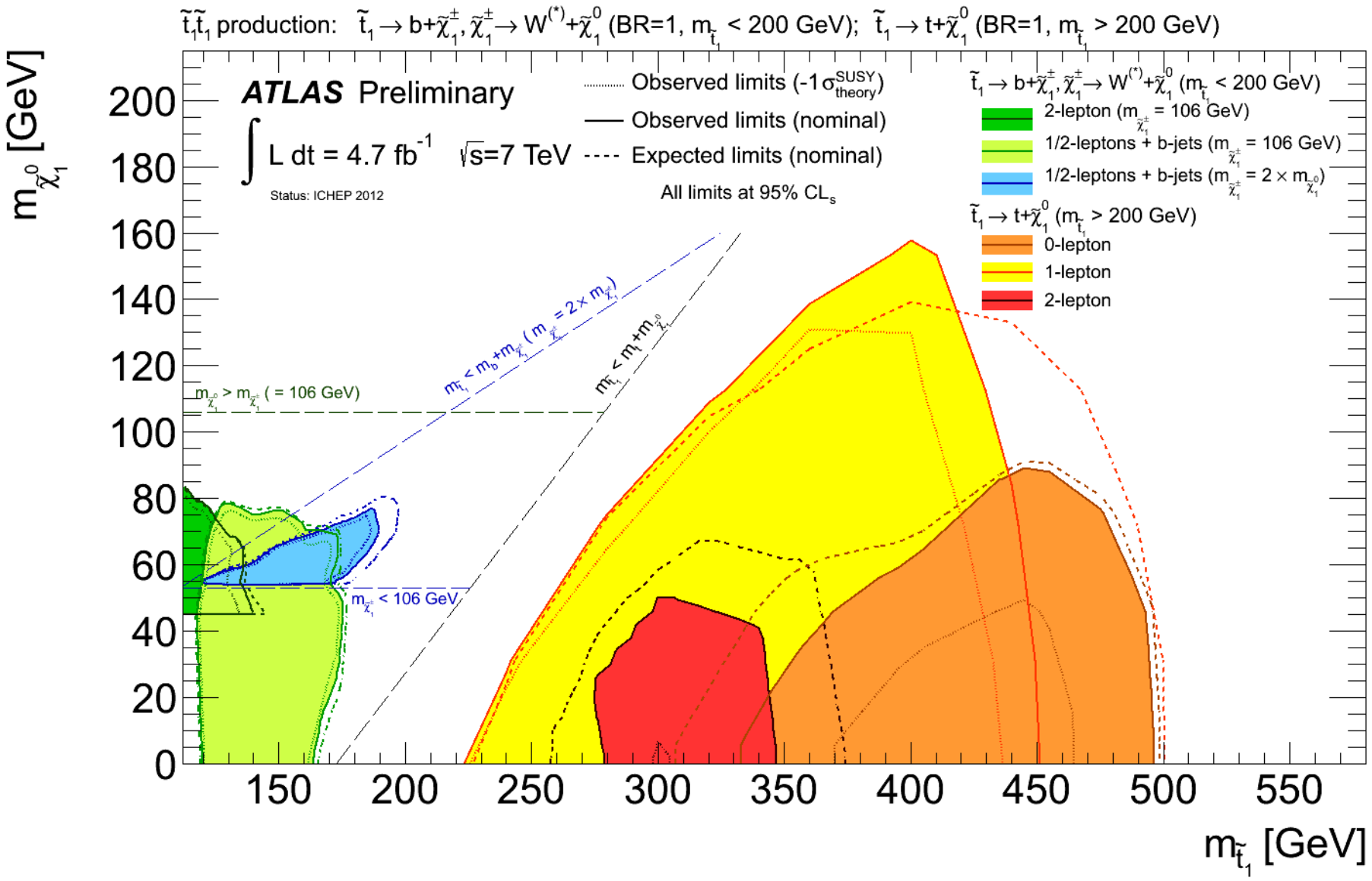
Final Results



Summary

- Five new SUSY results from ATLAS
- First limits for stop with mass > top
- Current best limits for stop with mass < top
- Hopefully the first of many direct stop results over the next several years

Thank You


$\tilde{t}_1\tilde{t}_1$ production: $\tilde{t}_1 \to b+\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \to W^{(*)}+\tilde{\chi}_1^0$ (BR=1, $m_{\tilde{t}_1} < 200$ GeV); $\tilde{t}_1 \to t+\tilde{\chi}_1^0$ (BR=1, $m_{\tilde{t}_1} > 200$ GeV)
ATLAS Preliminary
$\int L\,dt = 4.7\ fb^{-1}$ $\sqrt{s}$=7 TeV
Status: ICHEP 2012
Observed limits ($-1\sigma^{SUSY}_{theory}$)
Observed limits (nominal)
Expected limits (nominal)
All limits at 95% CL_s
$\tilde{t}_1 \to b+\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \to W^{(*)}+\tilde{\chi}_1^0$ ($m_{\tilde{t}_1} < 200$ GeV)
2-lepton ($m_{\tilde{\chi}_1^{\pm}}$ = 106 GeV)
1/2-leptons + b-jets ($m_{\tilde{\chi}_1^{\pm}}$ = 106 GeV)
1/2-leptons + b-jets ($m_{\tilde{\chi}_1^{\pm}} = 2 \times m_{\tilde{\chi}_1^0}$)
$\tilde{t}_1 \to t+\tilde{\chi}_1^0$ ($m_{\tilde{t}_1} > 200$ GeV)
0-lepton
1-lepton
2-lepton
$m_{\tilde{t}_1} < m_b+m_{\tilde{\chi}_1^{\pm}}$ ($m_{\tilde{\chi}_1^{\pm}} = 2 \times m_{\tilde{\chi}_1^0}$)
$m_{\tilde{t}_1} < m_t+m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^{\pm}}$ (= 106 GeV)
$m_{\tilde{\chi}_1^{\pm}} < 106$ GeV
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
20
40
60
80
100
120
140
160
180
200
150
200
250
300
350
400
450
500
550