ATLAS SUSY with tau

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NFS Student Conference in the Section of Subatomic- and Astrophysics

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UNIVERSITY OF BERGEN

Outline

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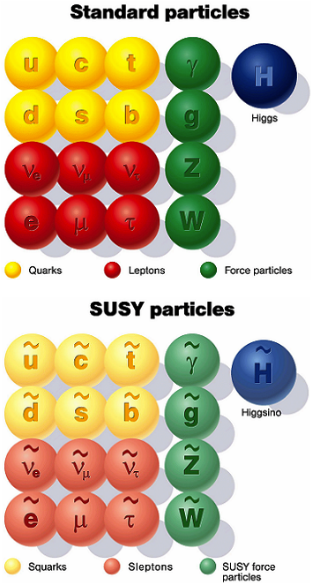
Supersymmetry (SUSY)

- Solves theoretical problems of the Standard Model (hierarchy, unification, DM)
- May contain viable dark matter candidate (stable, neutral LSP)
- Symmetry relating fermions to bosons
- Superpartners (sparticles) to each SM particle with the same quantum numbers but different spin
- Sparticles not detected $\rightarrow$ sparticles must be heavy/broken symmetry
- Introduces many new free parameters ($\sim$100). May be reduced by making assumptions on the breaking mechanism.



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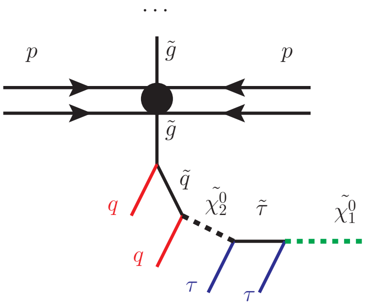
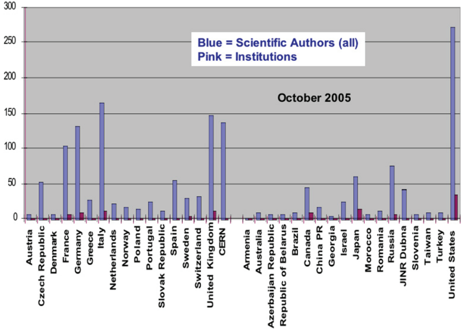


Outline

The ATLAS Collaboration

The ATLAS collaboration

- 38 countries
- 174 institutions
- $\sim$ 3000 scientific authors



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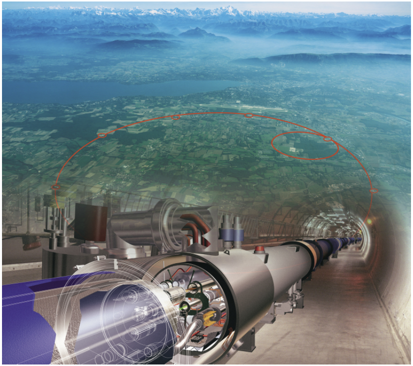
The Large Hadron Collider (LHC)

- Designed to collide protons at 0.9999c
- Protons are accelerated by several synchrotrons before being injected into LHC
- These are grouped into bunches of particles constituting the beam of LHC
- The beam is bent and focused by super-conducting magnets cooled by superfuid helium (1.9 K)
- Opposing beams are collided at four interaction points of the ring with a transverse beam size of 16 microns
- Resulting high energy and luminosity allows for searches of high mass particles and rare processes



The LHC Design (present) specs.

- CoM: 14 (8) TeV
- Luminosity: 10^{34} cm$^{-2}s^{-1}$
- Protons per bunch: $\sim 10^{11}$
- Time between bunches: $\sim$ 25 (31) ns

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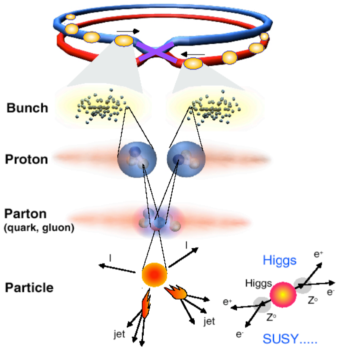

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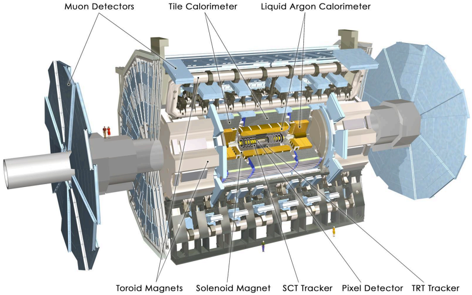
The ATLAS Experiment

- ATLAS is multipurpose detector placed at one of the four LHC interaction points
- Inner detector (ID) - precision measurement of tracks and vertices
- Magnet system - momentum measurement of charged particles
- Calorimeters - energy measurement
- Muon spectrometer - muon meas.
- Transverse momentum conservation $\rightarrow$ undetected particles results in missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$)
- Trigger - selects 100 interesting events per second out of 1000 million total



The ATLAS Detector components

- Inner Detector: Si pixel, Si strip and TRT
- Magnet: 2T Solenoid
- Calorimeter: lead/LAr EM, iron/scint.-tile hadronic, LAr forward/endcap
- Muon system: Toroid magnet

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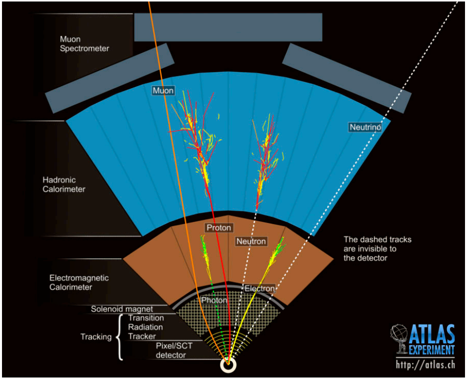
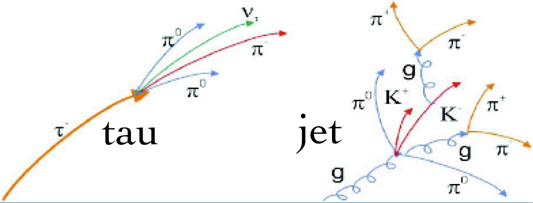


The Tau Lepton at ATLAS

- Taus are heavy and decay rapidly
- Reconstructed from well collimated mesons produced in hadronic tau decays
- Further identification from Boosted Decision Tree (BDT) discriminator
- Uses information from the tracker and the shape of calorimeter energy deposits
- "Medium" τ ID: 40% efficiency, rejection factor "fake taus" $\sim$ 50

The τ lepton

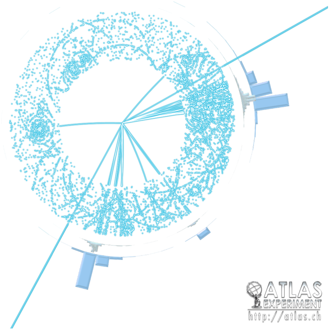
- 3rd generation lepton
- m_τ = 1.7 GeV
- $c\tau$ = 87 μm
- Hadronic decay $\sim$ 60%



Outline

Motivation

- The high energy and luminosity at the LHC allows for probing of large regions of SUSY parameter space
- Complementary to other DM experiments
- τ production is prominent in many models from various SUSY breaking mechanisms
- GMSB is a Minimal Supersymmetric Standard Model where supersymmetry is broken through SM gauge interactions
- DM candidate (LSP) is the light gravitino
- The lightest stau is the NLSP in large portions of the parameter space
  $\rightarrow$ tau rich final states!



Outline

Analysis Overview

- Search for SUSY in ATLAS with at least one τ decaying hadronically
- The full 2011 dataset used ($4.7\ \text{fb}^{-1}$ at center of mass energy of 7TeV)
- Combination of four orthogonal analyses
  - One tau (Bergen)
  - $\geq$ two taus (Sussex)
  - One electron and $\geq$ one tau (Bonn)
  - One muon and $\geq$ one tau (Bonn)
- Combined limits of the analyses set on GMSB models
- Paper already accepted for SUSY12 conference

University of Bergen (DAMARA)

A. Lipniacka, H. Sandaker, T. Buanes, T. Burgess, W. Liebig, T. Sjursen, A. Kastanas, Ø. Dale

University of Sussex

F. Salvatore, A. Rose

University of Bonn

P. Bechtle, K. Desch, T. Nattermann, S. Schaepe, M. Schultens

Other

P. Jackson (University of Adelaide), D. Ludwig (Desy)

Experimental Signatures

	1τ	2τ	$\tau+e$	$\tau+\mu$
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ + jets		Electron	Muon (+ jets)
$E_{\mathrm{T}}^{\mathrm{miss}}$	130/150 GeV		-	
Jets	2 jets, 130/30 GeV		-	1 jet (50 GeV)
Taus	$N_\tau = 1$	$N_\tau > 1$	$N_\tau \geq 1$	
Electrons	$N_e = 0$		$N_e = 1$	$N_e = 0$
Muons	$N_\mu = 0$		$N_\mu = 0$	$N_\mu = 1$

Analysis overlap strategy

- Combining results is easiest for non-overlapping selections
- 1τ is orthogonal to the 2τ analysis through a veto on events with more than one loose tau
- These are orthogonal to $\tau+e$ and $\tau+\mu$ through a veto on events with light leptons

Triggers

- 1τ and 2τ analyses rely on jet+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
- $\tau+e$ and $\tau+\mu$ analyses trigger on the light lepton

Background Processes and Signatures

Multijet

- Multiple jets, often high energy
- Almost no leptons
  $\rightarrow$ Select leptons (especially light leptons)
- Missing energy from instrumental effects
  $\rightarrow$ Remove events where $E_{\mathrm{T}}^{\mathrm{miss}}$ is in the same transverse direction as jet ($\Delta(\phi_{jet_{1,2}-E_{\mathrm{T}}^{\mathrm{miss}}})$)
  $\rightarrow$ Remove events where ratio of $E_{\mathrm{T}}^{\mathrm{miss}}$ to jet energy is low ($E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$)

Top, W+jets, Z+jets

- Leptons, jets and missing energy from neutrinos
- Top: Jets from b-quarks (b-jets)
- Masses of ~80-173 GeV
- For W+jets transverse mass (m_T) limited by W mass
  $\rightarrow$ Remove events with low m_T

Signal Selection

SUSY signal selection

- Produced SUSY particles are expected to be heavy O(∼100-1000 GeV)
  → large transverse energy in events (H_T)
- Dark matter candidate escapes detection
  → large transverse missing energy ($E_{\mathrm{T}}^{\mathrm{miss}}$)

Definition of Kinematic Variables

$$m_{\mathrm{T}}^{\tau,l} = \sqrt{2p_{\mathrm{T}}^{\tau,l} E_{\mathrm{T}}^{\mathrm{miss}}(1 - \cos(\Delta\phi(\tau/l, E_{\mathrm{T}}^{\mathrm{miss}})))}$$
$$H_{\mathrm{T}} = \sum p_{\mathrm{T}}^{\tau} + \sum p_{\mathrm{T}}^{\mathrm{jet}}$$
$$m_{\mathrm{eff}} = H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$$

Kinematic selection in the four analysis channels

Kinematic Selection	1τ	2τ	$\tau+e$	$\tau+\mu$
$\Delta(\phi_{jet_{1,2}} - E_{\mathrm{T}}^{\mathrm{miss}})$	0.3		-	
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	0.3		-	
$m_{\mathrm{T}}{}^{e/\mu/\tau}$ / $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2}$	110 GeV	100 GeV	100 GeV	
m_{eff}	-		1 TeV	
H_T	775 GeV	650 GeV	-	

Background Estimation - Control Regions

- To ensure that background processes are well understood control regions (CR) are used
- These are close to but orthogonal to the signal region, and dominated by a specific process
- Control regions are set up for W+jets, top, Z+jets and multijets
- Where possible CRs are further split into regions dominated by fake/true taus to account for differences in the quality of simulation information for fake and true taus

Top, W+jets and Z+jets

- The transverse mass of tau(s) (1τ and 2τ) or the selected light lepton ($\tau+e$ and $\tau+\mu$)
- Top (W + jets) CR requires the presence (absence) of jets from b-quarks

Multijet

- Low $\Delta\phi(jet^{1,2}, E_{\mathrm{T}}^{\mathrm{miss}})$
- Low $E_{\mathrm{T}}^{\mathrm{miss}}/m_{eff}$

Background Estimation - Methods

- The shape of the kinematic distributions of the data is usually well modeled by Monte Carlo simulations, but the overall normalization of simulations needs to be determined from the data
- Different methods are used to estimate the various background contributions, which are consecutively extrapolated to the signal region
- Most methods find scaling factors based on real data to be applied to MC simulations to get agreement between data and MC in CRs

	1τ	2τ	$\tau+e$	$\tau+\mu$
W + jets	True: Charge ratio Fake: Matrix method	Matrix method	Matrix method Split into true and fake	
Top	True: Template fit Fake: Matrix method	Matrix method	Matrix method	
Z + jets	Muons	Matrix method	-	-
Multijets	ABCD	Sidebands	Matrix method	

Background Estimation - Matrix Method

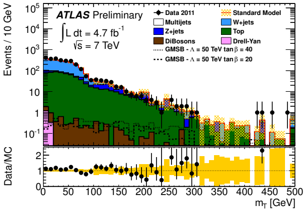
Matrix approach

- Used for determining top/W+jets true and fake τ scaling factors (4 CRs)
- For each CR that is defined extract the yield from each MC process and data
- These satisfy the following relation:

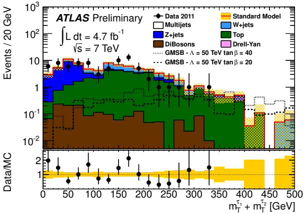
$$\underbrace{\begin{pmatrix} N_1^{\text{data}} - N_1^{\text{QCD,data}} - N_1^{\text{MC,rest}} \\ N_2^{\text{data}} - N_2^{\text{QCD,data}} - N_2^{\text{MC,rest}} \\ N_3^{\text{data}} - N_3^{\text{QCD,data}} - N_3^{\text{MC,rest}} \end{pmatrix}}_{\vec{N}} = \underbrace{\begin{pmatrix} N_1^{\text{Type 1}} & N_1^{\text{Type 2}} & N_1^{\text{Type 3}} \\ N_2^{\text{Type 1}} & N_2^{\text{Type 2}} & N_2^{\text{Type 3}} \\ N_3^{\text{Type 1}} & N_3^{\text{Type 2}} & N_3^{\text{Type 3}} \end{pmatrix}}_{A} \underbrace{\begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix}}_{\vec{\omega}}$$

- By inverting the matrix A, we can obtain vector of scaling factors $\vec{\omega} = A^{-1} \cdot \vec{N}$
- Varying all contributing parameters according to their uncertainties yields distribution of scaling factors - width of distribution is taken as uncertainty

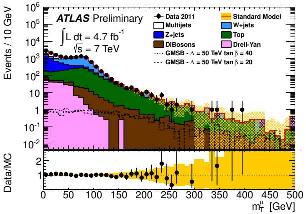
Backgrounds seem well modeled!



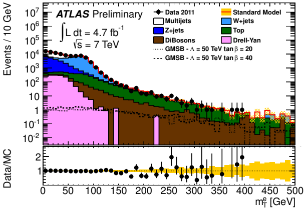
(a) m_T distribution for 1τ analysis



(b) $m_T^{\tau 1} + m_T^{\tau 2}$ distribution for 2τ analysis



(c) m_T^{μ} distribution for $\tau + \mu$ analysis



(d) m_T^{e} distribution for $\tau + e$ analysis

Systematic Uncertainties

Systematics common to all signatures

- Jets: JES (Up/down), JER.
- Taus: TES (Up/down), Tau ID.
- $E_{\mathrm{T}}^{\mathrm{miss}}$: Soft term ES (Up/down) and resolution.
- b-jets: Efficiency and mis-tag probability.
- Generator and pile-up uncertainties.
- Signal: Uncertainties on NLO cross sections

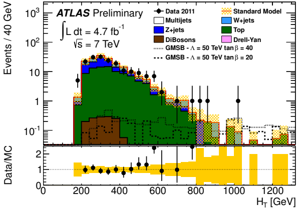
Light lepton specific

- e ES+RES
- μ-ID efficiency
- μ-trigger efficiency
- μ resolution

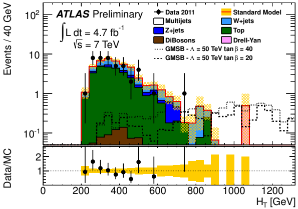
Relative size of main systematics

Source of Uncertainty	1τ	2τ	$\tau+\mu$	$\tau+e$
CR to SR Extrapolation	27 %	12 %	26 %	29 %
Jet Energy Resolution	21 %	6.5 %	5.4 %	13 %
Jet Energy Scale	20 %	4.8 %	11 %	8.5 %
Tau Energy Scale	10 %	8.5 %	0.3 %	4.3 %
Pileup re-weighting	5.1 %	14 %	20 %	3.5 %
MC statistics	21 %	32 %	39 %	46 %

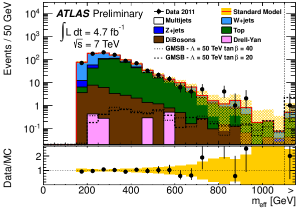
Distributions before final selection



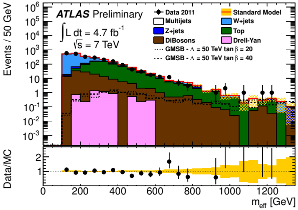
(e) H_T distribution for 1τ analysis



(f) H_T distribution for 2τ analysis



(g) m_{eff} distribution for $\tau + \mu$ analysis



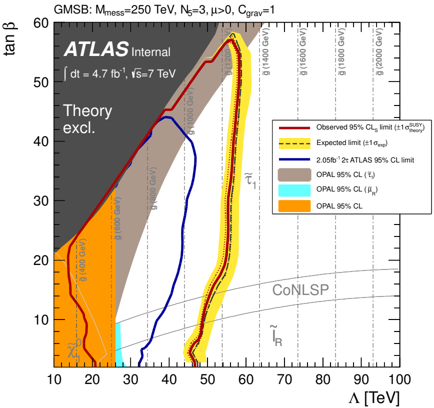
(h) m_{eff} distribution for $\tau + e$ analysis

Results - Estimated and Observed Events

–	1τ	2τ	$\tau+\mu$	$\tau+e$
Multi-jet	$0.17 \pm 0.04 \pm 0.11$	$0.17 \pm 0.15 \pm 0.36$	< 0.01	0.22 ± 0.30
W + jets	$0.31 \pm 0.16 \pm 0.16$	$1.11 \pm 0.67 \pm 0.30$	$0.27 \pm 0.21 \pm 0.13$	$0.24 \pm 0.17 \pm 0.27$
Z + jets	$0.22 \pm 0.22 \pm 0.09$	$0.36 \pm 0.26 \pm 0.35$	$0.05 \pm 0.05 \pm 0.01$	$0.17 \pm 0.12 \pm 0.05$
$t\bar{t}$	$0.61 \pm 0.25 \pm 0.11$	$0.76 \pm 0.31 \pm 0.31$	$0.36 \pm 0.18 \pm 0.26$	$1.41 \pm 0.27 \pm 0.84$
di-boson	< 0.05	$0.02 \pm 0.01 \pm 0.07$	$0.11 \pm 0.04 \pm 0.02$	$0.26 \pm 0.12 \pm 0.11$
Drell Yan	< 0.36	$0.49 \pm 0.49 \pm 0.21$	< 0.002	< 0.002
Total background	$1.31 \pm 0.37 \pm 0.65$	$2.91 \pm 0.89 \pm 0.76$	$0.79 \pm 0.28 \pm 0.39$	$2.31 \pm 0.40 \pm 1.40$
Signal MC Events (GMSB5020)	$2.36 \pm 0.30 \pm 0.60$	$4.94 \pm 0.45 \pm 0.74$	$2.48 \pm 0.30 \pm 0.39$	$4.21 \pm 0.38 \pm 0.46$
Data	4	1	1	3
Obs (exp) limit on signal events	7.7 (4.5)	3.2 (4.7)	3.7 (3.4)	5.2 (4.6)
Obs (exp) limit on Cross Section (fb)	1.67 (0.95)	0.68 (0.99)	0.78 (0.72)	1.10 (0.98)

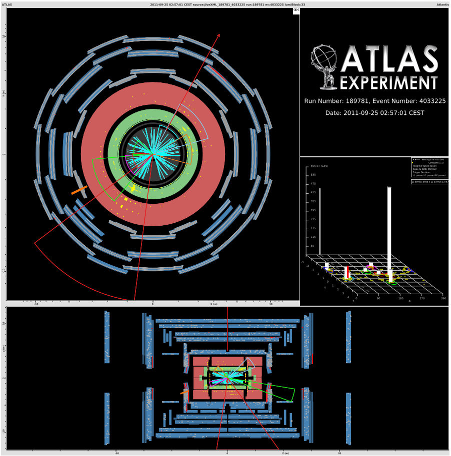
- Table shows the number of expected and observed events in the four final states along with an example GMSB points
- Also shows the 95% Confidence Level (CL) limit on the number of observed (expected) signal events from any new physics scenario for each channel

Results - GMSB Limit



- Observed and expected 95% CL lower limit for the combination of the four final states on the minimal GMSB model parameters λ and $\tan\beta$
- Dark grey area is theoretically excluded due to unphysical sparticle mass values
- Previous OPAL limits (light grey, orange and cyan) and recent (2 fb^{-1}) ATLAS 2τ (blue line) limits are also shown
- Additional model parameters and different NLSP regions indicated

Results - GMSB Exclusion



One of the 1τ events

- Leading jet
- Sub-leading jet
- τ
- $E_{\mathrm{T}}^{\mathrm{miss}}$ (red arrow)

- Selection efficiency of signal depends on analysis channel and region of the grid and varies from 0.1-3%
- Best exclusion of the combination is set for $\lambda = 58\,TeV$ for $\tan\beta > 45$
- The result extend previous limits and values of $\lambda < 47$ TeV are now excluded at 95% CL independent of $\tan\beta$

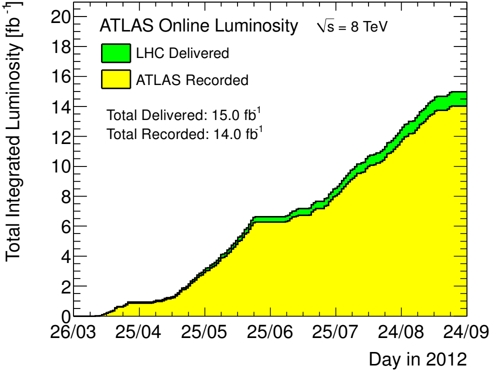
Outline

Conclusion

- A search for SUSY in final states with jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, light leptons ($e/\mu$) and hadronically decaying τ leptons is performed using $4.7\mathrm{fb}^{-1}$ of s = 7 TeV pp collision data recorded with the ATLAS detector at the LHC.
- In the four final states studied, no excess is found above the expected SM backgrounds
- 95% CL upper limits on numbers of signal events from new phenomena and the visible cross section are set. Along with limits on the model parameters of a minimal GMSB model.
- These results provide the most stringent test to date of GMSB SUSY breaking models in a large part of the parameter space considered, improving previous best limits from ATLAS τ analyses

Link to conference note: `https://cdsweb.cern.ch/record/1472933?ln=en`

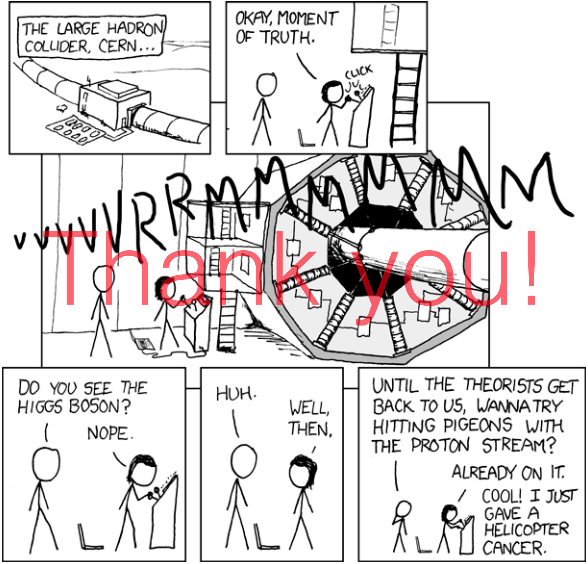
Further Work



[ATLAS collab.]

- Start looking at 2012 data
- Look at other SUSY models
- Different production mechanisms
- Investigate other triggers

Still a lot of work to be done!


THE LARGE HADRON COLLIDER, CERN...
OKAY, MOMENT OF TRUTH.
CLICK
VVVVVRRRMMMMMMMMM
DO YOU SEE THE HIGGS BOSON?
NOPE.
HUH.
WELL, THEN.
UNTIL THE THEORISTS GET BACK TO US, WANNA TRY HITTING PIGEONS WITH THE PROTON STREAM?
ALREADY ON IT.
COOL! I JUST GAVE A HELICOPTER CANCER.

Thank you!

Backup slides

Additional methods used in 1-tau

Charge ratio method

- Use the charge asymmetry in W production.
- Scale the W component to match the assymetry observed in data.

Z + jets estimation

- Use muon stream data.
- Perform the same selections as in the analysis to determine the scaling factor.

Top estimation

- Perform a MC template fit to the b-tagged jets ditribution from data.
- Use the fraction of the contributions to estimate the SF.

Selection

–	1τ	2τ	$\tau+\mu$	$\tau+e$
Trigger	jetMET $p_T^{jet} > 75$ GeV $E_T^{miss} > 45/55$ GeV	jetMET $p_T^{jet} > 75$ GeV $E_T^{miss} > 45/55$ GeV	muon/muon+jet $p_T^{\mu} > 18$ GeV $p_T^{jet} > 10$ GeV	electron $p_T^{e} > 20/22$ GeV
Jet req. E_T^{miss} req. $N_{e,\mu}$ N_τ	≥2 jets (130, 30 GeV) $E_T^{miss} > 130/150$ GeV 0 =1 medium (20 GeV), =0 loose	≥2 jets (130, 30 GeV) $E_T^{miss} > 130/150$ GeV 0 ≥2 loose (20 GeV)	≥1 jet (50 GeV) — 1 μ (20 GeV) ≥1 med. (20 GeV)	— — 1 e (25 GeV) ≥1 med. (20 GeV)
Kinematic criteria	$\Delta(\phi_{jet_{1,2}-\mathbf{p}_T{}^{miss}}) > 0.3$; $E_T^{miss}/m_{eff} > 0.3$, $m_T > 110$ GeV; $H_T > 775$ GeV	$\Delta(\phi_{jet_{1,2}-\mathbf{p}_T{}^{miss}}) > 0.3$ $m_T^{\tau_1} + m_T^{\tau_2} > 100$ GeV $H_T > 650$ GeV	$m_T^{e,\mu} > 100$ GeV $m_{eff} > 1000$ GeV	$m_T^{e,\mu} > 100$ GeV $m_{eff} > 1000$ GeV

Control Regions

Background	1τ	2τ	$\tau+\mu$	$\tau+e$
$t\bar{t}$	$\Delta(\phi_{jet_{1,2}-\mathbf{p}_T{}^{miss}}) > 0.3$ rad $m_T < 70$ GeV $E_T^{miss}/\mathrm{m_{eff}} > 0.3$ b-tag template fit	$\Delta(\phi_{jet_{1,2}-\mathbf{p}_T{}^{miss}}) > 0.3$ rad $m_T^{\tau_1} + m_T^{\tau_2} \geq 100$ GeV $H_T < 550$ GeV $N_{b-tag} \geq 1$	$30\ \mathrm{GeV} < E_T^{miss} < 100$ GeV $50\ \mathrm{GeV} < m_T^{e,\mu} < 150$ GeV $N_{b-tag} \geq 1$	
W+jets	$\Delta(\phi_{jet_{1,2}-\mathbf{p}_T{}^{miss}}) > 0.3$ rad $m_T < 70$ GeV $E_T^{miss}/\mathrm{m_{eff}} > 0.3$	$\Delta(\phi_{jet_{1,2}-\mathbf{p}_T{}^{miss}}) > 0.3$ rad $m_T^{\tau_1} + m_T^{\tau_2} \geq 100$ GeV $H_T < 550$ GeV $N_{b-tag} = 0$	$30\ \mathrm{GeV} < E_T^{miss} < 100$ GeV $50\ \mathrm{GeV} < m_T^{e,\mu} < 150$ GeV $N_{b-tag} = 0$	
Z+jets	2μ (20 GeV), $\lvert\eta\rvert < 2.4$ $\geq$2 jets (130, 30 GeV) $N_{b-tag} = 0$	$\Delta(\phi_{jet_{1,2}-\mathbf{p}_T{}^{miss}}) > 0.3$ rad $m_T^{\tau_1} + m_T^{\tau_2} < 80$ GeV $H_T < 550$ GeV	MC simulation	
Multi-jet	$\Delta(\phi_{jet_{1,2}-\mathbf{p}_T{}^{miss}}) < 0.3$ rad $E_T^{miss}/m_{eff} < 0.3$	$\Delta(\phi_{jet_{1,2}-\mathbf{p}_T{}^{miss}}) < 0.3$ rad $E_T^{miss}/m_{eff} < 0.4$	compare events with and without lepton isolation [63]	