A Search for Lepton-Jets with Muons in the ATLAS Detector

On behalf of the ATLAS Collaboration

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Introduction

A search for collimated muon pairs
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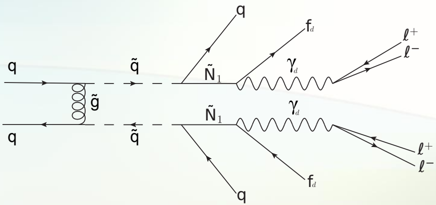
Overview
What we did
Why we did it
How we checked what we did
How it paid off

Overview

Model Overview

A Hidden Valley could explain high-energy cosmic ray positron and electron anomalies, and provide a solution to the origin of Dark Matter

- Weakly-interacting dark-sector with its own gauge bosons.
- Neutralino (squark pair production) decays to a dark photon (γ_D) and a ~ 1 GeV gaugino.
- SPS1a SUSY parameters



Squark pair production with cascade decay to dark states which in turn decay to lepton-jets.

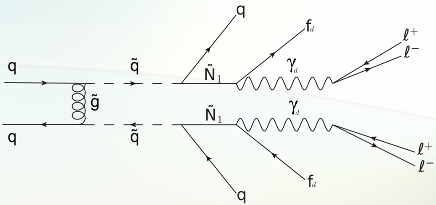
For some theory papers, check out: arXiv:0810.0713, arXiv:0901.0283, and arXiv:0909.0290

Model Overview

A Hidden Valley could explain high-energy cosmic ray positron and electron anomalies, and provide a solution to the origin of Dark Matter

- Weakly-interacting dark-sector with its own gauge bosons.
- Neutralino (squark pair production) decays to a dark photon (γ_D) and a $\sim$ 1 GeV gaugino.
- SPS1a SUSY parameters
- Model predicts $\gamma_D \to 2\mu$, $2e$, or 2π
- The dark photons are boosted and decay back to SM Particles in collimated jets of $\geq$ 2 leptons.

For some theory papers, check out: arXiv:0810.0713, arXiv:0901.0283, and arXiv:0909.0290



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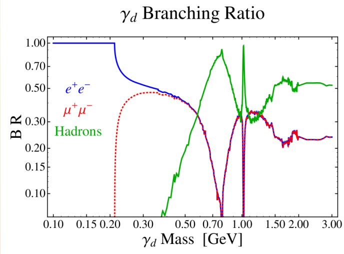
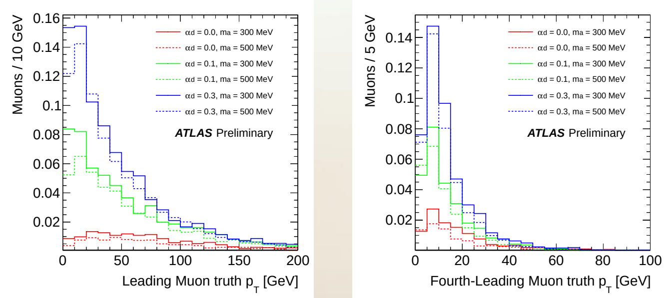


Branching ratio of the γ_D as a function of its mass.

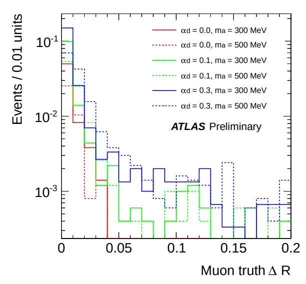
Signal Kinematics

- Showering in the dark-sector (f_d to γ_d) controlled by α_d
- More γ_d, more chances to produce muons, but softer p_T
- The dark-photon mass (m_a) determines the branching fractions and modifies p_T spectrum



The Leading and Fourth-Leading truth muon p_T.

Signal Kinematics



The ΔR between the two closest truth muons

- Showering in the dark-sector (f_d to γ_d) controlled by α_d
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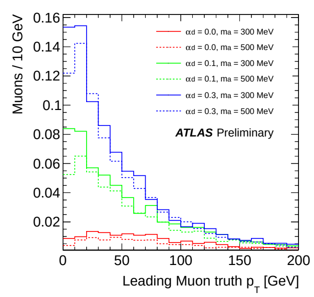

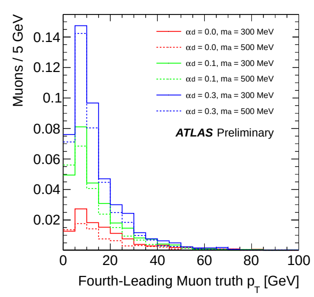

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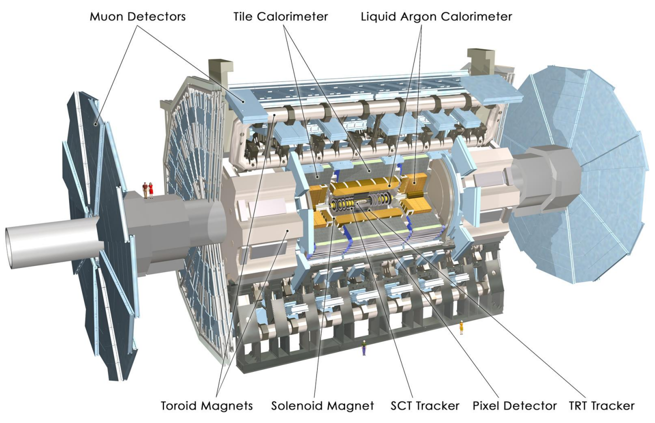
The ATLAS Detector



- **Tracks**: Silicon and Transition Radiation Tracking Inner Detector
- **Calorimetry**: Sampling LAr (EM), Plastic Scintillator (HAD) – Resolution $\sim 0.025 - 0.1$ rad
- **Muons**: Drift Tubes, Resistive Plate Chambers, and Thin Gap Chambers

Cuts and Systematics

- Collect data with a standard di-muon analysis trigger
- Require at least four reconstructed muons with $p_T > 7$ GeV, of which at least three must pass quality cuts
- Require at least two lepton-jets (muons with $\Delta R < 0.1$), each with at least two muons and at least one high quality muon,
- Require two such lepton-jets must have scaled isolation (E_T^{cone}/p_T) less than 0.7.

Main background is QCD, which is accompanied by a large systematic uncertainty

Other main concern is reconstruction efficiency at small ΔR ($\lesssim 0.01$)

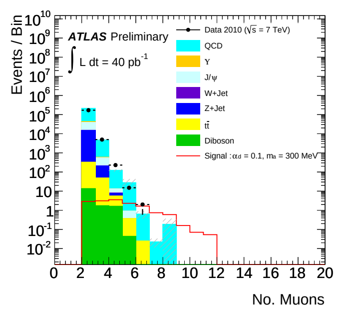
Muon channel provides a unique and almost background-free signal

Use data-driven methods to predict the background

Analysis Cuts in Detail

Muon Selection

Collect 39.7pb^{-1} of 2010 data
Trigger requires two 6 GeV muons



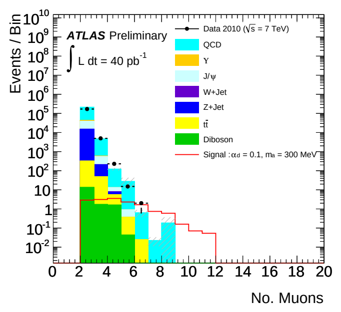
- Require ≥ 4 muons
  - reconstructed in the Muon Spectrometer
  - matched to tracks in the Inner Detector
  - with $p_T > 7$ GeV

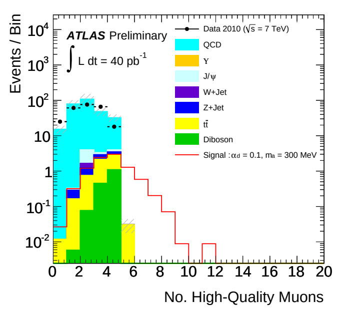
Muon Selection

Collect 39.7pb^{-1} of 2010 data
Trigger requires two 6 GeV muons

- Require $\geq$ 4 muons
  - reconstructed in the Muon Spectrometer
  - matched to tracks in the Inner Detector
  - with $p_T > 7$ GeV
- To reject QCD, require $\geq$ 3 "High-Quality" muons
  - must satisfy additional quality requirements on the Inner Detector tracks
  - and have track-match $\chi^2/NDF < 5$

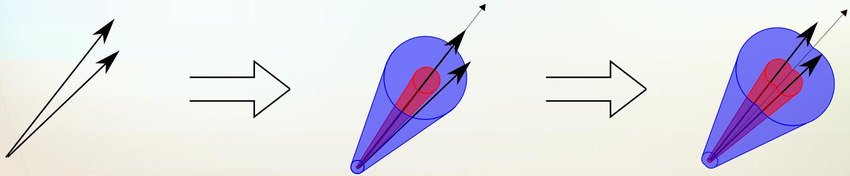
Number of High Quality muons plot is after $\geq$ 4 reconstructed muons cut





Lepton-Jet Reconstruction

- Composite objects formed by iterative cone algorithm around the highest p_T muon.
- Vector sum of muons momenta within $\Delta R < 0.1$ of center
- Center re-calculated after each addition

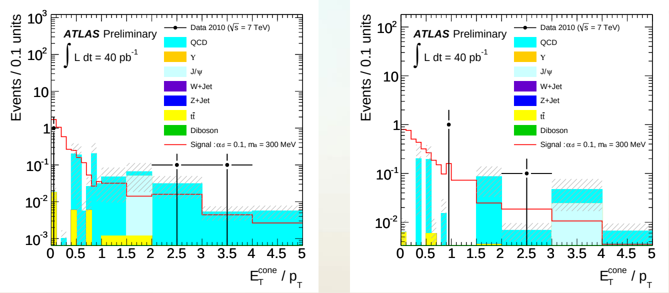


The isolation is defined by merging the calorimeter cells in each of the N muons' individual isolation cones ($\Delta R = 0.3$), and subtracting the cells in each's $\Delta R < 0.05$ cone core.

Isolation $E_T^{LJ-iso} = \sum E_T^{\Delta R<0.3} - \sum E_T^{\Delta R<0.05}$ Scaled Isolation $= E_T^{LJ-iso} / {p_T}^{LJ}$

Lepton-Jet Isolation Requirement

- Cut as loosely as possible, to preserve efficiency without introducing significant background
  - Cut determined in a higher-stat sample with looser quality cuts on the QCD (ie. multijet)
  - Avoid rejecting signal lepton-jets with e or π decays from nearby γ_d



The (E_T^{cone}/p_T) ($\Delta R < 0.3$) distribution of the Leading and Second-Leading lepton-jets in $\geq$ 4 muon events with $\geq$ 3 high quality.

Using a $0.05 < \Delta R < 0.3$ cone, require $E_T^{cone}/p_T < 0.7$

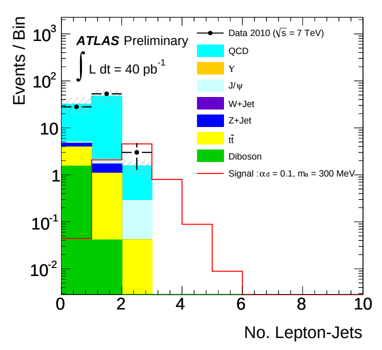
Note: The QCD has been normalized to the data (see slide 14)

Background Estimates and Cross-Checks

QCD Background Estimate

- QCD MC is normalized in a di-muon data sample
  - Fit to the data within the J/Ψ mass peak, Υ mass peak, and $20 < M_{\ell\ell} < 40$ GeV mass window
- Measure probability for a background reconstructed muon to pass the quality cuts
  - Use tag-and-probe method in background-dominated di-jet data sample

- Apply event weights equal to $p(m|n)$ the probability of finding m high-quality muons in a lepton-jet, given the presence of n reconstructed muons



This method predicts 0.19 ± 0.19 QCD events after isolation

QCD Cross-Check

The QCD prediction after all cuts is cross-checked using the ABCD method.

(A) The Signal sample	(B) The Anti-pT sample
≥ 4 muons with ≥ 3 super-tight. Scaled isolation ≤ 0.7 and muons with $p_T \geq 7$ GeV.	Cut requirement on the third and following muons is changed to be $4 < p_T < 7$ GeV.
(C) The Anti-Isolation sample	**(D) The Anti-Both sample**
One or more of the lepton-jets must fail the isolation cuts.	The third and following muons must land in the $4 < p_T < 7$ GeV window and one or more of the lepton-jets must fail the isolation cuts.

Number of QCD events in the signal region can be predicted using the ratio of events in the three control regions

Sample	Events in Data
(B) Anti-p_T	1
(C) Anti-Iso	3
(D) Anti-p_T and Anti-Iso	26
(A) Signal Region	0
	Prediction
(A) Signal Region	0.11 ± 0.11

Compared with the 0.19 ± 0.19 prediction from the event weight method

Results and Limits

Event Yields

	2 LJets	2 Isolated LJets
data	3	0
all bkg	1.74 ± 0.48	0.20 ± 0.19
QCD	1.46 ± 0.42	0.19 ± 0.19
$t\bar{t}$	0.041 ± 0.016	0.012 ± 0.0083
Diboson	0.00033 ± 0.00019	0.00033 ± 0.00019
Signal Samples		
$\alpha_d = 0.0,\ m_a = 300$	1.76 ± 0.12	1.38 ± 0.11
$\alpha_d = 0.0,\ m_a = 500$	1.35 ± 0.11	1.044 ± 0.096
$\alpha_d = 0.1,\ m_a = 300$	4.77 ± 0.21	2.90 ± 0.16
$\alpha_d = 0.1,\ m_a = 500$	4.08 ± 0.19	2.33 ± 0.14
$\alpha_d = 0.3,\ m_a = 300$	3.28 ± 0.22	1.25 ± 0.14
$\alpha_d = 0.3,\ m_a = 500$	3.29 ± 0.17	1.109 ± 0.099

- Signal produced by squark pair-production (SPS1a)
- Acceptance varies greatly as a function of α_d, the showering parameter
- Largest yields for $\alpha_d = 0.1$, best mix of extra dark photons without too much loss of p_T

Systematic Uncertainties

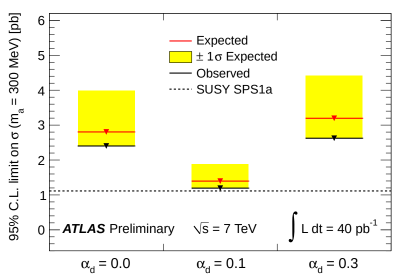
Counting experiment, so the included systematic uncertainties are all on the event yields:

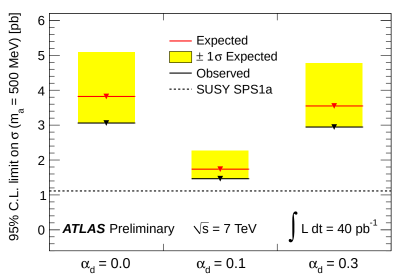
Systematic	Signal	QCD	J/Ψ	Υ	W+Jet	Z+Jet	$t\bar{t}$	Di-boson
Luminosity	3.4%				3.4%	3.4%	3.4%	3.4%
Trigger	1%				1%	1%	1%	1%
Reconstruction	2.9%				2.9%	2.9%	2.9%	2.9%
ΔR Efficiency	8%							
Muon Smearing	1%	1%	1%	1%	1%	1%	1%	1%
σ W					12%			
σ Z						1%		
σ $t\bar{t}$							7%	
σ Di-boson								4%

- Also: 100% statistical uncertainty on the QCD measurement

Limits

- No events seen, so set 95% CL limits
- Calculated using COLLIE
  - *CLs* method with a Log-Likelihood Ratio test statistic





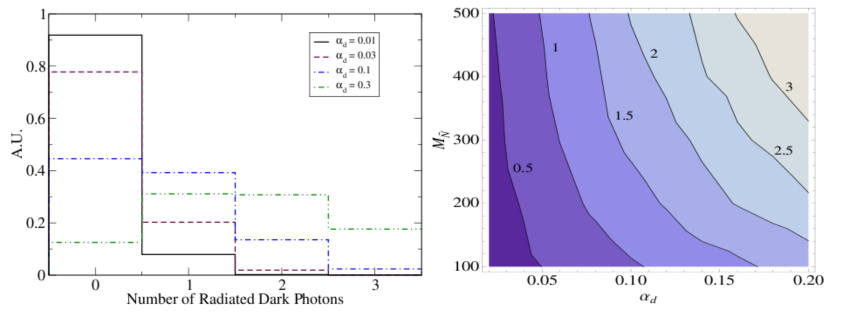
BR($\gamma_d \rightarrow \mu\mu$) is 0.47 (0.4) for $m_a = 300$ MeV (500 MeV)

Conclusions

- We have performed a search for collimated pairs of muons
- Using our data-driven modeling of the backgrounds, we find good agreement between the predicted SM and observed yields
- Developed extensive understanding of small angle track and muon reconstruction
- Computed 95% CL limits for decays to lepton-jets
- Electron channel underway
- **With large 2011/12 datasets, will be very sensitive to a large range of SUSY and other production mechanisms**

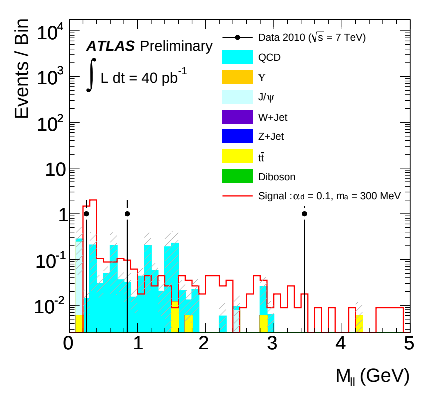
Backup Slides

Lepton-Jets Parameters

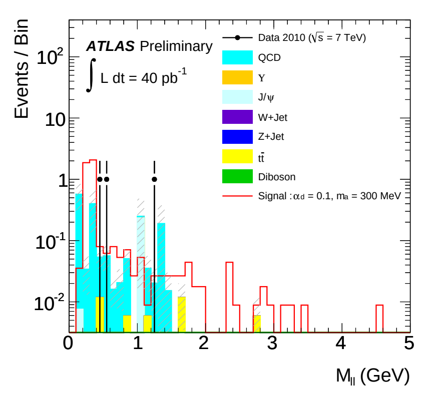


From "*Lepton Jets in (Supersymmetric) Electroweak Processes*"
http://arxiv.org/abs/0909.0290

Invariant Mass

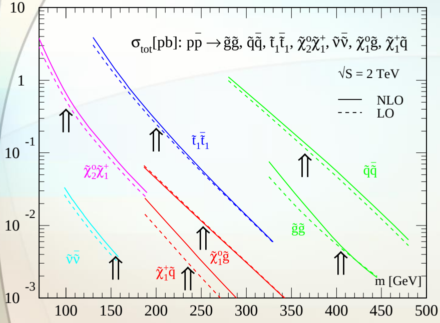


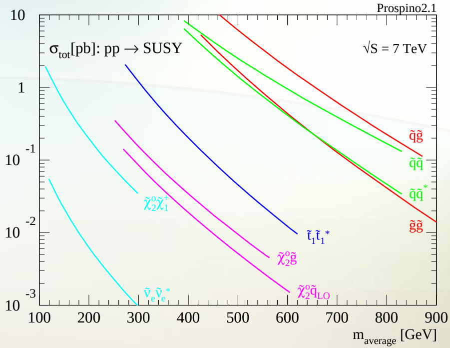
The invariant mass of the leading lepton pair in the leading lepton-jet



The invariant mass of the second-leading lepton pair in the leading lepton-jet

SUSY Cross-Sections





"Propaganda" plots from
http://www.thphys.uni-heidelberg.de/~plehn/prospino/
SUSY cross-sections are for the Tevatron (left) and LHC (right)

Limits of $\sigma \times$ BR($\rightarrow \geq 4\mu$)