A Search for Single Charged Massive Long-Lived Particles at the Fermilab Tevatron

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(for the DØ Collaboration)

Division of Particles and Fields

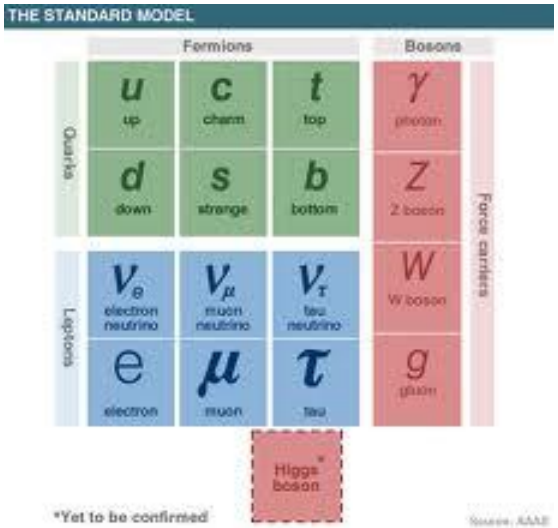
August 12, 2011

Outline

- Introduction
- Analysis Strategy
- Event Selection
- Analysis Method
- Results
- Summary

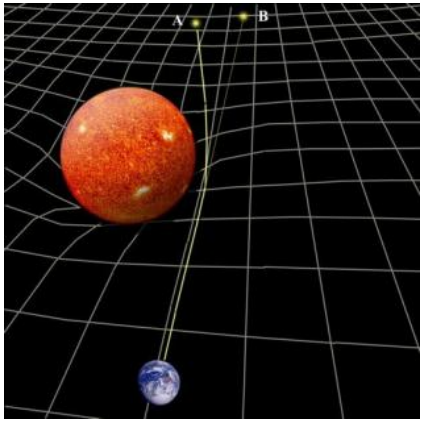
Motivation (I)

Standard Model…

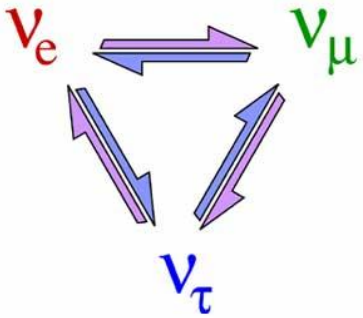


…Incomplete!

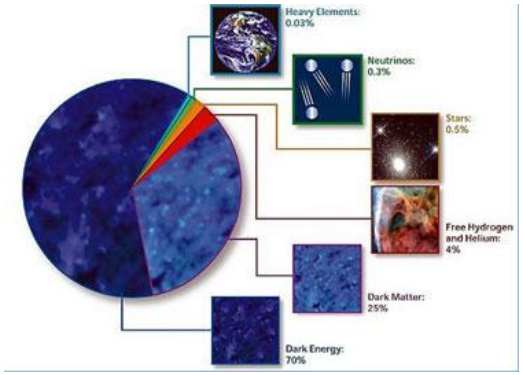
No gravity



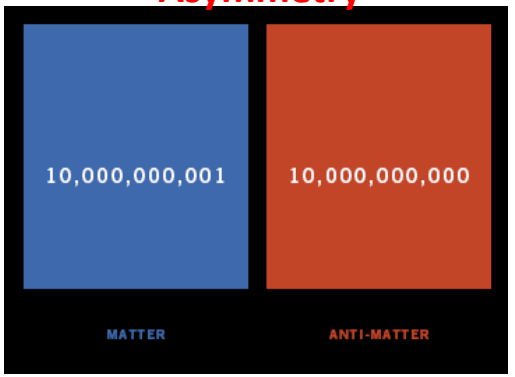
Neutrino Oscillations



Dark Matter, Dark Energy



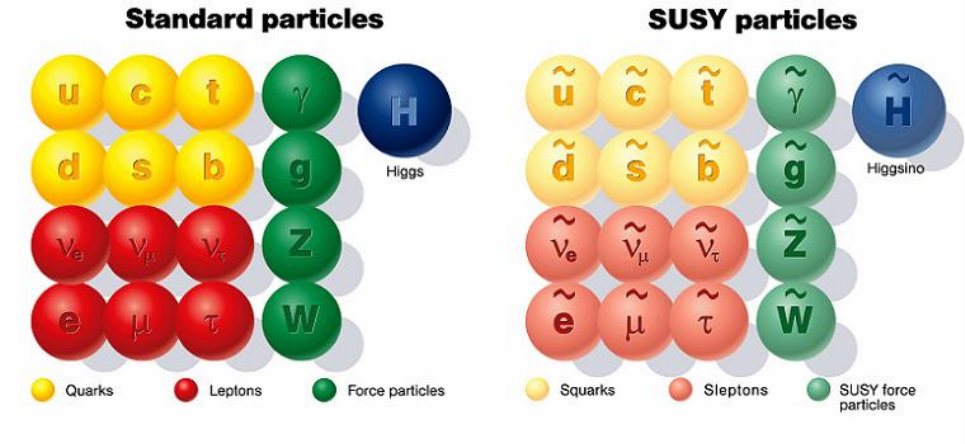
Matter-Antimatter Asymmetry



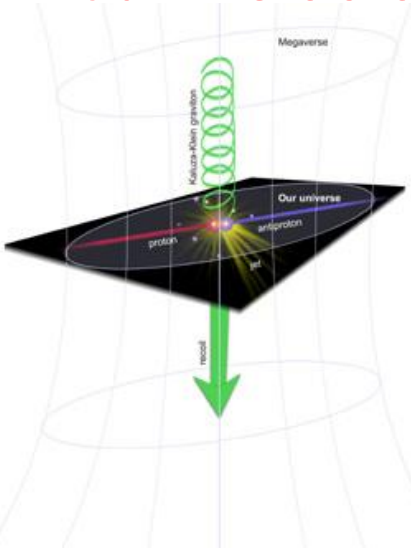
Motivation (II)

Beyond the Standard Model

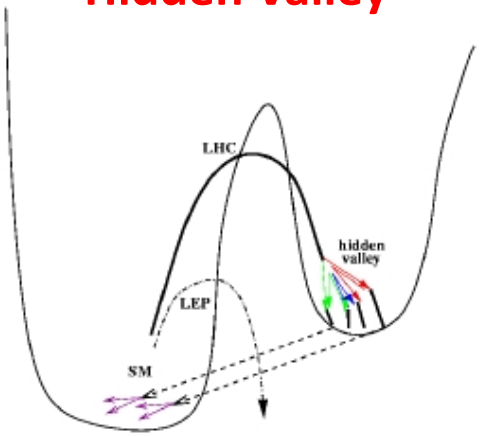
Supersymmetry



Extra Dimensions



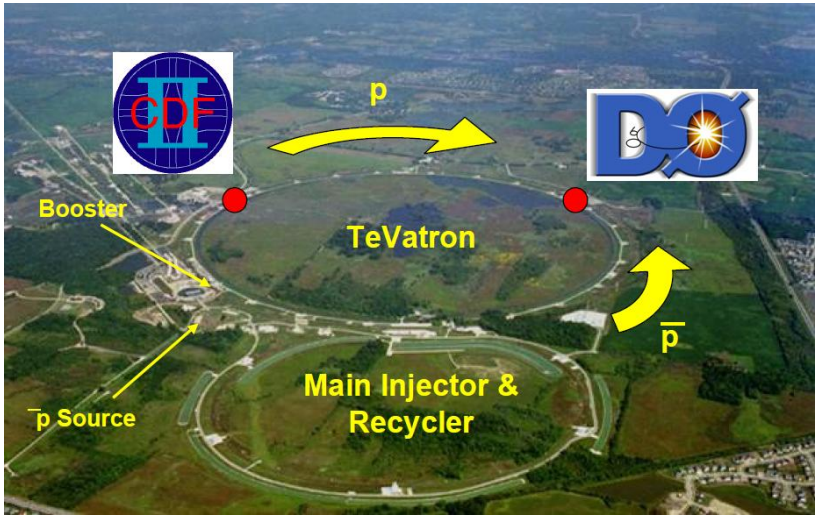
Hidden Valley

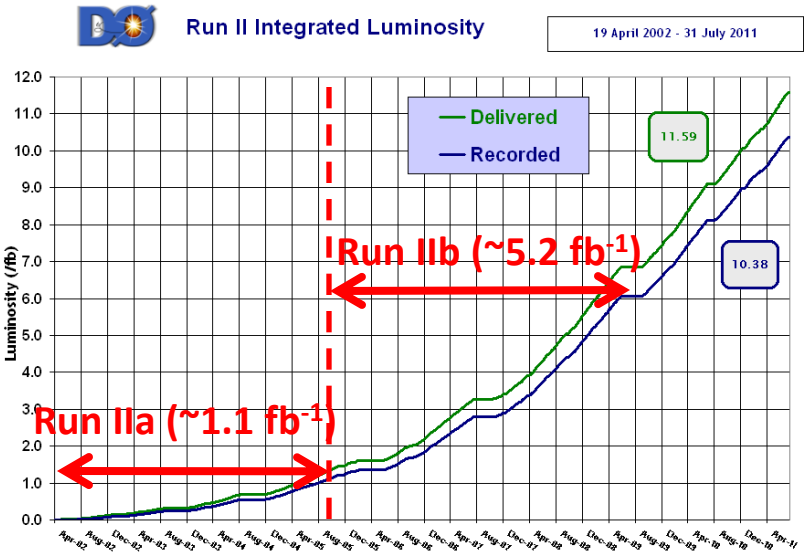


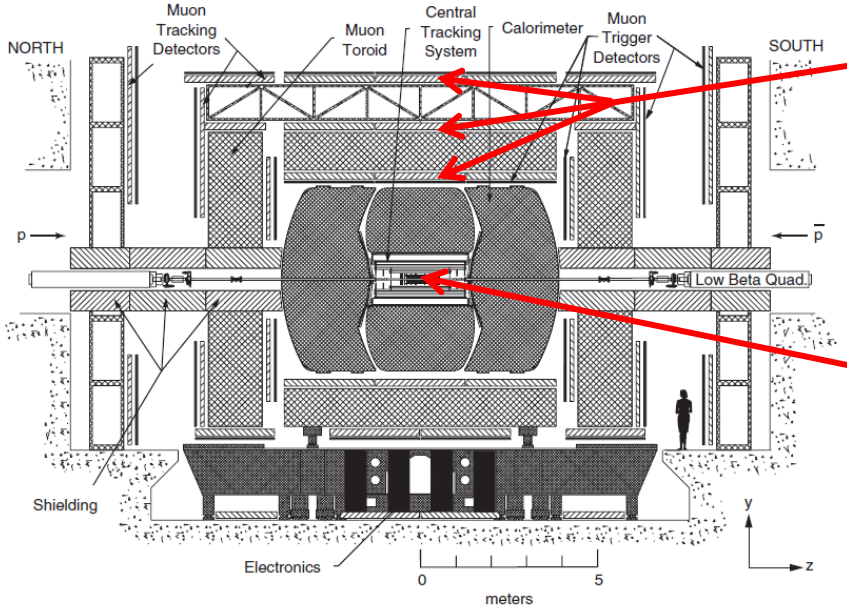
CMLLP Models

- Consider SUSY models: CMLLPs are Next-to-Lightest Supersymmetric Particles (NLSPs)
- In SUSY, the Lightest Supersymmetric Particle (LSP) is stable and must be neutral from cosmology
- NLSPs can be long-lived due to weak coupling to LSP
- Consider these long-lived NLSPs:
  - **Staus**: assume decays to gravitino LSP are suppressed
  - **Stops**: assume stop is lightest colored SUSY particle, then decays are suppressed
  - **Charginos**: assume chargino and neutralino LSP are nearly degenerate in mass
    - **Gaugino-like**
    - **Higgsino-like**

The Tevatron Collider and D0 Detector at Fermilab







Muon System

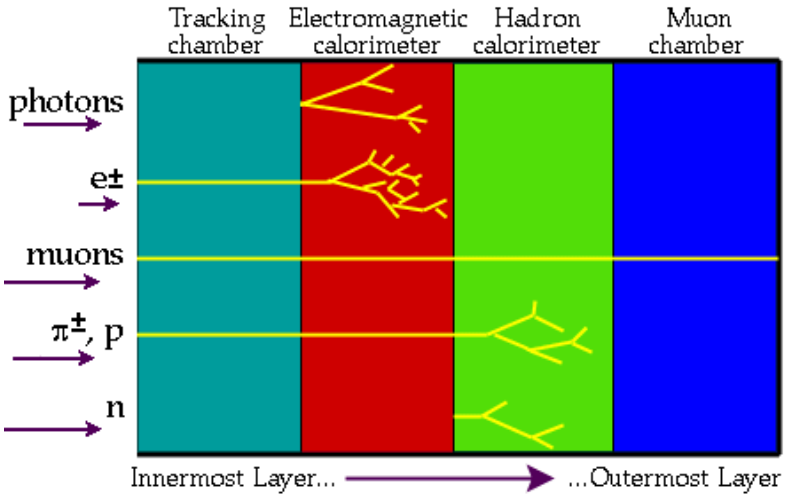
- Wires for muon tracking and scintillators for muon triggering, TOF information
- A, B and C layers, with 1.8T toroid
- Particles traveling at the speed of light are calibrated to arrive at 0 ns, while CMLLPs arrive at late times

Silicon Microstrip Tracker

- Triggering and vertexing
- Provides dE/dx measurement
- Muons are minimum ionizing particles, while CMLLPs are highly ionizing

CMLLPs and Their Detector Signature

- Charged, massive, high pT, long-lived particles beyond the SM
- Signature:
  - Look like slow, massive, long-lived muons
  - Distinguishable from muons with Time-of-Flight (TOF) and ionization energy loss (dE/dx) measurements

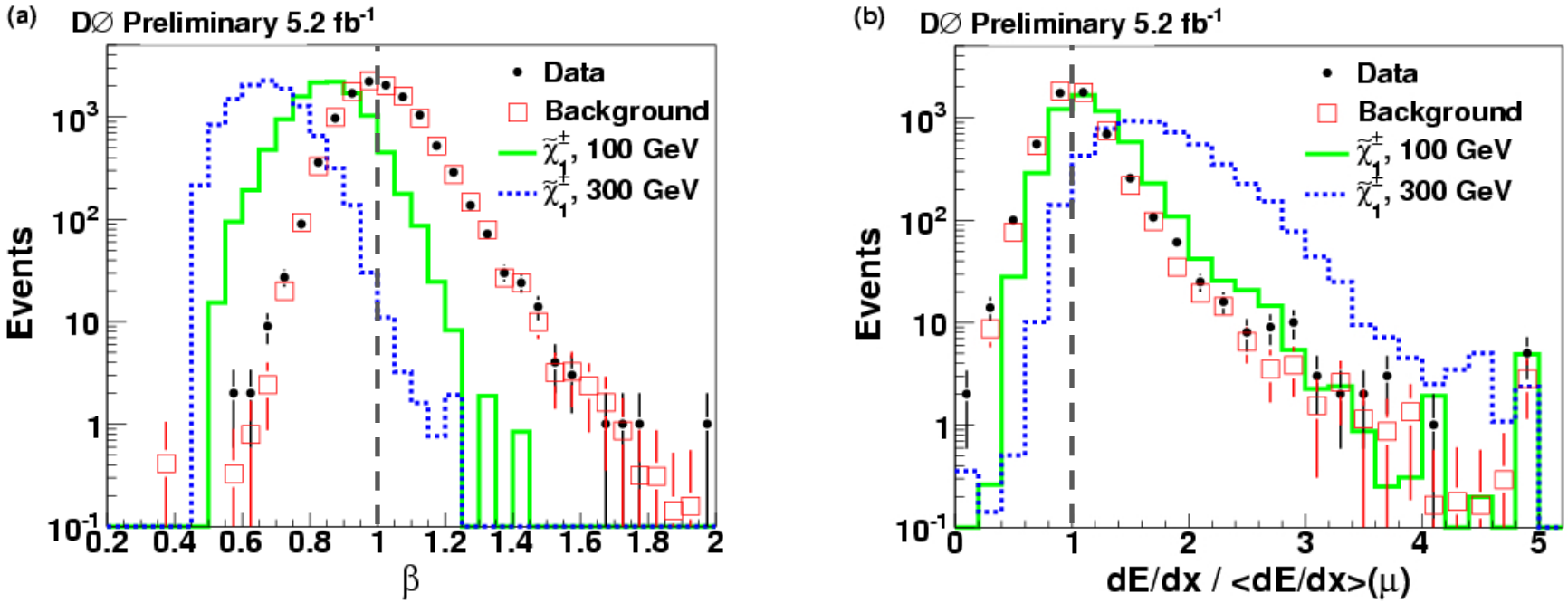


Signal Samples

- Signal samples generated in PYTHIA
  - staus, stops, gaugino-like charginos, higgsino-like charginos
  - stops hadronized by linking external code to PYTHIA
  - 100 GeV to 300 GeV in 50 GeV steps for each signal
- Pair production only, not including cascade decays
  - Considered including cascade decays, but did not give enough boost in signal to be worthwhile
- D0 detector GEANT simulation for detector response

Analysis Strategy

- Use speed (β), dE/dx, and related variables to distinguish signal (CMLLPs) from background (muons)
- **Cut hard on the kinematics to reduce the large background**
  - Speed and dE/dx are independent of kinematics (e.g. pT) for signal
- **Quasi-blinded when determining optimal kinematic cuts**
  - Made a kinematic selection to eliminate signal from data while we did studies/testing

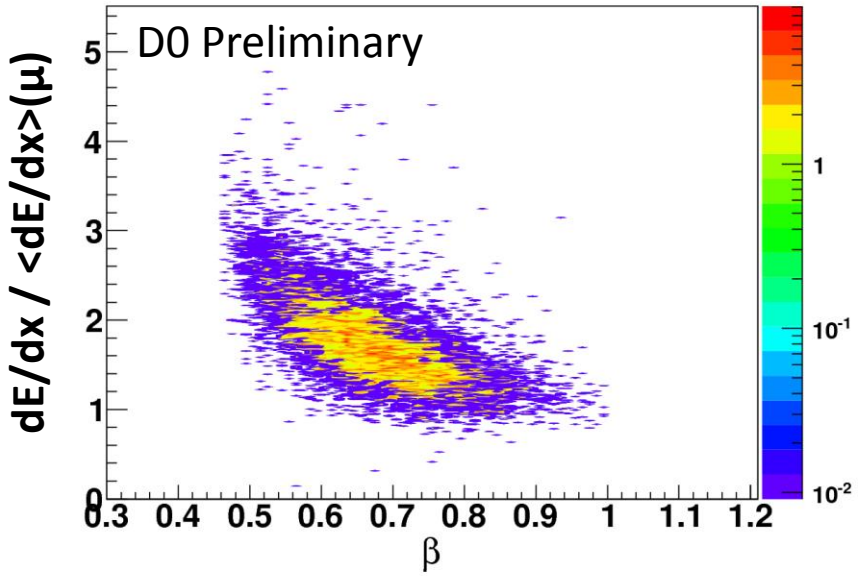


Timing and dE/dx calibrated so that muons are at β = dE/dx = 1

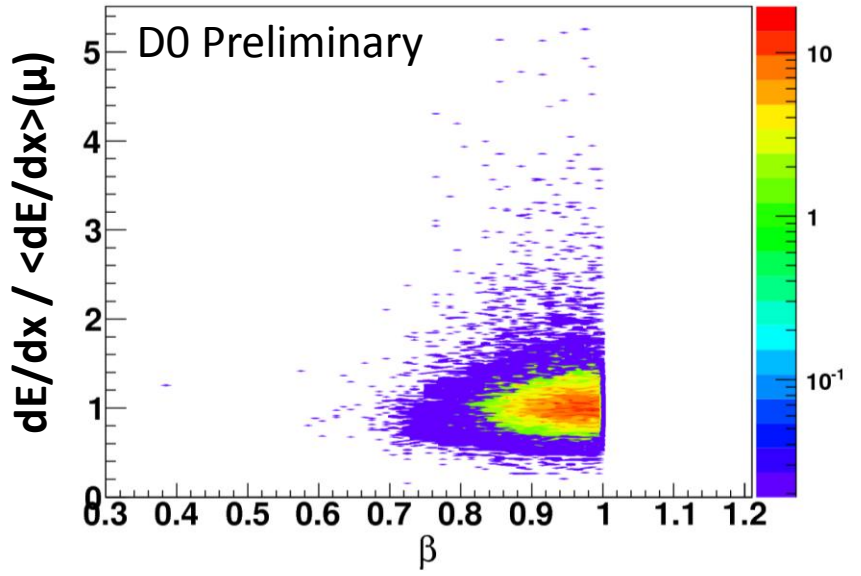
Key Variables – Speed vs dE/dx

- Speed and dE/dx are highly anti-correlated for signal, and not for background
- Speed and dE/dx give high separation between signal and background

Signal: 300 GeV gaugino-like chargino

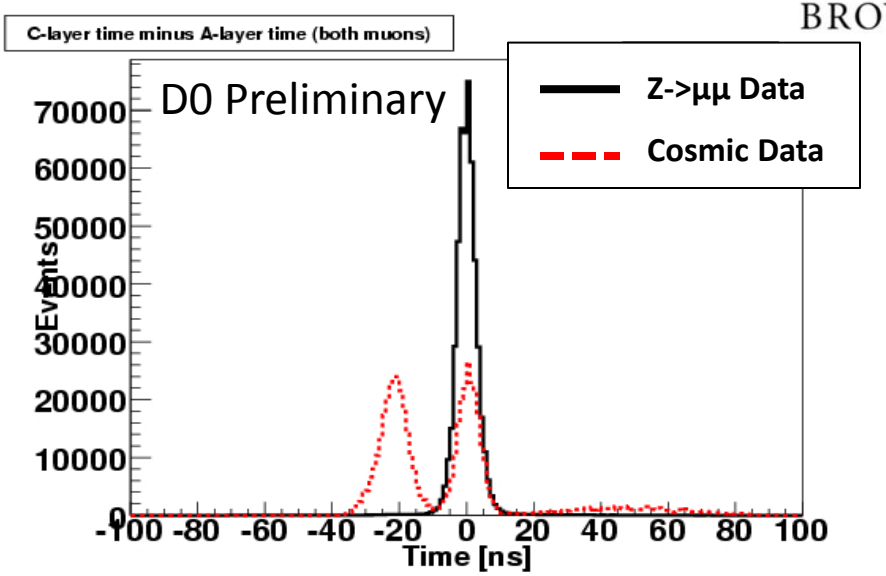


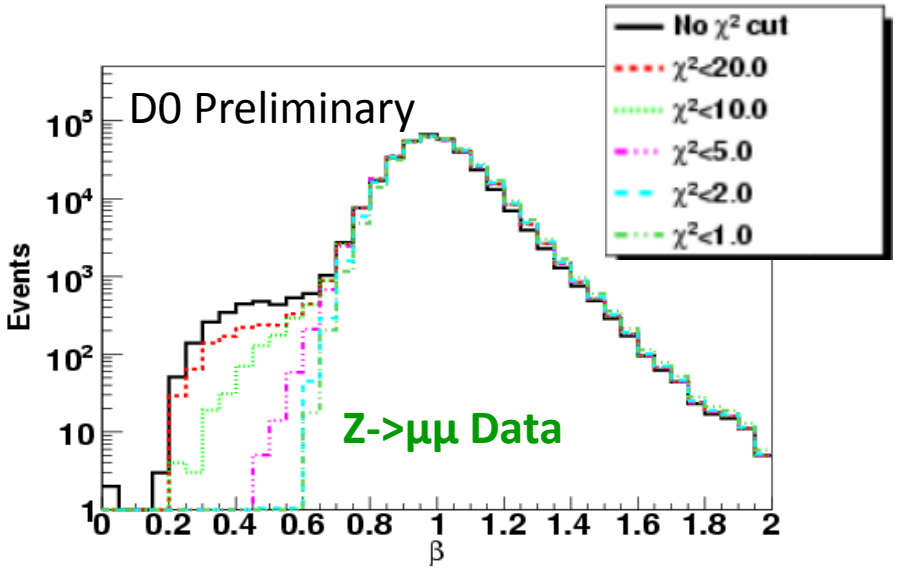
Background: Single Muon Data, mT<200



Event Selection

- At least one muon per event, then select the highest pT muon
- Single muon trigger without tight scintillator timing cut
- Good muon quality (good track, isolated)
- Cosmic timing and acolinearity cuts
- pT>60 GeV
- Speed < 1
- Speed χ^2 /dof < 2





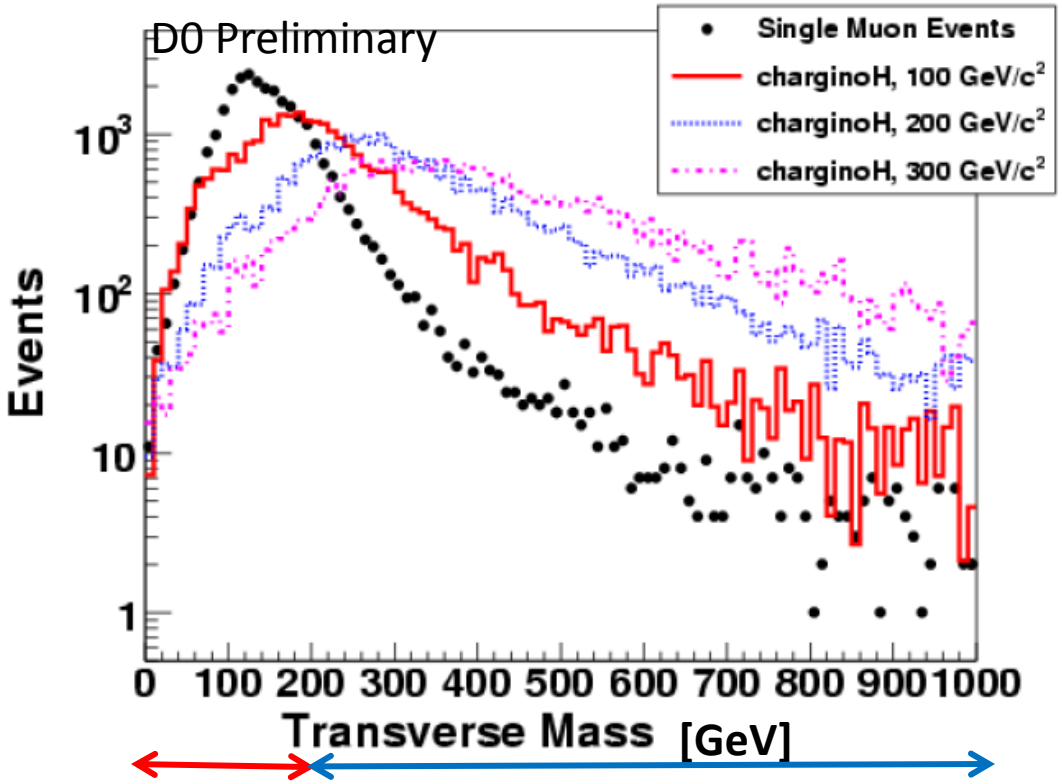
Background Sample

$$M_T = \sqrt{(E_T + \not{E}_T)^2 - (p_x + \not{E}_x)^2 - (p_y + \not{E}_y)^2}$$

Most of background in this sample are W->μν events, so use a mT cut of 200 GeV, as is done in the W mass group

Background: Single muon data with mT<200 GeV

Data: Single muon data with mT>200 GeV



Background Normalization

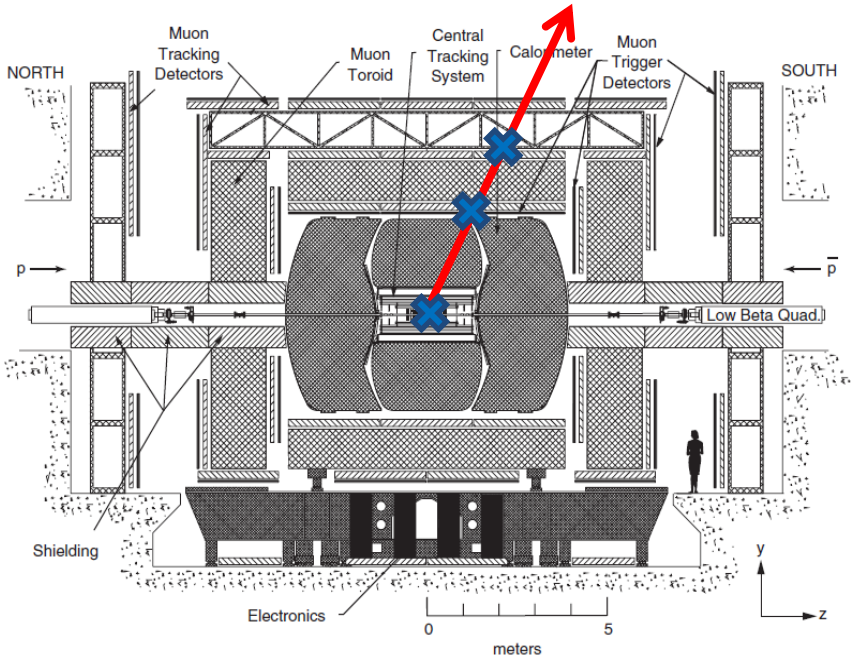
- Normalize **background** to **data** in a normalization region

	mT<200 GeV	mT>200 GeV
β>1	**Normalization background**	**Normalization data**
β<1	**Event background**	**Event data**

- Normalized background = **Background events***Normalization **data** events/Normalization **background** events

Stop Charge Flipping Probability

- 60% of stop hadrons will be charged after hadronization
- Passage through matter: after many interactions
  - All stop hadrons are baryons, so **2/3** will be charged
  - All antistop hadrons are mesons, so **1/2** will be charged
  - Probability of stop hadron charged at all 3 locations = 0.6(production)*0.67(end of cal)*0.67(end of muon system) = **0.27**
  - Probability of antistop hadron charged at all 3 locations = 0.6(production)*0.5(end of cal)*0.5(end of muon system) = **0.15**



- **Single CMLLP analysis**: either stop hadron and antistop hadron can be charged, or both can be charged
  - Probability of at least one charged in all 3 locations = 0.27*(1 - 0.15) + 0.15*(1 - 0.27) + 0.27*0.15 = **0.38**

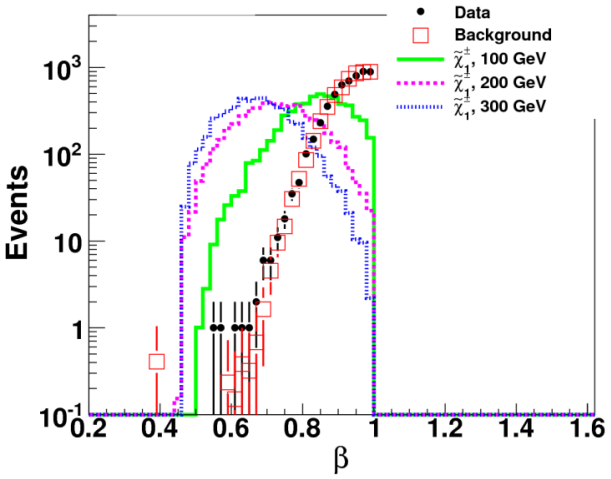
Analysis Method

1. Obtain **speed, dE/dx, and related variables distributions** for signal, background, and data
2. Input distributions into **multivariate techniques** (TMVA)
   - Boosted Decision Trees (BDT)
   1) Train BDT on signal and background distributions to get weights
   2) Apply weights to signal, background, and data distributions to get a "final variable" (BDT output) distributions
3. Obtain **systematic uncertainties**
4. Input final variable distributions and systematic uncertainties into **CLs method** to get 95% confidence level cross-section limits

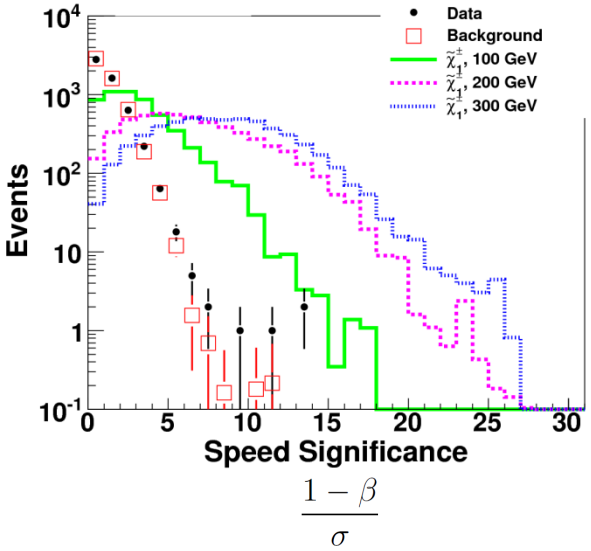
Input Variables

- **Focusing on speed and dE/dx related variables**

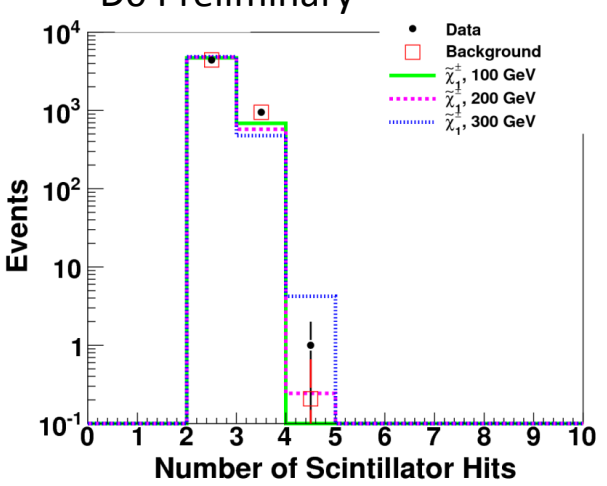
D0 Preliminary



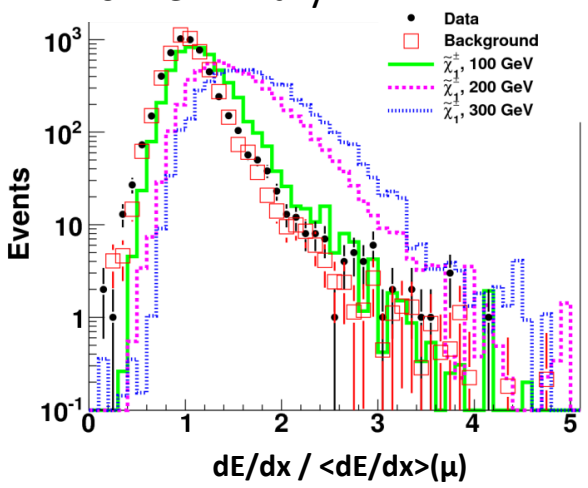
D0 Preliminary



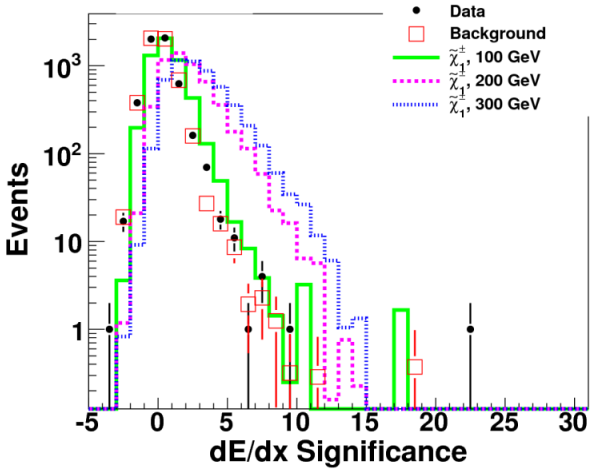
D0 Preliminary



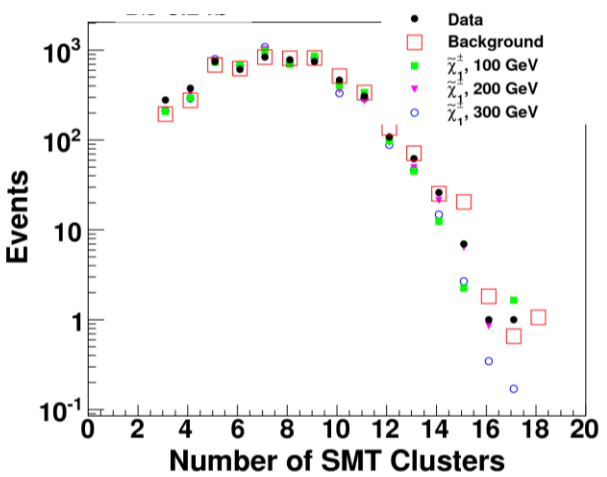
D0 Preliminary



D0 Preliminary

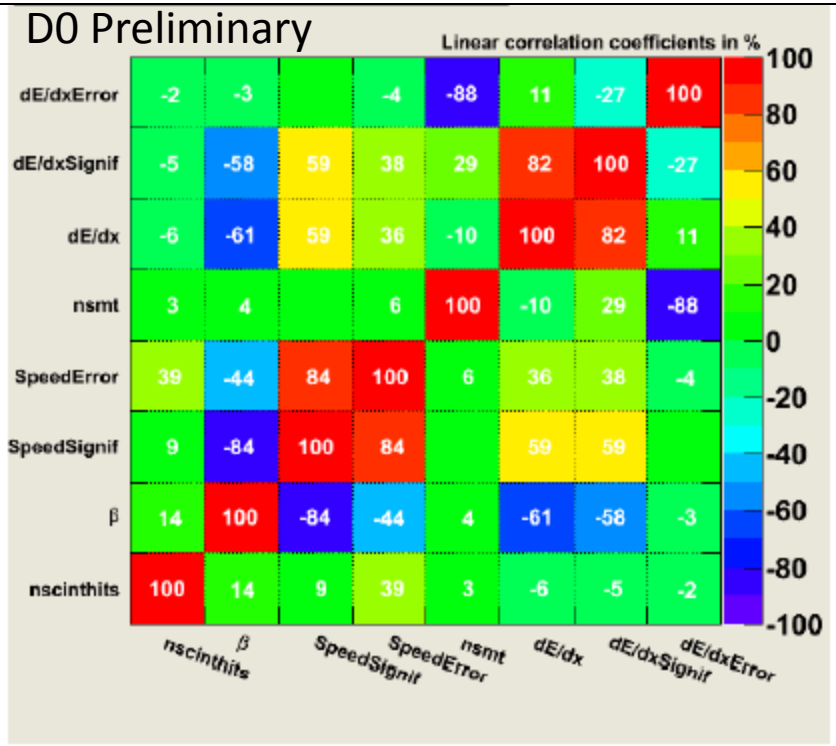


D0 Preliminary

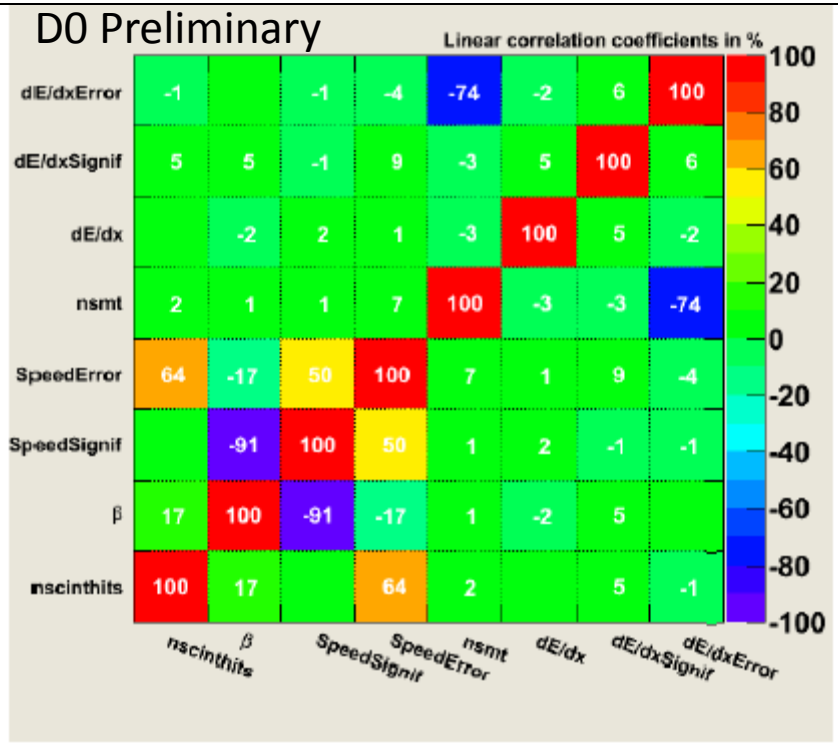


BDT Correlations

Signal: 300 GeV stau



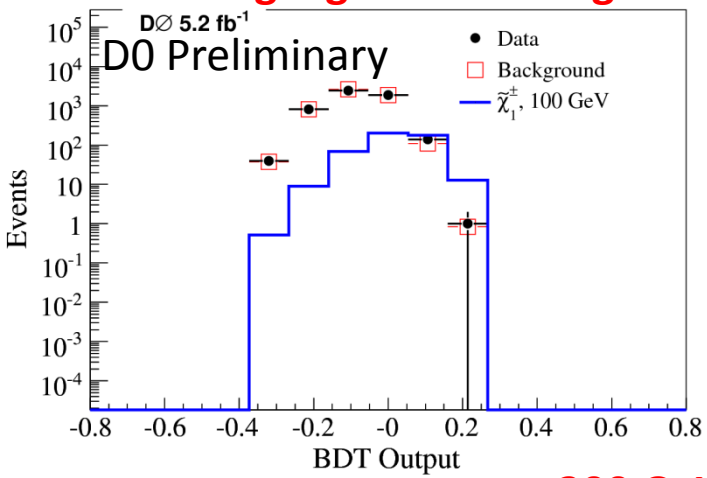
Background



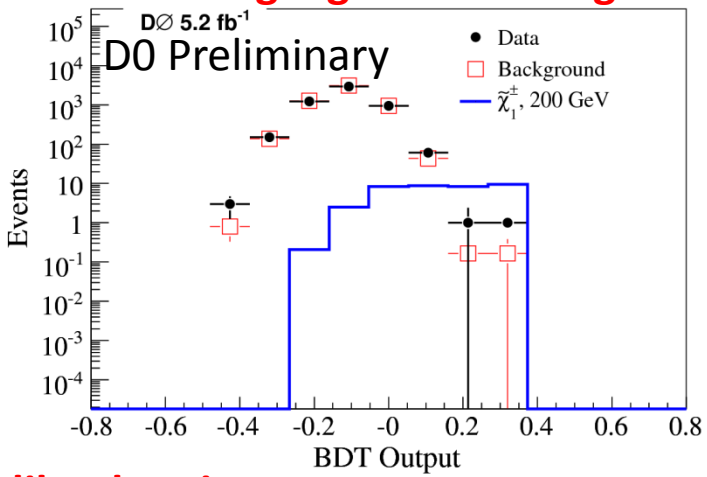
BDT Discriminant Distributions

Good agreement between data and background suggests little possible signal

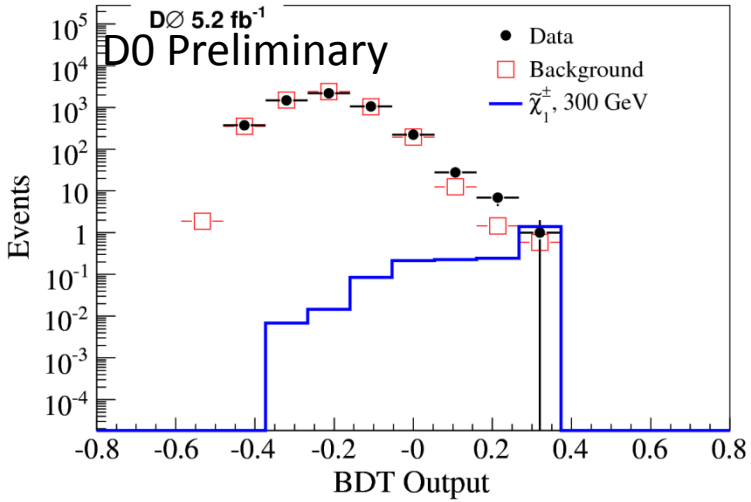
100 GeV gaugino-like chargino



200 GeV gaugino-like chargino



300 GeV gaugino-like chargino

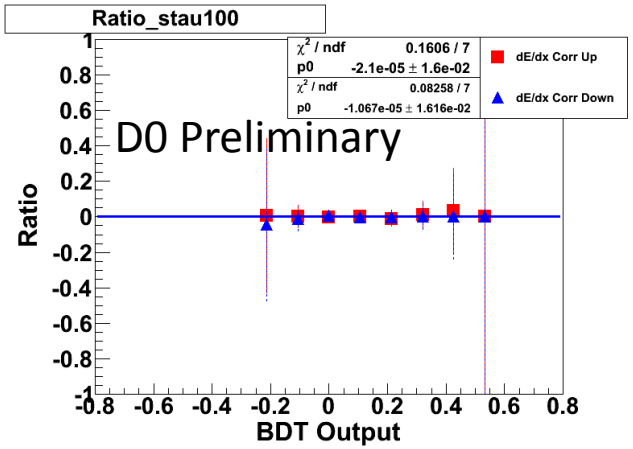


Systematic Uncertainties

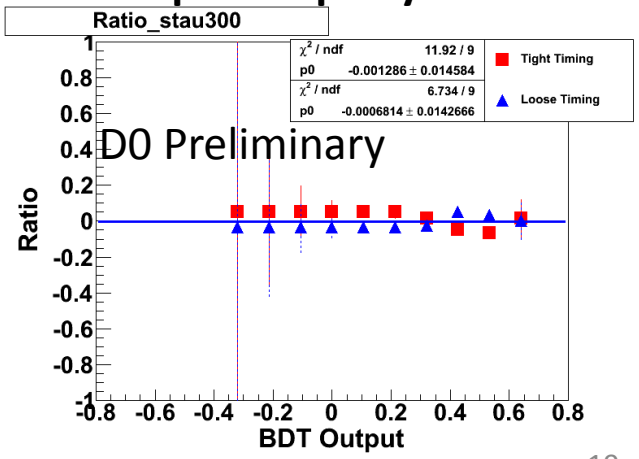
$$Ratio = \frac{BDT\_with\_systematic - BDT\_without\_systematic}{BDT\_without\_systematic}$$

- **Flat Systematics**
  - Luminosity Uncertainty (6.1%)
  - Muon ID Uncertainty (2.1%)
  - Background Normalization Uncertainty from β cut (7.2%)
  - Background Normalization Uncertainty from mT cut (2.2%)
  - Muon pT Smearing Uncertainty (0.2%)
  - PDF Uncertainty (<0.2%)
  - dE/dx Correction Uncertainty (<0.1%)
  - dE/dx Smearing Uncertainty (0.2%)
- **Shape Systematics**
  - Trigger Timing Gate Uncertainty
  - Timing Smearing Uncertainty

Example Flat Systematic



Example Shape Systematic



Cross-Section Limits (D0 Preliminary)

BROWN

Staus:

Mass (GeV/c^2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	0.0121	0.0400	$0.0263^{+0.0109}_{-0.0075}$
150	0.00214	0.0418	$0.0164^{+0.0062}_{-0.0035}$
200	0.0004799	0.0113	$0.00671^{+0.00122}_{-0.00061}$
250	0.000122	0.0132	$0.00556^{+0.00114}_{-0.00077}$
300	0.0000314	0.00581	$0.00538^{+0.00104}_{-0.00076}$

Stops:

Mass (GeV/c^2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	15.6	0.562	$0.218^{+0.078}_{-0.062}$
150	1.58	0.133	$0.0490^{+0.0190}_{-0.0111}$
200	0.266	0.0529	$0.0234^{+0.0106}_{-0.0037}$
250	0.0560	0.0269	$0.0201^{+0.0090}_{-0.0050}$
300	0.0130	0.0794	$0.0529^{+0.0140}_{-0.0128}$

Gaugino-like charginos:

Mass (GeV/c^2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	1.33	0.387	$0.153^{+0.068}_{-0.043}$
150	0.235	0.0435	$0.0167^{+0.0054}_{-0.0033}$
200	0.0566	0.0195	$0.00945^{+0.00368}_{-0.00057}$
250	0.0153	0.0136	$0.00988^{+0.00402}_{-0.00127}$
300	0.00417	0.0741	$0.0185^{+0.0046}_{-0.0027}$

Higgsino-like charginos:

Mass (GeV/c^2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	0.381	0.106	$0.110^{+0.050}_{-0.032}$
150	0.0736	0.0417	$0.0165^{+0.0053}_{-0.0038}$
200	0.0186	0.0128	$0.00852^{+0.00169}_{-0.00112}$
250	0.00525	0.00897	$0.00716^{+0.00267}_{-0.00100}$
300	0.00154	0.0174	$0.0119^{+0.0033}_{-0.0005}$

Summary

- Searched for charged, massive, long-lived particles with 5.2 fb^{-1} integrated luminosity collected with the D0 detector
- Key variables: dE/dx and Speed
- Required at least one muon per event, then study highest pT muon
- Cross-section and mass limits
  - **265 GeV for stop**
    - **281 GeV without charge flipping**
  - **251 GeV for gaugino-like chargino**
  - **230 GeV for higgsino-like chargino**
  - **stau cross-section limits between 0.04 and 0.006 pb, for stau masses between 100 and 300 GeV**

Currently Best Limits

95% C.L. Mass Limits

- D0 public results:

http://www-d0.fnal.gov/Run2Physics/WWW/results.htm

BACKUP

CMLLP Models

- GMSB model in which NLSP is a long-lived stau
- Light chargino predicted
  - Long-lived if mass difference between it and lightest neutralino is < 150 MeV
  - Can occur in AMSB or models that do not have gaugino mass unification
  - Consider a case where the chargino is mostly gaugino-like, and another where the chargino is mostly higgsino-like
- Stop predicted
  - stops hadronize into long-lived charged and neutral mesons and baryons
  - Hidden Valley models predict GMSB-like scenarios where stop acts like LSP: doesn't decay but hadronizes into charged and neutral hadrons that escape the detector
  - Any SUSY scenario where the stop is the lightest colored particle can have the stop as a CMLLP

Some Useful Equations

- Average Speed

$$\beta = \sigma^2 \sum_i \frac{\beta_i}{\sigma_i^2}$$

- Speed χ^2

$$\chi^2 = \frac{1}{i-1} \sum_i \frac{(\beta - \beta_i)^2}{\sigma_i^2}$$

- Speed Error

$$\frac{1}{\sigma^2} = \sum_i \frac{1}{\sigma_i^2}$$

- Speed Significance

$$\frac{1-\beta}{\sigma}$$

- Pseudo-acolinearity

$$\Delta\alpha = |\Delta\phi + \Delta\theta - 2\pi|$$

Expected Events Table

- With BDT>0.27 cut
- For illustrative purposes only – not considered in analysis method

Staus:

Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0.74 \pm 0.001(\text{stat.}) \pm 0.08(\text{sys.})$	$0 \pm 0(\text{stat.}) \pm 0(\text{sys.})$	0
150	$3.49 \pm 0.001 \pm 0.08$	$2.43 \pm 0.001 \pm 0.18$	4
200	$5.48 \pm 0.001 \pm 0.35$	$1.11 \pm 0.001 \pm 0.08$	2
250	$7.14 \pm 0.001 \pm 0.43$	$1.24 \pm 0.001 \pm 0.09$	7
300	$7.74 \pm 0.01 \pm 0.33$	$2.63 \pm 0.001 \pm 0.20$	3

Stops:

Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0.01 \pm 0.001(\text{stat.}) \pm 0.001(\text{sys.})$	$0 \pm 0(\text{stat.}) \pm 0(\text{sys.})$	0
150	$0.72 \pm 0.001 \pm 0.08$	$0.25 \pm 0.001 \pm 0.02$	2
200	$2.09 \pm 0.001 \pm 0.16$	$0.59 \pm 0.001 \pm 0.04$	3
250	$2.63 \pm 0.001 \pm 0.17$	$1.70 \pm 0.001 \pm 0.13$	1
300	$2.75 \pm 0.001 \pm 0.17$	$3.01 \pm 0.001 \pm 0.23$	2
350	$2.57 \pm 0.001 \pm 0.21$	$1.05 \pm 0.001 \pm 0.08$	4
400	$2.47 \pm 0.001 \pm 0.16$	$0.53 \pm 0.001 \pm 0.04$	1

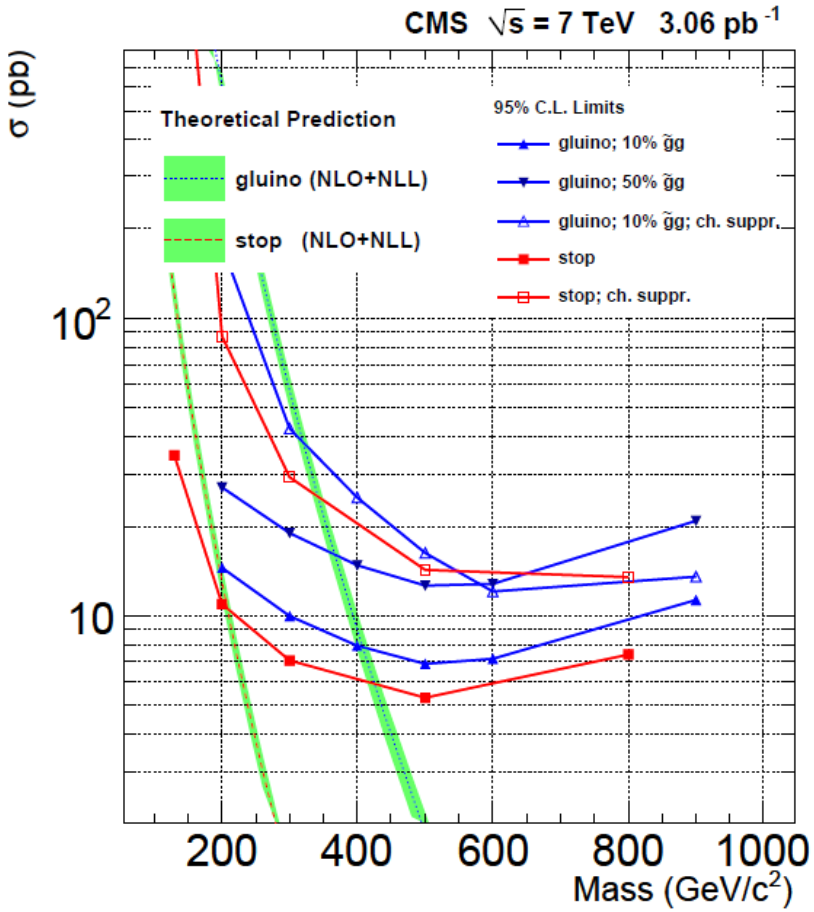
Gaugino-like charginos:

Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0 \pm 0(\text{stat.}) \pm 0(\text{sys.})$	$0 \pm 0(\text{stat.}) \pm 0(\text{sys.})$	0
150	$2.54 \pm 0.001 \pm 0.16$	$0.25 \pm 0.001 \pm 0.02$	2
200	$2.04 \pm 0.001 \pm 0.79$	$0.17 \pm 0.001 \pm 0.01$	0
250	$4.63 \pm 0.001 \pm 0.36$	$0.51 \pm 0.001 \pm 0.04$	1
300	$4.58 \pm 0.001 \pm 0.47$	$0.59 \pm 0.001 \pm 0.04$	1

Higgsino-like charginos:

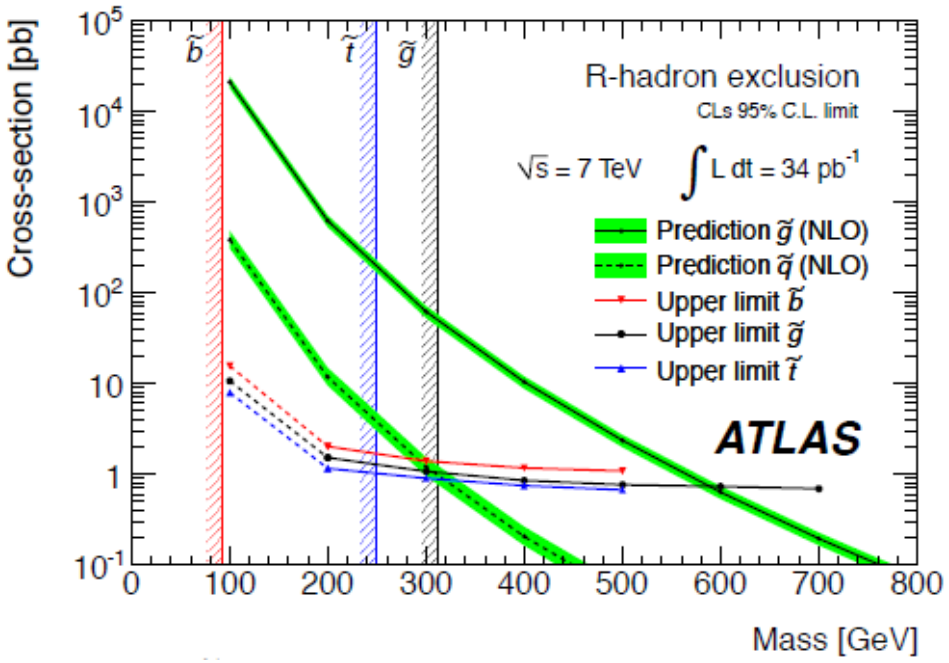
Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0.29 \pm 0.001(\text{stat.}) \pm 0.11(\text{sys.})$	$0 \pm 0(\text{stat.}) \pm 0(\text{sys.})$	0
150	$3.57 \pm 0.001 \pm 0.26$	$0.87 \pm 0.001 \pm 0.07$	3
200	$5.68 \pm 0.001 \pm 0.34$	$1.75 \pm 0.001 \pm 0.13$	5
250	$5.21 \pm 0.001 \pm 0.62$	$0.79 \pm 0.001 \pm 0.06$	2
300	$4.60 \pm 0.001 \pm 0.36$	$0.36 \pm 0.001 \pm 0.03$	0

Results from CMS and ATLAS



With 3.1 pb^{-1} of data, **CMS** excludes:

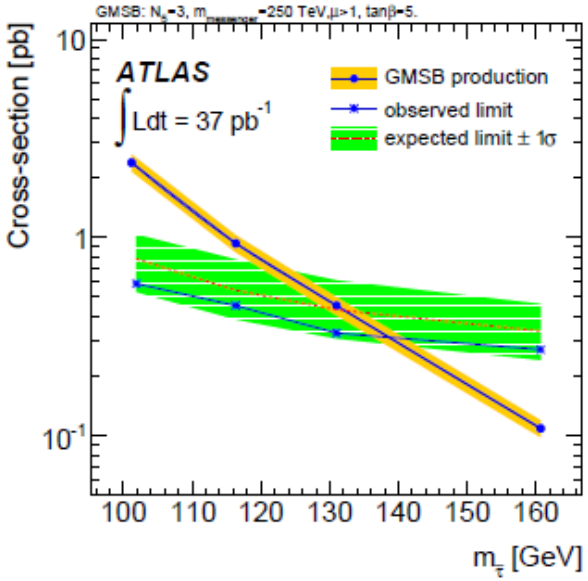
- **gluinos** below **398 GeV**
- **stops** below **202 GeV**

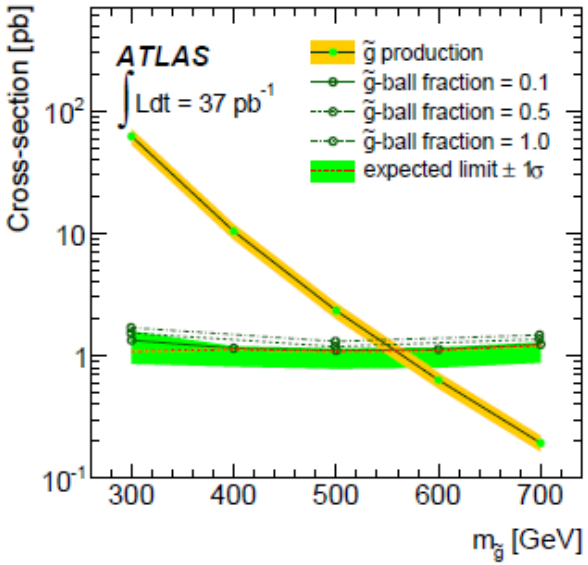


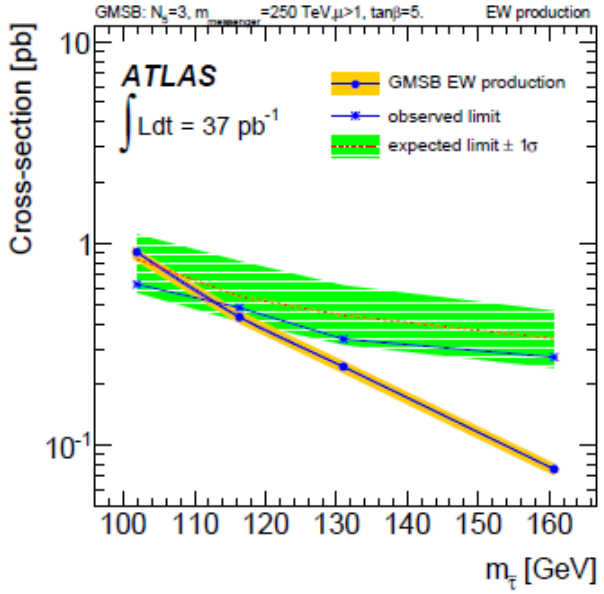
With 34 pb^{-1} of data, **ATLAS** excludes:

- **sbottoms** below **294 GeV**
- **gluinos** below **586 GeV**
- **stops** below **309 GeV**

More Results from ATLAS



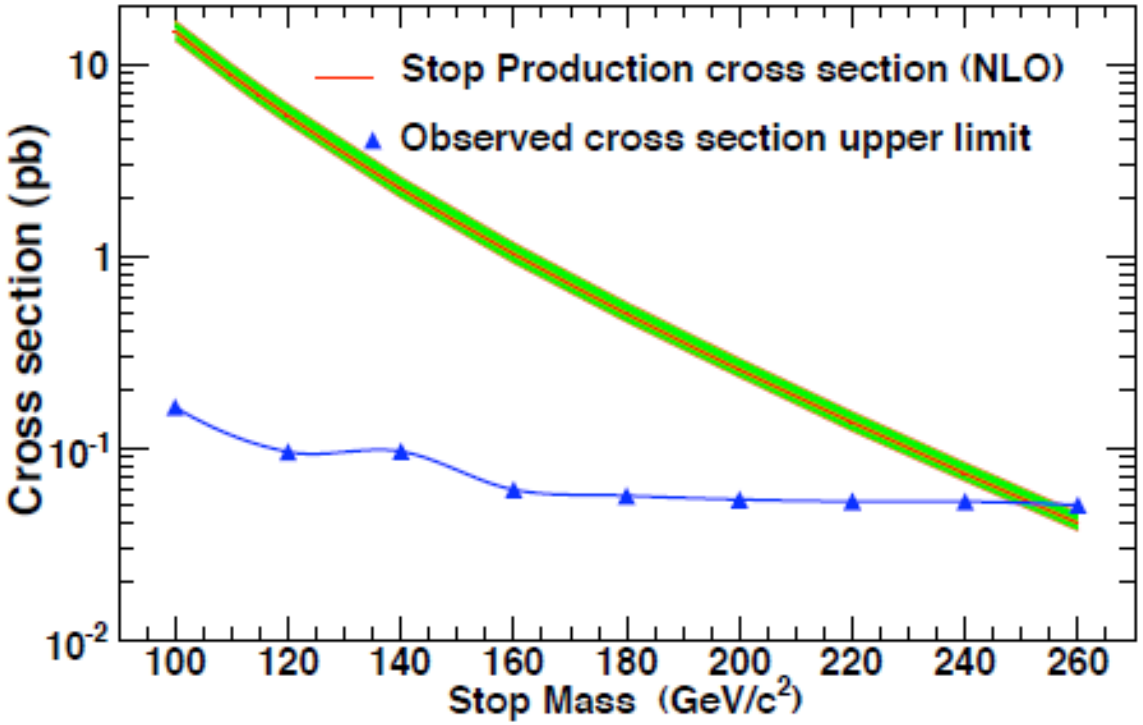




With 37 pb^{-1} of data, **ATLAS** excludes:

- **staus** below **136 GeV** (GMSB with N_5=3, $m_{messenger}$=250 TeV, sign(μ)=1, tan(β)=5
- **sleptons in EW only** below **110 GeV**
- **gluinos** below **530-544 GeV** (depends on fraction of R-hadrons produced as gluino-balls)

Results from CDF



With 1.0 fb^{-1} of data, **CDF** excludes:

- **stops** below **249 GeV**