A Search for Charged Massive Long-Lived Particles at D0

Sudeshna Banerjee

Tata Institute of Fundamental Research

For the DØ Collaboration

Europhysics Conference on High-Energy Physics

Grenoble, France

21 – 27 July 2011

Motivation

Historically, the strange, long-lived kaons started a new era in particle physics.

Today some extensions of Standard Model and some SUSY models suggest the existence of another kind of massive long-lived particles (MLLP).

Existence of these particles could solve some of the puzzles that have no answers yet.

- Dark matter in the universe
- Charge quantization – magnetic monopoles
- Lithium abundance (not explained by the present model of Big Bang Nucleosynthesis (BBN))

Possible solution – Existence of a MLLP that decays during or after the time of BBN

These massive long-lived particles can have different colour and electric charge

- $\tilde{q}/\tilde{g}$ (bound states – R hadrons)
- $\tilde{l}$ or $\tilde{\chi}^{+}$

Current results are on the search of Charged Long-Lived Particles (CMLLPs) at D0

Models

Supersymmetry (Susy) Models :

- The Lightest Supersymmetric Particle (LSP) is stable and must be neutral (cosmology)
- CMLLPs could be Next-to-Lightest Supersymmetric Particles (NLSPs)
- NLSPs can be long-lived due to weak coupling to LSP

CMLLPs considered in this analysis :

Staus - GMSB with stau NLSP (if stau →gravitino (LSP) decays suppressed)

Charginos - If there is a "wino-LSP" (small $\tilde{\chi}_1^+$ -$\tilde{\chi}_1^0$ mass difference), chargino will have a long life time. Two extreme scenarios are explored.

1. chargino = gaugino
2. chargino = higgsino

Stops –

- if Stop is the lightest colored particle its decay will be suppressed
- Hidden Valley theories (stop LSP)

CMLLPs in the D0 Detector

Important properties for detection:

- **Charged**
  Leaves a track in the tracker
- **Long-Lived**
  Does not decay inside the detector
- **Massive**
  Slow moving
  (large Time of Flight to muon system → small β,
  large energy deposit (dE/dx))

Acts like a muon but is heavier

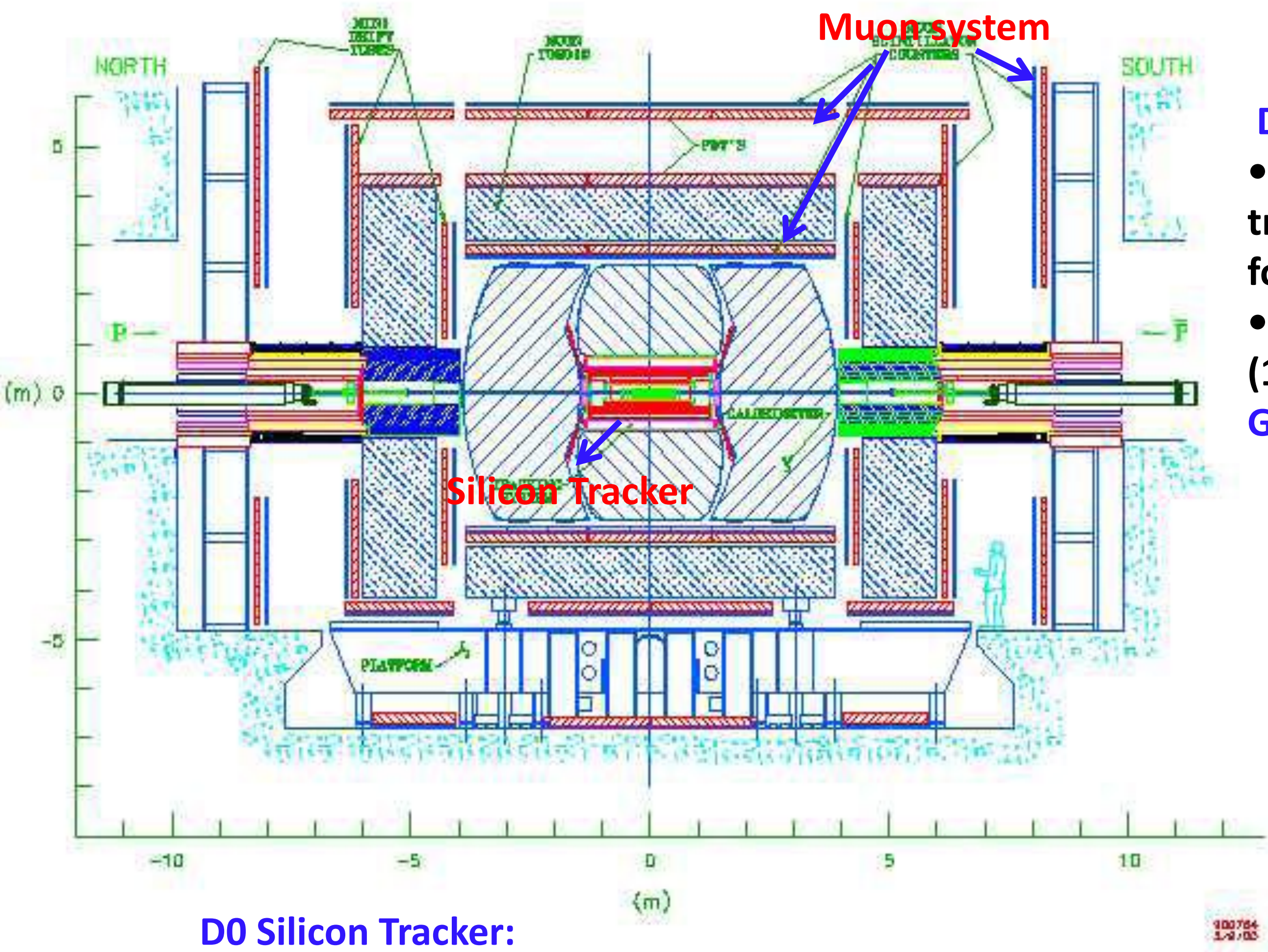
Differences:

- Time Of Flight through the detector will be larger
- dE/dx will be larger

D0 Search:

- Examine events with one or more muons
- Select events in which the muon looks like a CMLLP candidate

The DØ Experiment



D0 Muon System :

- **Wire chambers for muon tracking and Scintillation counters for muon triggering**
- **3 scintillator layers, A, B,and C, (1.8 T Toroid between A and B)**

Good Time of Flight measurement

D0 Silicon Tracker:

- **9 layers of Silicon in the central region**
- **Accurate momentum measurement**
- **dE/dx measurement**

Signal, background, Data

Signal:

Pairs of CMLLPs Generated using PYTHIA

Cascade decays are not included

- **Stau, chargino (Higgsino and Gaugino type)**
  - 100, 150, 200, 250, 300 GeV samples
- **Stop**
  - 100, 150, 200, 250, 300, 350, 400 GeV samples
  - Stop quarks are hadronized by linking an external routine with PYTHIA

Passage of the particles through the D0 detector is simulated with GEANT3

Background:

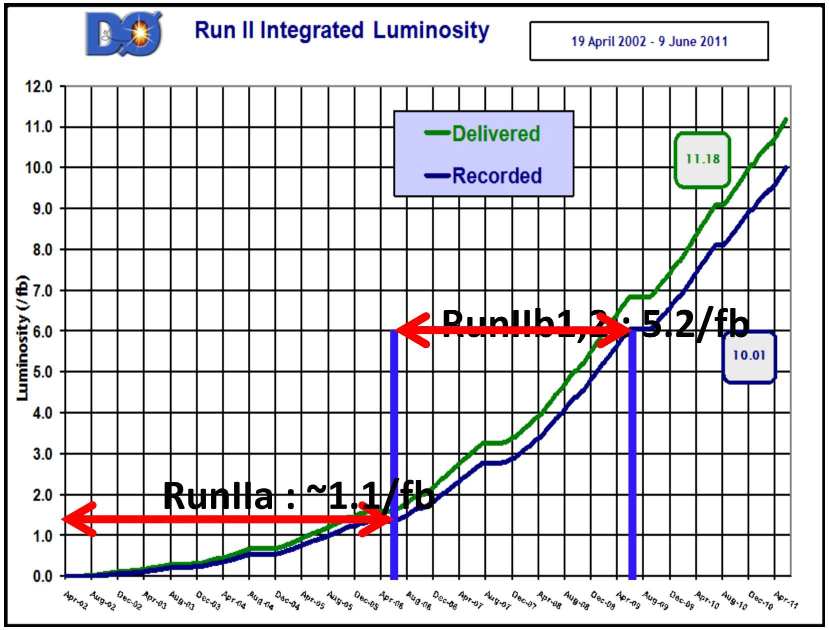
Mismeasured muons (wrong β and dE/dx)

Biggest source – W→μν events

D0 Data:

5.2 fb^{-1} of data, taken during June/2006 - June/2009)

Use events triggered by a single high p_T (>20 GeV) muon



Event Selection Criteria

- Require at least one muon in the event
- If more than one muon, select the highest p_T muon
- Good quality isolated muon track
- Matched with a track in the Silicon Tracker
- $|\eta| < 1.6$ (limited by the tracker η coverage)
- $p_T > 60$ GeV (very effective for the W background)
- Speed (β) < 1,

  [β is the weighted average of speeds related to scintillator hits]
- Speed χ2 < 2

Speed χ2 →
$$\chi^2 = \frac{1}{i^{max} - 1} \sum_i \frac{(\beta - \beta_i)^2}{\sigma_i^2}$$

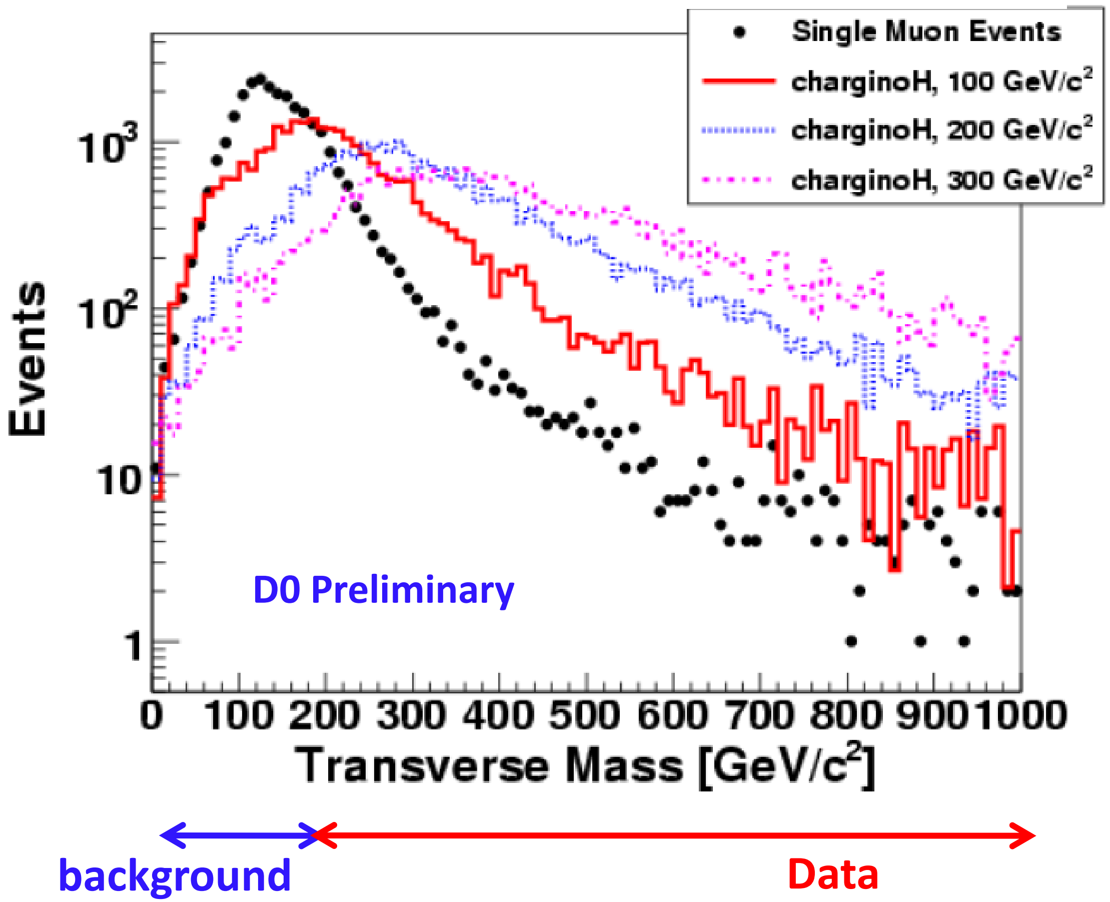
i = ith muon hit on a good muon track

Background sample

Since background is mostly **W→μν** events

- Shape of the background is determined using W rich data (m_T <200 GeV)
- Background normalization is done using a signal free data sample (β > 1)

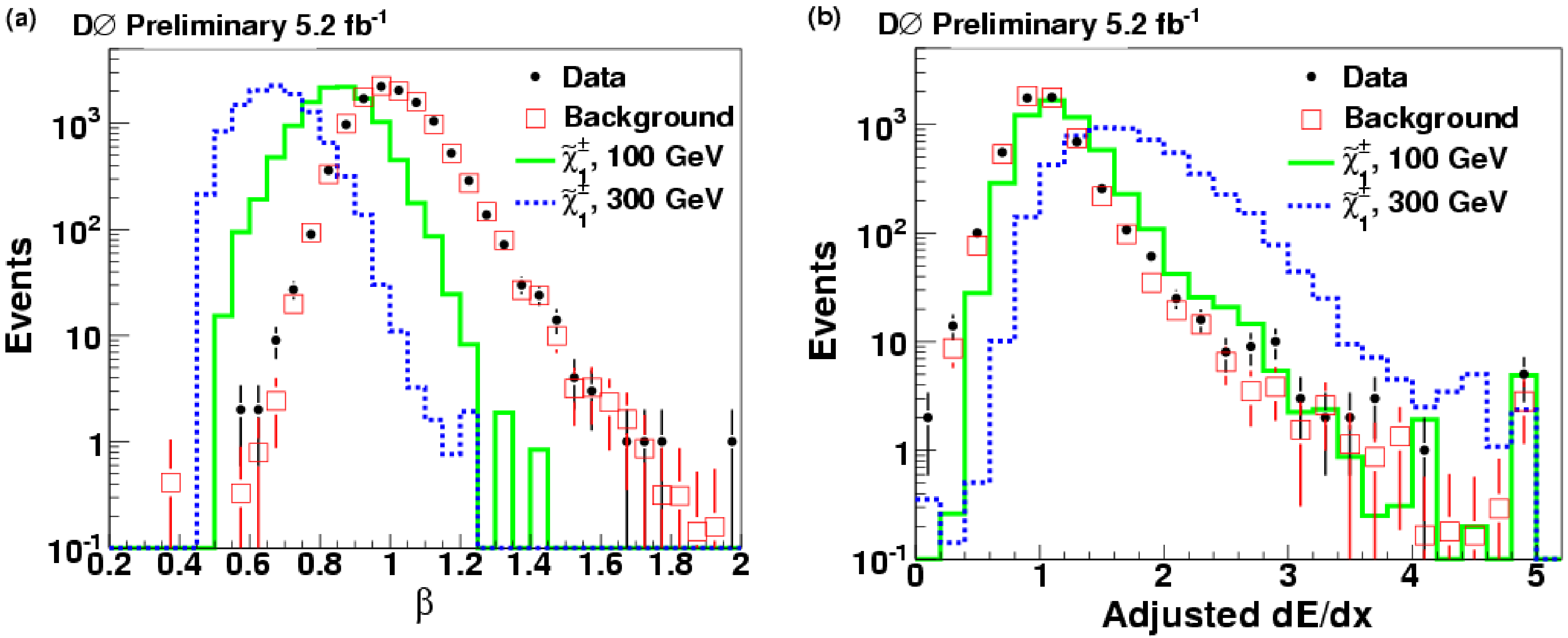
$$M_T = \sqrt{(E_T + \not{E}_T)^2 - (p_x + \not{E}_x)^2 - (p_y + \not{E}_y)^2}$$



Signal-Background Separation

p_T > 60 GeV reduces background

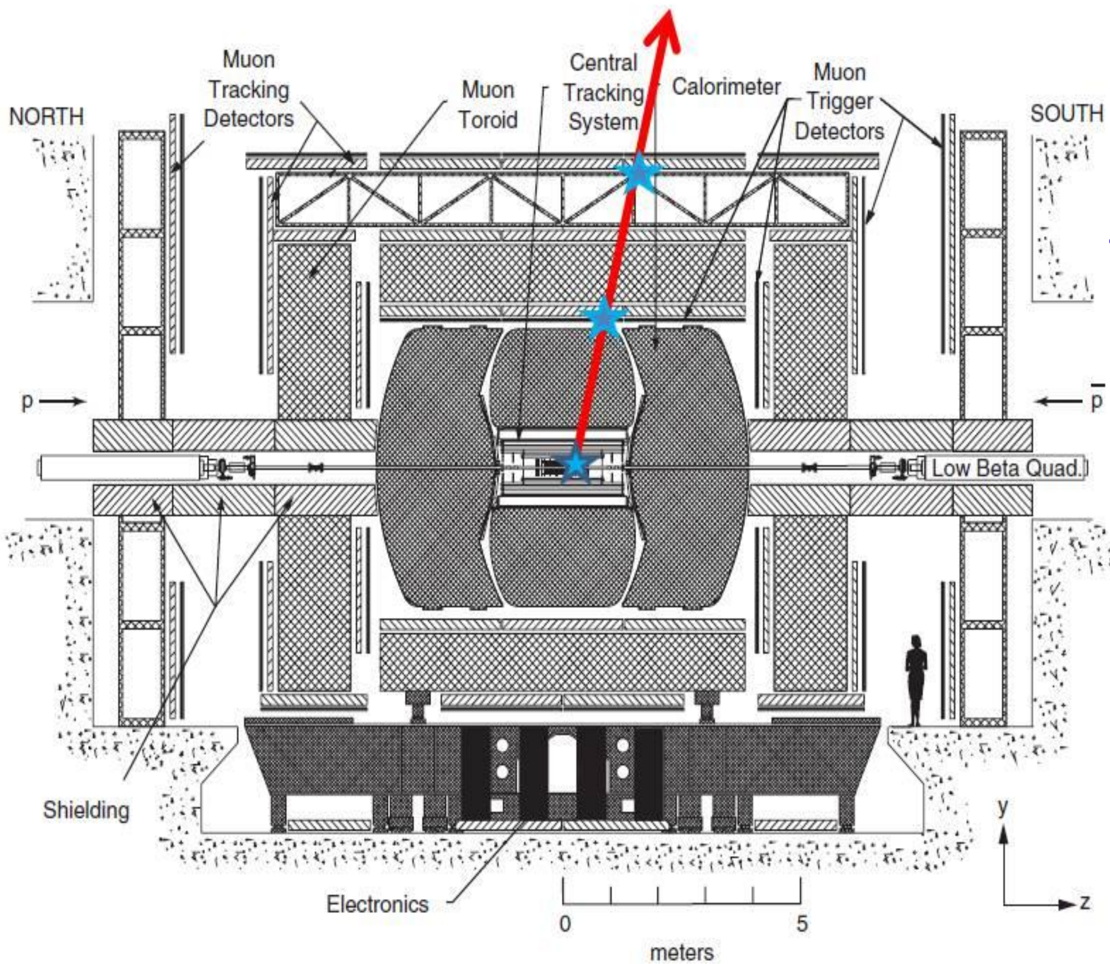
Speed (β) and dE/dx can be used to further distinguish background from signal events.



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

Sudeshna Banerjee
Tata Institute of Fundamental Research

Unique Feature of Stop quarks



- Stop quarks hadronize into neutral and charged mesons and baryons
- These hadrons flip charge due to nuclear interactions while passing through matter
- In order to be detected in the D0 detector they have to be charged, at least at certain points in the detector
  1. As they enter the Silicon Tracker
  2. When they enter the Muon System
  3. After the Toroid in the Muon System

- This feature reduces the efficiency of Stop detection
- In this analysis either stop or anti-stop can be charged
- The probability that at least one is charged and can be detected = 38%

Road to CMLLP Detection

Use Multivariate Techniques - 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) distribution

Use CLS method to get 95% confidence level cross-section limits

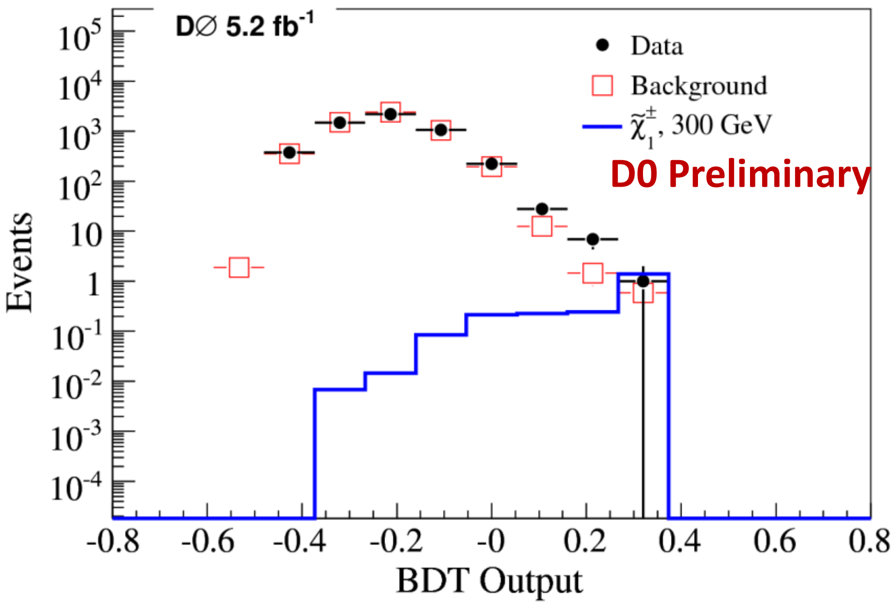
Input to the limit setting procedure are the BDT distribution and systematic errors

Variables for BDT:

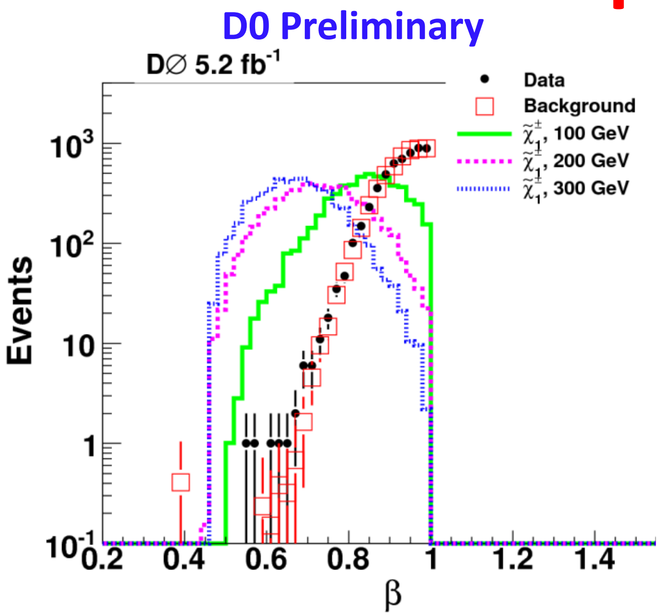
Speed, dE/dx and related variables

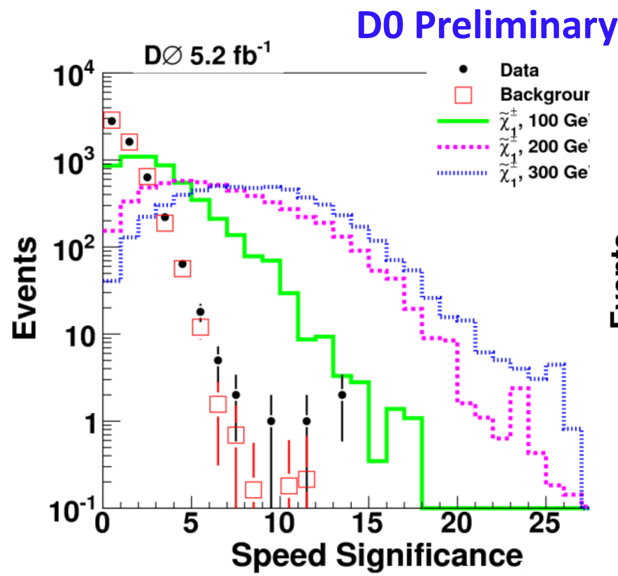
- **Speed (β)**
- **Speed significance**
  - [(1- β)/(uncertainty in β)]
- **No. of scintillator hits in the muon system**
- **dE/dx**
- **dE/dx significance**
  - [(dE/dX - 1)/(uncertainty in dE/dx)]
- **No. of clusters in the Silicon Tracker**

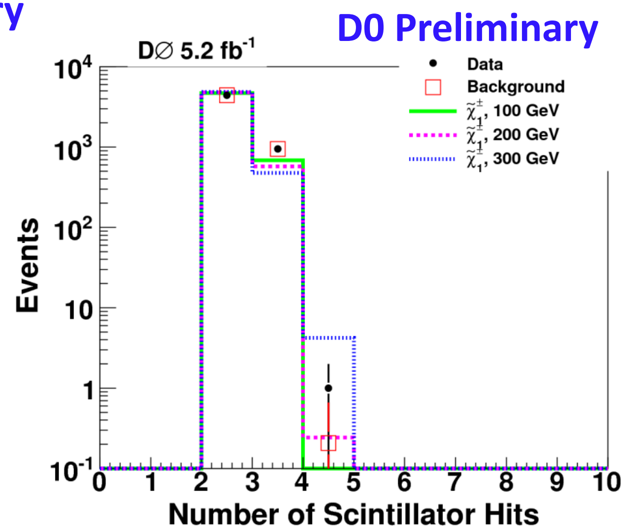
300 GeV Gaugino like Chargino

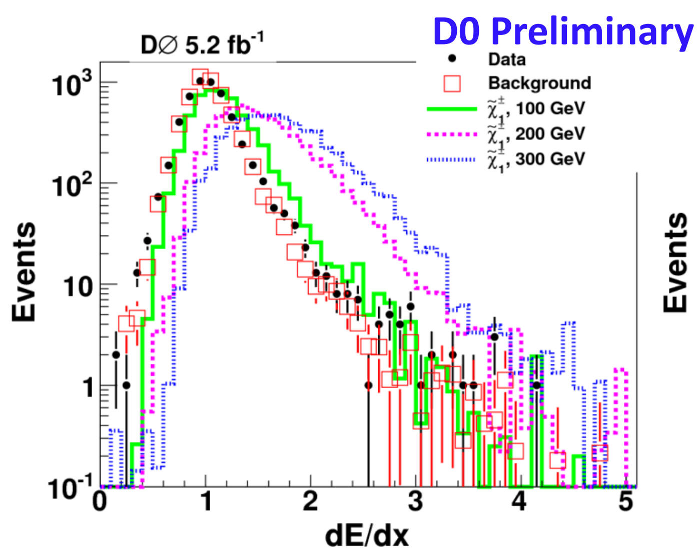


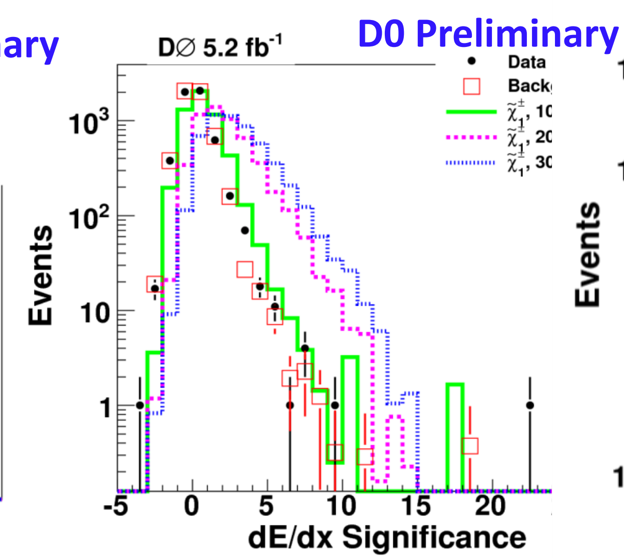
Input Variables to BDT

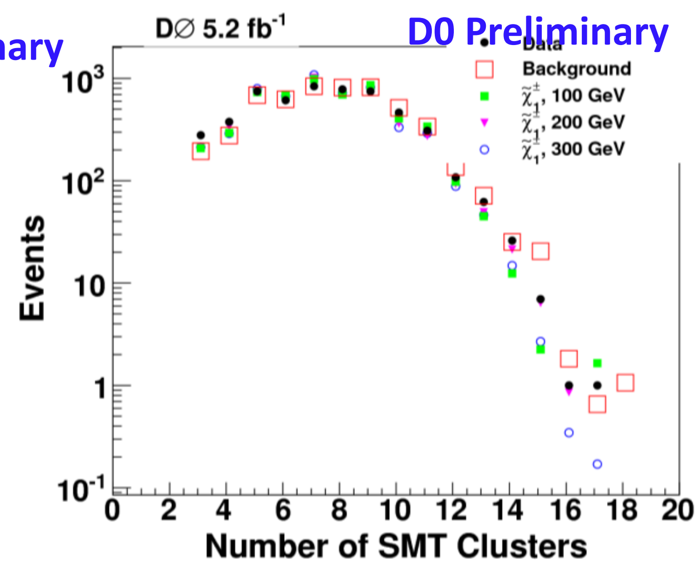






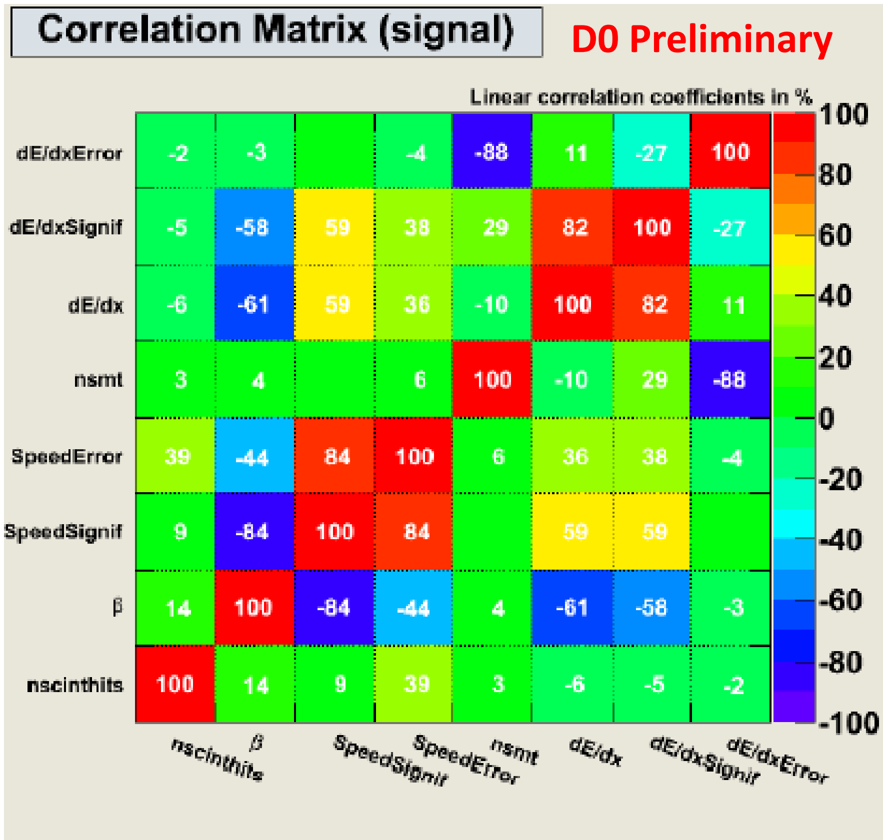


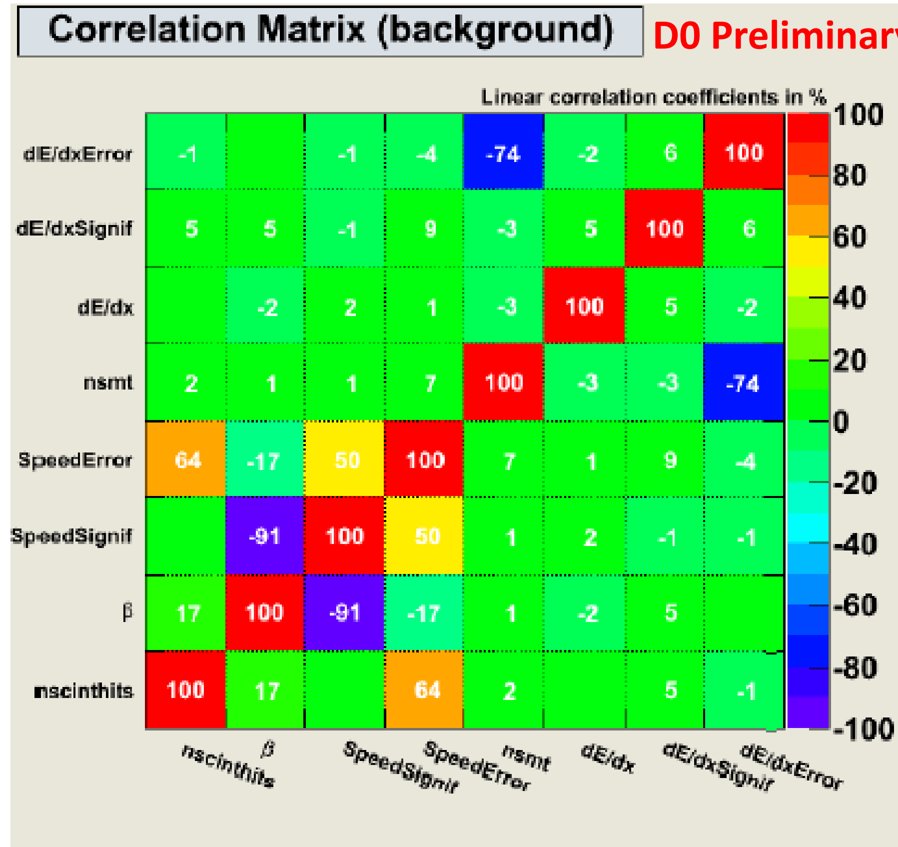




Sudeshna Banerjee
Tata Institute of Fundamental Research

TMVA Correlation Matrix





Cross section Limits (D0 Preliminary)

NLO cross-sections and cross-section limits for staus.

Mass (GeV/c2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit 1s [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

NLO cross-sections and cross-section limits for stops, assuming a charge survival probability of 38%.

Mass (GeV/c2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit 1s [pb]
100	15.6	0.562	0.218 +0.078 -0.062
150	1.58	0.133	0.049 +0.019 -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

Cross section Limits (D0 Preliminary)

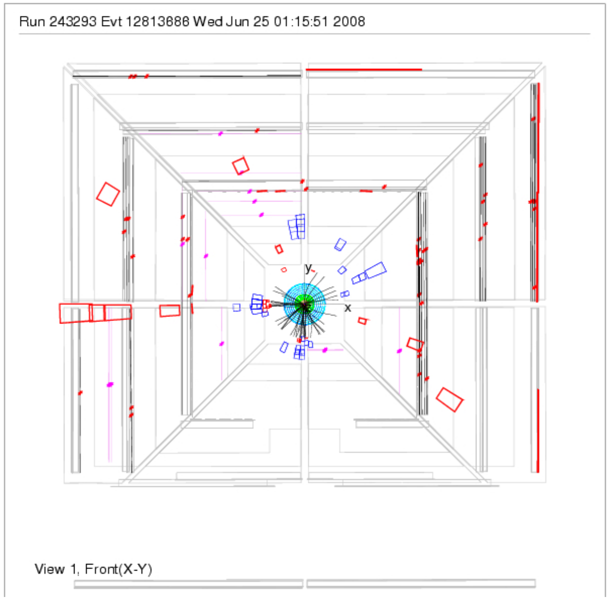
NLO cross-sections and cross-section limits for gaugino-like charginos.

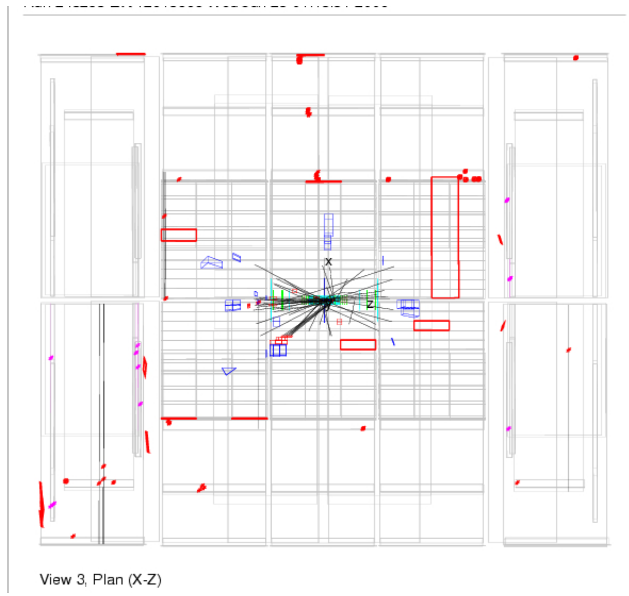
Mass (GeV/c2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit 1s [pb]
100	1.33	0.387	0.153 +0.068 -0:043
150	0.235	0.0435	0.0167 +0.0054 -0.0033
200	0.0566	0.0195	0.00945 +0.00368 -0.00057
250	0.0153	0.0136	0.00988 +0.00402 -0.00127
300	0.00417	0.0741	0.0185 +0.0046 -0.0027

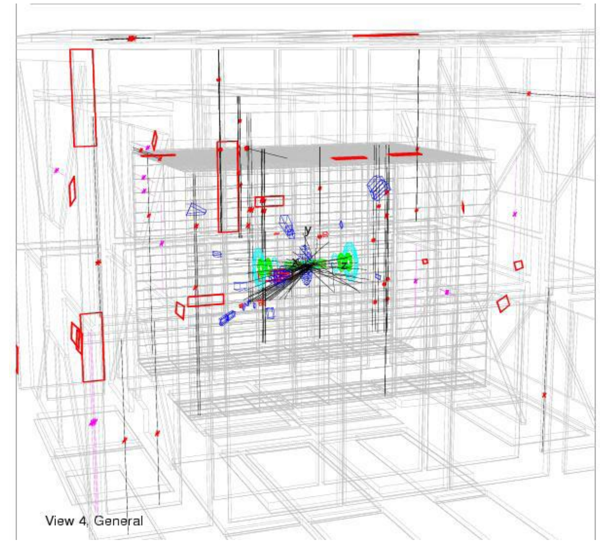
NLO cross-sections and cross-section limits for higgsino-like charginos

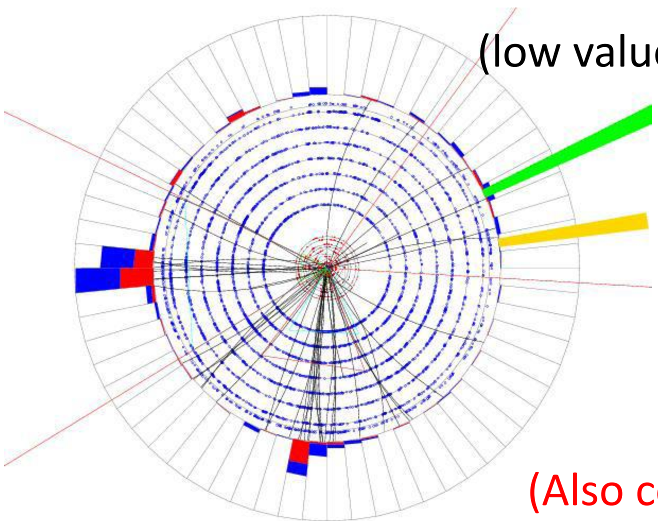
Mass (GeV/c2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit 1s [pb]
100	0.381	0.106	0.110 +0.050 -0:032
150	0.0736	0.0417	0.0165 +0.0053 -0.0038
200	0.0186	0.0128	0.00852 +0.00169 -0.00112
250	0.00525	0.00897	0.00716 +0.00267 -0.00100
300	0.00154	0.0174	0.0119 +0.0033 -0.0005

Candidate Event – I









(low value of speed, high value of dE/dx)

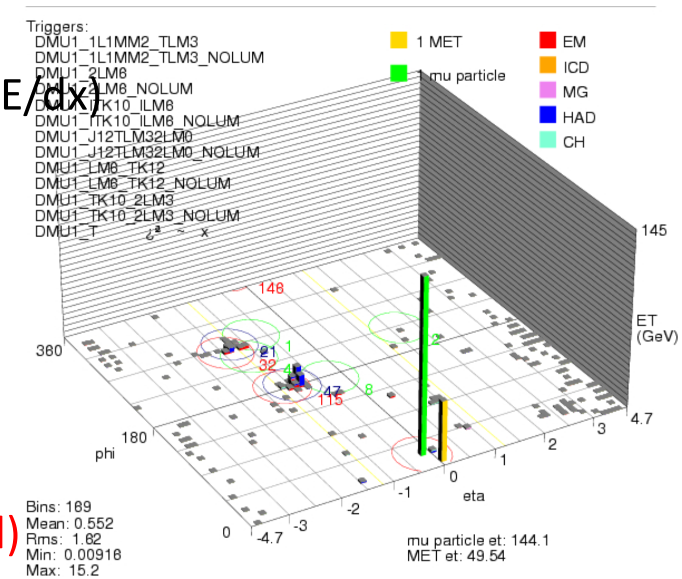
Speed = 0.742

scintillator hits =2

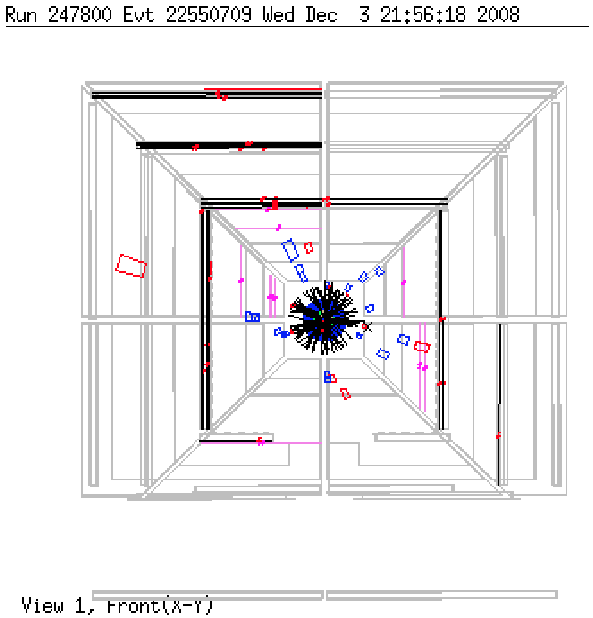
Adjusted dE/dx = 3.33

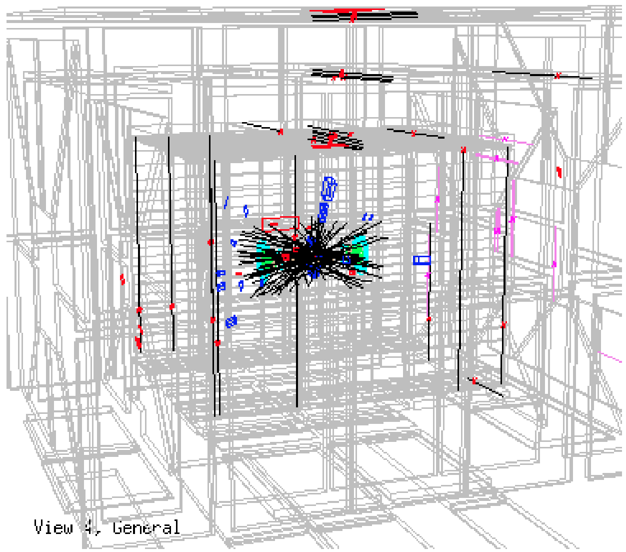
SMT hits = 5

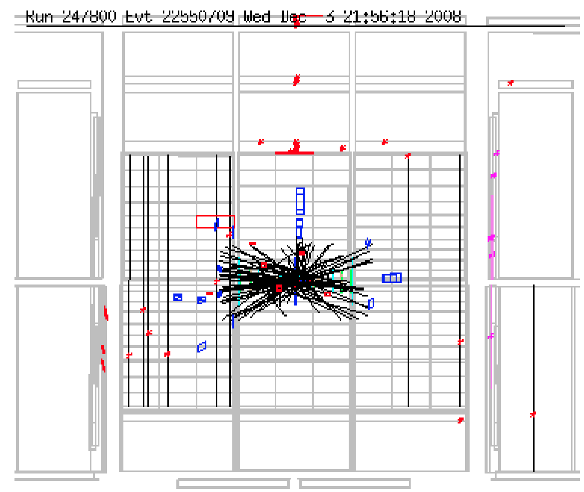
(Also consistent with background)

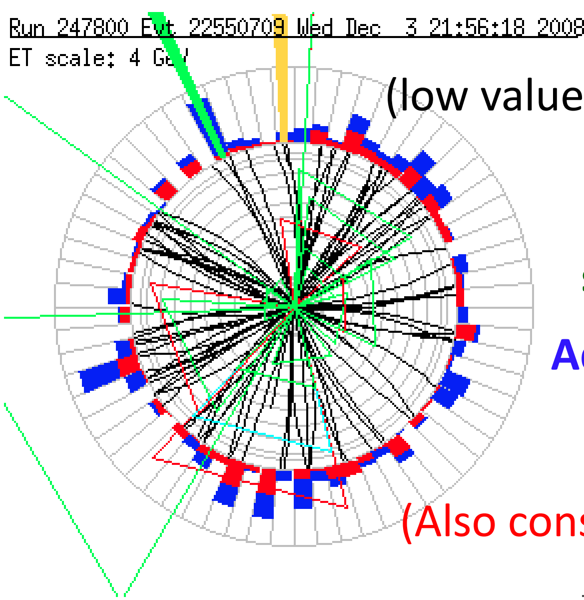


Candidate Event - II









(low value of speed, high value of dE/dx)

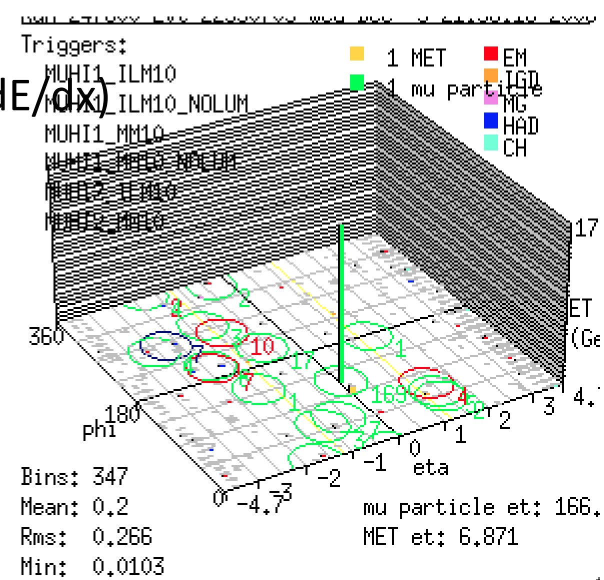
Speed = 0.654

scintillator hits =2

Adjusted dE/dx = 1.43

SMT hits = 9

(Also consistent with background)



Summary

Searched for Charged Massive Long-Lived Particles in 5.2 fb^{-1} of D0 data

Main variables for the Search:

- Time of Flight of the particles through the D0 detector
- Energy deposit (dE/dx) in the D0 Silicon Tracker

Mass and Cross-section limits (95% CL): D0 Preliminary

– 265 GeV mass limit for stop
  - 281 GeV mass limit for stop (without charge flipping)

– 251 GeV mass limit for gaugino like chargino

– 230 GeV mass limit for higgsino like chargino

★ Currently the Best Limits

– stau cross-section limits between 0.04 and 0.006 pb, for stau masses between 100 and 300 GeV

DØ public results:

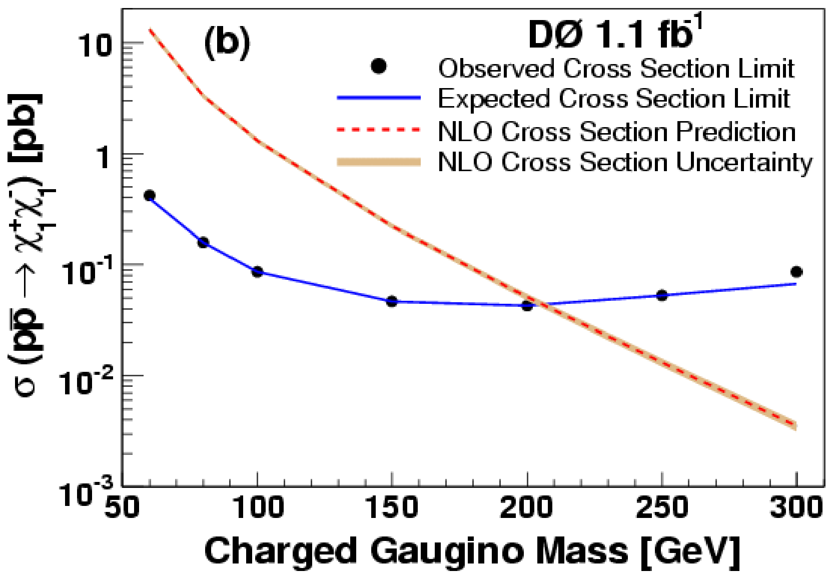
http://www-d0.fnal.gov/Run2Physics/WWW/results.htm

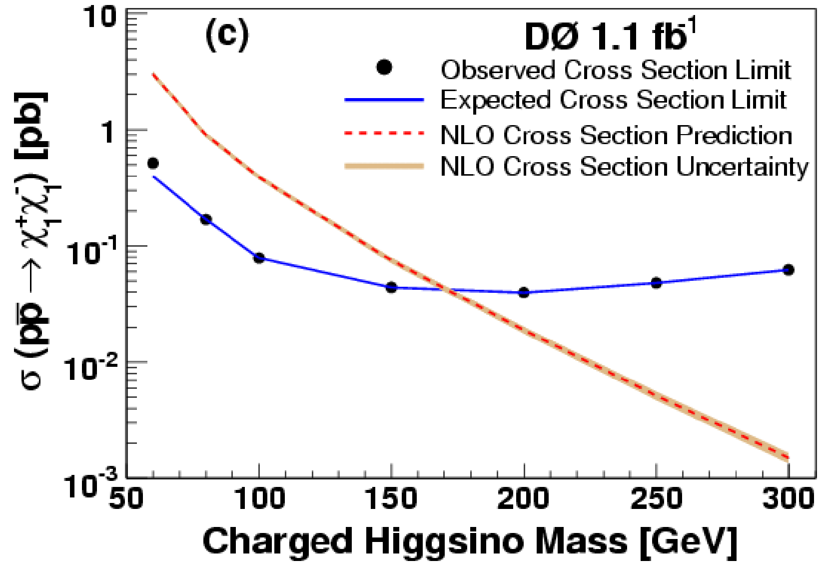
Backup

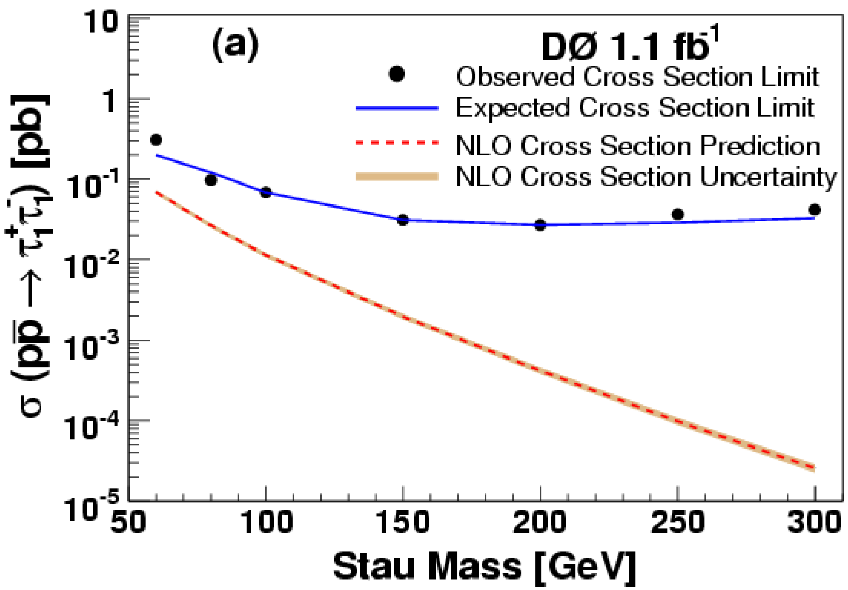
Sudeshna Banerjee
Tata Institute of Fundamental Research

Charged Massive Stable Particles

D0 Published Results







Data set – 1.1 fb-1

Cross section limit for

Stable staus – 0.31 pb to 0.04 pb in the mass range 60 to 300 GeV

Mass limit for

Chargino (gaugino type) – 206 GeV

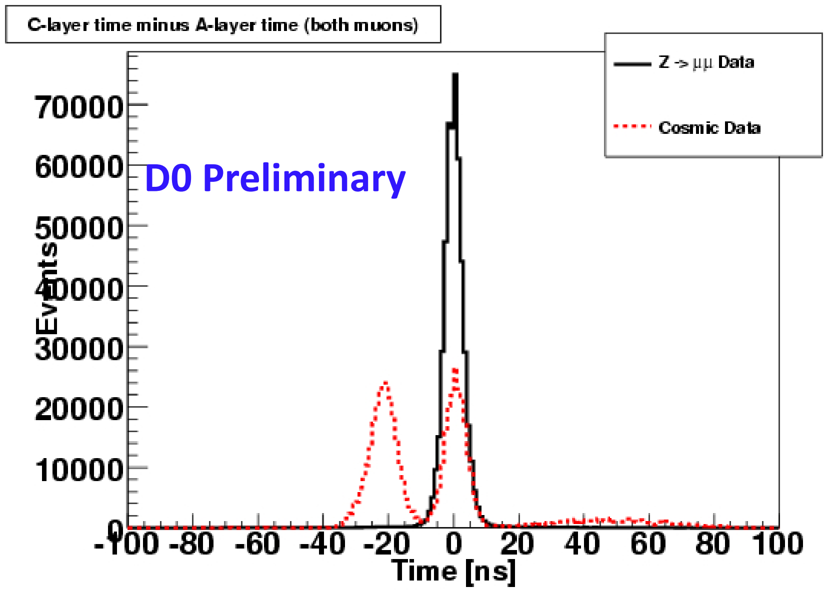
Charginoh (Higgsino type) – 171 GeV

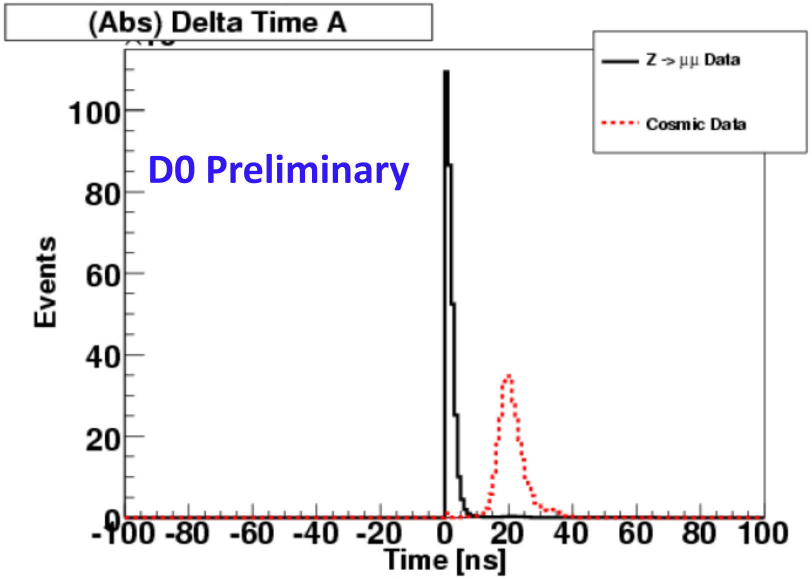
Published - PRL 102 , 161802 (2009)

Cosmic Ray Muon rejection

Proton-Antiproton Collision

- The highest p_T muon must have:
  - dca< 0.2 cm
  - (C-layer time) - (A-layer time) > -10 ns
- If there are exactly 2 muons in event, event is rejected if
  - dca of either muon > 0.2 cm
  - | A layer time for Muon 1 – A layer time for Muon 2| > 10 ns
  - The C-layer time minus the A-layer time for either muon < -10 ns.
  - pseudo-acolinearity: $\Delta\alpha = |\Delta\phi + \Delta\theta - 2\pi| < 0.05$

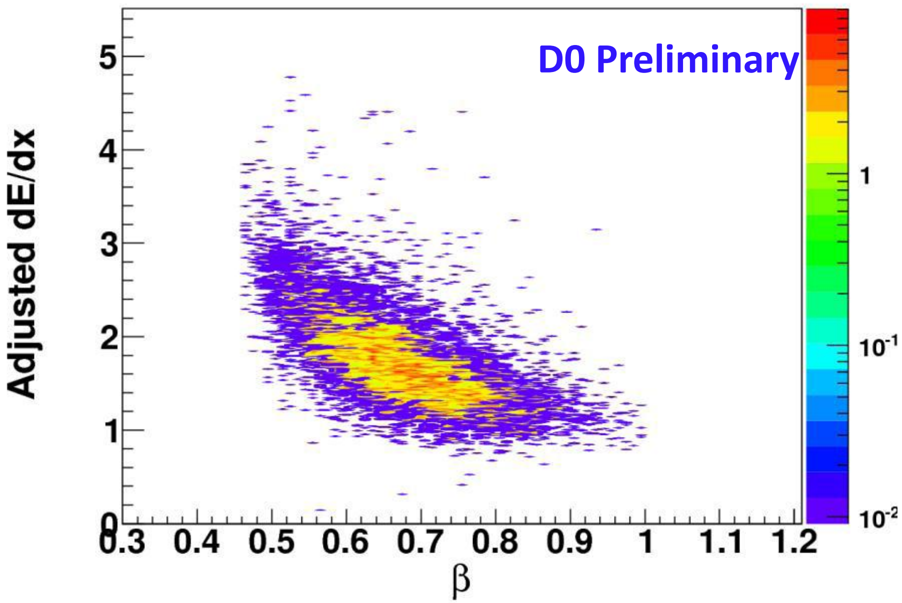




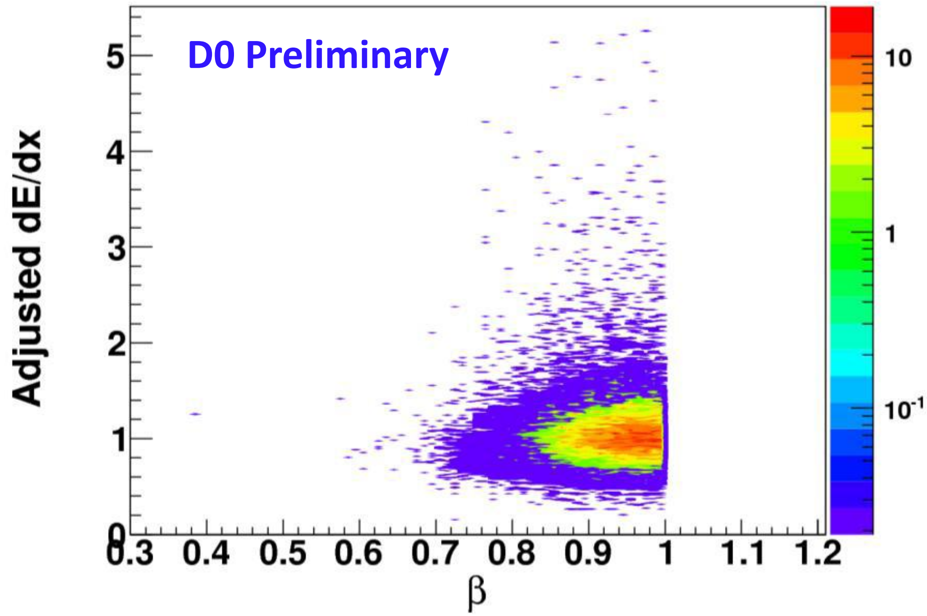
Speed and dE/dx variables

- Speed and dE/dx variables are anticorrelated for signal
- They are not correlated for background
- They can be used to separate signal from background

Signal: 300 GeVgaugino-like chargino



Background: Single Muon Data, mT<200



Background Normalization

normalization region

B>1	**Normalization background**	**Normalization data**
$\beta<1$	**Event background**	**Event data**
	mT<200 GeV	mT>200 GeV

Normalized background = **Backgroundevents*Normalization data events/ Normalization background events**

Expected No. of Events

With BDT>0.27 cut

D0 Preliminary

Stau

Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0.74 \pm 0.001(stat.) \pm 0.08(sys.)$	$0 \pm 0(stat.) \pm 0(sys.)$	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

Stop

Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0.01 \pm 0.001(stat.) \pm 0.001(sys.)$	$0 \pm 0(stat.) \pm 0(sys.)$	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 chargino

Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0 \pm 0(stat.) \pm 0(sys.)$	$0 \pm 0(stat.) \pm 0(sys.)$	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 chargino

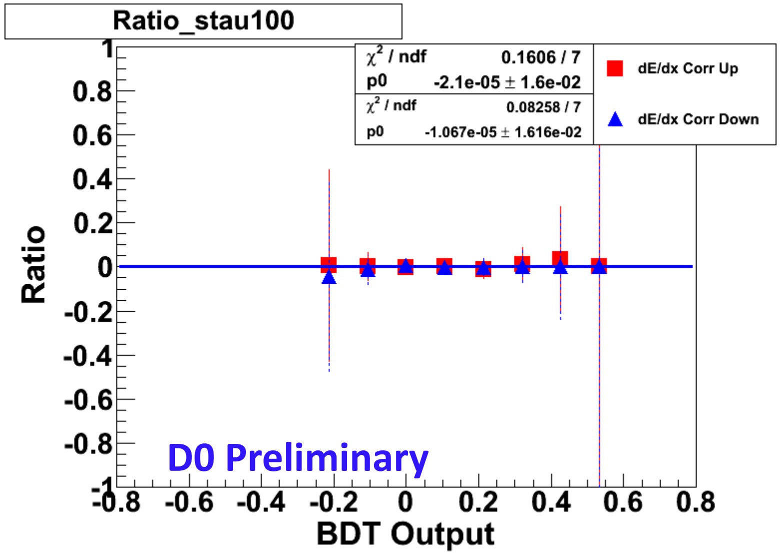
Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0.29 \pm 0.001(stat.) \pm 0.11(sys.)$	$0 \pm 0(stat.) \pm 0(sys.)$	0
150	$3.57 \pm 0.001 \pm 0.26$	$0.87 \pm 0.001 \pm 0.07$	3
200	$5.68 \pm 0.001 \pm 0.34$	$1.75 \pm 0.001 \pm 0.13$	5
250	$5.21 \pm 0.001 \pm 0.62$	$0.79 \pm 0.001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

Systematic uncertainties

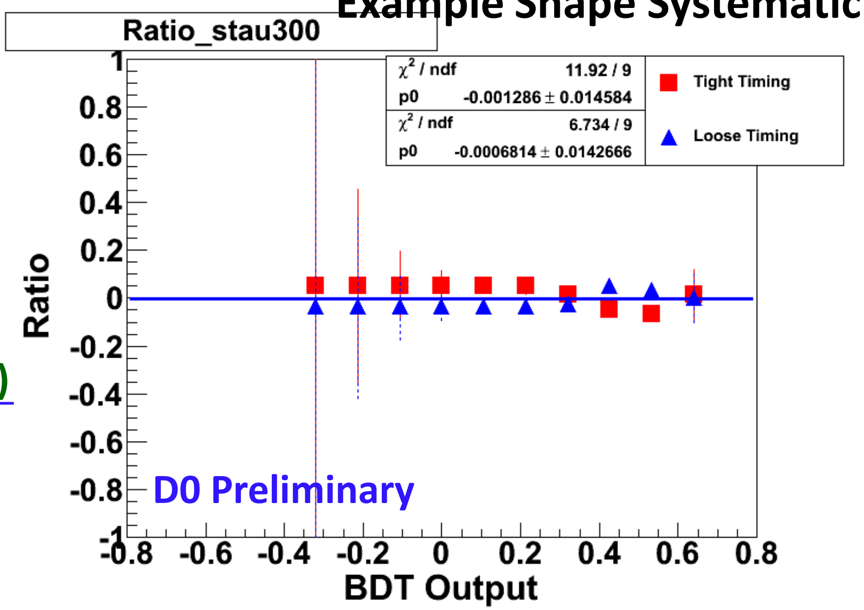
- **Flat Systematics**
  - Luminosity Uncertainty (6.1%)
  - Muon ID Uncertainty (2.1%)
  - Background Normalization Uncertainty from β cut (7.2%)
  - Background Normalization Uncertainty from mT cut (2.2%)
  - Muon pT Smearing Uncertainty (0.2%)
  - PDF Uncertainty (<0.2%)
  - dE/dx Correction Uncertainty (<0.1%)
  - dE/dx Smearing Uncertainty (0.2%)
- **Shape Systematics**
  - L1 Timing Gate Uncertainty
  - Timing Smearing Uncertainty

$$\text{Ratio} = \frac{\text{BDT (with systematic)} - \text{BDT (without systematic)}}{\text{BDT (without systematic)}}$$

Example Flat Systematic



Example Shape Systematic



Model Parameters

Staus

Parameter	Description	Value
Λ_m	Scale of SUSY breaking	19 to 100 TeV
M_m	Messenger mass scale	$2\Lambda_m$
N_5	Number of messenger fields	3
$tan\beta$	Ratio of Higgs VEVs	15
$sgn\mu$	Sign of Higgsino mass term	+1
C_{grav}	Factor multiplying effective mass of gravitino	1

Charginos

Model	μ(GeV)	M_1(GeV)	M_2(GeV)	M_3(GeV)	$tan\beta$	Squark Mass (GeV)
gaugino-like chargino	10,000	$3M_2$	varied from 60 to 300	500	15	800
higgsino-like chargino	varied from 60 to 300	100,000	100,000	500	15	800