Searching for High Speed Long-lived **CHA**rged **M**assive **P**articles at the LHC

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- Introduction
- Detecting CHAMPs at the LHC
- A new method
- Summary

CHAMP Introduction

- Popular Beyond Standard Model (BSM) theories predict dark matter candidates. E.g., SUSY: Lightest SUSY Particle (LSP)
- Small coupling/mass splitting between next-to-lightest SUSY Particle (NLSP) and LSP → NLSP long-lived (i.e., does not decay inside the detector)
- CHArged Massive Particle (CHAMP)
- Weakly interacting (colorless) CHAMP: lepton-like
  - Minimal Universal Extra Dimensions (mUED) → Kaluza-Klein (KK) tau
  - Minimal Gauge Mediated SUSY Breaking (mGMSB) → stau
  - New vector-like confinement model (Di-CHAMP) → hyper-K
  - ……

Experimental Limits

- Combined LEP CHAMP limit:
  > 99.5 GeV

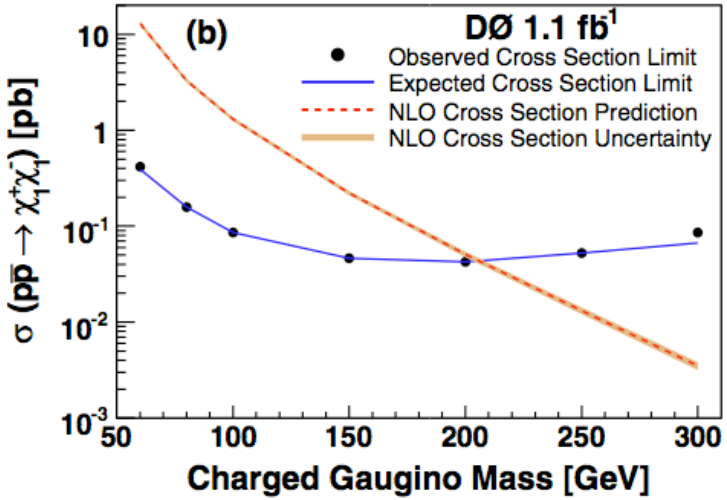
  LEP SUSY Working Group, ALEPH, DLEPHI, L3 and OPAL collaborations, note LEPSUSYWG/02-05.1(http://lepsusy.web.cern.ch/lepsusy/Welcome.html)

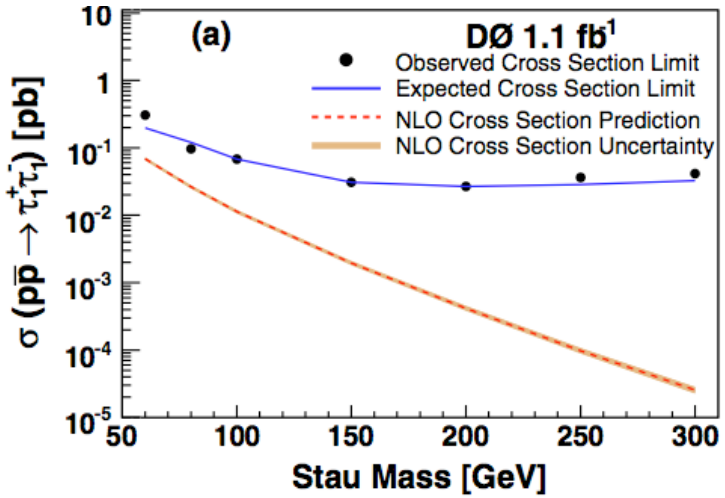
- D0: slepton cross section
  < 0.1 pb, for Drell-Yan pair production

  Phys. Rev. Lett 102, 161802, 2009

- CDF: model-independent limit on singly produced weakly interacting CHAMP cross section:
  < 10 fb, within CDF acceptance

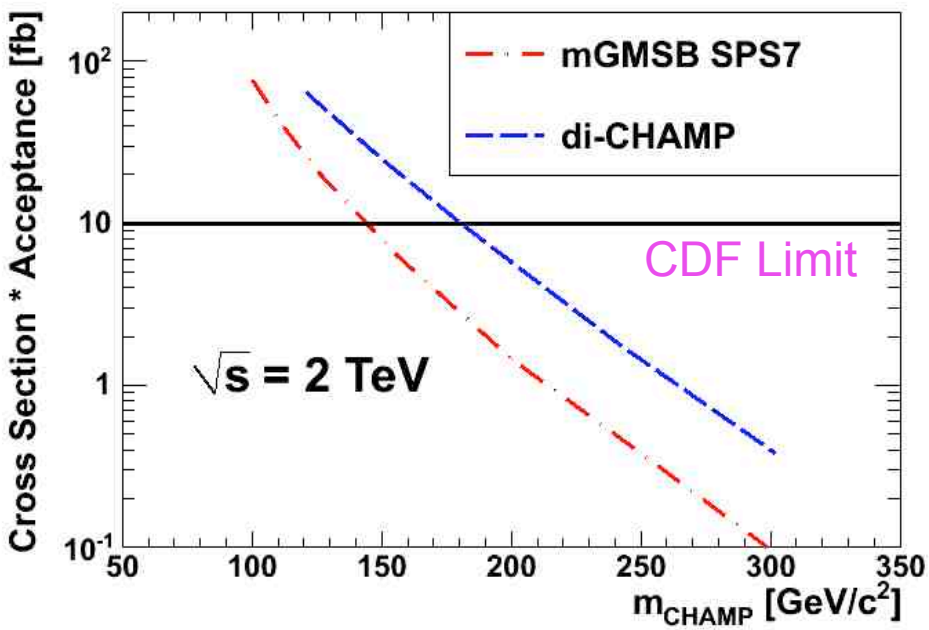
  Phys. Rev. Lett 103, 021802, 2009





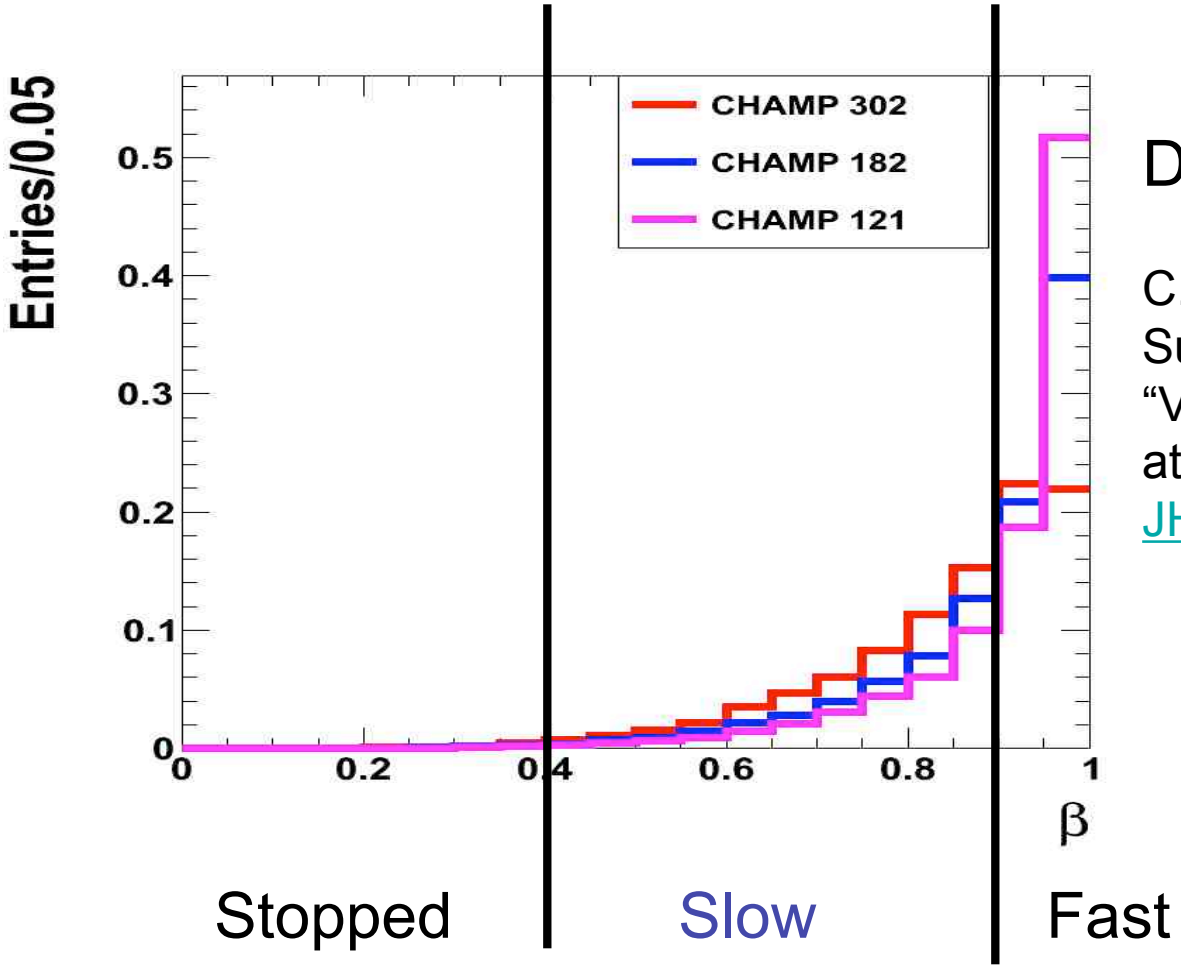
Interpretation of CDF Result

- GMSB SPS7(cascades):
  - long-lived stau, stau masses = 100-308 GeV
- **Di-Champ** (C. Kilic, T. Okui, and R. Sundrum, "Vectorlike Confinement at the LHC", JHEP 02 (2010) 018)
  - M(CHAMP)/M(resonance) = 0.12
  - CHAMP masses = 121-302 GeV
- **Recalculate the CDF acceptance**
  - **accounting for events with 2 champs passing CDF acceptance**



- **Approximate mass limits**
  - **champ mass > 180 GeV**
  - **stau mass > 140 GeV**

β Distributions @ 10 TeV LHC



Di-CHAMP Model

C. Kilic, T. Okui, and R. Sundrum, "Vectorlike Confinement at the LHC", JHEP 02 (2010) 018

Methods to Detect CHAMP

Stopped:

- For stau CHAMPs, look for energetic jet from CHAMPs when beams not colliding

  Shoji Asai et al., Phys. Rev. Lett. 103,141803 (2009), "Measuring lifetimes of long-lived charged massive particles stopped in LHC detectors"

Slow:

- Measure β from delayed time of flight (T.O.F) and tracker dE/dx (ionization energy loss per path length)
- Can measure mass from p/(βγc)

  M. Fairbairn et al., Phys. Rept. 438, 1 (2007) "Stable massive particles at colliders"

Fast: (previously unexplored)

- J. Chen and T. Adams, "Searching for High Speed Long-lived Charged Massive Particles at the LHC" Eur. Phys. J. **C67** 335 (2010)

Pre-selection

Select events (based on generator level)

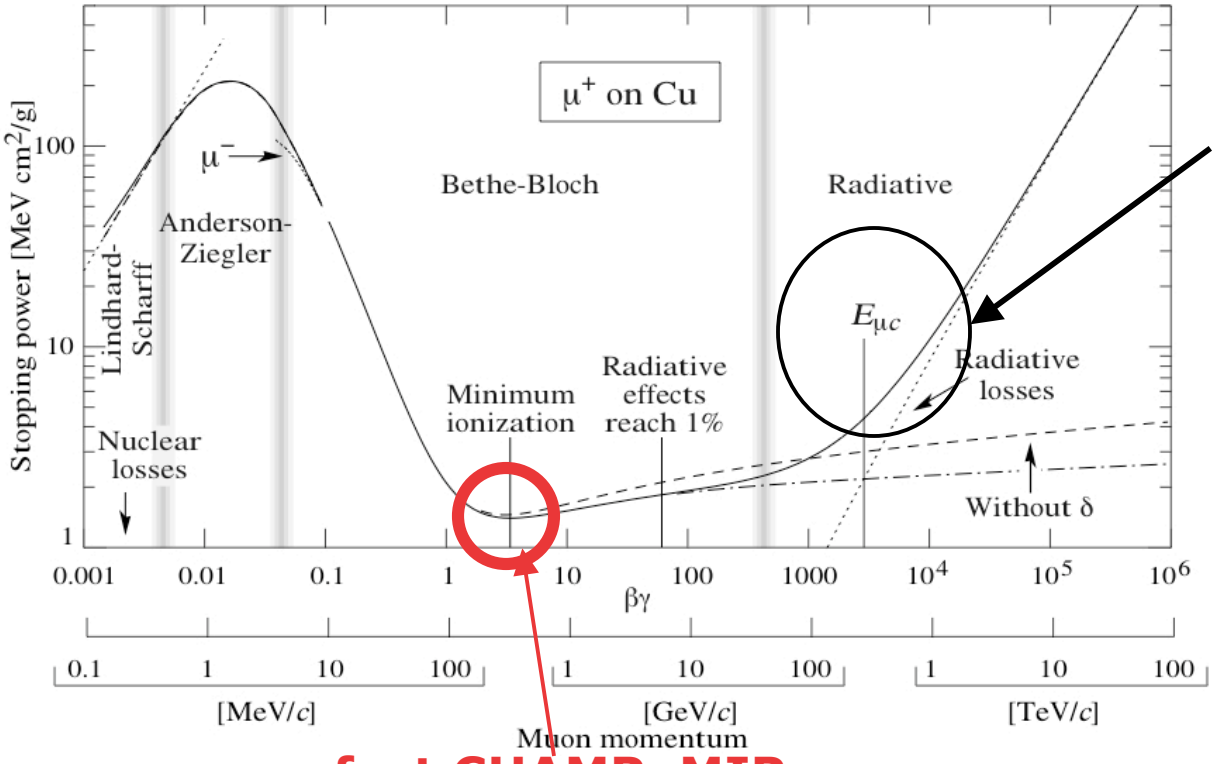
- Leading muon-like: P > 500 GeV and $|\eta| < 1.497$
- Second leading muon-like: P > 100 GeV, P_T > 20 GeV, $|\eta| < 2.5$

Cross section after selection @ 10 TeV LHC

Process	$\sigma(pb)$	$\geq$1 high p μ $\sigma(pb)$	2nd μ $\sigma(pb)$
W+(jets)	75600	0.3	0.002
Z/γ^*+(jets)	7240	0.09	0.03
$t\bar{t}$	234	0.03	0.003
WZ,WW,ZZ	69.4	0.005	0.001
multijet	20100	<0.01	<0.01
Total Background	103000	0.43	0.04
stau156	0.32	0.09	0.08
di-CHAMP182	0.18	0.05	0.05

Methods to Detect Fast CHAMP

Basic Idea: look for energy difference between high speed CHAMP (now MIP like) and high momentum muons.

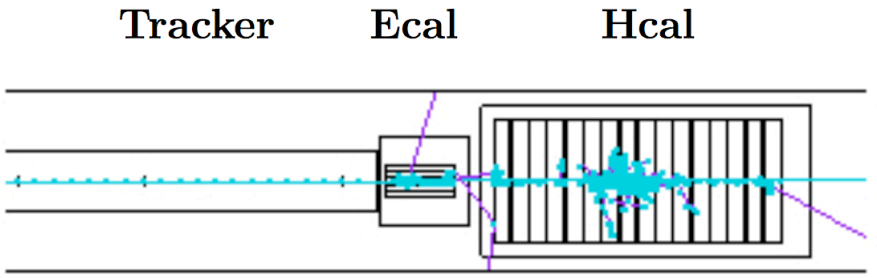


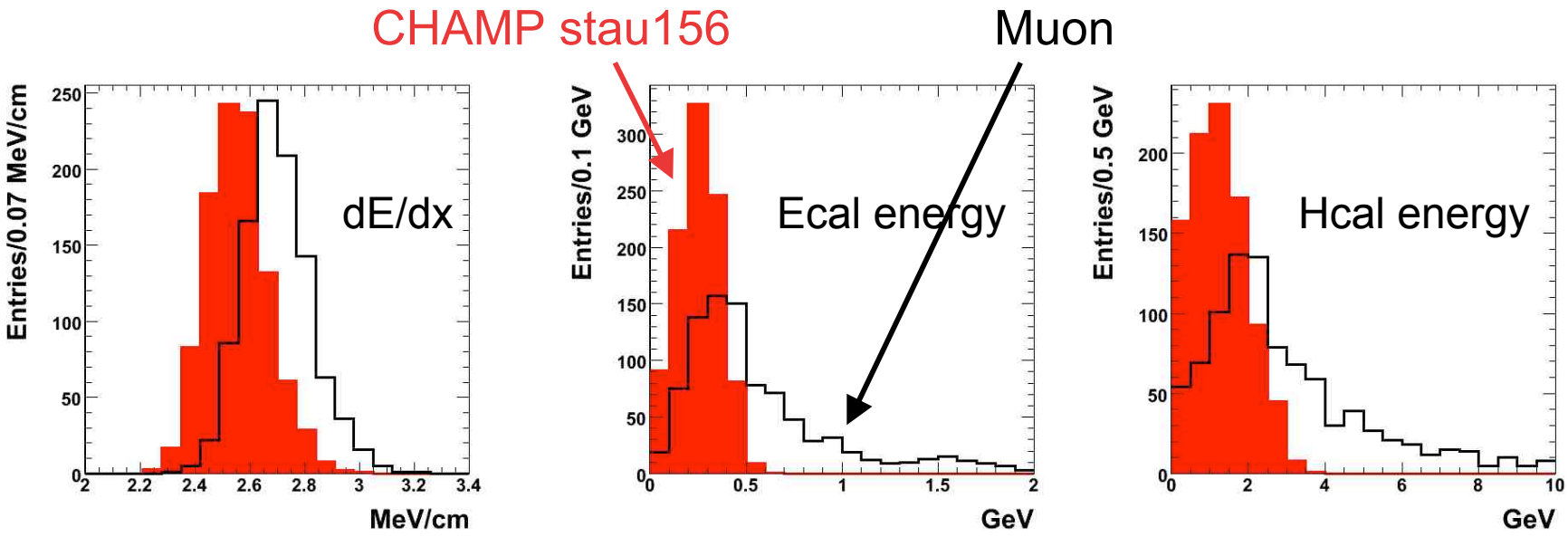
Simulation

Idea applicable to any detector at LHC

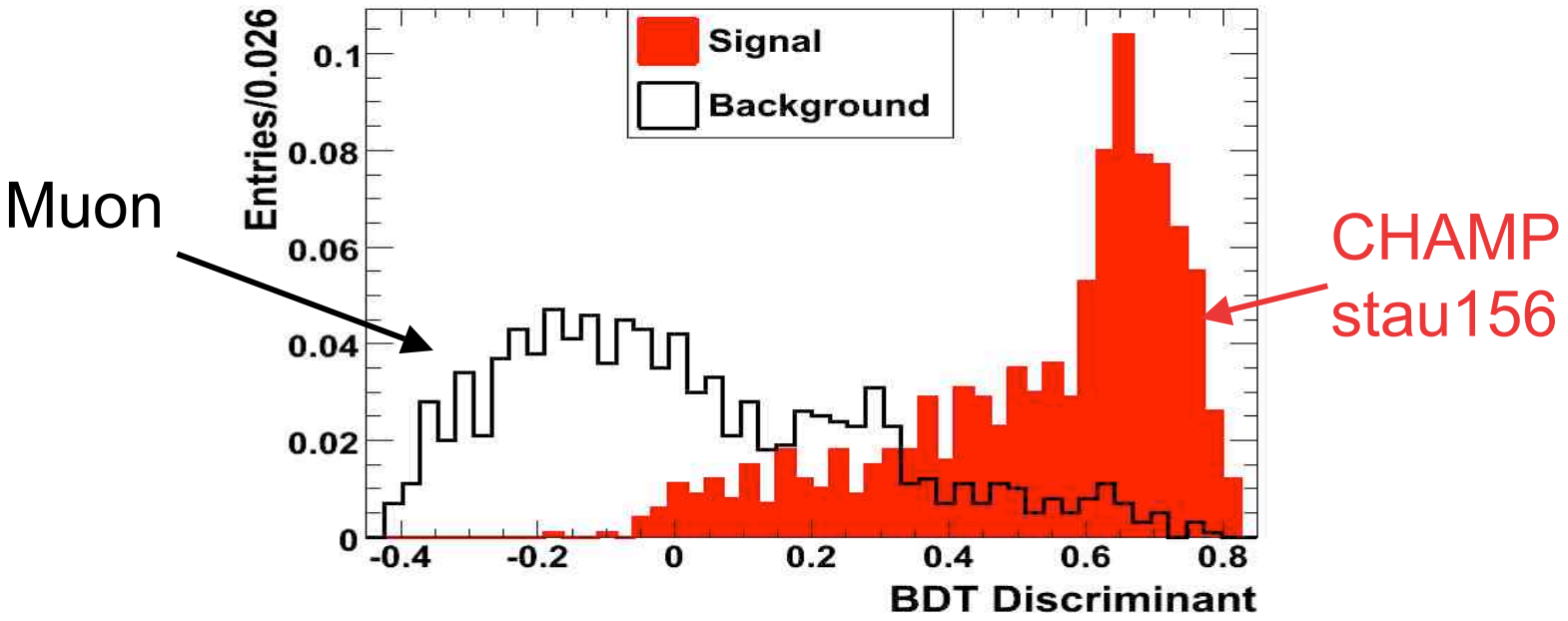
Simple GEANT4 simulation
(use CMS detector as an example)

- 20 layers of silicon, 5x5 PbWO4 crystals, 30 layers of brass
- No magnetic field





Boosted Decision Tree



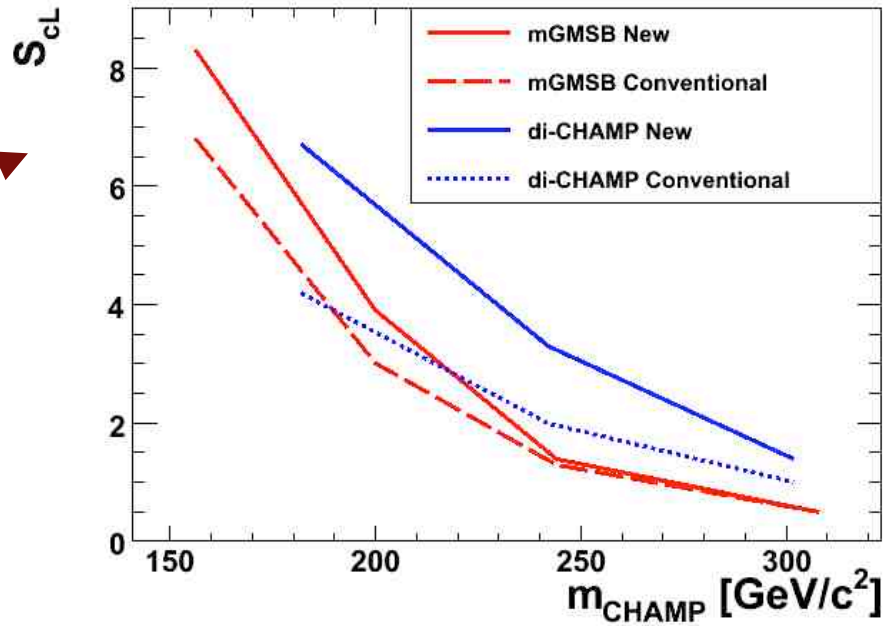
To enhance discrimination power:

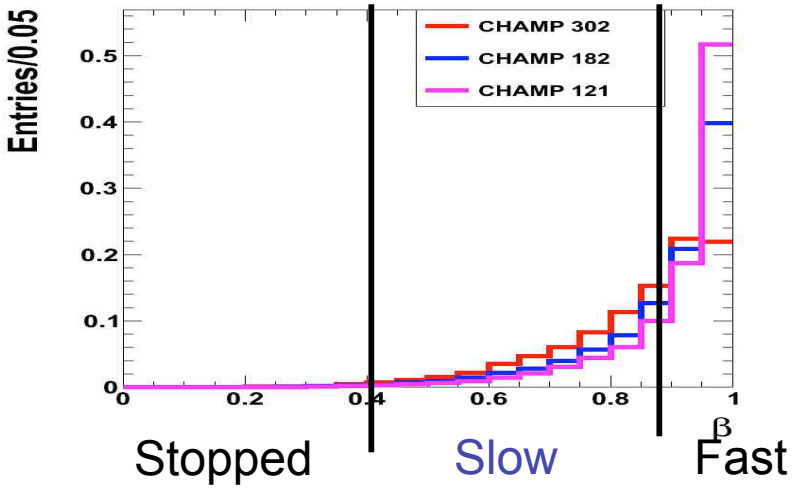
Combine tracker dE/dx, Ecal and Hcal energies into a discriminant, a Boosted Decision Tree (BDT)

Discovery Reach

For 200 pb^{-1} data at 10 TeV LHC.

- Optimized significance for new and conventional methods as a function of the CHAMP mass

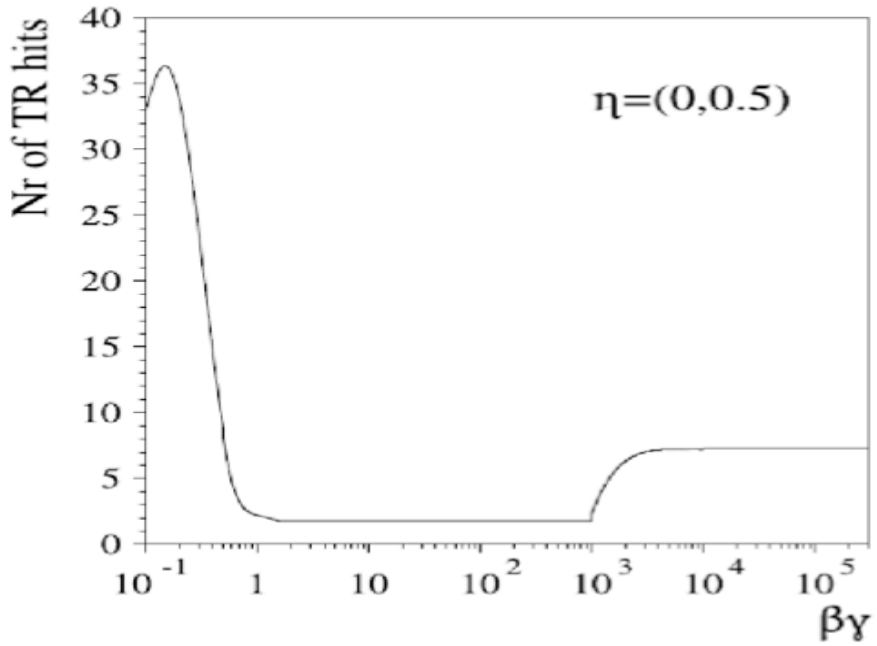




Similar discovery power to conventional slow method

Atlas Potential

- The BDT method is applicable to Atlas: expecting similar discovery potential.
  - Similar Ecal/Hcal energy resolution as CMS,
  - No tracker dE/dx, but the number of hits in the Transition Radiation Tracker (TRT) would give similar discriminating power.



A. C. Kraan, J. B. Hansen, and P. Nevski,
Eur. Phys. J. C 49, 623 (2007).

Summary

- CHAMPs are well motivated by theory but experimental limits are not strong.
- CHAMPs can be stopped, slow or fast in detectors at the LHC.
- J. Chen and T. Adams, "Searching for High Speed Long-lived Charged Massive Particles at the LHC" Eur. Phys. J. **C67** 335 (2010), arXiv:0909.3157[hep-ph]

– New mass limits for two CHAMP models, using CDF result.

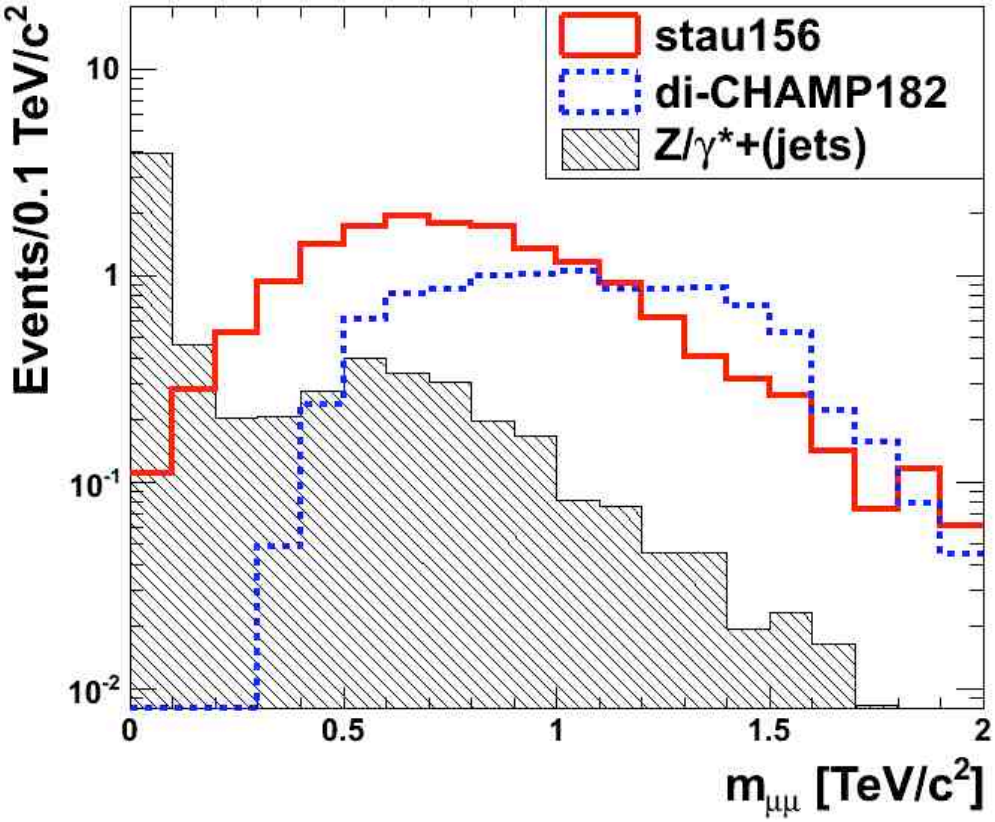
– New method to search for **fast** CHAMPs.

– The new method has complementary discovery power to the conventional slow CHAMP search method, thereby expanding the discovery potential at the LHC.

Back Up

Di-muon Mass

- Broad excess in di- “muon”(assume particles are muon) mass: fake signal for contact interaction, RS graviton…

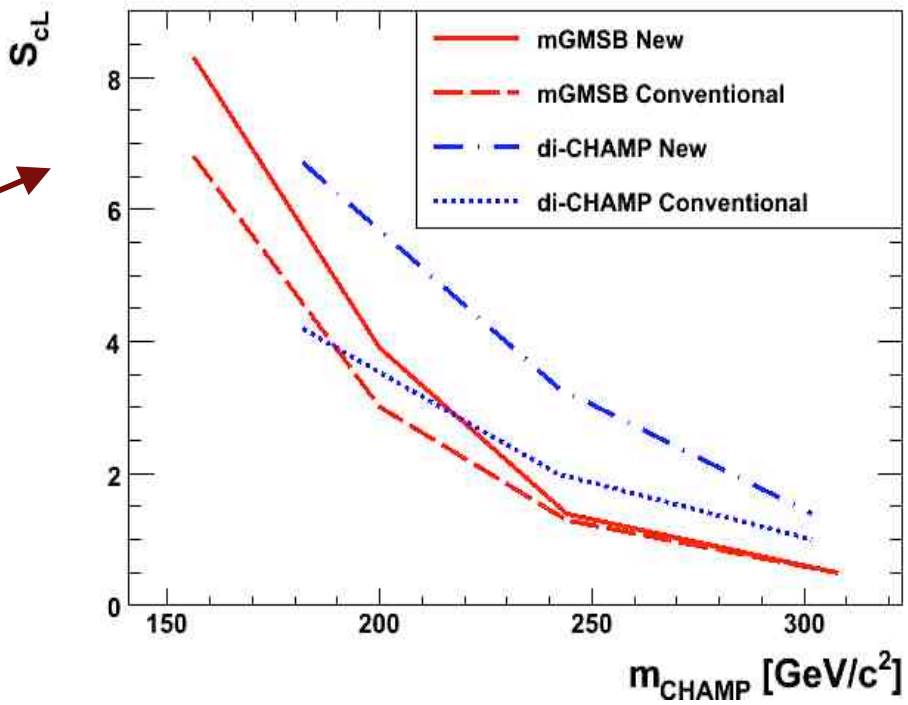


scaled to 200/pb data at $\sqrt{S} = 10$ TeV

Hint for extra selection

Significance

- For 200 pb^{-1}data at 10 TeV LHC.
  - Optimized significance based o BDT output, vs. estimated conventional method in functior of mass.
  - We assume conventional method (CMS Collaboration, CMS-PAS-SBM-07-002)
    - 1 event background
    - p_T > 40 GeV
    - |η| < 0.8
    - 0.6 < β < 0.8

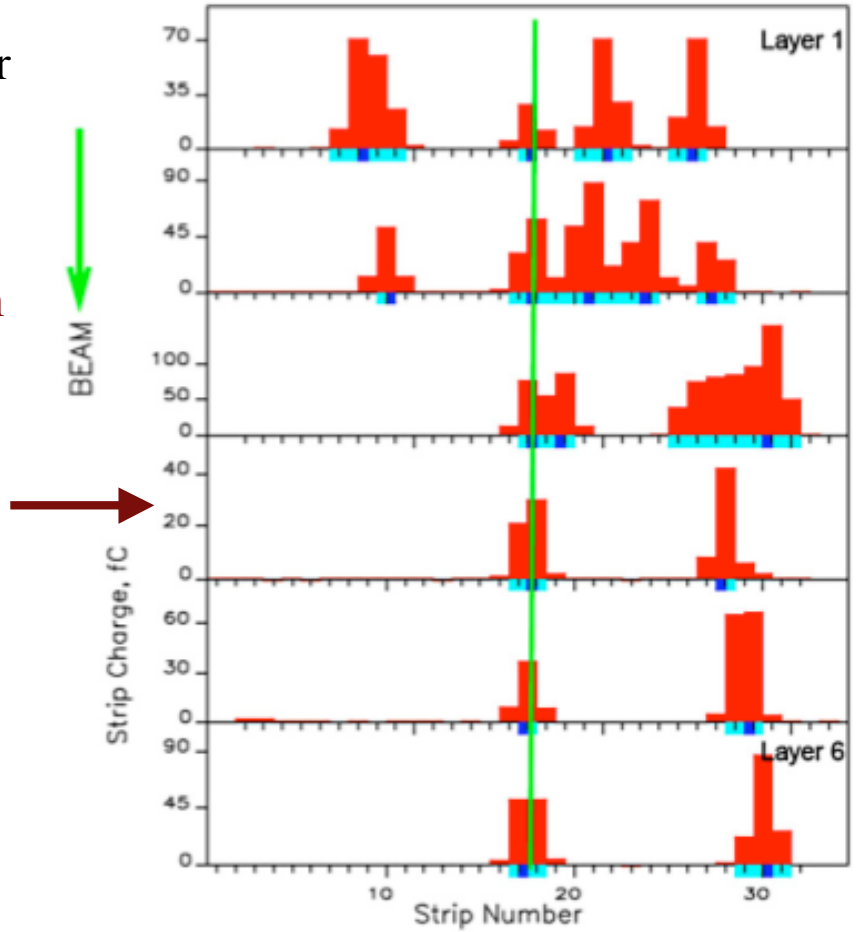


$$S_{cL} = \sqrt{2((S+B)\ln(1+\frac{S}{B}) - S)}$$

taken from CMS Physics TDR

Possible Improvement

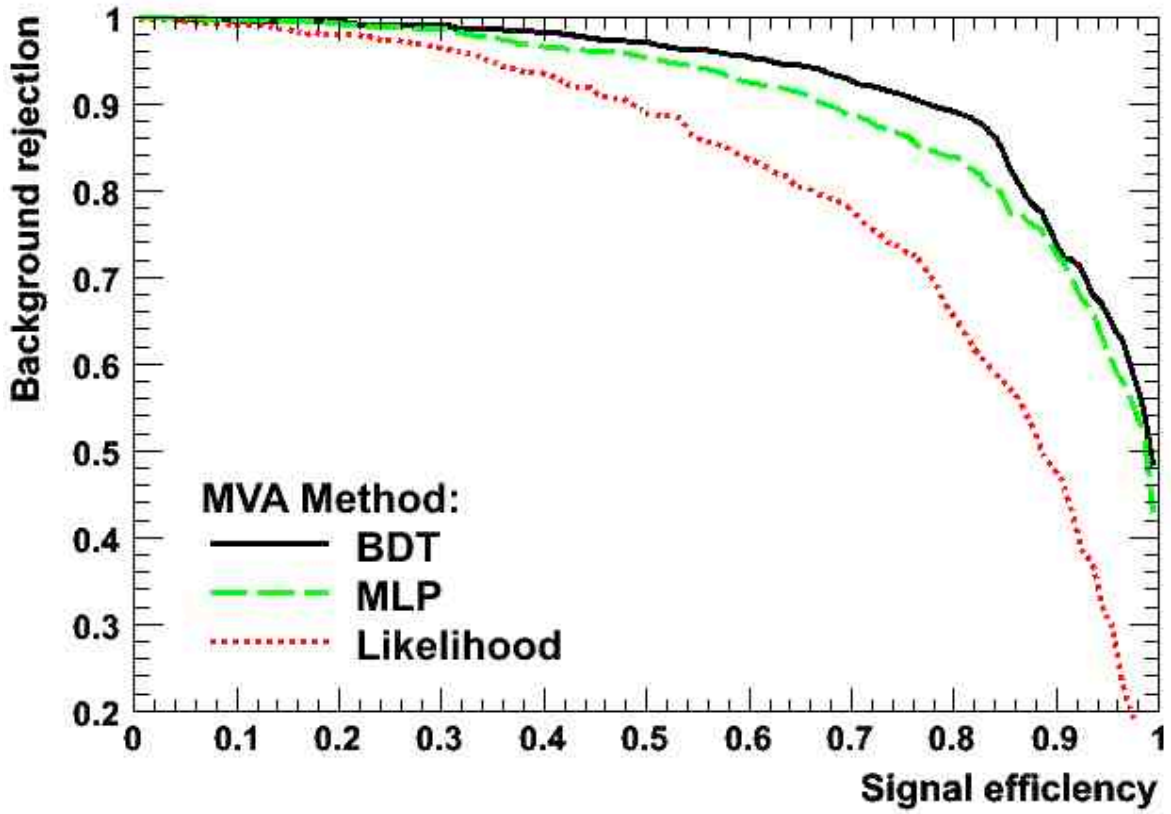
- Extra cut on di-muon mass to further reject background (~ factor of 2)
- Extra hits for high momentum muon in Muon system, an extra input for the BDT method.
- Train BDT in momentum bins: The higher the momentum, the better separation power.



300 GeV muon passing through one Cathod Strip Chamber (CSC)

CMS Collaboration, JINST 3 (2008) S08004

MVA Method


Background rejection
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Signal efficiency
MVA Method:
BDT
MLP
Likelihood

Xsec @ 2 & 10 TeV-SPS7

Table 1. Cascade and pair production cross sections at Tevatron and LHC energies for the SPS7 benchmark scenario in mGMSB. The last column shows the acceptance for an event to have at least one CHAMP within the CDF analysis selection for cascade production at the Tevatron energy.

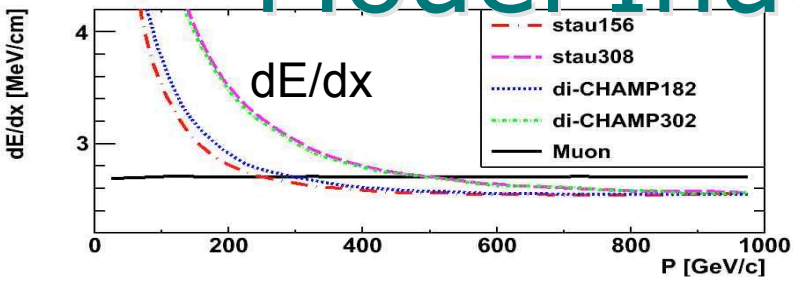
mass (GeV/c^2)	$\sigma(\sqrt{s} = 2$ TeV) cascade (fb)	pair (fb)	$\sigma(\sqrt{s} = 10$ TeV) cascade (fb)	pair (fb)	Acceptance for CDF analysis
100	113	10.6	4716	57	0.68
112	58	7.5	2433	34	0.69
126	28	4.8	1212	21	0.74
156	7.7	1.7	320	11	0.82
200	1.6	0.5	88	4	0.90
247	0.43	0.2	29	2	0.96
308	0.08	0.03	9	0.8	0.96

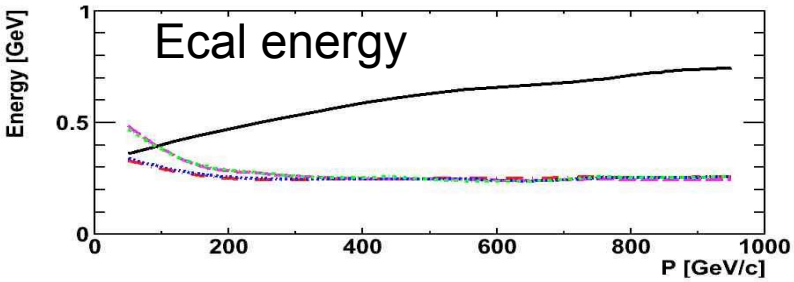
Double Background

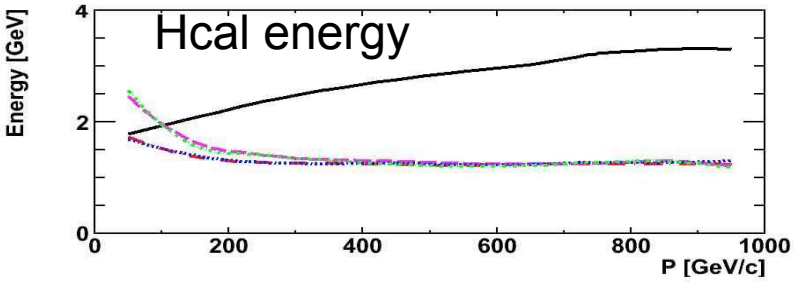
Table 4. Signal significance assuming 200 pb^{-1} data at $\sqrt{s} =$ 10 TeV LHC, using simple counting method or BDT.

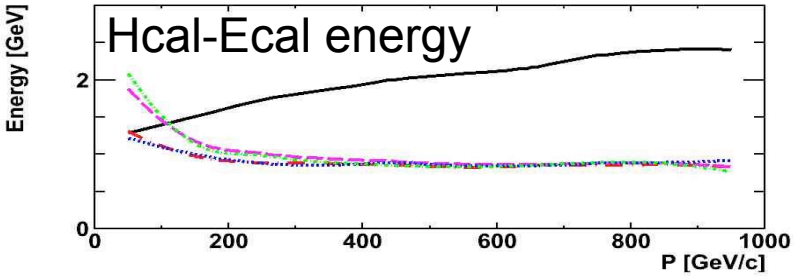
model	nominal background		double nominal background	
	counting	BDT	counting	BDT
stau156	5.6σ	8.3σ	4.4σ	7.1σ
di-CHAMP182	4.2σ	6.7σ	3.2σ	5.8σ

Model Independence





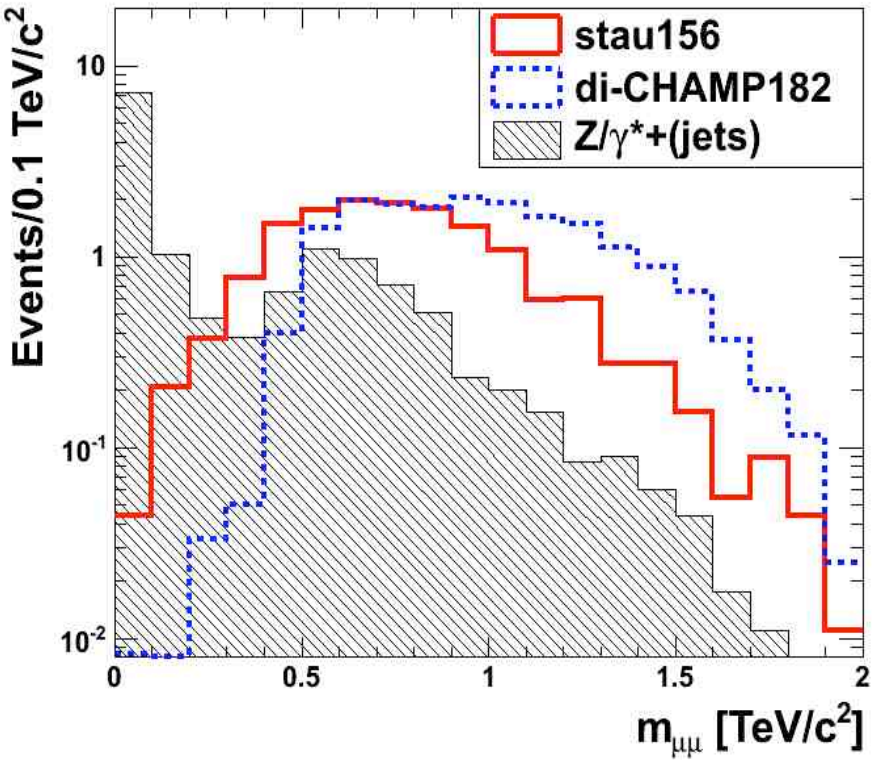




Model independent in high momentum (p>500) region.

7 TeV Result

- For 1 fb^{-1} 7 TeV data, same selection as 10 TeV study.



7 TeV Reach

- For 1 fb^{-1} 7 TeV data, same assumption for conventional method.
- BDT method is at least a complementary method to conventional one.