Search for Heavy Stable Charged Particles (HSCPs) at CMS

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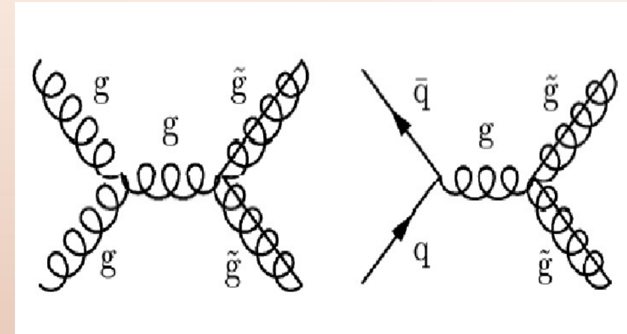
Introduction

- Heavy Stable Charged Particles (HSCPs) are-
  - heavy
  - long-lived (lifetime large enough to travel detector length scales)
  - have electric charge
- HSCPs can be-
  - lepton-like- have only electromagnetic interaction
  - hadron (coloured) like- in addition, also have nuclear interaction
- Constrained decay between Next-to-lightest-Stable-Particle (NLSP) and Lightest-Stable-Particle (LSP) in several Beyond Standard Model theories yield HSCPs. Example- SUSY, Extra Dimensions etc.
- Useful signatures-
  - Large p_T
  - Large ionisation energy loss
  - Slow moving

Signal Sample



- **Hadron HSCPs (R-hadrons)**-

  - pair-produced stops (MSSM)

  - pair-produced gluinos (split SUSY)

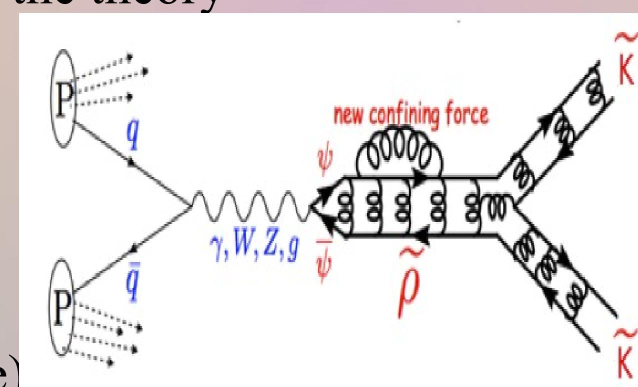
  Two R-hadron interaction scenarios are considered-

  - *Cloud Model*- Most R-hadrons are charged after several nuclear interactions (Eur. Phys. J. C50 (2007) 353)

  - *Complete charge supression*- Each nuclear interaction suffered by the R-hadron causes it to become neutral

  Initial fraction of gluino-gluon, *f*, is a free parameter of the theory

  - Gluino searches are done with *f* being 10% and 50%



- **Lepton HSCPs**-

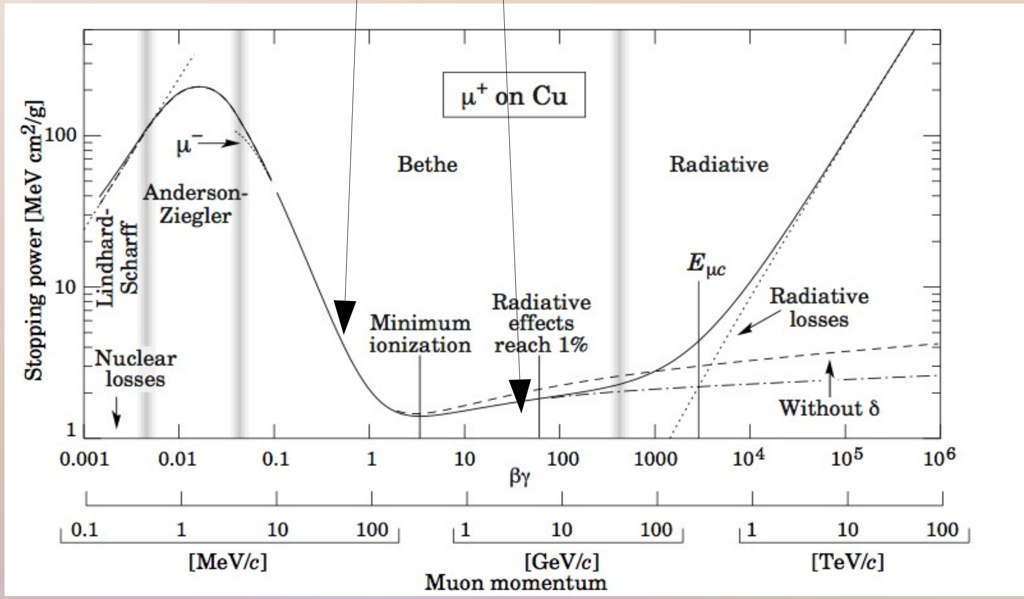
  - pair-produced stau in mGMSB model (SPS7 line)

  - stau from cascade decay in mGMSB model (SPS7 line)

  - pair-produced hyper-K- via DY and hyper-ρ resonance (JHEP 02 (2010) 018)

How do we search for our signal?

Signal region   Background region



dE/dx for positive muons in Copper
K. Nakamura et al. (Particle Data Group),
J. Phys. G 37, 075021 (2010)

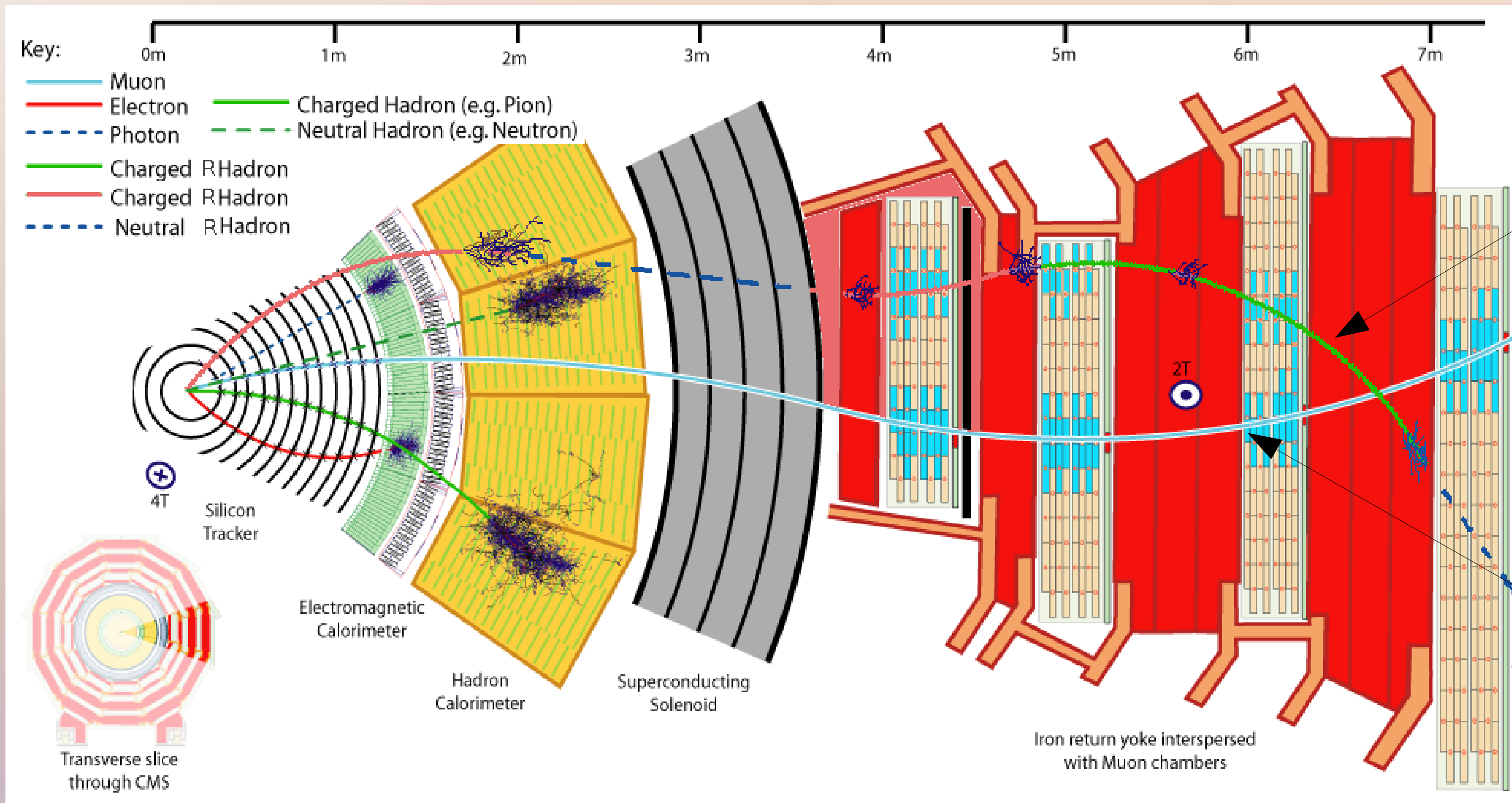
HSCPs would be produced with a large p_T

HSCPs are long-lived
→ identify using the muon system

HSCPs are massive → slow-moving
→ longer time-of-flight
→ larger dE/dx

Backgrounds consist of muons
→ low p_T
→ fast-moving ($\beta \sim 1$)
→ low dE/dx

Passage of HSCPs through the CMS detector



Hadron HSCP

Lepton HSCP

Making detector measurements

- p_T- computed by measuring the curvature in the tracker
- dE/dx of a candidate track is computed using charge depositions in Silicon strip and pixel detectors in the CMS tracker-

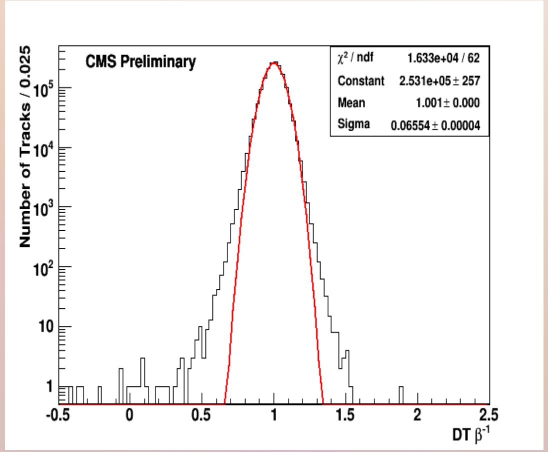
$$\frac{dE}{dx} = \left(\frac{1}{N}\sum_{i=1}^{N} c_i^k\right)^{\left(\frac{1}{k}\right)}$$

c_i is the charge/unit path length of the i^{th} measurement, k=2, N is the total number of measurements

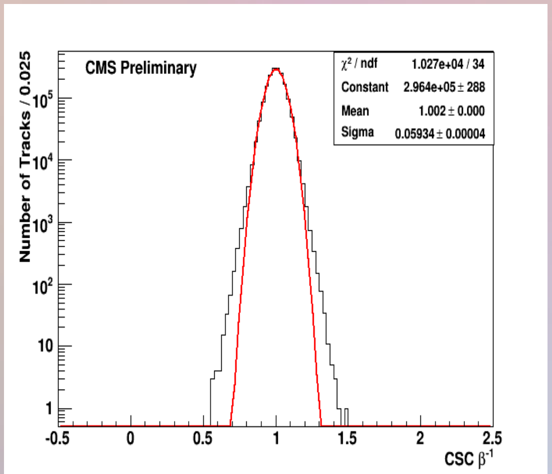
I_{as} (derived from dE/dx) discriminator used for particle id

- Candidate β is computed using timing information in the drift tubes (DT) and cathode strip chambers (CSC) in the muon system.

1/β resolution in muon system



DT



CSC

Data Sample

- Triggers

  Muon40- identify HSCPs which (continue to) remain charged in the muon system

  L1 Resistive Plate Chamber (RPC) trigger- checks in the (25ns) BX and BX+1

  MET150- identify HSCPs which become neutral after traversing the tracker and also those that fail the muon threshold

- The analysis uses all 2011 data collected at CMS (~5 fb^{-1})

- Two analysis strategies-

Tracker-only

→ effective for HSCPs which are charged in the tracker, but become neutral in the calorimeter

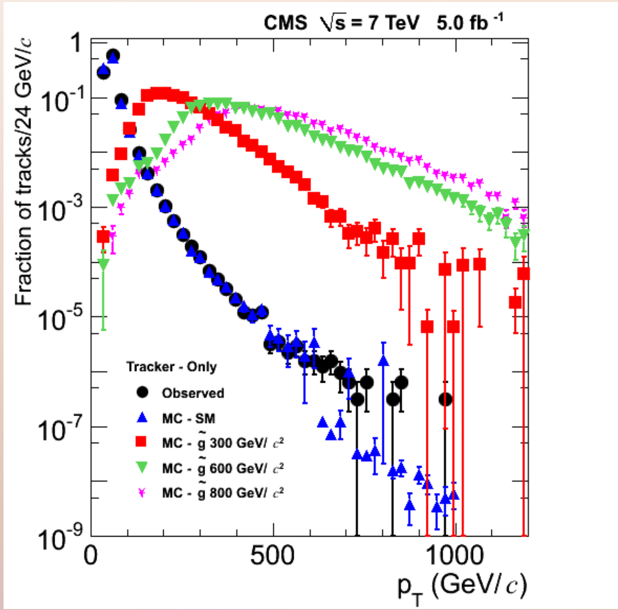
→ Identified with large p_T and large dE/dx (I_{as})

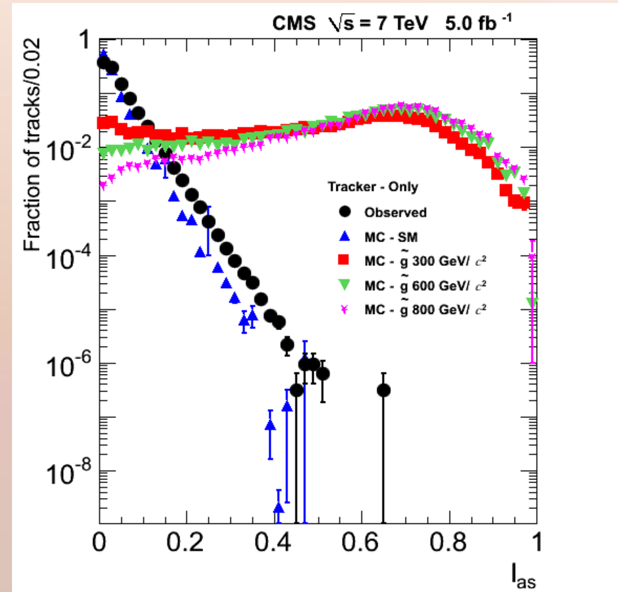
Tracker+TOF

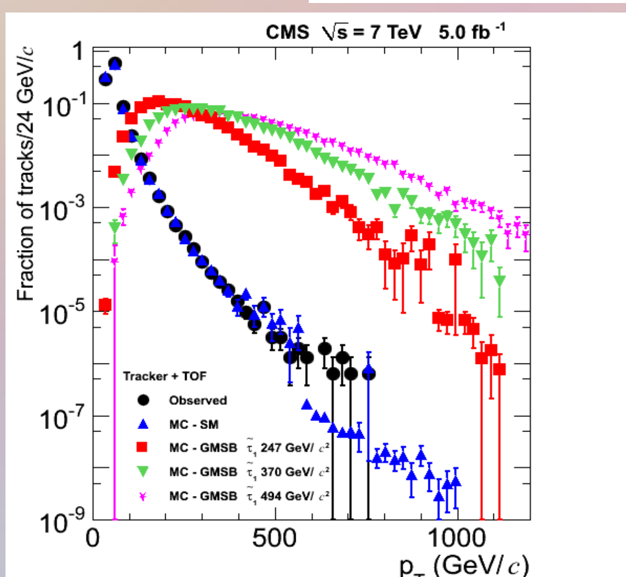
→ effective for HSCPs which are charged in the tracker and also in the muon system

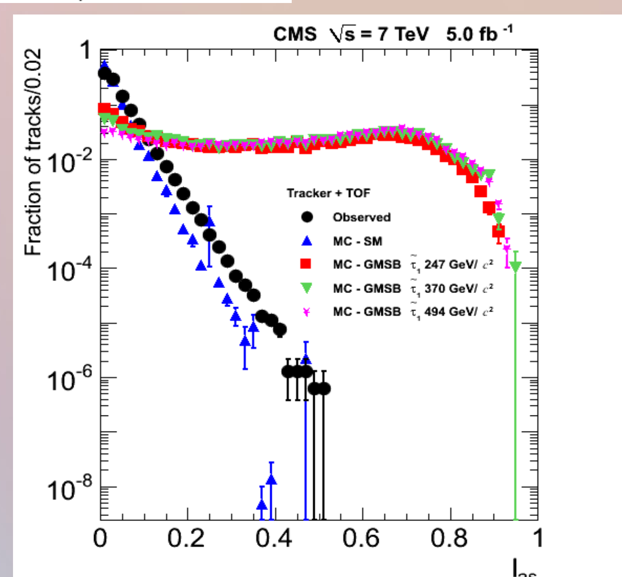
→ Identified with large p_T and large dE/dx (I_{as}) and large $1/\beta$

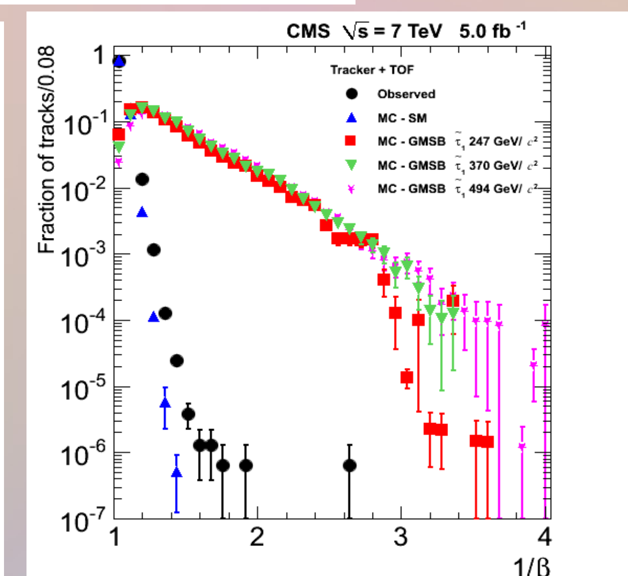
p_T, I_{as} and $1/\beta$ shapes for signal and data



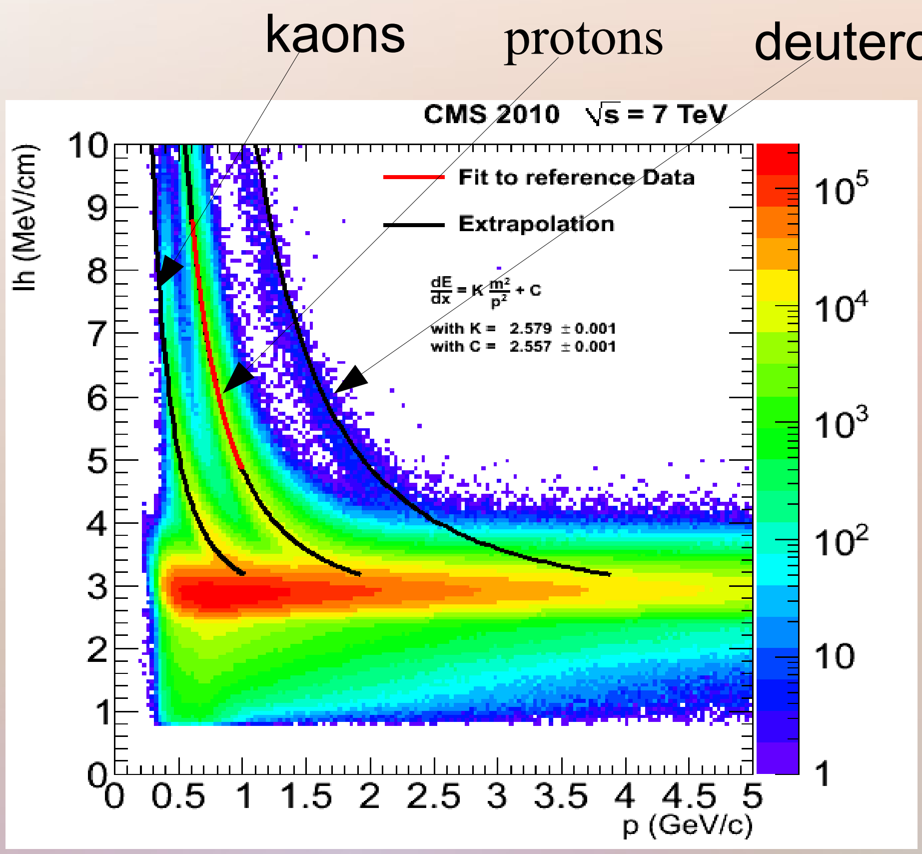








Mass computation using measured dE/dx and p



Approximation to the Bethe-Bloch formula in range $0.4 < \beta < 0.9$

$$\frac{dE}{dx} = K\frac{M^2}{p^2} + C$$

Constants K and C- derived from data using a sample of low-momentum protons

Use measured dE/dx and measured p to compute the particle's measured mass

Analysis

- Signal region-

  Tracker-only- large values of p_T and I_{as}

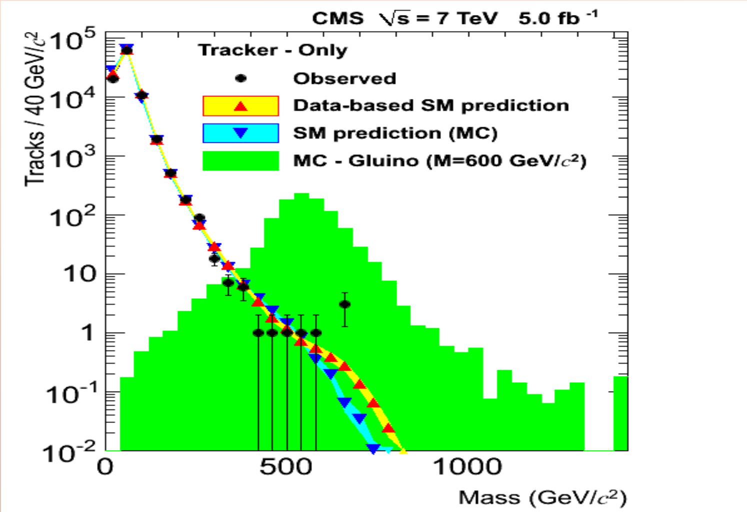
  Tracker+TOF- large values of p_T, I_{as} and $1/\beta$

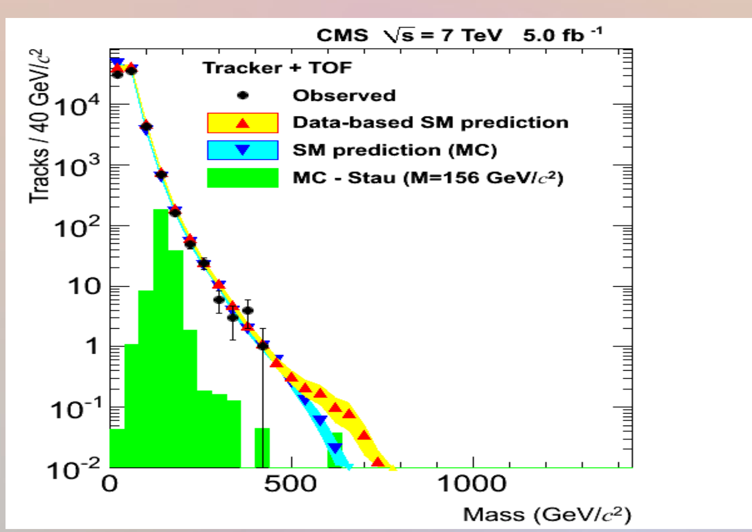
- Use non-correlation between p_T, I_{as} and $1/\beta$ to make a data-driven prediction for the background in the signal region

- Background mass spectrum in the signal region is built from pseudo-experiments using p and dE/dx PDFs from non-signal regions

- Counting experiment is done in a mass window of $[M_{reco} - 2\sigma_{Mreco}, 2\ \text{TeV}]$

- Final Selection of p_T, I_{as} and $1/\beta$ is optimised for the best discovery potential for each signal point.





Good matching between prediction and observation for loose selection

Results

- No significant excess is seen with respect to prediction and 95% CL upper limits on the HSCP production cross sections are set and translated to mass limits

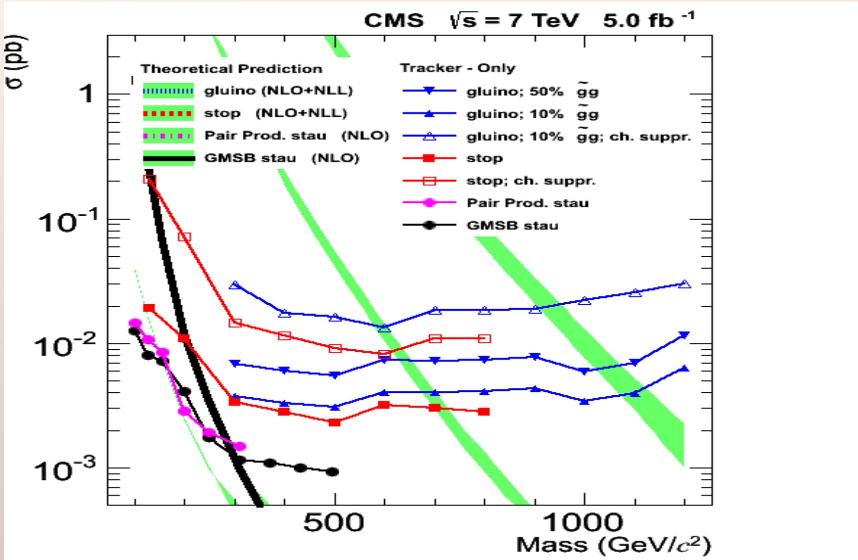
- **Mass limits for Hadron HSCPs-**

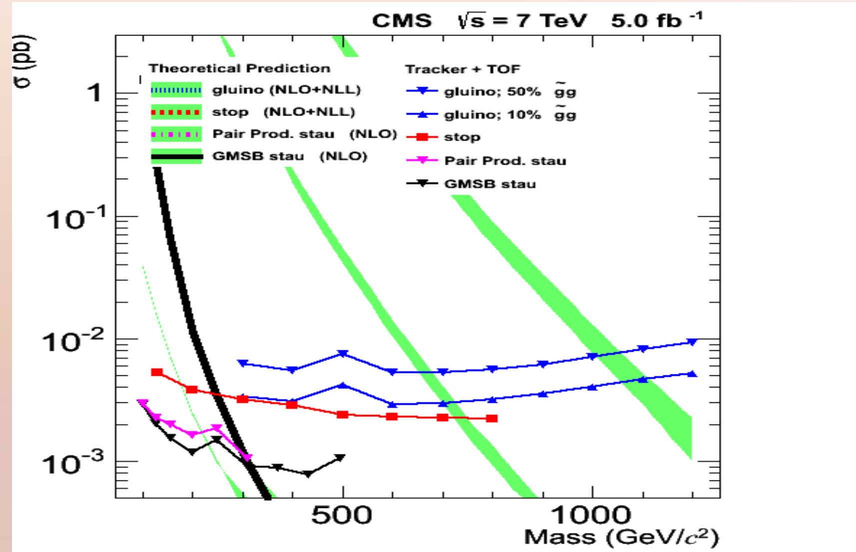
R-hadron		Cloud Model (GeV/c^2)	Charge suppression model (GeV/c^2)
gluino	*f* = 10%	1098	928
	f = 50%	1046	NA
stop		737	626

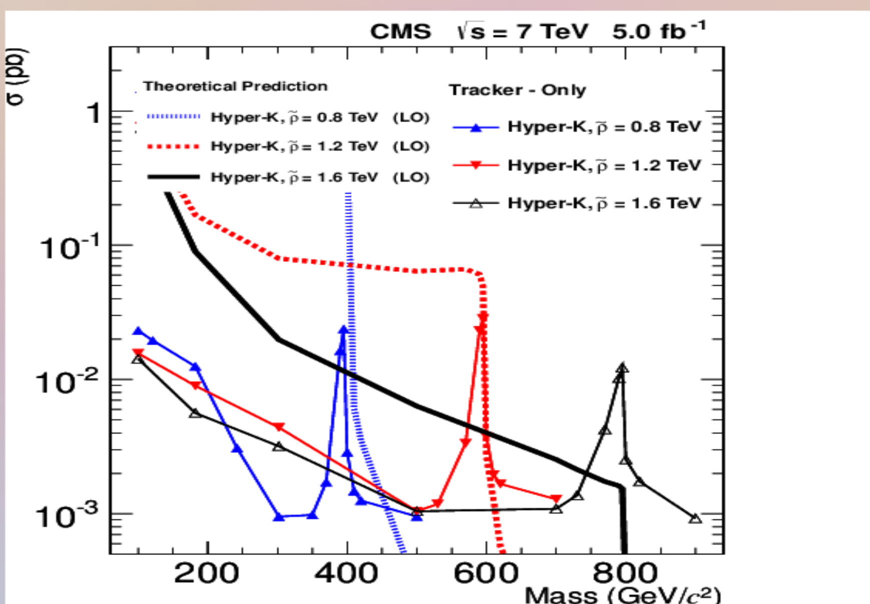
- **Mass limits for Lepton HSCPs-**

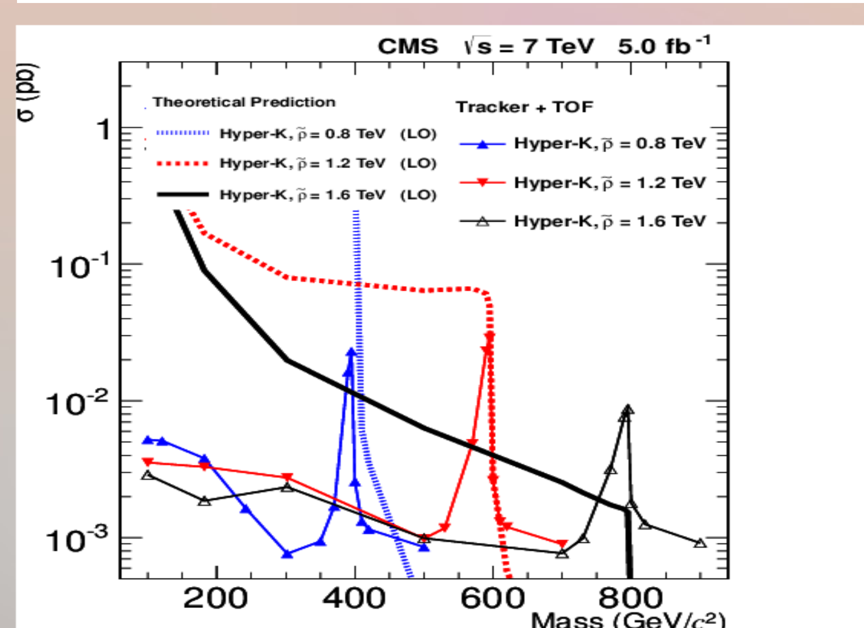
Lepton HSCP			(GeV/c^2)
stau		cascade-decay	314
		pair-produced	223
hyper-K	hyper-ρ_M (GeV/c^2)	800	484
		1200	602
		1600	747

Observed cross section limits









Summary

- We searched for HSCPs in data collected with the CMS detector during the 2011 run of the LHC (~5 fb^{-1}). Two scenarios-
  - Tracker-only- HSCPs are searched for using p_T and dE/dx
  - Tracker+TOF- HSCPs are searched for using p_T, dE/dx and $1/\beta$
- Observed number of data events compatible with prediction.
- We set 95% CL upper limit on the cross section of various HSCP models and lower limits on their mass.
- Documentation-

  Public page- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11022Winter2012

  Paper- http://arxiv.org/abs/1205.0272 (submitted to Physics Letters B).

Back-Up

I_{as} discriminator

- Estimator of the degree of compatibility of the observed charge measurements with the MIP hypothesis

$$I_{as} = \frac{3}{N}\left(\frac{1}{12N} + \sum_{i=1}^{N}\left[P_i\left(P_i - \frac{(2i-1)}{2N}\right)^2\right]\right)$$

N is the number of charge measurements in the silicon-strip detectors

P_i is the probability for a minimum ionising particle to produce a charge smaller or equal to the i^{th} charge measurement for the observed path length in the detector. The sum is over the track measurements ordered in terms of increasing P_i

dE/dx computed using both silicon strip and pixel measurements. I_{as} is computed using only silicon strip measurements.

PreSelection Used

- Common to both Tracker-only and Tracker+TOF-
  - tracker track should be good
    - large number of track hits, good track fitting
  - vertex offset should be compatible with the beam-spot
  - $dE/dx > 3$ MeV/cm, $I_{as} > 0.0$
  - $p_T > 45$ GeV, $|\eta| < 1.5$

Tracker-only

- calorimeter isolation < 0.3
- tracker isolation < 50 GeV

Tracker+TOF

- muon track quality should be good
- tracker track and muon track should form a good global muon
- $1/\beta > 1.0$ and uncertainty on $1/\beta < 0.07$
- calorimeter isolation < 0.6
- tracker isolation < 100 GeV

calorimeter isolation = $[(\sum \text{Energy}_{ECAL} + \sum \text{Energy}_{HCAL})/p]_{|\Delta R<0.3}$

tracker isolation = $[\sum p_T]_{|\Delta R<0.3}$ ($\sum$ does not include the candidate track)

Loose Selection

Table 1: Selections used to create the 'loose' samples with large number of events and the expected (Exp.) and observed (Obs.) event yields. The selections are defined in terms of thresholds in p_T, I_{as}, and β^{-1} (measured from TOF).

Selection	p_T^{min} (GeV/c)	I_{as}^{min}	$\beta^{-1 min}$	Exp.	Obs.
Tk-Only	50	0.10	-	103450 ± 10350 (syst) ± 210 (stat)	94910
Tk+TOF	50	0.05	1.05	88010 ± 8800 (syst) ± 290 (stat)	72079

Systematic Uncertainties

Source of systematic uncert.	Relative uncert. (%)
Signal acceptance:	
- Trigger efficiency	5
- Track momentum scale	< 4
- Ionization energy loss	2
- Time-of-flight	2
- Track reconstruction eff.	< 2
- Muon reconstruction eff.	< 2
- Pile-up	< 0.5
Total uncert. in signal acc.	7
Expected background	10
Integrated luminosity	2.2

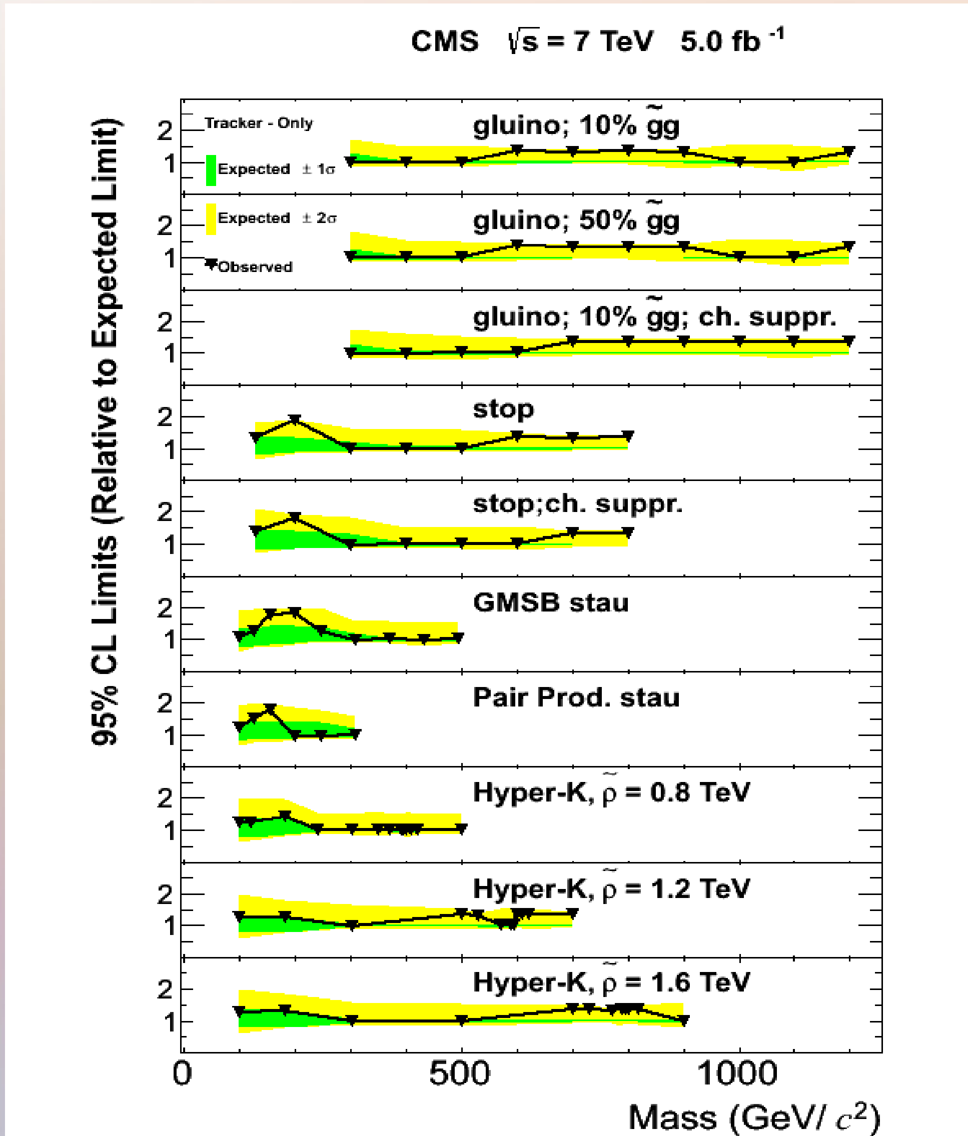
Results (Tracker-only)

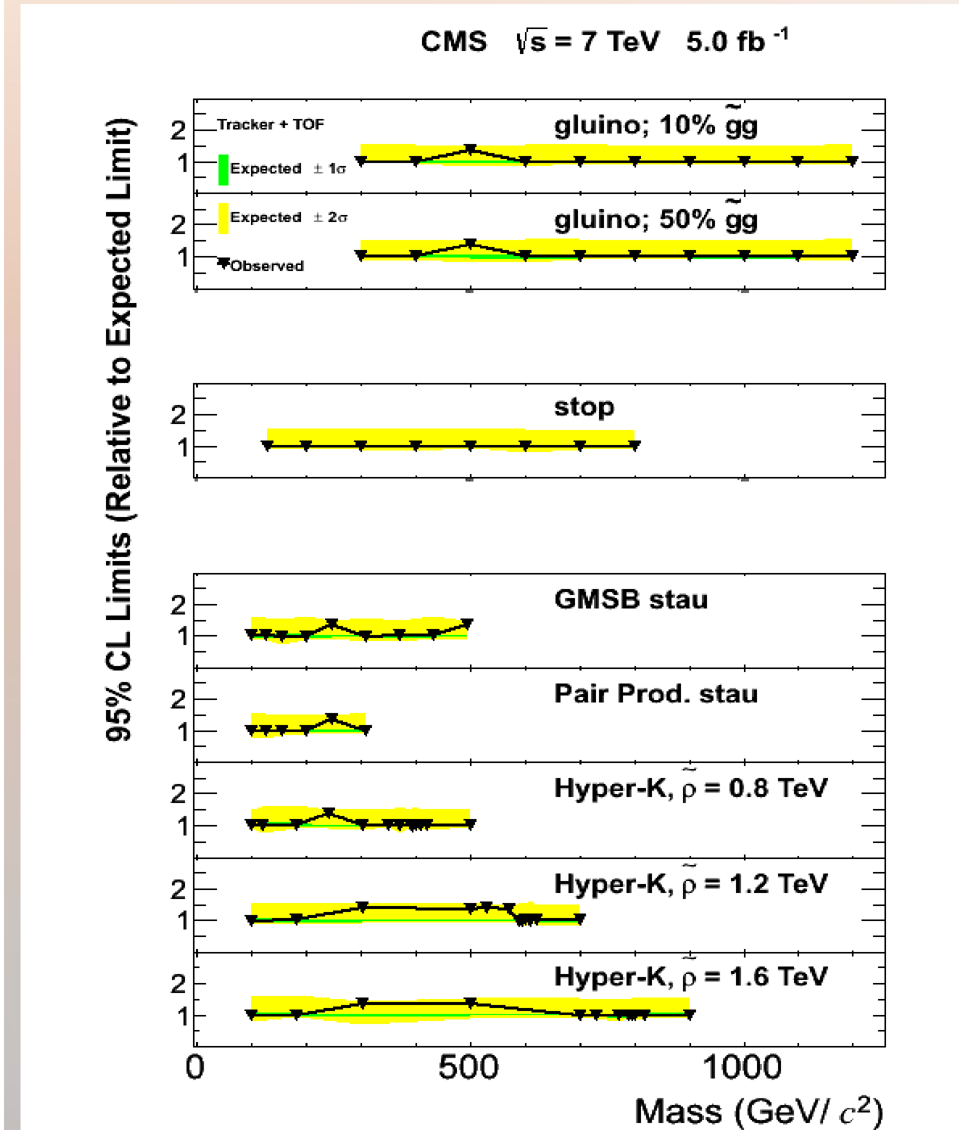
Model	Mass	p_T^{min}	I_{as}^{min}	M_{reco}^{min}	Acc.	Exp.	Obs.	Th. σ	Exp. σ	Obs. σ
$\tilde{g}$ ($f = 0.1$)	300	60	0.400	180	0.158	0.328 ± 0.040	0	6.6E+01	3.8E-03	3.7E-03
$\tilde{g}$ ($f = 0.1$)	700	50	0.300	410	0.206	0.089 ± 0.009	1	2.1E-01	3.0E-03	4.0E-03
$\tilde{g}$ ($f = 0.1$)	1100	120	0.225	570	0.149	0.094 ± 0.010	0	3.9E-03	4.0E-03	3.9E-03
$\tilde{g}$ ($f = 0.5$)	300	60	0.400	180	0.086	0.328 ± 0.040	0	6.6E+01	6.9E-03	6.8E-03
$\tilde{g}$ ($f = 0.5$)	700	50	0.300	410	0.116	0.089 ± 0.009	1	2.1E-01	5.3E-03	7.1E-03
$\tilde{g}$ ($f = 0.5$)	1100	120	0.225	570	0.085	0.094 ± 0.010	0	3.9E-03	7.0E-03	6.9E-03
$\tilde{g}$ ($f = 0.1$, ch. suppr.)	300	60	0.400	180	0.020	0.328 ± 0.040	0	6.6E+01	3.0E-02	3.0E-02
$\tilde{g}$ ($f = 0.1$, ch. suppr.)	700	50	0.325	370	0.045	0.092 ± 0.010	1	2.1E-01	1.4E-02	1.8E-02
$\tilde{g}$ ($f = 0.1$, ch. suppr.)	1100	50	0.275	460	0.032	0.085 ± 0.009	1	3.9E-03	1.9E-02	2.6E-02
$\tilde{t}_1$	200	60	0.400	130	0.142	1.250 ± 0.160	4	1.3E+01	5.8E-03	1.1E-02
$\tilde{t}_1$	500	50	0.350	310	0.242	0.126 ± 0.014	0	4.8E-02	2.4E-03	2.3E-03
$\tilde{t}_1$	800	50	0.275	450	0.290	0.095 ± 0.010	1	1.1E-03	2.1E-03	2.8E-03
$\tilde{t}_1$ (ch. suppr.)	200	70	0.400	120	0.021	1.520 ± 0.202	4	1.3E+01	4.0E-02	7.2E-02
$\tilde{t}_1$ (ch. suppr.)	500	50	0.375	280	0.064	0.102 ± 0.012	0	4.8E-02	9.1E-03	9.1E-03
$\tilde{t}_1$ (ch. suppr.)	800	50	0.325	370	0.077	0.092 ± 0.010	1	1.1E-03	8.1E-03	1.1E-02
GMSB $\tilde{\tau}_1$	100	65	0.400	20	0.122	6.980 ± 0.908	7	1.3E+00	1.2E-02	1.3E-02
GMSB $\tilde{\tau}_1$	494	65	0.350	300	0.639	0.126 ± 0.014	0	6.2E-05	9.3E-04	9.3E-04
pair prod. $\tilde{\tau}_1$	100	70	0.400	40	0.105	4.840 ± 0.608	6	3.8E-02	1.2E-02	1.5E-02
pair prod. $\tilde{\tau}_1$	308	70	0.400	190	0.390	0.237 ± 0.030	0	3.5E-04	1.5E-03	1.5E-03
$\tilde{K}$ ($\tilde{\rho}$ (800))	100	70	0.400	10	0.065	4.880 ± 0.613	6	1.4E+00	1.9E-02	2.3E-02
$\tilde{K}$ ($\tilde{\rho}$ (800))	500	50	0.350	320	0.611	0.107 ± 0.012	0	2.8E-04	9.6E-04	9.6E-04
$\tilde{K}$ ($\tilde{\rho}$ (1200))	600	50	0.325	370	0.221	0.092 ± 0.010	1	2.6E-03	2.8E-03	3.8E-03
$\tilde{K}$ ($\tilde{\rho}$ (1200))	700	50	0.275	440	0.647	0.106 ± 0.011	1	6.1E-05	9.6E-04	1.3E-03
$\tilde{K}$ ($\tilde{\rho}$ (1600))	800	140	0.250	480	0.329	0.118 ± 0.012	1	2.6E-04	1.9E-03	2.5E-03
$\tilde{K}$ ($\tilde{\rho}$ (1600))	900	135	0.225	530	0.617	0.128 ± 0.014	0	1.3E-05	9.3E-04	9.3E-04

Results (Tracker-TOF)

Model	Mass	p_T^{min}	I_{as}^{min}	$\beta^{-1 min}$	M_{eco}^{min}	Acc.	Exp.	Obs.	Th. σ	Exp. σ	Obs. σ
$\tilde{g}$ ($f = 0.1$)	300	55	0.175	1.175	180	0.170	0.119 ± 0.012	0	6.6E+01	3.4E-03	3.4E-03
$\tilde{g}$ ($f = 0.1$)	700	110	0.050	1.125	430	0.194	0.113 ± 0.015	0	2.1E-01	3.0E-03	3.0E-03
$\tilde{g}$ ($f = 0.1$)	1100	110	0.025	1.075	620	0.127	0.111 ± 0.033	0	3.9E-03	4.6E-03	4.6E-03
$\tilde{g}$ ($f = 0.5$)	300	55	0.175	1.175	180	0.094	0.119 ± 0.012	0	6.6E+01	6.3E-03	6.2E-03
$\tilde{g}$ ($f = 0.5$)	700	110	0.050	1.125	430	0.109	0.113 ± 0.015	0	2.1E-01	5.4E-03	5.3E-03
$\tilde{g}$ ($f = 0.5$)	1100	110	0.025	1.075	620	0.072	0.111 ± 0.033	0	3.9E-03	8.2E-03	8.2E-03
$\tilde{t}_1$	200	50	0.200	1.200	130	0.150	0.109 ± 0.011	0	1.3E+01	3.9E-03	3.8E-03
$\tilde{t}_1$	500	60	0.075	1.150	330	0.246	0.125 ± 0.013	0	4.8E-02	2.4E-03	2.4E-03
$\tilde{t}_1$	800	105	0.025	1.125	490	0.262	0.096 ± 0.019	0	1.1E-03	2.2E-03	2.2E-03
GMSB $\tilde{\tau}_1$	100	50	0.300	1.275	30	0.195	0.093 ± 0.011	0	1.3E+00	2.9E-03	2.9E-03
GMSB $\tilde{\tau}_1$	494	55	0.025	1.175	320	0.779	0.113 ± 0.014	1	6.2E-05	7.8E-04	1.1E-03
pair prod. $\tilde{\tau}_1$	100	50	0.250	1.275	50	0.193	0.109 ± 0.012	0	3.8E-02	3.0E-03	2.9E-03
pair prod. $\tilde{\tau}_1$	308	65	0.125	1.200	190	0.545	0.105 ± 0.011	0	3.5E-04	1.1E-03	1.1E-03
$\tilde{K}$ ($\tilde{\rho}$ (800))	100	50	0.300	1.275	20	0.112	0.095 ± 0.011	0	1.4E+00	5.3E-03	5.2E-03
$\tilde{K}$ ($\tilde{\rho}$ (800))	500	60	0.075	1.150	330	0.680	0.125 ± 0.013	0	2.8E-04	8.6E-04	8.5E-04
$\tilde{K}$ ($\tilde{\rho}$ (1200))	600	70	0.025	1.150	380	0.223	0.107 ± 0.015	0	2.6E-03	2.6E-03	2.6E-03
$\tilde{K}$ ($\tilde{\rho}$ (1200))	700	110	0.050	1.125	450	0.658	0.087 ± 0.013	0	6.1E-05	9.0E-04	9.0E-04
$\tilde{K}$ ($\tilde{\rho}$ (1600))	800	50	0.050	1.100	500	0.325	0.119 ± 0.021	0	2.6E-04	1.8E-03	1.8E-03
$\tilde{K}$ ($\tilde{\rho}$ (1600))	900	85	0.075	1.075	550	0.606	0.123 ± 0.022	0	1.3E-05	9.3E-04	9.1E-04

Ratio of observed and expected cross section limits





Signal Models used- mGMSB model

Benchmark points on the SPS7 line are used

- stau = 156 GeV

  $N = 3$, $\Lambda = 50000$ GeV, $M = 100000$ GeV, $\tan\beta = 10$, $sign(\mu) = 1$, $c_{grav} = 10000$

- stau = 247 GeV

  $N = 3$, $\Lambda = 80000$ GeV, $M = 160000$ GeV, $\tan\beta = 10$, $sign(\mu) = 1$, $c_{grav} = 10000$

Signal Models used
Vector-like confinement model

- Proposes a QCD-like confinement force between new elementary particles (hyper-quarks)
- Hyper-quarks are confined into Standard Model hadron-like hypermesons like hyper-π, hyper-K, hyper-ρ.
- Model assumption used-

  Hyper-K is pair-produced via either Drell-Yan process or via production of a resonant, hyper-ρ.