Search for Heavy Stable Charged Particles in CMS

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Outline

- Introduction
- The CMS detector at the LHC
- Analysis strategy
- Online selection
- Offline reconstruction and selection
    - Ionization energy loss
    - Mass measurement
- Background estimation
- Systematic uncertainties
- Results
- Summary

Introduction

- Theoretical motivation:
  - Heavy Stable Charged Particles (HSCP) are predicted by many BSM theories
    - Some SUSY flavors predict long living gluino, stop, stau, etc.
    - Hidden valley models, extra dimensions, certain GUTs, etc.
  - Two main classes of particles:
    - Lepton-like, no strong interactions
    - Hadron-like, color-charged – hadronize to form "R-hadrons"
      - Strongly interacting particles form stable states with quarks/gluons
- Detector signature:
  - Slowly moving high momentum particle, typically reconstructed and identified as a muon
  - High momentum track
  - Anomalously high ionization energy loss (dE/dx)
  - High time-of-flight (currently not used)

Compact Muon Solenoid Detector

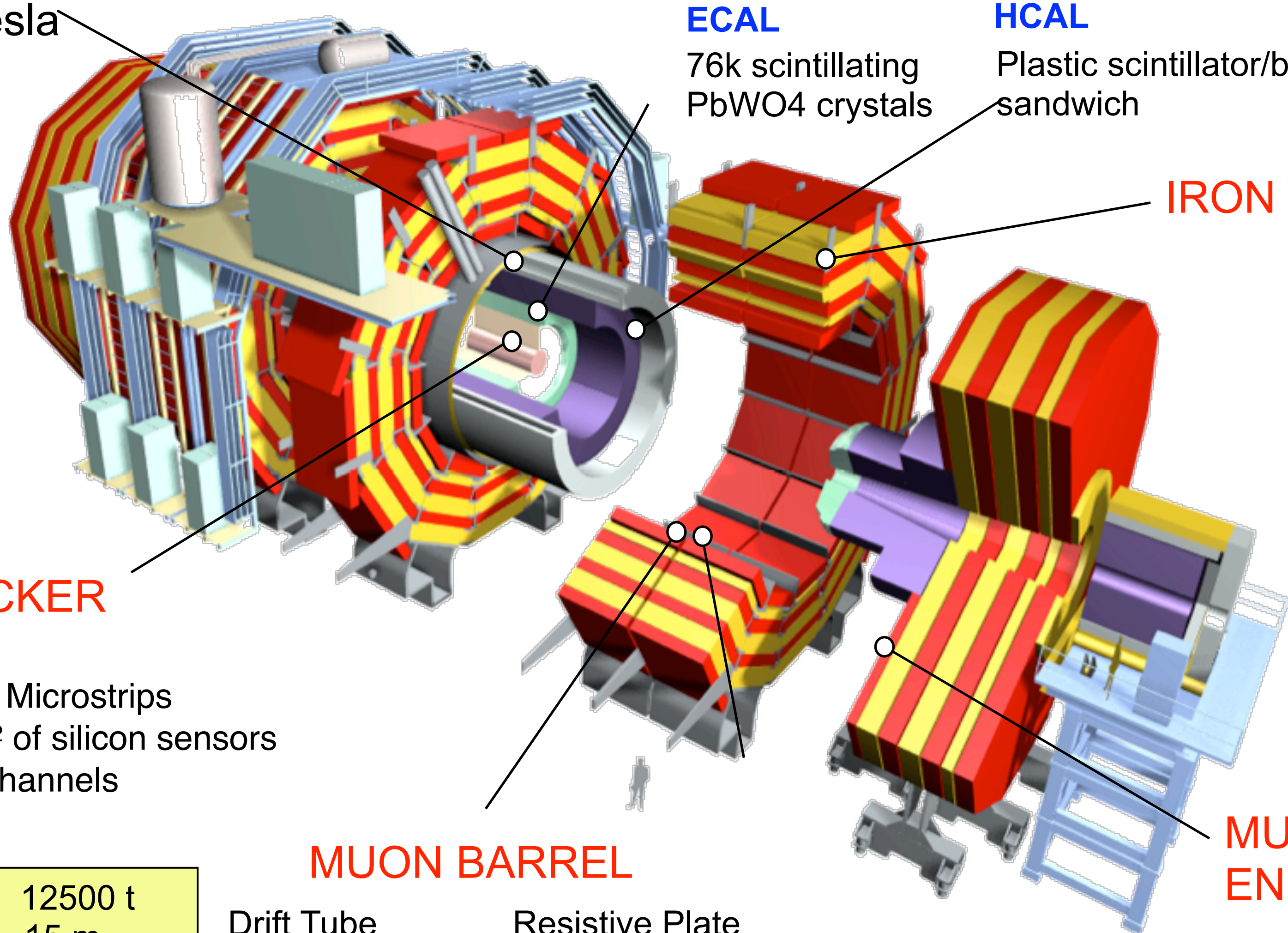
Superconducting Coil, 3.8 Tesla

CALORIMETERS

ECAL
76k scintillating PbWO4 crystals

HCAL
Plastic scintillator/brass sandwich

IRON YOKE



TRACKER

Pixels
Silicon Microstrips
210 m² of silicon sensors
9.6M channels

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

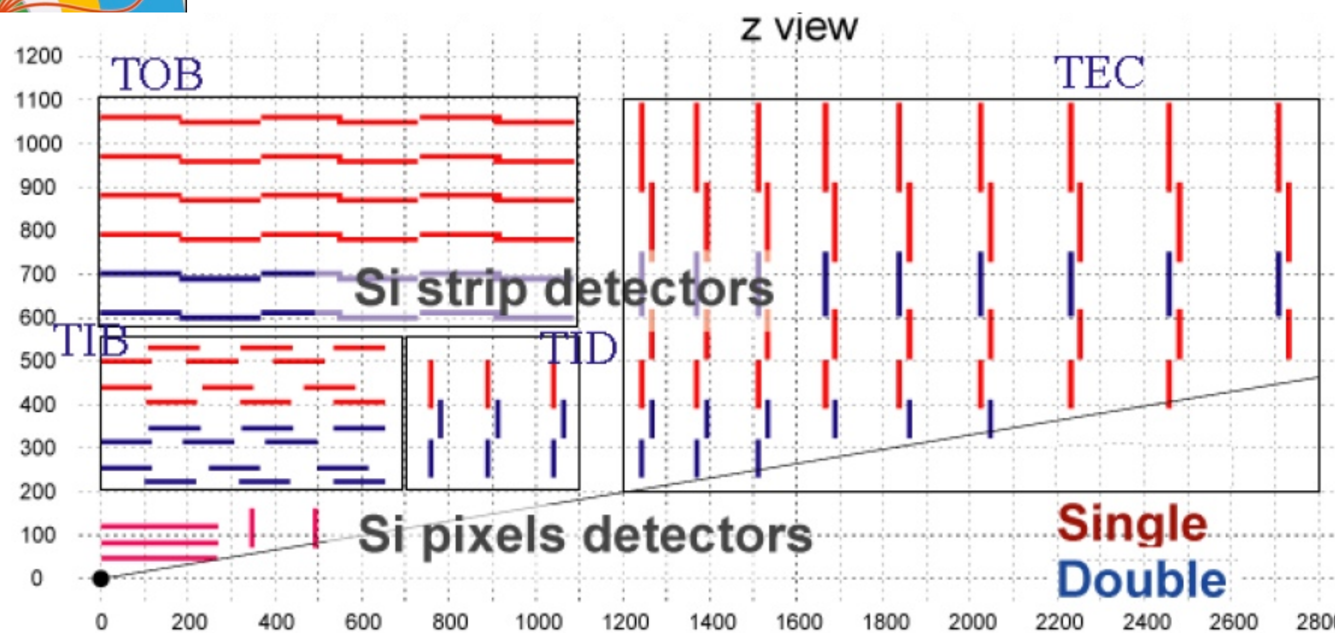
MUON BARREL

Drift Tube Chambers (**DT**)
Resistive Plate Chambers (**RPC**)

MUON ENDCAPS

Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

The CMS Tracker

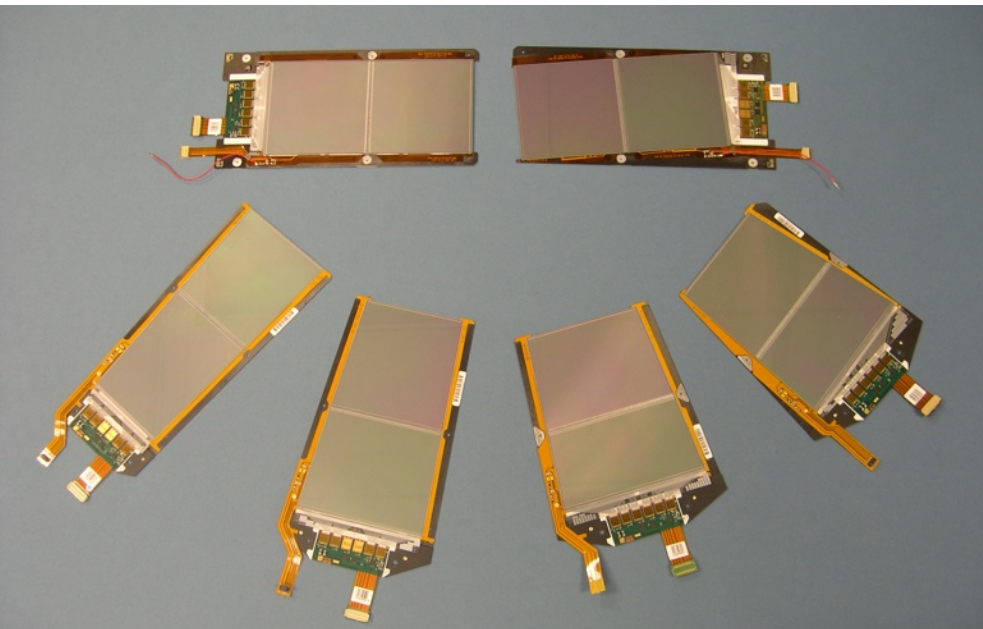


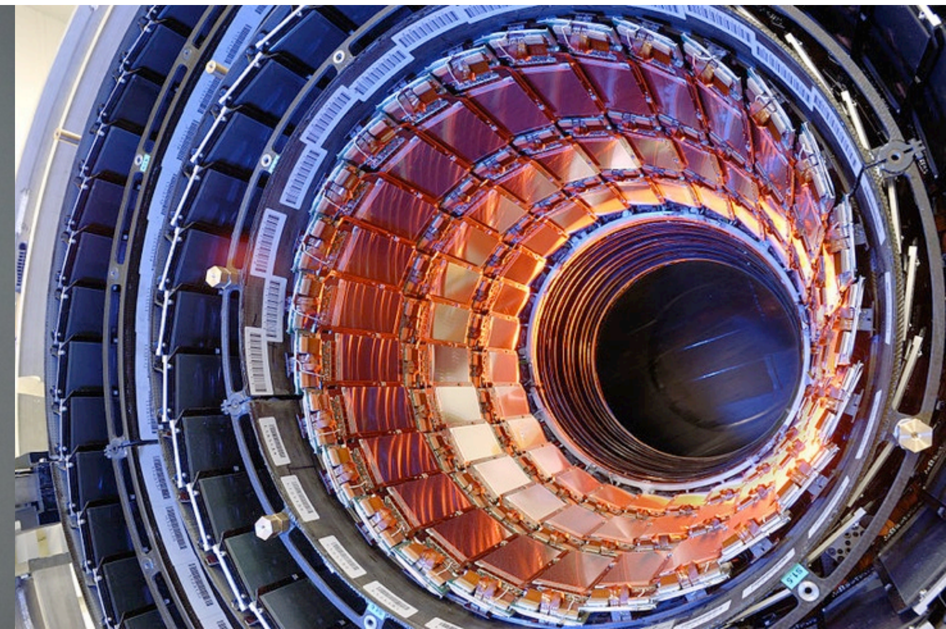
Strip Detector:

15148 modules

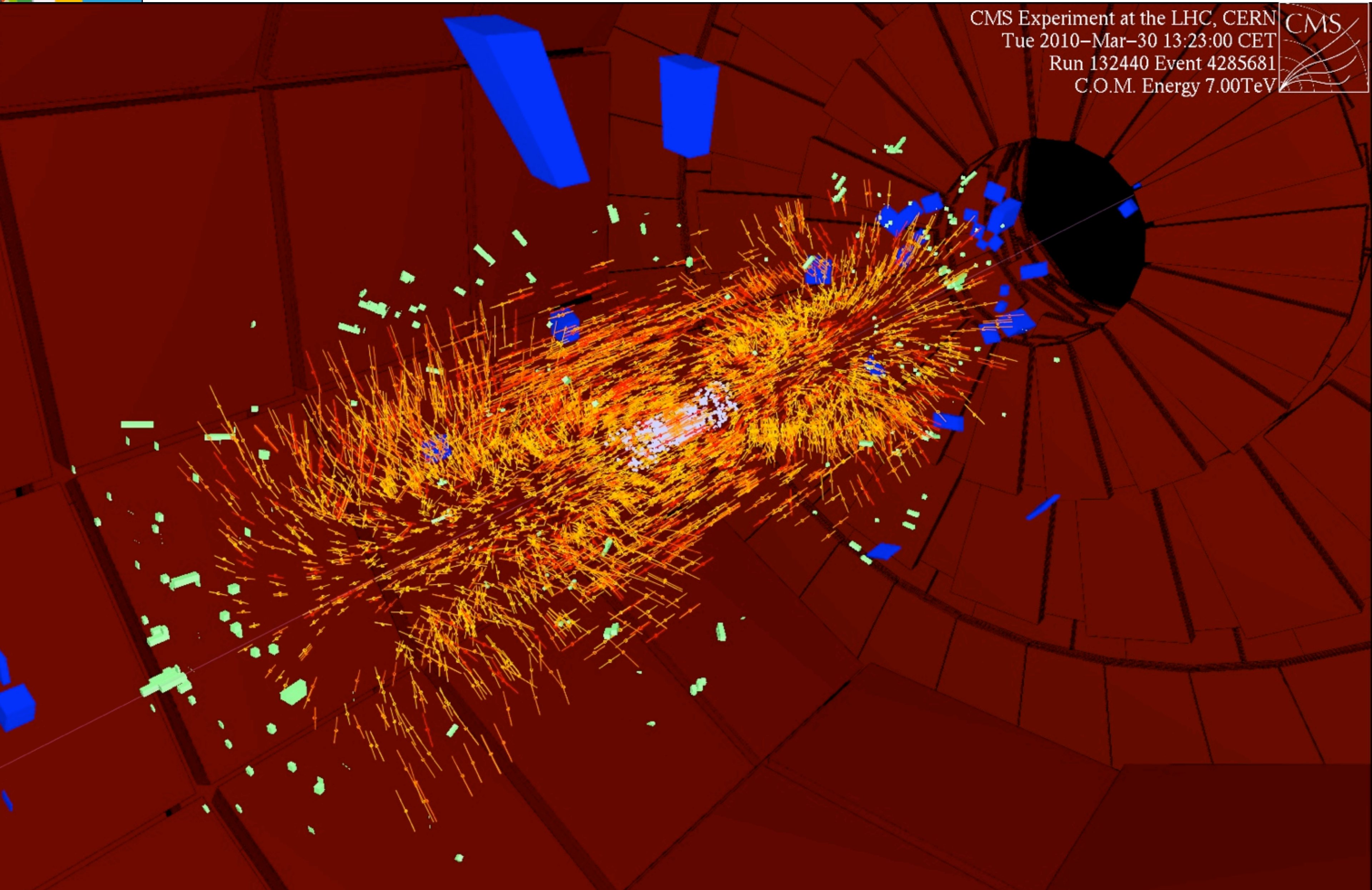
9.7M channels

A particle crosses ~20 modules





CMS Tracker in Operation



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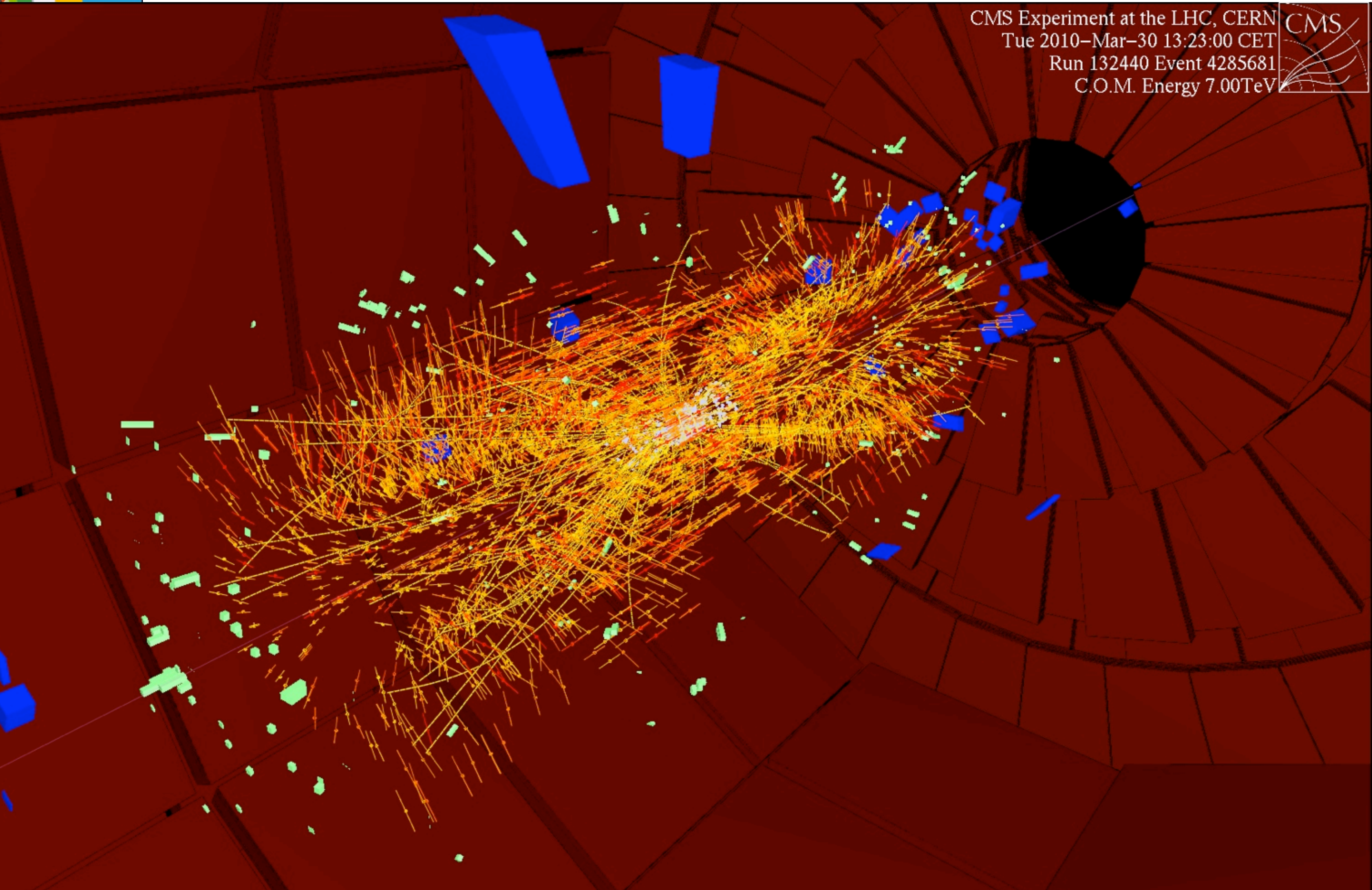

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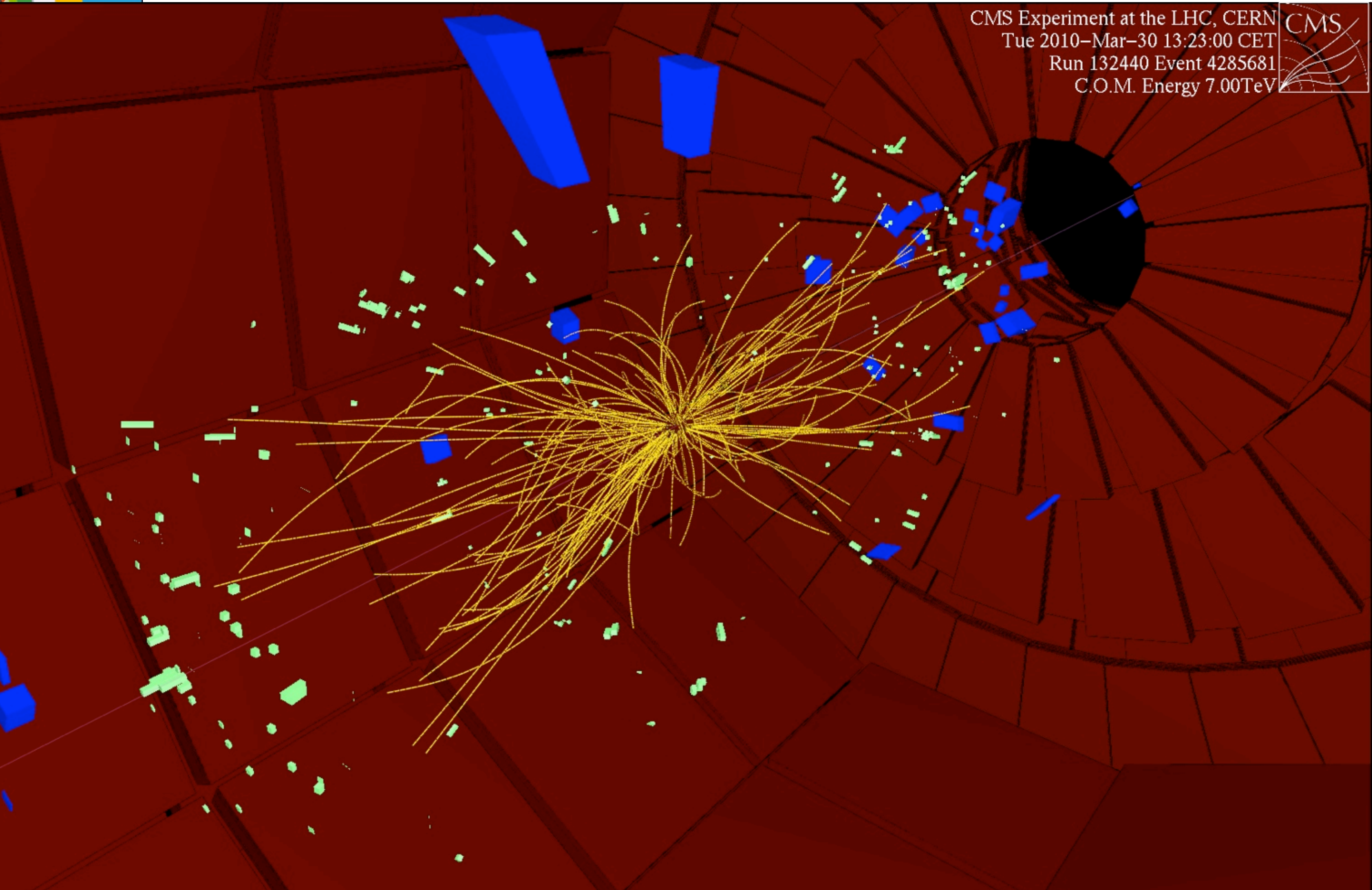
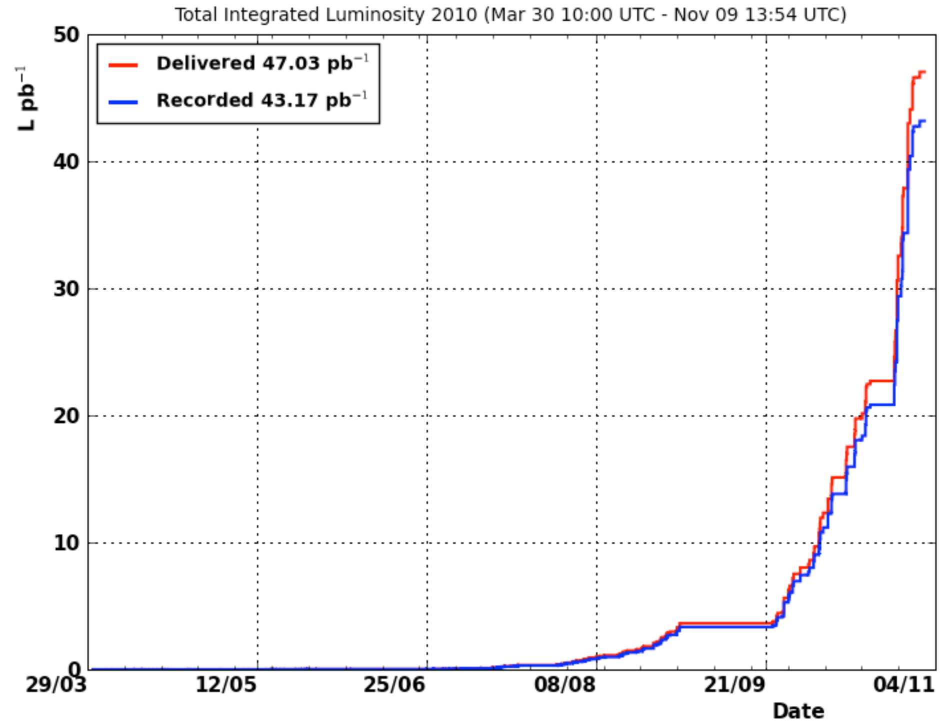


Data

- CMS recorded 43.17 pb^{-1} at $\sqrt{s}$ = 7 TeV in 2010
- Data recording efficiency exceeds 90%
- Only highest quality data used for physics analyses
- Results shown today use a partial sample:
  - April to July 2010
  - Corresponding to 198 nb^{-1}
- Publication based on 3 pb^{-1} in preparation



Phenomenology

M. Fairbairn et al, Phys. Rept. 438 (2007) 1-63

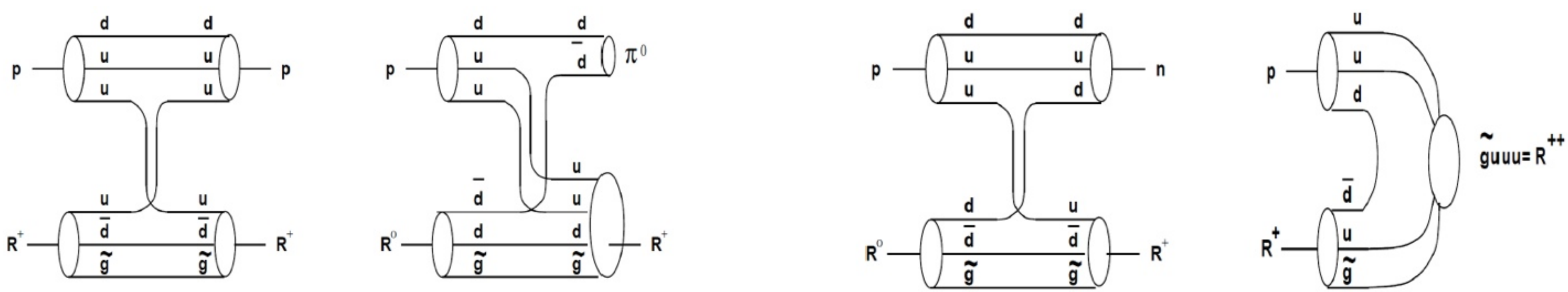
➢ Properties

- Very Heavy: O(100 GeV/c²) or more → In general non-relativistic
- cτ ~ O(m) or larger → Usually, do not decay in detector
- Have electric and/or strong charge

➢ Allowed by many models beyond SM (mGMSB, Split SUSY, MSSM,UED)

- In general, long lifetime is a consequence of a quantum number conservation
  → e.g. : SUSY with R-parity or UED with KK-parity
  → Heavier states could also be quasi stable if decay phase space is small
- If coloured, HSCP will hadronize and form an "R-Hadron"
  → Fraction of gluino-balls is a relevant unknown parameter from the experimental point of view.

Baryons $\tilde{g}qqq$, $\tilde{t}_1qq$
Mesons $\tilde{g}q\bar{q}$, $\tilde{t}_1\bar{q}$
Gluino-balls (pure neutral state) $\tilde{g}g$



Benchmark Models

- Lepton-like (tracker+muon analysis)
  - mGSMB staus on SPS Line 7 [100 - 300] GeV
    - PYTHIA
- R-Hadrons (tracker-only analysis)
  - Direct pair-production of stops
    - PYTHIA and MadGraph; K-factors from PROSPINO (NLO)
  - Direct pair-production of gluinos
    - PYTHIA, K-factors from PROSPINO (NLO+NLL)
- Masses: ~130 - 900 GeV
- Cross sections: $[10^{-3}, 10^{3}]$ pb
- Hadronization performed by PYTHIA
  - For gluinos : gluino-ball fraction = 10%
- R-Hadron interaction with matter simulated by Geant4

R.Mackeprang and A.Rizzi, Eur.Phys.J.C50 (2007) p.353

Cross Sections

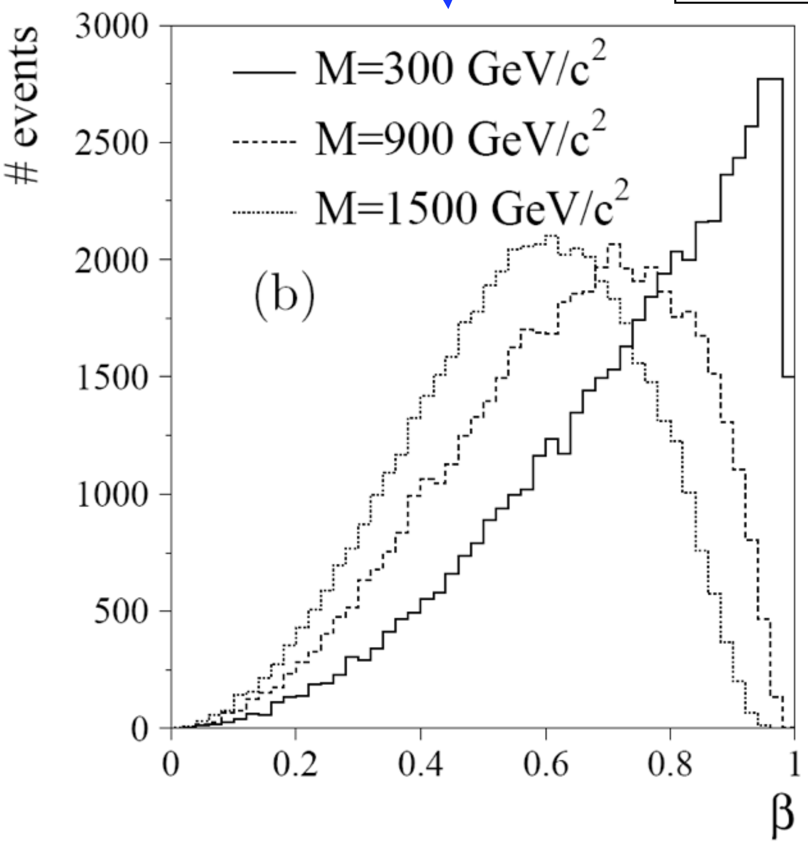
Theoretical Model	HSCP	Mass (GeV)	Expected Cross Section (Pb)		
			$\sqrt{s} = 14$ TeV	$\sqrt{s} = 10$ TeV	$\sqrt{s} = 7$ TeV
mGMSB	τ_1	156	$1.19 \times 10^{+0}$	3.60×10^{-1}	1.00×10^{-1}
mGMSB	τ_1	247	9.70×10^{-2}	3.00×10^{-2}	8.24×10^{-3}
mUED	τ_{kk}	300	2.15×10^{-2}	1.19×10^{-2}	5.70×10^{-3}
split SUSY	$\tilde{g}$	200	$2.20 \times 10^{+3}$	$9.22 \times 10^{+2}$	$3.27 \times 10^{+2}$
split SUSY	$\tilde{g}$	300	$1.00 \times 10^{+2}$	$9.89 \times 10^{+1}$	$2.77 \times 10^{+1}$
split SUSY	$\tilde{g}$	600	$5.00 \times 10^{+0}$	$1.09 \times 10^{+0}$	1.71×10^{-1}
split SUSY	$\tilde{g}$	900	4.60×10^{-1}	4.47×10^{-2}	3.94×10^{-3}
split SUSY	$\tilde{g}$	1200	6.10×10^{-2}	3.26×10^{-3}	1.69×10^{-4}
split SUSY	$\tilde{g}$	1500	1.00×10^{-2}	3.24×10^{-4}	1.11×10^{-5}
MSSM	$\tilde{t}_1$	130	$1.11 \times 10^{+3}$	$4.84 \times 10^{+2}$	$1.81 \times 10^{+2}$
MSSM	$\tilde{t}_1$	200	$1.77 \times 10^{+2}$	$6.92 \times 10^{+1}$	$2.22 \times 10^{+1}$
MSSM	$\tilde{t}_1$	300	$2.74 \times 10^{+1}$	$9.30 \times 10^{+0}$	$2.47 \times 10^{+0}$
MSSM	$\tilde{t}_1$	500	$1.27 \times 10^{+0}$	3.42×10^{-1}	6.39×10^{-2}
MSSM	$\tilde{t}_1$	800	7.80×10^{-2}	1.49×10^{-2}	1.56×10^{-3}

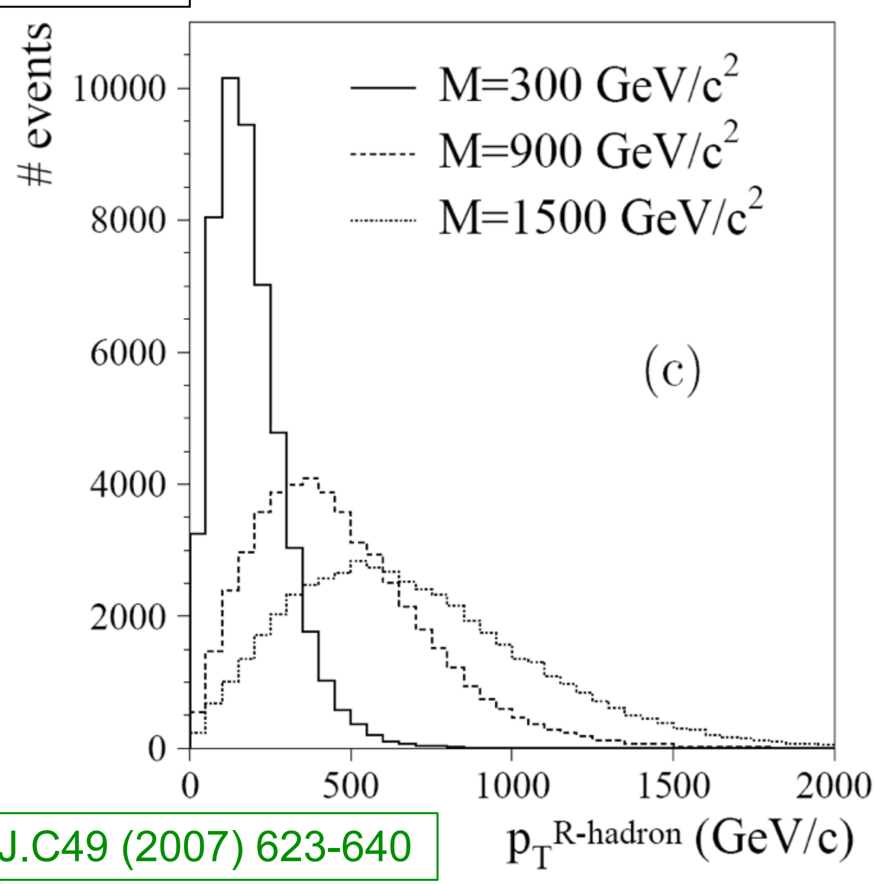
Cross sections up to ~300 pb @ 7TeV

Signature

Non-relativistic track with High Momentum

Gluino pair production from PYTHIA: R hadron p_T and β normalized differential distributions

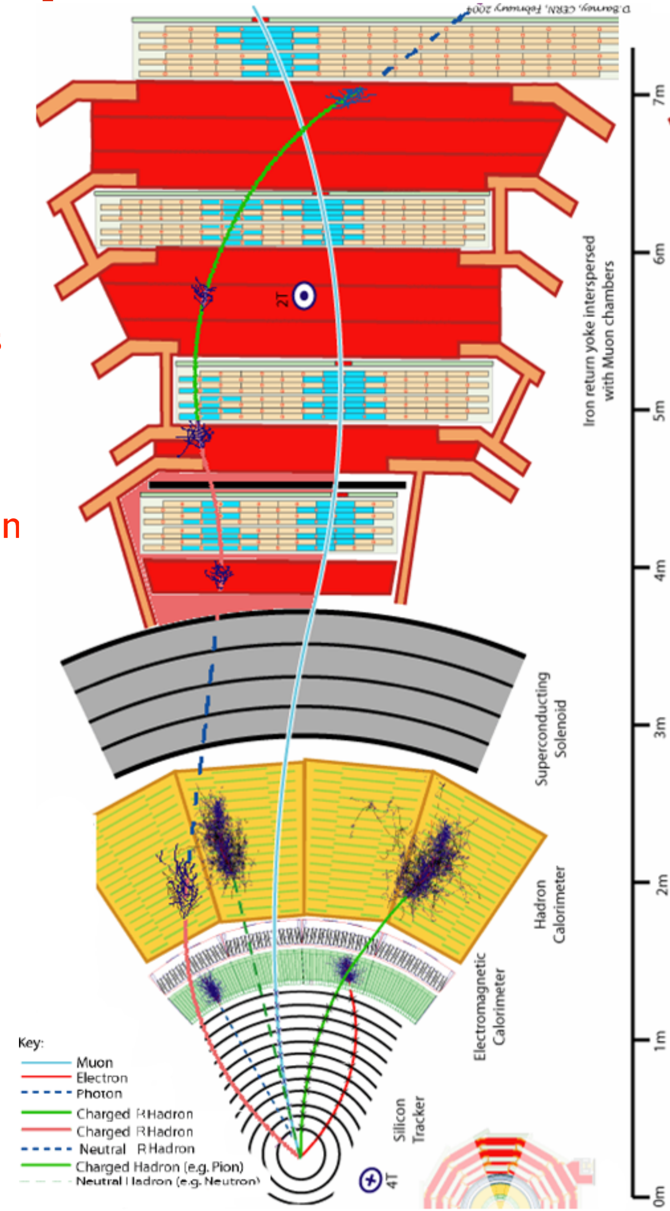




Eur.Phys.J.C49 (2007) 623-640

Detection Techniques

- Typical signature of an HSCP particle in CMS detector is quite similar to a muon with some differences:
  - Low velocity (β<1): so late arrival in outer detectors
  - Low velocity: so higher ionization compared to SM particles in the same momentum range
- Methods:
  - p measured from track bending in inner tracker/muon systen
  - β from
    - Energy loss in inner tracking system
    - Time of Flight in muon system (not used in this analysis)
  - m from p / ($\beta\gamma$c)
  - if m is heavier than any stable SM particle → HSCP
- Issues:
  - Neutral R-Hadrons will give no signal in the detectors
  - Charge flipping when suffering hadronic interactions (gluino or stop hadrons)
    - Makes tracking more difficult



Analysis Overview

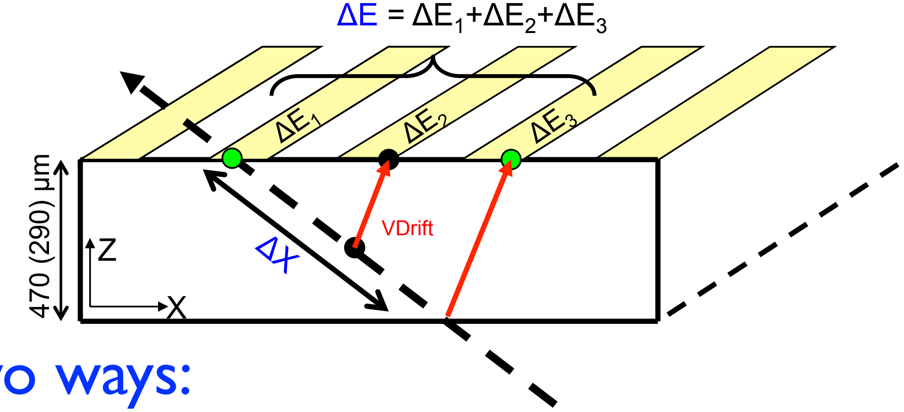
- Signature based search
  - look for high p_T tracks with high dE/dx
- Two analysis paths:
  - **Track+muon:**
    - Muon Id + dE/dx in silicon strip tracker
    - HSCP that get reconstructed as muons
    - Lepton-like and R-hadrons without charge suppression
  - **Track-only:**
    - dE/dx in silicon strip tracker
    - R-hadrons that become neutral, etc.
    - R-hadrons with charge suppression

Trigger Strategy

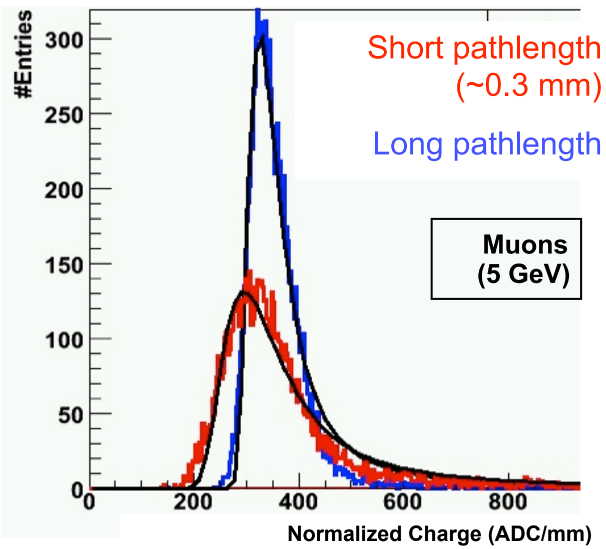
- Muon triggers:
  - Useful for most models
  - Efficiency depends on the HSCP mass and model
  - Very robust with respect to the p_T threshold
  - single μ: p_T > 3 GeV
  - double μ: p_T > 0 GeV
  - 15 - 45% efficiency for R-Hadrons (low mass-high mass)
  - >90% efficiency for staus
- Jet /Missing E_T triggers:
  - Useful for certain models (in particular for mGMSB)
  - Less sensitive to timing/β issues
  - Jet p_T > 30 GeV
  - MET > 45 GeV
  - 25 - 85% efficiency for R-Hadrons (low mass-high mass)
  - >60% efficiency for staus
- Combined trigger efficiency: >50% for R-Hadrons, >95% for staus

Ionization Energy Loss (I)

- Energy loss is measured in the Silicon Strip Tracker
  - ~O(10) ΔE/Δx measurements (with large statistical fluctuation)
  - can be combined to estimate the Most Probable ΔE/Δx



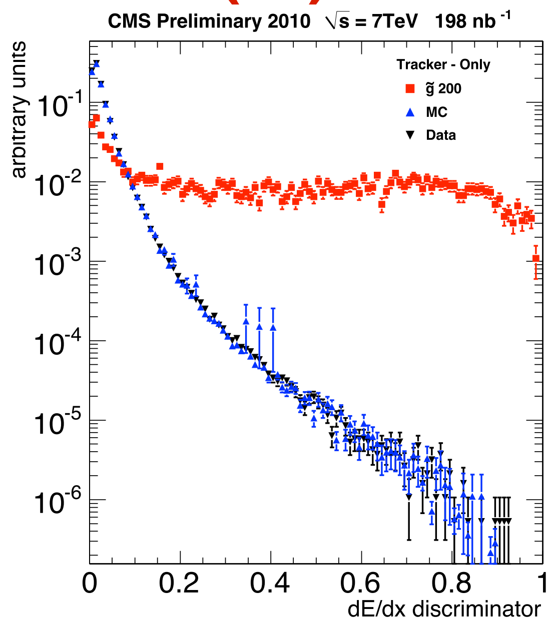
- Cluster charge interpreted in two ways:
  1. dE/dx discriminator
  2. dE/dx harmonic estimator
- Assume that all measurements are extracted from a unique Landau distribution
  - Need accurate strip detector inter-calibration

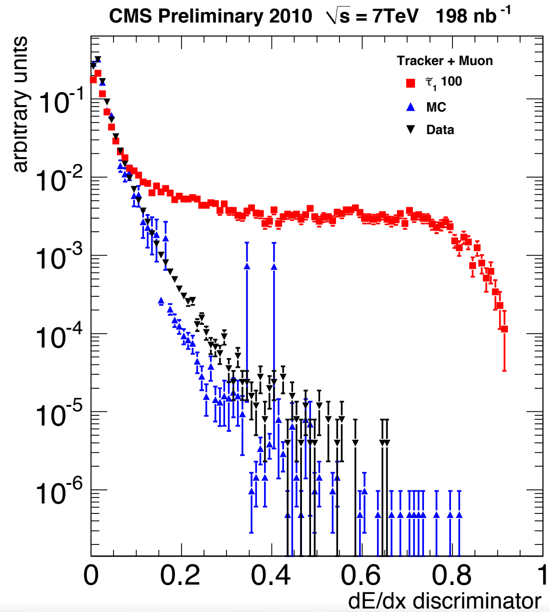


Ionization Energy Loss (II)

- dE/dx MPV estimator
  - Harmonic-2 estimator: $I_h = \left(\frac{1}{N}\sum_i c_i^k\right)^{1/k}$ with $k = -2$
  - Measuring ionization MPV to be used in HSCP mass reconstruction
- dE/dx discriminators
  - Full use of charge information
    - Tail prob. depends on the path-length
    - ADC cut-off
  - Optimal discrimination → candidate selection
  - Test statistic $f(P_h)$
    - P_h = Probability for a MIP to release as much or less charge than observed
    - Modified Smirnov-Cramer-von Mises:

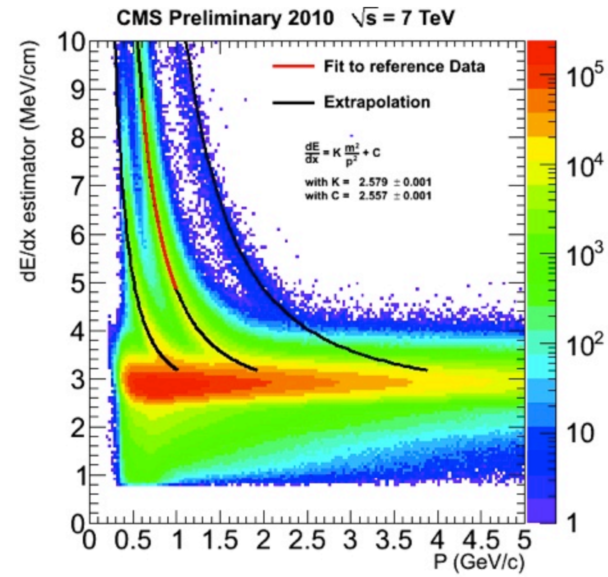
$$I_{as} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{i=1}^{N} \left[P_i \times \left(P_i - \frac{2i-1}{2N} \right) \right]^2 \right)$$





Mass Reconstruction (I)

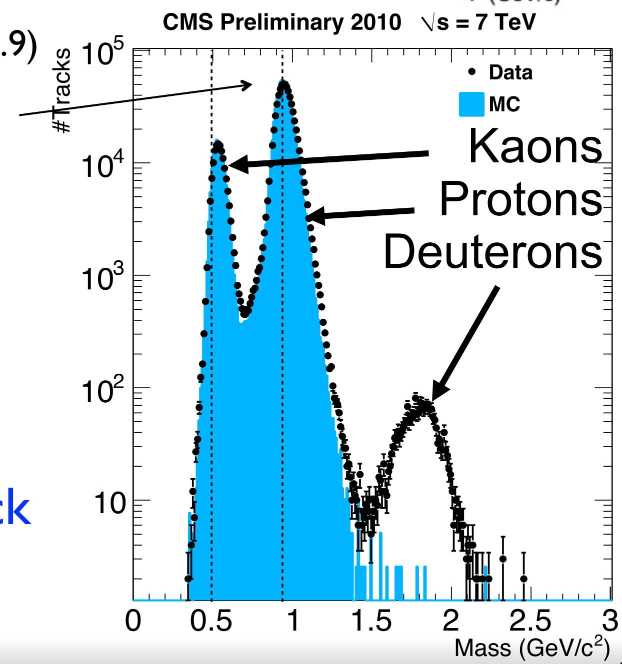
- Mass reconstruction tuned on high quality tracks from a minimum bias sample
  - $\geq$ 12 strip hits, good primary vertex
- dE/dx estimator



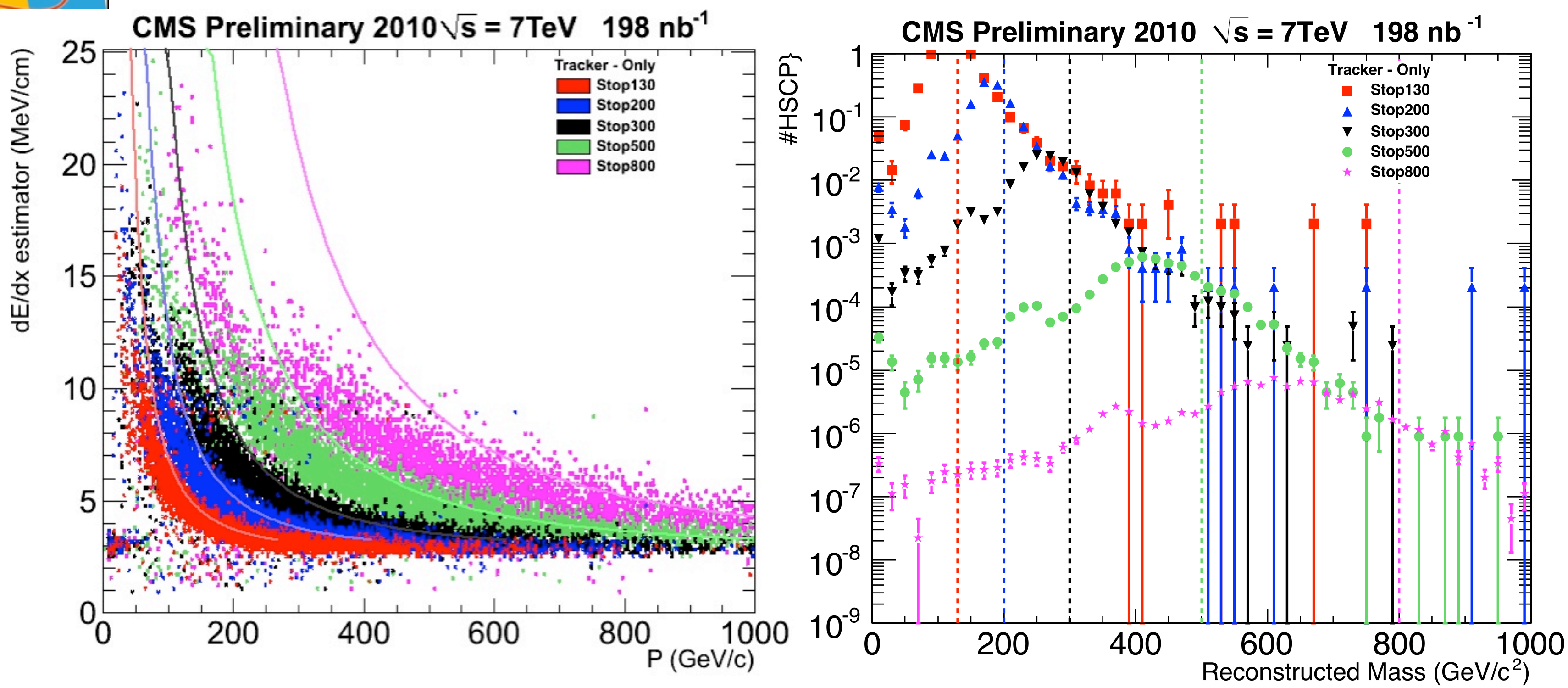
$$I_h = K\frac{m^2}{p^2} + C$$

(approximation of the Bethe-Bloch formula, good to 1% in the range $0.4<\beta<0.9$)

- *K* and *C* parameters extracted from proton mass line
  - K = 2.579 ± 0.001
  - C = 2.557 ± 0.001
- Approximate Bethe-Bloch Formula before minimum ($0.2<\beta<0.9$), few % agreement
- Reverse the relation to compute the mass of any track from dE/dx estimator and p



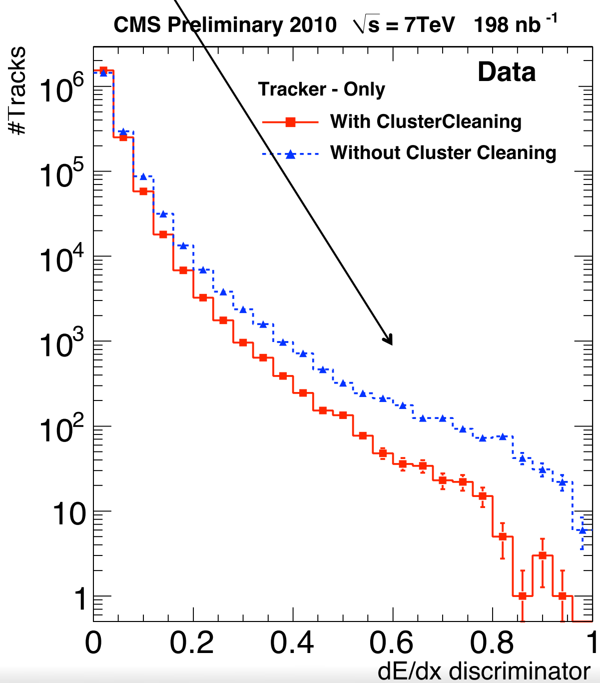
Mass Reconstruction (II)

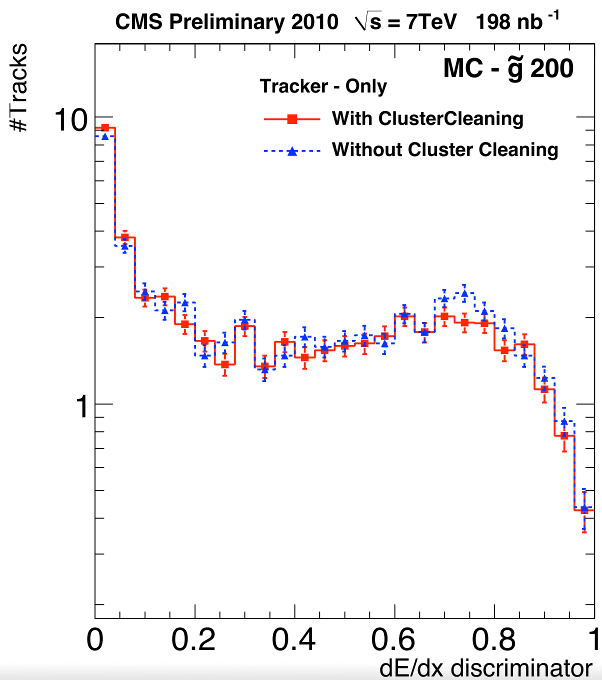


- At high masses the reconstructed is biased due to an due an ADC cut-off
- ADC Range is limited to [0,253] counts
    - 254 indicates a charge in [254,1023]
    - 255 indicates a charge above 1023
- Second peak at lower mass also due to this effect… (>1 strip saturating / cluster)
- **This effect has no impact on this analysis (counting experiment)**

Cluster Cleaning

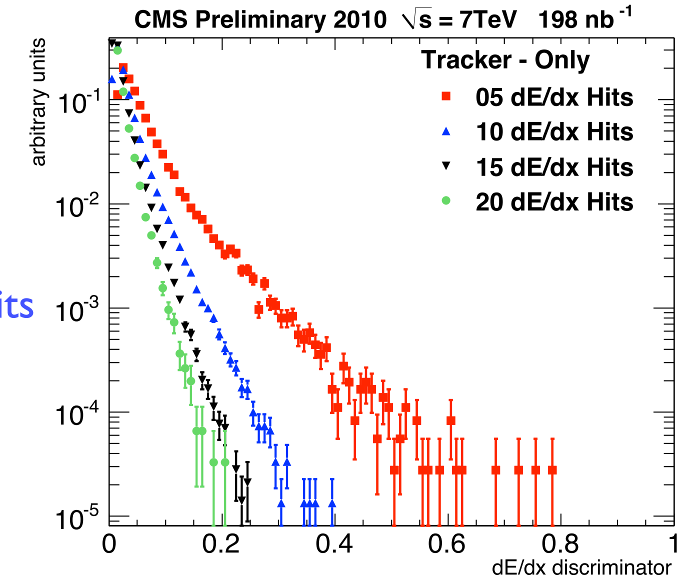
- Single tracks produce clusters distributed over 1-2 strips
- Cluster cleaning: discard clusters likely to be produced by overlapping tracks, nuclear interactions, etc.
  - multiple maxima from the dE/dx computation
  - >2 consecutive strips with comparable charge
- dE/dx tail (data) highly reduced
- No significant modification of the signal dE/dx distribution

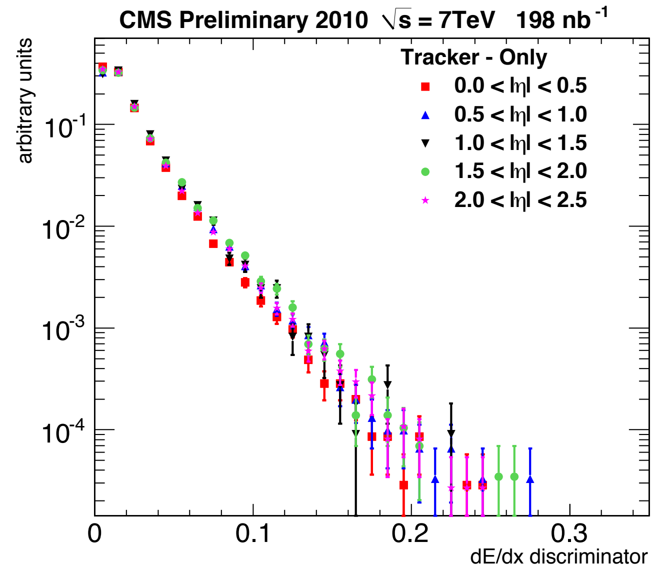


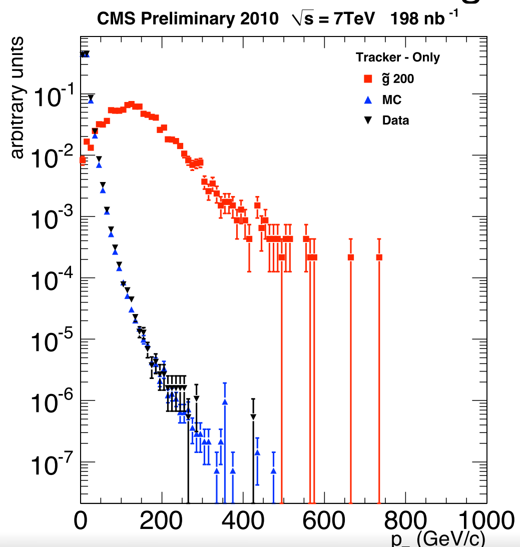


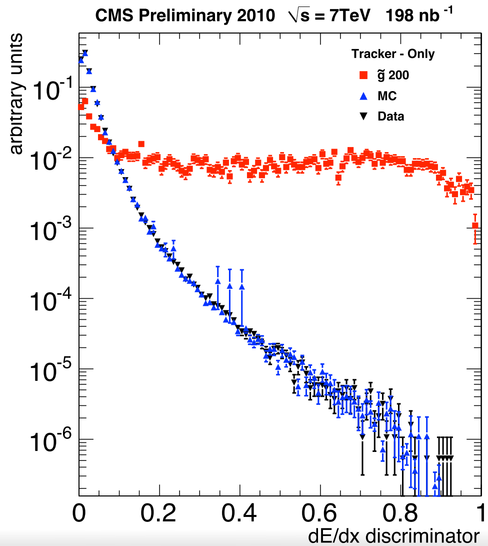
Event Selection

- Preselect tracks:
  - $p_T > 7.5$ GeV
  - $\delta p_T/p_T < 15\%$
  - Impact parameter: $|d_Z| < 2$ cm, $|d_{xy}| < 0.25$ cm
  - Number of dE/dx measurements: at least 3 Silicon Strips hits
- Apply cluster cleaning
- Split into subsamples by η and nHits
- Cut on p_T and dE/dx discriminator
- Tracker+Muon analysis:
  - Inner track from Global muons and Tracker muons
  - No inner track sharing allowed





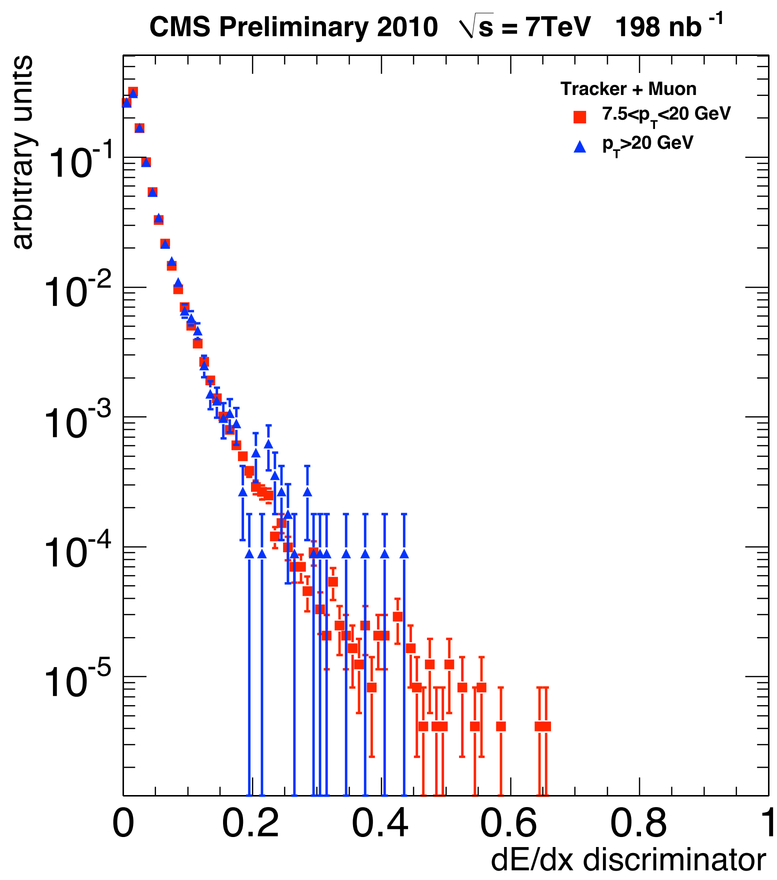


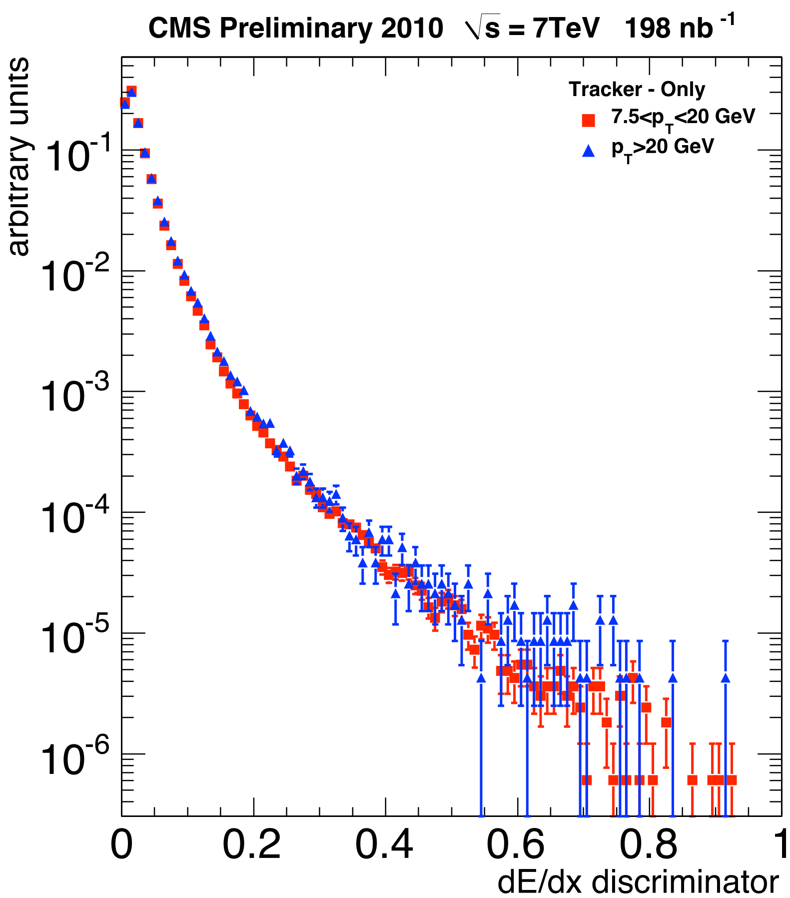


Cuts chosen per subsample

➔2x S/B ratio improvement

Background Estimation (I)

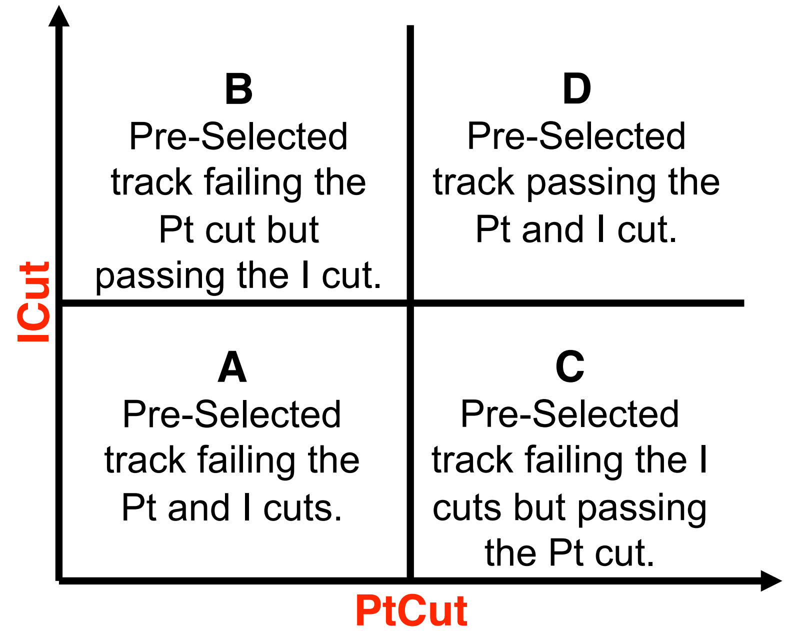




- dE/dx discriminator distribution for pre-selected tracks
  - Control ($7.5 < p_T < 20$ GeV) and signal-like samples ($p_T > 20$ GeV)
- No significant correlation between dE/dx and p_T

Background Estimation (II)

- Independence of p_T and dE/dx selection cuts allows a data-driven background estimation
  - Using ABCD method method to estimate background in the signal region
  - # entries in signal region D = (B*C)/A
  - Can also predict shape of mass distribution



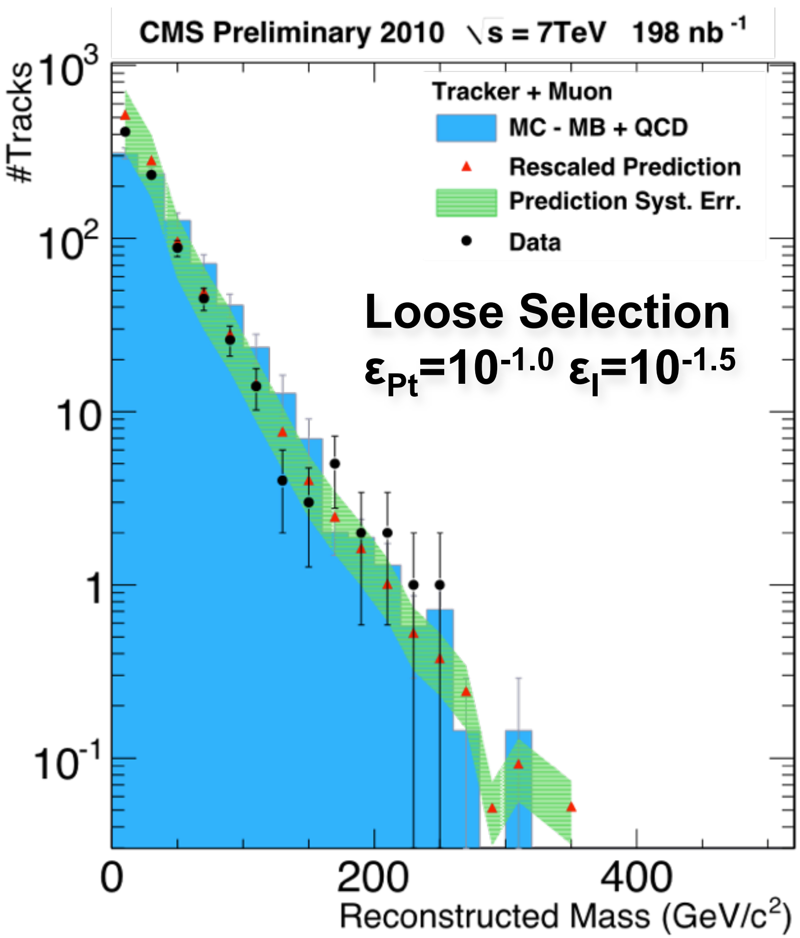
- Cut placement does not impact signal yield
  - optimize for constant background rejection across nHits and η subsamples
- Procedure is applied in every nHit/η sub-samples and results are combined
- Two sets of selections
  - Tight (signal search)
  - Loose (control sample)

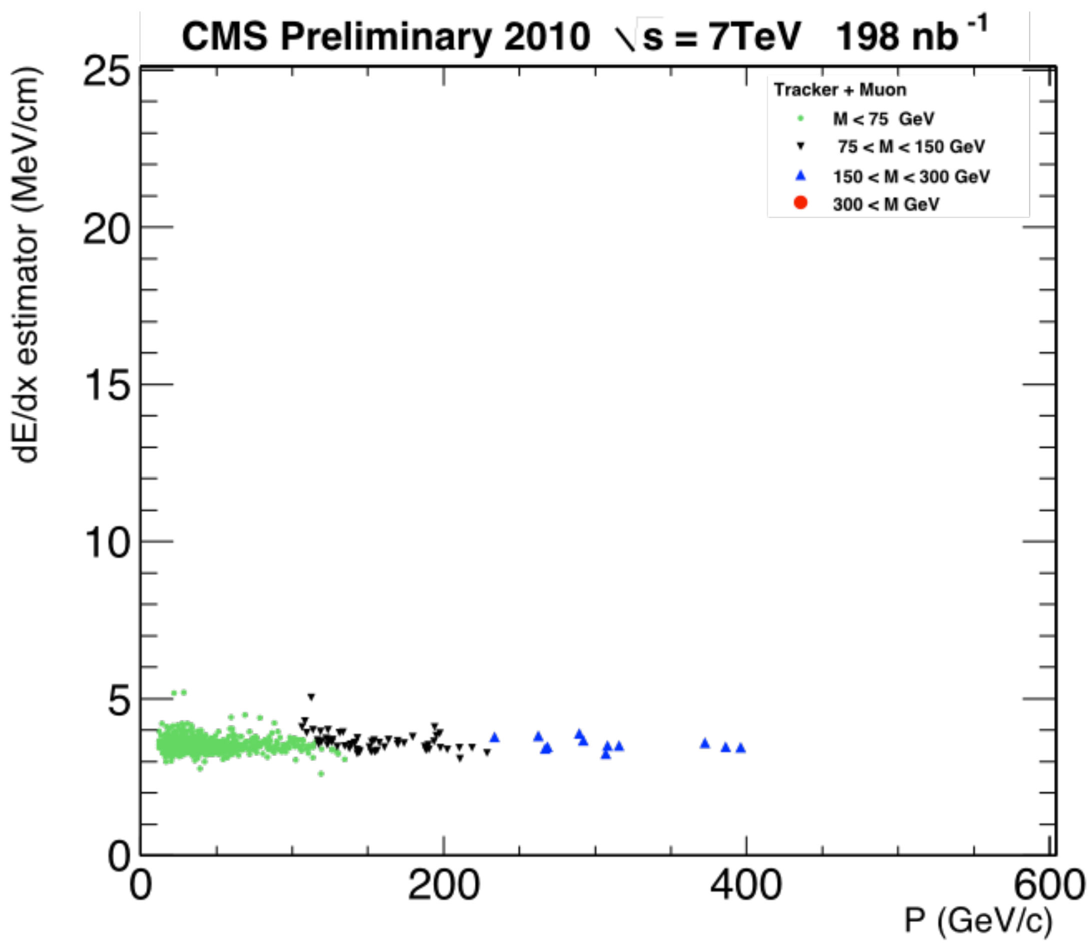
Tracker+Muon: Loose Selection

- Good agreement between data and MC

LOOSE	Exp.	Obs.	Exp. in full spectrum	Obs. in full spectrum
Tracker+Muon	82 ± 33	77	1007 ± 200	838
Tracker Only	108 ± 38	122	184 ± 250	260

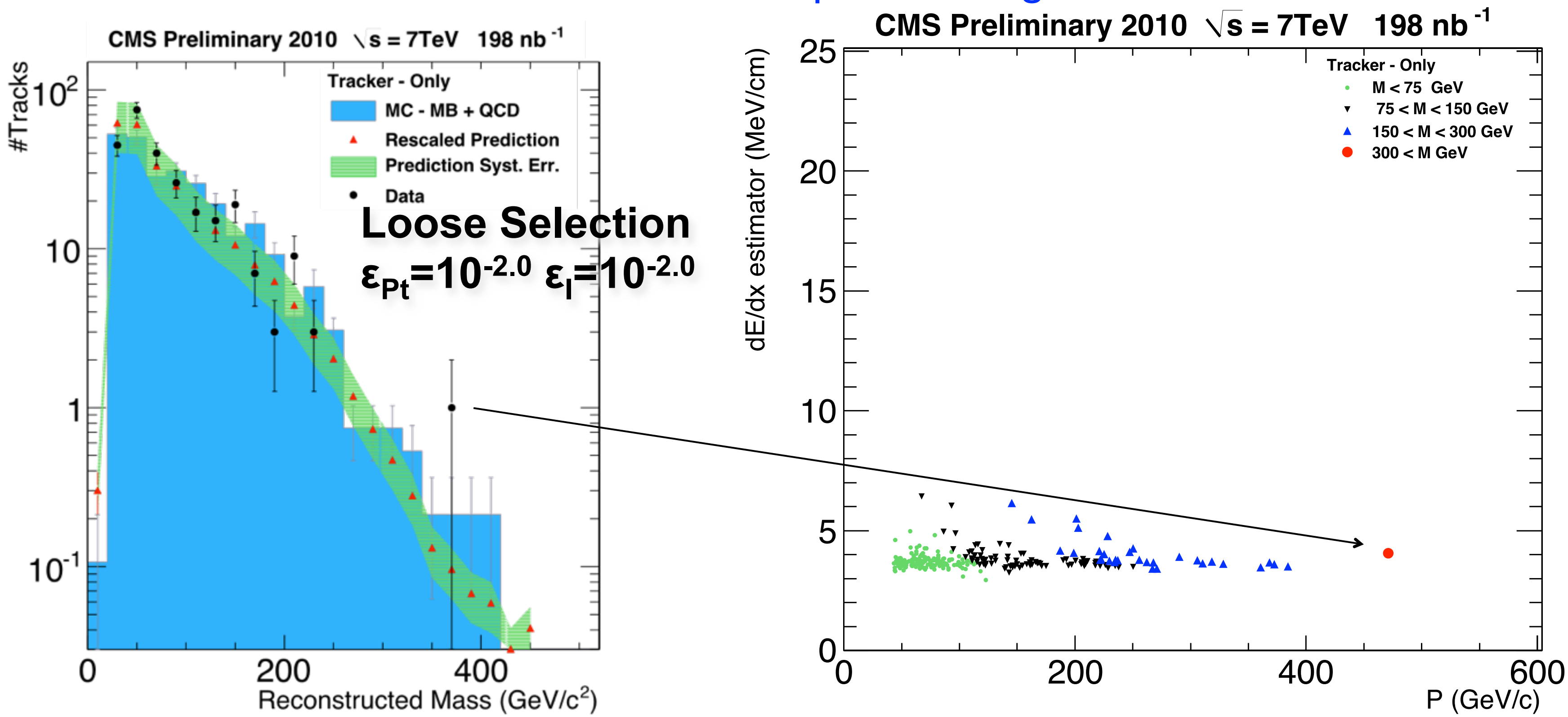
LOOSE	ϵ_{p_T}	p_T^{cut}	ϵ_I	I_{as}^{cut}
Tracker+Muon	$10^{-1.0}$	7.7 - 25.9	$10^{-1.5}$	0.0036 - 0.4521
Tracker only	$10^{-2.0}$	7.9 - 67.4	$10^{-2.0}$	0.0037 - 0.5293





Tracker-Only Loose Selection

- High mass (M>300) candidate have a relatively small ionization and a large momentum, not a strong candidate
- All points with $I_h > 5$ MeV/cm are small tracks (<5 hits) at high eta, with generally few of their SiStrip clusters having at least one saturating strip
- None of them are real candidates, but well expected background



Search Strategy

- Define a mass region for signal search: [75,1200] GeV
- Choose optimal selection from data-driven background prediction (~0.05 events) and simulated signal samples
- Count events in signal region
- If compatible with expected background, set 95% C.L. upper limit on cross section for benchmark signals

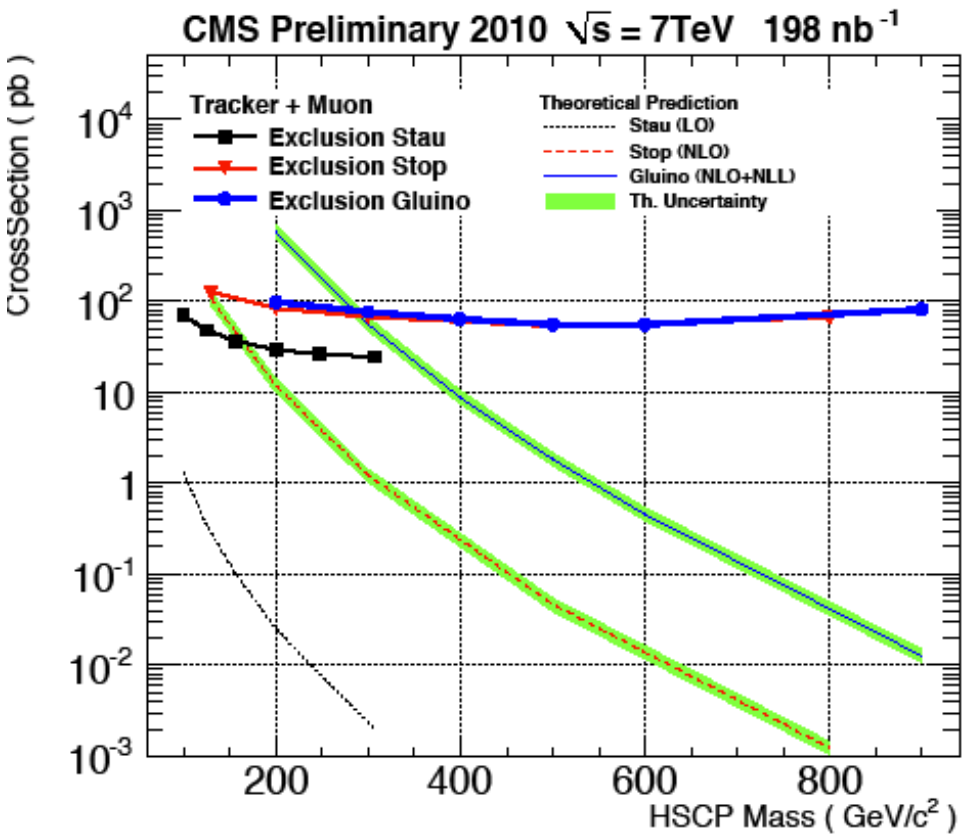
- Statistical methods
  - Full Bayesian method with lognormal prior for integration over nuisance parameters
- Signal region:
  - ~0.05 events expected for both analyses
  - No events are observed for chosen selections

Systematics

- Search performed as a counting experiment in the reconstructed mass range of 75 - 1200 GeV
- 95% C.L. limits computed with a fully Bayesian method with lognormal prior for nuisance parameter integration; assuming zero expected background events

Source of Systematic Error		Relative Uncertainty (%)
Theoretical cross section		15
Expected background		36(Tk) ; 40 (Tk+Mu)
Integrated luminosity		11
Trigger efficiency	Signal Acceptance	15
Muon reconstruction efficiency	Signal Acceptance	5
Track reconstruction efficiency	Signal Acceptance	< 5
Momentum scale	Signal Acceptance	< 5
Ionization energy loss scale	Signal Acceptance	< 3 (8 for 100 GeV$/c^2$ $\tilde{\tau}_1$)
Total uncertainty on signal acceptance		20

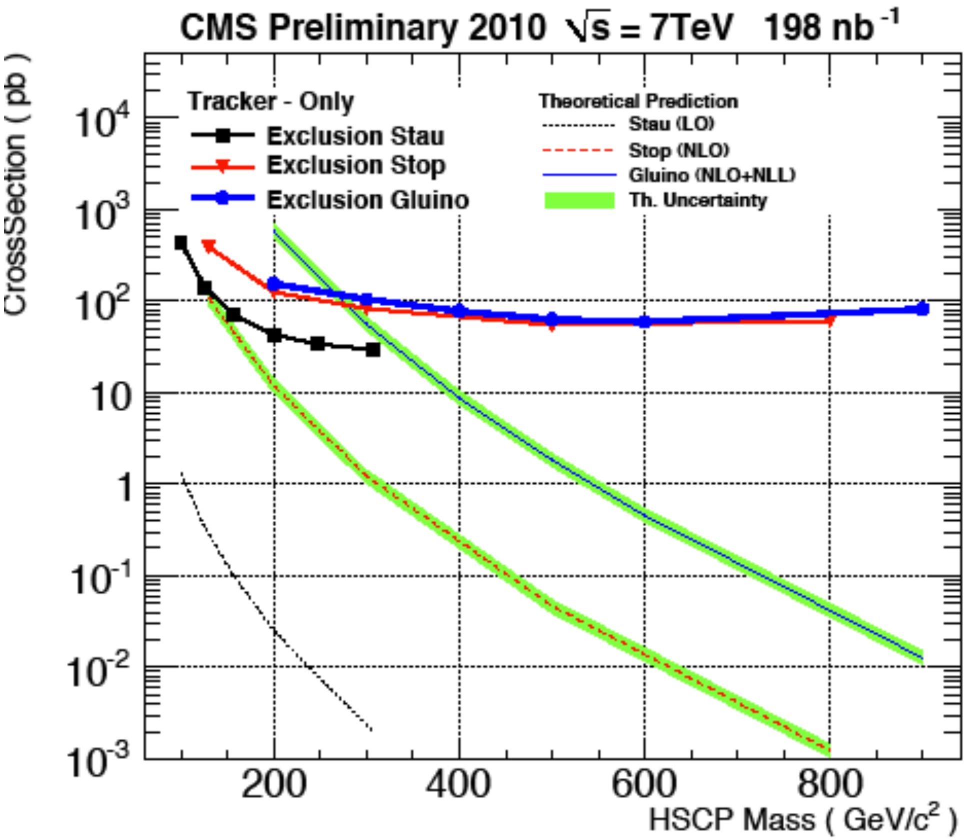
Tracker+Muon Results



gluino mass (GeV/c^2)	200	300	400	500	600	900
Total acceptance (%)	17	21	25	29	29	20
Expected 95% C.L. limit (pb)	106	84	69	60	60	89
Observed 95% C.L. limit (pb)	98	77	64	56	52	83
Theoretical cross section (pb)	606	57.2	8.98	1.87	0.46	0.013
stop mass (GeV/c^2)	130	200	300	500	800	
Total acceptance (%)	12	19	24	30	25	
Expected 95% C.L. limit (pb)	139	91	74	58	72	
Observed 95% C.L. limit (pb)	128	85	68	53	67	
Theoretical cross section (pb)	109	11.9	1.23	0.047	0.00123	
stau mass (GeV/c^2)	100	126	156	200	247	308
Total acceptance (%)	23	34	44	55	63	67
Expected 95% C.L. limit (pb)	76	53	40	32	28	27
Observed 95% C.L. limit (pb)	70	49	37	30	26	25
Theoretical cross section (pb)	1.32	0.33	0.105	0.025	0.008	0.002

- Gluino masses **< 284 GeV/c²** are excluded (under 15% TH-uncertainty hypothesis)
- Systematic errors already incorporated in Cross-Section limits

Tracker-Only Results



gluino mass (GeV/c^2)	200	300	400	500	600	900
Total acceptance (%)	11	16	21	26	28	20
Expected 95% C.L. limit (pb)	161	109	81	66	61	85
Observed 95% C.L. limit (pb)	156	105	78	63	59	83
Theoretical cross section (pb)	606	57.2	8.98	1.87	0.46	0.013
stop mass (GeV/c^2)	130	200	300	500	800	
Total acceptance (%)	4	13	20	29	27	
Expected 95% C.L. limit (pb)	409	131	87	57	63	
Observed 95% C.L. limit (pb)	395	127	84	55	61	
Theoretical cross section (pb)	109	11.9	1.23	0.047	0.00123	
stau mass (GeV/c^2)	100	126	156	200	247	308
Total acceptance (%)	4	12	23	38	48	56
Expected 95% C.L. limit (pb)	461	146	74	45	35	31
Observed 95% C.L. limit (pb)	445	141	72	43	34	29
Theoretical cross section (pb)	1.32	0.33	0.105	0.025	0.008	0.002

- Gluino masses **< 271 GeV/c^2** are excluded (under 15% TH-uncertainty hypothesis)
- Systematic errors already incorporated in Cross-Section limits

Conclusions

- Search for both hadron- and lepton-like HSCP performed in CMS with 198 nb^{-1} of 7 TeV LHC data
- Signature-based analysis looking for highly ionizing, high momentum tracks in the Silicon Tracker
- Two versions of the analysis, with and without the requirement of having the track identified as a muon in the Muon System
- Obtained 95% C.L. limits on benchmark model cross sections
- Tracker-only analysis excluded Gluino masses below 284 GeV/c^2 under the 15% theoretical uncertainty hypothesis
- Tracker-muon analysis excluded Gluino masses below 271 GeV/c^2 under the 15% theoretical uncertainty hypothesis