First Results from the Searches for Stopped Gluinos and Heavy Stable Charged Particles in pp collisions at 7 TeV

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Motivation & Overview

- Many new physics scenarios predict heavy long-lived particles
  - Some flavours of SUSY predict long lived stau, gluino, stop
  - Hidden valley models, certain GUTs
  - Lifetimes around 100-1000s are of particular interest in cosmology
    - **May explain the ^{6}Li, ^{7}Li abundance discrepancy** between measurement and conventional nucleosynthesis
- These particles may be strongly interacting and form bound states with quarks/gluons - "R-hadrons"

- If charged, these particles will lose energy as they traverse the detector
  - Slow moving heavy particles **will lose energy at a greater rate than a MIP**
  - Some fraction of particles **will stop altogether**

- Results from two complementary search methods are presented here
  - Searching for tracks with **anomalously high dE/dx**
  - Searching for **decays of particles that have stopped** in the detector
  - Stopped particle search more sensitive to low β (< 0.3), dE/dx method more sensitive at moderate β (>0.3)

- Both methods offer high sensitivity with the early LHC data

Search for Heavy Stable Charged Particles

- Attempt to identify the HSCP as it moves through the detector
  - Looking for an excess of tracks with **high p_t, high dE/dx**

- HSCP will be highly penetrating and identified as a muon
  - R-hadrons undergo nuclear interactions, and may change charge/flavour
  - Some models of R-hadron interactions **predict they become neutral and remain so**

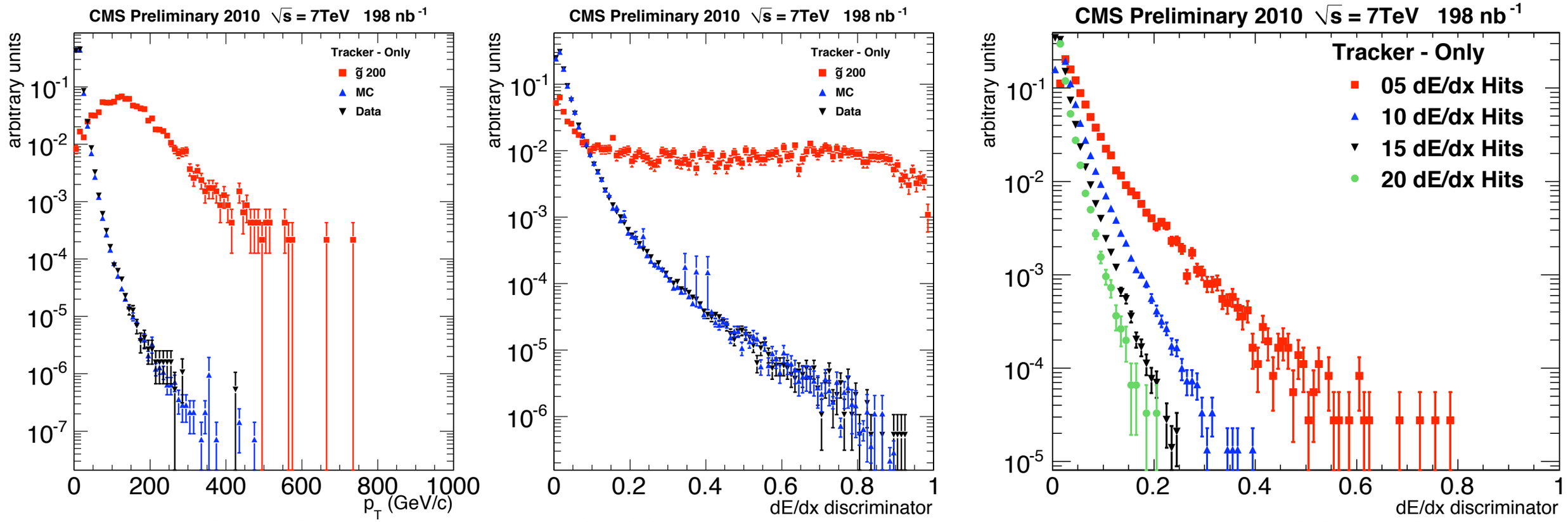
referred to later as "Neutral R-baryon" model

- Perform two analyses
  - Track+muon - for muon-like HSCP
  - Track-only - for non muon-like HSCP

- Benchmark signals
  - Track+muon => mGMSB stau (100-300 GeV)
  - Track only => stop & gluino R-hadron (130-900 GeV), with "Cloud model" of R-hadron interactions

- Triggers
  - For muon-like HSCP, use muon triggers (muon > 3 GeV, double muon > 0 GeV)
  - For non muon-like HSCP, trigger on other products of the event (jet > 50 GeV, E_t^{miss} > 45 GeV)

HSCP Selection

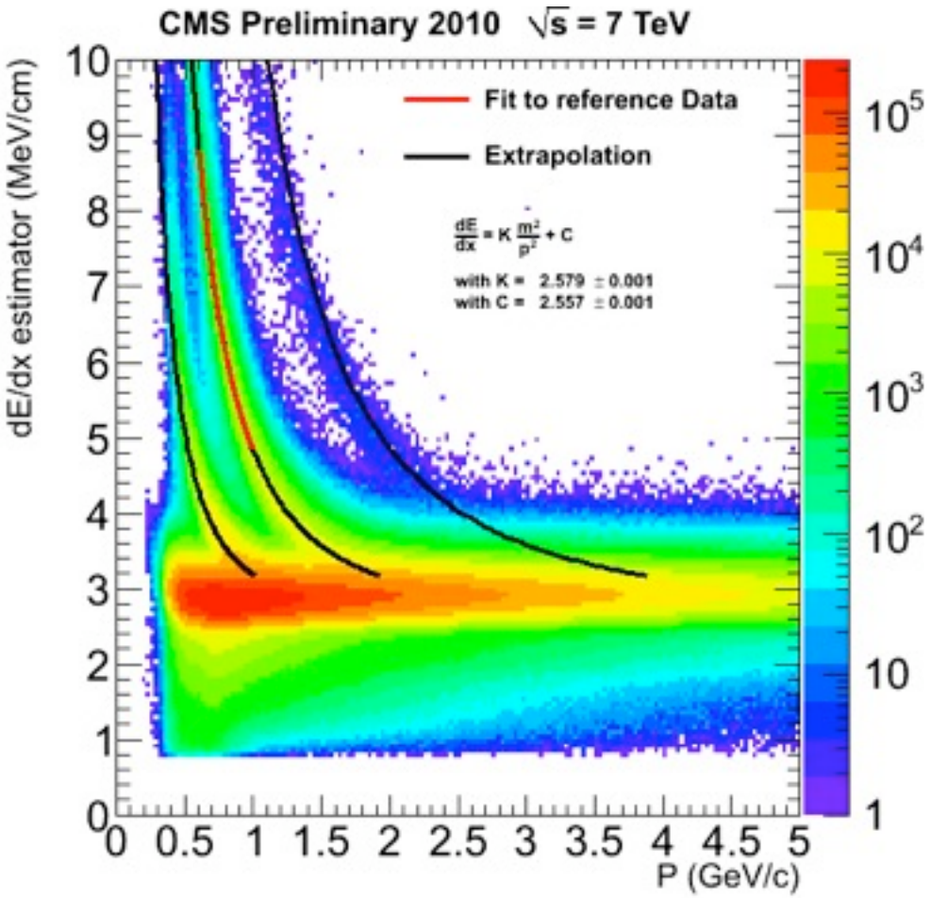


p_t distribution *dE/dx discriminator* *...binned by #hits*

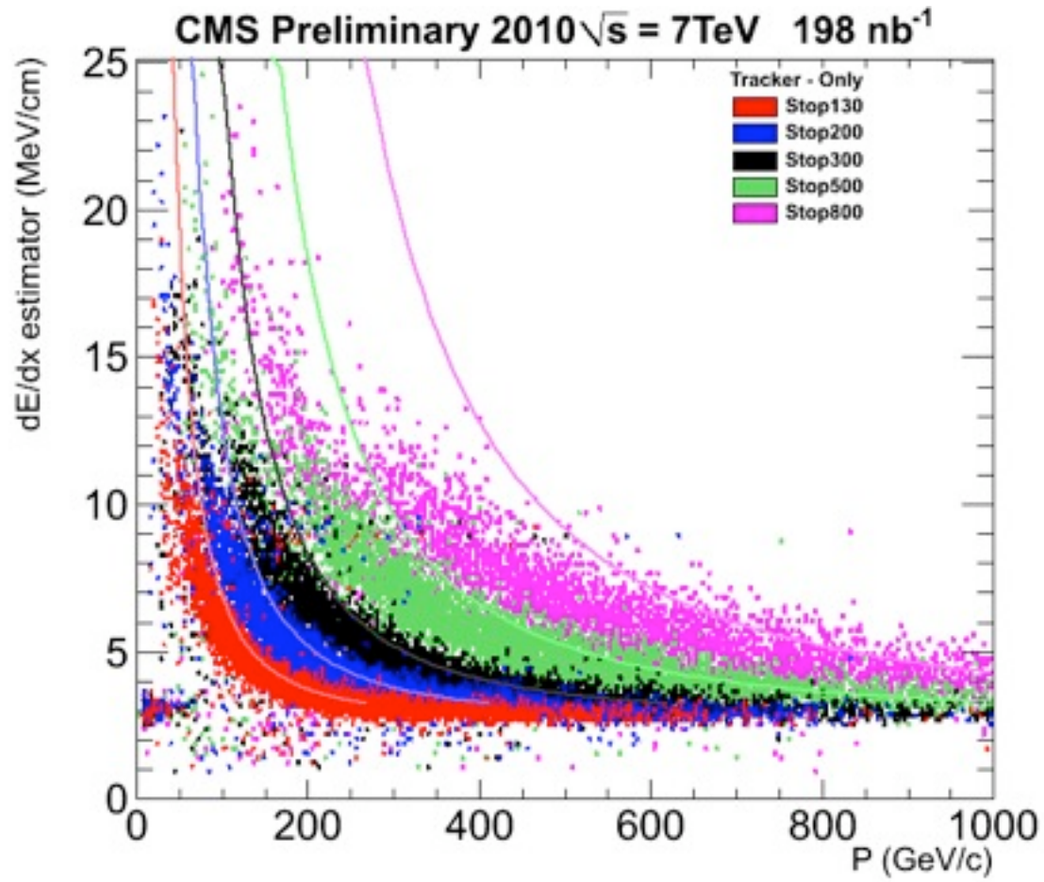
- Select tracks with high p_t and dE/dx
  - Use a discriminator for dE/dx based on measured energy loss for MIPs
  - Good discrimination, and MC-data agreement in both variables
- Analysis is performed in bins of η and N_{hits}
  - Thresholds set separately for each bin to give a uniform background rejection
  - Important for tracks with few hits;
  - **Important for R-hadrons which may change charge**

Improves S/B by factor 2 at current luminosity

Mass Reconstruction

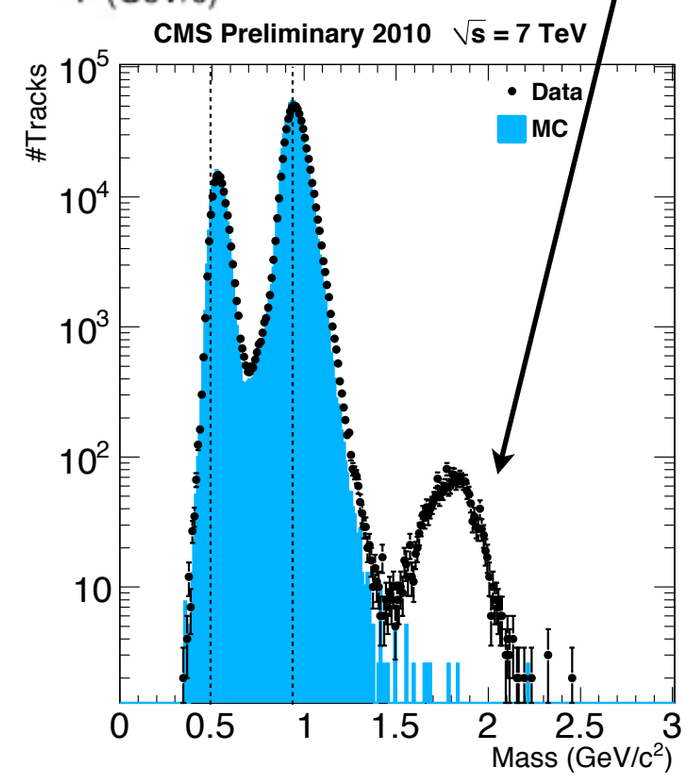


min-bias data



...and stop MC

Discovery of the deuteron!



- Mass reconstruction
  - Approximate Bethe-Bloch formula before minimum

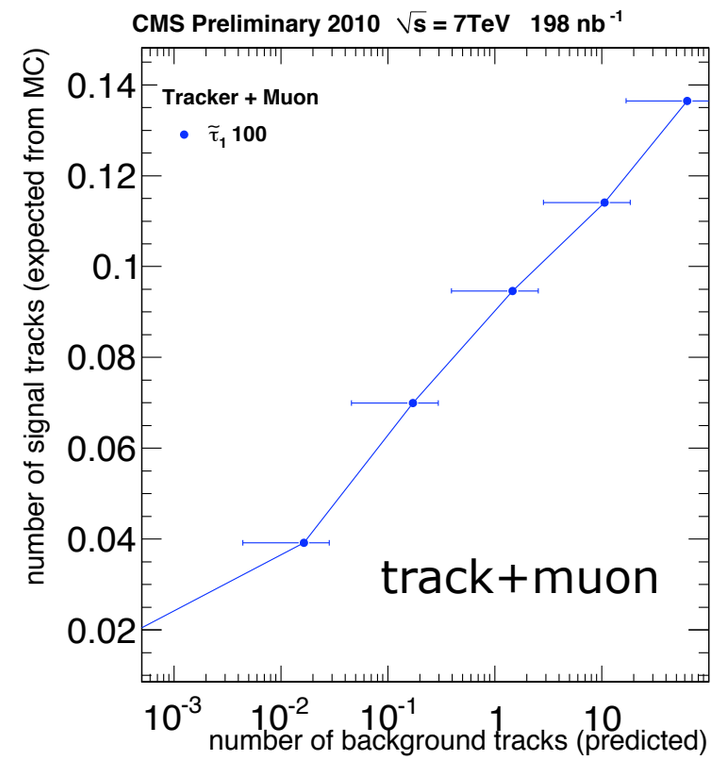
$$I_h = K\frac{m^2}{p^2} + C$$

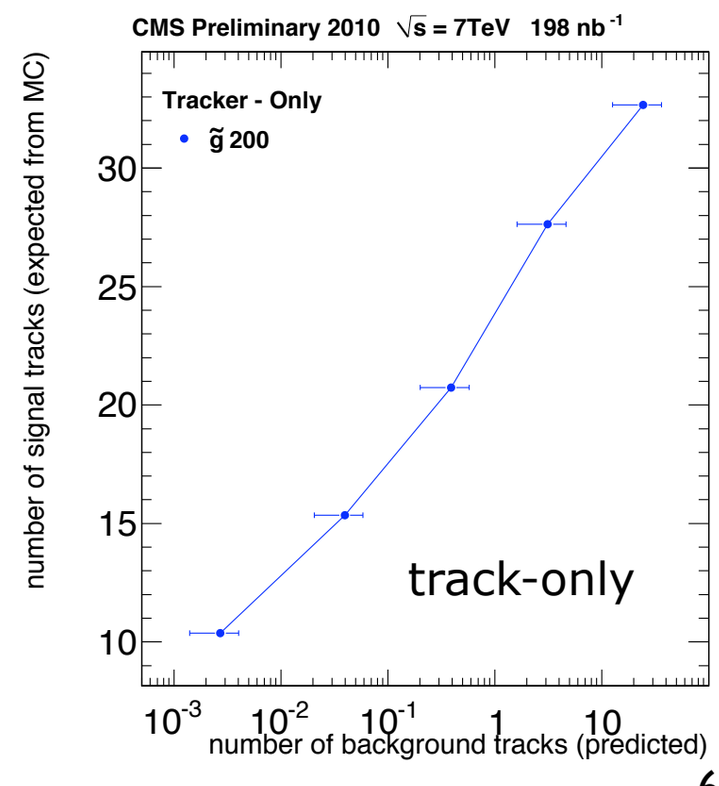
  - Extract parameters K, C by fitting to the proton line
  - Reverse to compute higher masses

Search Procedure

- Perform a counting experiment in the mass range 75-1200 GeV/c2 using 198 nb^{-1} data
  - Summing over bins in η, N_{hits}
  - Background for each bin determined from data using an "ABCD" method + (data-determined) correction
- Signal efficiency does not depend strongly on threshold (see right)
  - Optimise thresholds to yield desired background
- Define a tight selection for the search
- And a background enriched selection for cross-checks

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
TIGHT	ϵ_{p_T}	p_T^{cut}	ϵ_I	I_{as}^{cut}
Tracker+Muon	$10^{-3.0}$	7.7 - 125.9	$10^{-3.0}$	0.0036 - 0.6526
Tracker only	$10^{-4.0}$	7.9 - 259.0	$10^{-3.5}$	0.0037- 0.8901



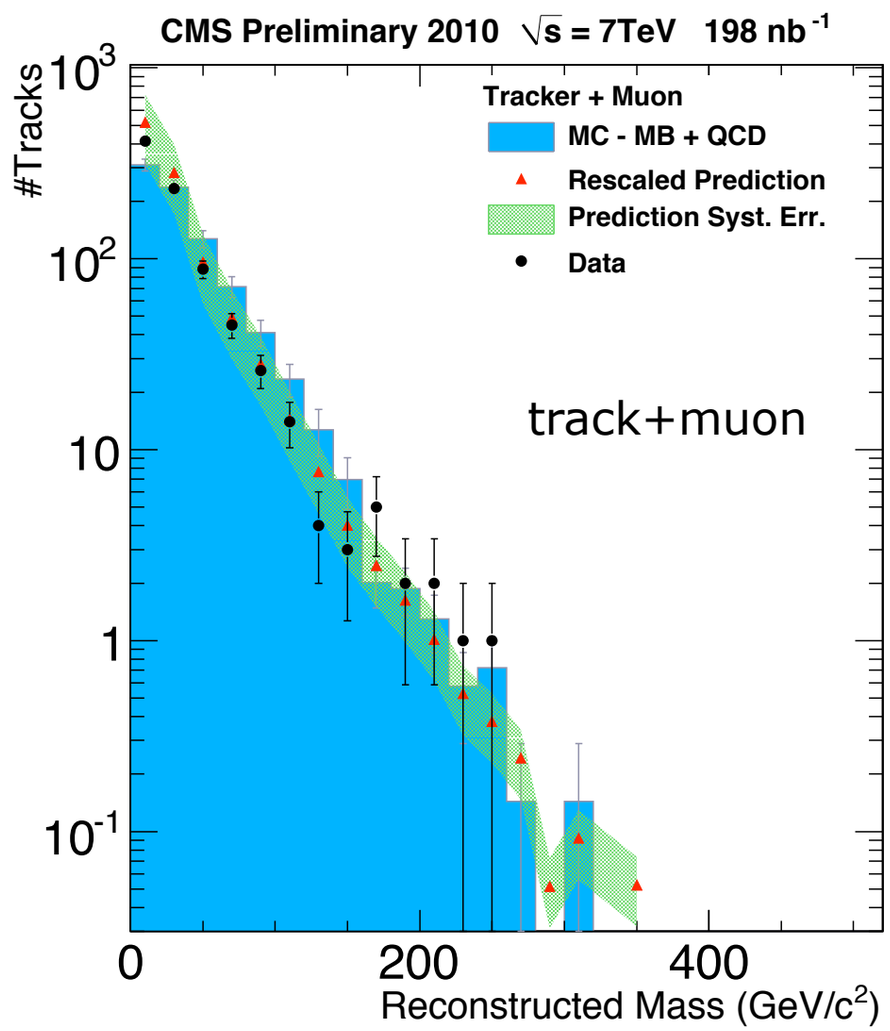


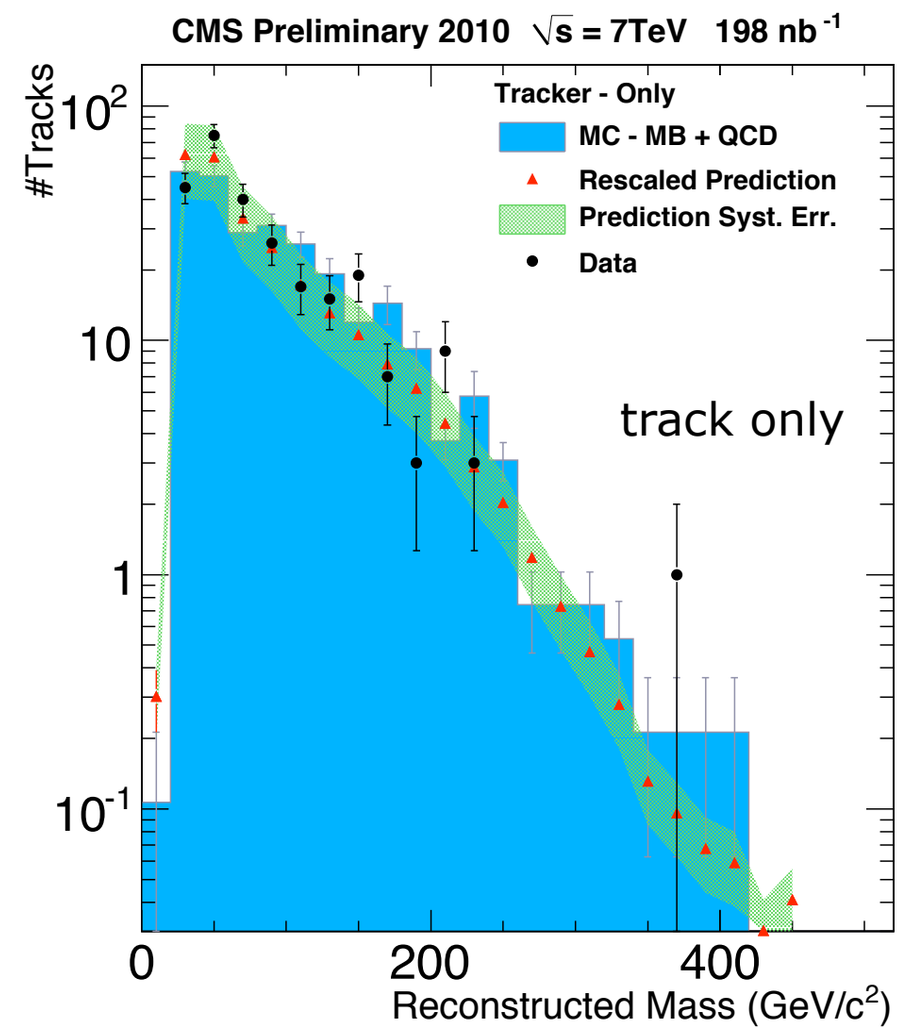
Background-Enriched Selection

- Good agreement between expected background and observation
- Both in event counts :

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

- And in mass distribution :



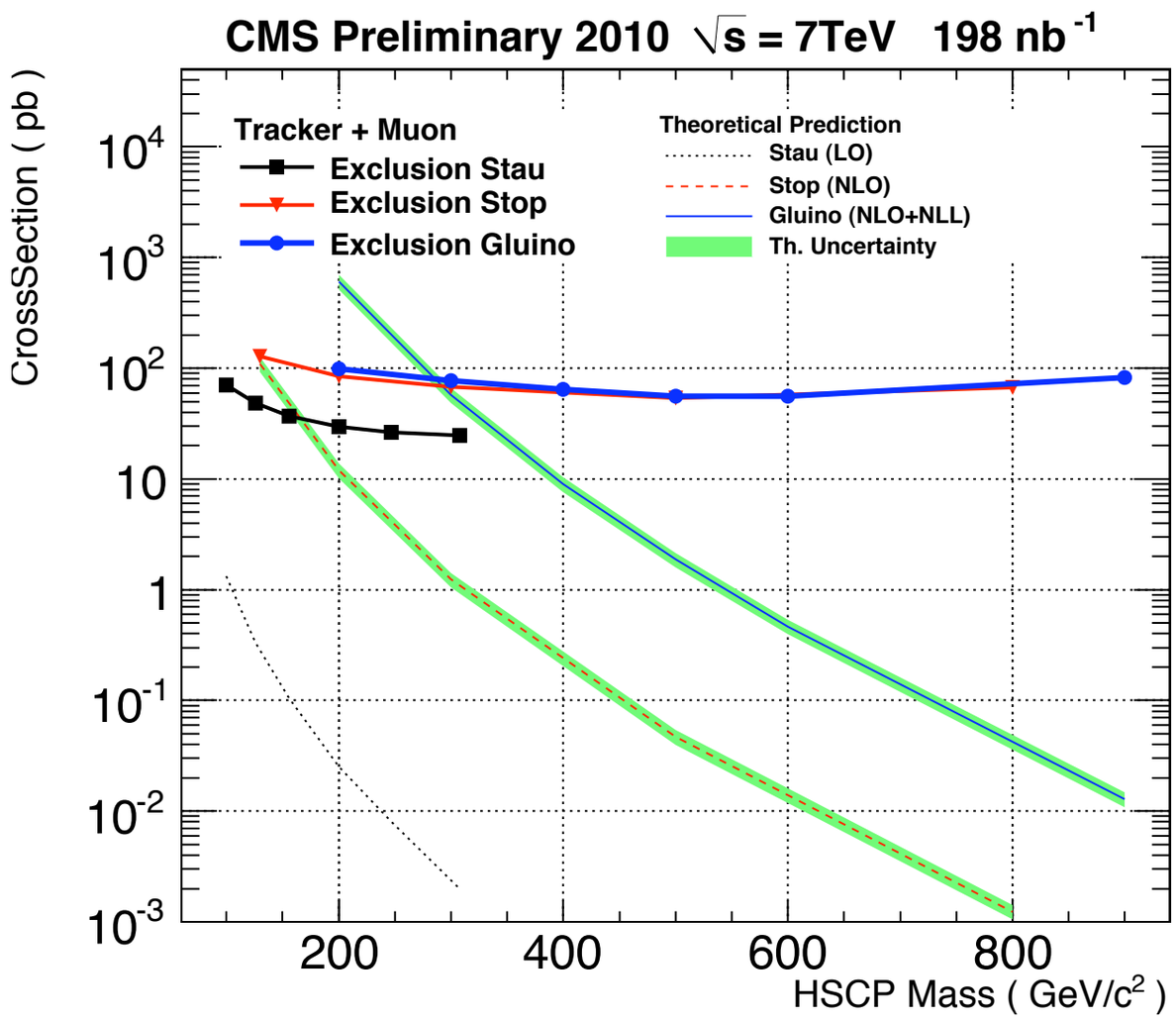


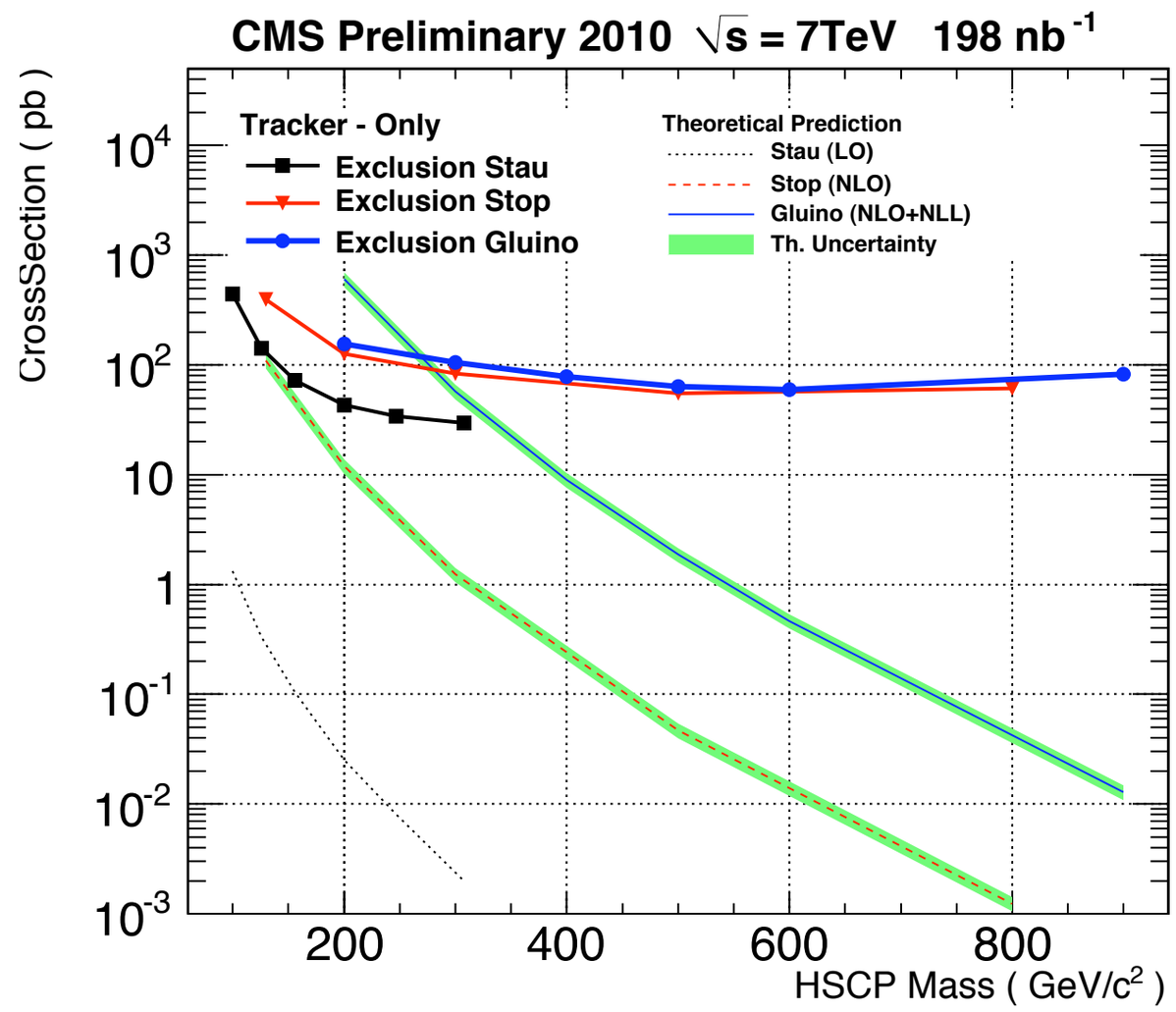
Search Results

- Null result in signal region and full mass spectrum

TIGHT	Exp.	Obs.	Exp. in full spectrum	Obs. in full spectrum
Muon-like	0.153 ± 0.061	0	0.249 ± 0.050	0
Tk-only	0.060 ± 0.021	0	0.060 ± 0.011	0

- 95% CL limits on the production cross-section for stau, stop and gluino
  - Track-only analysis => **exclude $m_{\tilde{g}} < 271$ GeV/c^2**
  - Track+muon analysis => **exclude $m_{\tilde{g}} < 284$ GeV/c^2**

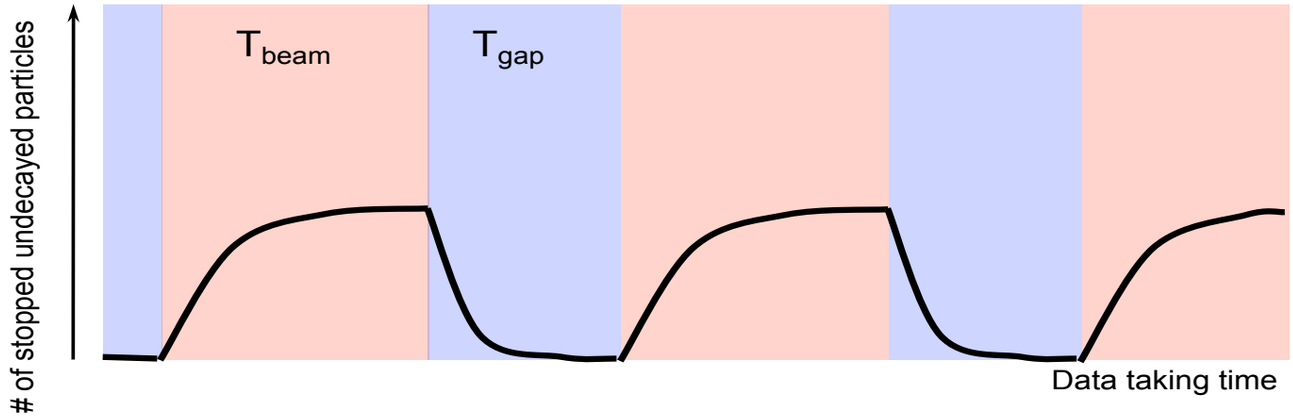




Search for Stopped Gluinos

- This is a highly unorthodox search, for the decays of long-lived particles that have stopped in the detector

- Use a dedicated calorimeter trigger to search during periods when **no collisions are expected**
  - In gaps between filled bunches during an LHC fill, and between LHC fills (not used yet)
  - Trigger includes a no-beam condition using beam position and timing monitors (BPTX)

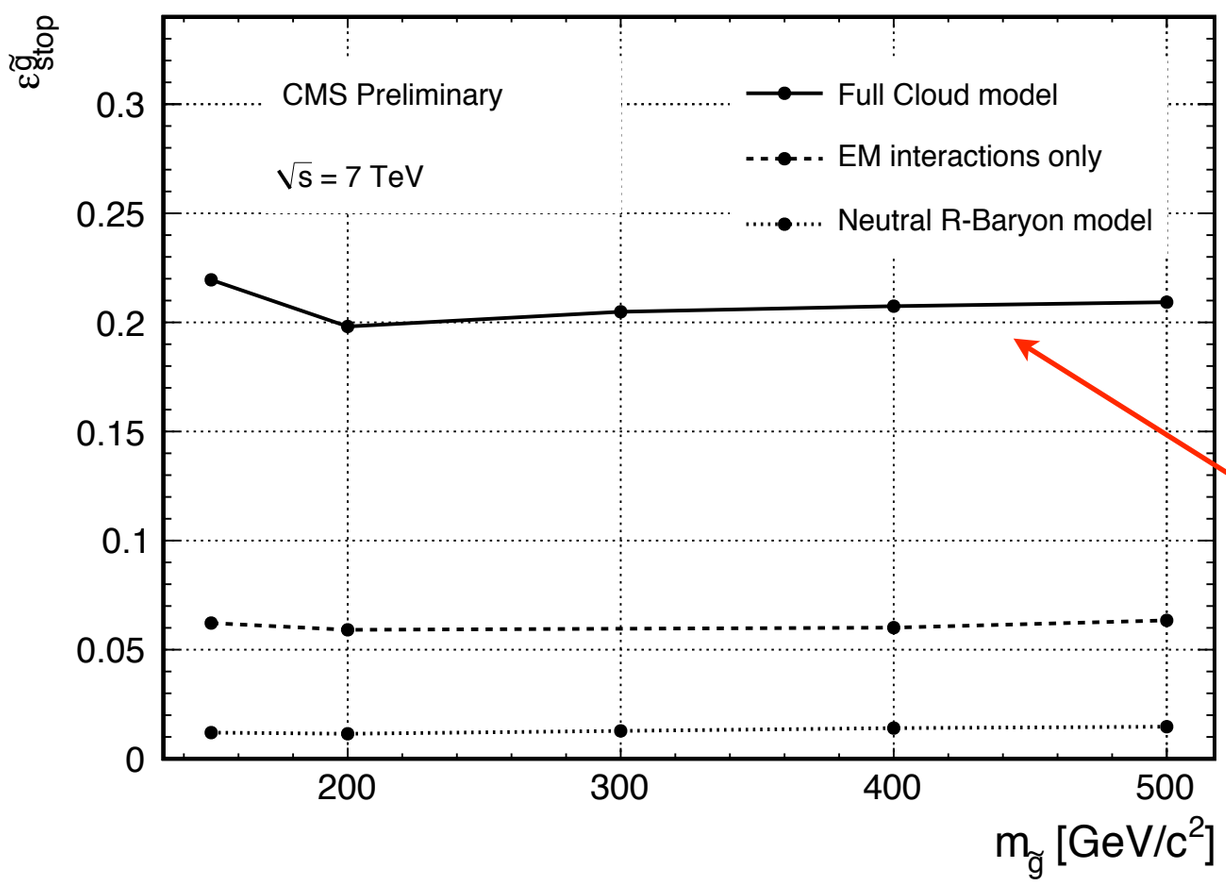


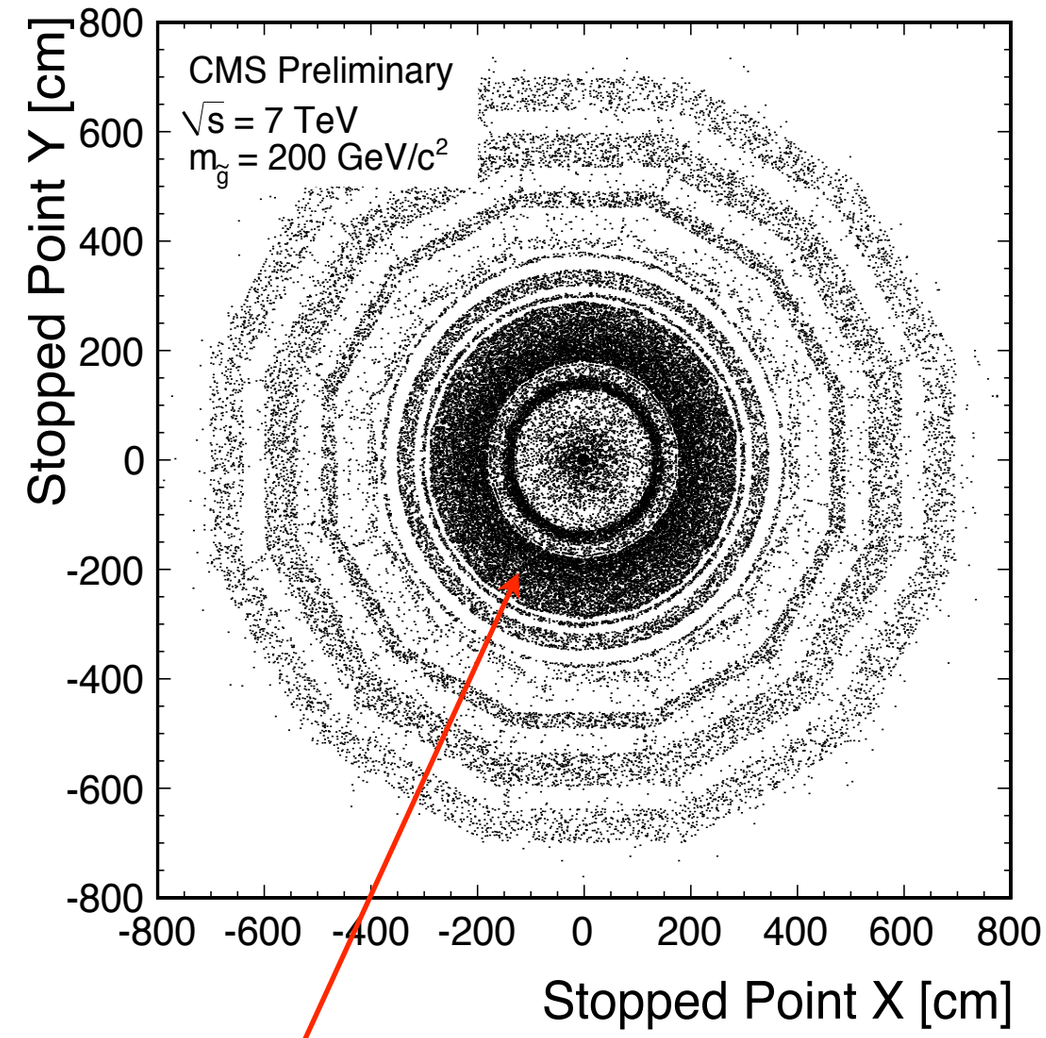
- Observation of a signal during these periods will be an **unambiguous sign of BSM physics**

- **Analysis started in 2008/2009** with background measurements
  - CMS-PAS-EXO-09-001

Simulation

- Solve the problem of simulating long lifetimes by factorising into 3 phases :
  1. R-hadron production, interaction with detector, and map stopping points
  2. Decay stopped R-hadron and simulate interaction of decay products with detector
  3. Simulate time of production (based on *delivered* luminosity profile), time of decay and calculate "time acceptance"





We search in CMS HCAL

~20% probability for an R-hadron to stop somewhere in CMS

Event Selection

- Backgrounds : instrumental effects, cosmic rays, out of time beam triggers
- Cosmic & noise background originally measured with 2008 cosmic data
  - Confirmed with 2009 cosmic data, 2009/2010 collision data
  - Selection to reject these backgrounds **unchanged since 2009 public note**

- Beam backgrounds observed in 900 GeV and 7 TeV data
  - Mostly **early collision triggers** (but potentially also beam halo, beam-gas, parasitic collisions)
  - Reject this by vetoing events within +/-1 BX of passage of beam through CMS

Beam background rejection

Cosmic rejection

Jet topology cuts

Calorimeter pulse shape cuts

Selection Criteria	Background Rate (Hz)
L1+HLT (HB+HE)	3.27
Calorimeter noise filters	1.12
BPTX/BX veto	1.11
muon veto	6.6×10^{-1}
$E_{jet} > 50$ GeV, $\lvert\eta_{jet}\rvert < 1.3$	7.6×10^{-2}
$n_{60} < 6$	7.6×10^{-2}
$n_{90} > 3$	3.1×10^{-3}
$n_{phi} < 5$	1.3×10^{-4}
$R_1 > 0.15$	1.1×10^{-4}
$0.1 < R_2 < 0.5$	8.5×10^{-5}
$0.4 < R_{peak} < 0.7$	7.9×10^{-5}
$R_{outer} < 0.1$	6.9×10^{-5}

Rates measured in low lumi 7 TeV collision runs ($2\text{-}7 \times 10^{27}$ cm^{-2}s^{-1})

Signal efficiency ~17% (of all R-hadrons that stop anywhere in CMS)

Counting Experiment

- Perform a counting experiment in bins of lifetime, τ
  - For small τ, select events in a window 1.256 x τ after each collision
- We divide the collision data into two sets :
  - The first, low lumi, set is used to measure the background rate
  - Then perform the search in the second, high lumi, set
    - L_{int} = 203 (232) nb^{-1} recorded (delivered)
- Observed counts compatible with background expectation

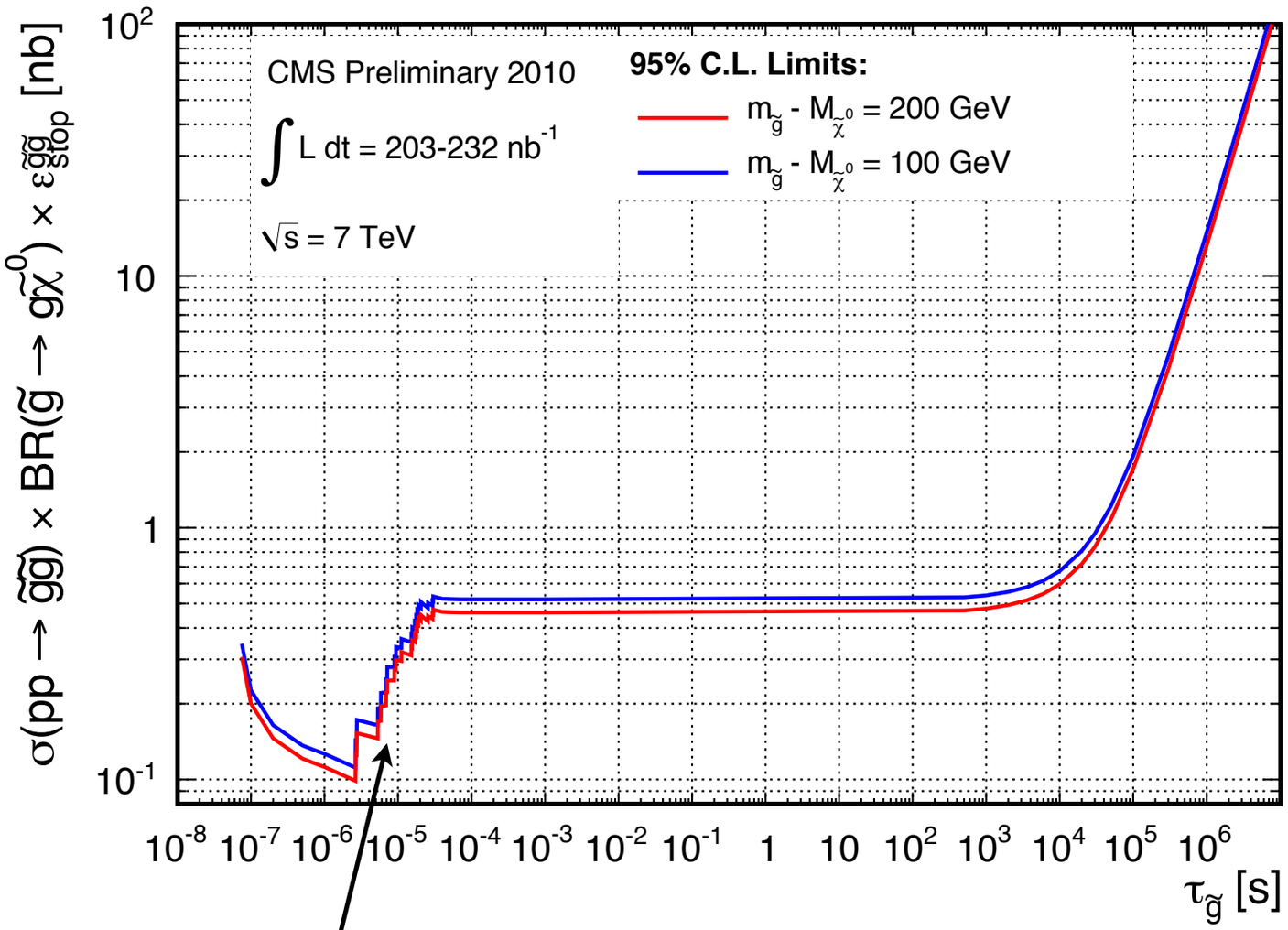
Lifetime [s]	Expected Background (± stat ± syst)	Observed
1e-07	$0.15 \pm 0.04 \pm 0.05$	0
1e-06	$1.8 \pm 0.5 \pm 0.5$	0
1e-05	$11.7 \pm 3.2 \pm 3.5$	8
1e-04	$28.3 \pm 7.8 \pm 8.5$	19
1e-03	$28.3 \pm 7.8 \pm 8.5$	19
1e+03	$28.3 \pm 7.8 \pm 8.5$	19
1e+04	$28.3 \pm 7.8 \pm 8.5$	19
1e+05	$28.3 \pm 7.8 \pm 8.5$	19
1e+06	$28.3 \pm 7.8 \pm 8.5$	19

- Can then calculate a cross-section, given the integrated luminosity
  - Potentially **sensitive to lumi delivered when CMS was not running**!
  - Use the delivered lumi profile + Toy MC, to calculate this

Model-Independent Result

- First result is a limit on cross-section x stopping probability
  - Independent of the model for interactions with matter
- τ < few 100 ns
  - Decays occur during vetoed BXs
- $\tau < T_{orbit}$ (~10^{-4} s)
  - Decays occur within the orbit, but we optimise the time window
- $T_{orbit} < \tau < T_{fill}$ (~10^{4} s)
  - Accept events over the full orbit - sensitivity plateau
- $\tau > T_{fill}$
  - Lose sensitivity as increasing fraction of decays occur post-fill

Cross-section x stopping probability



14 orders of magnitude !

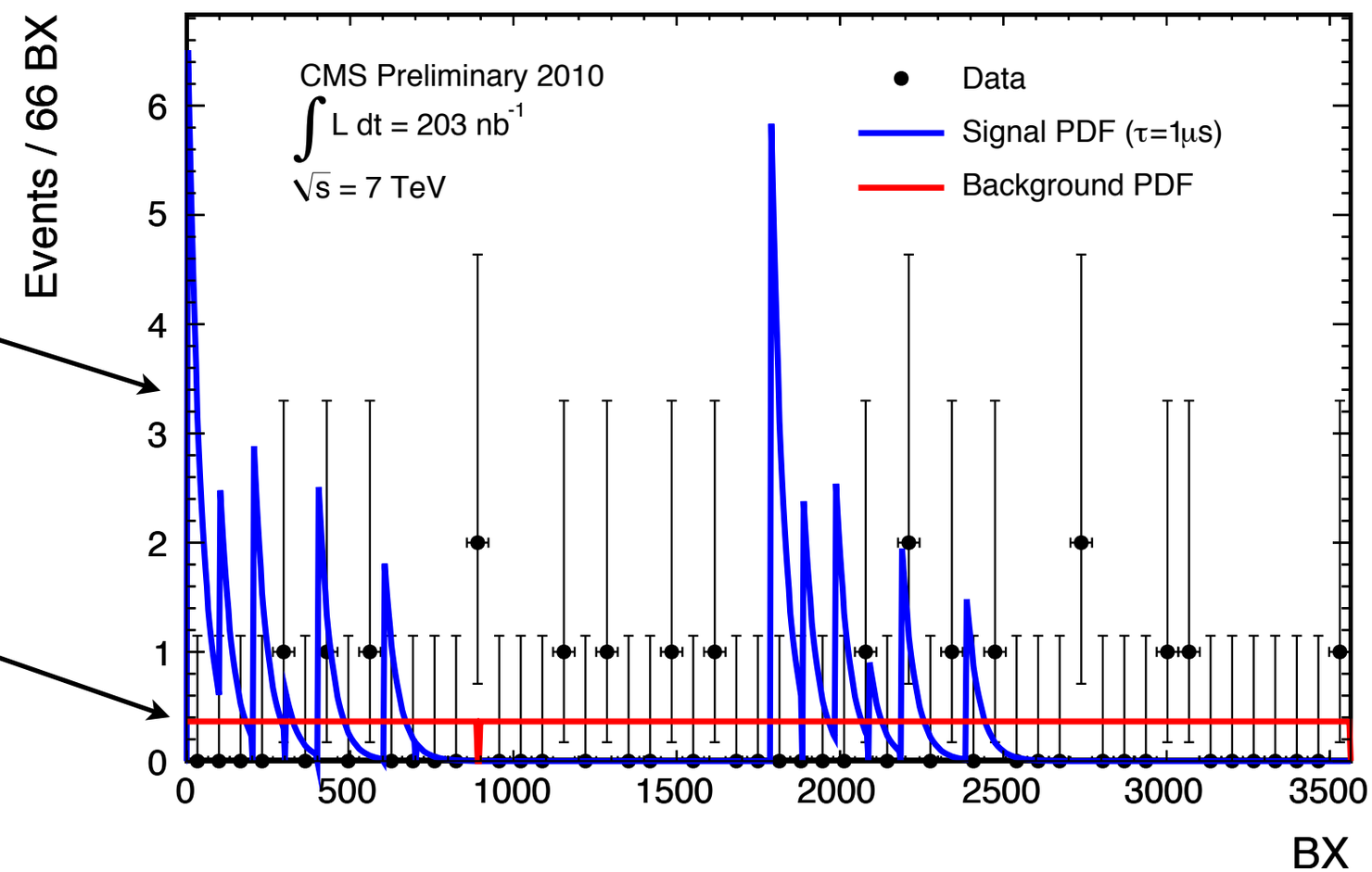
Steps occur between time-windows as N_{obs} increments for each observed event

Time Profile Analysis

- As well as counting expt, we analyse the distribution of observed event times
  - For a given lifetime hypothesis, calculate a PDF for signal event time, using the delivered luminosity profile
  - Background PDF is flat in time
- Fit data and calculate a 95% CL on the signal
- We do this for lifetimes less ~100 μs
  - Using event time within the orbit, ie. BX

Signal PDF peaks at collision BXs

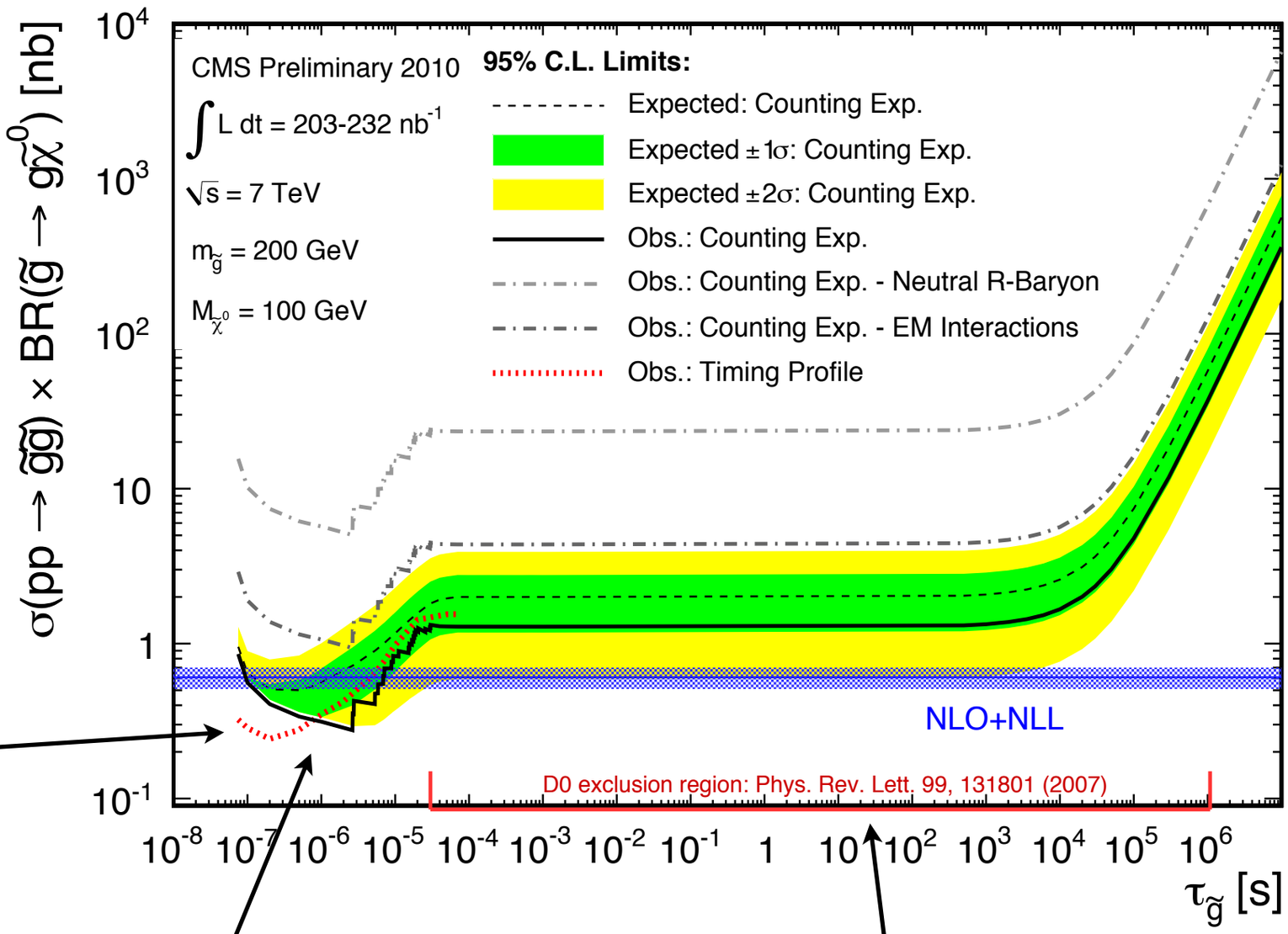
Background PDF is flat



Cross-section Limit

- Use the stopping probability to obtain a limit on the cross-section
  - For $m_{\tilde{g}}$=200, $M_{\tilde{\chi}^0}$=100 GeV
- Stopping probability depends on models of R-hadron interactions
  - Default "Cloud model"
  - "EM only"
  - "Neutral R-Baryon" model

Cross-section limit



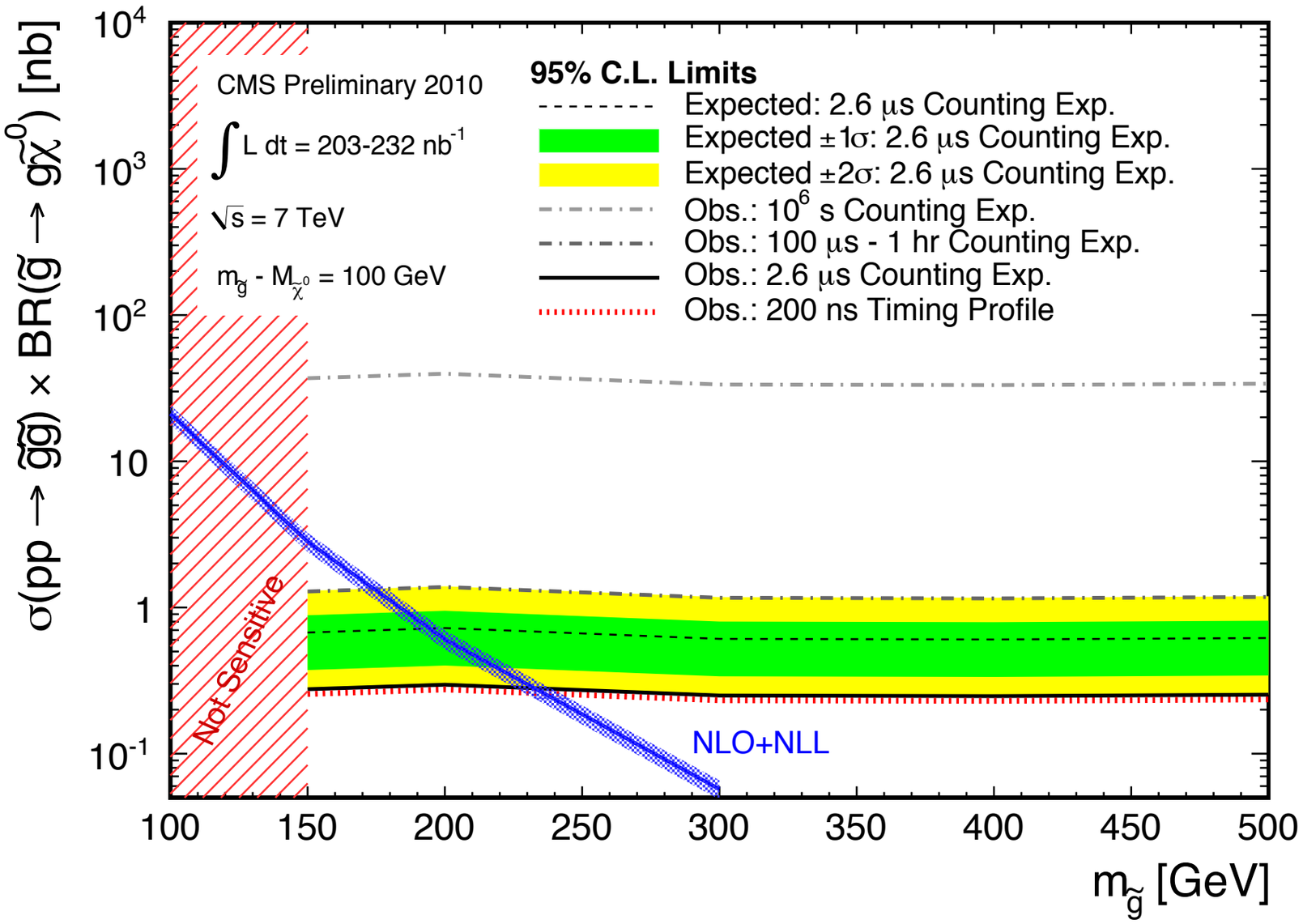
Time profile analysis improves sensitivity to small lifetimes

For $m_{\tilde{g}}$<200 GeV,
exclude lifetimes
120 ns < τ < 6 μs

Extends D0 limit (valid for τ > 30 μs)

Mass Exclusion Limit

- Present limit for fixed lifetime, as a function of $m_{\tilde{g}}, M_{\tilde{\chi}^0}$
  - Fixed $m_{\tilde{g}} - M_{\tilde{\chi}^0} = 100$ GeV
- Trigger/reco/stopping efficiency is roughly flat
  - And valid for mass differences > 100 GeV
- Results not presented for region below $m_{\tilde{g}} = 150$ GeV
  - Being to encroach on LEP neutralino limit
  - And/or trigger/reco efficiency declines



Time profile analysis:
for τ=200 ns,
exclude m_g < 229 GeV

Counting experiment:
for τ=2.6 μs,
exclude m_g < 225 GeV

Summary

- **Search for heavy stable charged particles**
  - Searched for high-p_t, high dE/dx tracks, with and without muon ID, in 198 nb^{-1} data at $\sqrt{s}$=7 TeV
  - For masses 130-900 GeV, **gluino/stop cross-section limited to ~100pb**
  - Track-only analysis => **exclude gluino below 271 GeV**
  - Track+muon analysis => **exclude gluino below 284 GeV**

already approaching Tevatron limits

  - **CMS-EXO-PAS-10-004 (on CERN CDS soon)**

- **Search for stopped gluinos**
  - Searched for decays of particles stopped in CMS, in 203-232 nb^{-1} of data at $\sqrt{s}$=7 TeV
  - Using a novel calorimeter trigger to record decays during gaps between LHC collisions
  - For 120 ns < τ < 6 μs, **exclude gluinos of mass up to 200 GeV/c^2**
  - For lifetimes of 2.6 μs, **exclude gluinos of mass up to 225 GeV/c^2**
  - For lifetimes of 200 ns, **exclude gluinos of mass up to 229 GeV/c^2**

extending D0 limit for τ > 30 μs

  - **CMS-EXO-PAS-10-003 (on CERN CDS soon)**

Backup Slides (HSCP)

dE/dx estimators

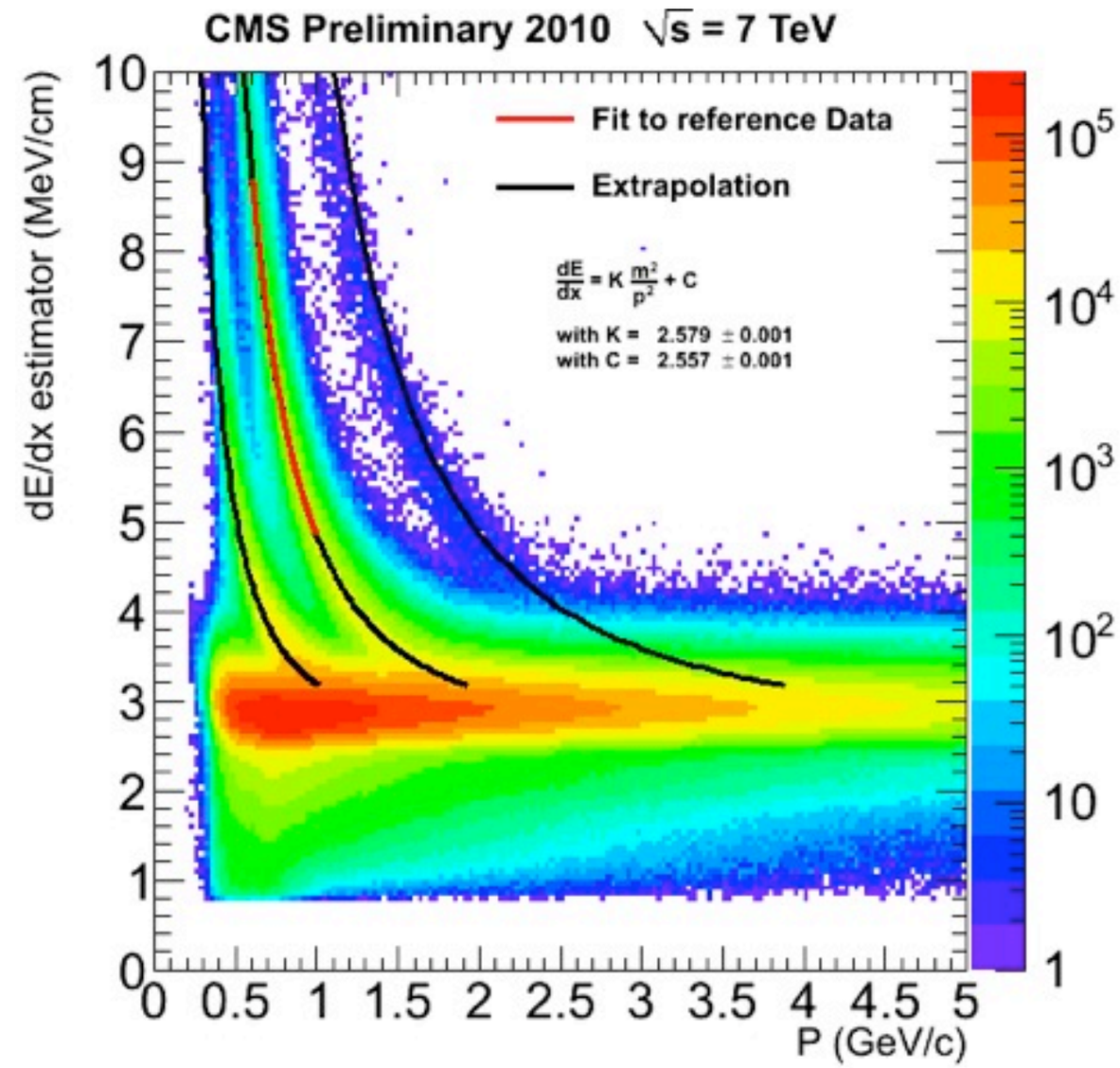
- Mass reconstruction
  - Harmonic 2 estimator

$$I_h = \left(\frac{1}{N}\sum_i c_i^k\right)^{1/k} \text{ with } k = -2$$

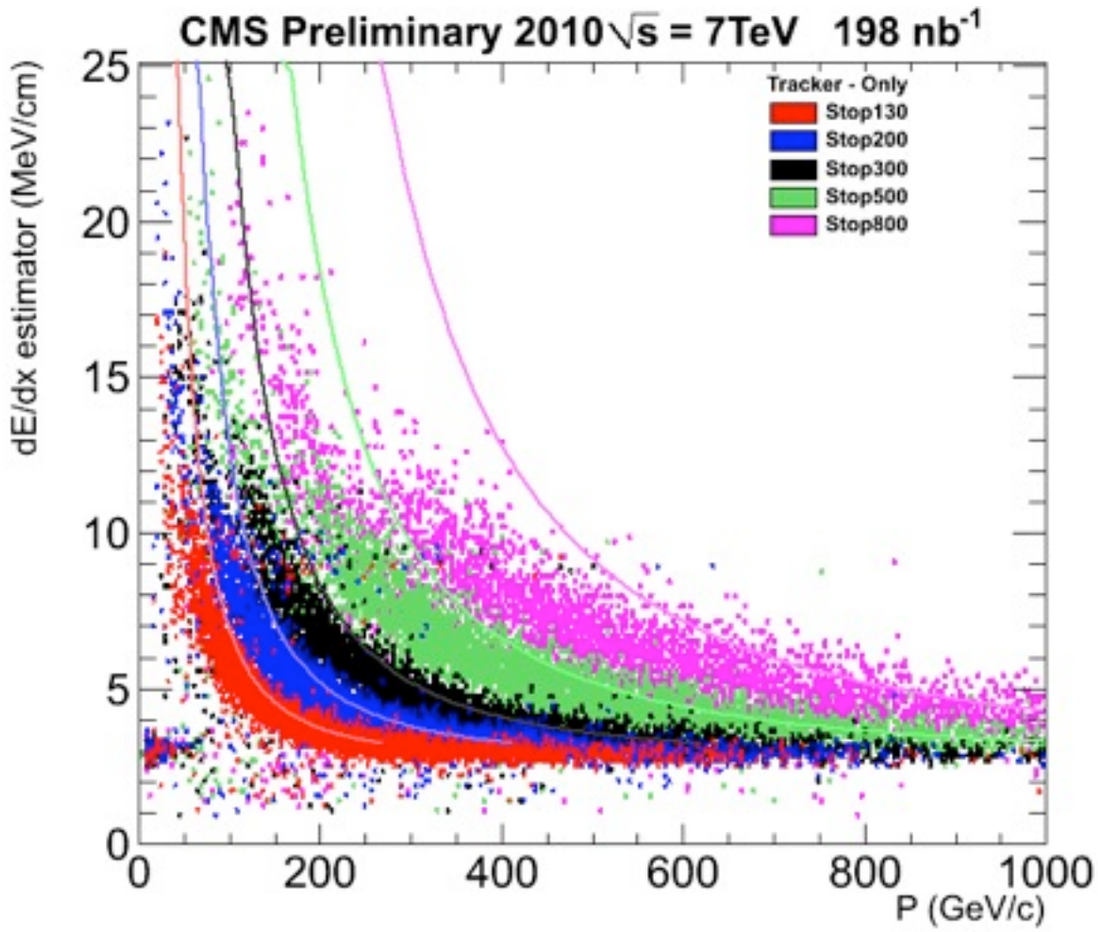
- Event selection
  - Modified Smirnov-Cramer-von Mises estimator

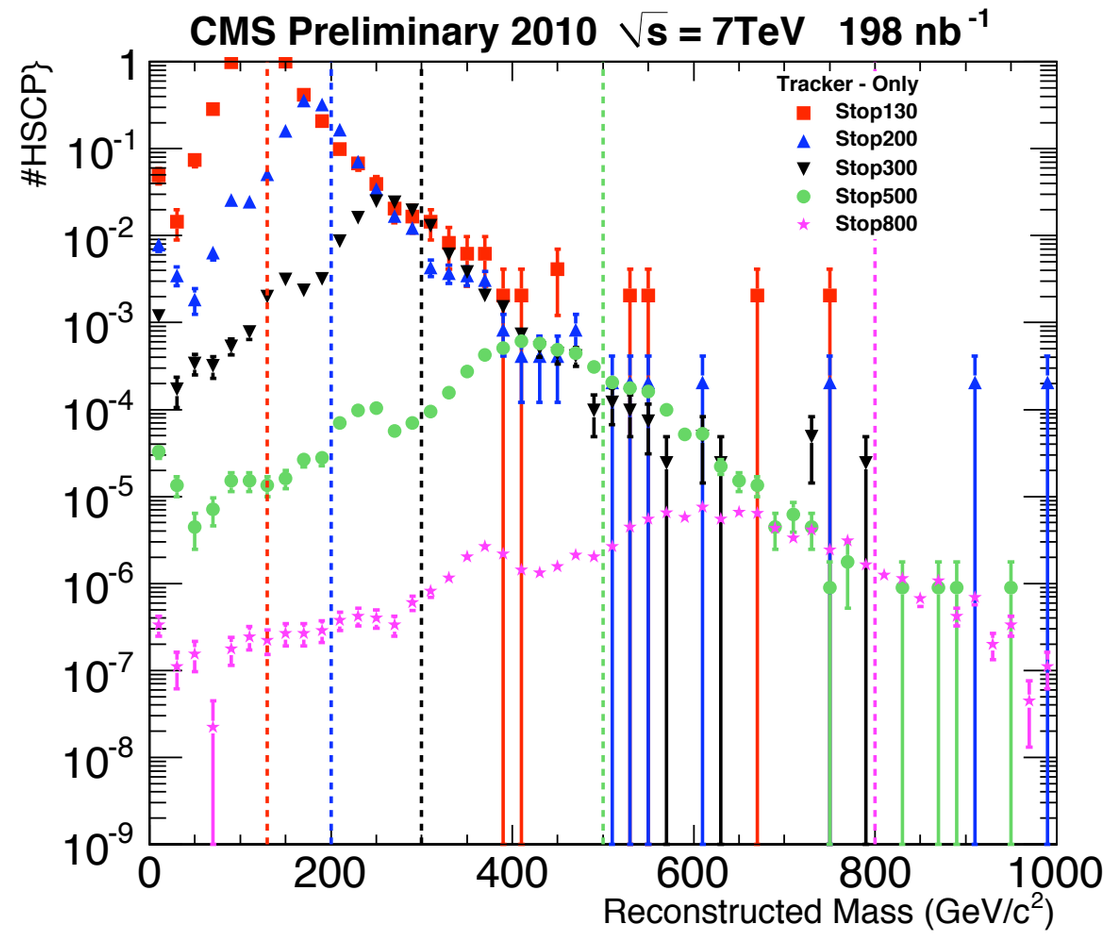
$$I_{as} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{i=1}^{N}\left[P_i \times \left(P_i - \frac{2i-1}{2N}\right)\right]^2\right)$$

  - P_i = probability for a MIP to produce equal or less charge than that observed, for the observed path length
  - The PDFs used to compute P_i are determined from tracks (p_t > 5 GeV) taken on a minimum bias trigger



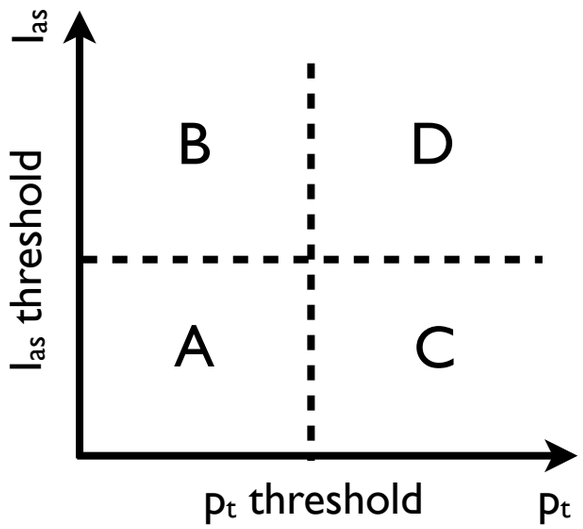
Mass Reconstruction

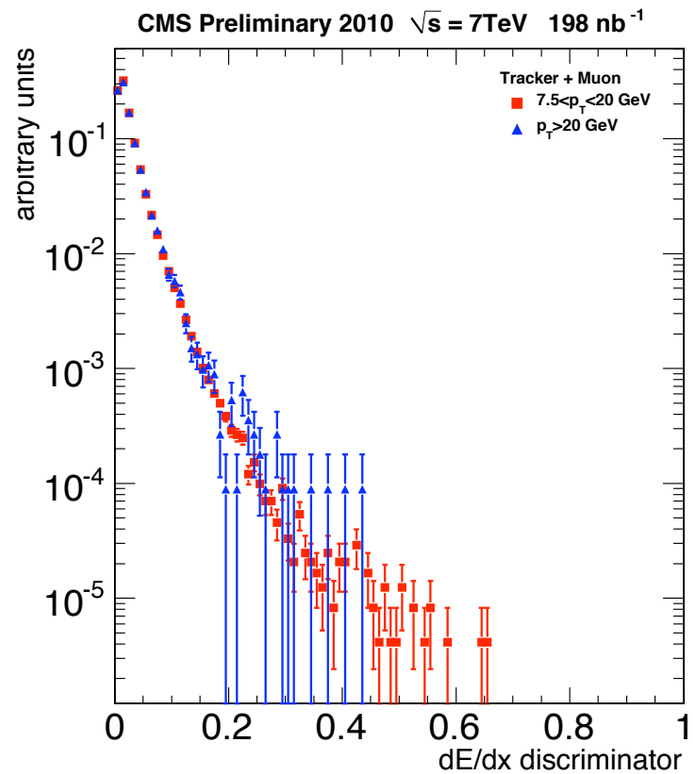


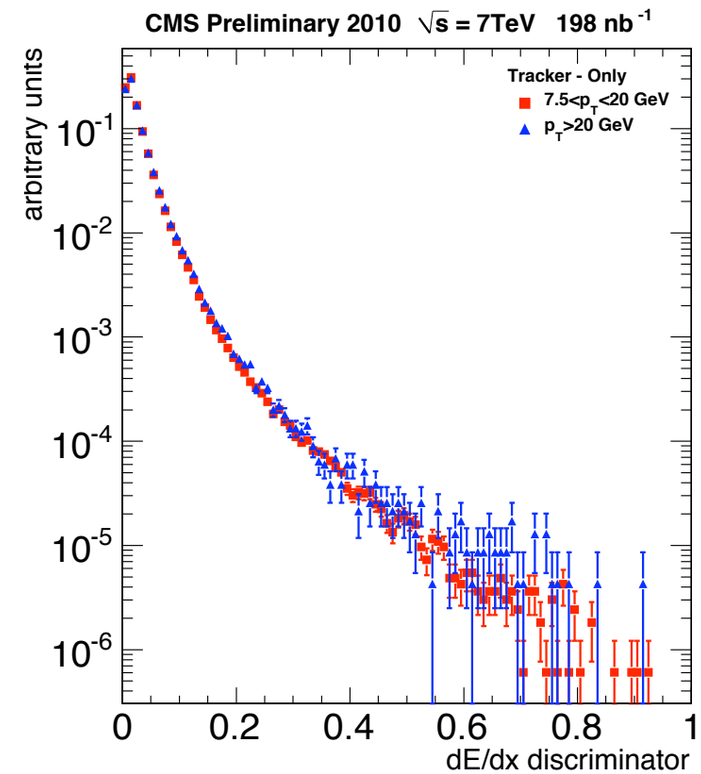


- I_h vs p, and reconstructed mass distribution for stop MC samples
  - Reconstructed tracks matched to the MC truth stop
  - Bias at high mass is due to ADC saturation
    - Does not affect this analysis, which is purely a counting experiment

Background Determination



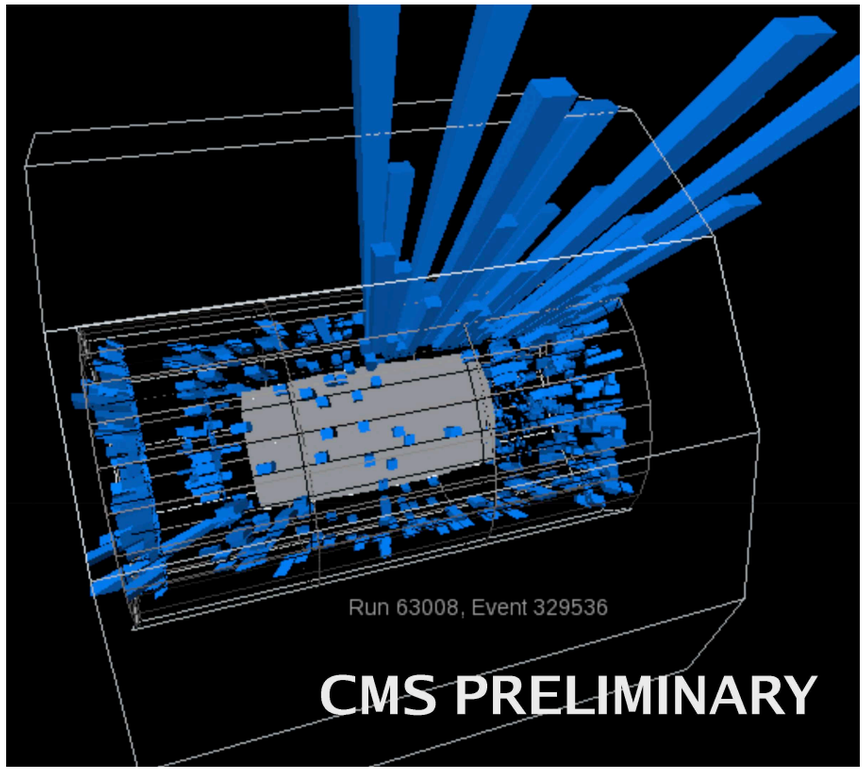


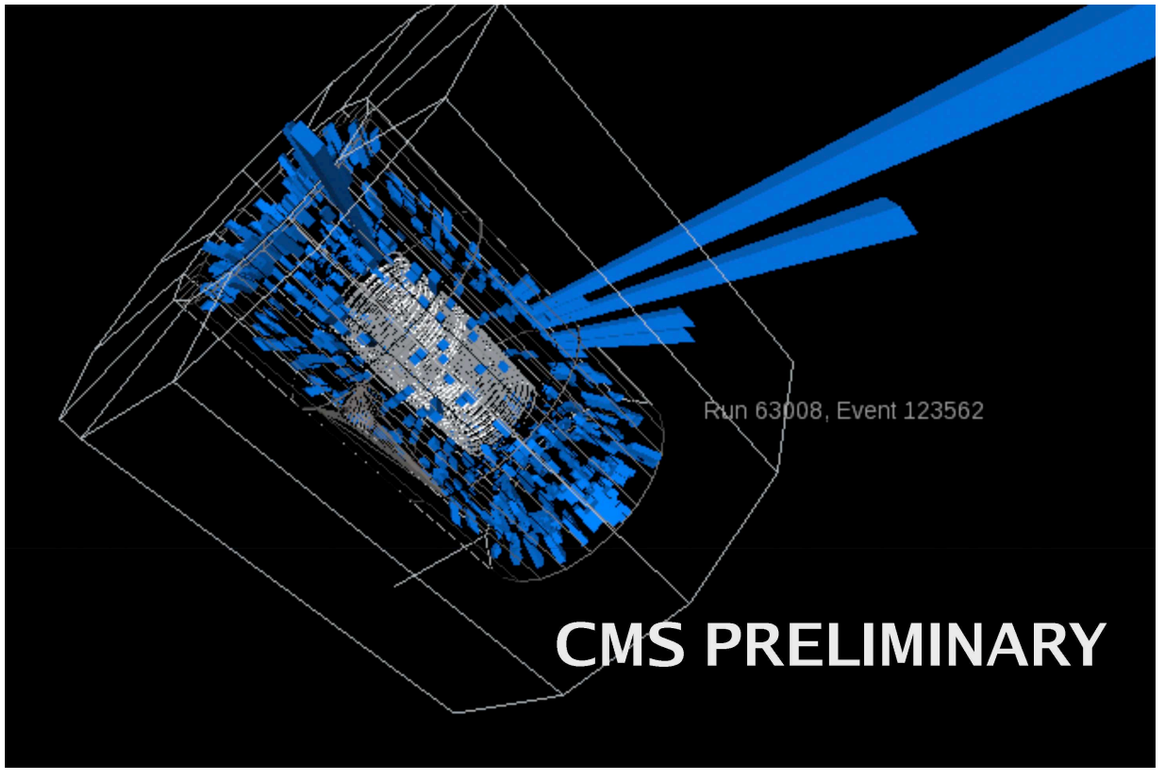


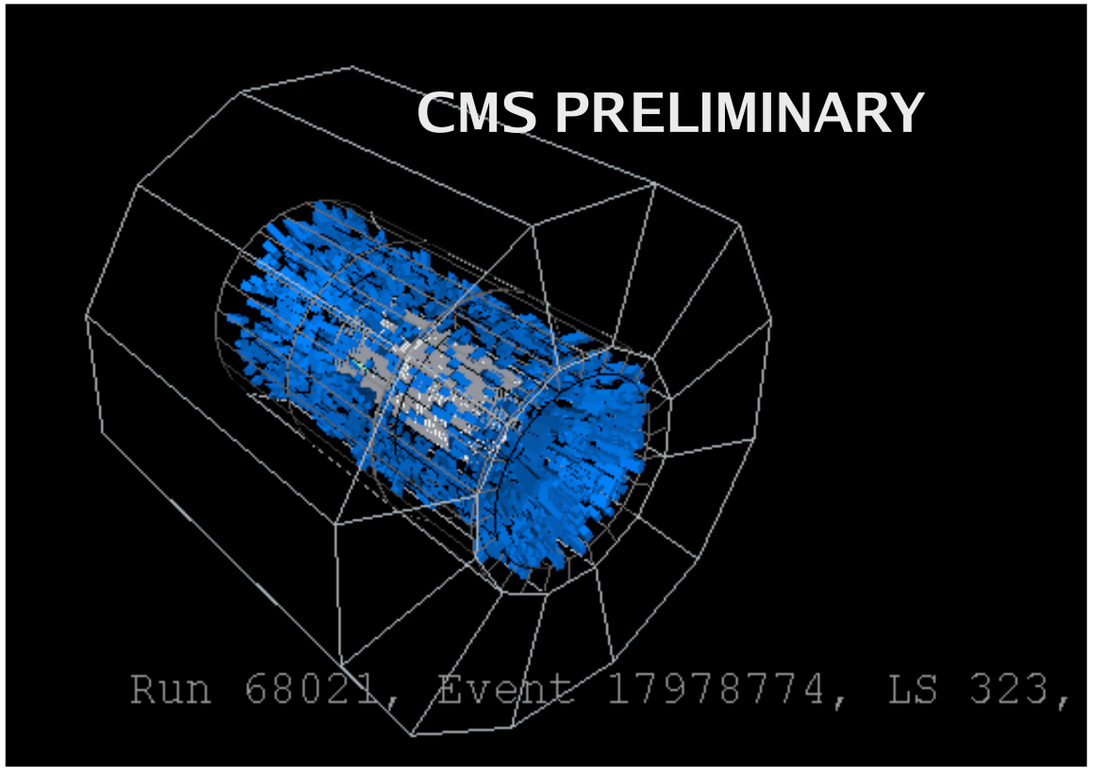
- Background for each (N_{hits}, η) bin is determined using an "ABCD" method
  - Background in signal region, D = BC/A
  - This relies on non-correlation of p_t and dE/dx measurements
  - Shown above, I_{as} distribution for two pt ranges
  - This method is extended to also predict the expected background mass spectrum
- Cross-check the background determination by comparing observed with expected background counts for a control region (mass < 75 GeV/c^2)
  - Find that a correction is required, average factor 1.32 (tk+muon), 1.36 (tk only)
  - Also use this to determine the systematic uncertainty on the background

Backup Slides
(Stopped Gluinos)

Know Thy Enemy







Noise events from 2008 cosmic data