Searches for Stable Massive Particles

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Motivation & Overview

- Many new physics scenarios predict heavy long-lived particles
  - Some flavours of SUSY predict long-lived gluino, stop, stau
  - 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

- 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**

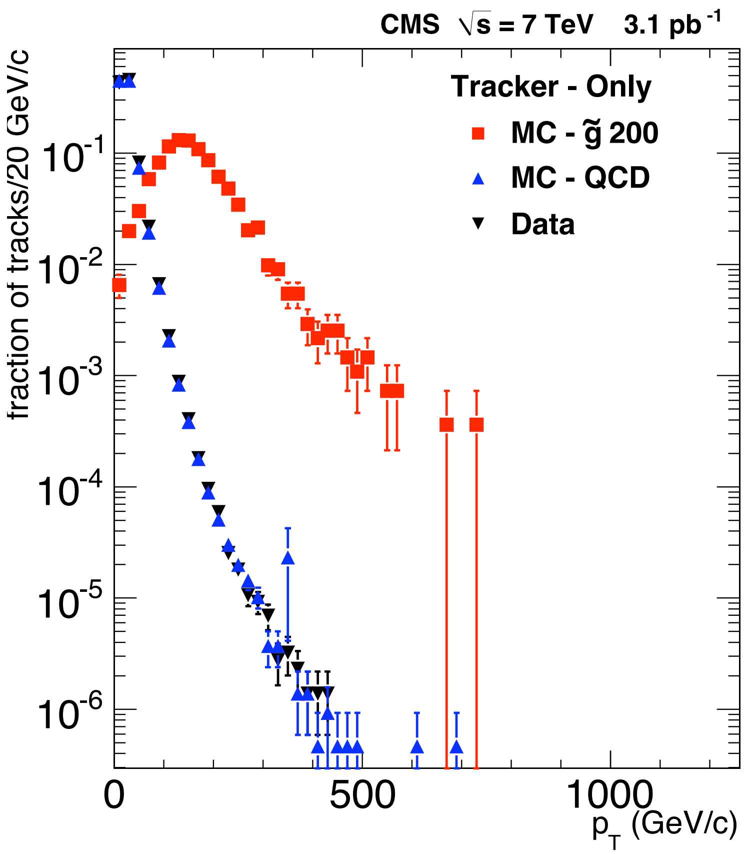
- Results from two complementary search methods are presented here
  - Search for tracks with **anomalously high dE/dx**
  - Search for **decays of particles that have stopped** in the detector
  - Stopped particle search more sensitive to low β (< 0.3), dE/dx method more sensitive at moderate β (>0.3)

- Results here couched in terms of strongly interacting stops/gluinos bound with quarks/gluons - "R-hadrons"
  - Results affected by model of R-hadron interactions with matter

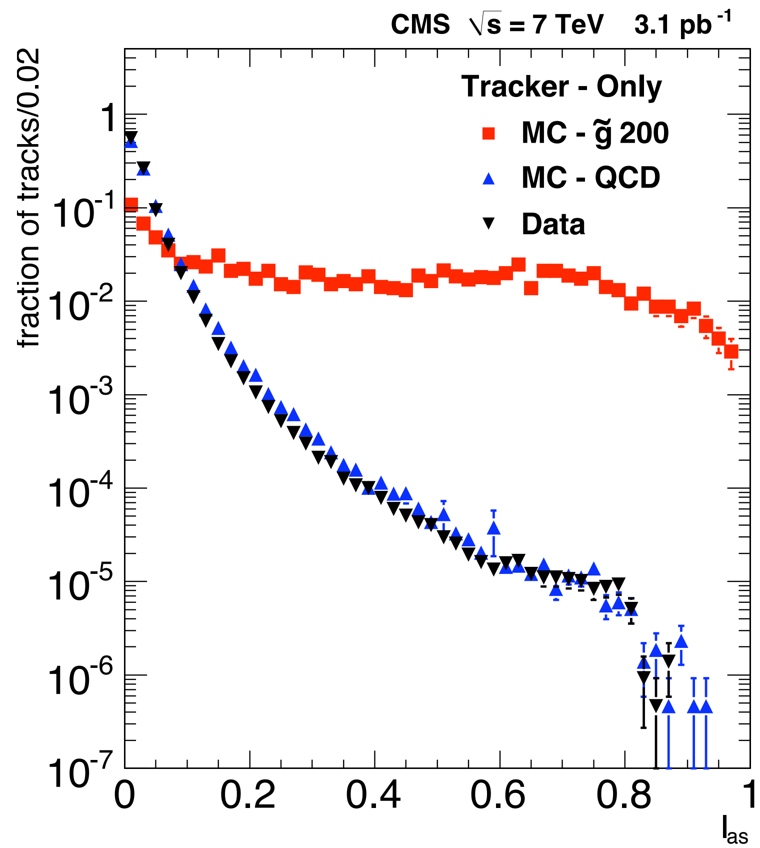
Search for Heavy Stable Charged Particles

- 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
  - But R-hadrons undergo nuclear interactions, and may change charge/flavour
  - **R-hadrons may be neutral while traversing the muon system**
- Perform both 'track+muon' and 'track-only' analyses
- Triggers
  - Track+muon uses muon triggers : **mu > 9 GeV**, **di-mu > 3 GeV**
  - Track-only uses other products of the event : **E_t^{miss} > 100 GeV**
- NB : R-hadrons may also be neutral in tracker
  - More difficult - need a muon-only analysis...

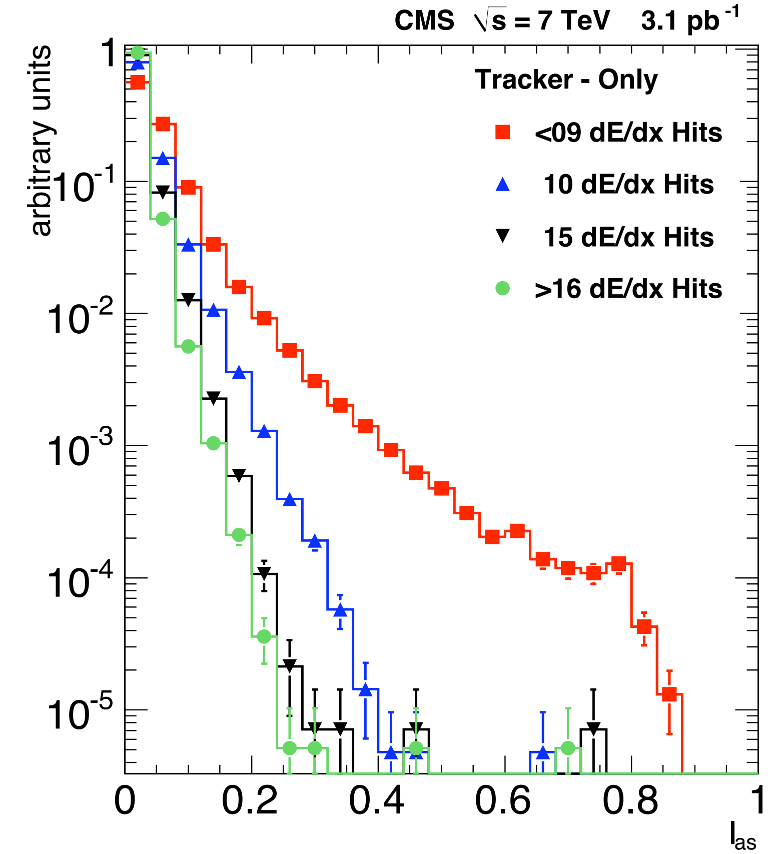
HSCP Selection



p_t distribution



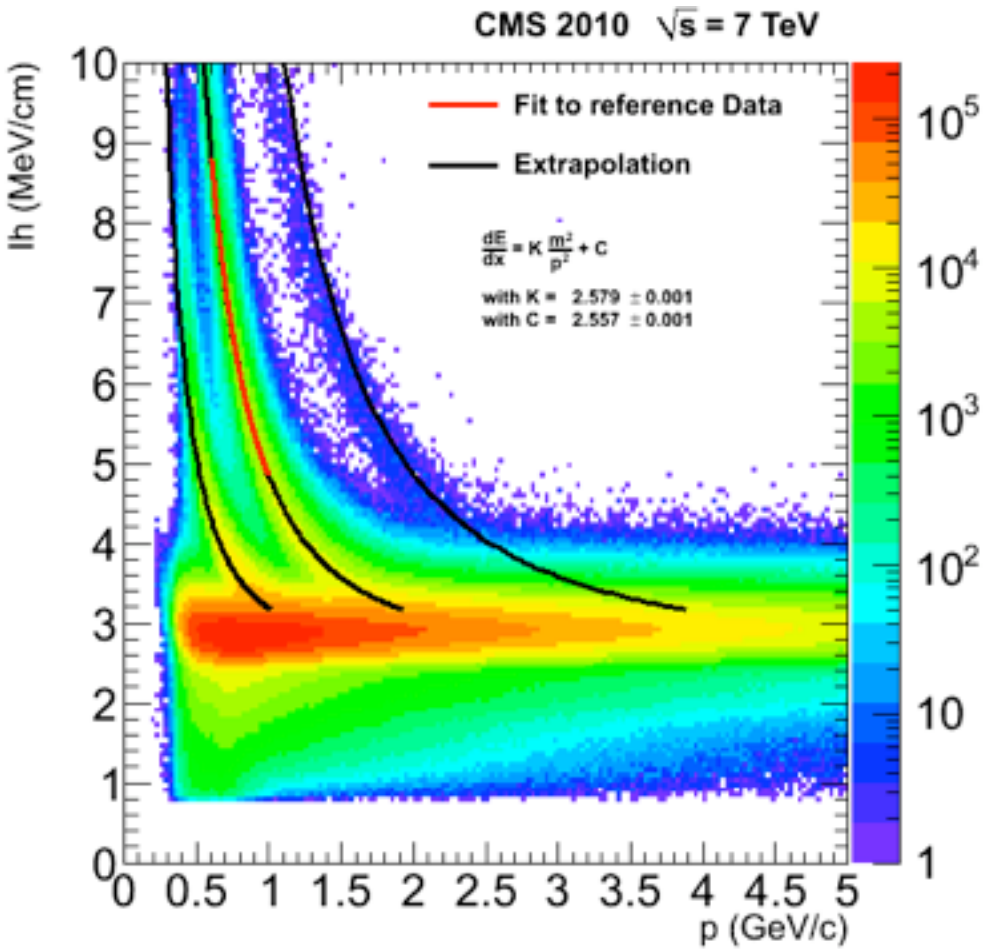
dE/dx discriminator



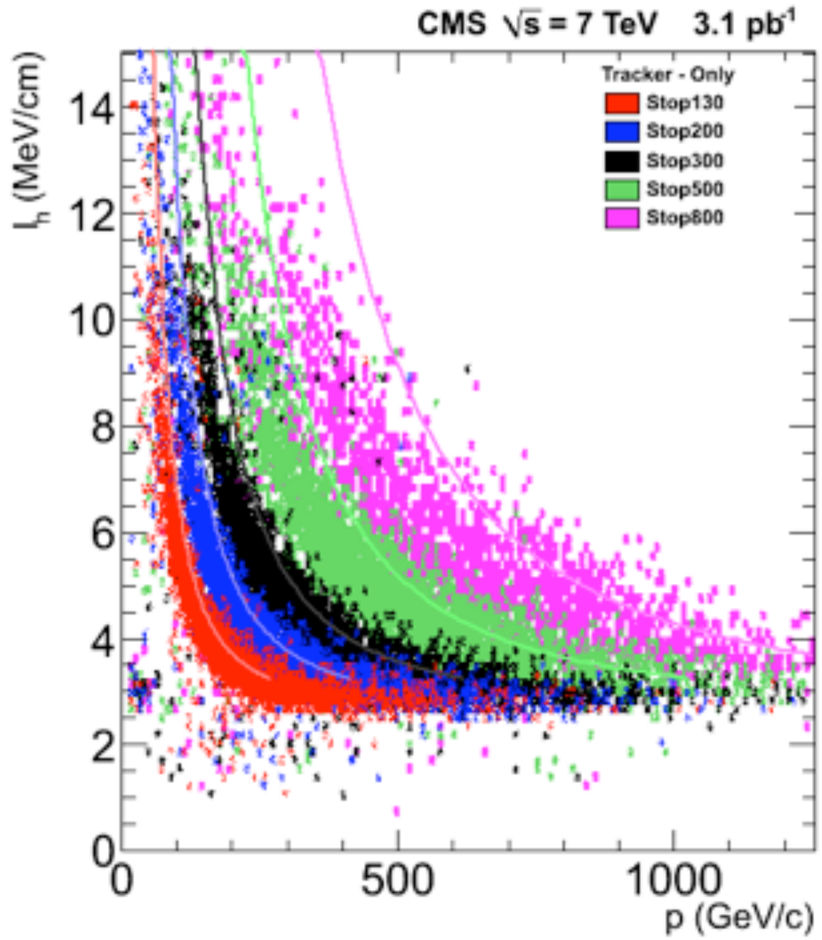
...binned by #hits

- 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 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 change charge**

Mass Reconstruction



min-bias data

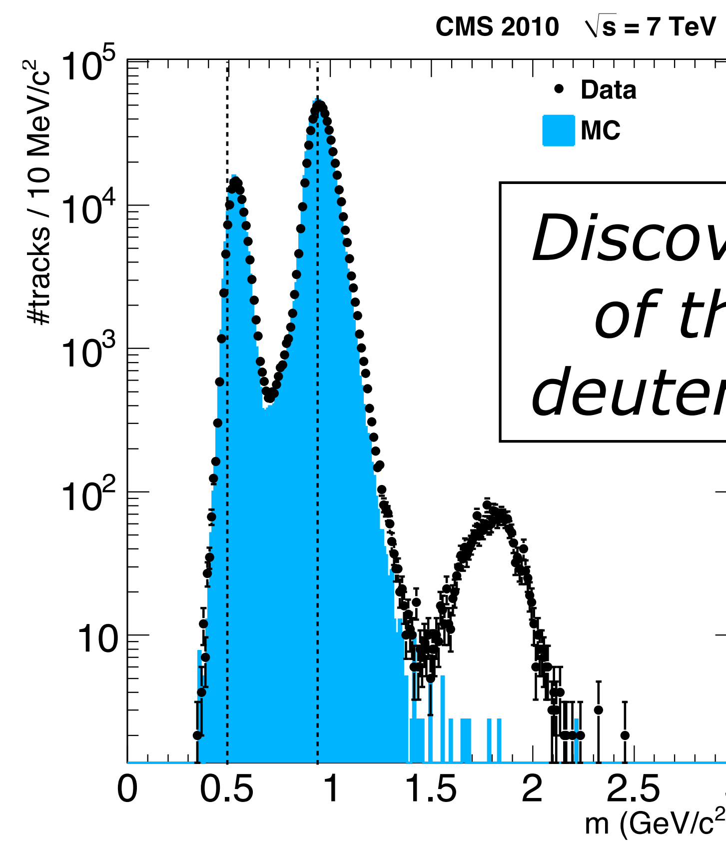


...and stop MC

- 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



Discovery of the deuteron!

Search Procedure

- Perform a counting experiment in the mass range 75-2000 GeV/c^2
  - Summing over bins in N_{hits}
  - Background for each bin determined from data using an "ABCD" method + (data-determined) correction
- Signal efficiency does not depend strongly on threshold
  - Optimise thresholds to yield desired background

- Define a tight selection for the search

Efficiency for background (arrows point to ϵ_I and ϵ_{p_T})

TIGHT	Mu	Tk
ϵ_I	1.0×10^{-4}	1.0×10^{-4}
I_{as}^{min}	0.184 - 0.782	0.186 - 0.784
ϵ_{p_T}	1.0×10^{-3}	3.2×10^{-4}
p_T^{min} (GeV/c)	115 - 118	154 - 210

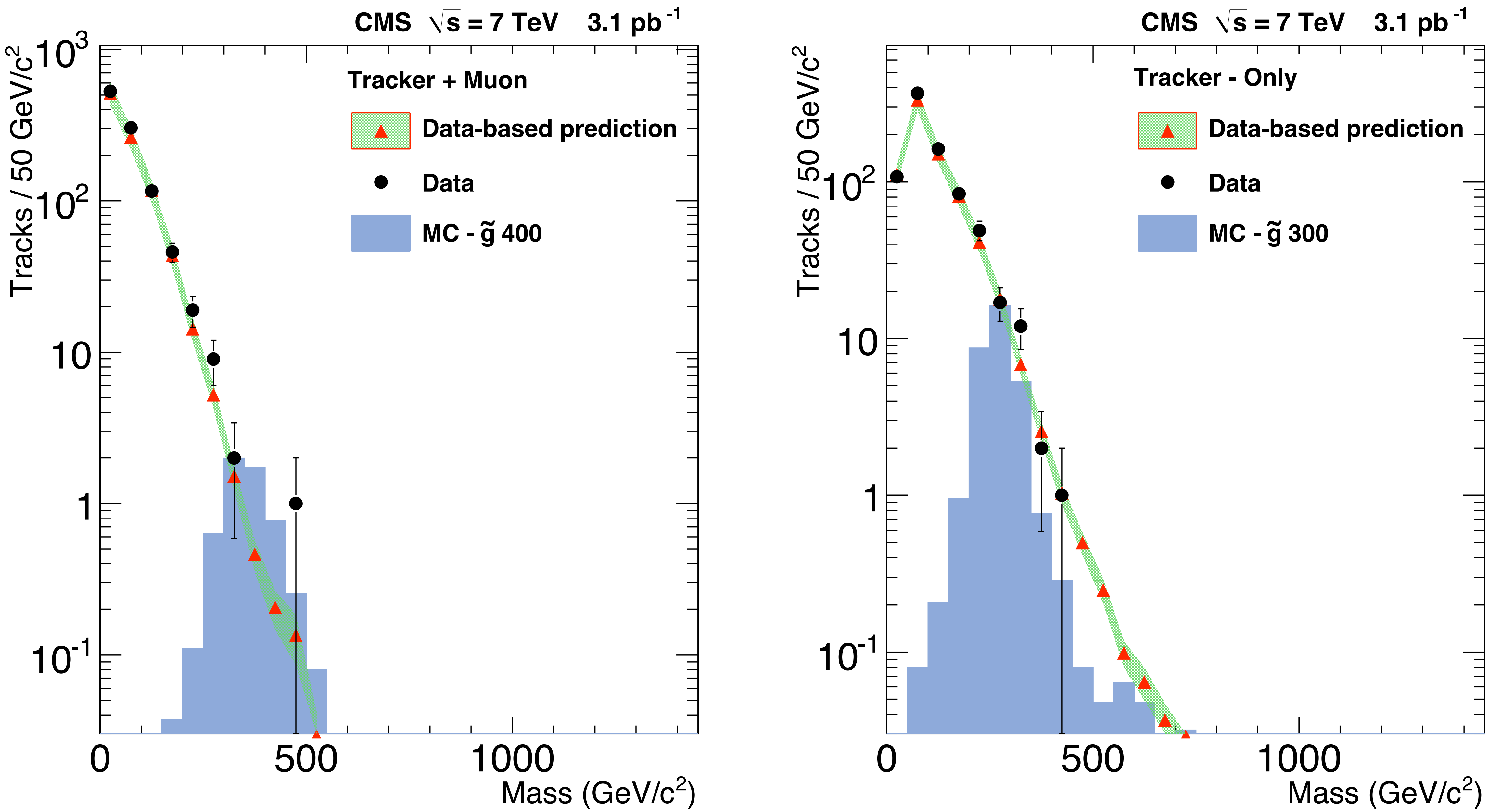
- And a loose, background enriched selection for cross-checks

LOOSE	Mu	Tk
ϵ_I	3.2×10^{-2}	1.0×10^{-2}
I_{as}^{min}	0.049 - 0.162	0.007 - 0.278
ϵ_{p_T}	1.0×10^{-1}	3.2×10^{-2}
p_T^{min} (GeV/c)	34 - 36	59 - 62

Background-Enriched Selection

- Good agreement between expected background and observation

LOOSE	Mu	Tk
Expected	$281 \pm 2(stat.) \pm 49(syst.)$	$426 \pm 1(stat.) \pm 62(syst.)$
Observed	307	452

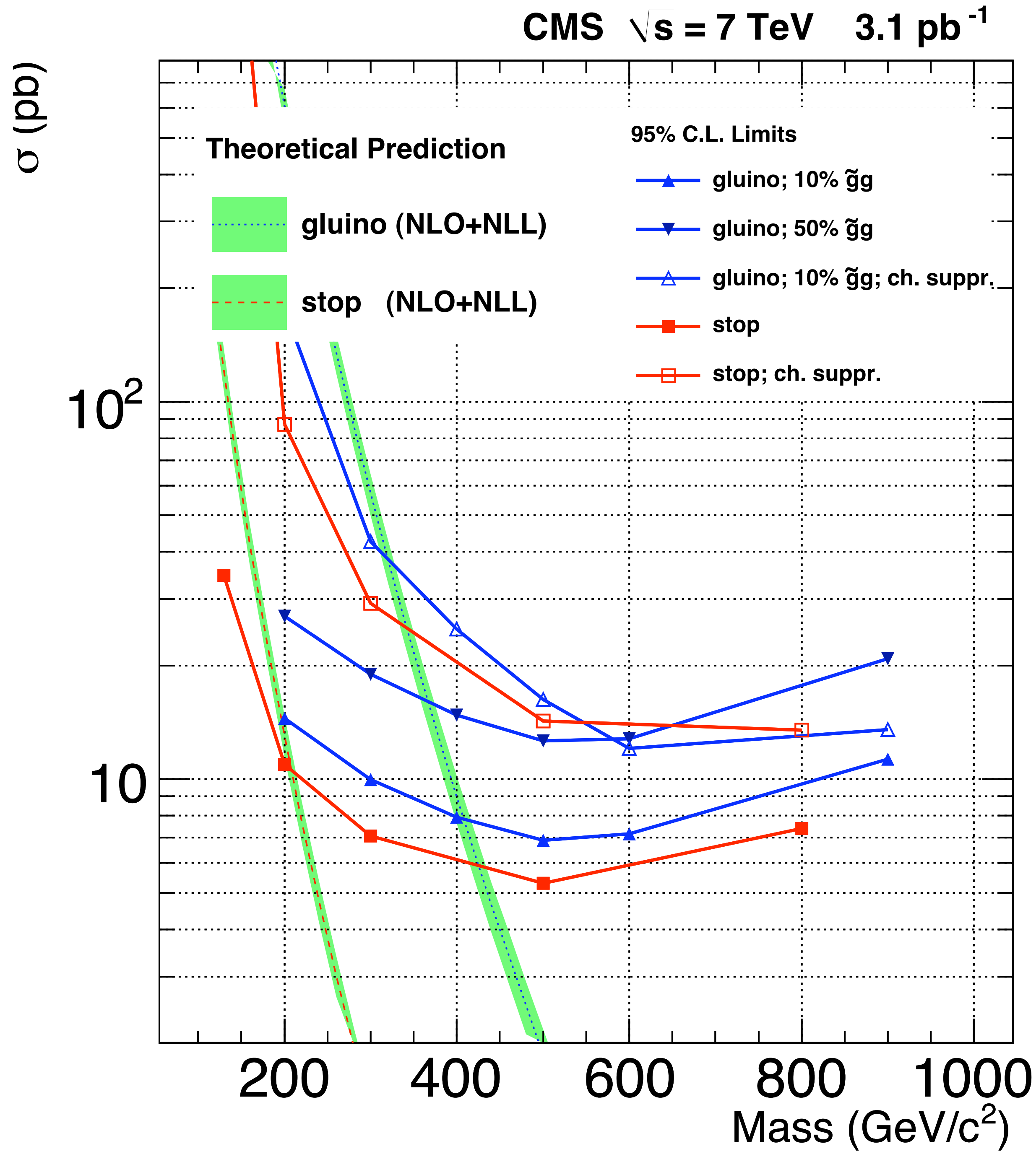


Search Results

- Null result in signal region

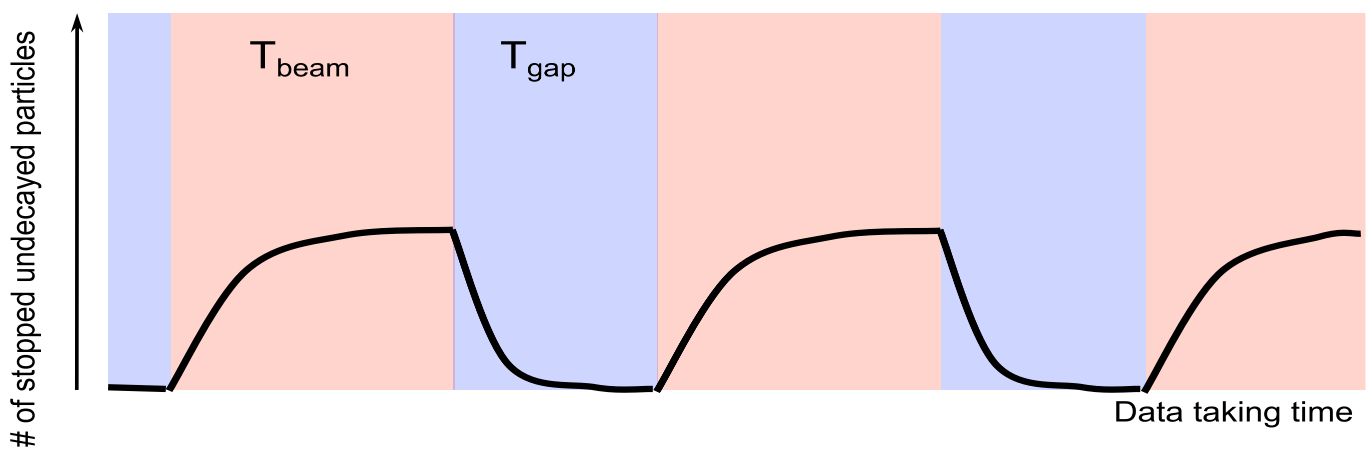
TIGHT	Mu	Tk
Expected	$0.025 \pm 0.002(stat.) \pm 0.004(syst.)$	$0.074 \pm 0.002(stat.) \pm 0.011(syst.)$
Observed	0	0

- 95% CL limits on the production cross-section for **stop** and **gluino**
  - Bayesian method (uniform prior for signal, lognormal for nuisance parameters)
- Different models of R-hadron interactions
  - Cloud model
  - "Charge suppressed" model
    - Neutral R-hadrons remain neutral
- Initial fraction of $\tilde{g}g$
  - Free parameter of the theory
  - Gluino limit presented for 10% and 50%



Search for Stopped Gluinos

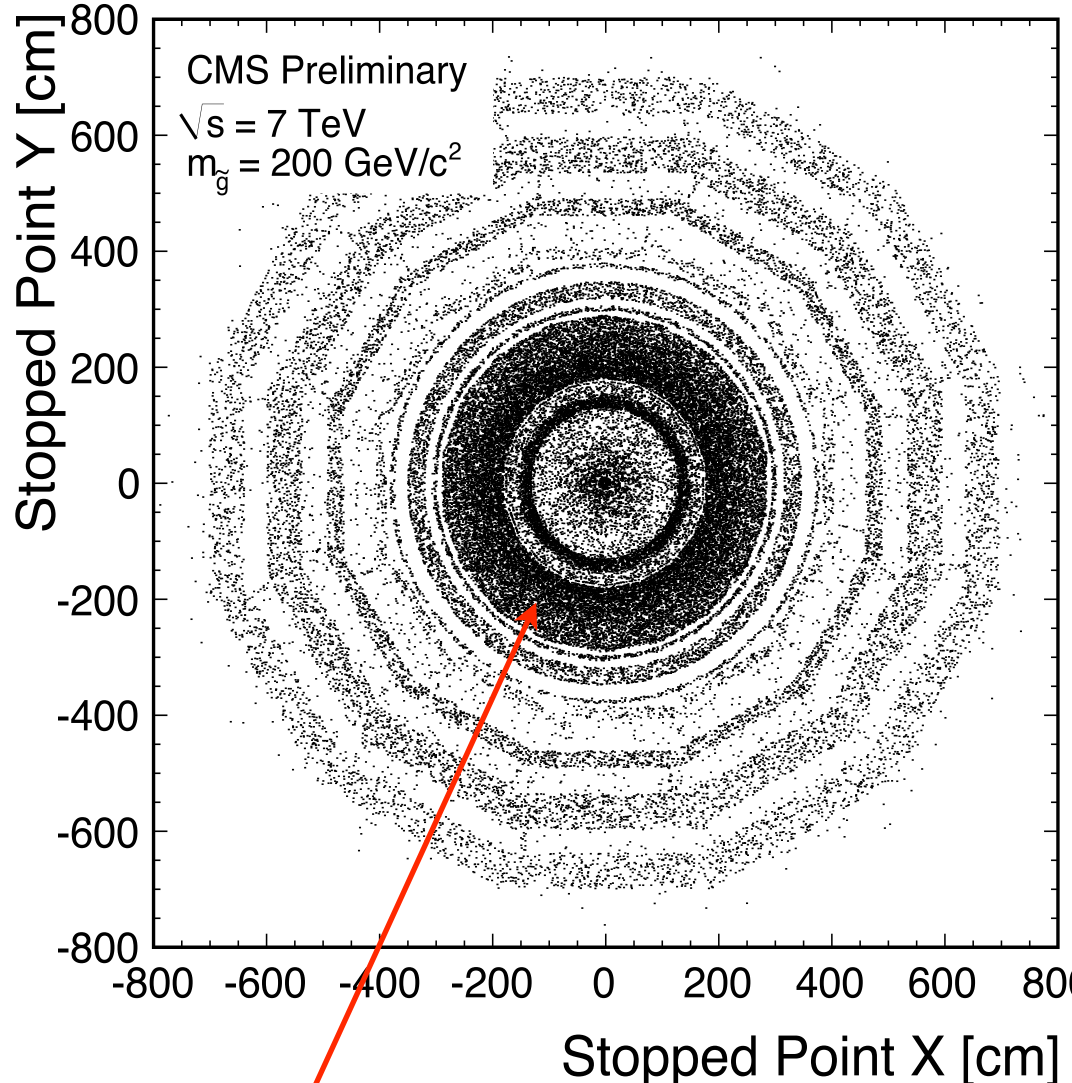
- This is a highly unorthodox search, for the decays of long-lived particles that have stopped in the detector
- Use a dedicated calorimeter trigger to search during periods when **no collisions are expected**
  - In gaps between filled bunches during an LHC fill, and between LHC fills (not used yet)
  - Trigger includes a no-beam condition using beam position and timing monitors (BPTX)



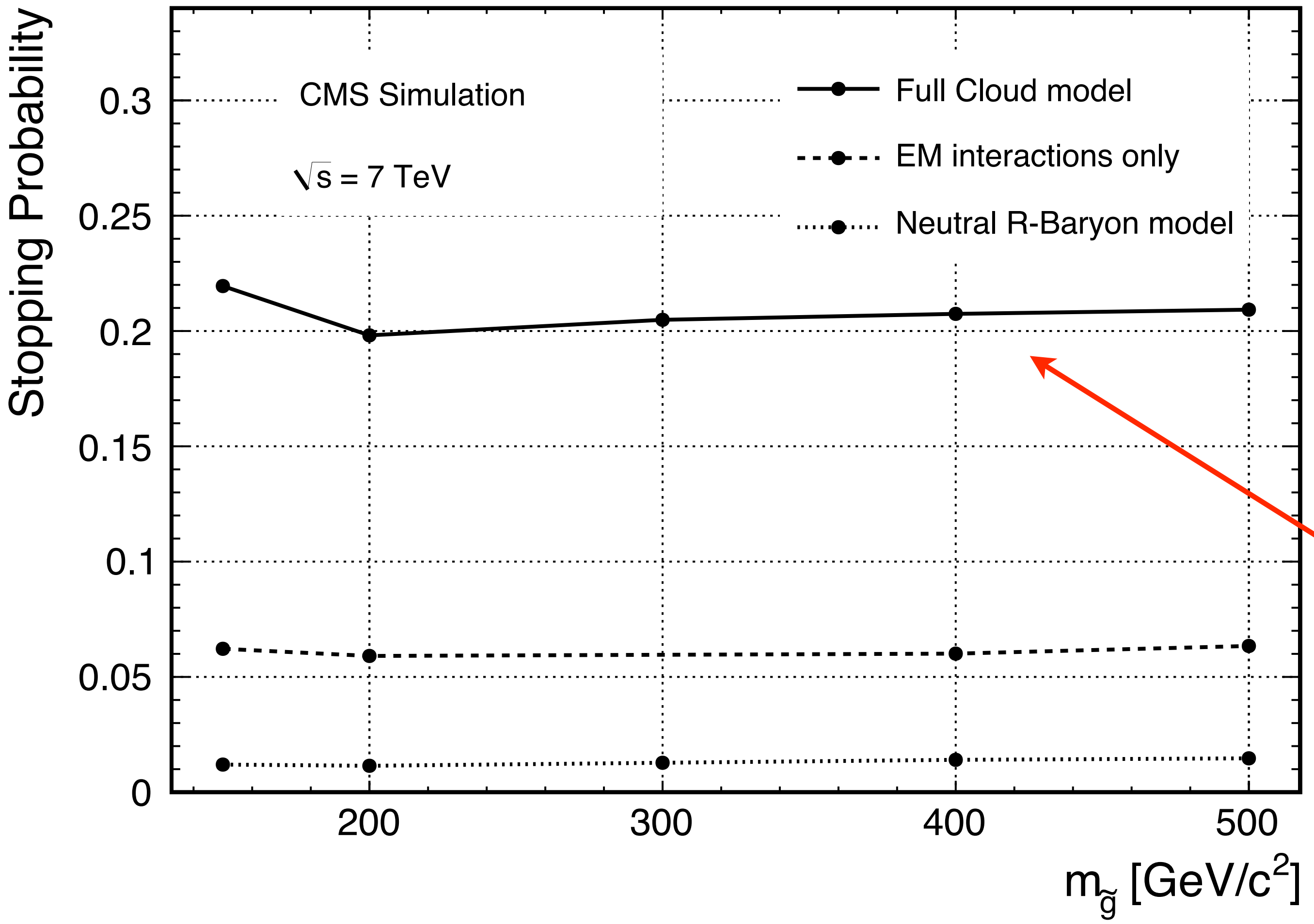
- Observation of a signal during these periods will be an **unambiguous sign of BSM physics**
- **Analysis started in 2008/2009** with background measurements

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 collision data
  - Bulk is beam halo events
    - Reject using standard beam halo ID from muon endcaps
  - Remainder are beam-gas and early collision triggers
    - Reject this by vetoing events within +1/-2 BX of passage of beam through CMS

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}

Beam background rejection → BPTX/BX veto

Cosmic rejection → muon veto

Jet topology cuts → E_{jet}, n_{60}, n_{90}, n_{phi}

Calorimeter pulse shape cuts → R_1, R_2, R_{peak}, R_{outer}

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

- We divide the collision data into control and search samples
  - **Control sample** consists of very low lumi data, $\mathbf{L_{inst}^{max} = 7\times10^{27}\ cm^{-2}s^{-1}}$
  - **Search sample** is taken from highest lumi data, $\mathbf{L_{inst}^{max} = 1x10^{32}\ cm^{-2}s^{-1}}$ (total 10.2 pb^{-1})

- Use control sample to predict background rate in signal sample
  - Calculate **ratio of R_{N-1} (rate after N-1 cuts) to R_N (rate after N cuts)** in control
  - Use this to extrapolate expected background from R_{N-1} in search sample

- Perform a counting experiment in bins of lifetime, τ
  - For small τ, select events in a window **1.256 x τ** after each collision

- Observed counts compatible with background expectation

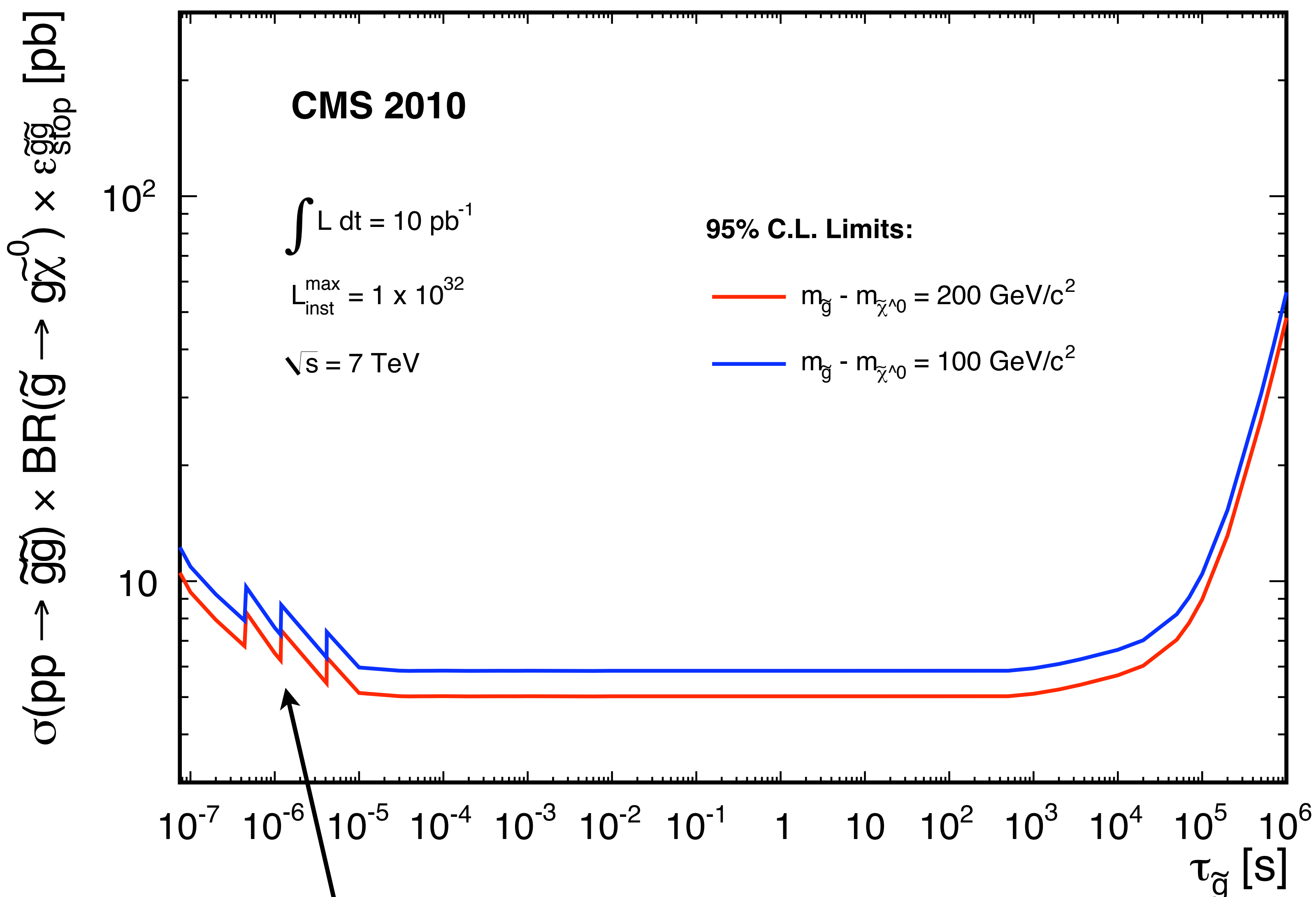
Lifetime [s]	Expected Background (± stat ± syst)	Observed
1×10^{-7}	$0.8 \pm 0.2 \pm 0.2$	2
1×10^{-6}	$1.9 \pm 0.4 \pm 0.5$	3
1×10^{-5}	$4.9 \pm 1.0 \pm 1.3$	5
1×10^{6}	$4.9 \pm 1.0 \pm 1.3$	5

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

Model-Independent Result

- No assumption about interaction model
- Hybrid CLs limit
  - Inspired by Highland Cousins
  - Gaussian priors for nuisance parameters
- τ < few 100 ns
  - Decays occur during vetoed BXs
- $\tau < T_{orbit}$ ($\sim 10^{-4}$ s)
  - Decays occur within the orbit, but we optimise the time window
- $T_{orbit} < \tau < T_{fill}$ ($\sim 10^{4}$ s)
  - Accept events over the full orbit - sensitivity plateau
- $\tau > T_{fill}$
  - Lose sensitivity as increasing fraction of decays occur post-fill

Cross-section × BR × stopping probability



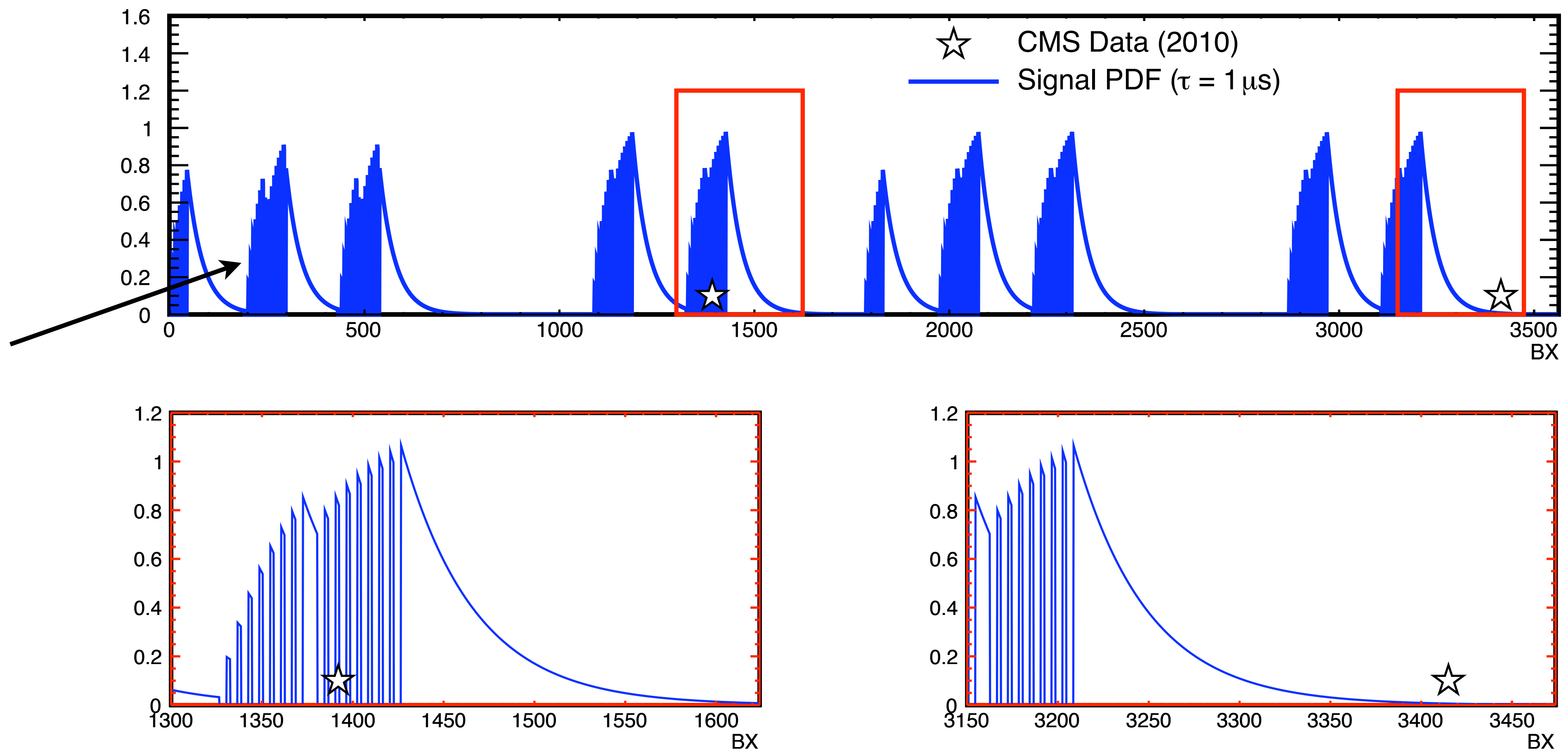
Steps occur between time-windows as N_{obs} increments for each observed event

14 orders of magnitude !

Time Profile Analysis

- Use observed event times to discriminate between signal and background
  - For lifetimes < ~100 μs, using time of event within orbit ie. BX number
  - For a given lifetime hypothesis, calculate a PDF for event time, using the delivered luminosity profile
  - Background PDF is flat in time
- Fit data and calculate a 95% CL on the signal
  - Calculate Bayesian integral over all S, B contributions, assuming uniform priors
  - Integrate over nuisance parameters using Gaussian priors
  - Obtain PDF for cross-section and calculate 95% quantile

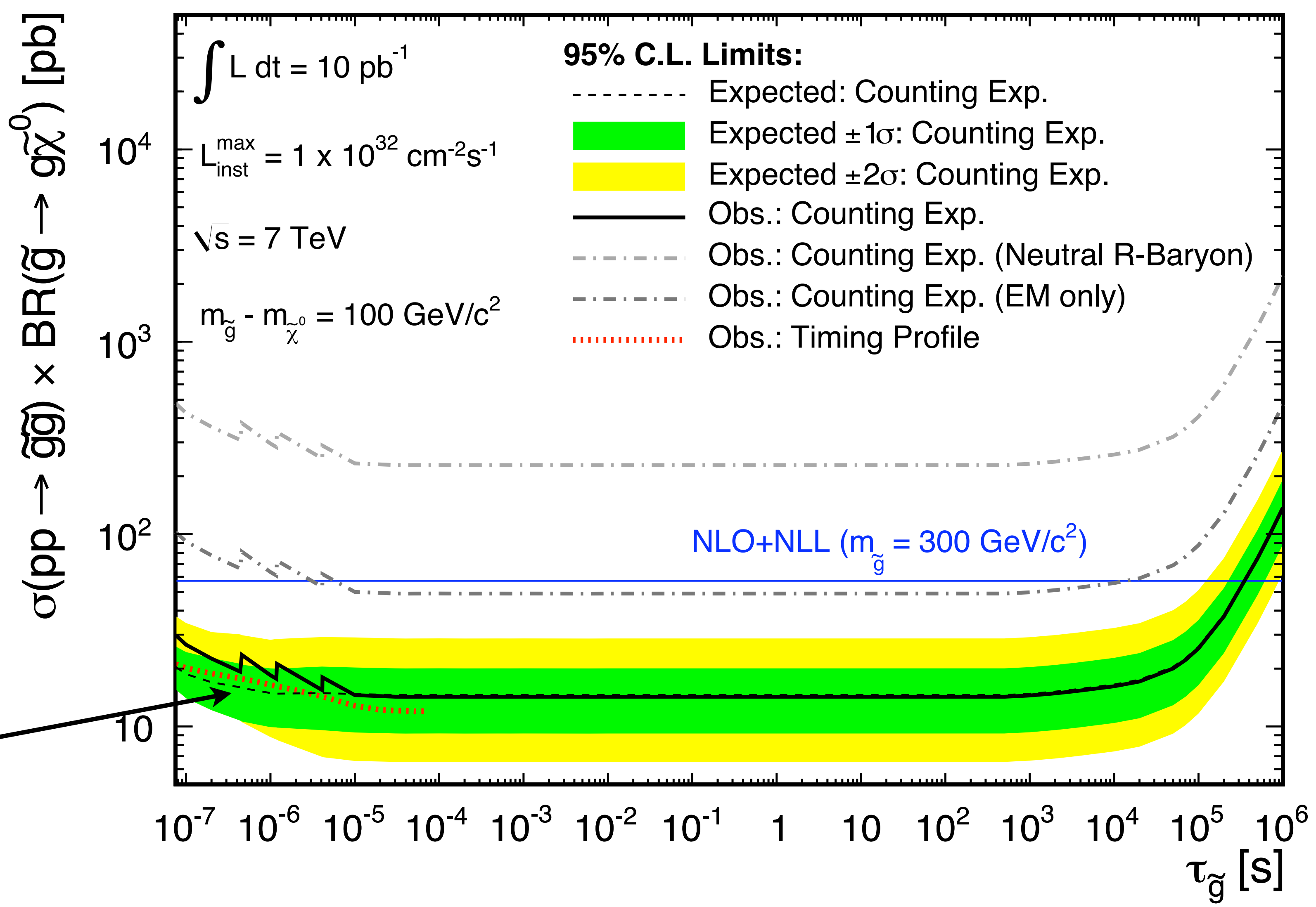
Signal PDF peaks at collision BXs



Cross-section Limit

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

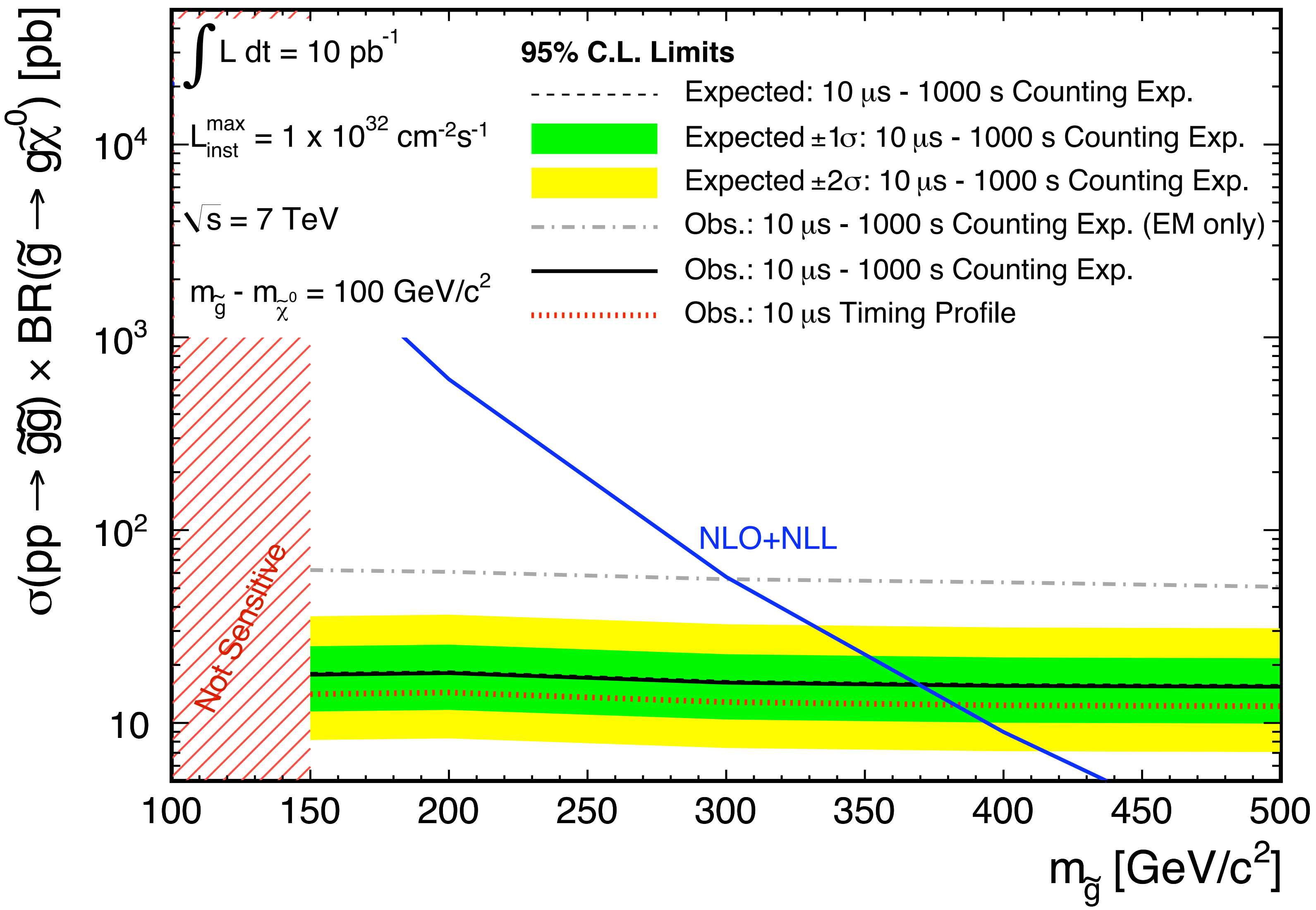
Cross-section limit



Time profile analysis improves sensitivity to small lifetimes

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= 10 μs,
exclude $m_{\tilde{g}}$ < 382 GeV

Counting experiment:
for τ=10μs-1000s,
exclude $m_{\tilde{g}}$ < 370 GeV

Summary

- Use complementary methods to search for heavy stable charged particles
  - Search for **highly ionizing tracks**
  - Search for **decays of particles stopped in the detector**

- Highly ionizing track search, with and without muon ID, using 3 pb^{-1}
  - Track+muon analysis places limits on **stop (398 GeV/c^2)** and **gluino (202 GeV/c^2)**
  - Track-only analysis used to place limits on pessimistic model of complete charge suppression (**gluino excluded < 311 GeV/c^2**)
  - Published in JHEP03 (2011) 024

- Stopped particle search, using 10pb^{-1}
  - Counting experiment **excludes gluinos < 370 GeV/c^2** with 10 μs < τ < 1000s
  - Time profile analysis **excludes gluinos < 382 GeV/c2** for τ =10 μs
  - Published in Phys. Rev. Lett. 106, 011801 (2011)

Backup Slides
(HSCP)

dE/dx estimators

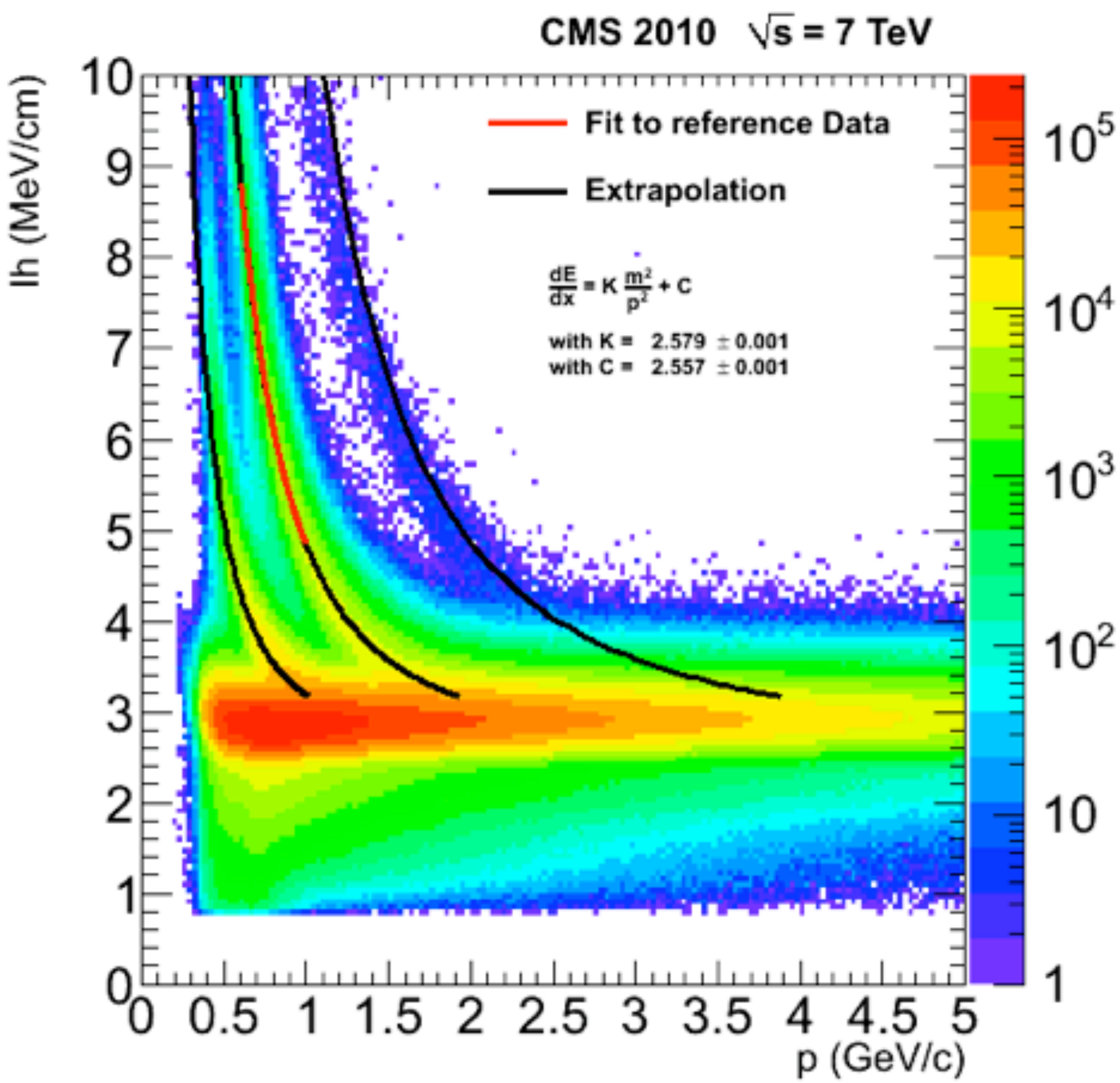
- Mass reconstruction
  - Harmonic 2 estimator

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

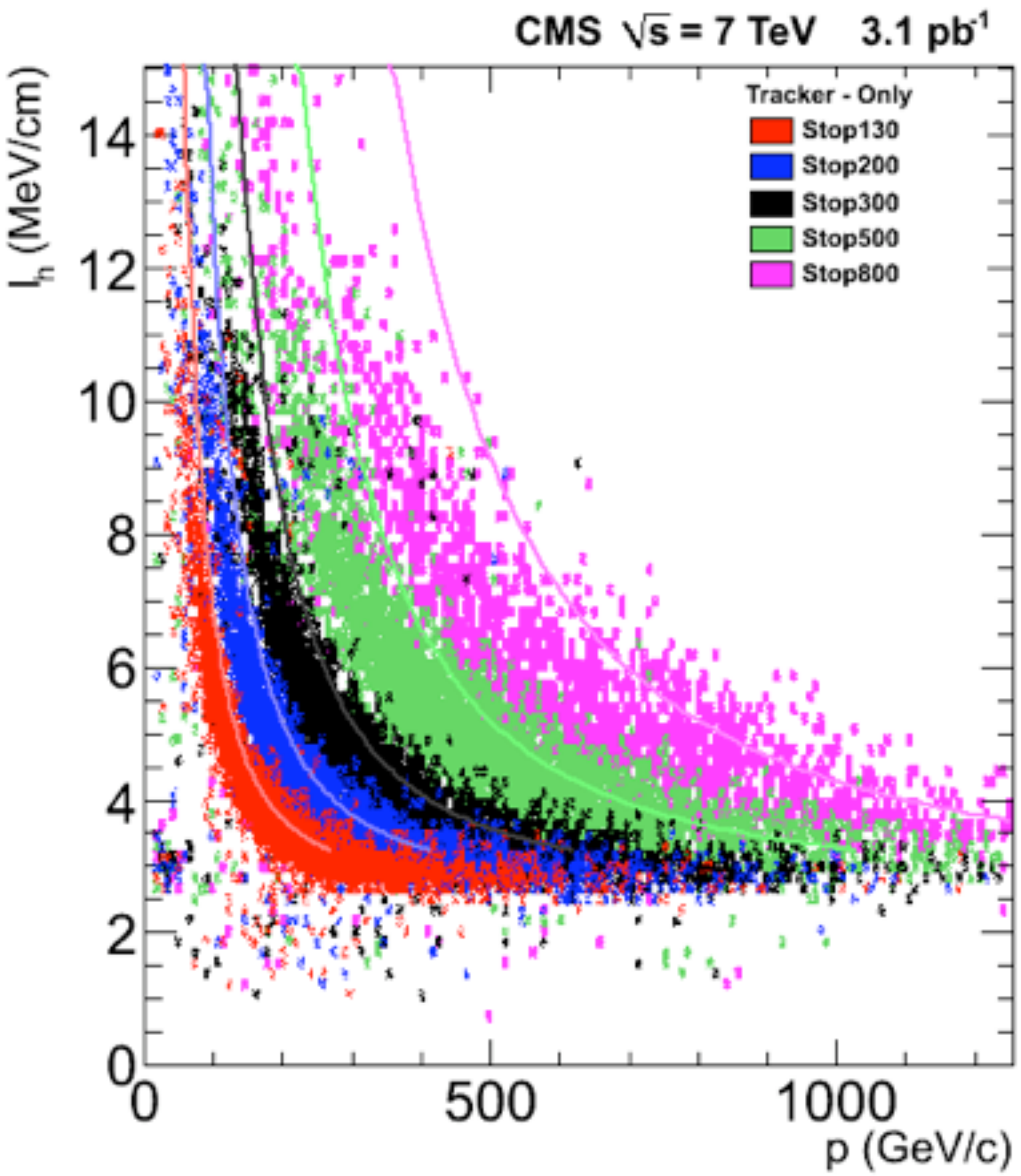
- Event selection
  - Modified Smirnov-Cramer-von Mises estimator

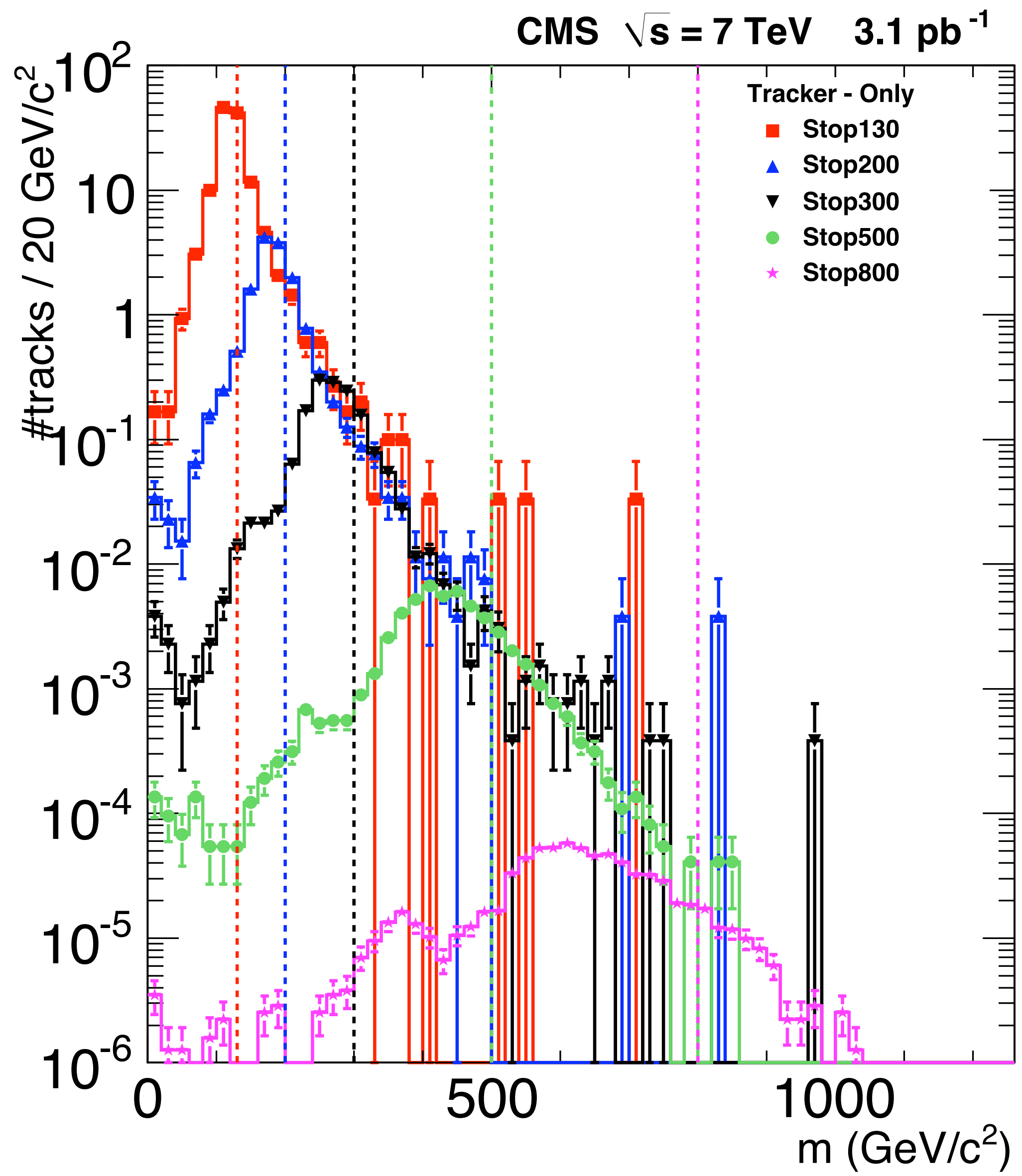
$$I_{as} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{i=1}^{N}\left[P_i \times \left(P_i - \frac{2i-1}{2N}\right)\right]^2\right)$$

  - 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



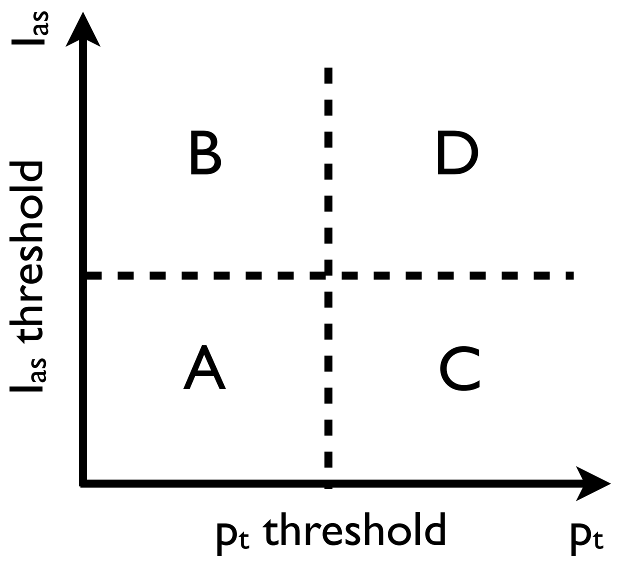
Mass Reconstruction

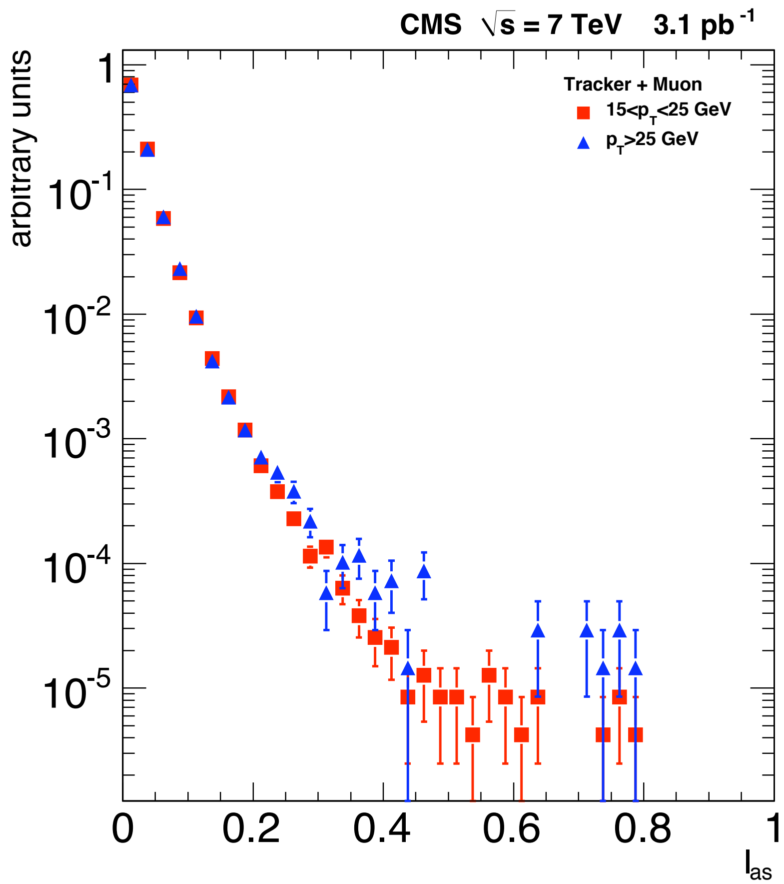


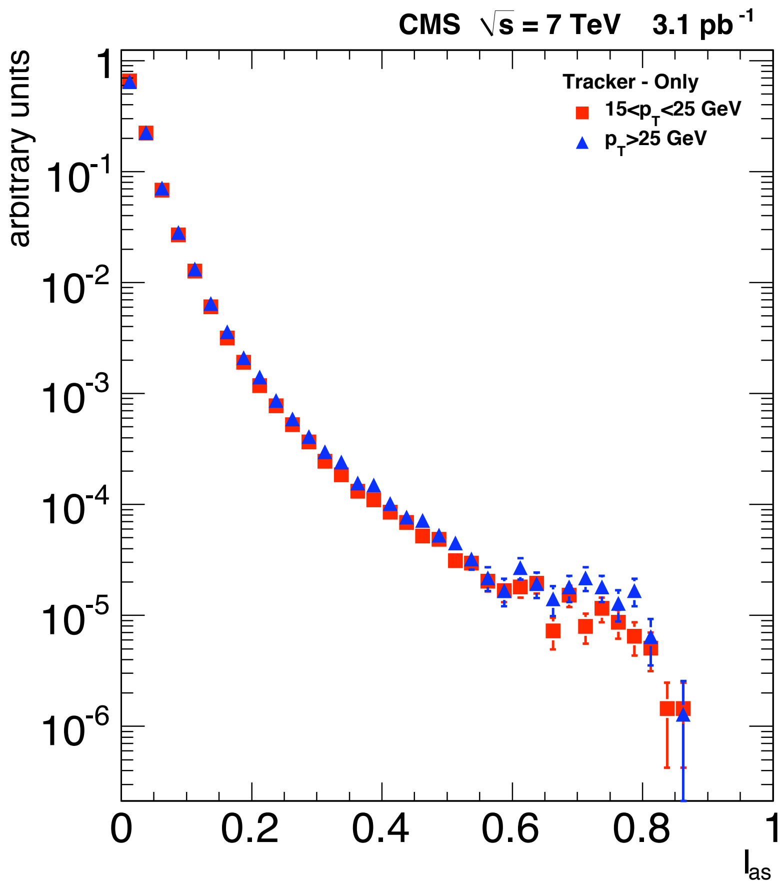


- I_h vs p, and reconstructed mass distribution for stop MC samples
  - Reconstructed tracks matched to the MC truth stop
  - Bias at high mass is due to ADC saturation
    - Does not affect this analysis, which is purely a counting experiment

Background Determination







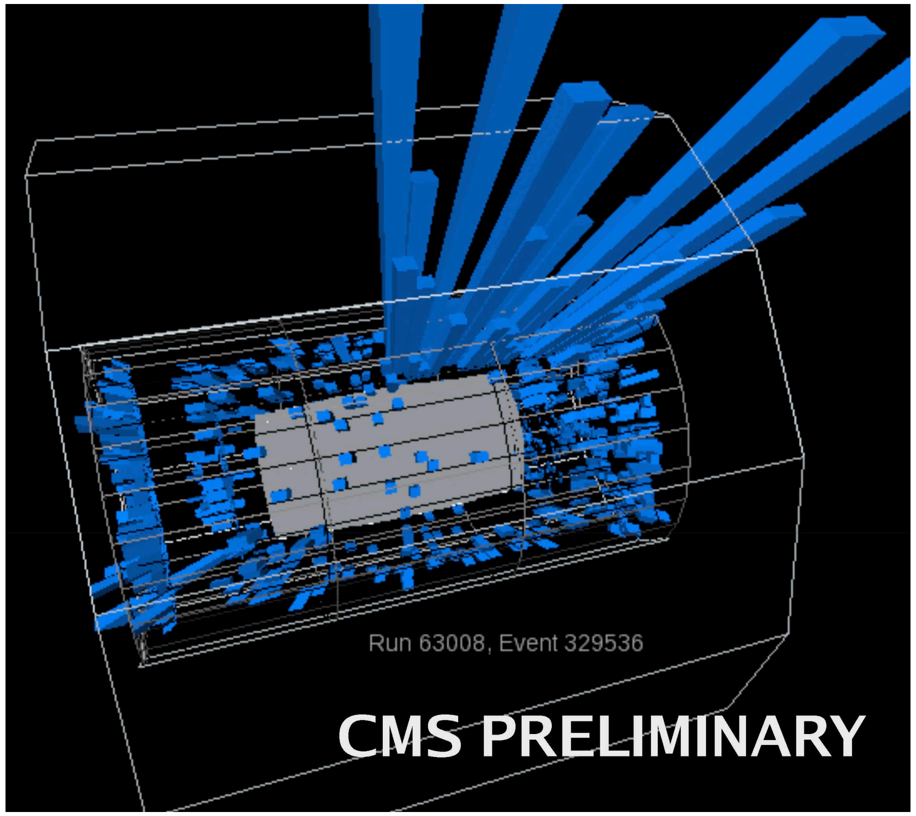
- Background for each (N_{hits}, η) bin is determined using an "ABCD" method
  - Background in signal region, D = BC/A
  - This relies on non-correlation of p_t and dE/dx measurements
  - Shown above, I_{as} distribution for two pt ranges
  - This method is extended to also predict the expected background 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

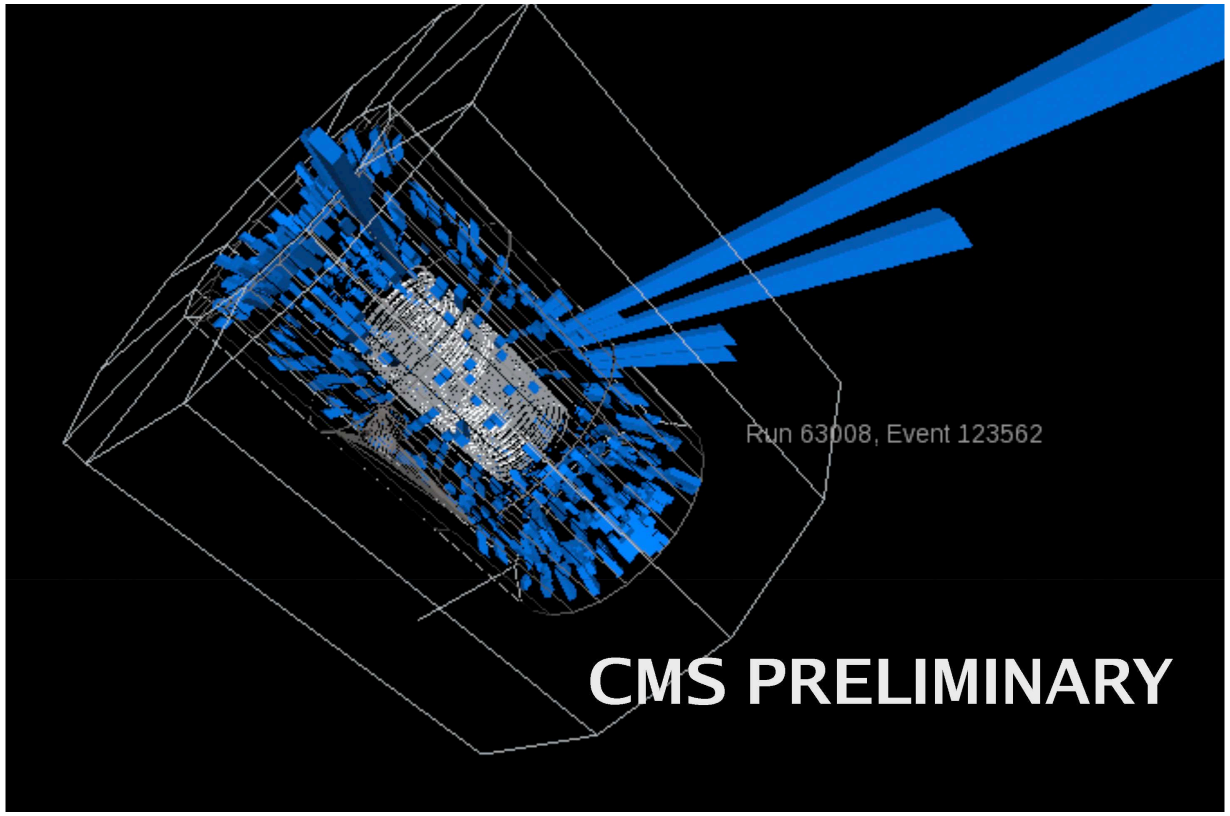
Systematics

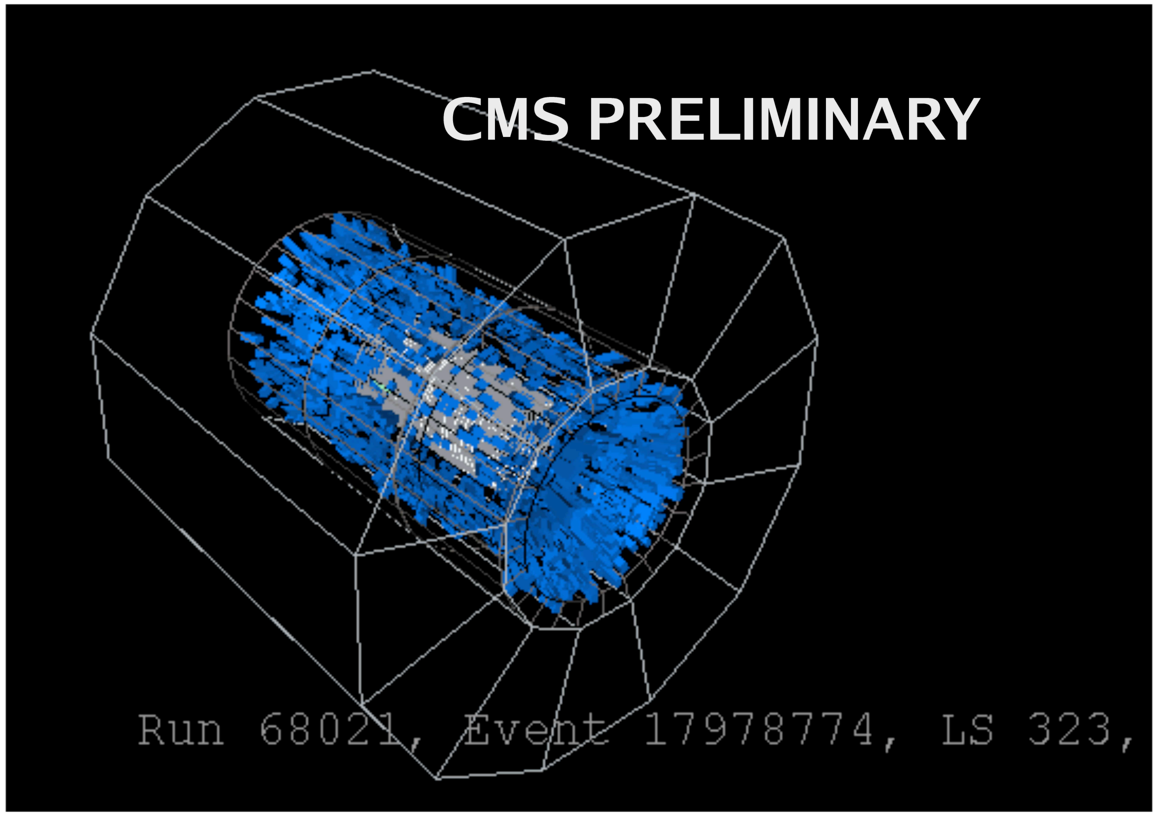
Source of Systematic Uncertainty	%
Theory cross-section	10-25
Int Luminosity	11
Trigger efficiency	12
Muon reco efficiency	5
Track reco efficiency	<5
p_T scale	<5
dE/dx scale	<3
Total efficiency	15

Backup Slides
(Stopped Gluinos)

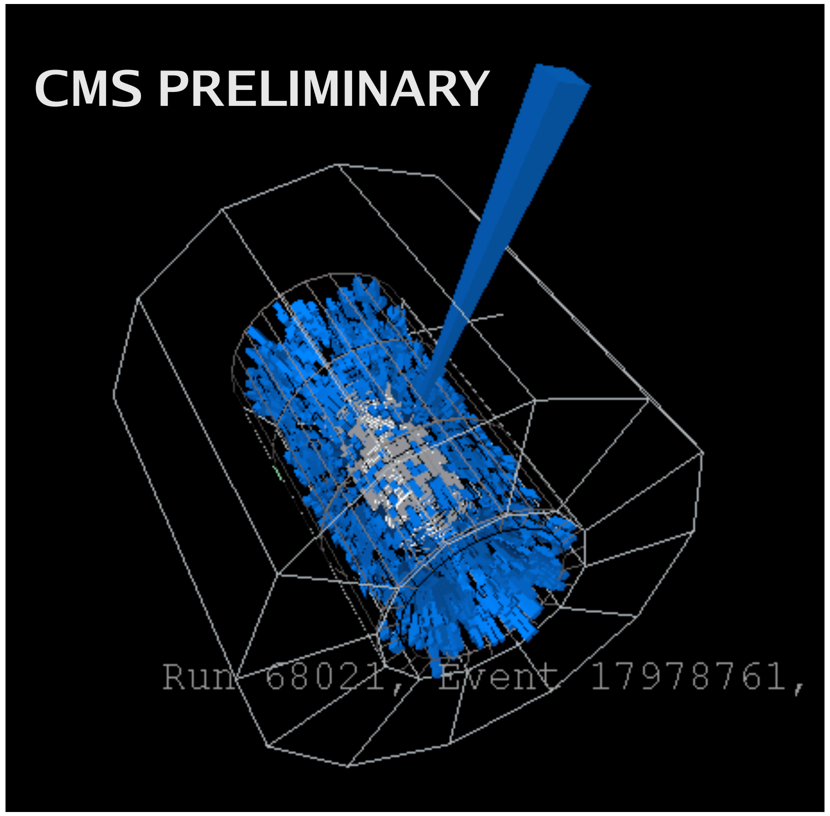
Know Thy Enemy







Noise events from 2008 cosmic data



Systematics

Source of Systematic Uncertainty	%
Background estimation	23
E_t scale	7
Int Luminosity	11