Search for Displaced Leptons using the CMS Detector

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For the CMS Collaboration

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Caffeine is Our Best Friend

古人云：“望咖而止困”

As a proverb goes, “stare at the coffee and stay awake”

Motivation for Long-lived Searches

I. The discovery of the Higgs boson is a great victory of the Standard Model (SM), but it is not the end of the story(hierarchy problem, etc)……

   Many extensions to the Standard Model have been proposed and many searches targeting those models have been conducted, especially for one of the most popular models known as Supersymmetry(SUSY).

II. SUSY becomes more and more constrained by searches done both in CMS and ATLAS.

III. However, new physics might be overlooked since:

   1. Most of the previous searches are concentrated on prompt products.
   2. Most of the previous searches are assuming the lightest super symmetric particle(LSP) can not decay(R-Parity conservation), leading to large missing energy in the detector.

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"Leave no stone unturned"

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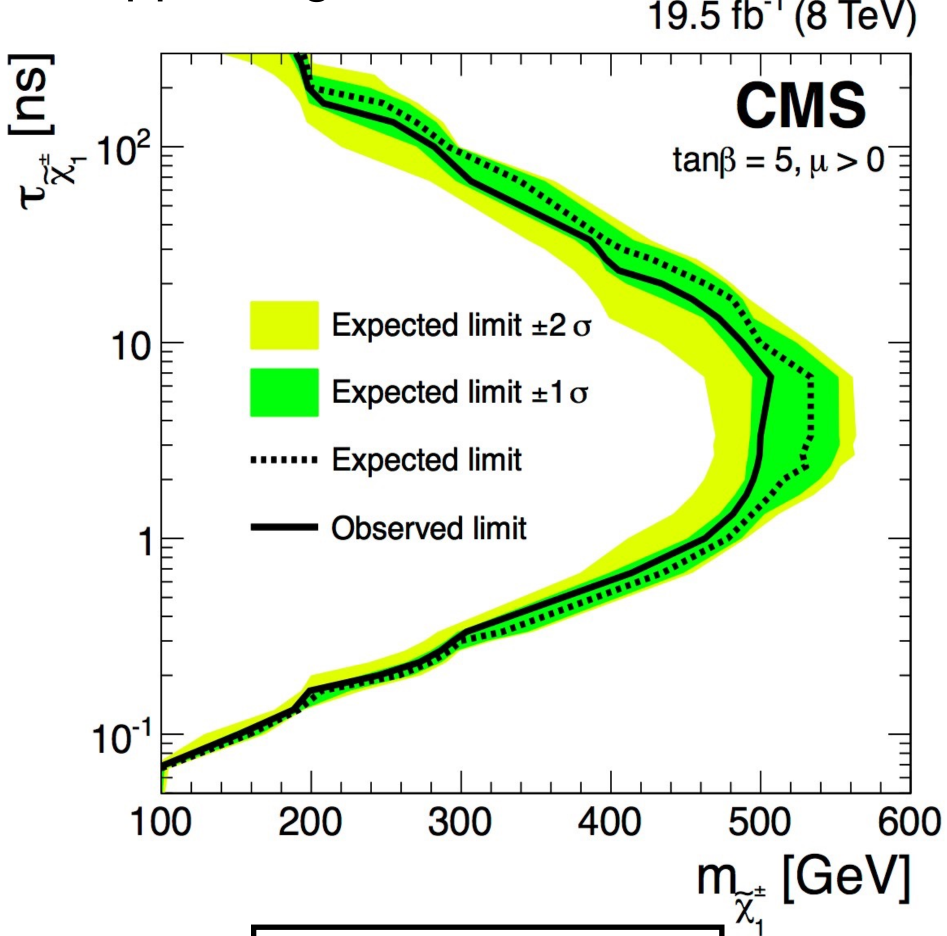
Motivation for This Search

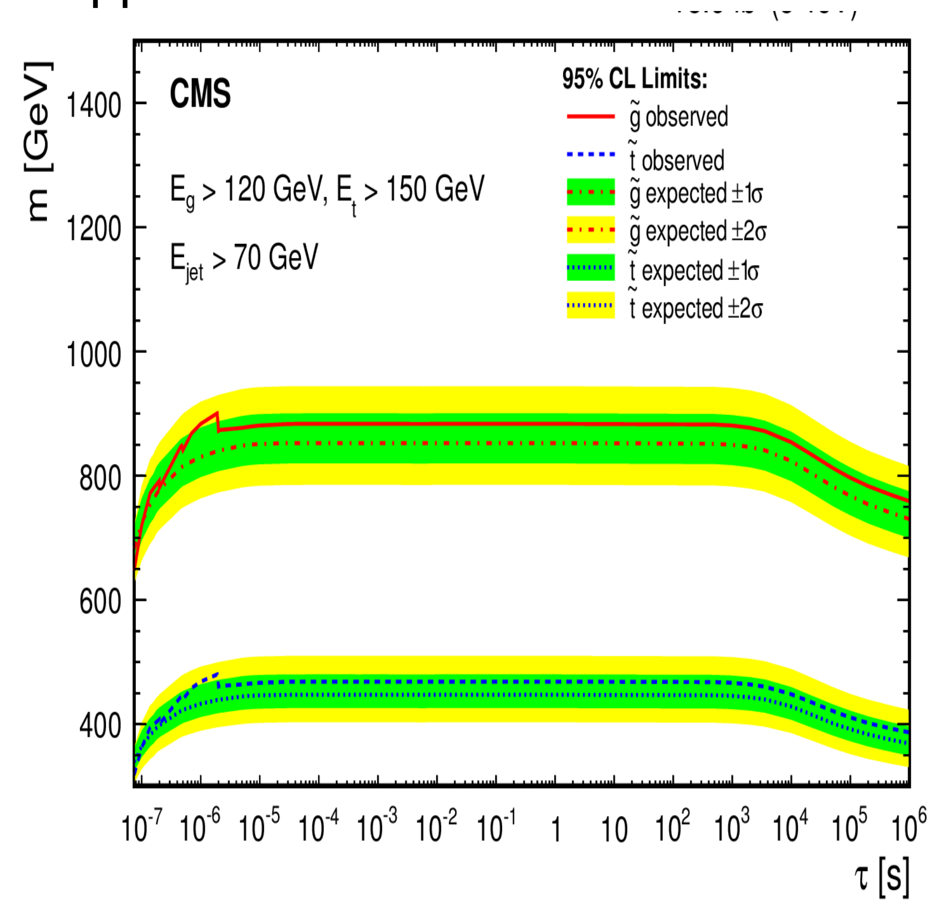
Several analyses in CMS are searching for non-prompt signatures, however, there are gaps not covered especially in the relatively shorter lifetime regime.

Disappearing Track



JHEP01(2015)096

Stopped Particle

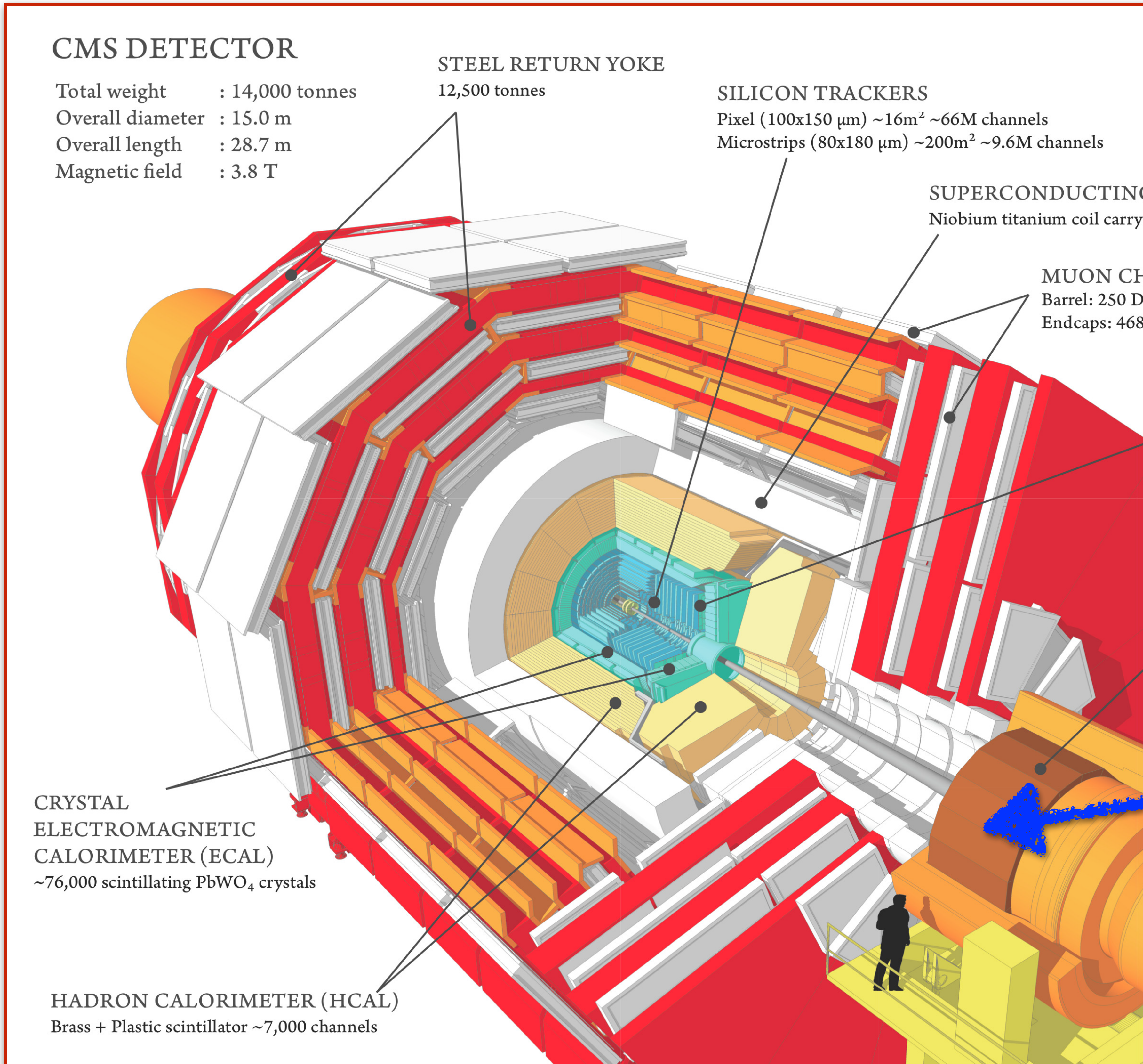


EPJC (2015) 75:151

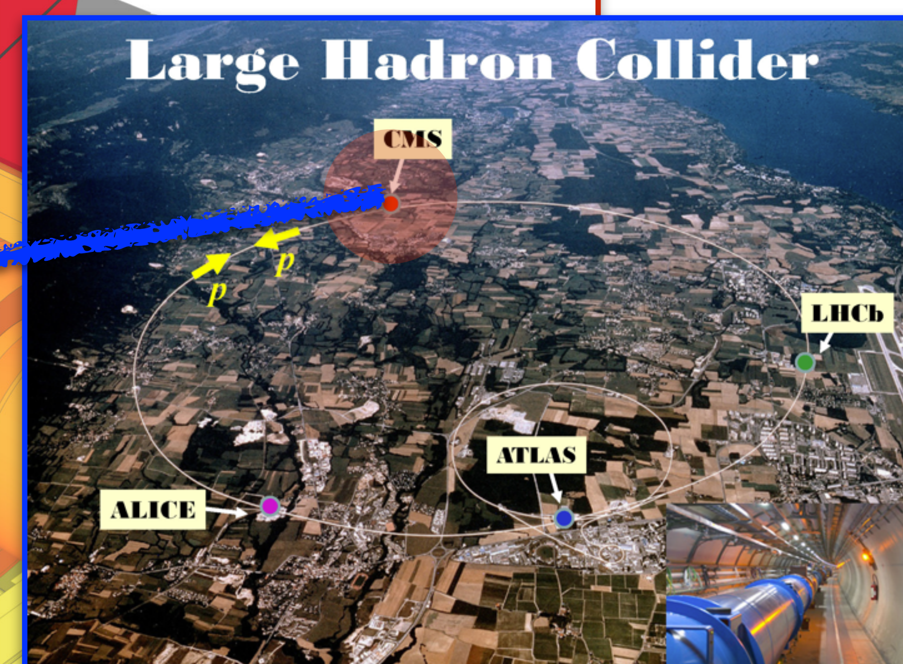
This search is focusing on the gap between prompt and very long-lived signatures. In addition, it is designed to use simple and standard event selections.

The LHC and CMS

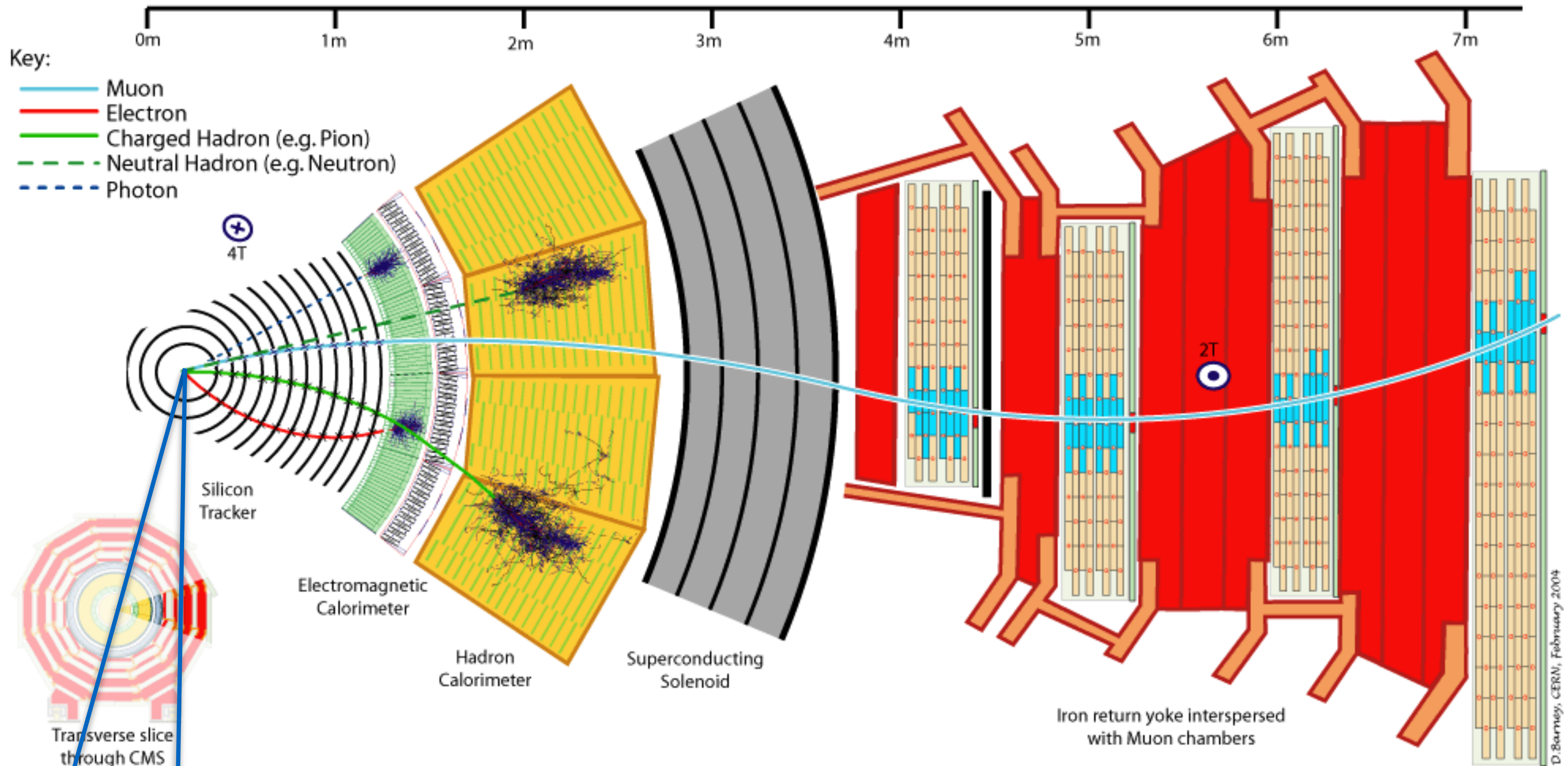
The LHC and CMS



Sectional View of the CMS detector

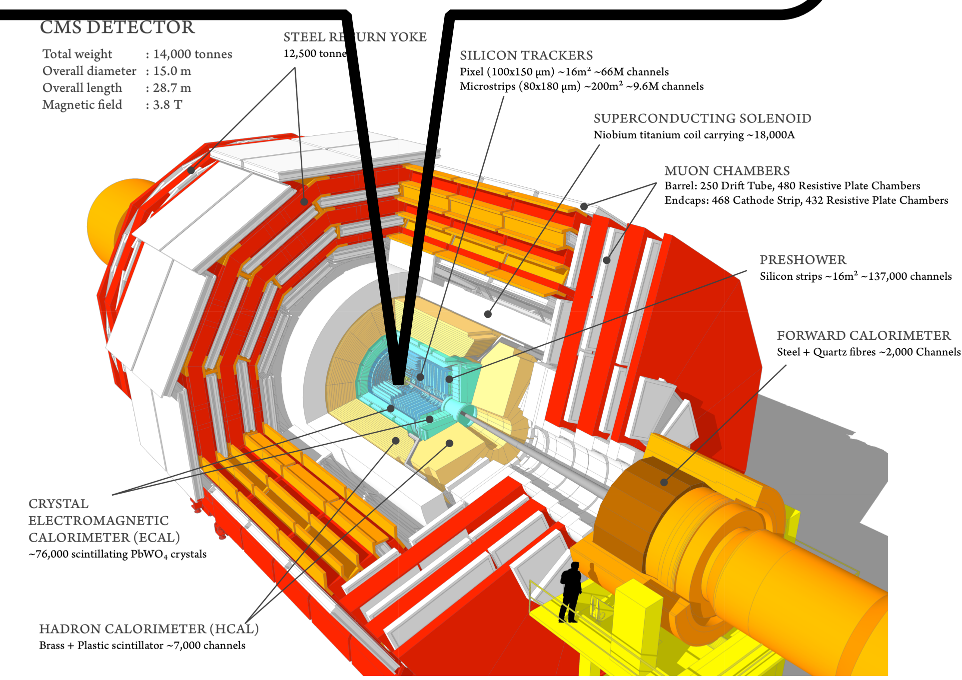


The LHC and CMS



Transverse view of CMS

Three layers of silicon pixels not drawn in this small region (4-11 cm to the beam).
Let's have a closer look.



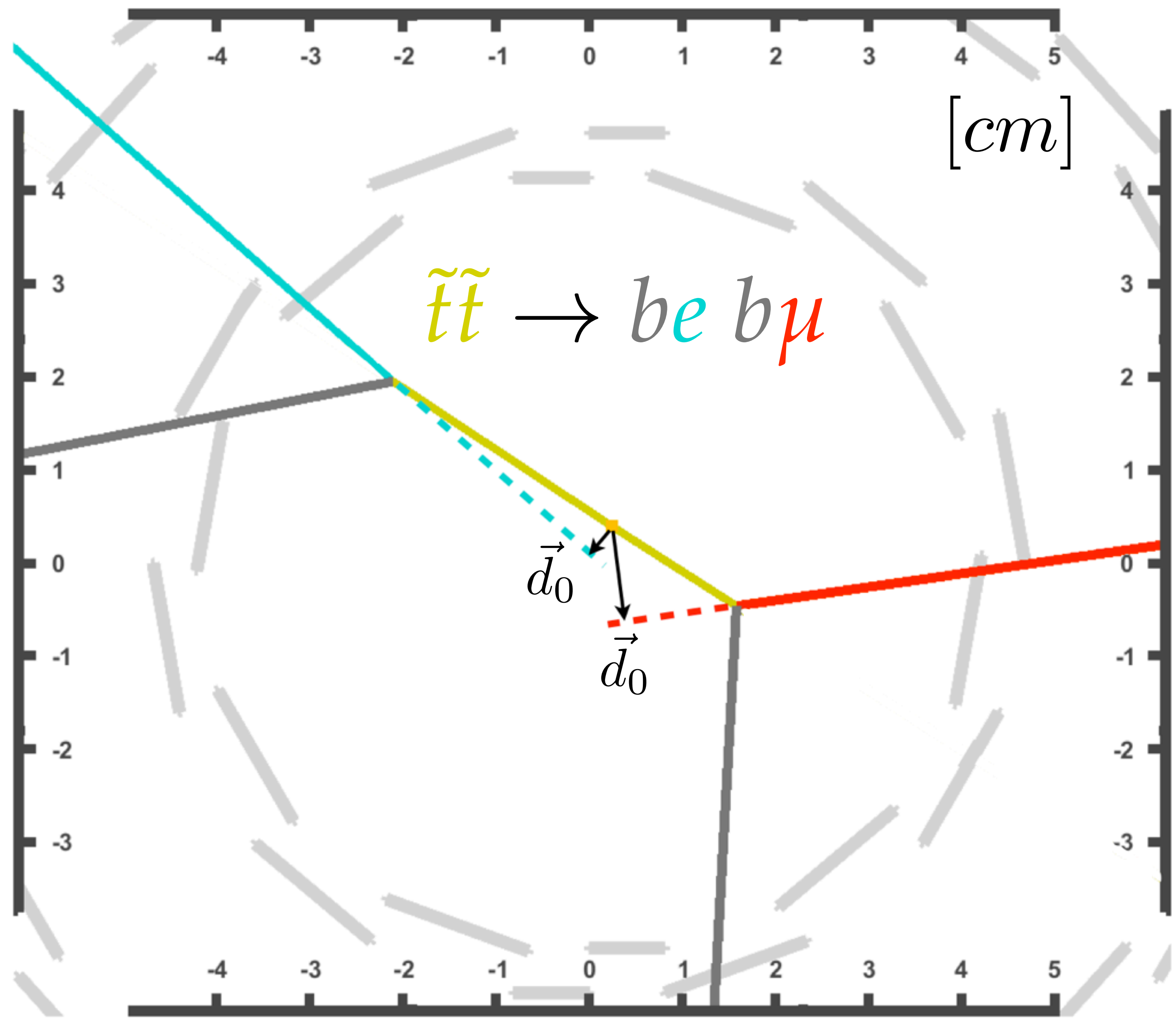
Theory Model and Experimental Signature

Theory model:
Displaced Supersymmetry
arXiv:1204.6038v1

Key features of the model:
LSP can decay
LSP can have long lifetime
(R-Parity Violating)

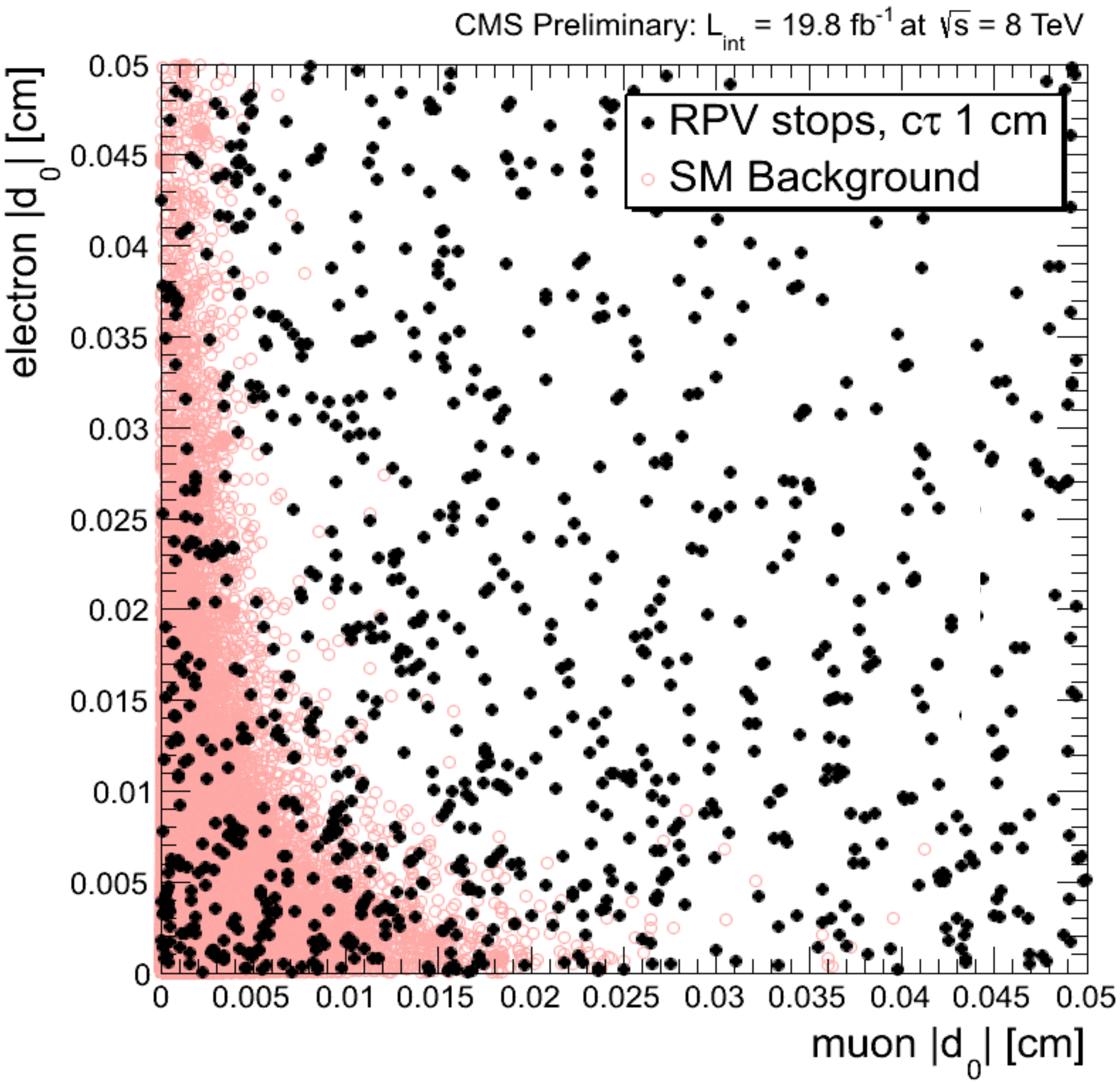
Benchmark:
We consider the **top squark** as the LSP, decaying to **a bottom quark** and a lepton.

Final state:
An **electron** and a **muon**.



Leptons from top squark will have large impact parameters(|d0|) due to top squarks' long lifetime.

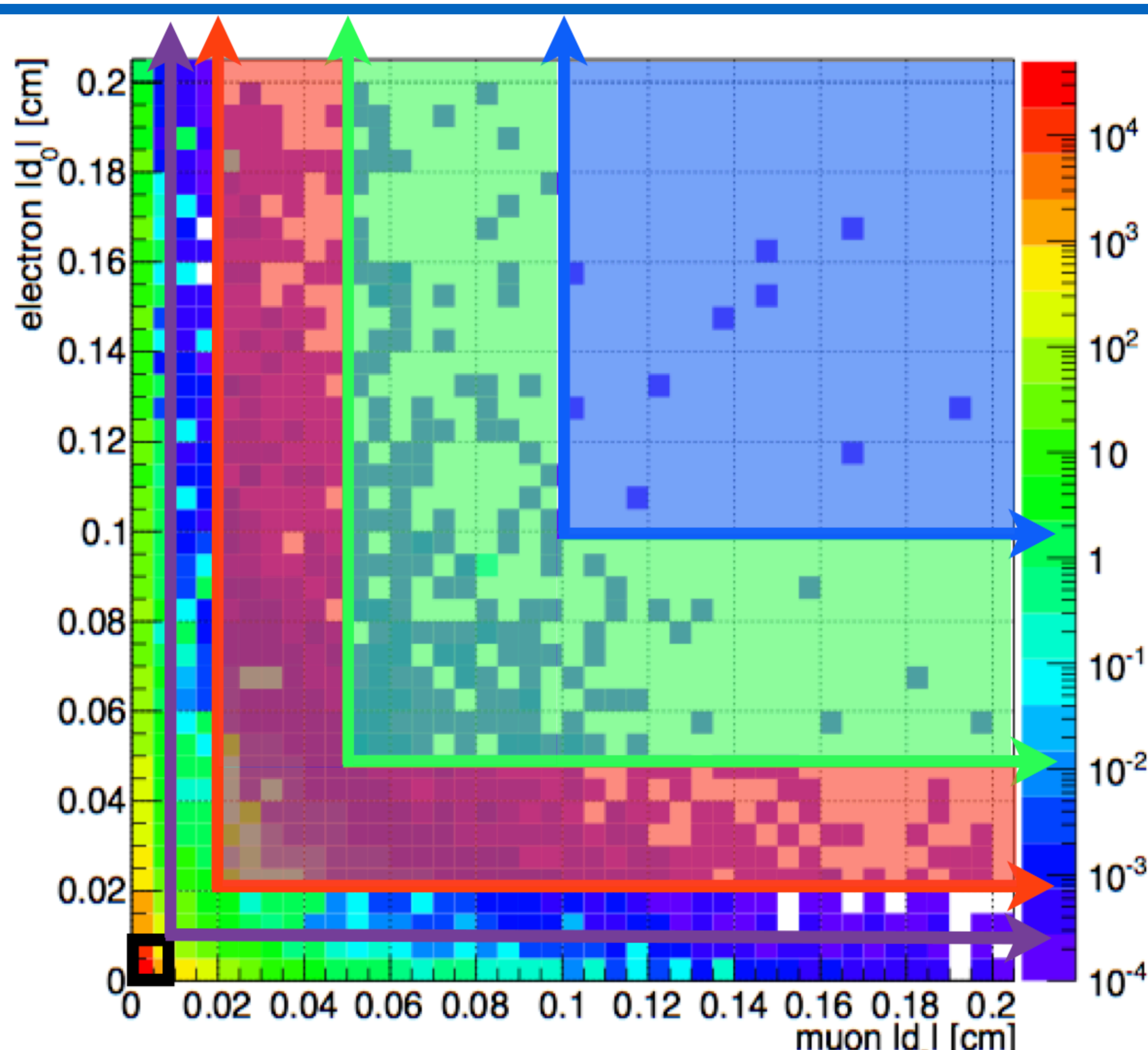
Run 1 Search Strategy in a Nutshell: Discriminating Variable



- Distributions of **SM background** and **signal** events in μ |d0|-e |d0| 2-D plane.
- Impact parameter is a powerful discriminating variable!

Run 1 Search Strategy in a Nutshell: Region Definitions

- Background: W+jets, $t\bar{t}$, DY, single top, diboson, QCD
- $Z \to \tau\tau$ and heavy flavor QCD (HF) contribute more given their relatively longer lifetimes.
- The fraction of each background changes as the impact parameters of the leptons increase.



- Prompt control region($|d0| < 0.01$ cm): Check the analysis setup such as normalization, corrections to MC, etc.
- Displaced control region($|d0| > 0.01$ cm): Perform data-driven background estimate and the closure test
- Three non-overlapping search regions:
  SR III: Both 0.10 cm < $|d0|$ < 2 cm
  SR II: Both 0.05 cm < $|d0|$ < 2 cm but not in SR III
  SR I: Both 0.02 cm < $|d0|$ < 2 cm but not in SR II or III

Run 1 Background Estimates

- W+jets, $t\bar{t}$, DY, single top, diboson are estimated using Monte Carlo (MC) simulations.
- Apply a data-driven method ("ABCD" method) to estimate contribution from HF:

A isolated SS	B isolated OS
C anti-isolated SS	D anti-isolated OS

Benchmark signal considered has isolated, oppositely charged (OS) lepton pairs, populating in region **B**.

Inverting the isolation or/and OS increases the contribution from HF in **A**, **C** and **D**.

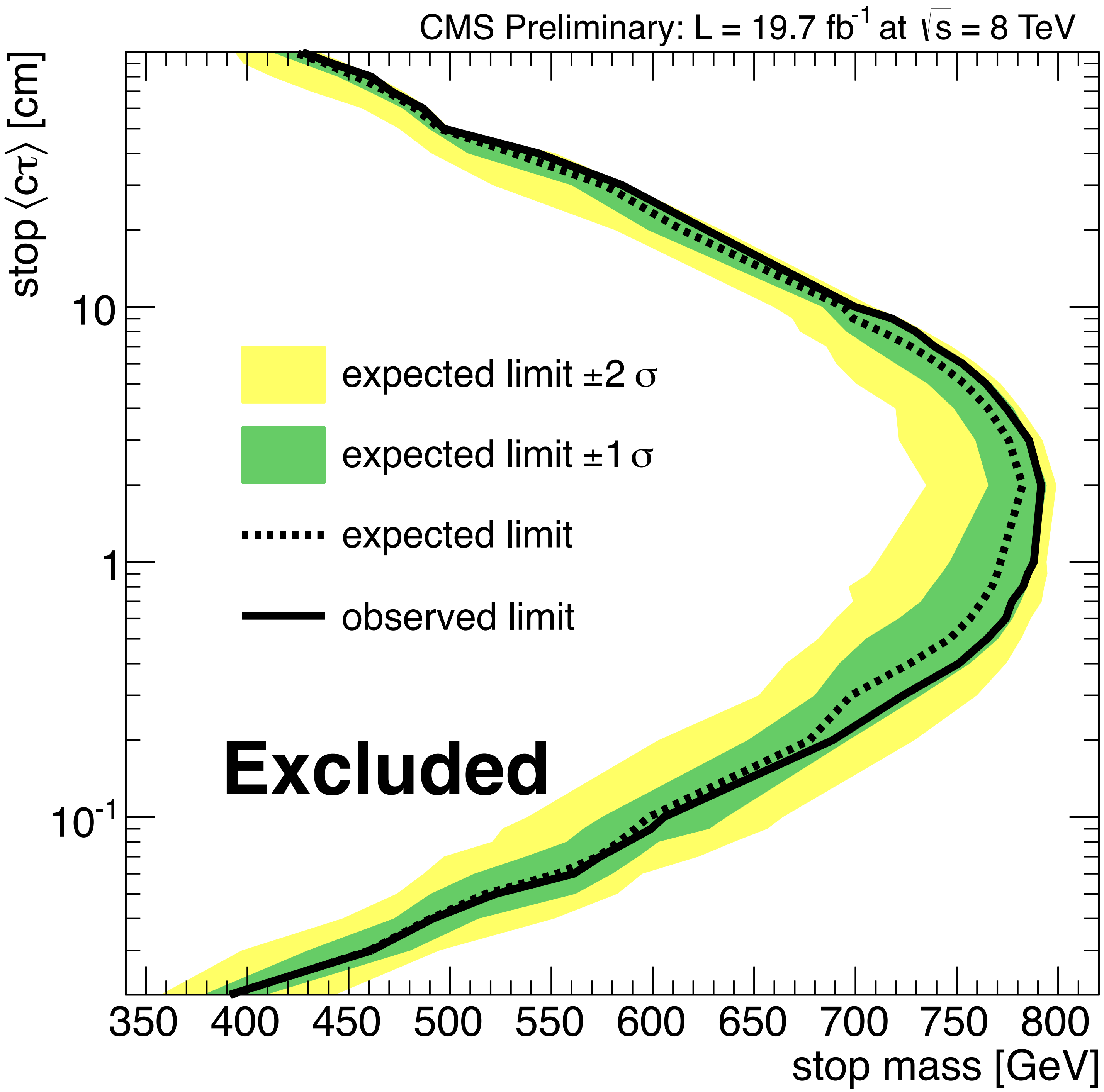
$$\frac{A}{C} = \frac{B}{D} \qquad B = \frac{A}{C} \times D$$

Run 1 Results: Yields Table

Event source	SR1	SR2	SR3
Other EW	$0.65 \pm 0.13 \pm 0.09$	$(0.89 \pm 0.53 \pm 0.12) \times 10^{-2}$	$<(89 \pm 53 \pm 12) \times 10^{-4}$
Top quark	$0.77 \pm 0.04 \pm 0.08$	$(1.25 \pm 0.26 \pm 0.12) \times 10^{-2}$	$(2.4 \pm 1.3 \pm 0.2) \times 10^{-4}$
$Z \to \tau\tau$	$3.93 \pm 0.42 \pm 0.39$	$(0.73 \pm 0.73 \pm 0.07) \times 10^{-2}$	$<(73 \pm 73 \pm 7) \times 10^{-4}$
HF	$12.7 \pm 0.2 \pm 3.8$	$(98 \pm 6 \pm 30) \times 10^{-2}$	$(340 \pm 110 \pm 100) \times 10^{-4}$
Total expected bkgd.	$18.0 \pm 0.5 \pm 3.8$	$1.01 \pm 0.06 \pm 0.30$	$0.051 \pm 0.015 \pm 0.010$
Observed	19	0	0
$pp \to \tilde{t}\tilde{t}^*$ ($M_{\tilde{t}} = 500\,\mathrm{GeV}$)			
$c\tau = 0.1\,\mathrm{cm}$	$30.1 \pm 0.7 \pm 5.3$	$6.54 \pm 0.34 \pm 1.16$	$1.34 \pm 0.15 \pm 0.24$
$c\tau = 1\,\mathrm{cm}$	$35.3 \pm 0.8 \pm 6.2$	$30.3 \pm 0.7 \pm 5.3$	$51.3 \pm 1.0 \pm 9.0$
$c\tau = 10\,\mathrm{cm}$	$4.73 \pm 0.30 \pm 0.83$	$5.57 \pm 0.32 \pm 0.98$	$26.3 \pm 0.7 \pm 4.6$

- Observation is consistent with the background estimate. No significant excess is observed.

Run 1 Results: Limit



- Limits are set on the DisplacedSUSY benchmark model.
- For a top squark life-time of 2 cm, the top squark mass is excluded up to 790 GeV.
- Most stringent limit set on this model **at that time**. First displaced lepton search without requiring a common vertex.

Published:
[Phys. Rev. Lett. 114, 061801]
Fermilab Today:
[Off the Beaten Path]

Run2 Analysis

Lessons learned from Run1 analysis:

I. The search power of the analysis is limited by the high level trigger and reconstruction performance.

II. Several selections on the event topologies put constraints on the search such as extra lepton veto, oppositely charged lepton pair, and lepton isolation.

III. Other final states like di-μ, and di-e are worth investigating.

Strategies for Run2 analysis:

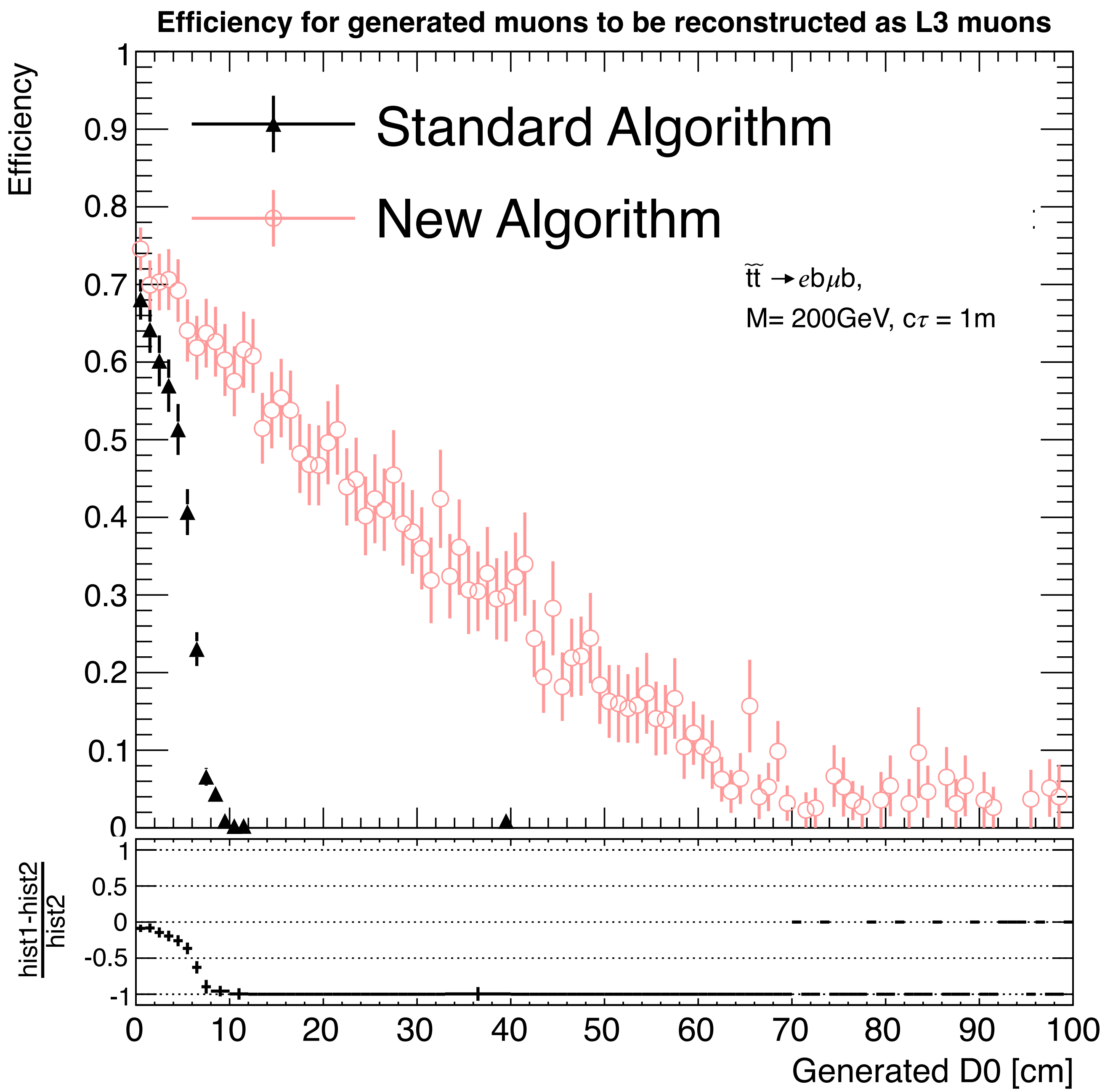
I. Develop dedicated high level trigger and reconstruction algorithms.

II. Design new data-driven QCD background estimation method as most of the selections mentioned above are introduced because because of the data-driven method.

III. Perform searches in the di-μ, and di-e final states.

Displaced Muon Trigger Improvement

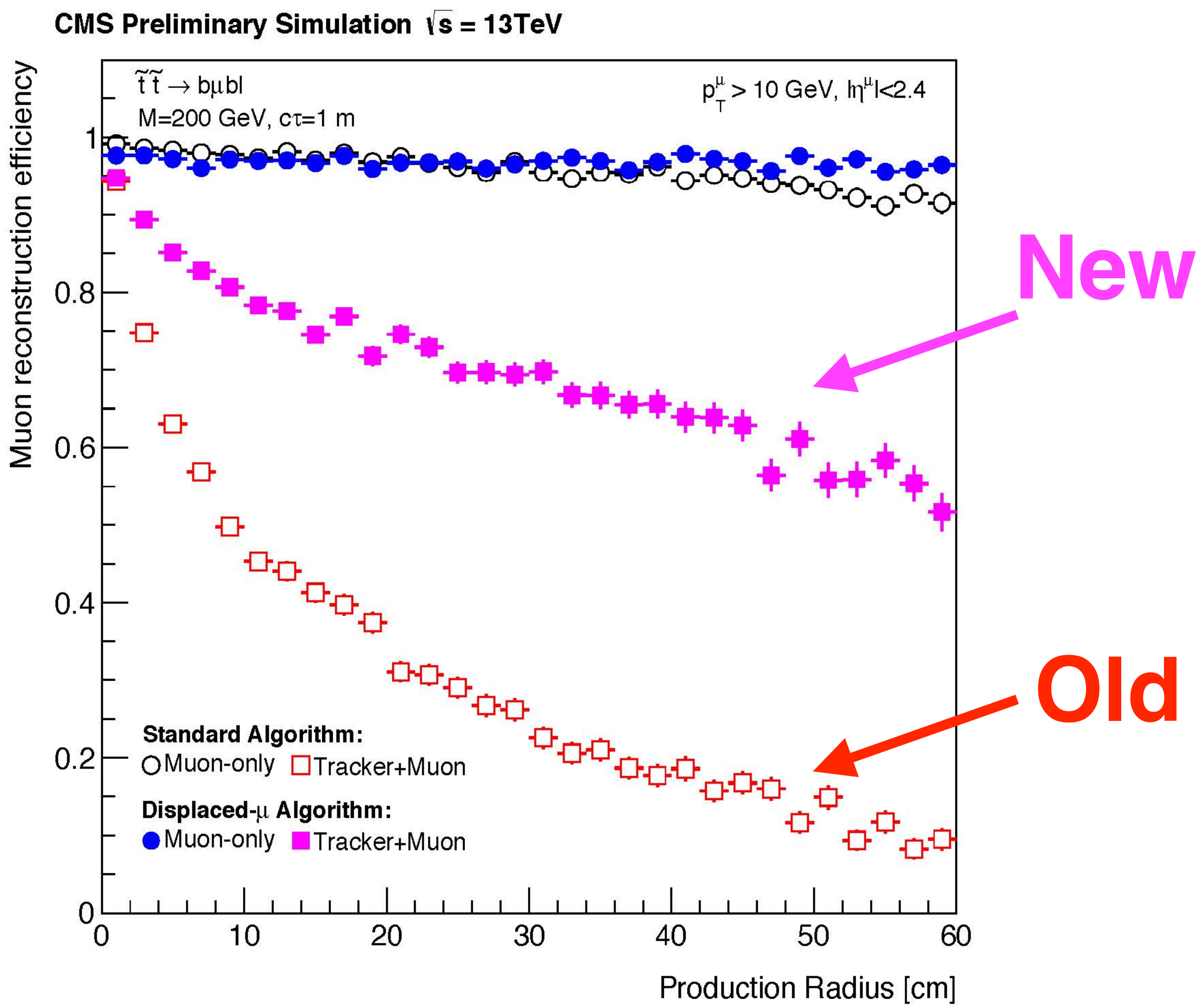
Private work



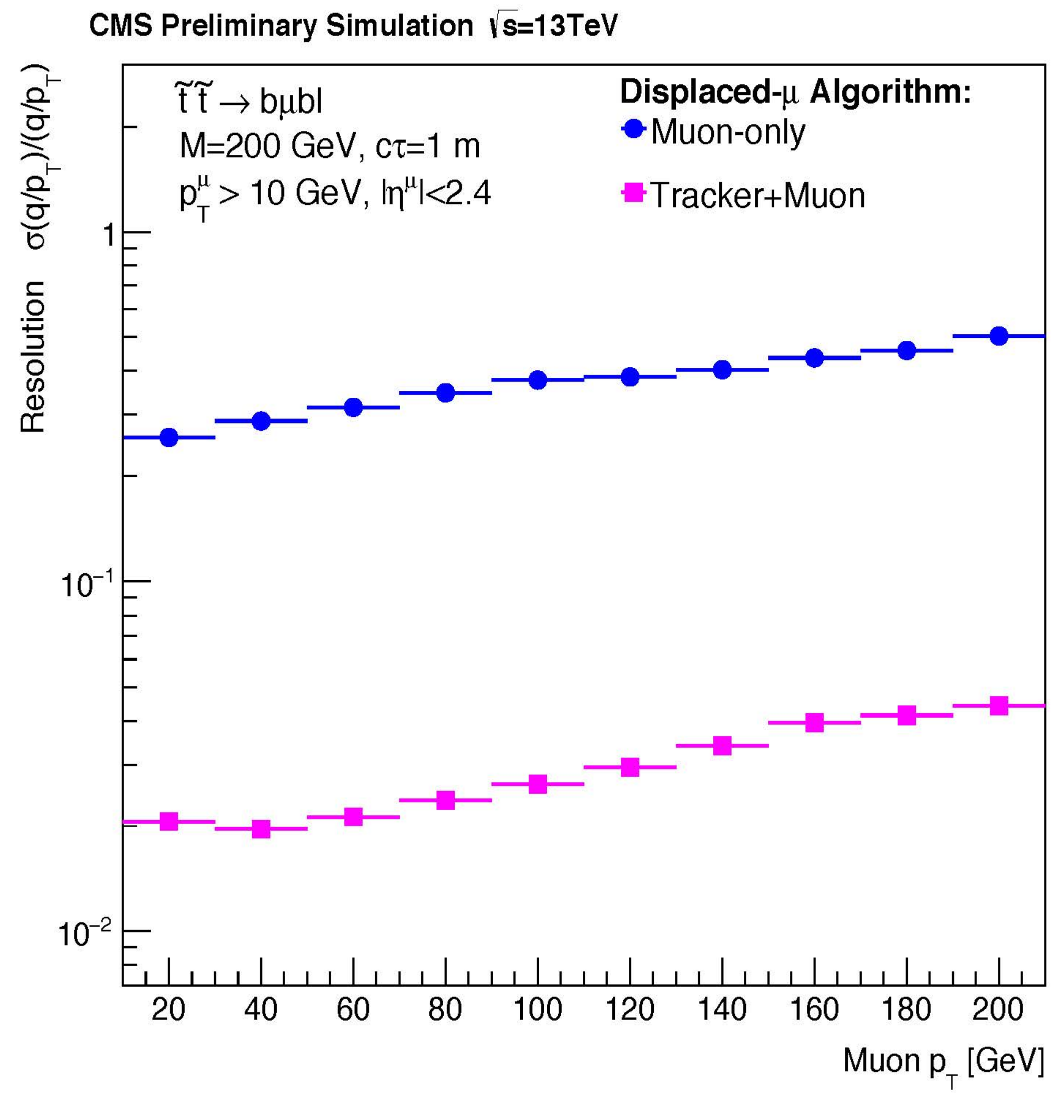
- Developed a special high level trigger algorithm (the red curve) to increase the efficiency for displaced muons.
- The performance is much better than that of the standard HLT algorithm.
- This greatly increases the sensitivity to particles with longer life-time.
- This algorithm is used in multiple HLT paths by several analysis teams.

Displaced Muon Reconstruction Improvement

Efficiency w.r.t Production Radius



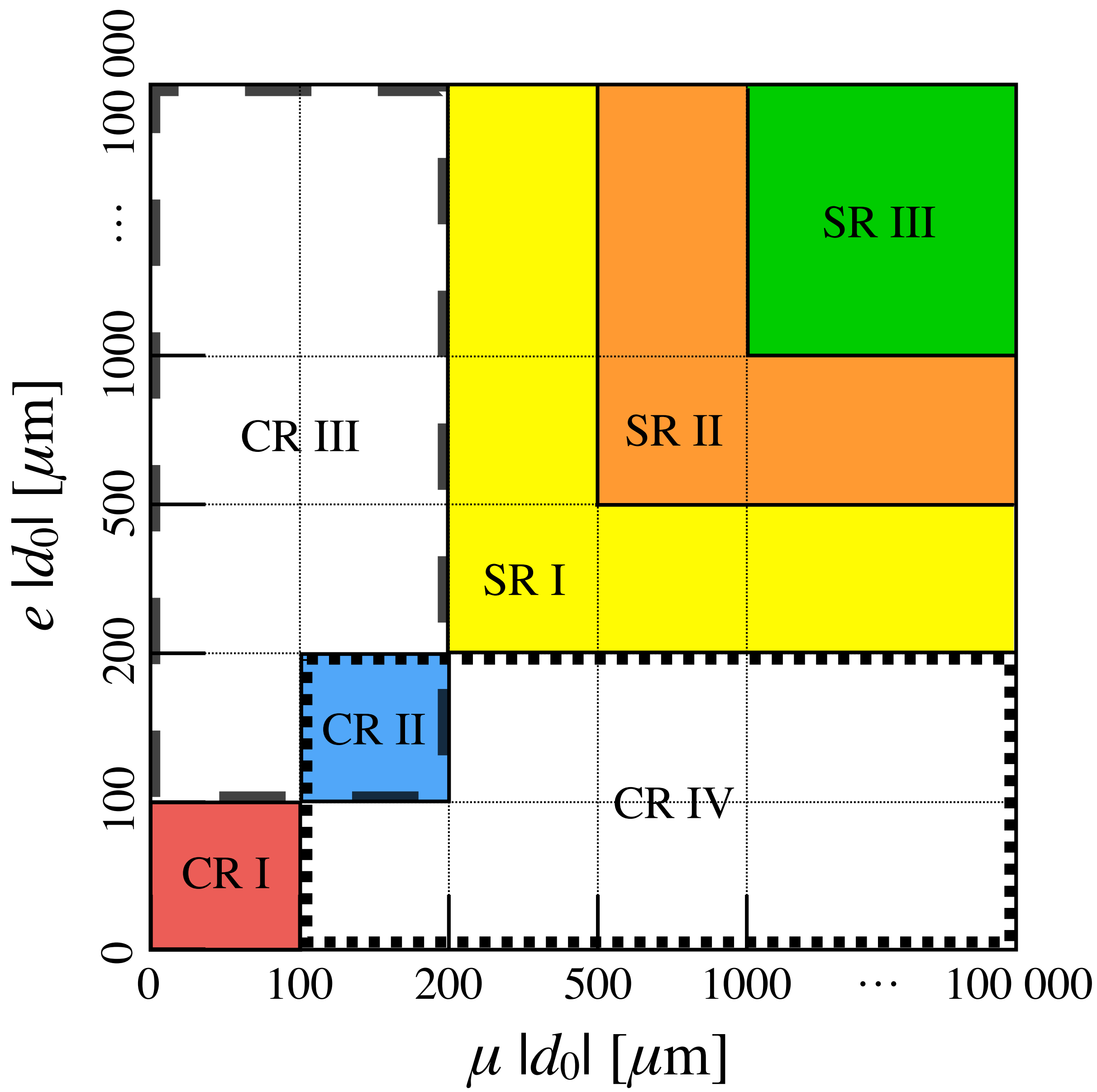
pT Resolution w.r.t pT



CMS DP -2015/015

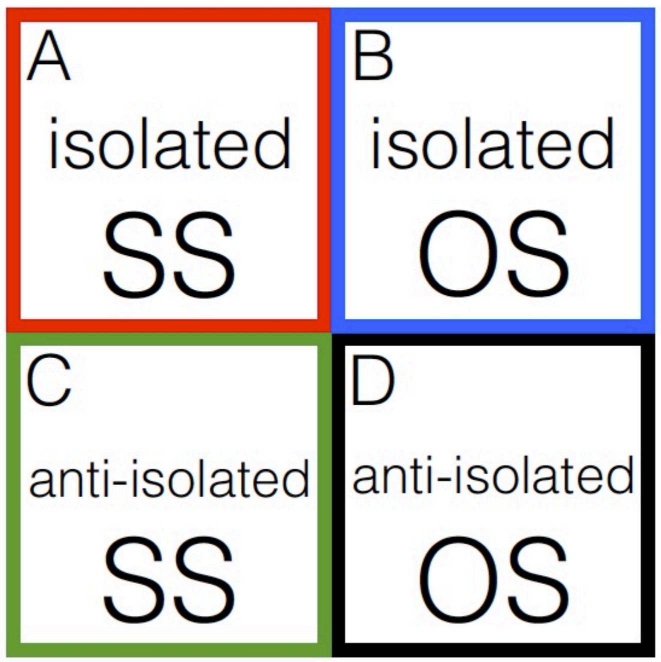
- Developed a dedicated reconstruction algorithm for displaced muon.
- The efficiency for muons with large impact parameter is increased greatly.

Run 2 Search Strategy in a Nutshell: Region Definitions



- Prompt control region(|d0| < 100 um): Check the analysis setup such as normalization, corrections to MC, etc.
- Displaced control region(100 cm < |d0| < 200 um): Perform data-driven background estimate
- Three non-overlapping search regions:
  - SR III: Both |d0| > 1000 um
  - SR II: Both |d0| > 500 um but not in SR III
  - SR I: Both |d0| > 200 um but not in SR II or III
- Displaced Electron Control Region (CR III)
  e: |d0| > 100 um, μ: |d0| < 200 um
- Displaced Muon Control Region (CR IV)
  e: |d0| < 200 um, μ: |d0| > 100 um

New HF Data-driven Estimation Method

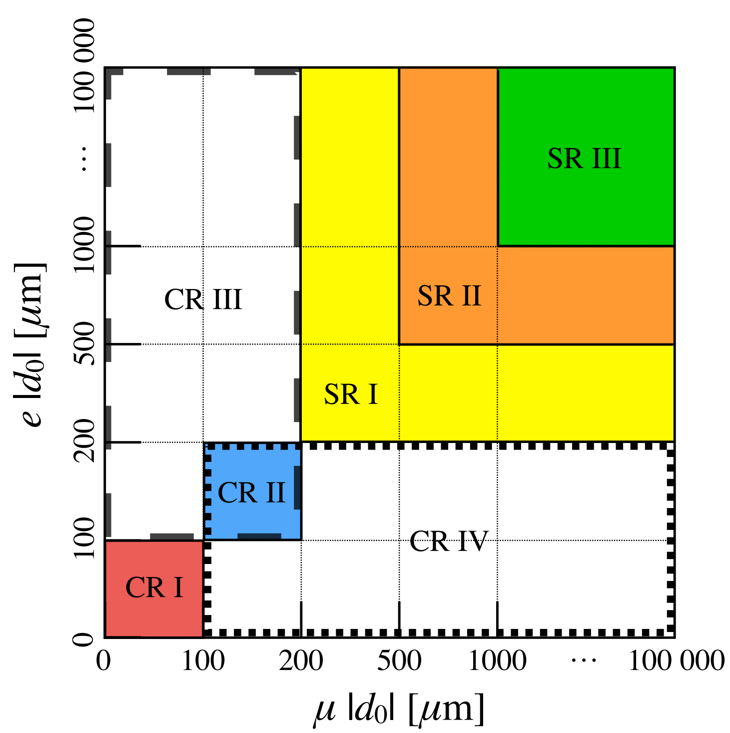


Old Method

- The "ABCD" method used in Run 1 worked well, however:

  The two variables used in defining the orthogonal regions (A,B,C,D) are model dependent.

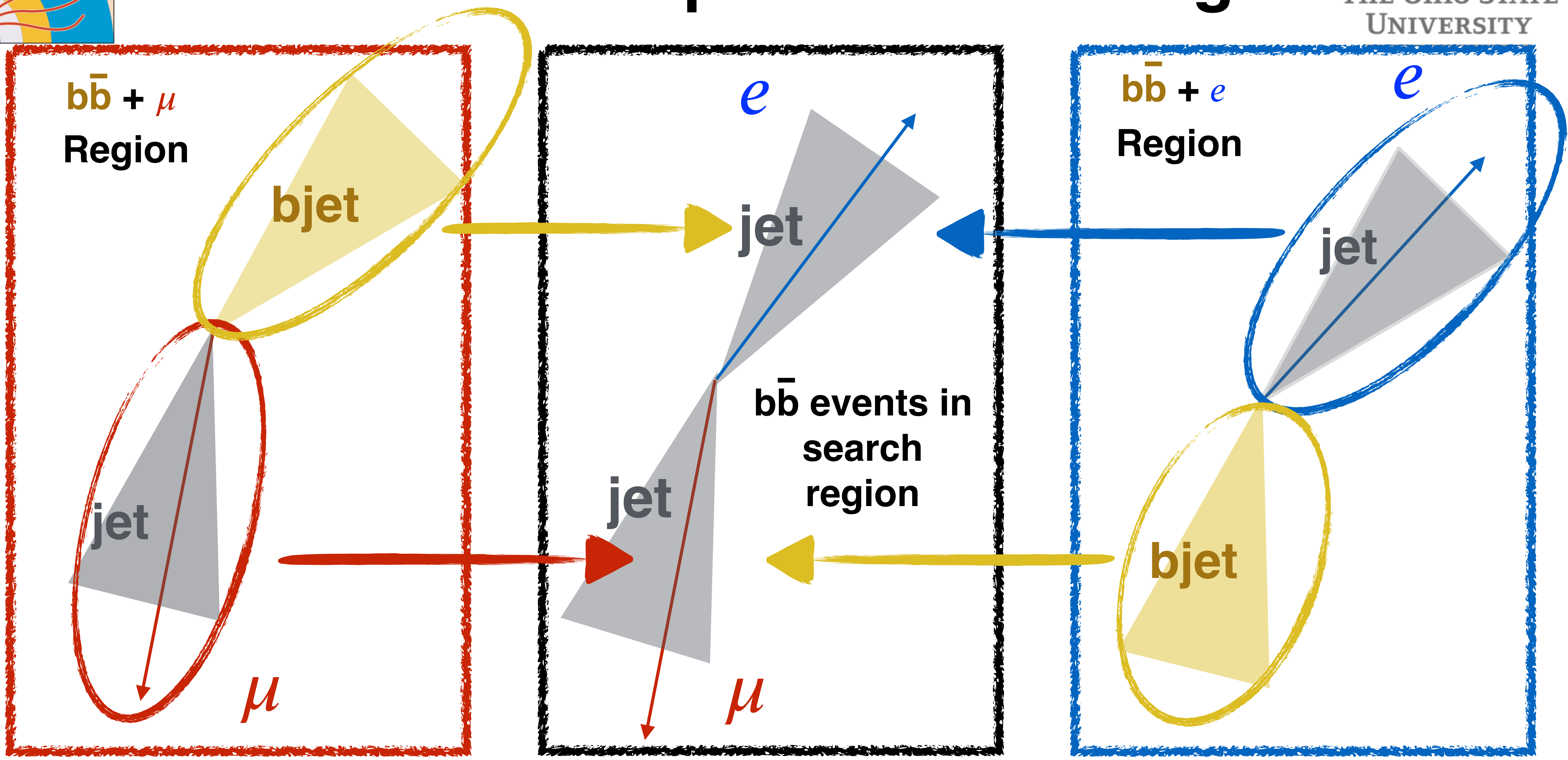
  Same strategy only works for signals with isolated, oppositely charged lepton pairs in the final state.



New Method

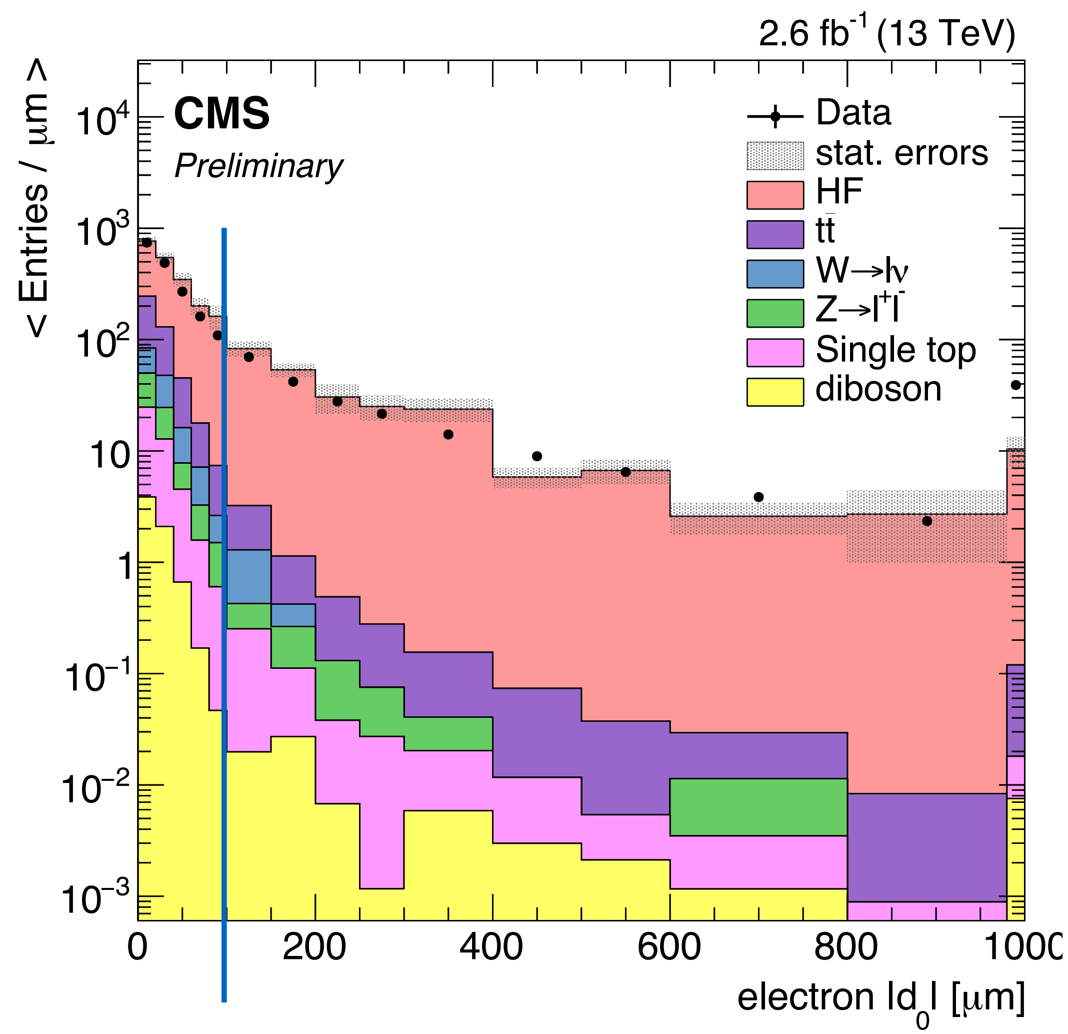
- Get the HF normalization in CR II, N_{HF}
- Scale N_{HF} to the search regions
- The scale factors are calculated using the impact parameter shapes in HF lepton enriched control regions.
- Validated in Displaced Electron (Muon) Region.

Construct HF + lepton Control Region

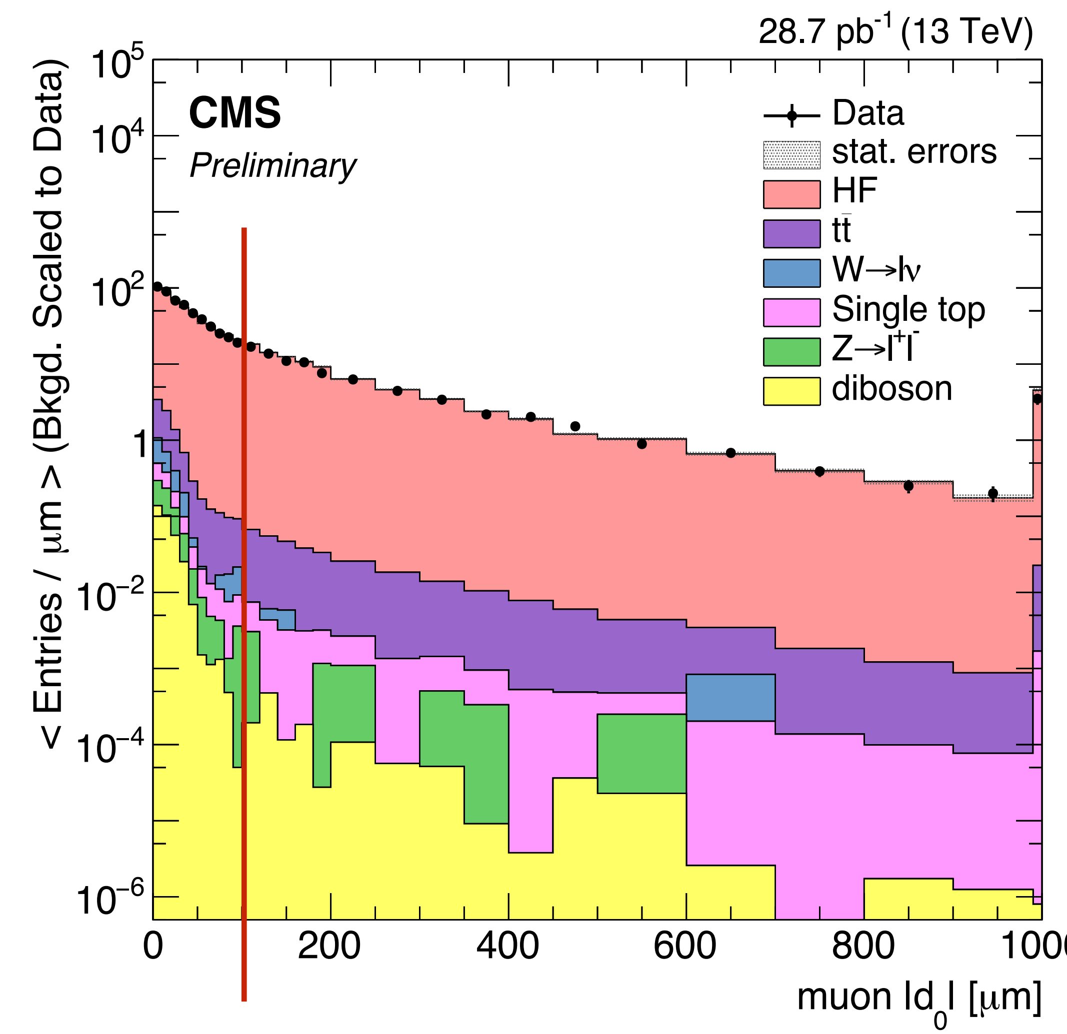


- We do not have cuts on the **jets** in the e-μ search region.
- Similar to **tag-and-probe** method, we construct HF + lepton regions with no tight cuts (except pT, eta, tight lepton veto Jet Id) on the **jets** near the leptons.
- Choose the criteria on tag **bjet** individually given different selection efficiency of requiring e or μ inside bjets.

HF + Lepton Enriched Region



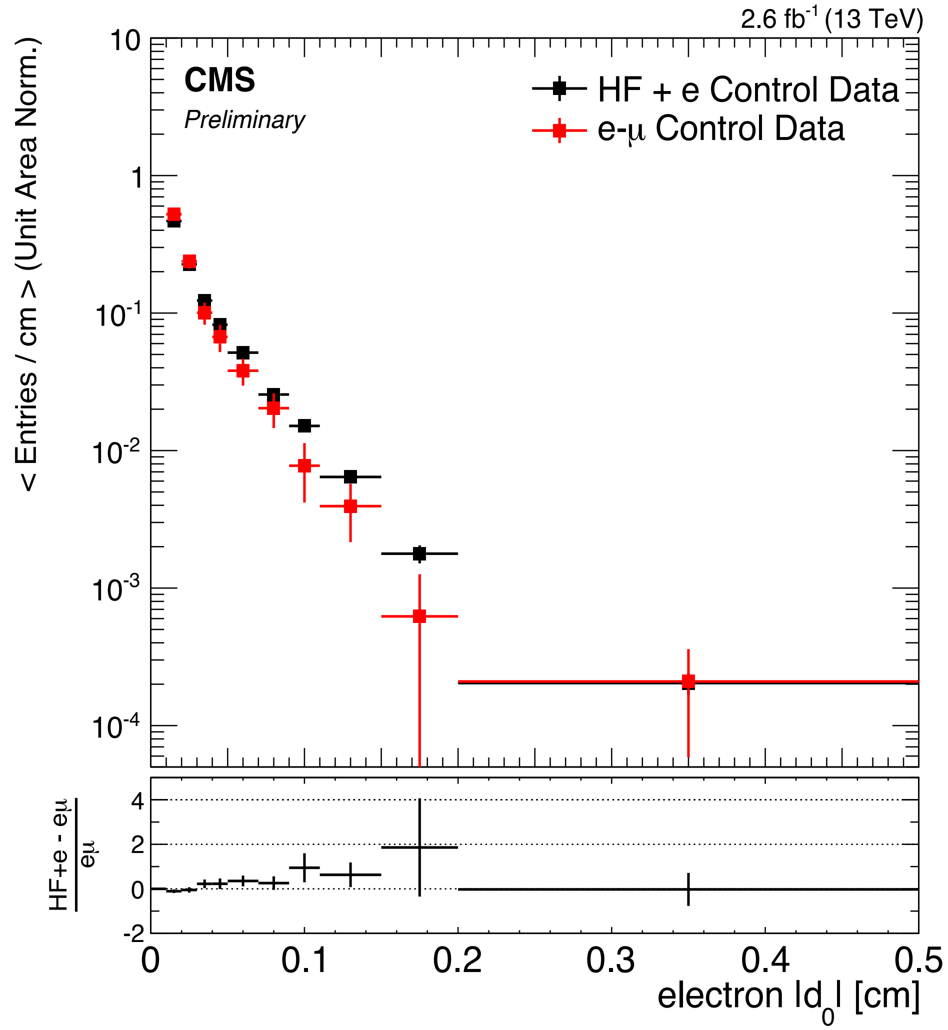
HF + **Electron** Enriched Region



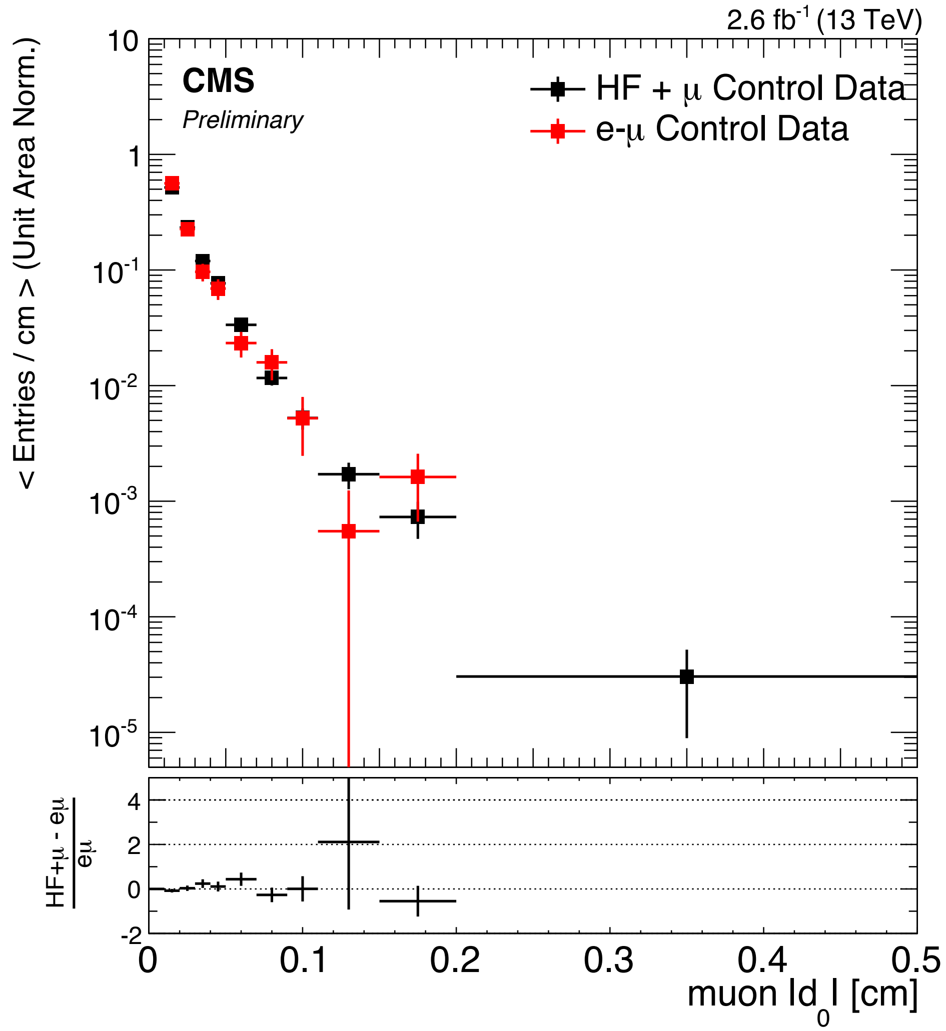
HF + **Muon** Enriched Region

- The impact parameter distributions agree well between data and MC.
- Dominated by HF events after passing 100 microns.

Impact Parameter Distribution Validation



Electron IP Validation



Muon IP Validation

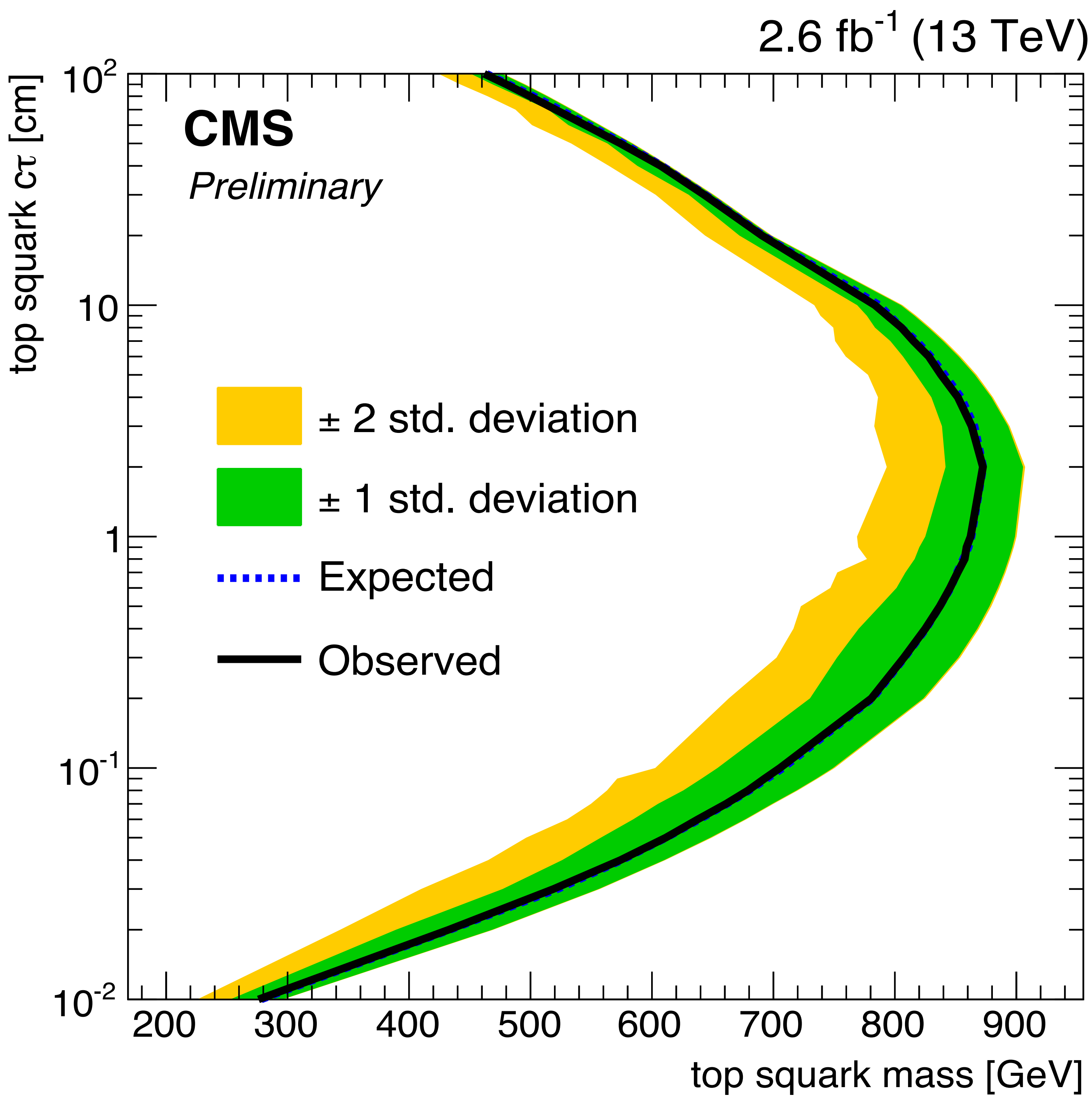
- Compare the impact parameter of electron (muon) in Displaced Electron (Muon) and HF + Electron (Muon) control region.
- Leptons in HF + Lepton control regions model leptons from HF in e-μ final state well.

Run2 Results: Yields Table

Event Source	Search Region I	Search Region II	Search Region III
$W \to l\nu$	$(1.1 \pm 0.5) \times 10^{-3}$	$(2.4 \pm 1.7) \times 10^{-5}$	$(0.25 \pm 0.29) \times 10^{-5}$
single top	$(8.4 \pm 1.2) \times 10^{-3}$	$(35 \pm 12) \times 10^{-5}$	$(1.50 \pm 0.91) \times 10^{-5}$
diboson	$(18.2 \pm 5.8) \times 10^{-3}$	$(39 \pm 25) \times 10^{-5}$	$(4.0 \pm 4.6) \times 10^{-5}$
$Z \to ll$	$(115 \pm 25) \times 10^{-3}$	$(100 \pm 160) \times 10^{-5}$	$(69 \pm 71) \times 10^{-5}$
$t\bar{t}$	$(60.6 \pm 5.1) \times 10^{-3}$	$(226 \pm 25) \times 10^{-5}$	$(8.0 \pm 1.6) \times 10^{-5}$
non-HF sum	$(203 \pm 26) \times 10^{-3}$	$(410 \pm 170) \times 10^{-5}$	$(82 \pm 71) \times 10^{-5}$
data-driven HF	< 3.0	< 0.50	< 0.019
total background	< 3.2	< 0.50	< 0.020
observation	1	0	0
$pp \to \tilde{t}_1 \tilde{t}_1^* (M_{\tilde{t}_1} = 700\,\mathrm{GeV})$			
$c\tau = 0.1\,\mathrm{cm}$	3.8 ± 0.2	0.94 ± 0.06	0.16 ± 0.02
$c\tau = 1\,\mathrm{cm}$	5.2 ± 0.4	4.1 ± 0.3	7.0 ± 0.3
$c\tau = 10\,\mathrm{cm}$	0.8 ± 0.1	1.0 ± 0.1	5.8 ± 0.2
$c\tau = 100\,\mathrm{cm}$	0.009 ± 0.005	0.03 ± 0.01	0.27 ± 0.03

- Observation is consistent with the background estimate. No significant excess is observed.

Run2 Results: Limit



- Limits are set on the DisplacedSUSY benchmark model.
- For a top squark life-time of 2 cm, the top squark mass is excluded up to 870 GeV. Most stringent limit on this model **today**.

Approved by CMS:
Link to public page
Presented in ICHEP:
Link to the talk

Summary

1. An analysis using simple event selections was done in Run1 to probe a wide range of new physics than can produce and electron and a muon with large impact parameters in the final states
2. Various improvements on the high level trigger and offline reconstruction have been made during the time when the LHC was shut down.
3. Preliminary Run2 result using data collected in 2015 is now public!

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1. An analysis using simple event selections was done in Run1 to probe a wide range of new physics than can produce and electron and a muon with large impact parameters in the final states
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3. Preliminary Run2 result using data collected in 2015 is now public!

#MoarData#CMS#Exotica#LongLived

Thank you!