Search for long-lived particles in dilepton final states

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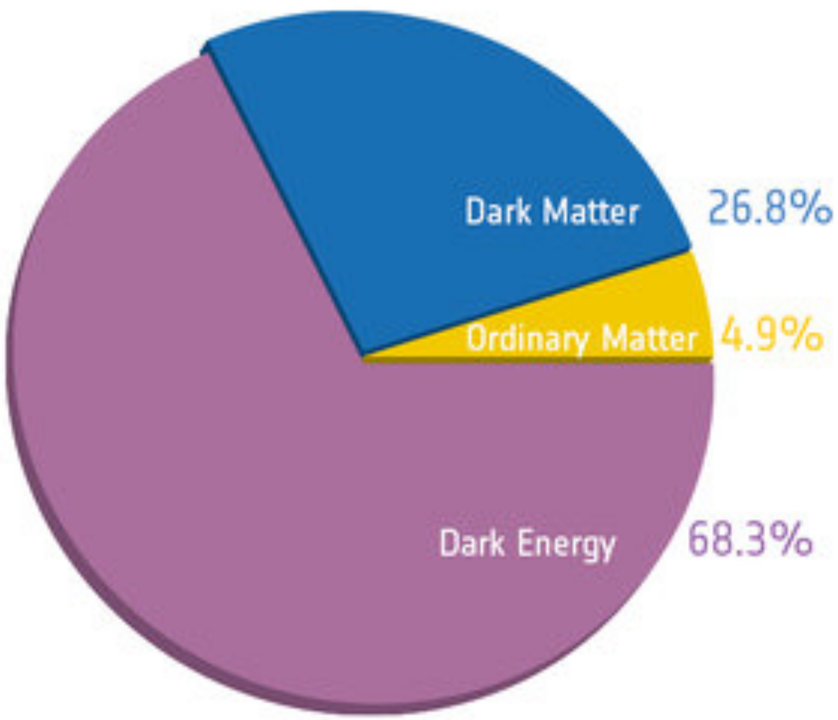
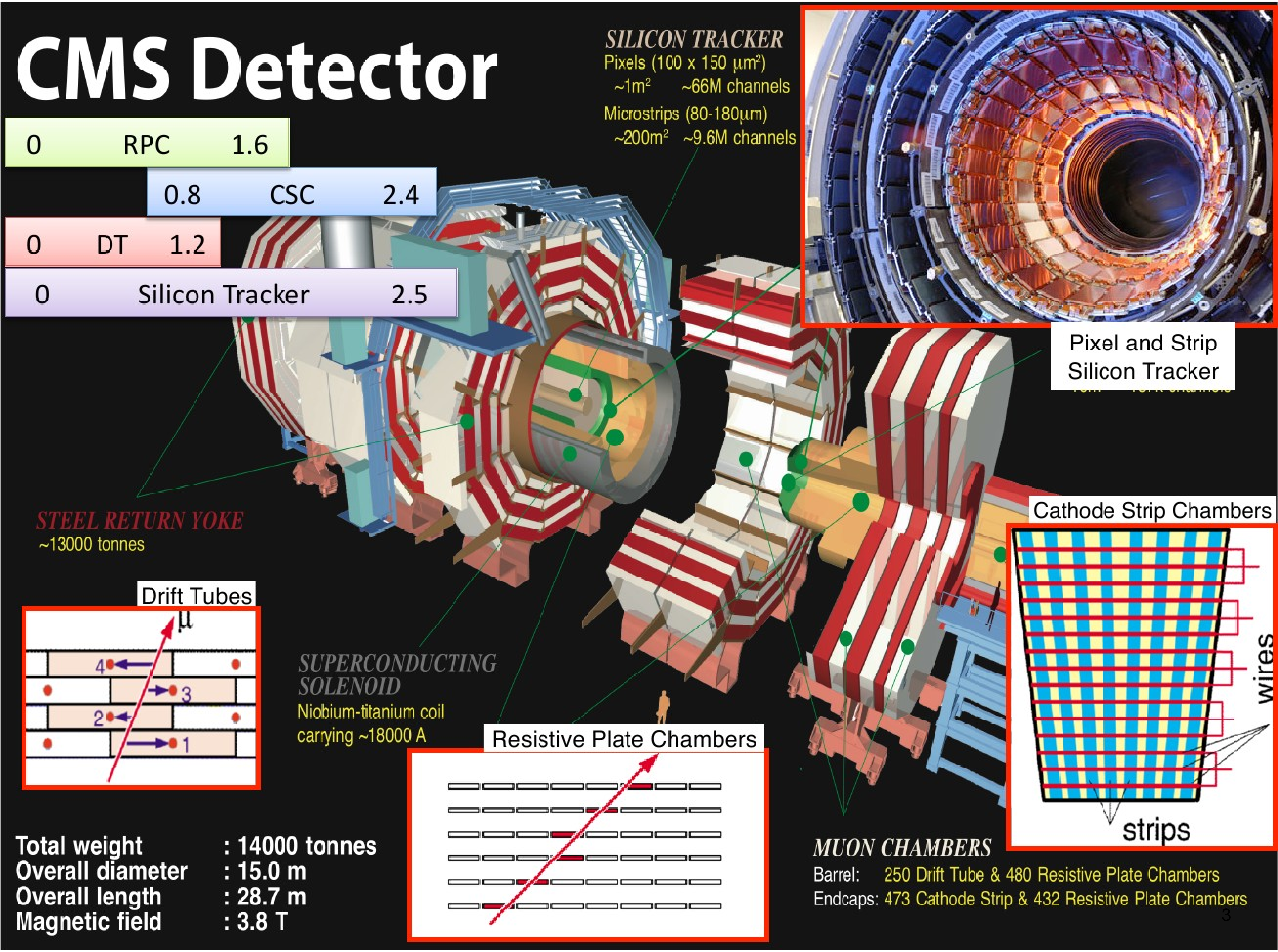
Mitchell Workshop on Collider and Dark Matter Physics

Introduction

- Several open questions remain after finding the Higgs-like boson
    - For example: how do we explain dark matter?
    - No answer in the Standard Model
- Many ways in which new physics BSM may manifest
- Search for new long-lived particles
    - Almost background-free at higher mass, striking signature, largely model independent
- Results of the analysis of 2012 data and future prospects for Run 2

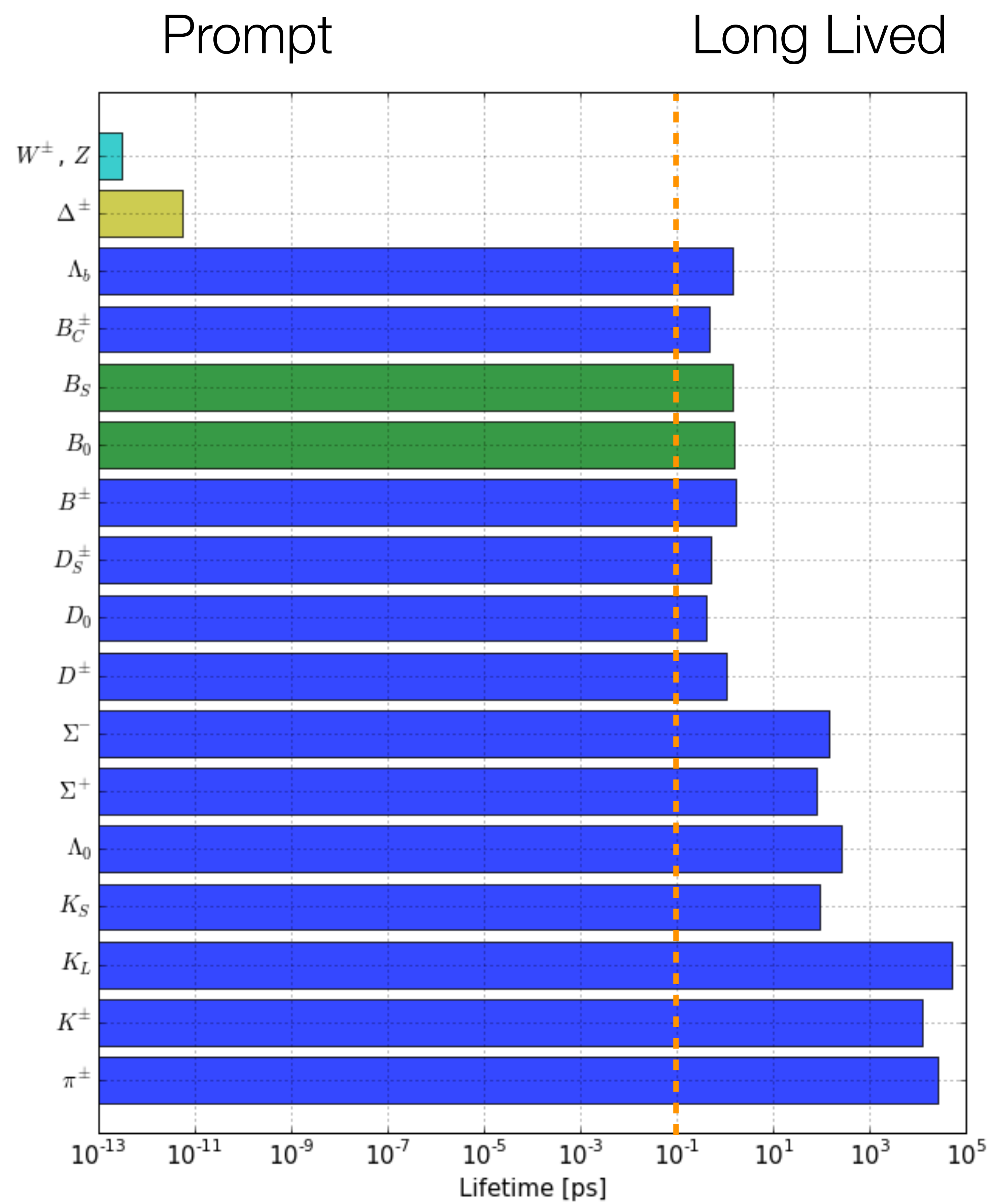




CMS Detector
0 RPC 1.6
0.8 CSC 2.4
0 DT 1.2
0 Silicon Tracker 2.5
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
Pixel and Strip
Silicon Tracker
STEEL RETURN YOKE
~13000 tonnes
Cathode Strip Chambers
wires
strips
Drift Tubes
μ
4
3
2
1
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers

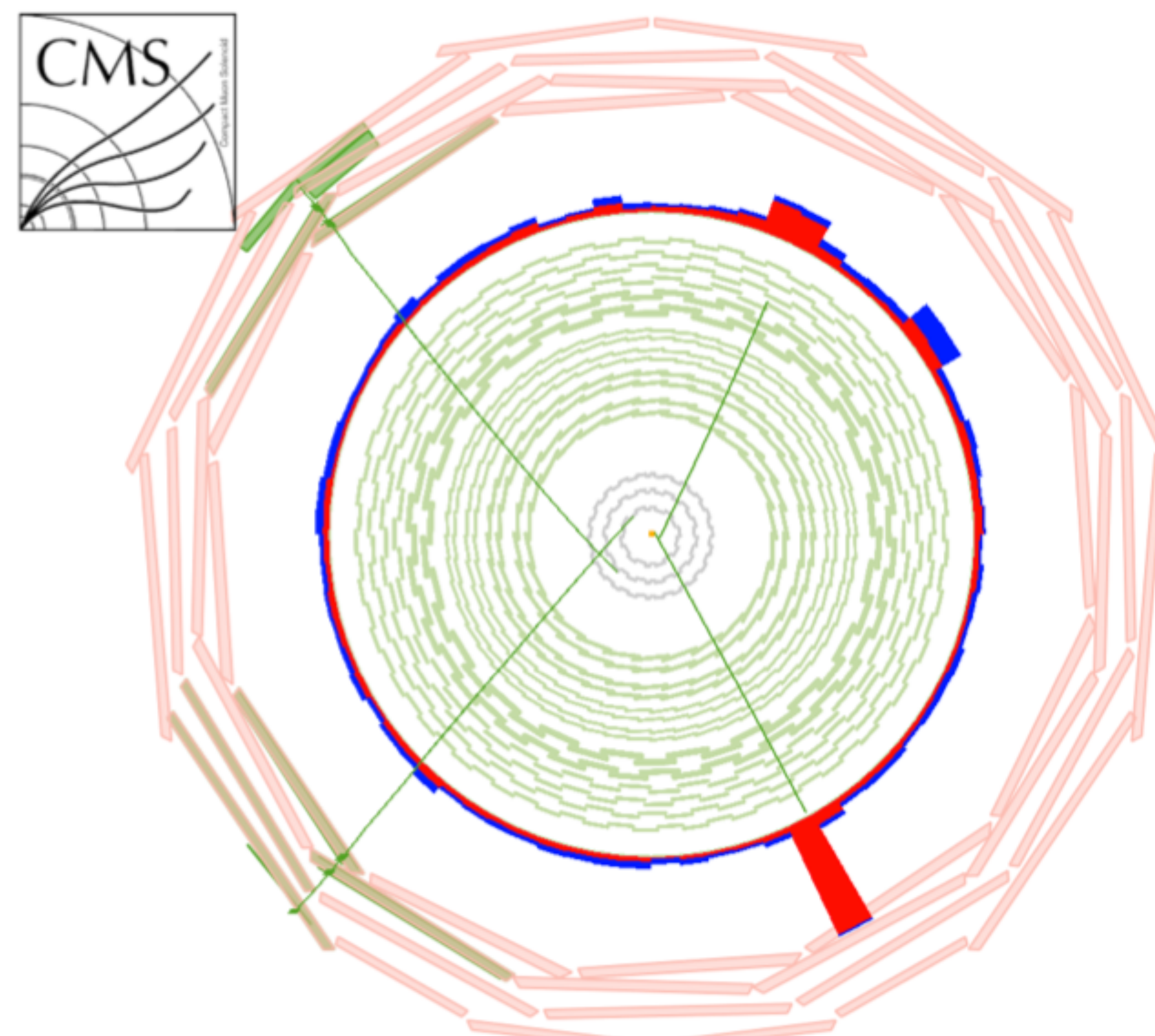
Long-Lived Particles at the LHC

- Only a few particles in nature have lifetimes long enough for us to trace them experimentally from the point of birth to the point of decay:
  - particles **decaying via weak force**
  - Small couplings -> long lifetimes
- Particles decaying via electromagnetic and strong interactions have typical lifetimes $\sim 10^{-19}$–10^{-20} s and $\sim 10^{-23}$–10^{-24} s, respectively
- Are there any long-lived particles from physics BSM?



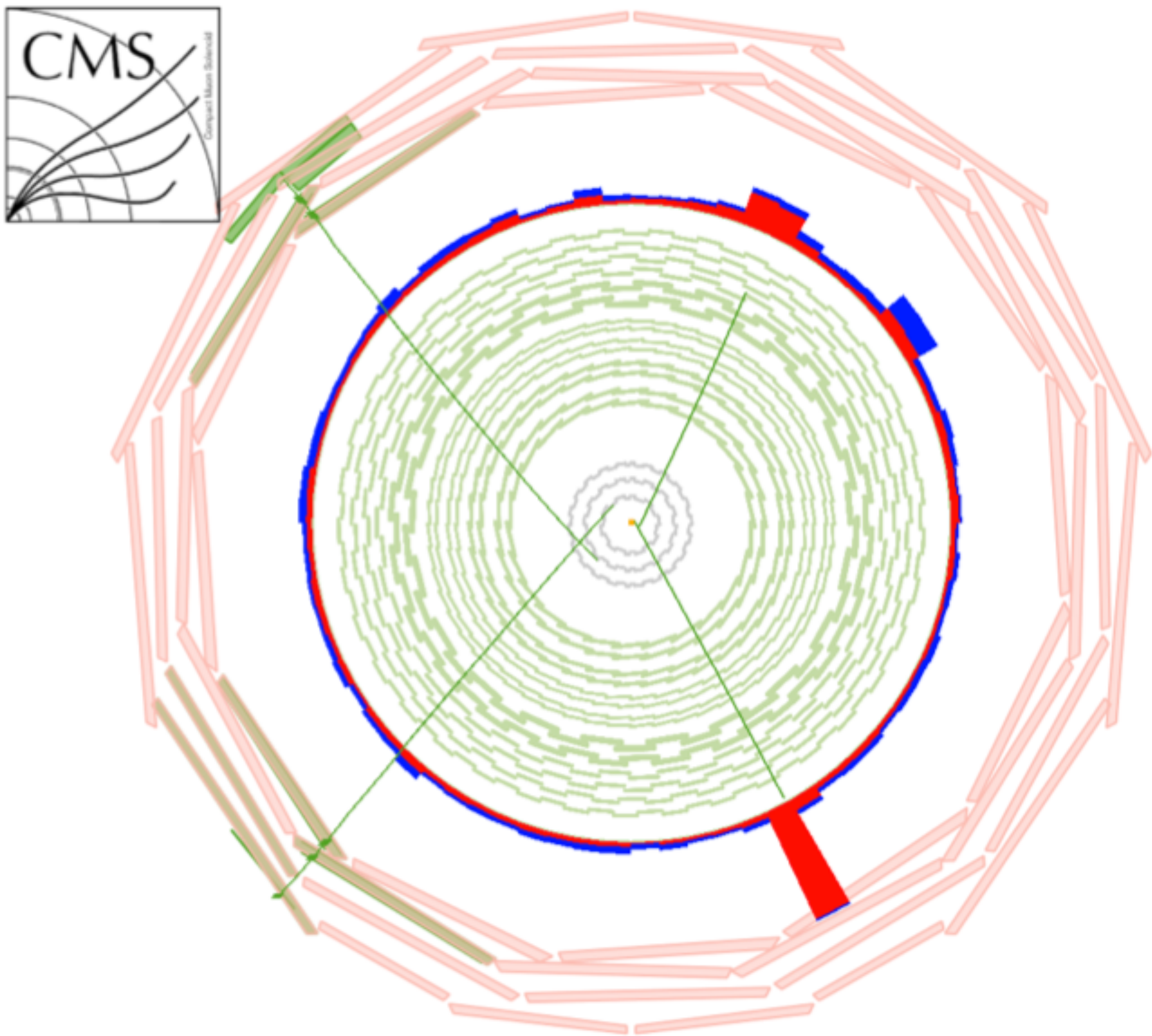
Search for long-lived particles decaying to muon and electron pairs with displaced vertices

- Are there new, yet unobserved particles decaying displaced from the interaction point within CMS?
- Striking signature for physics beyond the SM
- Models predict a variety of possible decay lengths
- Challenging since detector and software are not designed for this!



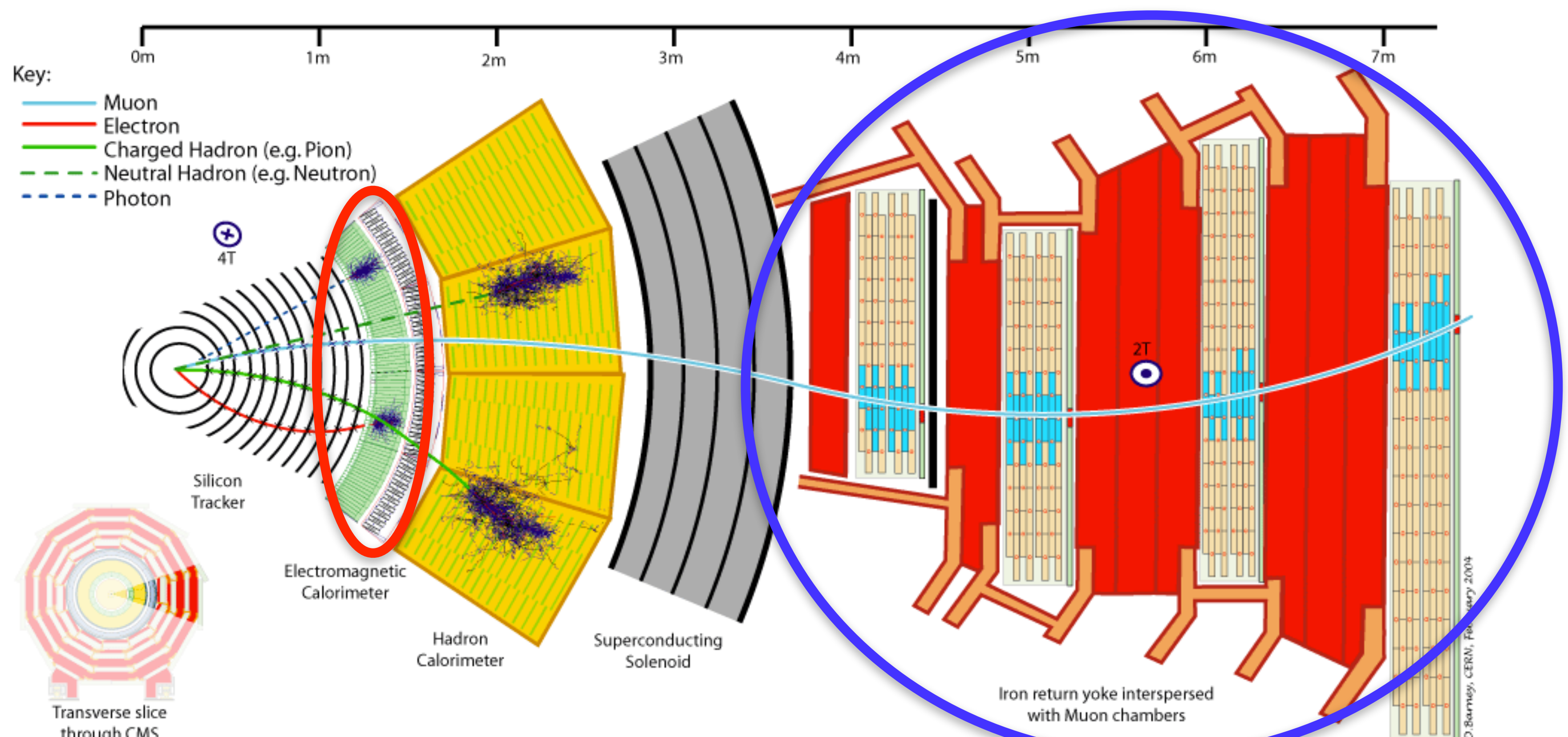
Benchmark Models

- Many new physics scenarios predict long-lived particles:
  - Weak RPV SUSY
  - Split SUSY
  - Hidden Valley Scenarios
- Look for the **signature**
- Two benchmark models
  - H→XX, X→l^+l^- with H a spin 0 boson and X a long-lived spin-0 boson
  - 2*squark→2*(quark+χ^0), χ^0→l^+l^-v, with χ^0 being a long-lived neutralino
  - l are electrons or muons (cleaner signatures)



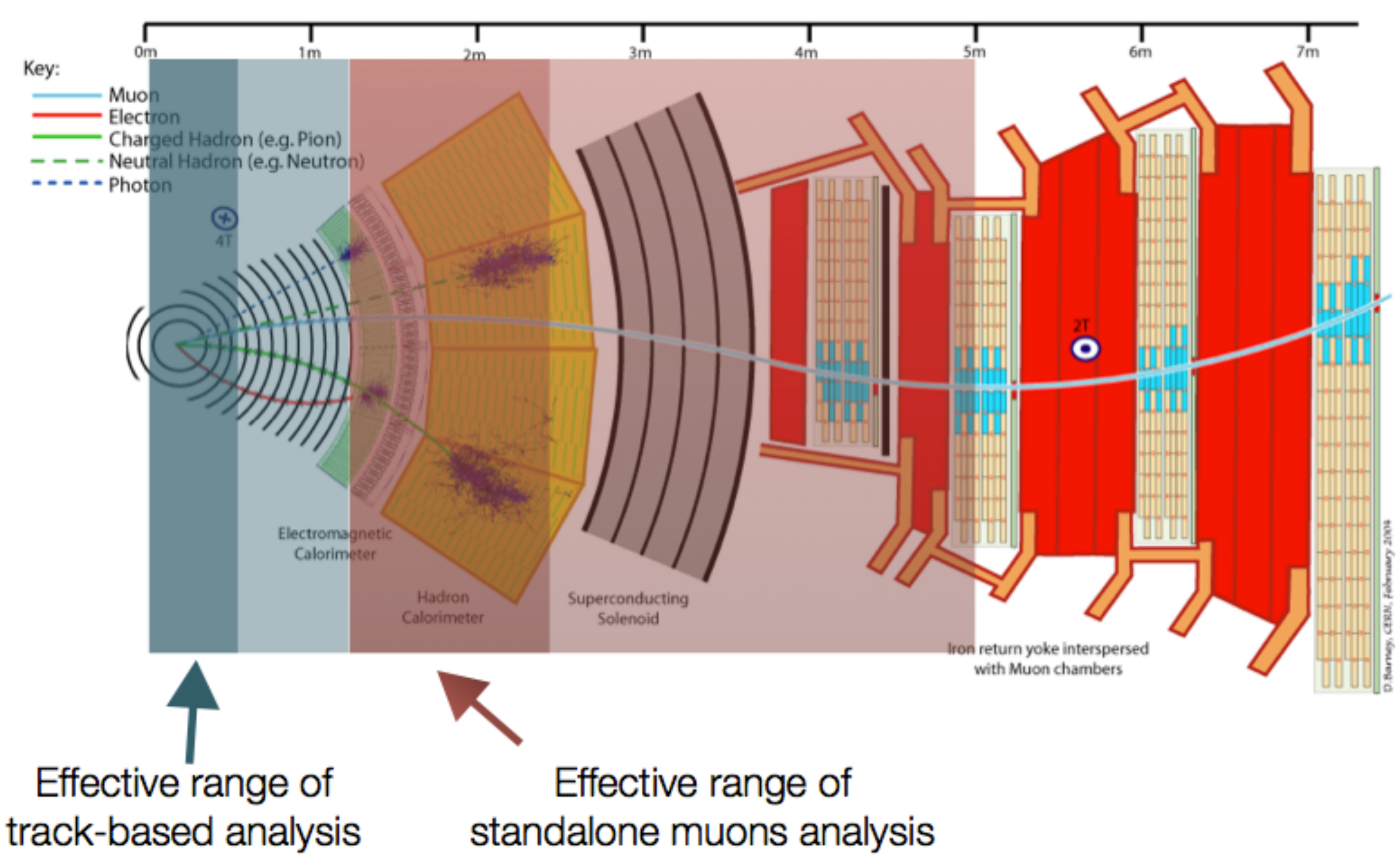
Triggers

- At colliders the analyses search for prompt particles >99%
- Special triggers for long-lived particles:
  - Electron channel: two deposits in the calorimeters compatible with electron/photon -> no track requirement -> no vertex
  - Muon channel: two muons reconstructed in the muon chambers, no vertex constraint

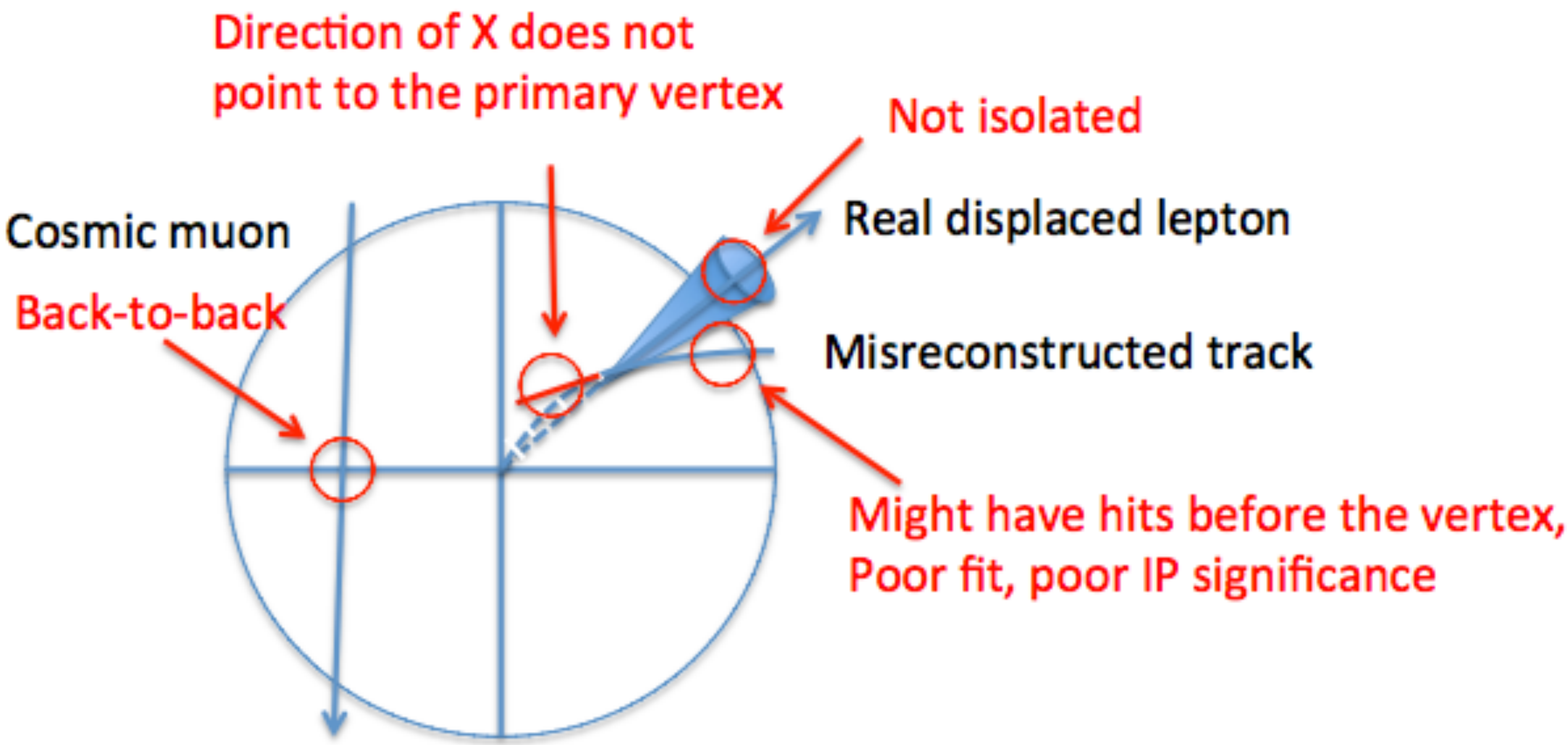


Orthogonal Analyses

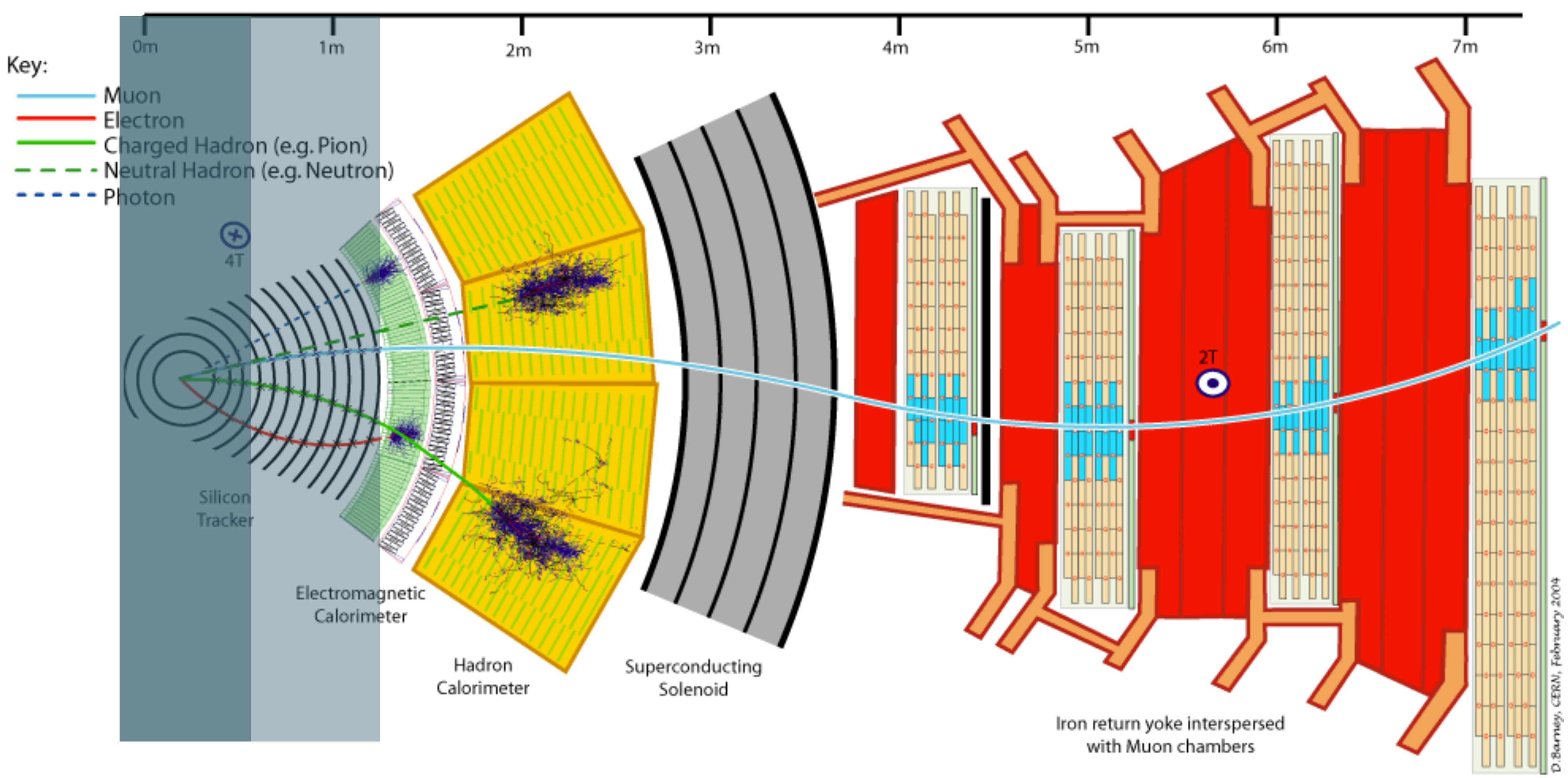
- To make the most out of the collected datasets we perform two orthogonal analyses
  - **Track-based**: utilize tracks reconstructed in the silicon tracker (electrons and muons)
  - **Standalone muons**: utilize tracks reconstructed only in the muon chambers (muons only)



Sources of Background



Track-based Analysis

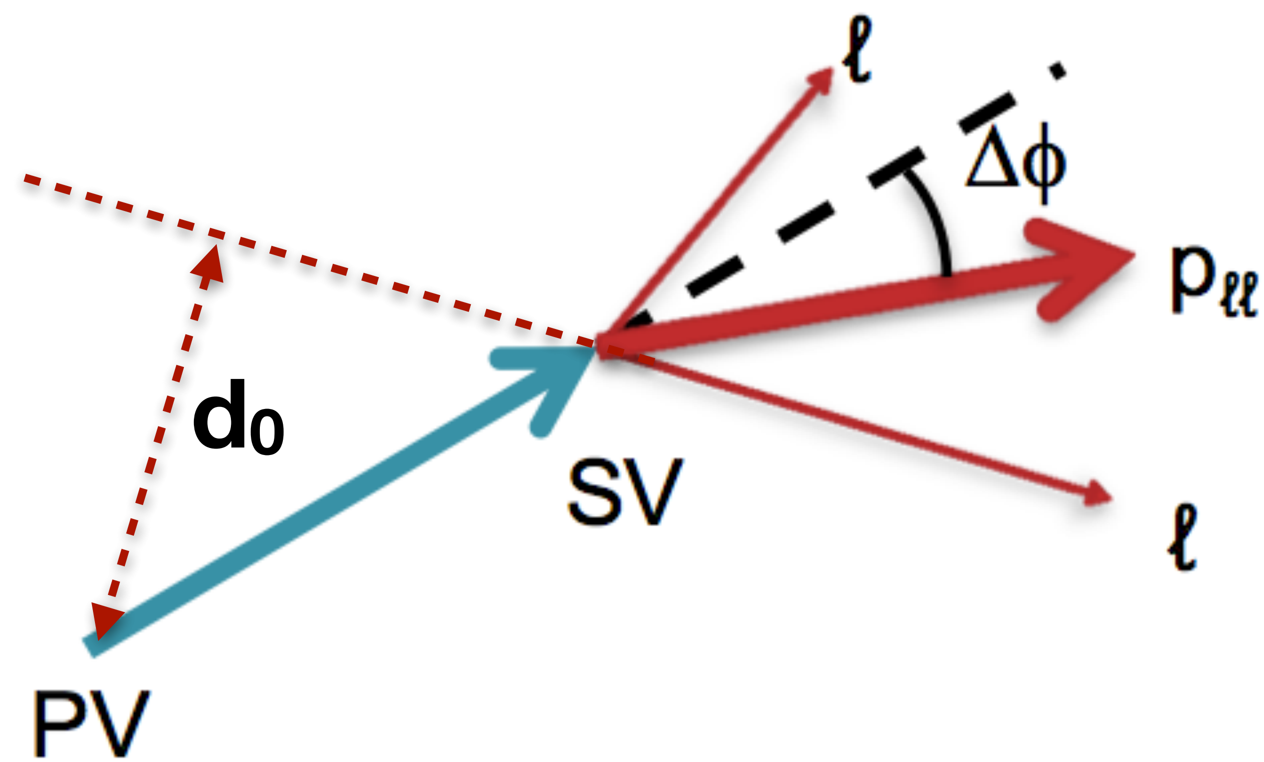


Phys. Rev. D 91, 052012

http://journals.aps.org/prd/abstract/10.1103/PhysRevD.91.052012

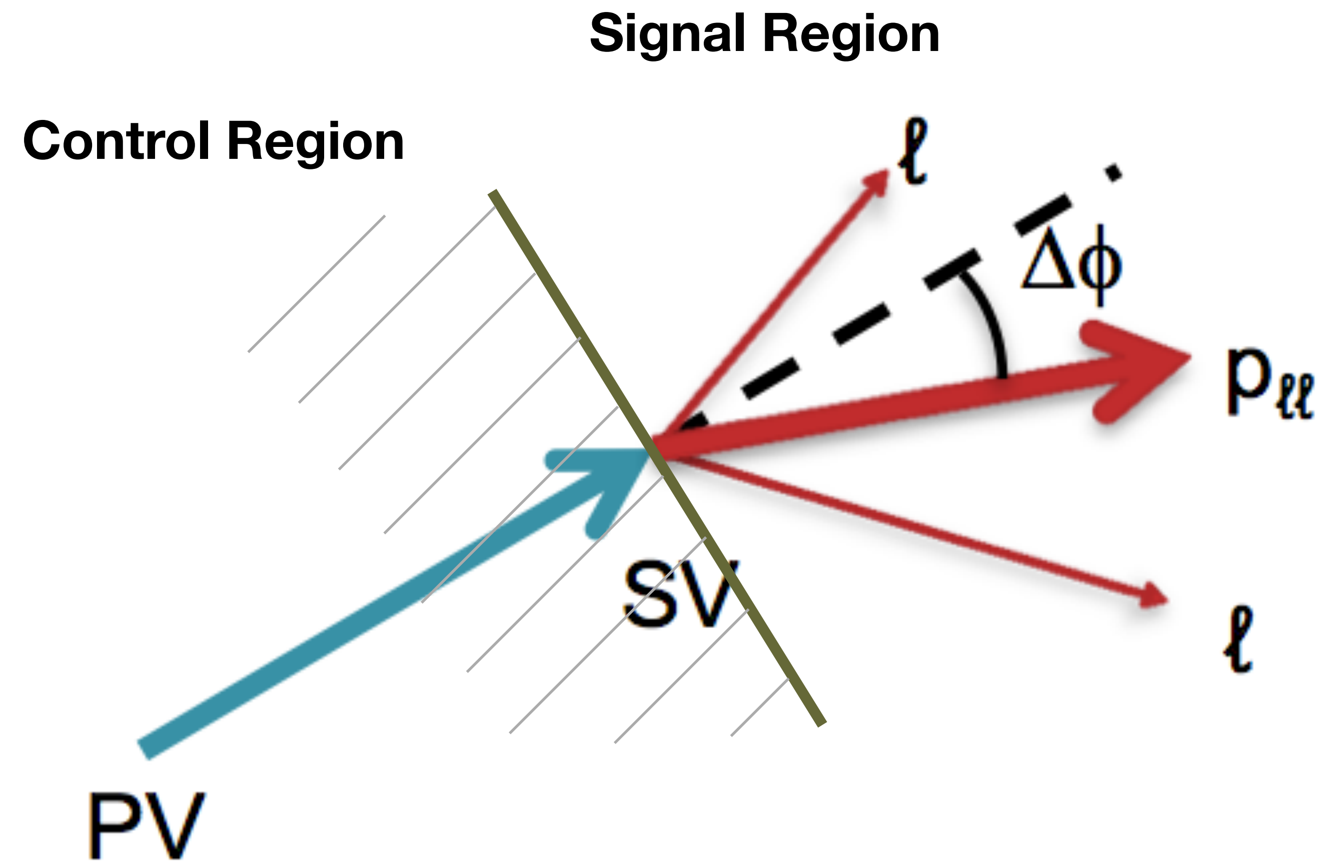
Analysis Strategy

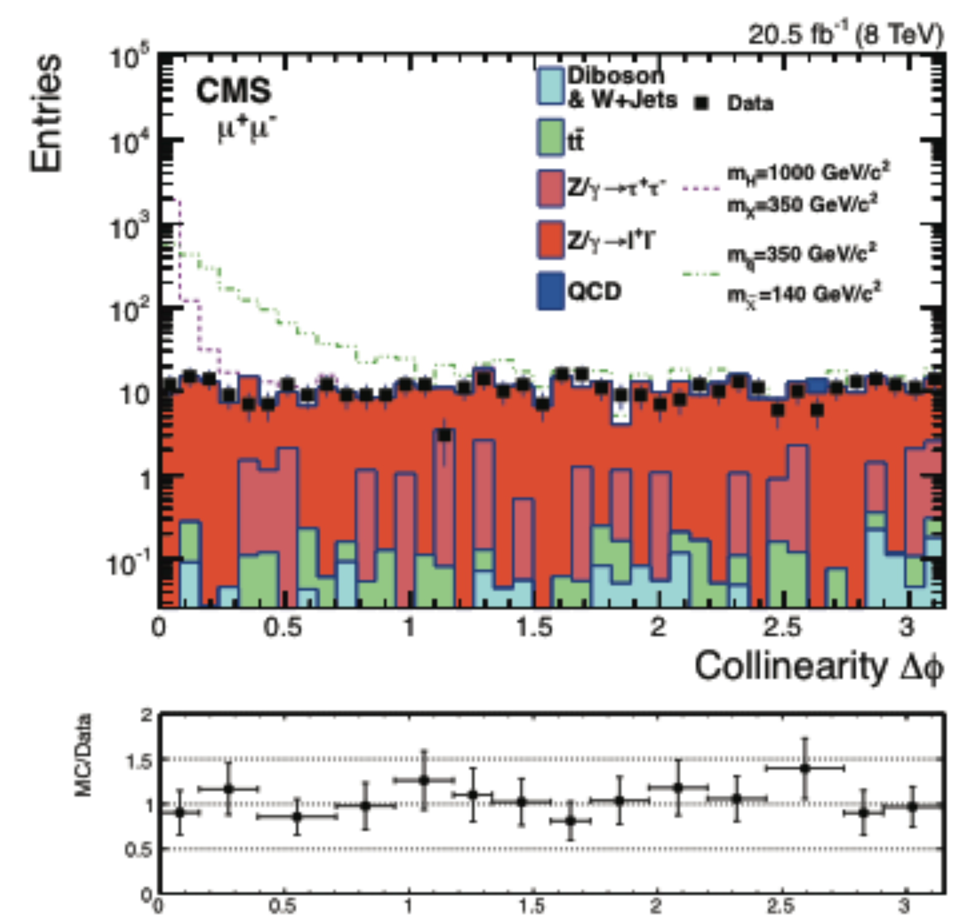
- Match high-p_T, isolated tracks to
  - offline photon (electron channel)
  - trigger muon (muon channel)
- Search for pairs of leptons that form a genuine, high-quality vertex
- Both leptons with large transverse impact parameter significance (d_0/σ_d)
- Blind analysis

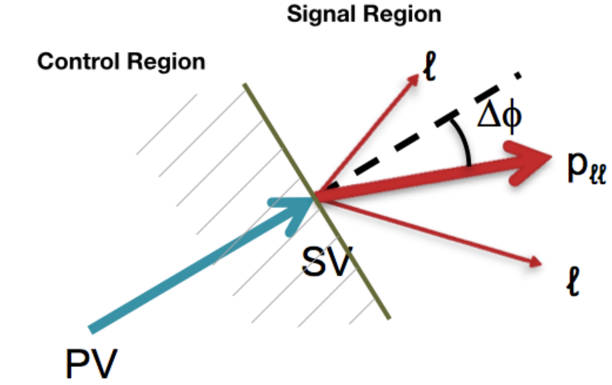


Signal and Control Regions

- ΔΦ : angle between the dilepton momentum and vector between the primary vertex and dilepton vertex
  - In r-ϕ plane
- Define signal and control regions
  - Signal region: $\Delta\Phi < \pi/2$
  - Control region: $\Delta\Phi > \pi/2$
- Signal is expected to have $\Delta\Phi \sim 0$
- ΔΦ symmetric about π/2 for background



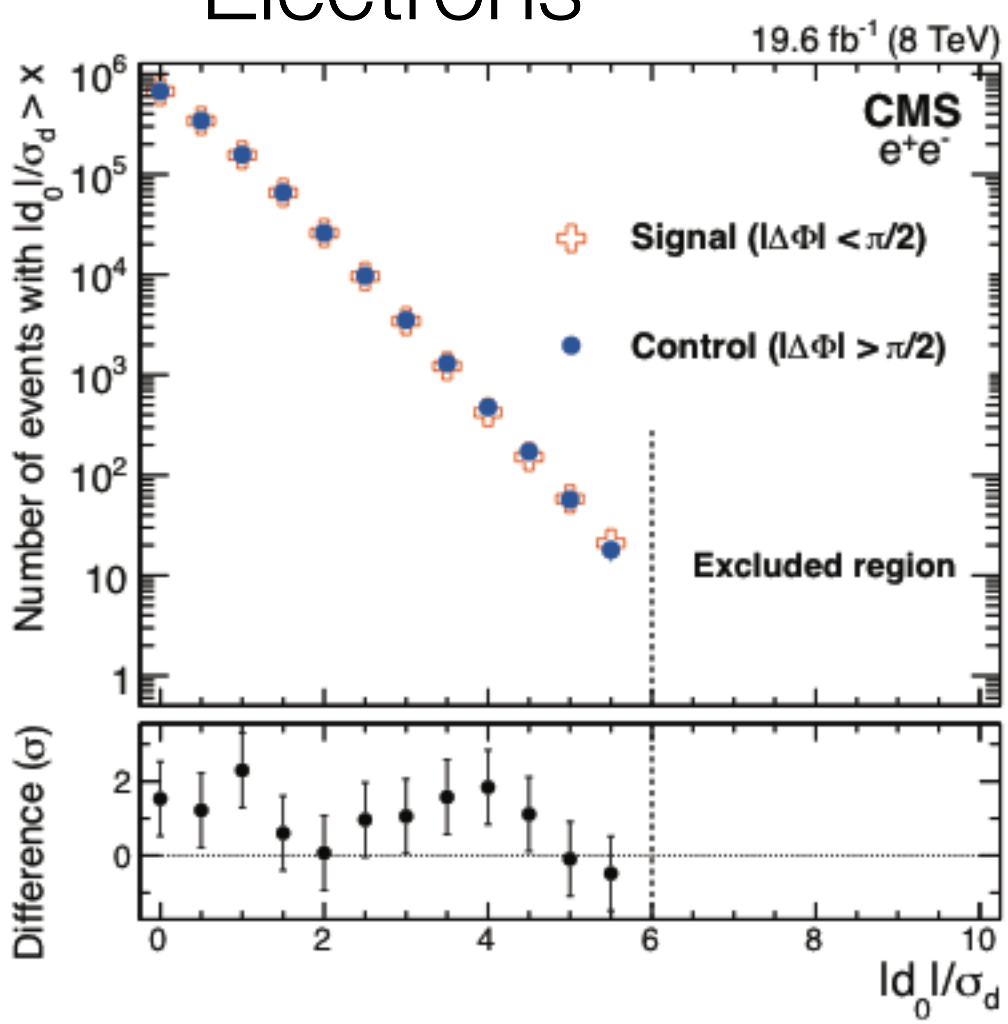




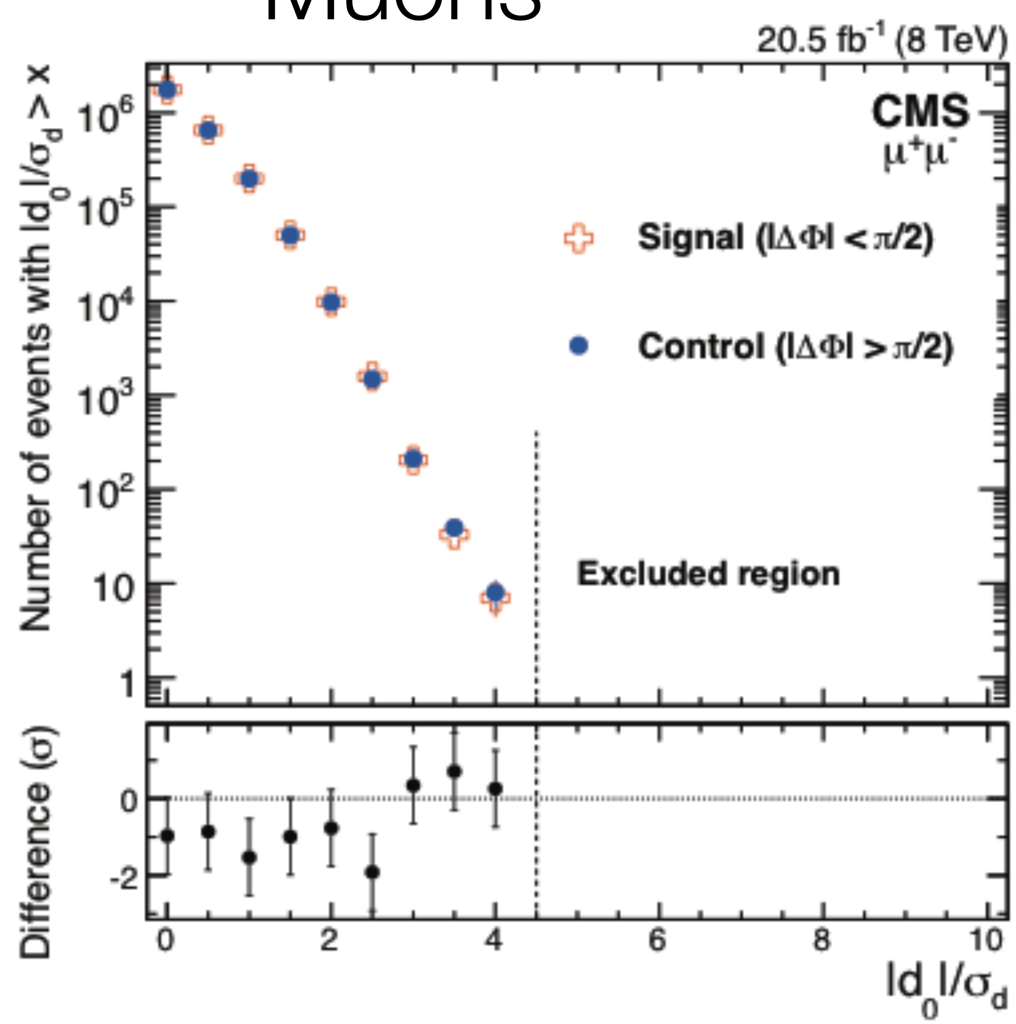
Data-Driven Background Estimate

- Estimate background from control region
- Background expected to be symmetric in signal and control region
- Verified for smaller d_0/σ_d on data from **cumulative distributions**

Electrons



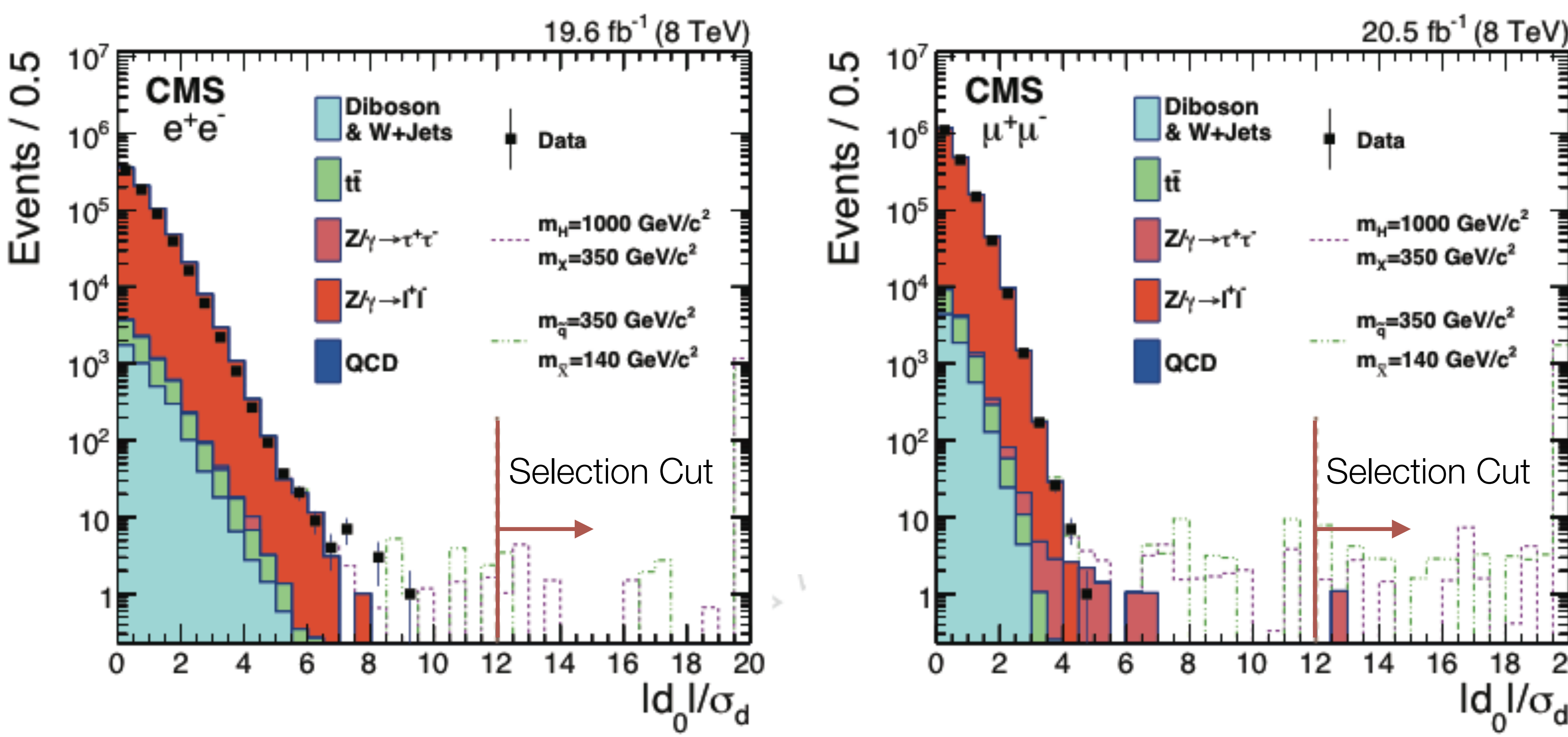
Muons



Results

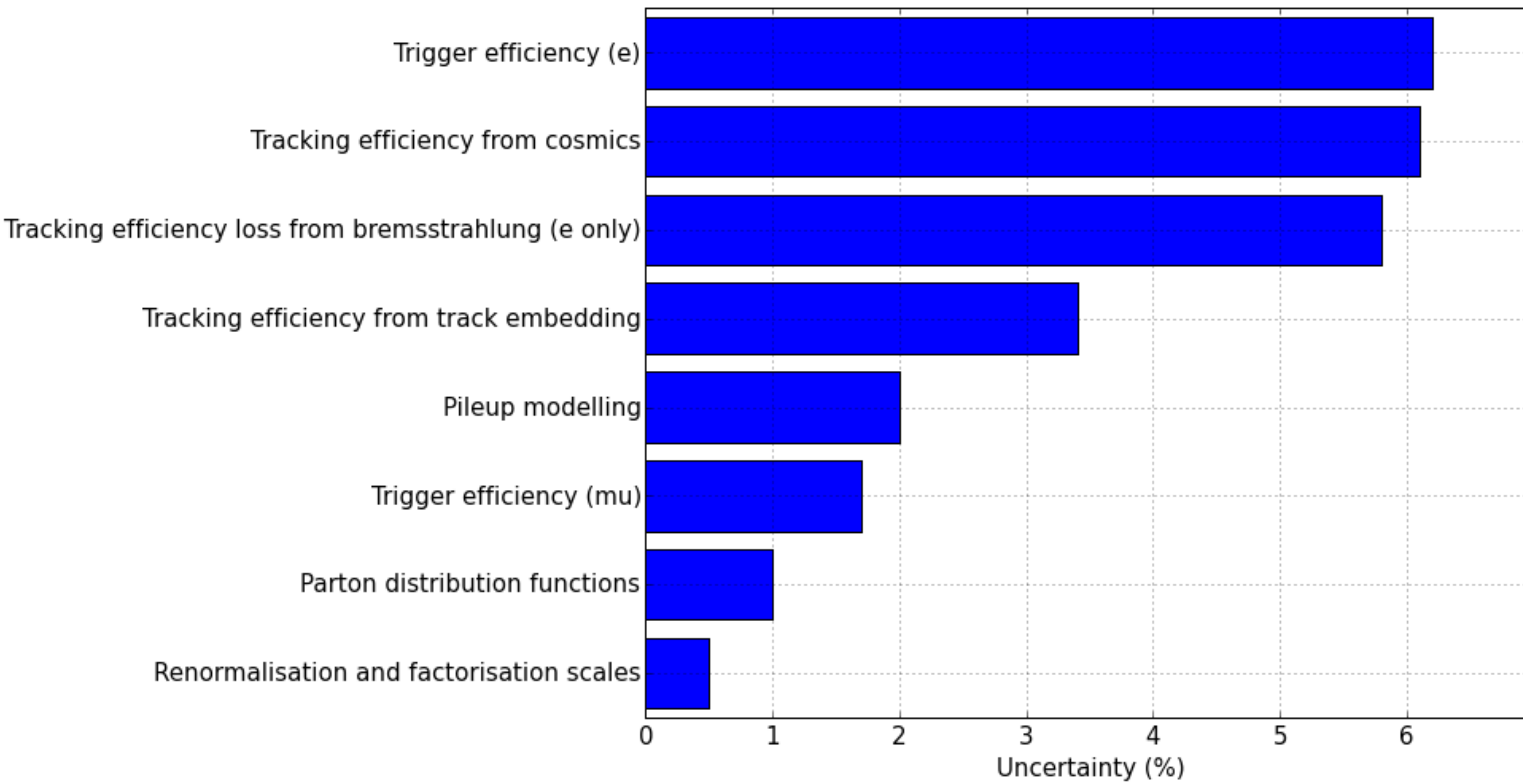
- No excess observed after the full selection in the signal region

d_0/σ_d distributions - signal region



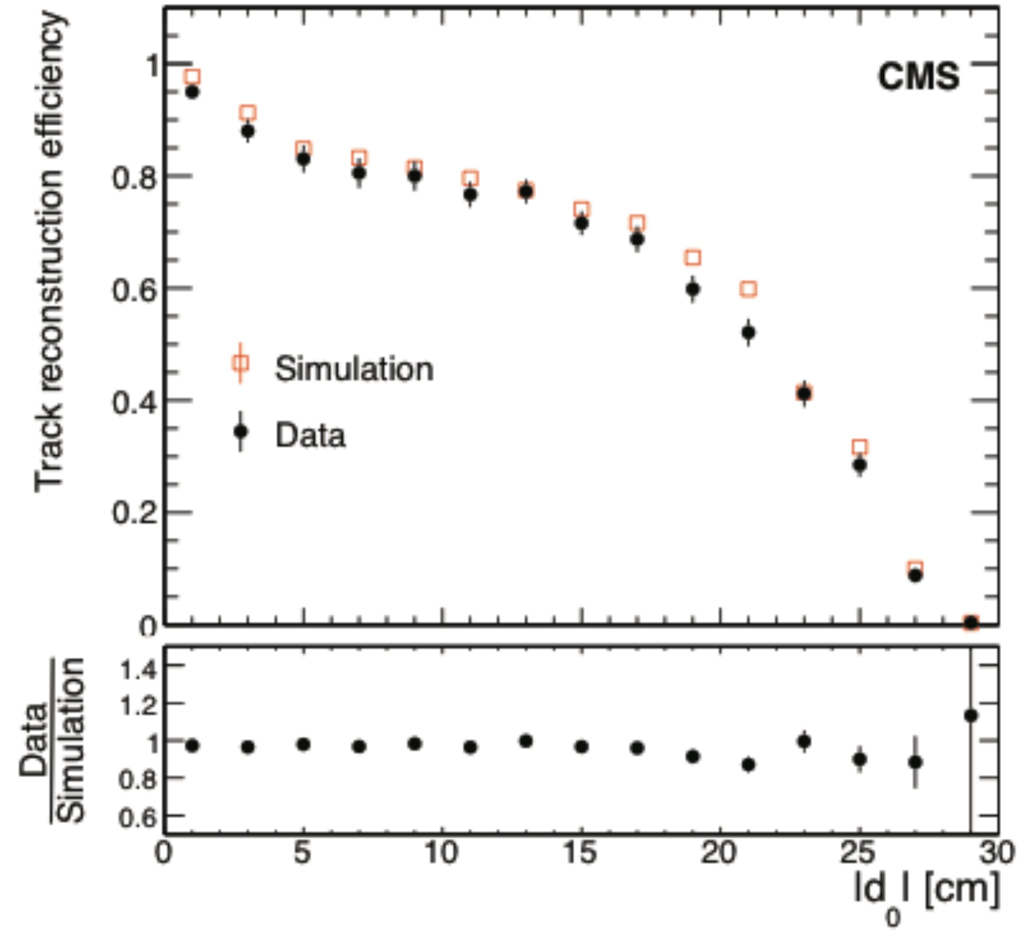
Systematic Uncertainties

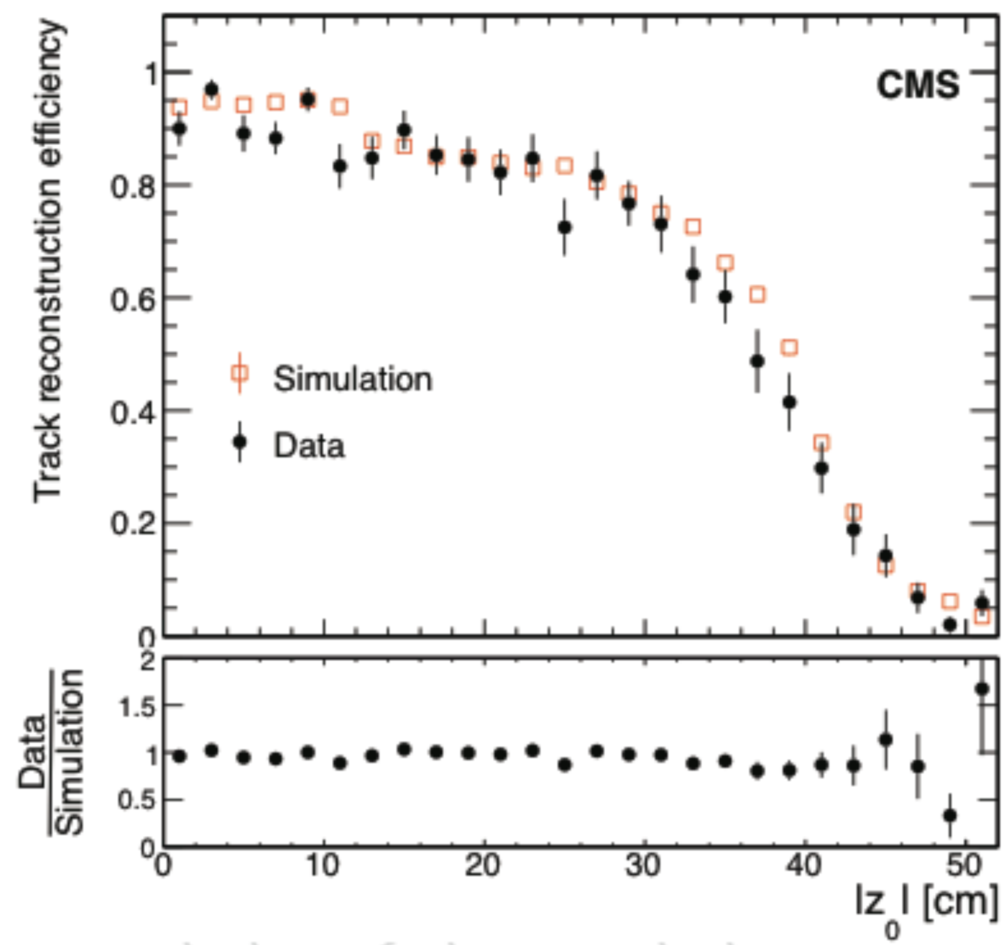
- Main systematic uncertainties are from tracking and trigger efficiencies



Tracking Efficiency

- Measured for displaced tracks with cosmic muons
- Additional systematic for electrons from uncertainty on material model
- Additional dependence on presence of other tracks in the event measured by embedding cosmics in collision events

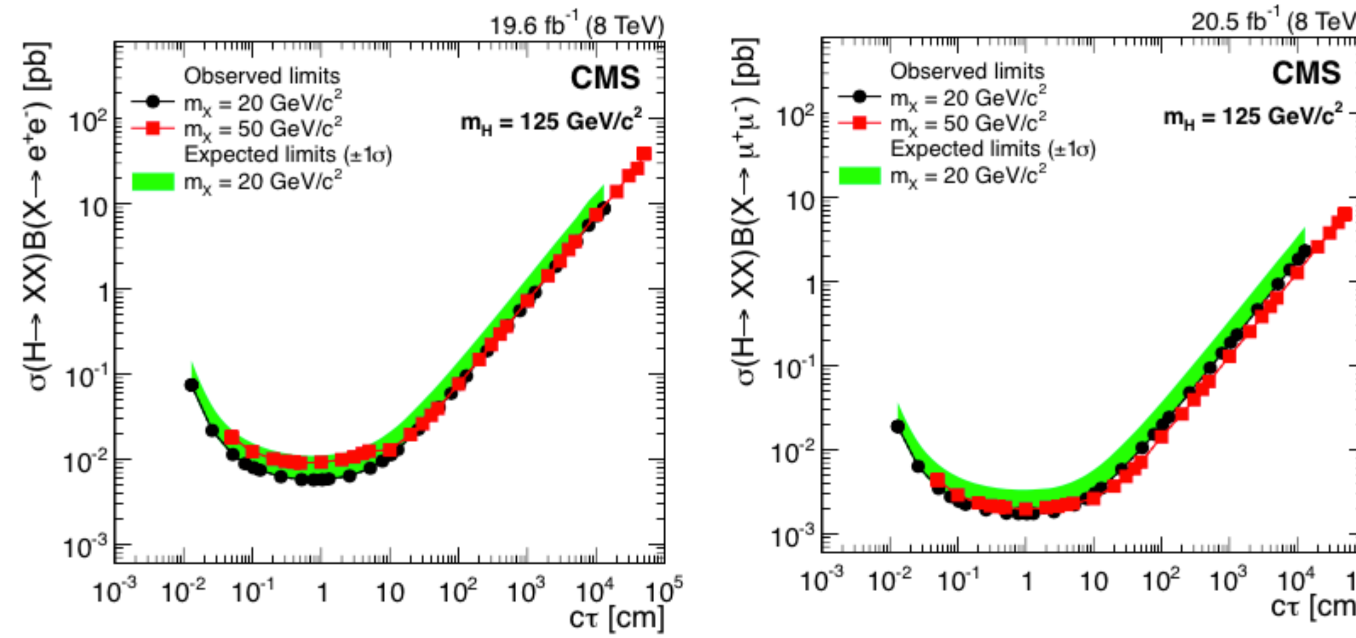




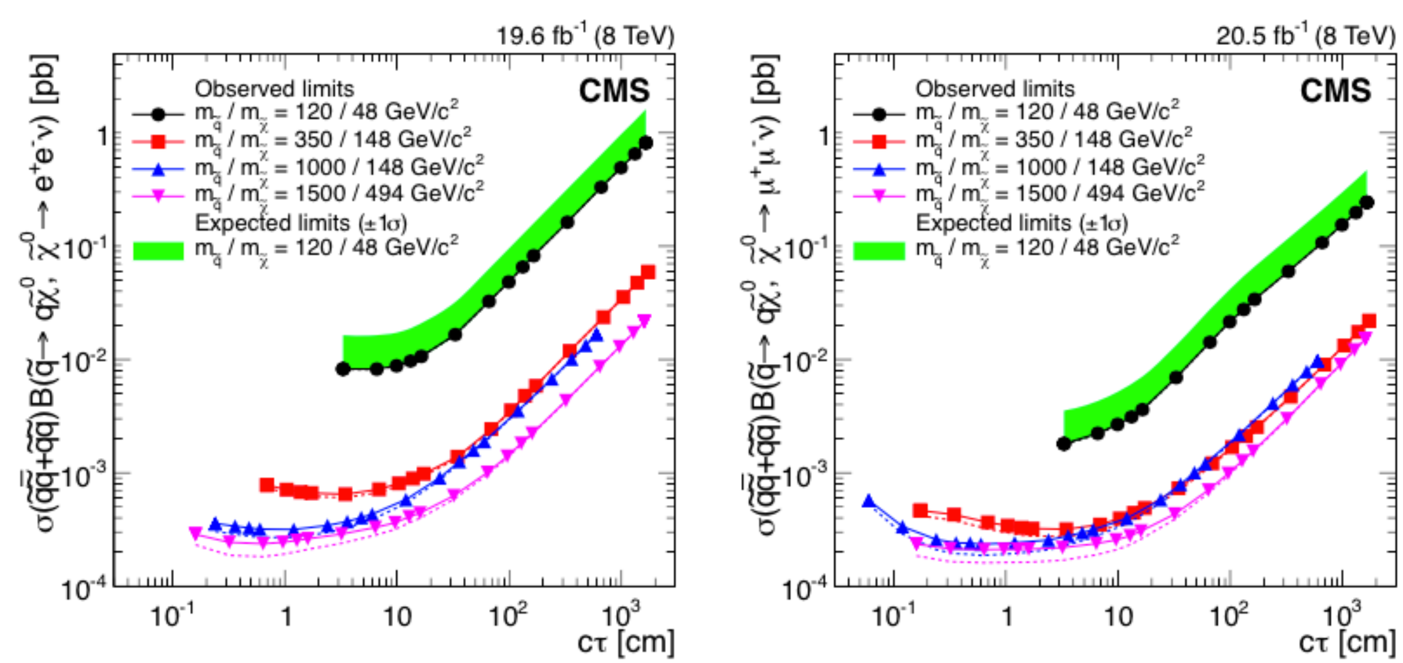
Limits

- Cross section X branching ratio upper limits for a wide range of lifetimes
- Limits are also provided within acceptance
  - Simpler for theorists to translate them into limits for other models
- Assuming a cross section of 20pb and an H mass of 125 GeV/c^2
  - Best branching ratio limit for electrons ~ 0.3*10^{-3} and for muons ~ 10^{-4}

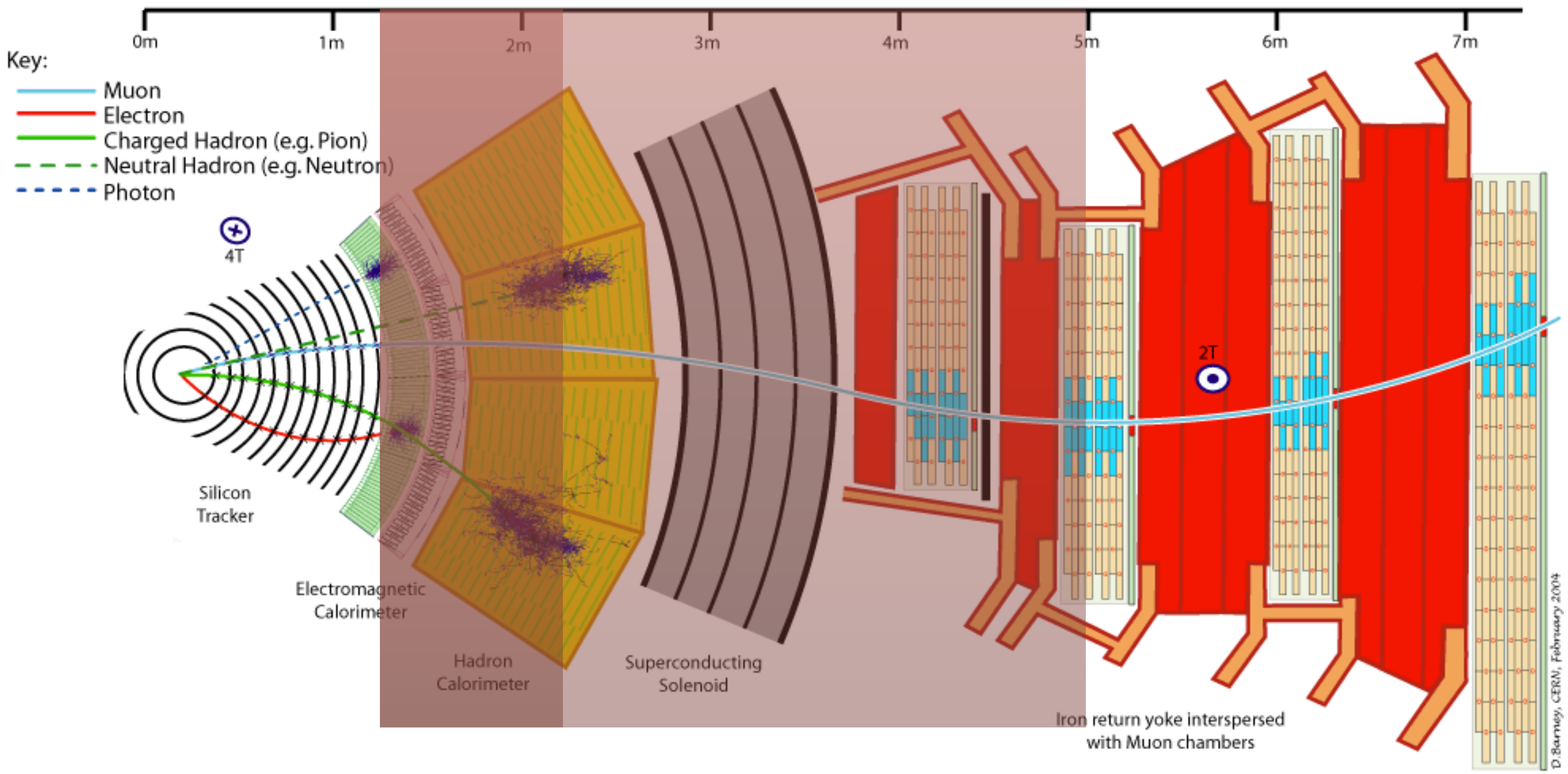
2-body signature



3-body signature



Standalone Muons Analysis

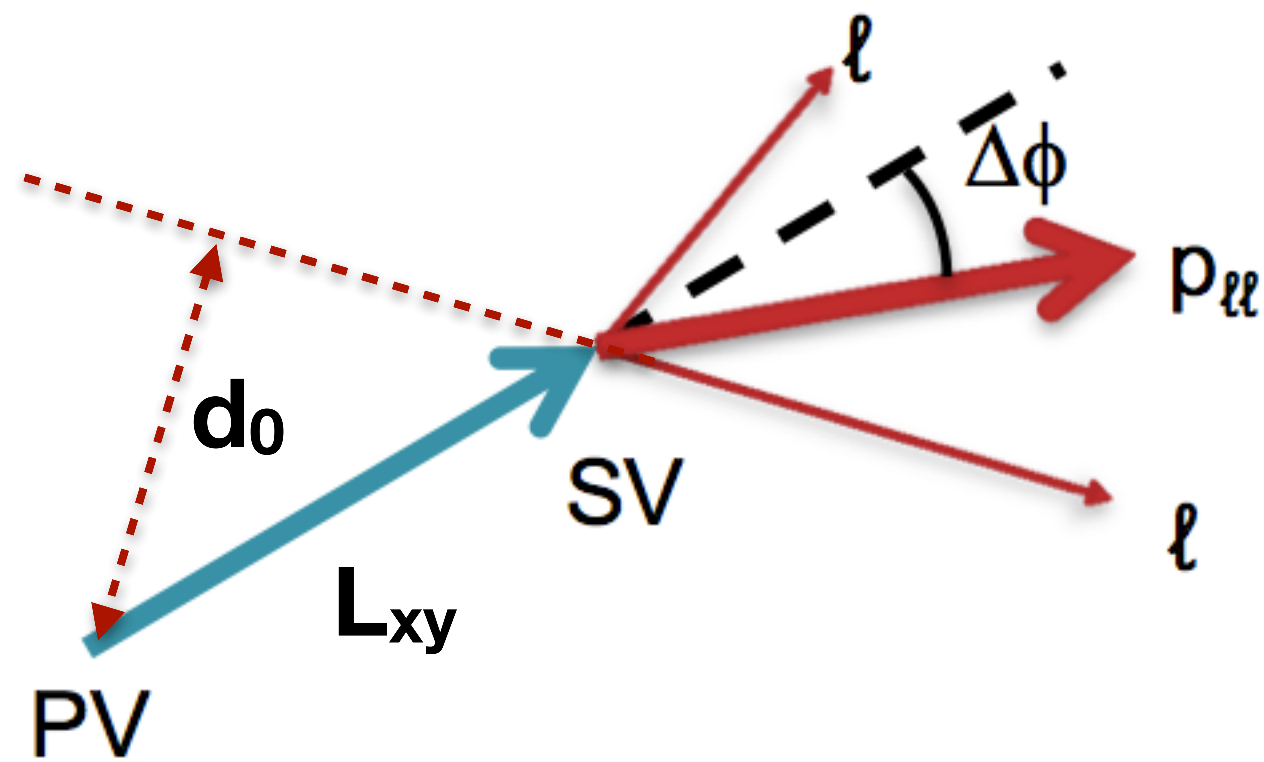


CMS-PAS-EXO-14-012

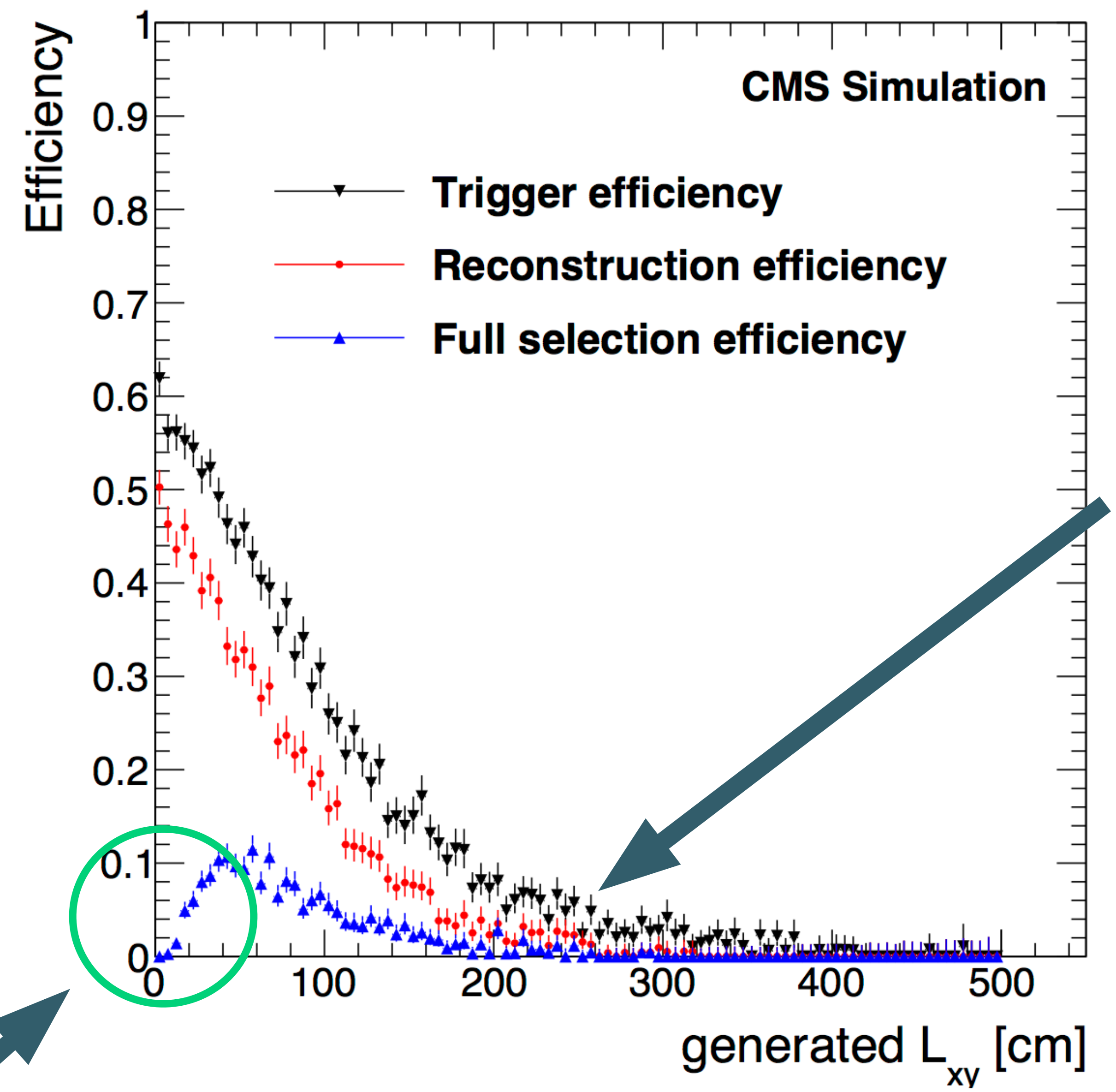
http://cds.cern.ch/record/2005761?ln=en

Analysis Strategy

- Search for pairs of high-pT stand-alone muons that cannot be matched to tracker tracks
  - **Orthogonal to track-based analysis**
- Muon candidates form a genuine, high-quality vertex
- Large transverse decay length significance ($L_{xy}/\sigma_{L_{xy}}$)
- Both muons with large transverse impact parameter significance (d_0/σ_d)
- Reject back-to-back muons (cosmics)
- Blind analysis



Selection Efficiency

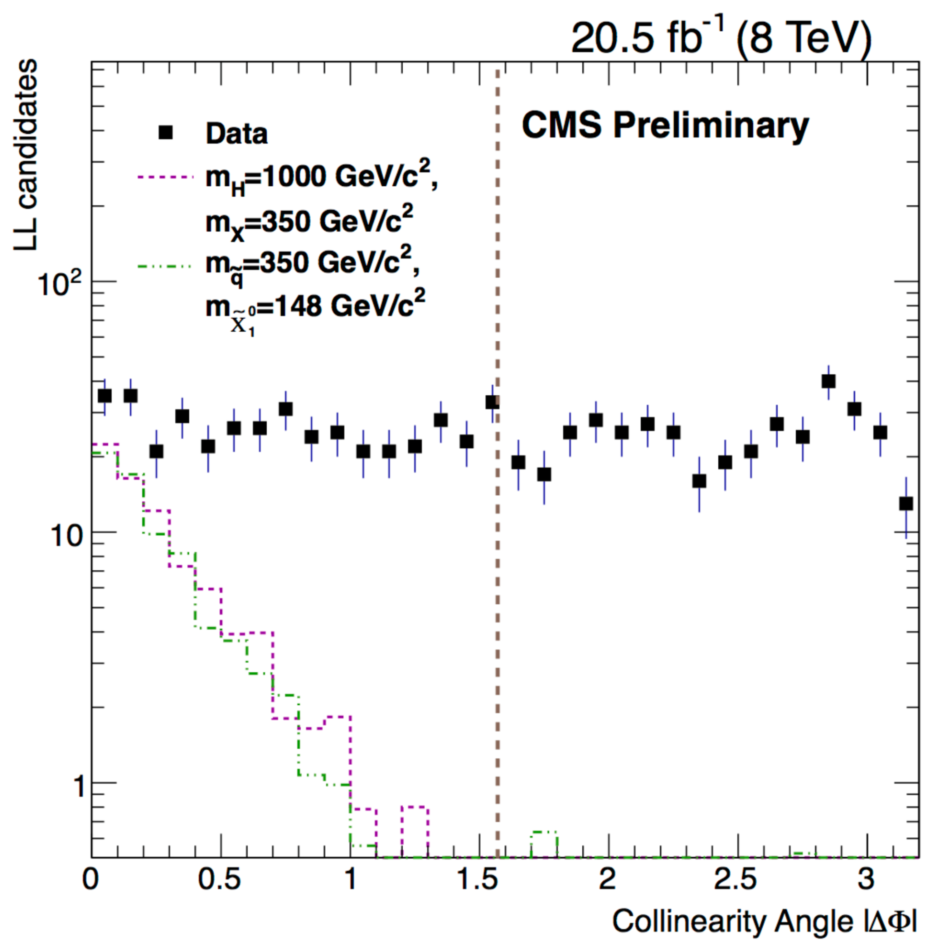


At large L_{xy} dominated by trigger efficiency

At small L_{xy} dominated by tracker-track veto

Background Estimate and Results

- The background is still approximately symmetric in ΔΦ, even with higher cosmic contamination

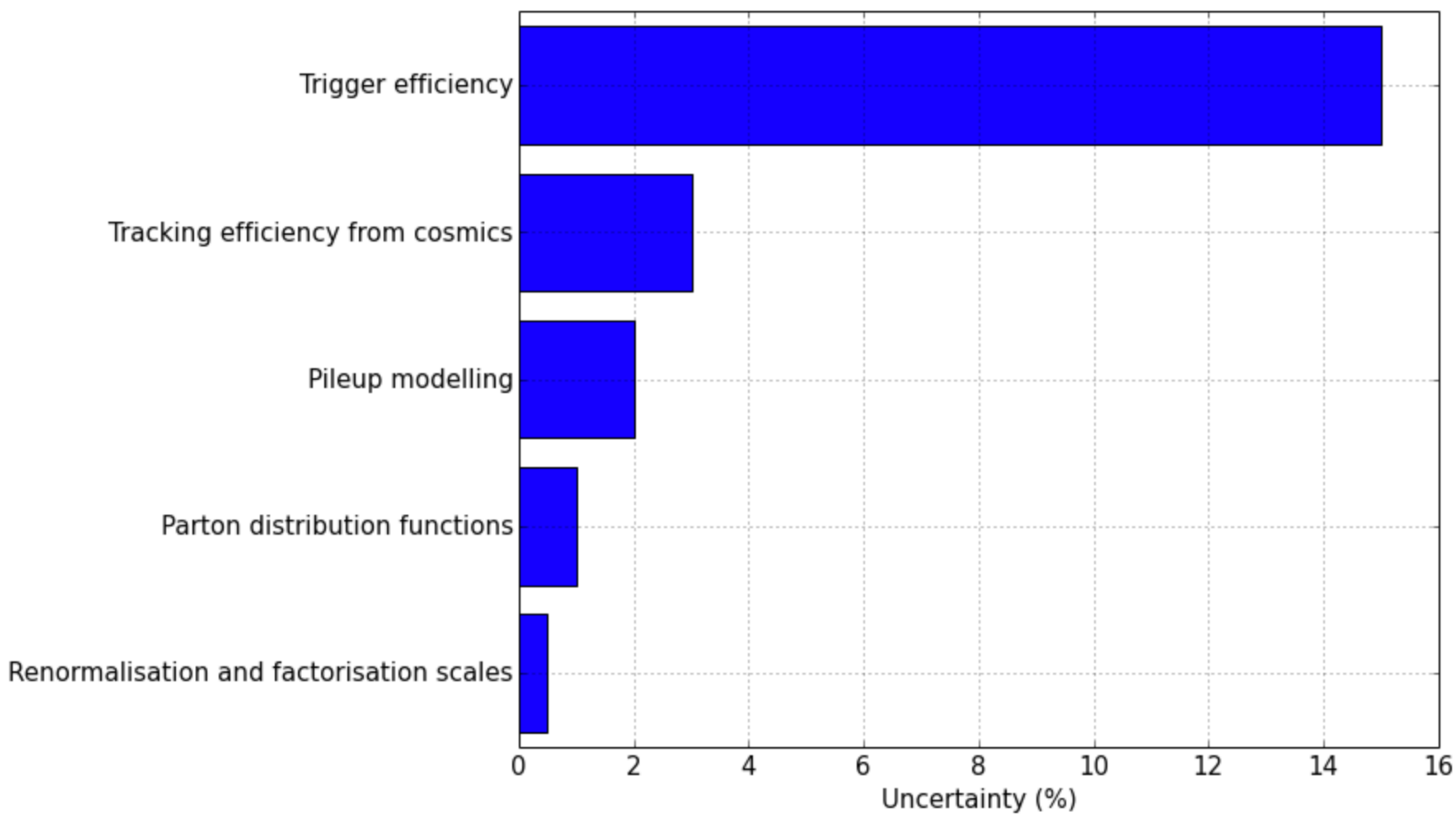


Background distribution with relaxed selection

Zero candidates observed in signal region, consistent with expectations

Systematic Uncertainties

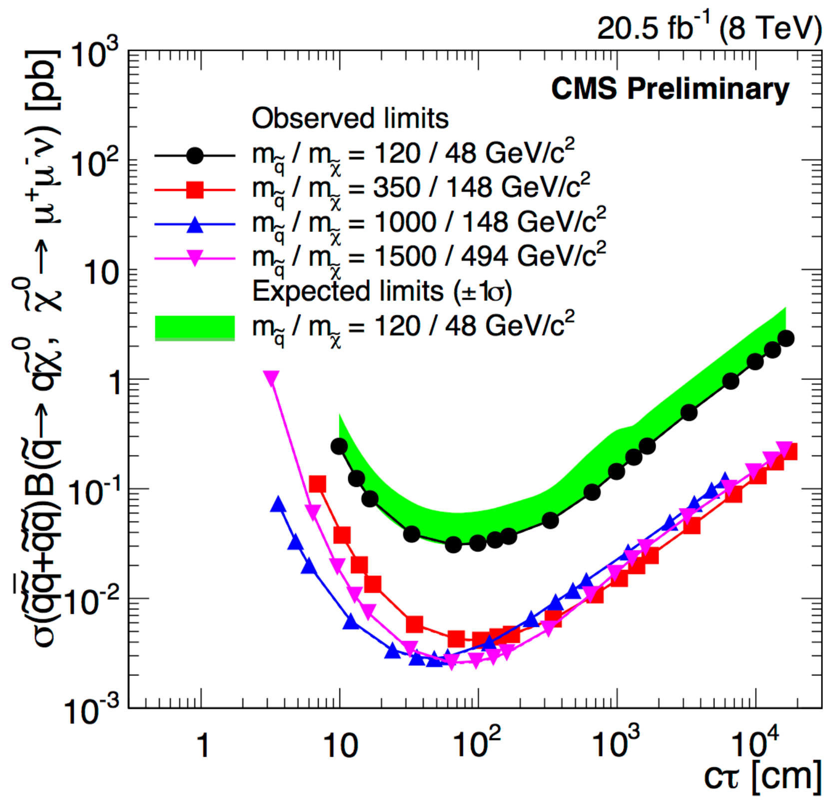
- Dominated by trigger efficiency



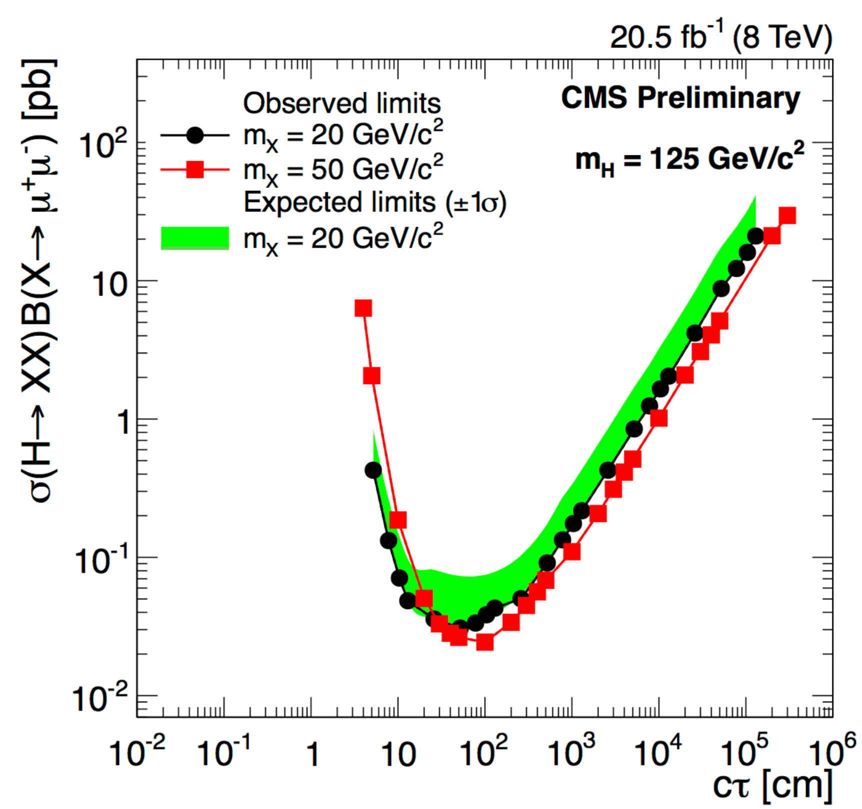
Limits

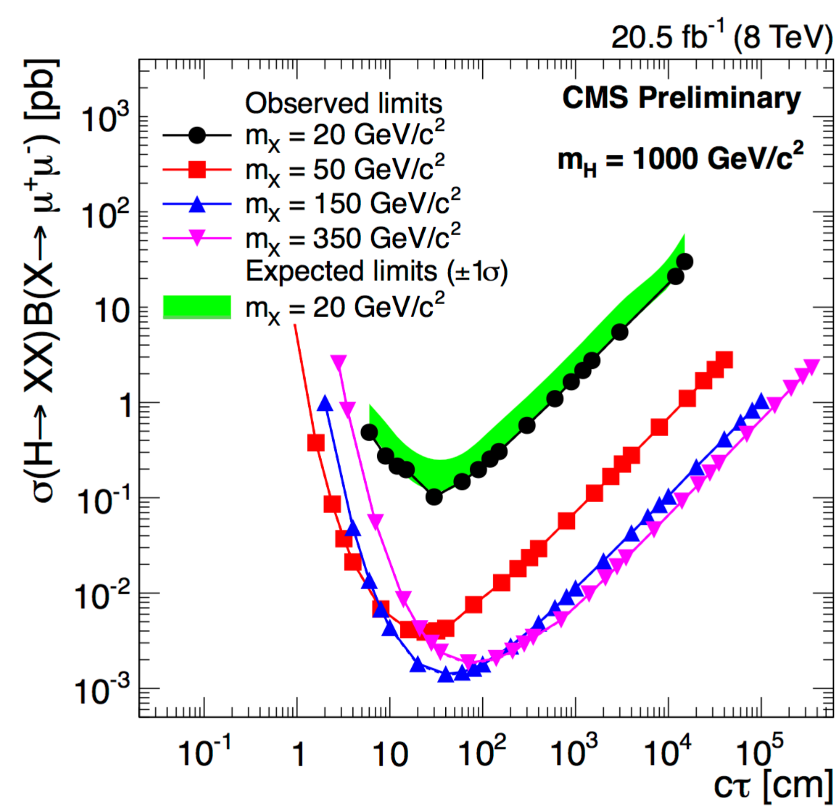
- Cross section X branching ratio upper limits for a wide range of lifetimes
- Also provided with acceptance

3-body signature



2-body signature

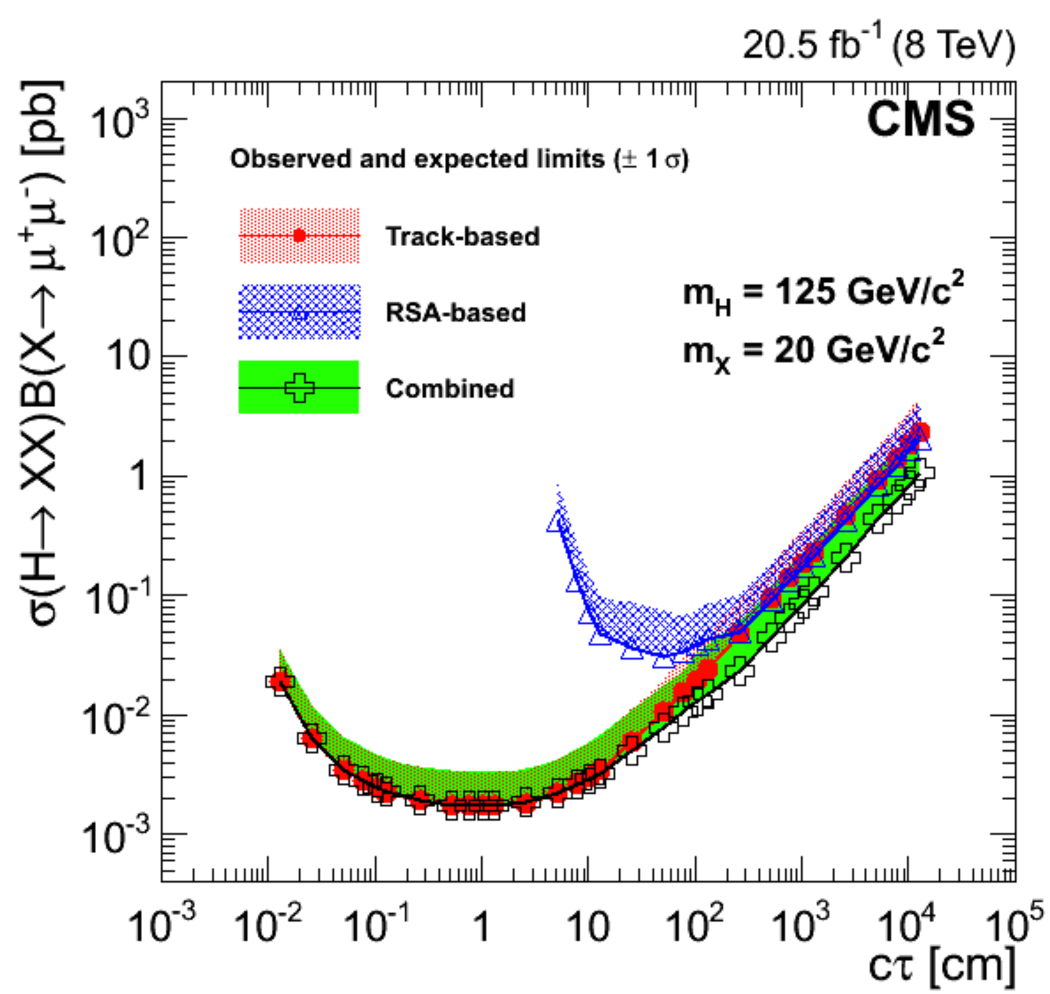




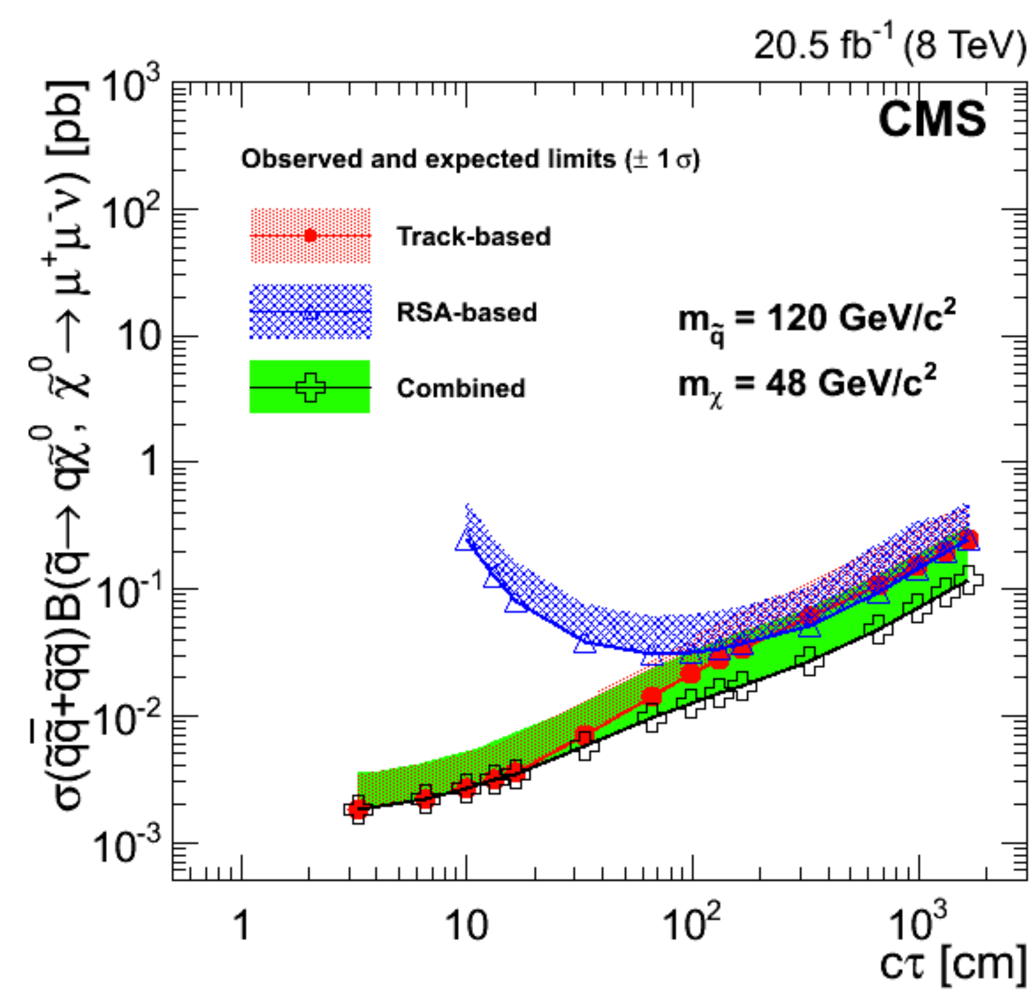
Combined Limits

- The two analyses are orthogonal, the efficiencies can be added and the limits combined
  - Approximately doubles the sensitivity to longer lifetimes

2-body signature

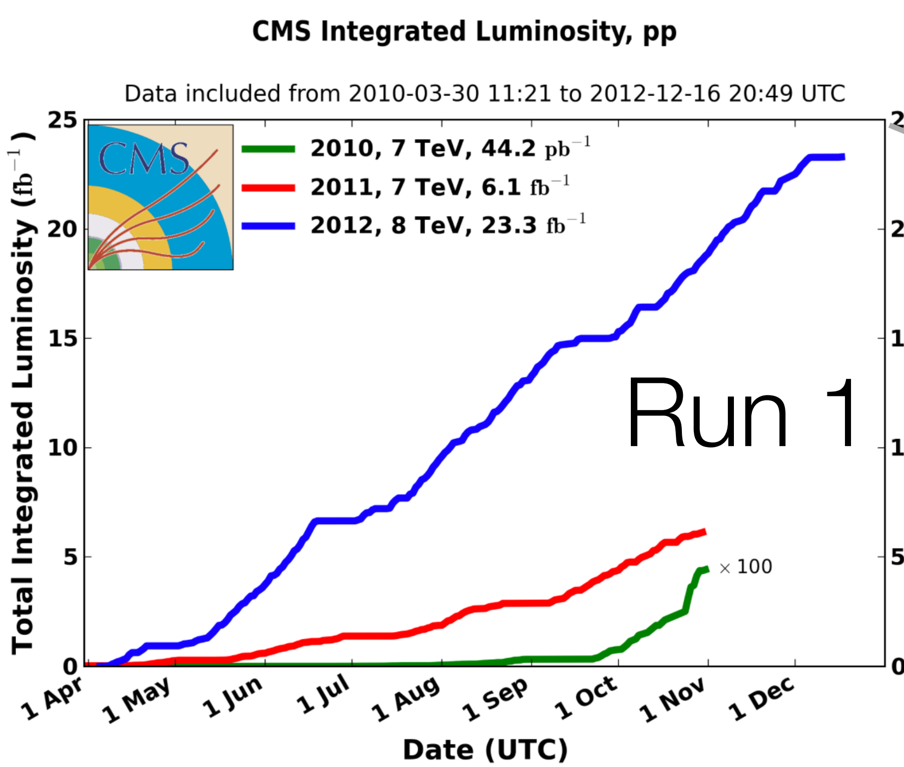


3-body signature



Prospects for Run 2

- Major limitation to the stand-alone muon analysis was the trigger
    - New triggers in Run 2 expected to improve sensitivity to longer lifetimes
    - Improvements in offline algorithms for electrons and muons expected to further improve sensitivity
- Higher energy extends sensitivity to higher masses

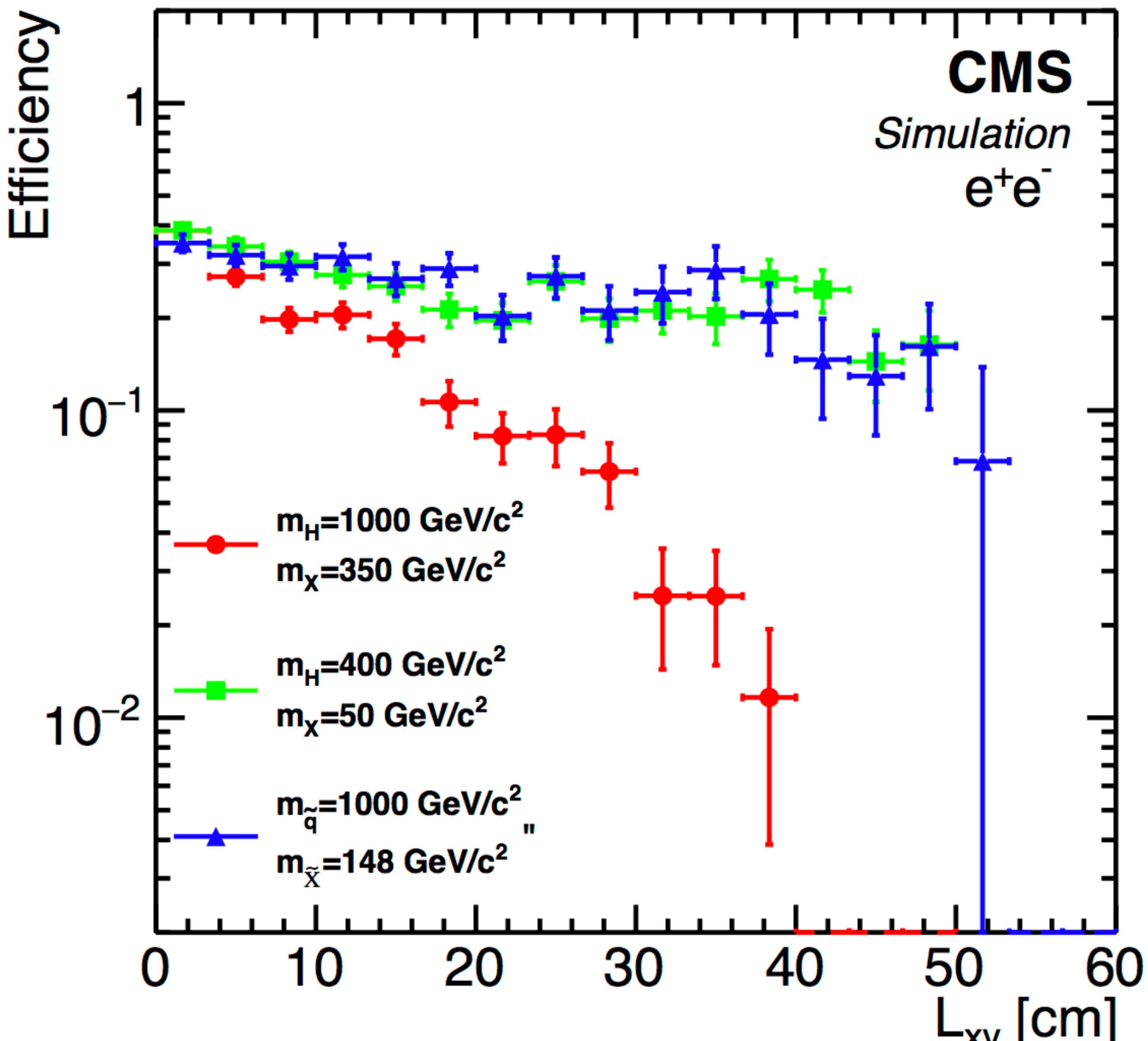


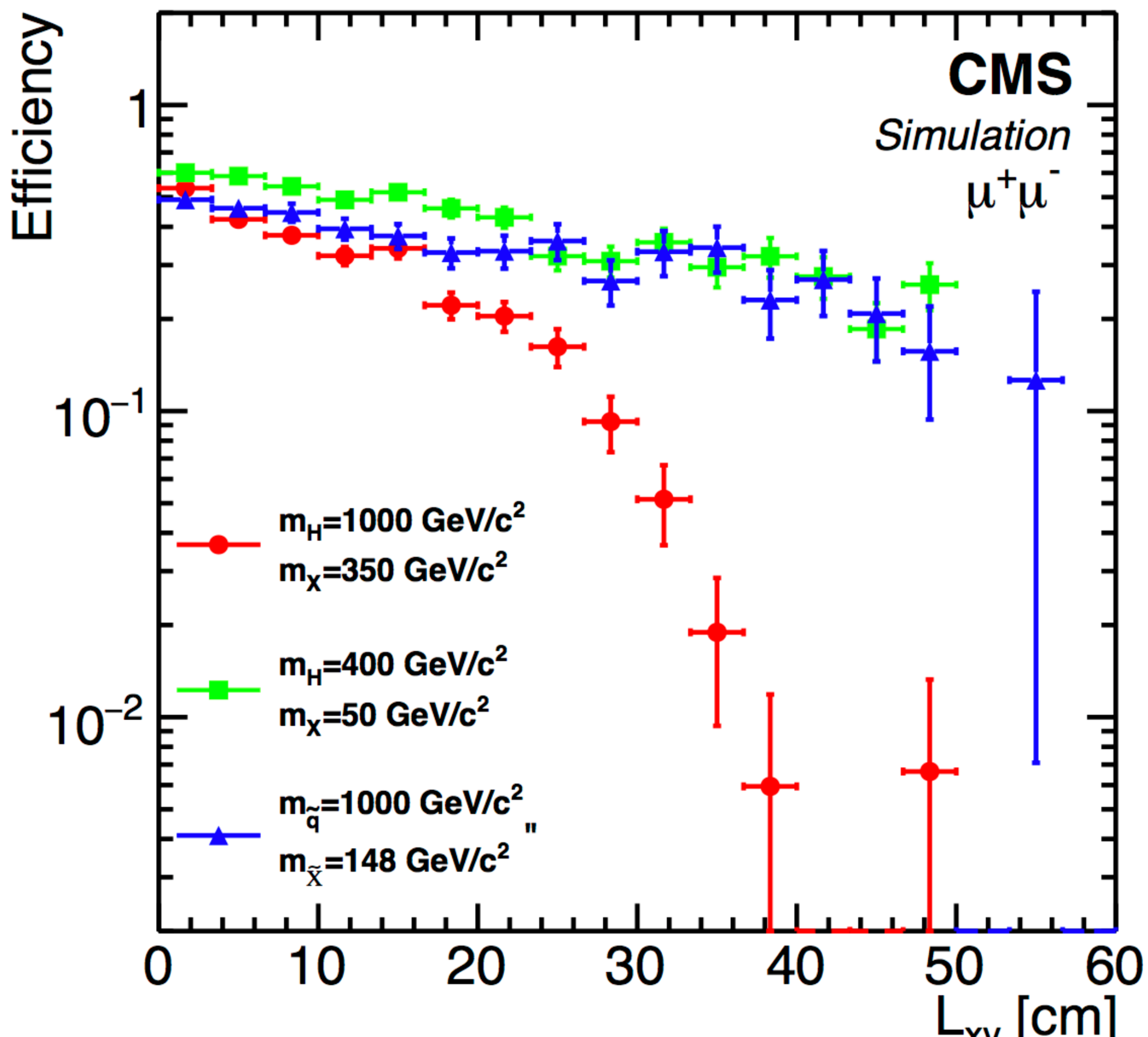
Thank You

Backup

Efficiency for Track-Based Analysis

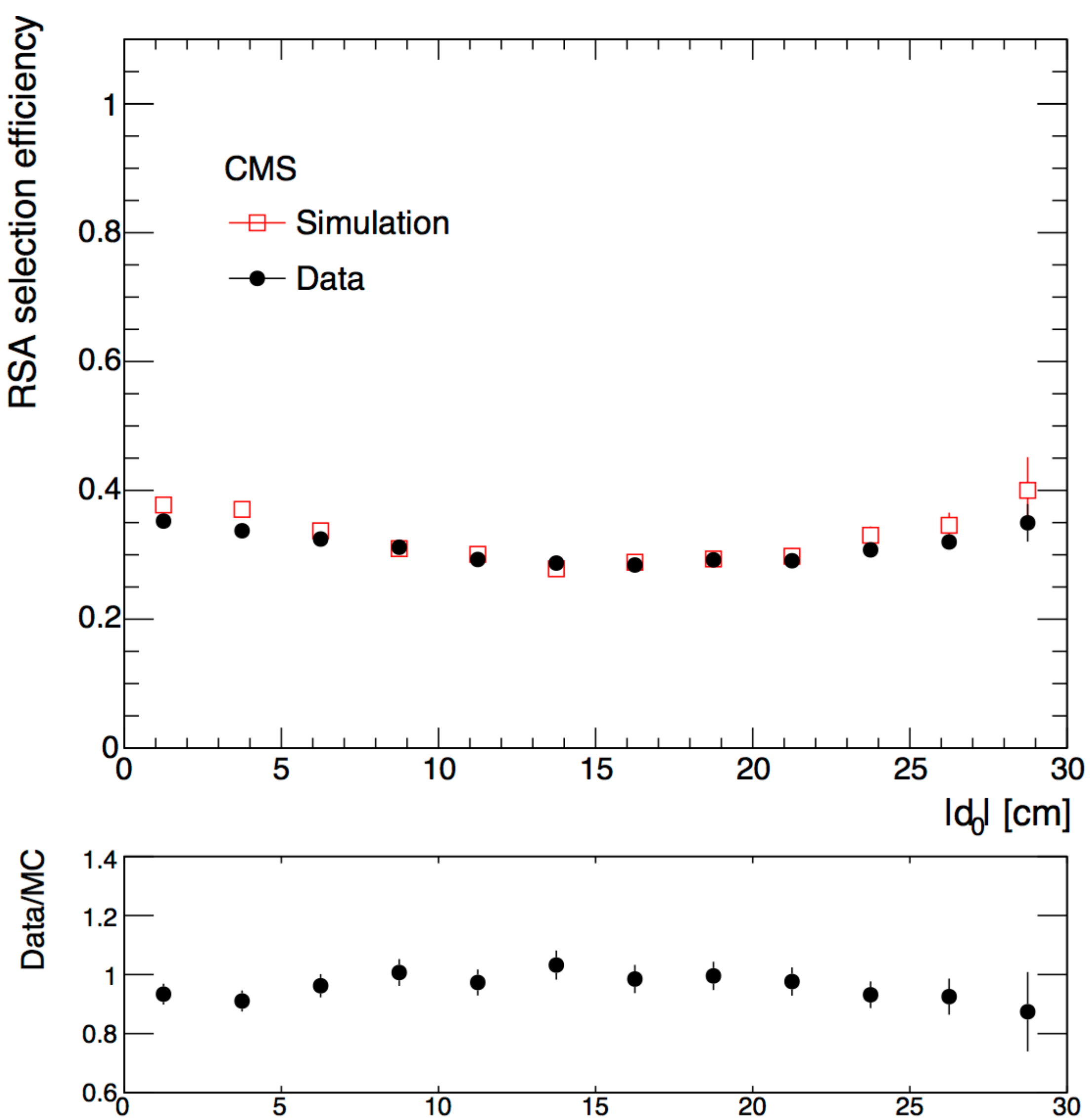
- Top value of 36% (46%) in the electron (muon) channel, but it becomes significantly smaller at lower H masses or at longer and shorter lifetimes. For example, if cτ is increased to 20 cm for this set of masses, then ε1 drops to 14% (20%) in the electron (muon) channel.

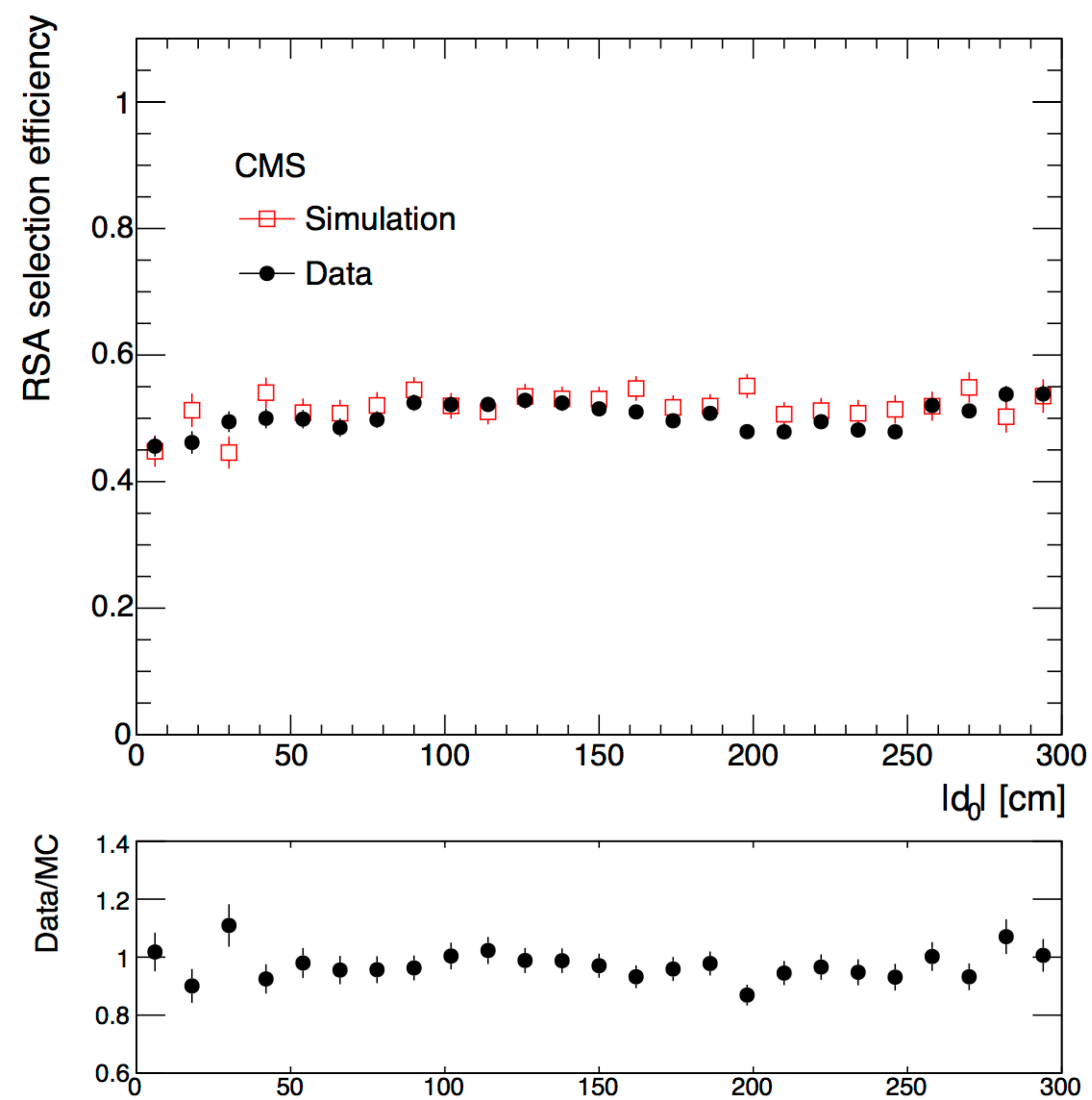




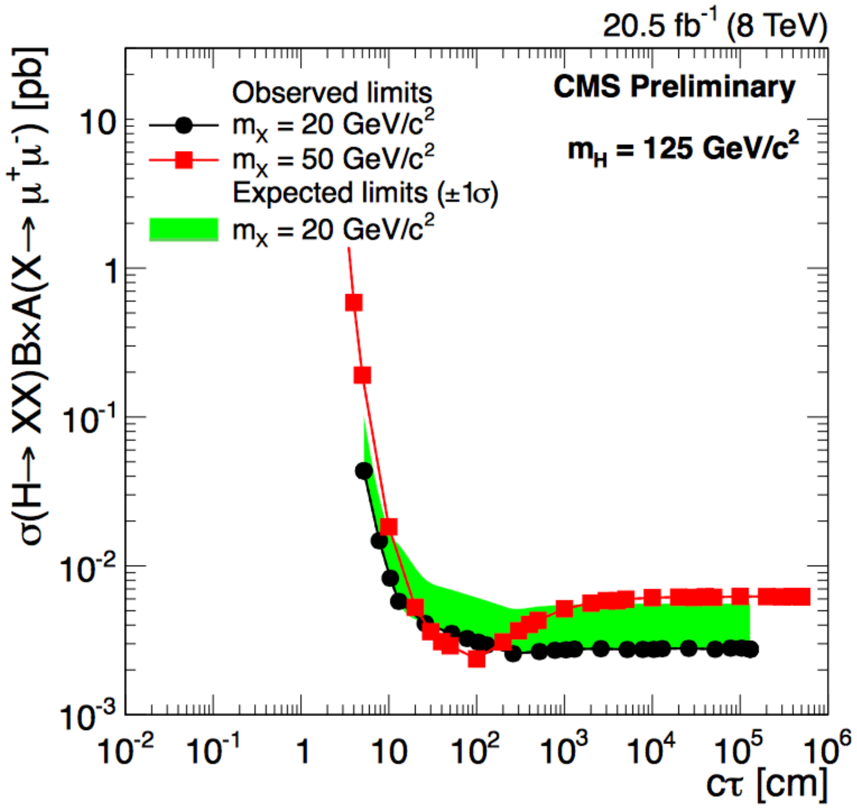
Offline Reconstruction and Selection Efficiency Standalone Muons

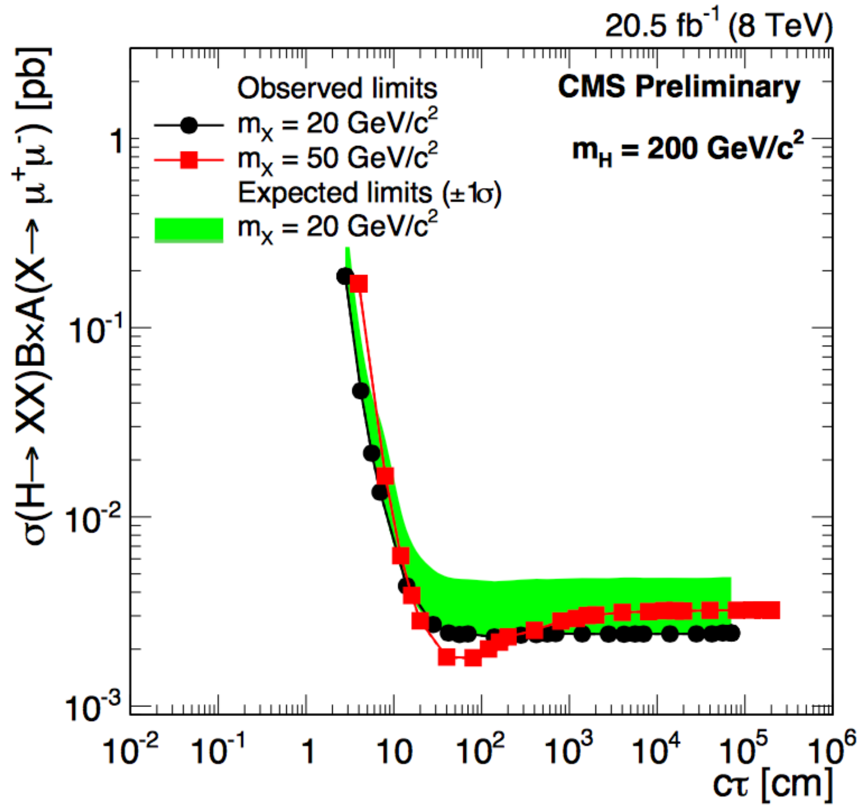
- Measured with respect to tracker and with muon chambers only
- Excellent agreement between data and simulation

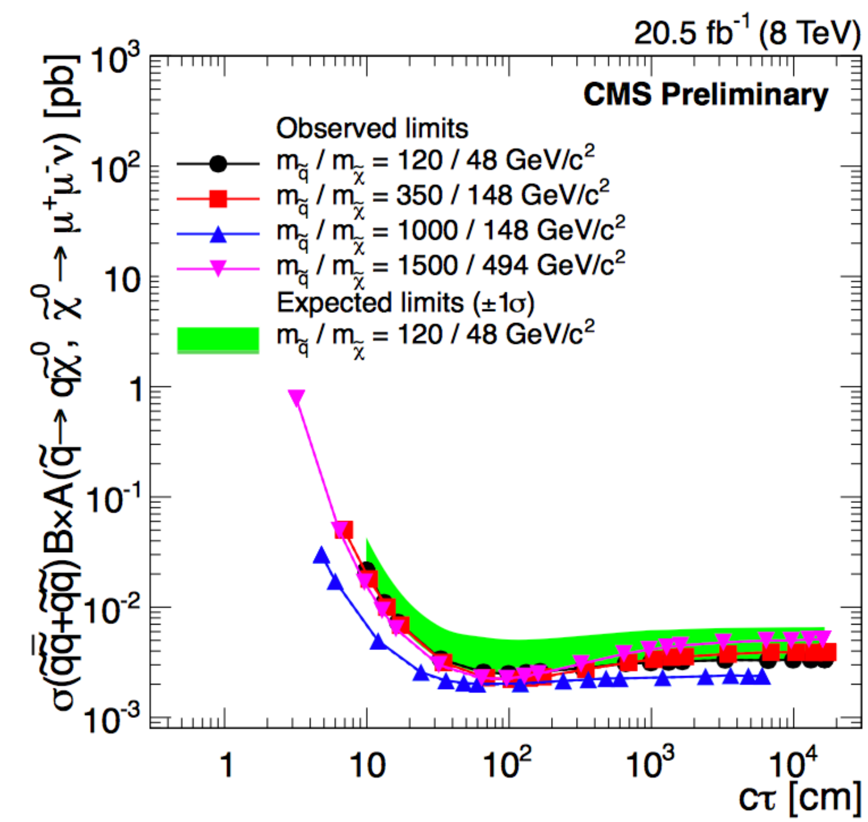


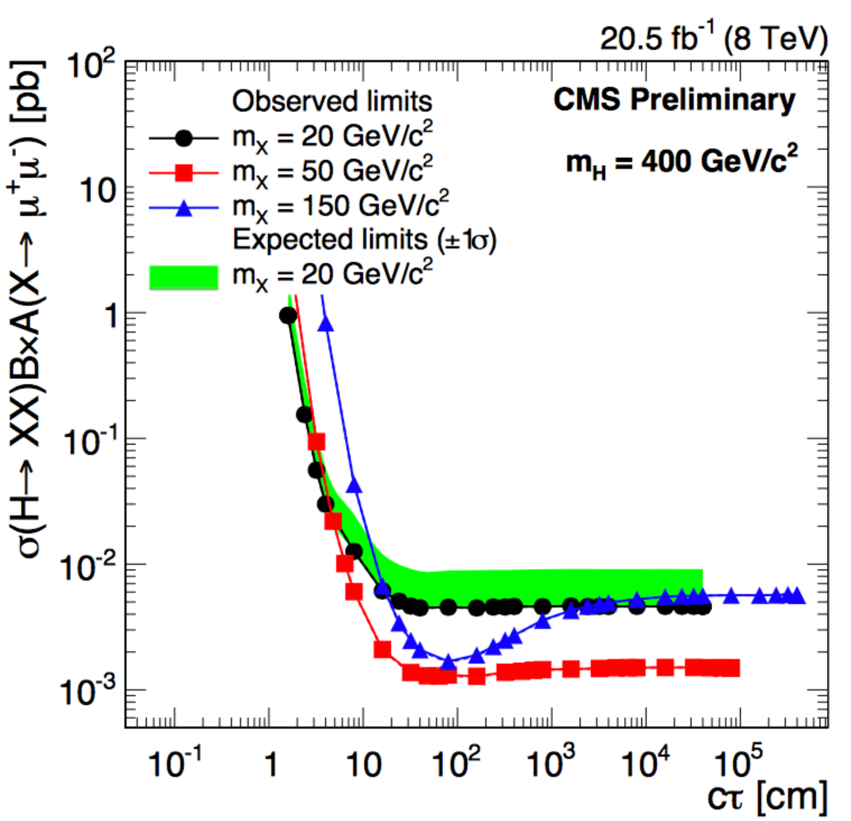


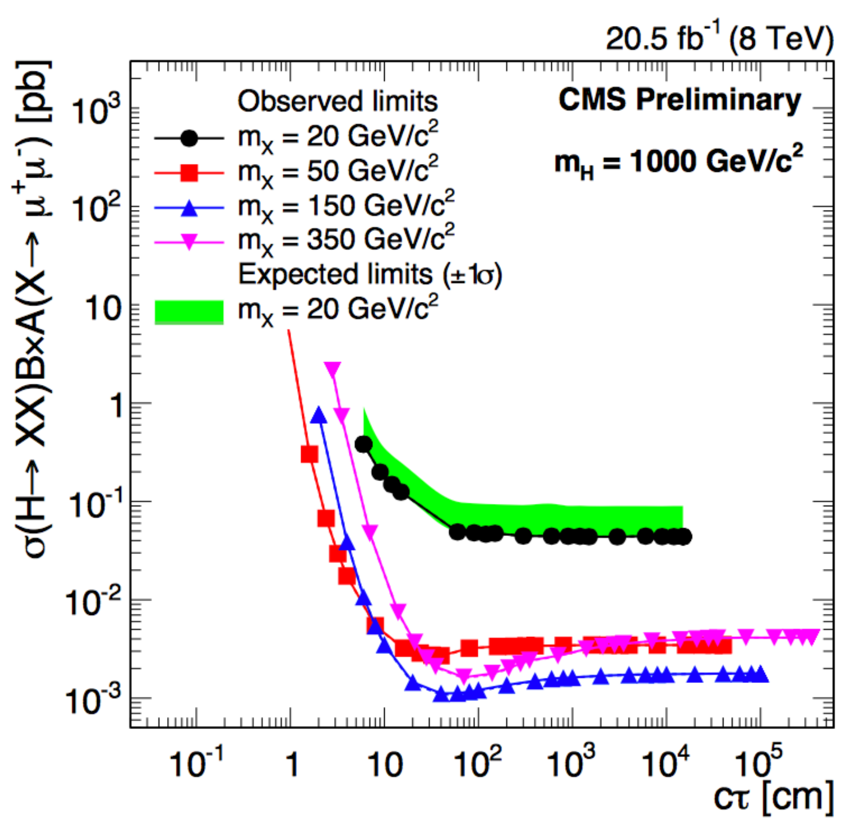
Upper Limits within Acceptance







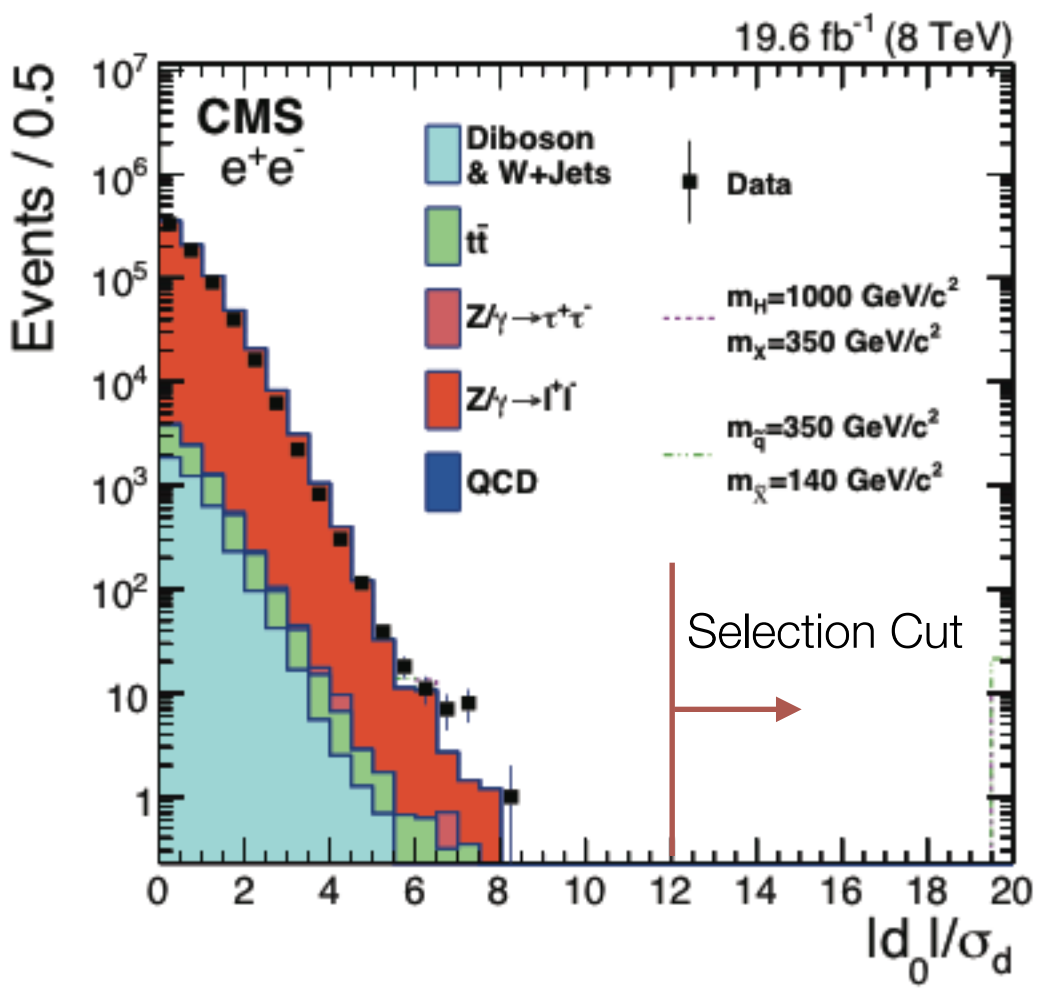


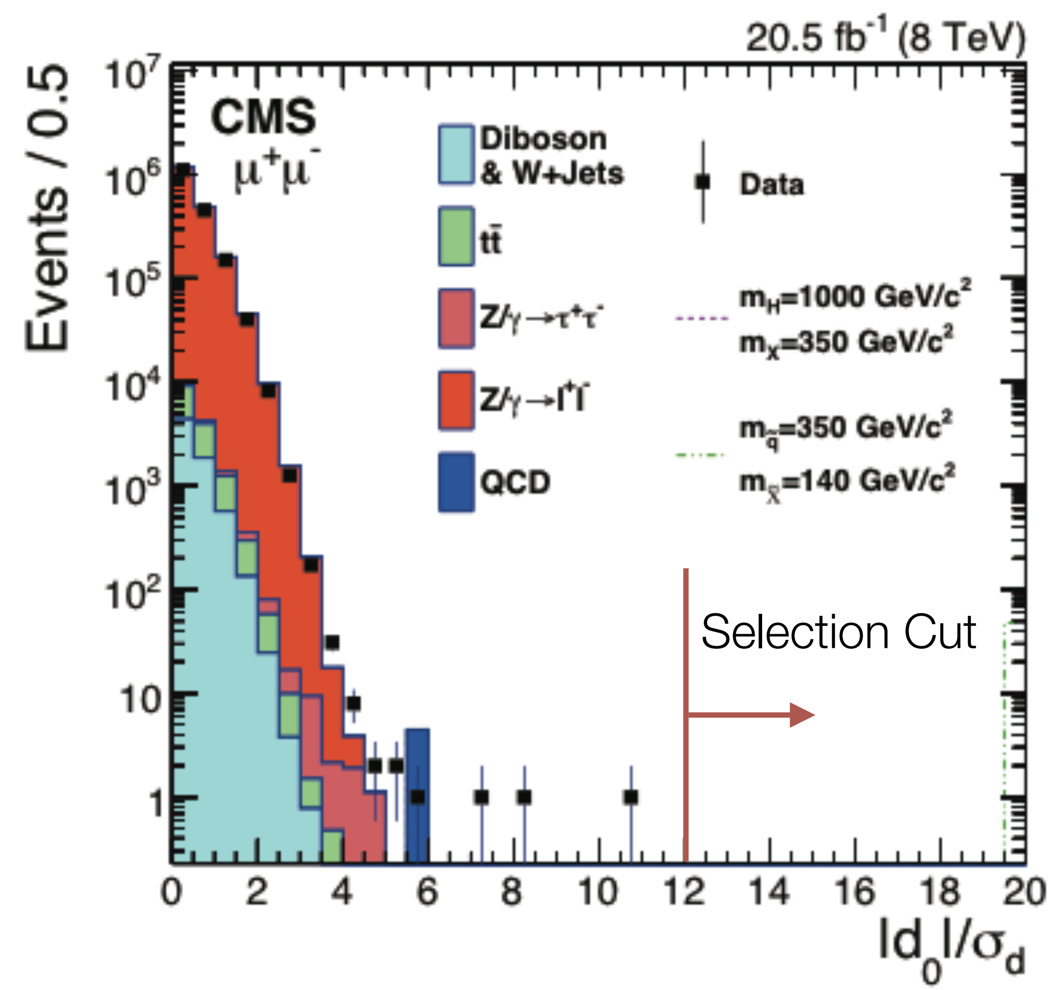


Data-Driven Background Estimate (Cont.)

- Estimated from the number of observed events in the control region after full selection: zero

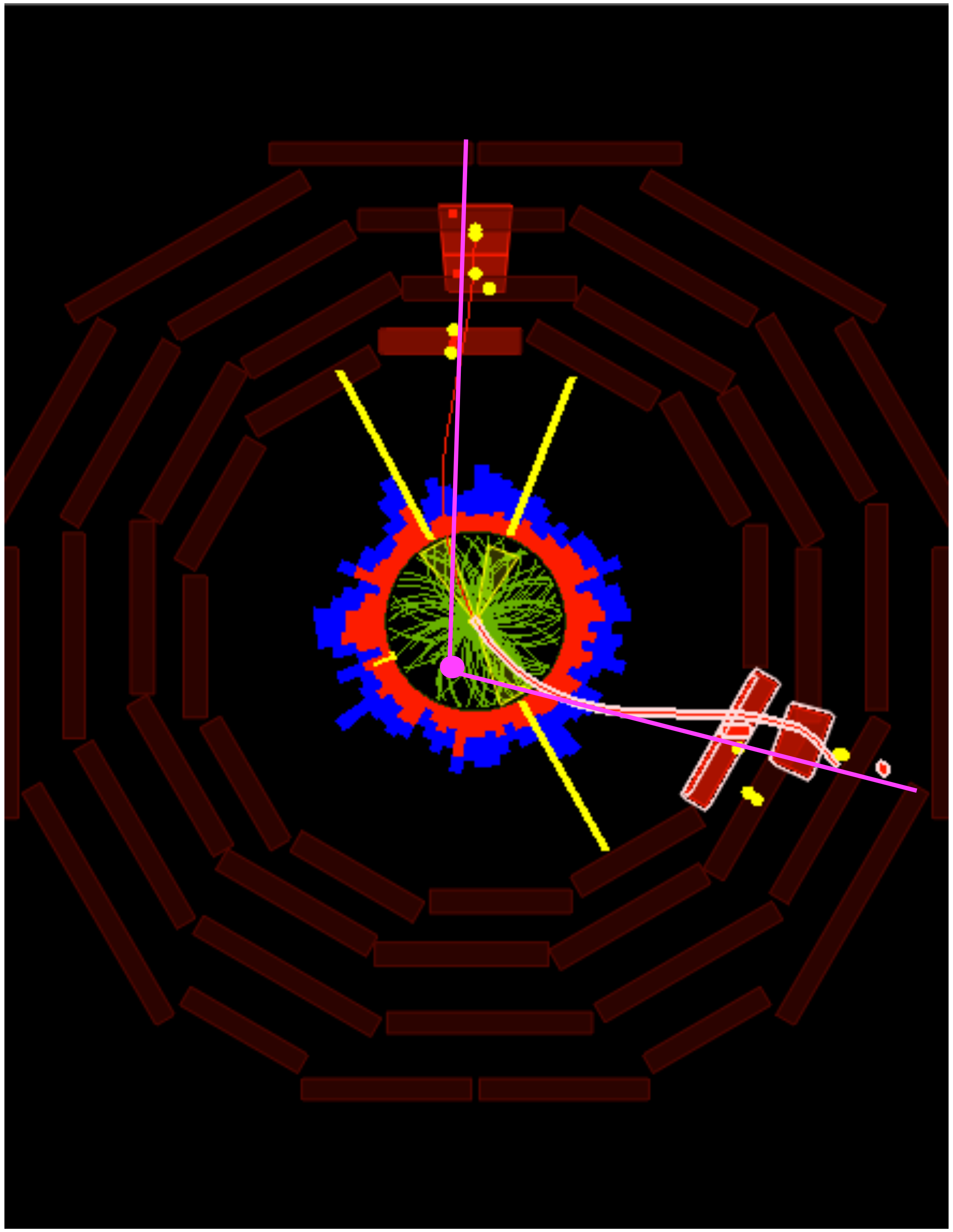
d_0/σ_d distributions - control region





Track Veto

- By design this analysis is **complementary** to the track-based analysis
- Any **signal events** that would satisfy the **track-based analysis** would by definition **not satisfy this analysis**
- Track veto also **removes prompt background** from mis-measured (and mis-propagated) RSAs
- Extrapolate **tracker-track** to innermost hit of RSA, match in $\Delta R < 0.1$
- Use tracker tracks with $p_T > 10$ GeV
  - tracker-tracks are more precise, extrapolating RSA to tracker might lead to failed match



Magenta lines show the direction of the RSA. This event would pass the selection and it would be rejected by the track veto

Analysis Strategy

- Utilizing the **silicon tracker**:
  - Match high-p_T, isolated tracks to
    - offline photon (electron channel)
    - trigger muon (muon channel)
  - Search for pairs of leptons that form a genuine, high-quality vertex
  - Both leptons with large transverse impact parameter significance (d_0/σ_d)

- Utilizing the **muon chambers only**:
  - Search for pairs of high-p_T stand-alone muons that cannot be matched to tracker tracks
    - Orthogonal to track-based analysis
  - Muon candidates form a genuine, high-quality vertex with large transverse decay length significance ($L_{xy}/\sigma_{L_{xy}}$)
  - Both muons with large transverse impact parameter significance (d_0/σ_d)

Blind Analysis

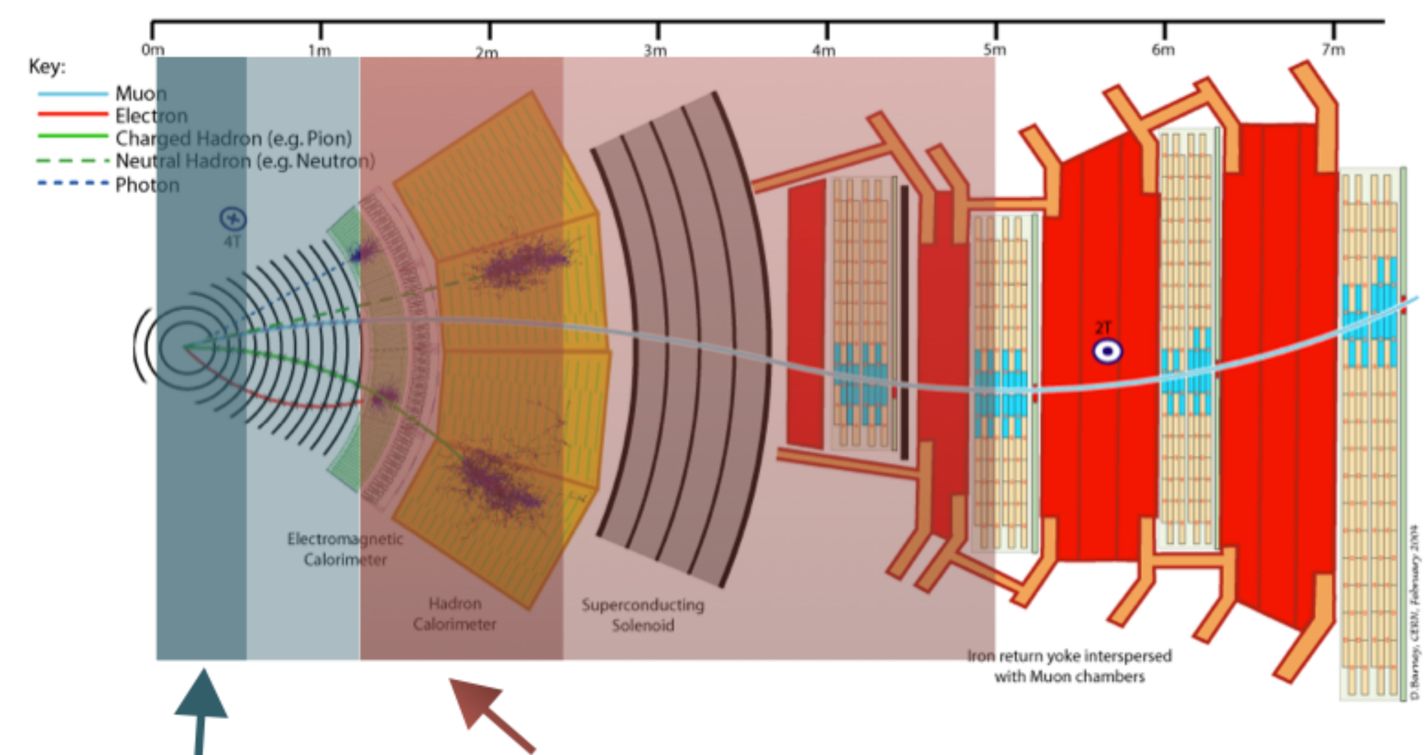
Analysis Challenges

- Sensitivity to longer decay lengths, mostly limited by trigger efficiency
- Higher background due to lower resolutions by using muons reconstructed only using the muon chambers (RSA muons)
  - Cosmic muons are an important source of background
- Veto muons matched

StandAlone Muons

http://cds.cern.ch/record/2005761?ln=en

- Improve sensitivity of the analysis to longer lifetimes in muon channel
- **Muons reconstructed using only muon chambers** (RSA)
- Same trigger, same analysis strategy, similar selection
- Analysis by design **orthogonal** to track-based analysis
    - Combination increases acceptance and improves expected limits by factor two



Effective range of track-based analysis

Effective range of standalone muons analysis