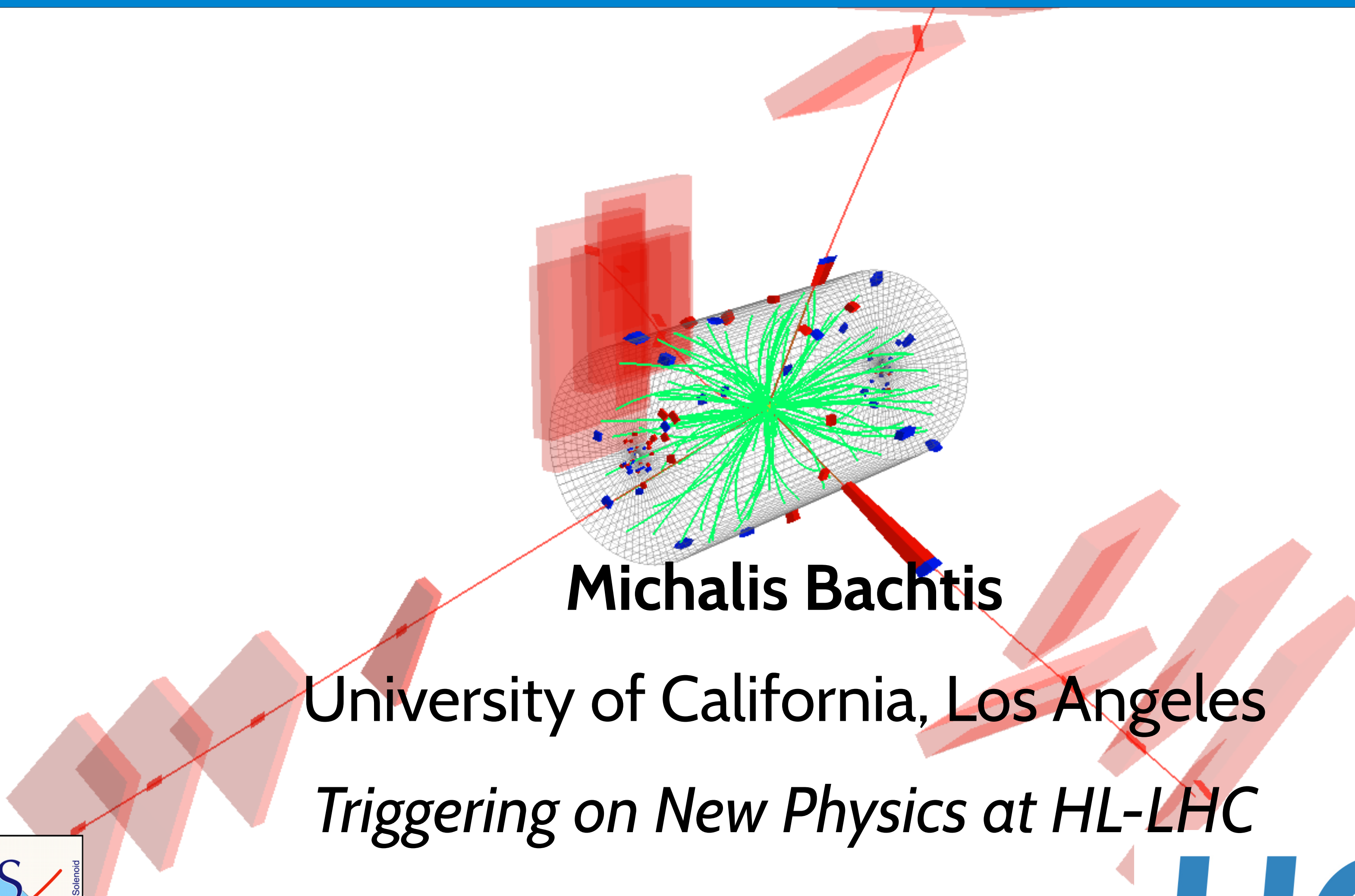
Upgrade of the CMS Muon Trigger for High Luminosity LHC



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Triggering on New Physics at HL-LHC

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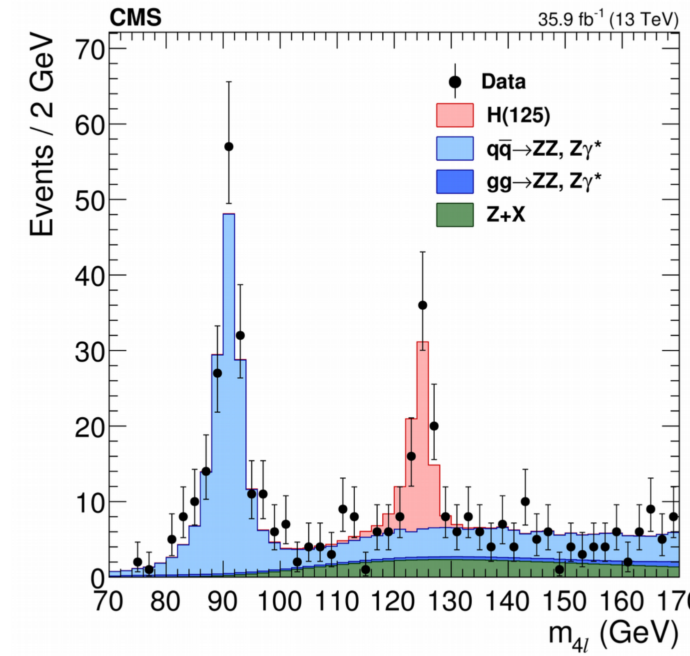
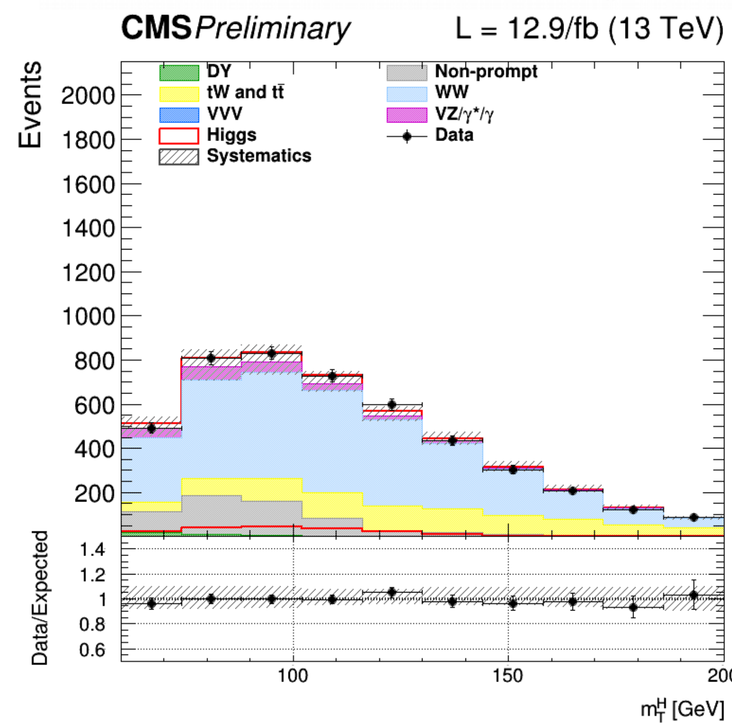
UCLA

Introduction

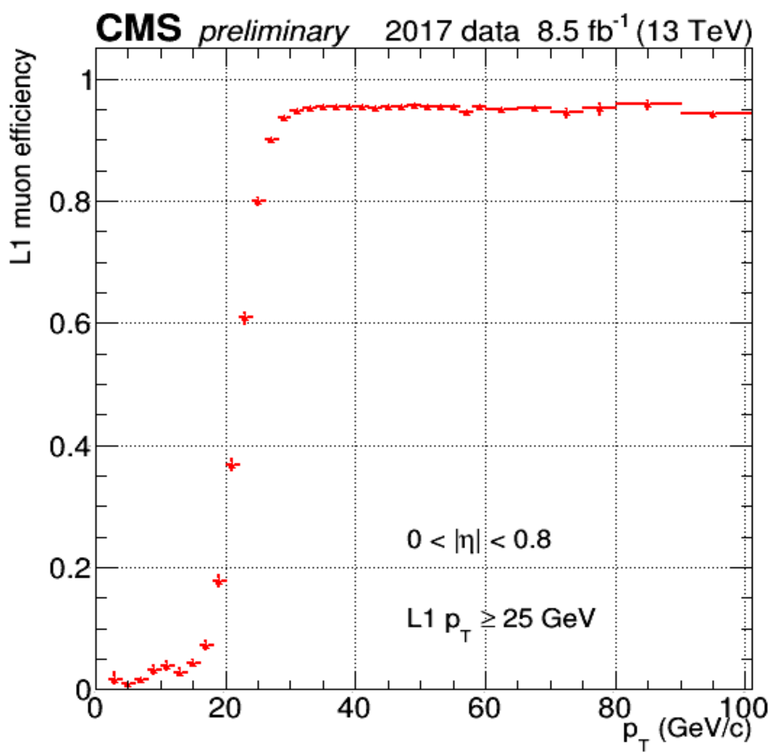
- Muon Trigger: Workhorse of the CMS Physics program
  - **75% of data analyses** in CMS rely on Muon Trigger to collect their data
    - Four out of the five main Higgs final states
  - Cleanliness of muon experimental signature makes physics with muons even more important for High Luminosity LHC
- Phase II muon trigger requirements
  - Trigger muons from prompt processes with very high efficiency
    - SM processes, Higgs, SUSY, 2HDM, exotic resonances
  - Exploit the muon detectors to enable new triggers for exotic physics searches
    - Obvious candidate: Long lived particles

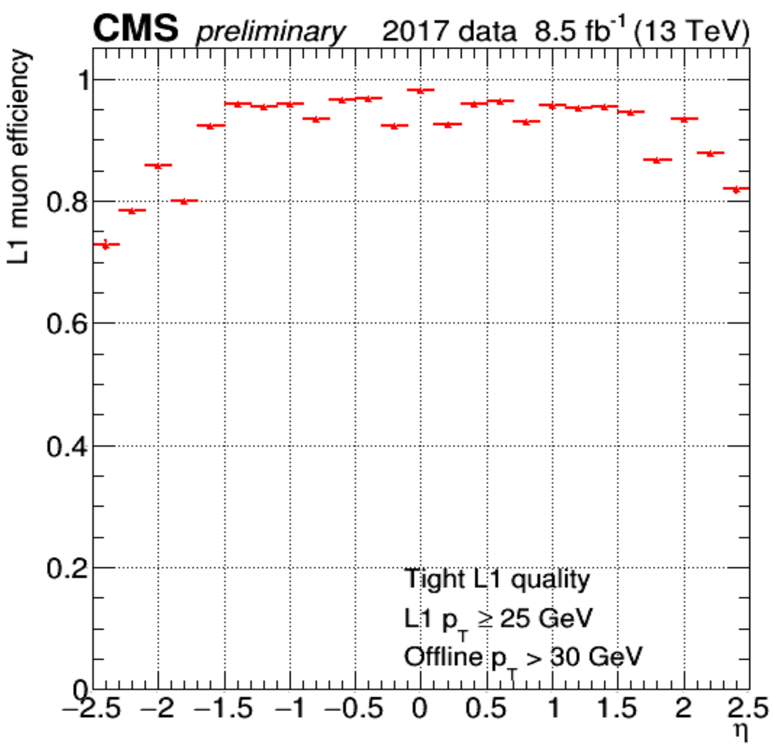




Current muon trigger in CMS

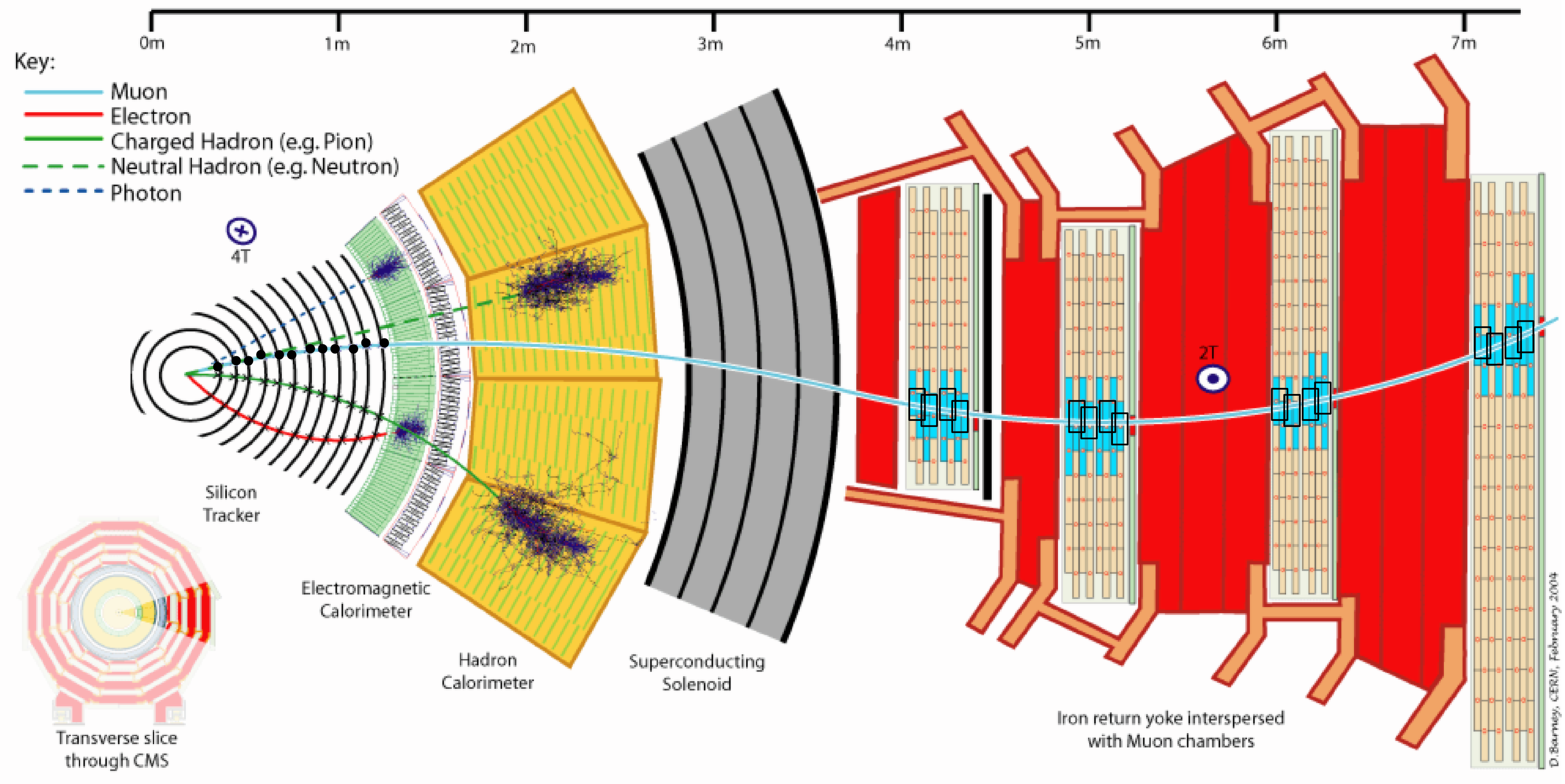
- Current muon trigger uses **only the muon detectors** to reconstruct tracks
- Implemented in modern FPGAs → Algorithms can be changed
- Very good performance for muons originating from the collision vertex





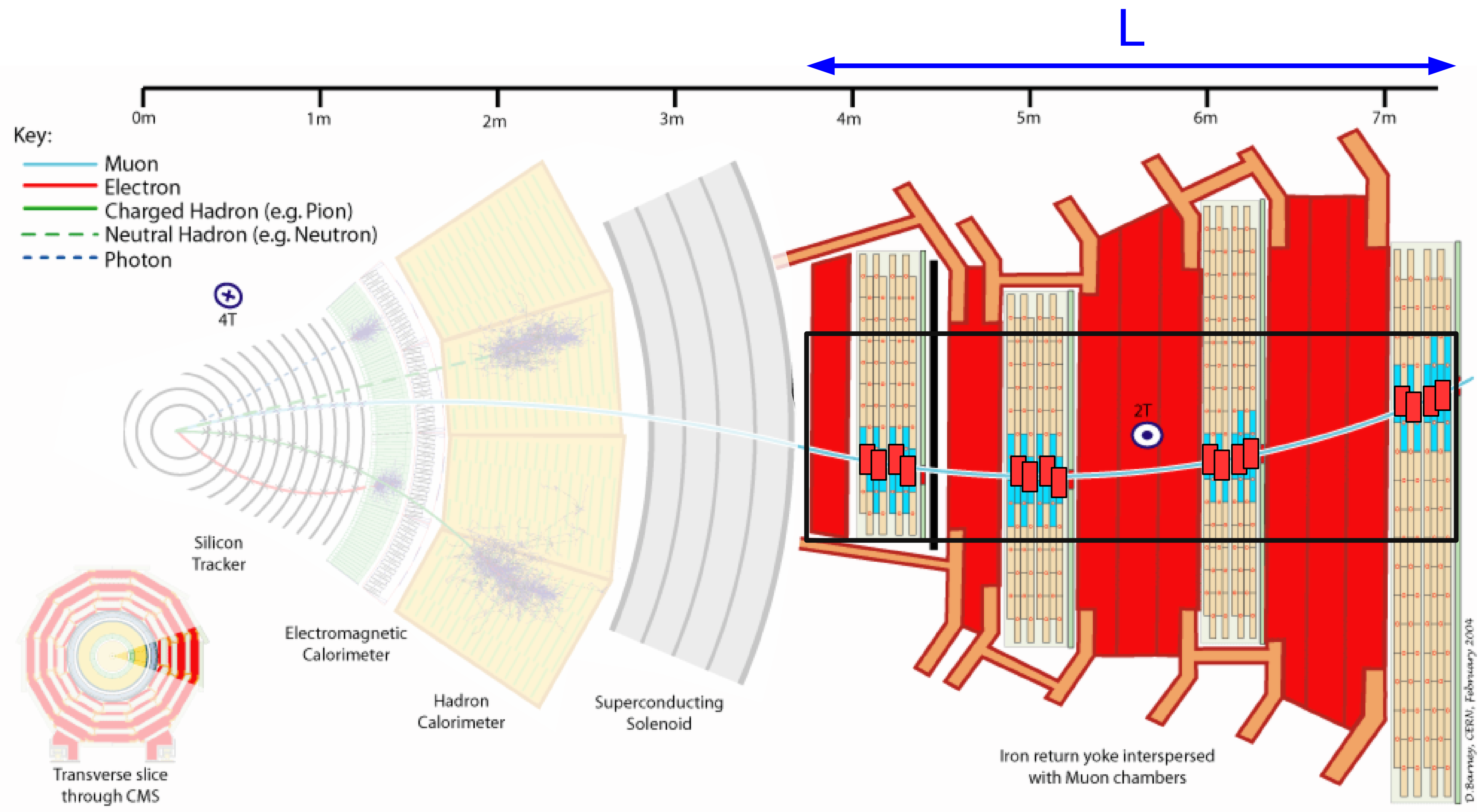
- Satisfies current physics requirements for 99% of the analyses
  - Let's talk about the 1% missing

Muon reconstruction in data analysis



- Muons traverse the full detector leaving a distinct track in the inner tracker and the muon system
- For muons from SM electroweak processes (P_T~**50** GeV), the inner tracker dominates the measurement
  - The muon system is mainly used for ID

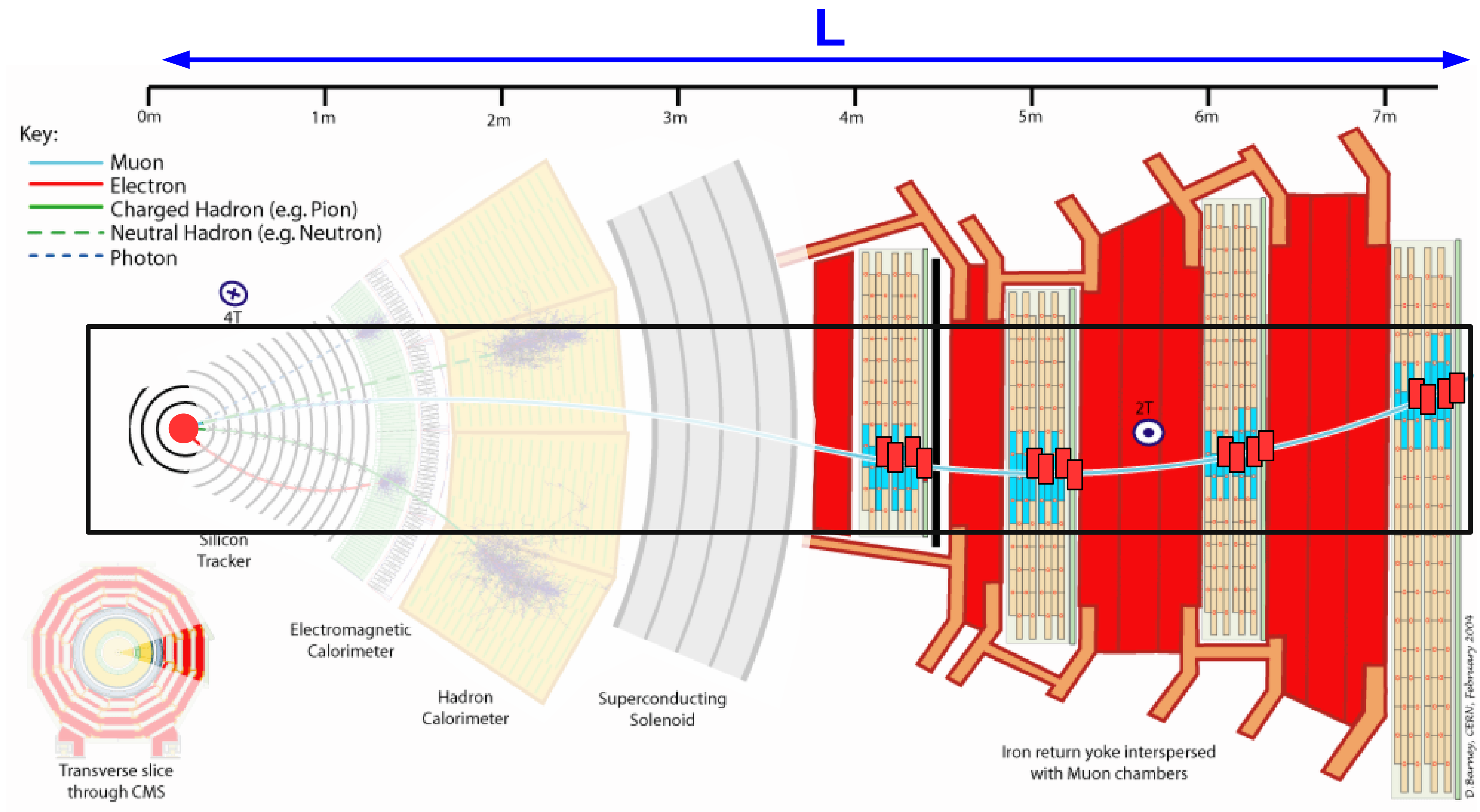
Standalone Track



- Uses only the hits in the muon system
- Momentum resolution very coarse (~25%)

$$\frac{\sigma_{p_T}}{p_T} \sim \frac{1}{BL^2}$$

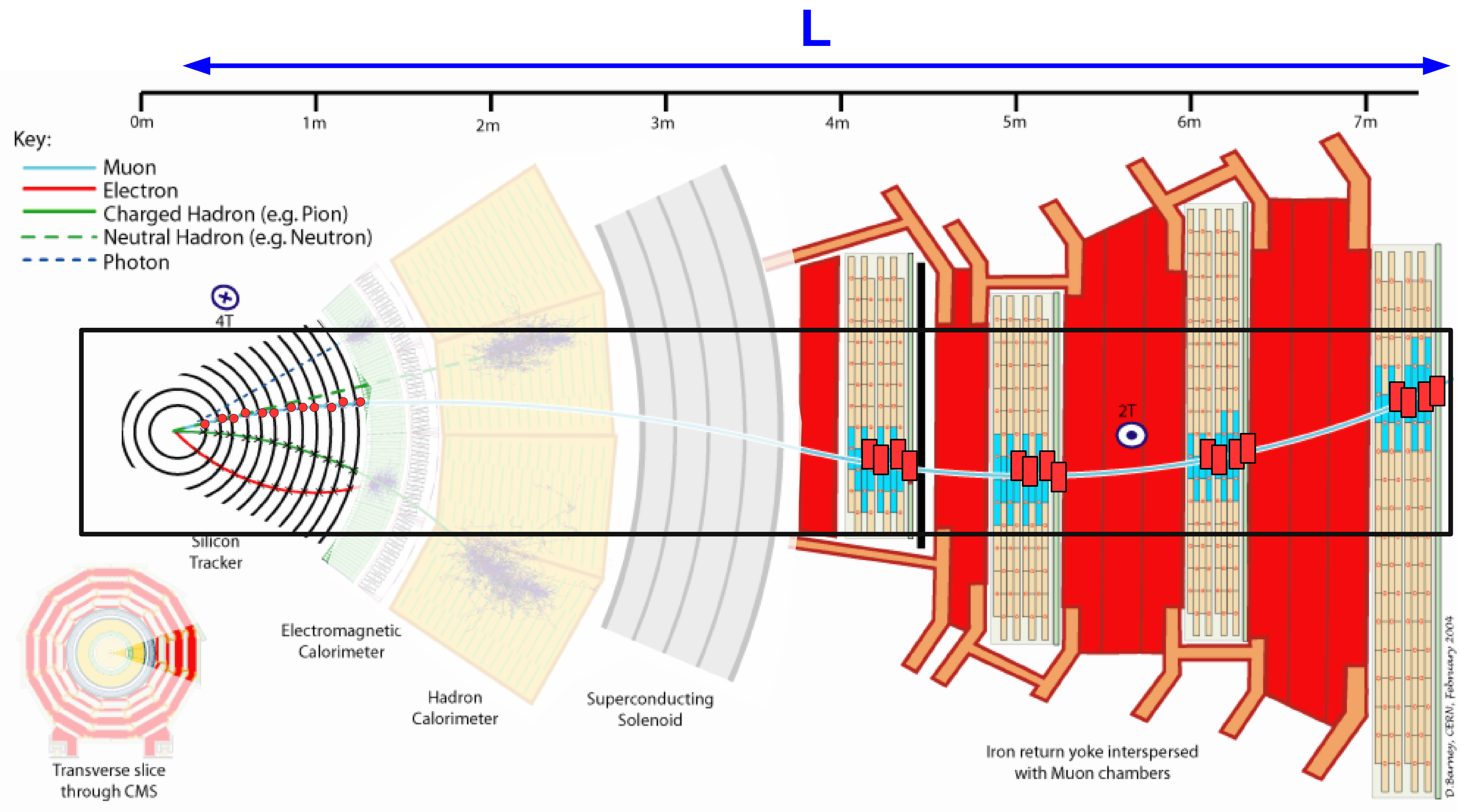
Standalone Track+vertex



- Uses the hits of the muon system plus the vertex
- Exploits the full leverarm of the detector providing modest resolution (~10%)

$$\frac{\sigma_{p_T}}{p_T} \sim \frac{1}{BL^2}$$

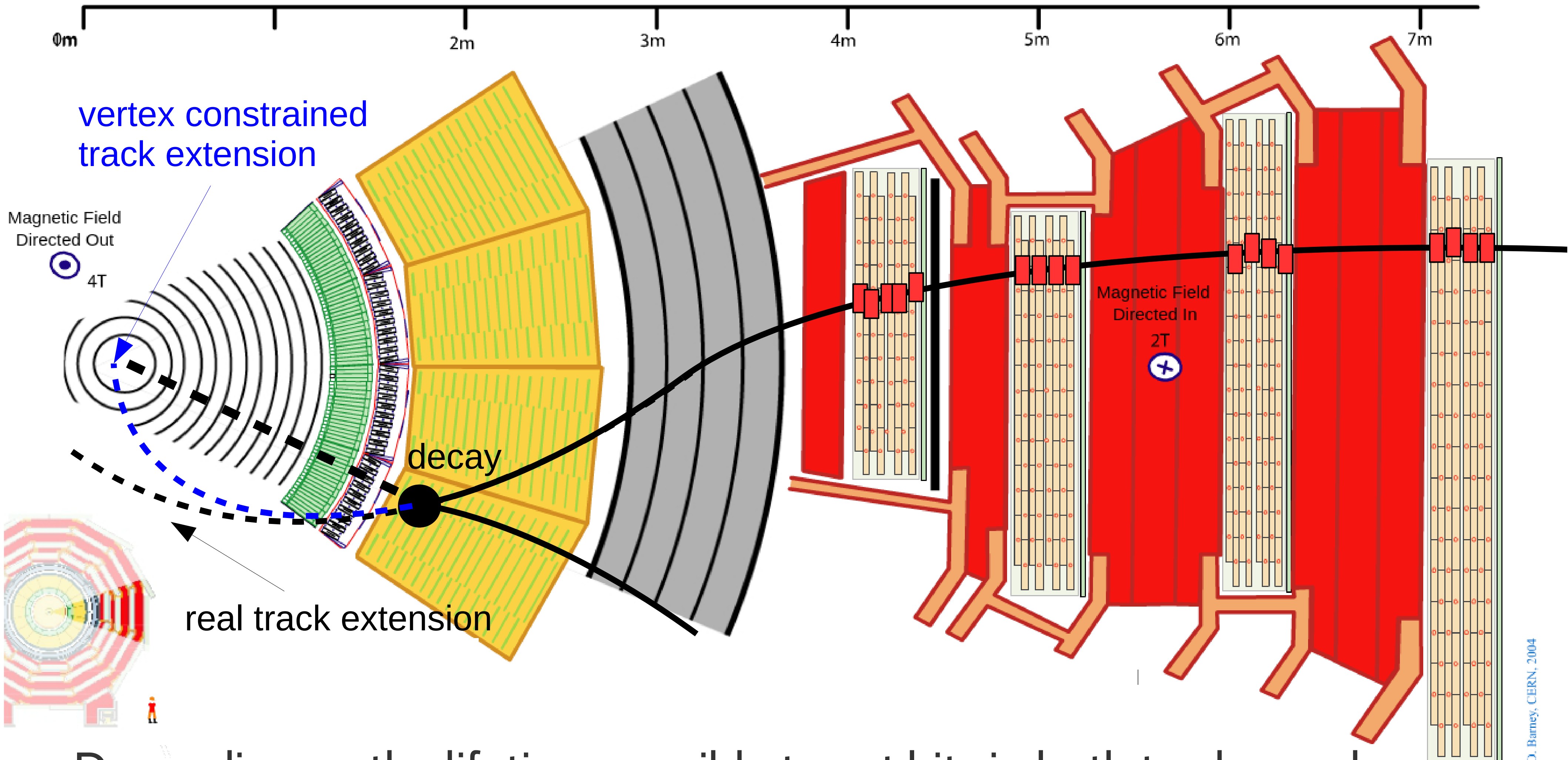
Combined track



- Uses both muon system and the inner tracker
- For $P_T < 200$ GeV the inner tracker provides the measurement (~1%)
- **Used in 99% of the analyses**

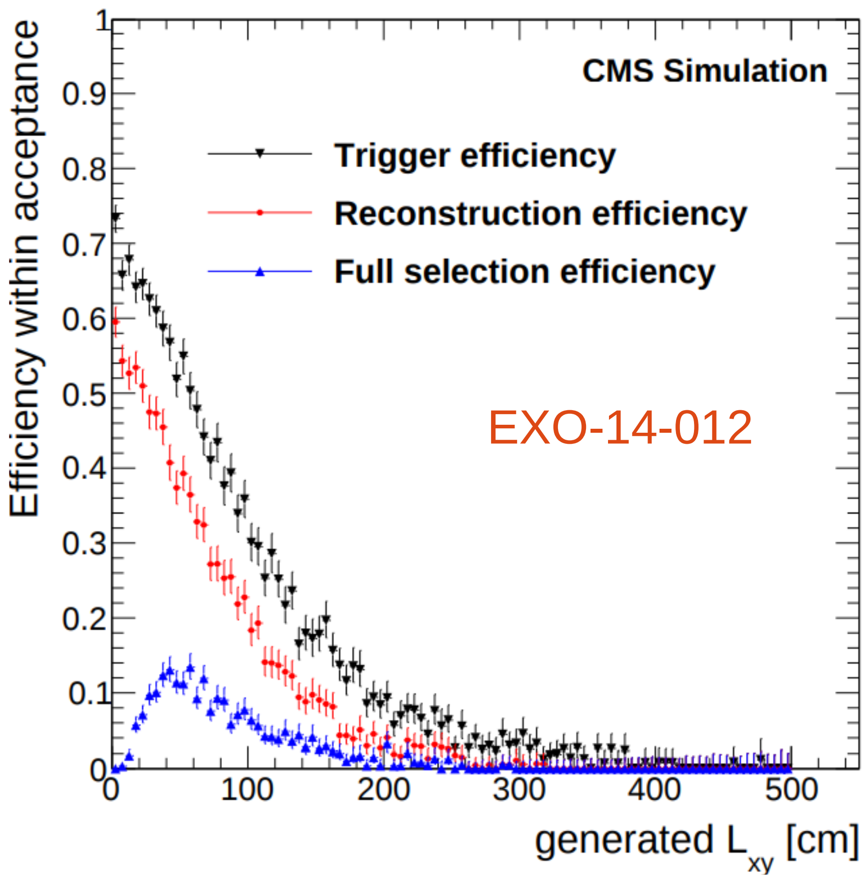
$$\frac{\sigma_{p_T}}{p_T} \sim \frac{1}{BL^2}$$

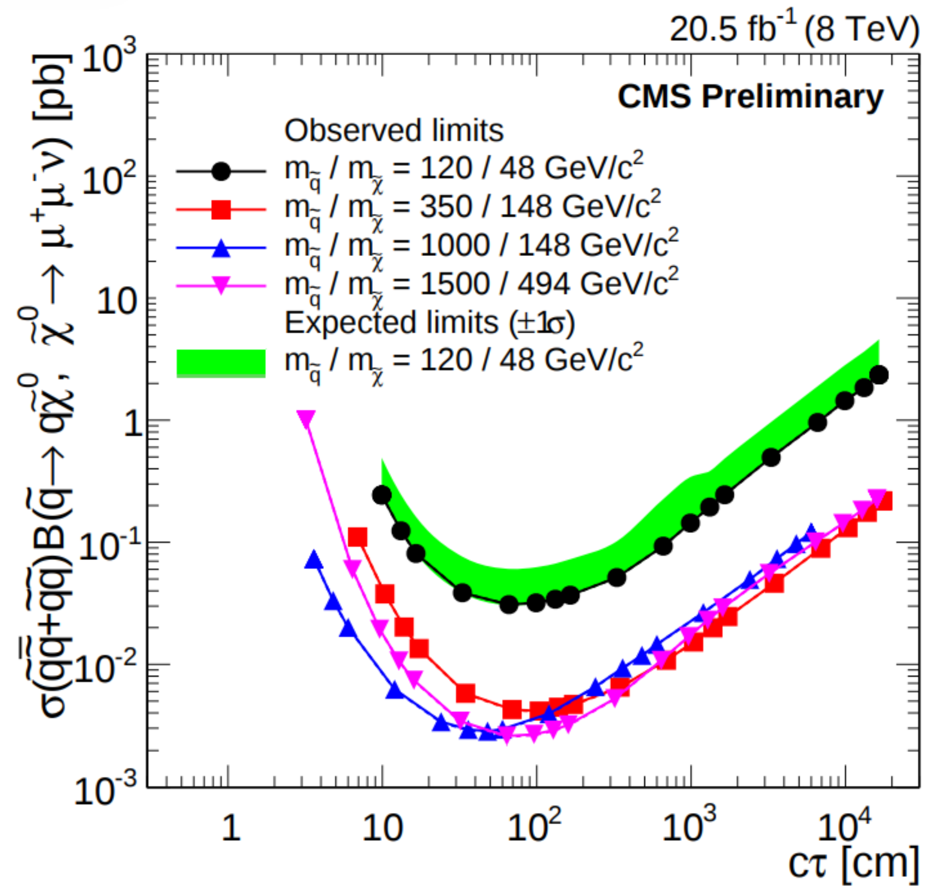
Long lived particles and vertex constraint



- Depending on the lifetime,possible to get hits in both tracker and muon system (very displaced → muon system only)
- If a vertex constraint is used in this example: P_T underestimated – can fail the trigger
    - Standalone track without vertex constraint crucial for long lived particles

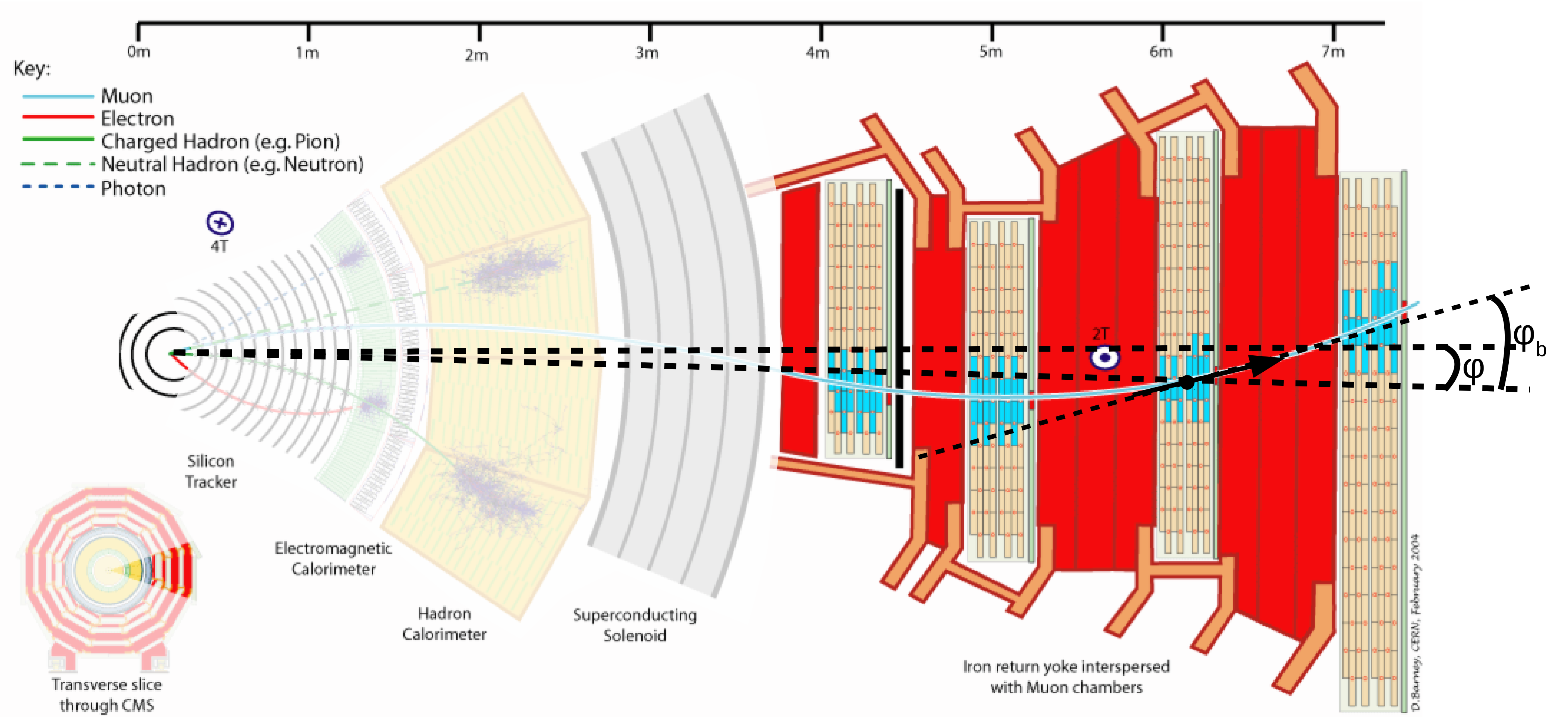
Effect of trigger performance in long lived searches





- Analyses that uses muon tracks without vertex constraint offline and in High Level Trigger
- Efficiency degrades as a function of the decay length
  - Dominated by the vertex constraint in the L1 Muon trigger
- Crucial step towards extending experimental reach is to improve the L1 trigger for displaced particles

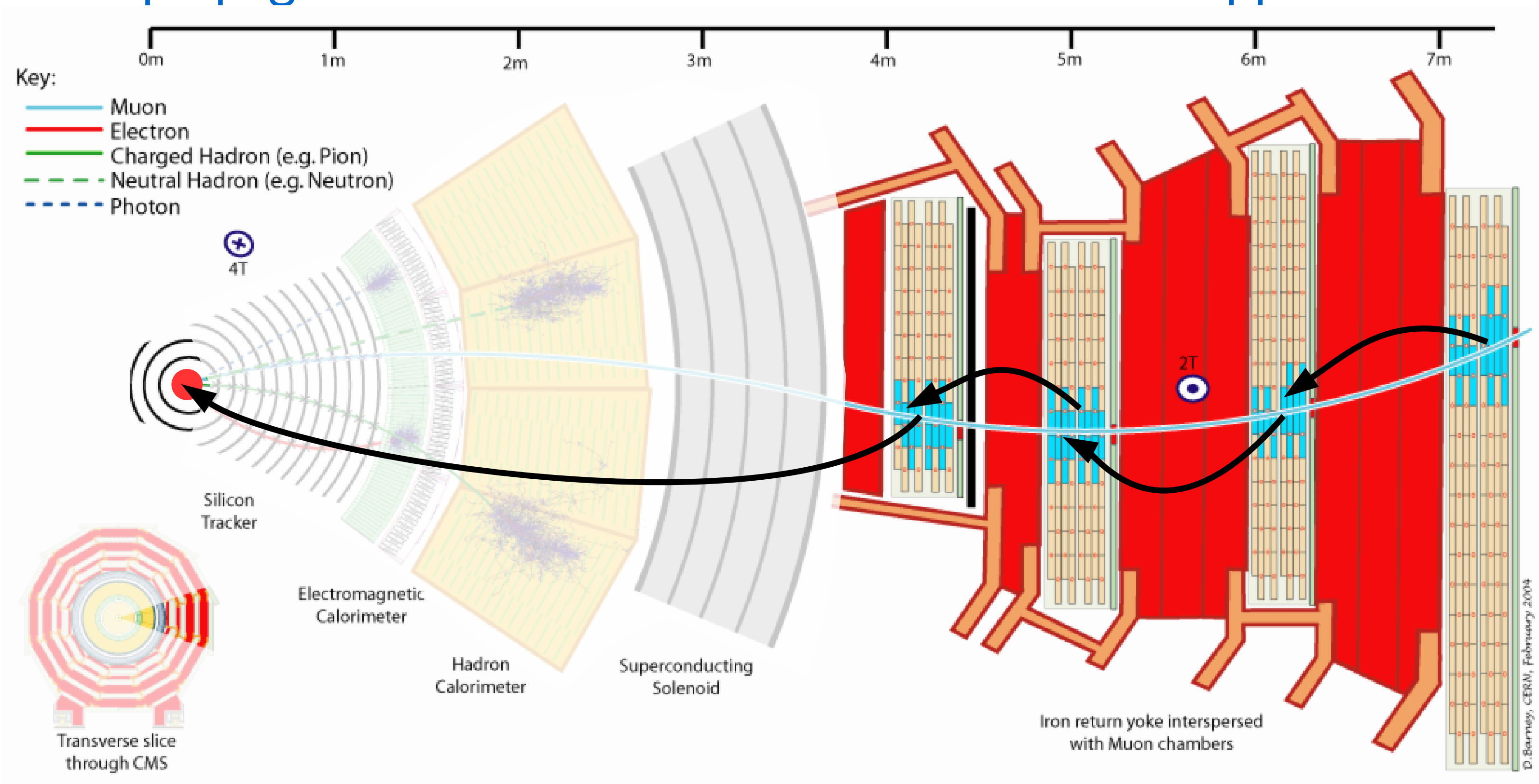
Technical challenges



- Input information to tracking: Up to four coordinates (position,bend)
  - Momentum assignment through a memory lookup using limited information from two station (due to memory size limit)
- 2x the memory is needed to implement a lookup “training” also for displacement muons **(Larger memory modules are being considered in Phase II)**

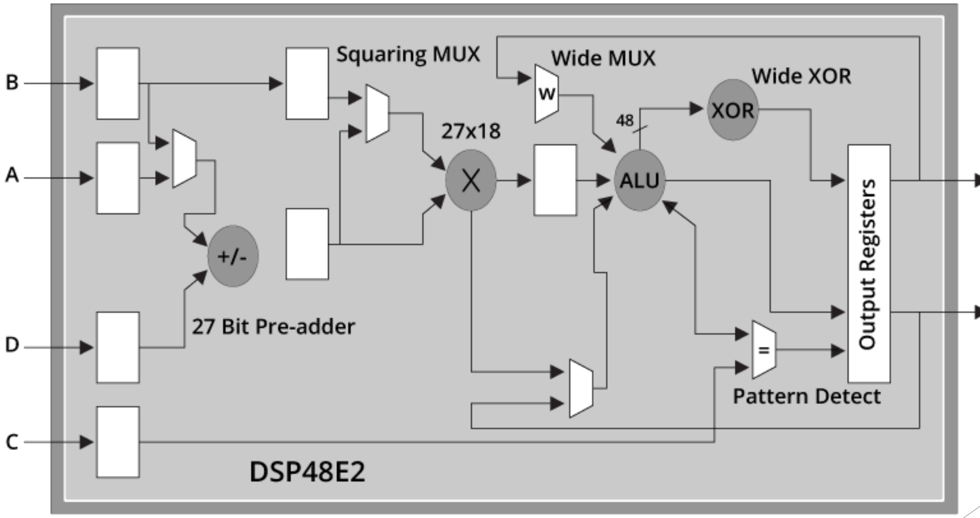
Ideas for Phase II: Kalman Filter Reconstruction

- Kalman Filter: The standard method to reconstruct tracks offline
  - Also studied for the Phase II L1 Track Trigger
- Iterative algorithm:
  - Starts from a given point and propagate track and uncertainty from layer to layer
  - Match compatible hits and update track state
  - Algorithm iterates to the next layer
  - **Parameters saved at muon system with no vertex constraint**
  - Track is propagated to the vertex and vertex constraint is applied



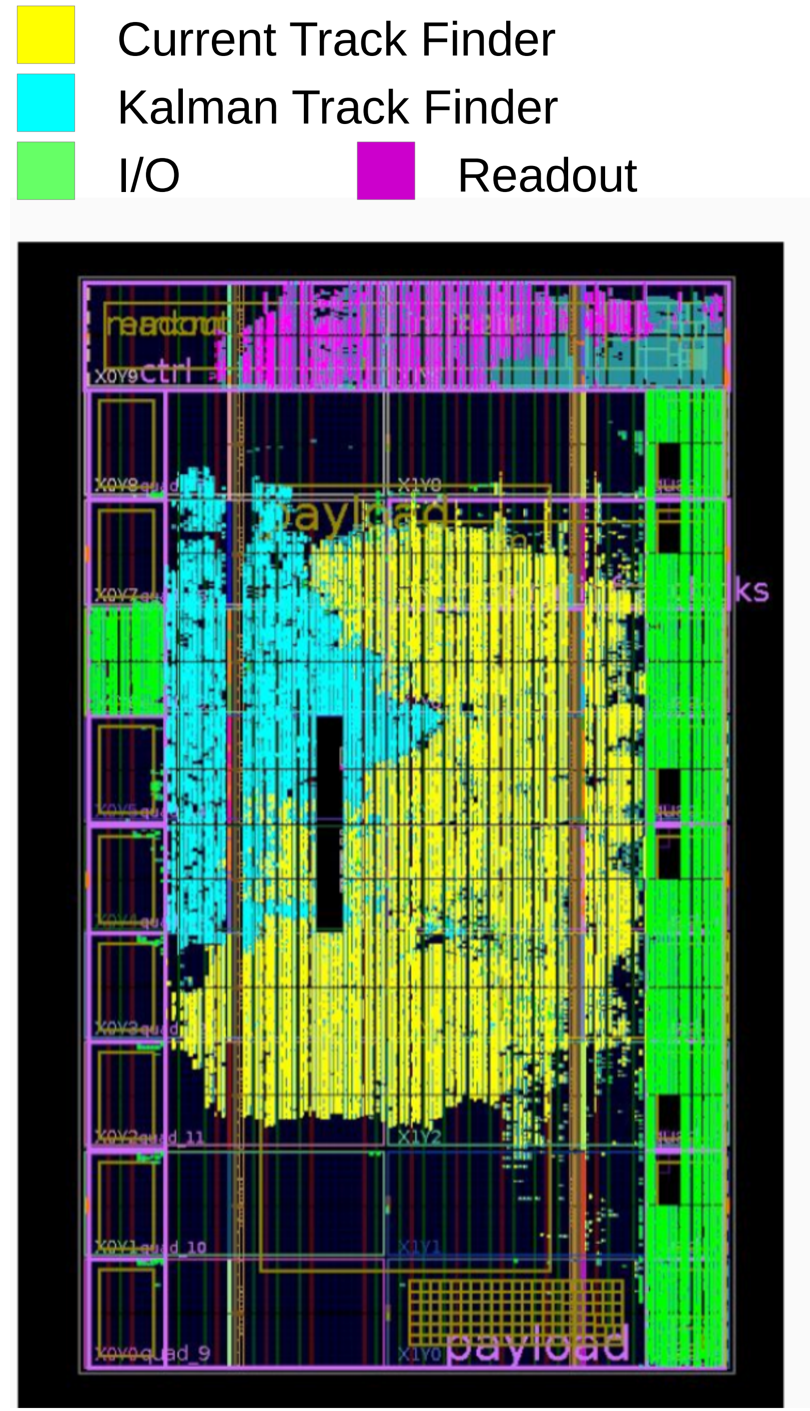
Gains, challenges and solutions

- Solves both problems at once:
  - Provides measurement with maximum available information from all hits providing better momentum resolution
  - Provides measurement without vertex constraint for displaced triggers
- Challenge
  - Track propagation involves math calculations that are challenging in hardware
  - Track update involves 3x3 matrix algebra → Lots of math!
    - Turns out algebra can be simplified to some memory lookups for the parameters
  - But still a lot of calculations → Exploit DSP cores in modern FPGAs
- DSP cores exist for radar and filtering applications
  - Allows calculations such as A+B*C to be implemented with no overhead in standard logic!
  - Allows more complex algorithms



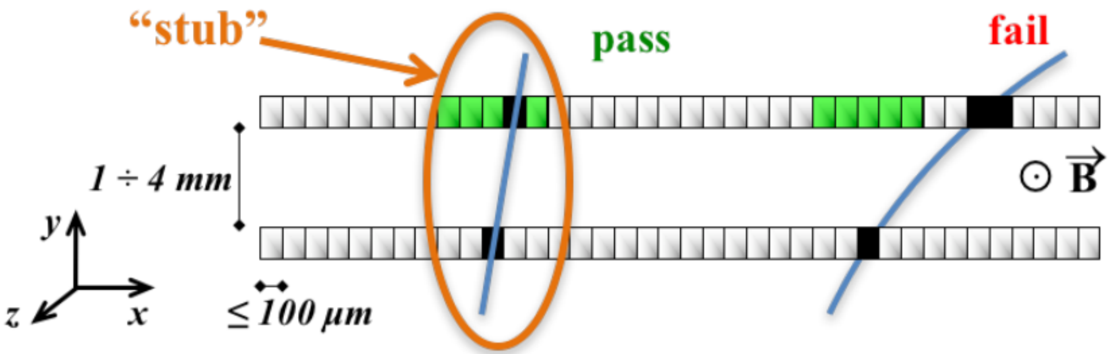
Kalman Filter FPGA utilization for current trigger

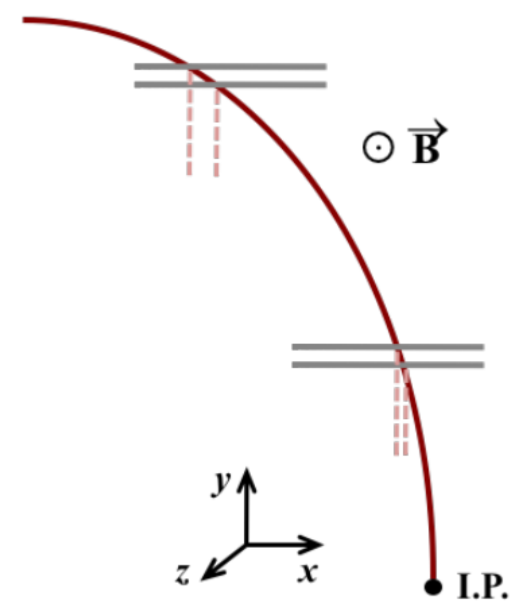
- The DSP usage reduces a lot the size of the algorithm
- Current studies show that the new algorithm is smaller than the current one
  - In fact we can fit both in the chip and run in parallel
- We started working towards running the new algorithm in parallel with the standard Muon Trigger in 2018
- Opportunity to study both prompt and displaced triggers and put the algorithm in production later this year or in Run III



Phase II track trigger for muons

- Phase II track trigger allows to migrate the combined muon track at the L1 using both tracker and muon system
- However due to the input rates, tracker is designed to be optimal for particles coming from the collision point

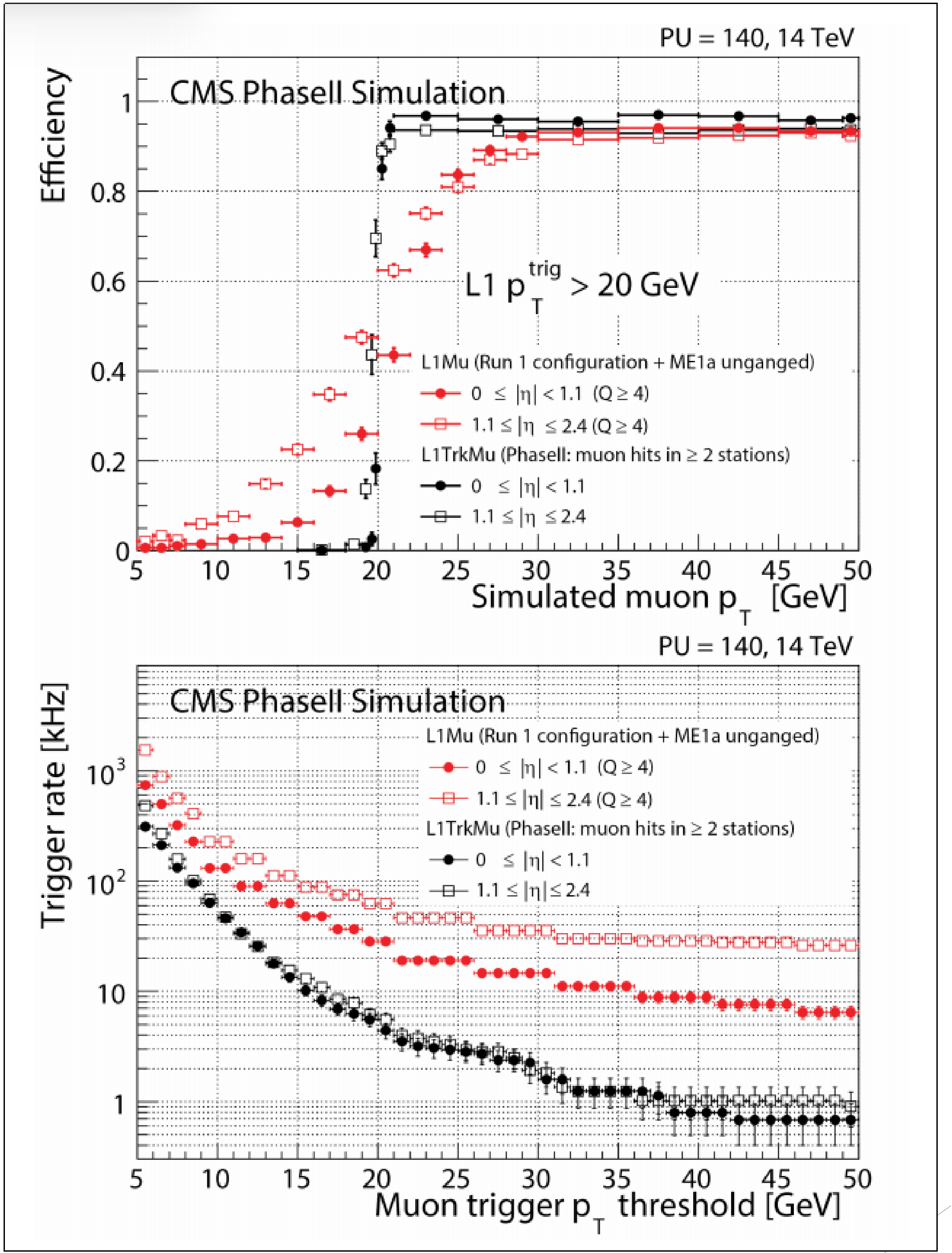




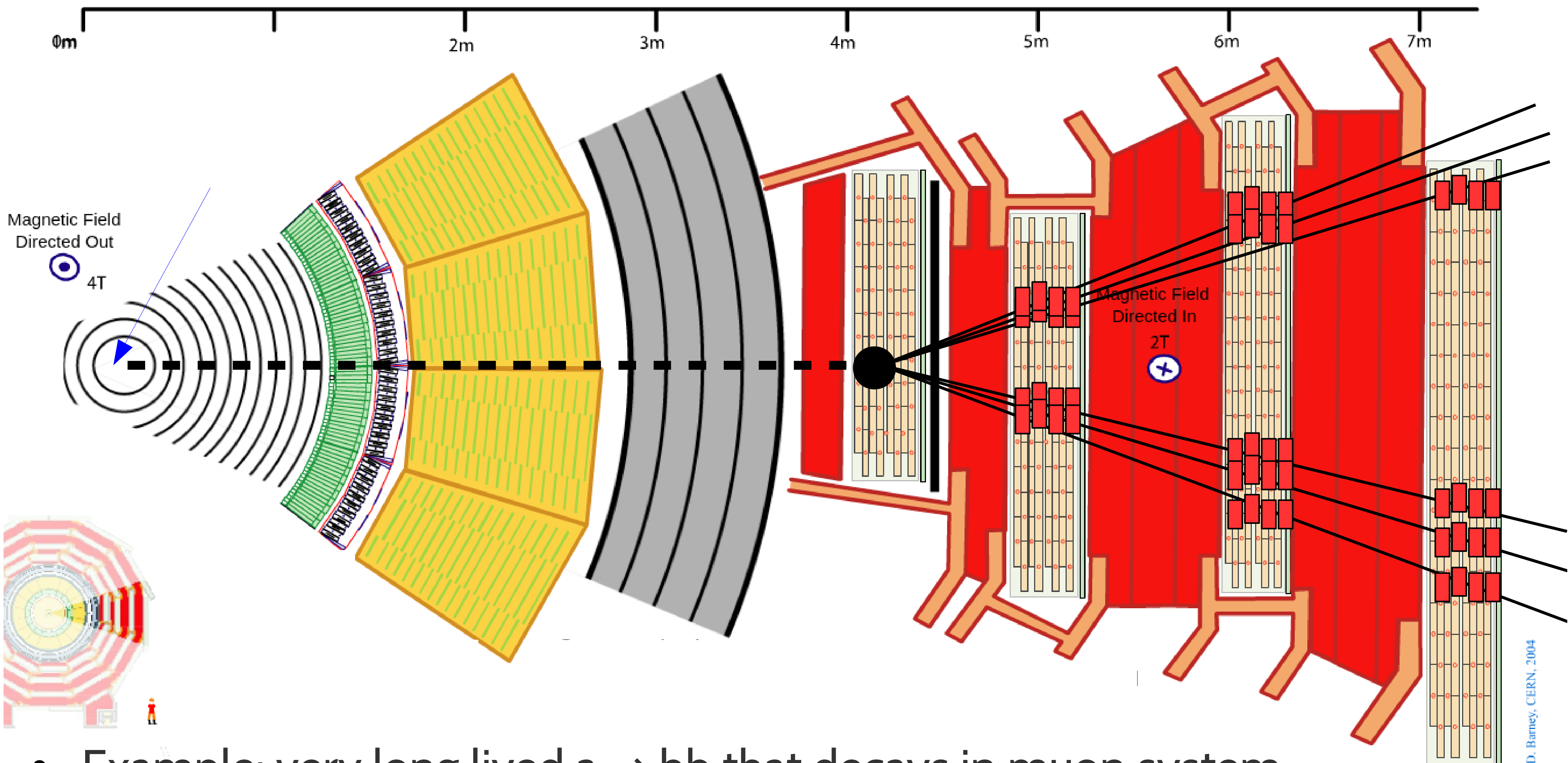
- Input reduced by using hits consistent with a track with P_T > 2 or 3 GeV
- Using a Pt module of two stacked layers

Triggering combined muons in Phase II

- Inner tracking improves dramatically trigger performance
  - Resolution 10% → 1%
  - Expected to maintain excellent performance on triggering all analyses with prompt muons
- Ideas exist to try to use the track for displaced muons as well
  - By combining tracks in muon system with outer track layer hits for better resolution
  - Challenging due to high occupancies at high pileup. Need to be studied



Other ideas: Very displaced jets



- Example: very long lived a → bb that decays in muon system
  - Iron in yoke can be used as an absorber as well…
- Collect hits (not necessery from same track) and build muon jets
- Unfortunately in current trigger only two stubs per station
  - Could still work but for sure we could have something optimal for Phase II

Summary

- A lot of work towards designing the future CMS trigger for Phase II
- Integration of the tracker in the L1 trigger ensures highest trigger performance for 99% of the analysis
- New ideas in muon track reconstruction improve standalone performance and enable displaced muons
  - Large external memories for Lookup tables
  - Kalman Filter tracking
- The programmability and huge capacity of recent FPGAs allows for implementation of several new ideas on algorithms
- We need to know where new physics could be and then we will make sure to collect the data!