Using Muon in CMS Data Analysis

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24 July 2020

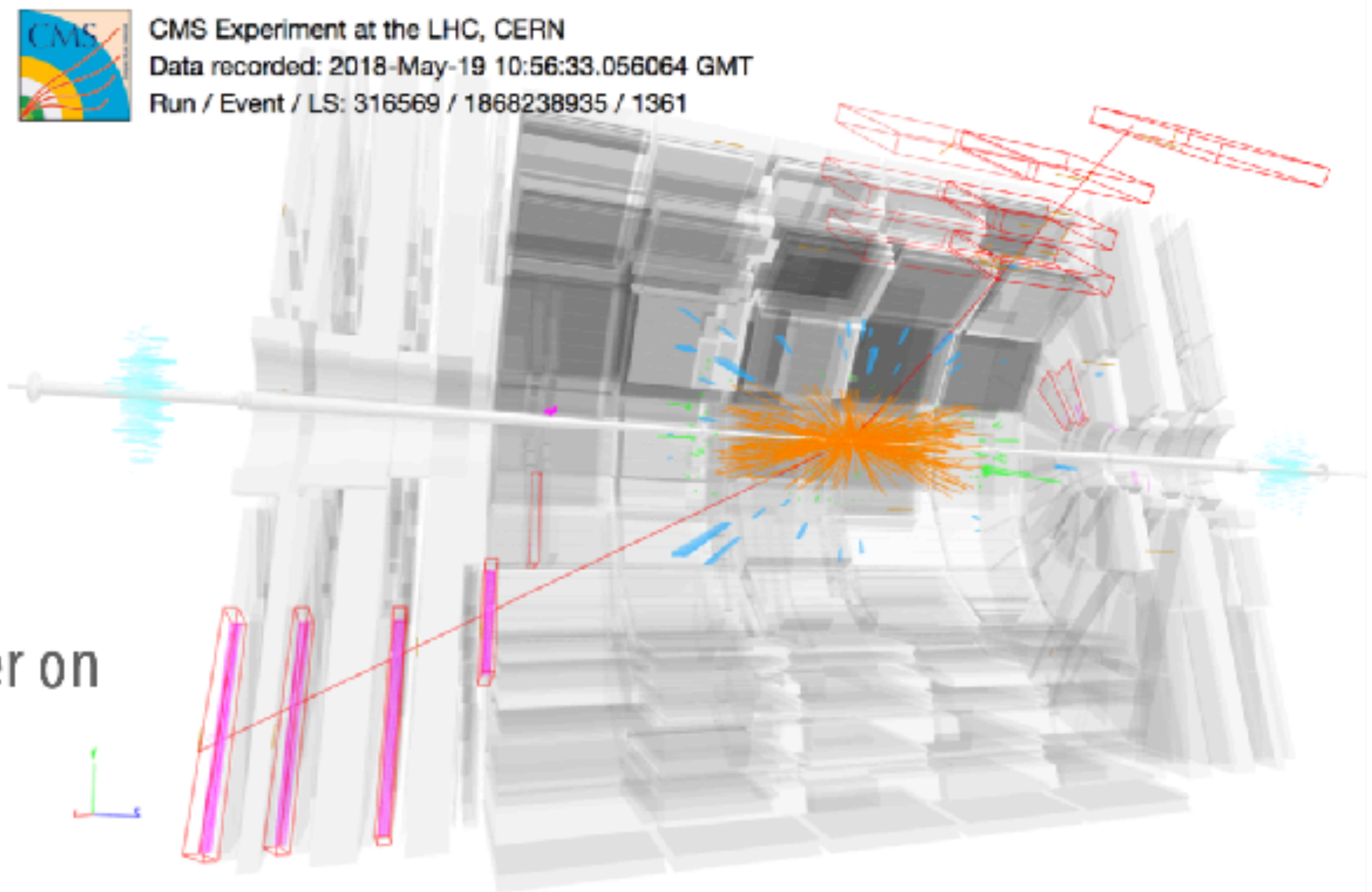
Sources

- Muon in data analysis (link)
- Muon CMS DAS Piza Review by Carlo (link)
- Determination of MuonReconstruction and Identification Efficienciesin the CMS Experiment - PhD. Thesis here
- Performance of the reconstruction and identification of high-momentum muons in proton-proton collisions @ 13 TeV (link) - CMS-MUO-17-001

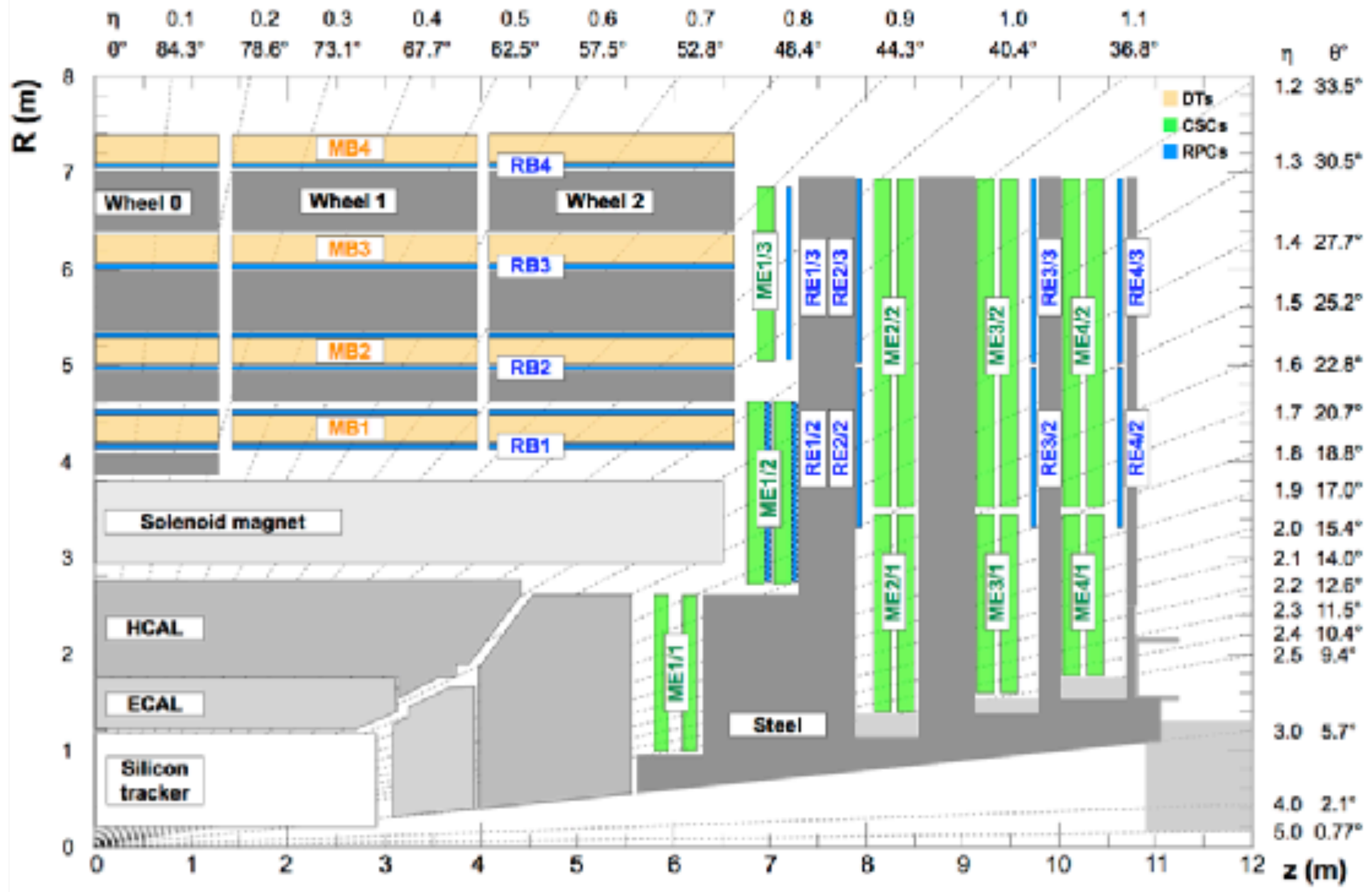
Outline

- The CMS muon spectrometer
- Muon reconstruction and identification
    - Why Muon identification?
- Tag and Probe Efficiency studies using JPsi Open Data
    - Tag and Probe Ntuples Datasets

Muons in the CMS Experiment



- Why muons?
  - CMS aim is to:
    - search for new physics at the TeV scale
    - perform precision measurements of the Standard Model
  - Many of the signatures of such phenomena involve muons
  - Muons provide a clear signature, easy to reconstruct and to trigger on



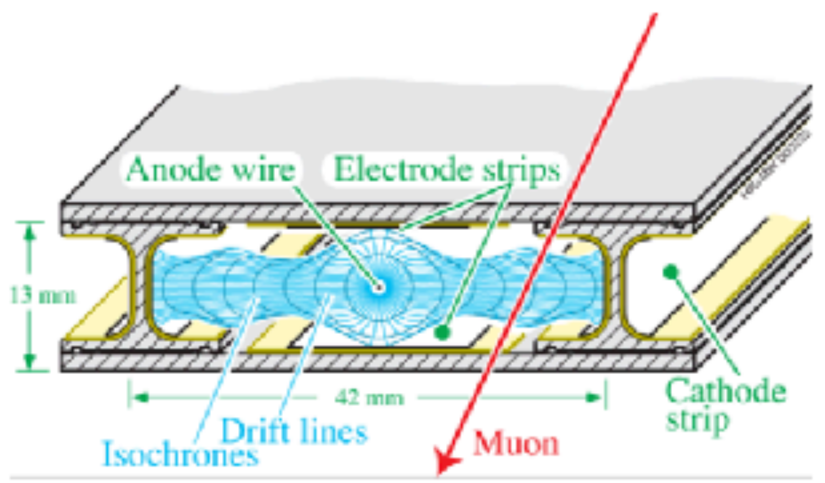
- The CMS muon system
  - Is built to:
    - provide standalone Level-1 muon trigger capabilities
    - provide efficient muon identification
    - improve μ's momentum measurement for energies ≳ 200 GeV
  - Consists of three different detector technologies (*):
    - drift tubes (DT) - barrel
    - cathode strip chambers (CSC) - end-caps
    - resistive plate channels (RPC) - barrel + end caps

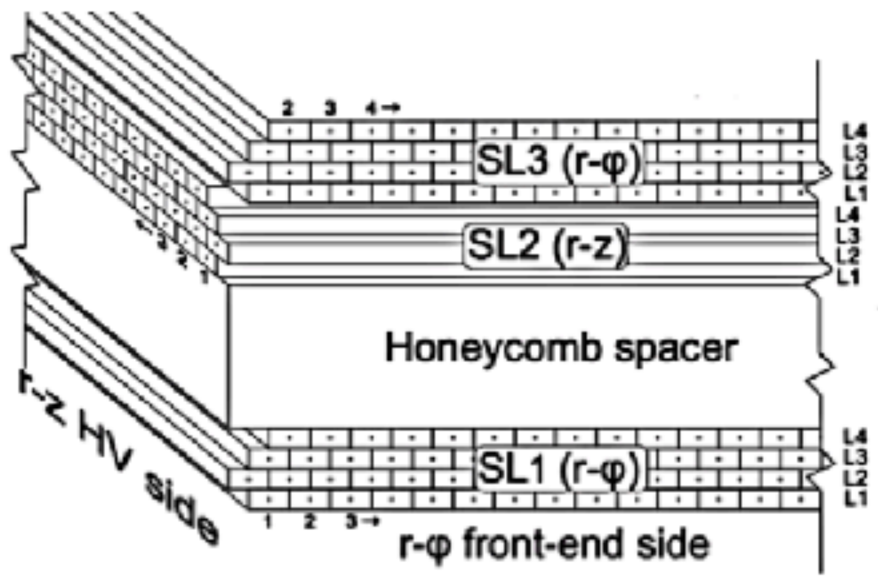
(*) gas electron multiplier (GEM) chambers will be added in Run-3 and later

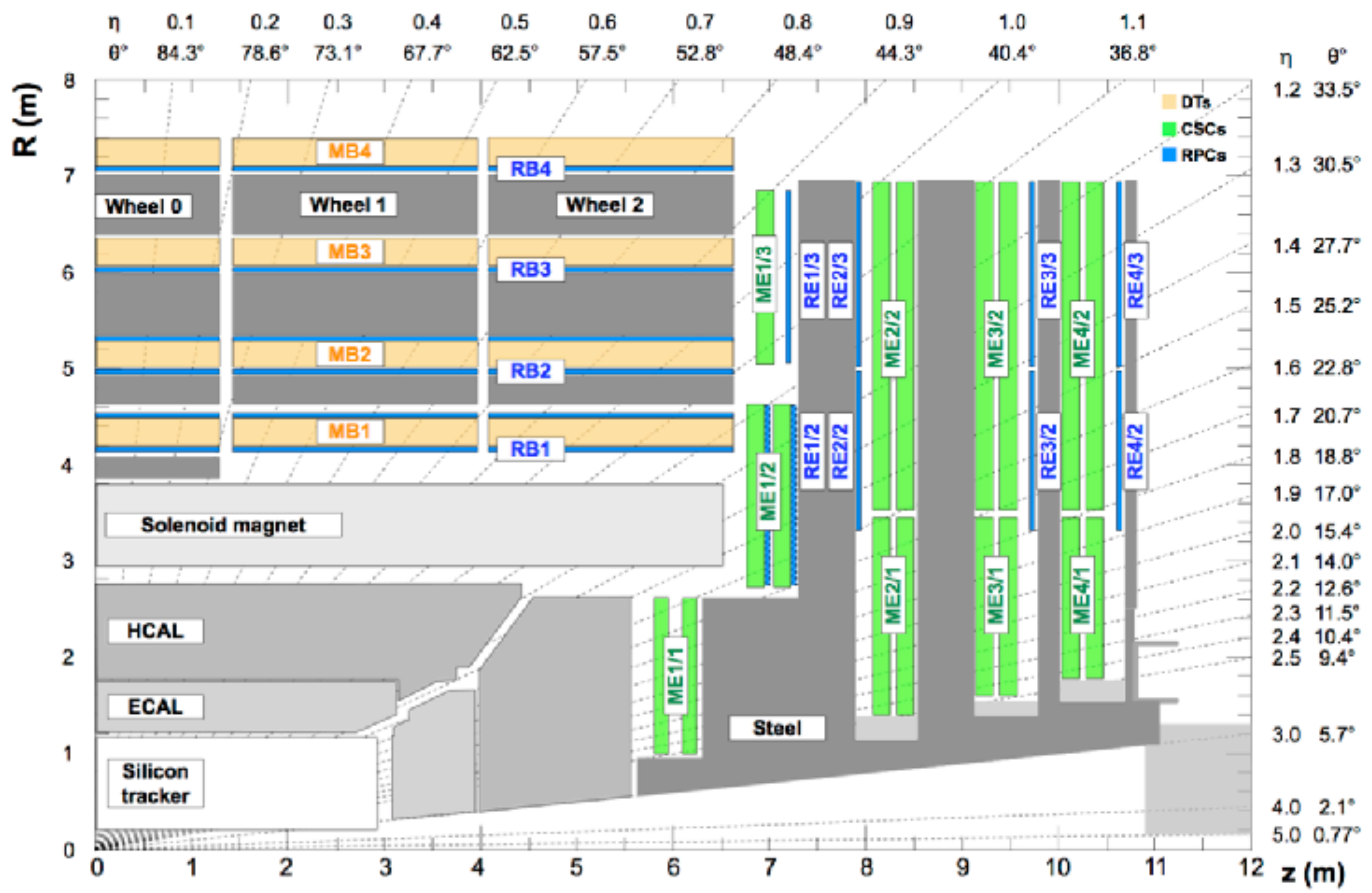
The CMS muon system: DT

Drift Tubes (DT) cover up to |η| < 1.2

- **Both a tracking and trigger detector**
- Basic unit: 4.2 x 1.3 cm² cell with ~ constant 54 μm/ns v_{drift}
- 8 (4) layers per chamber in r-φ (z)
- Segment spatial resolution **~100 μm**
- Segment time resolution **~2 ns**







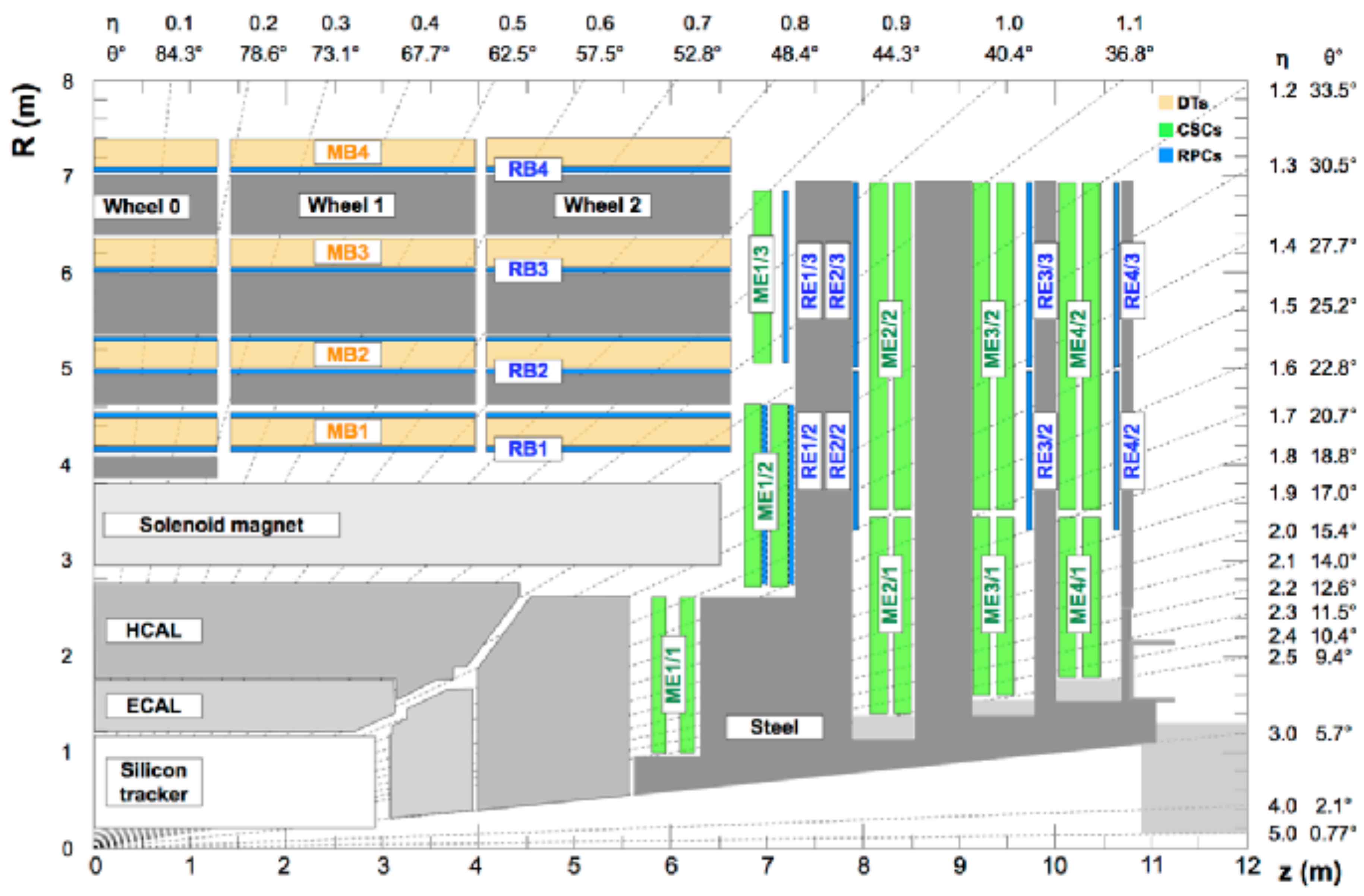
Geometry (250 chambers in total)

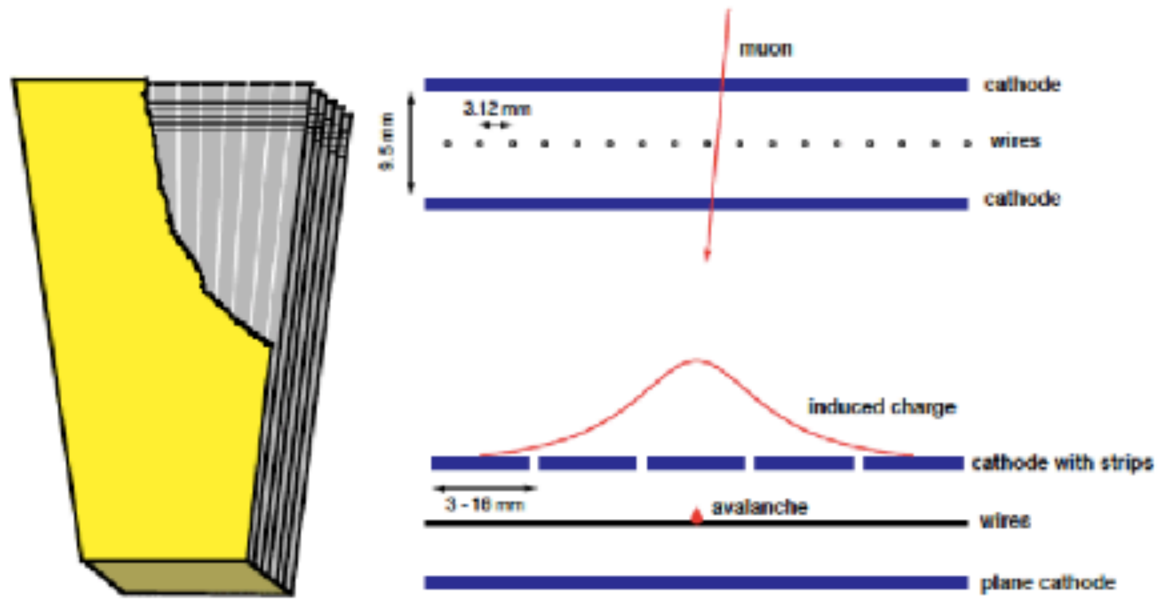
- 4 concentric rings of stations
- 12 sector slices
- 5 wheels in the whole barrel

The CMS muon system: CSC

Cathode Strip Chambers (CSC) cover $0.9 < |\eta| < 2.4$

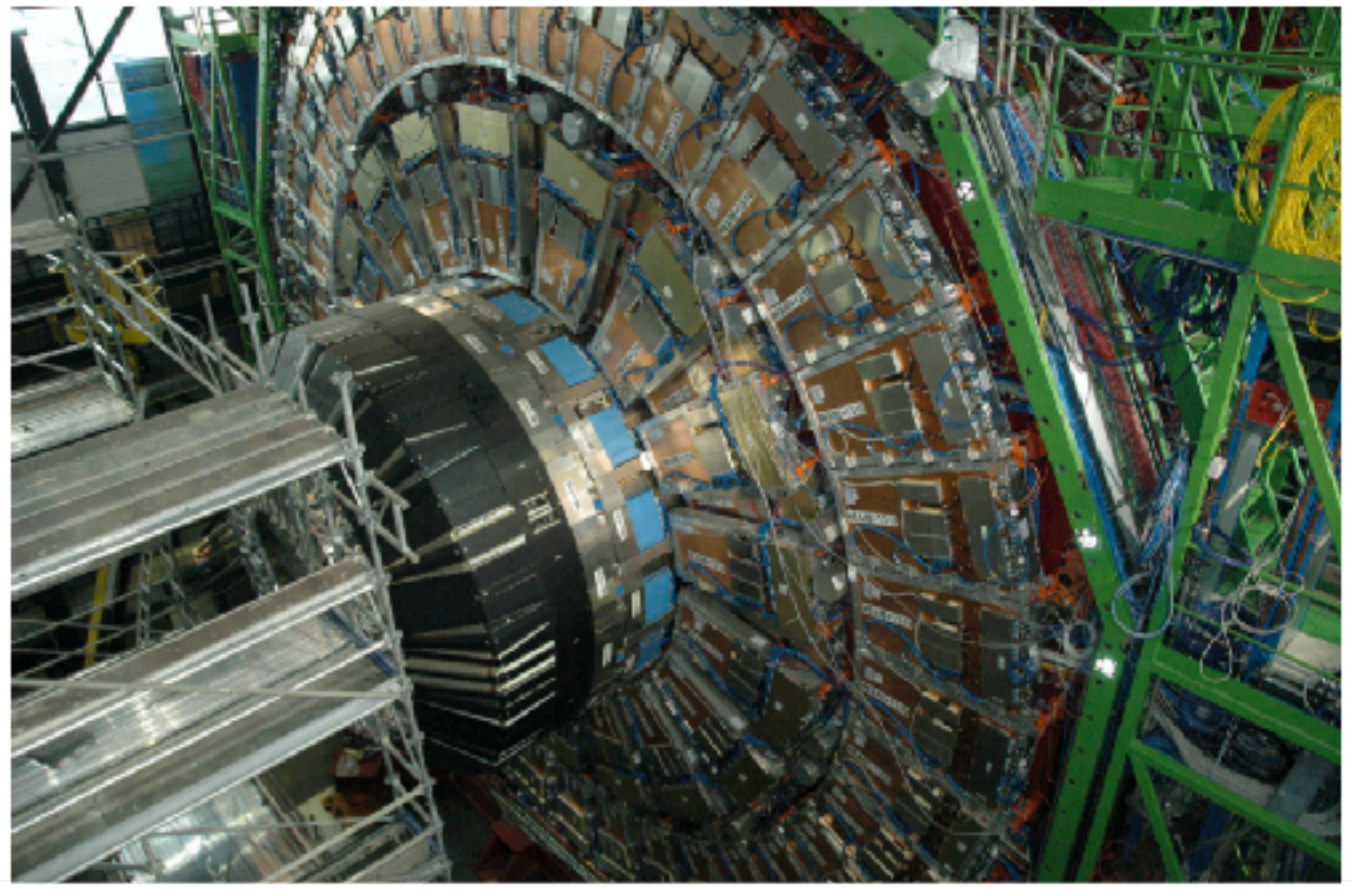
- **Used for both tracking and trigger**
- MWPC with cathode strip readout
- 6 layers per chamber
- Segment spatial resolution ~ **50 to 150 μm**
- Segment time resolution ~**3 ns**





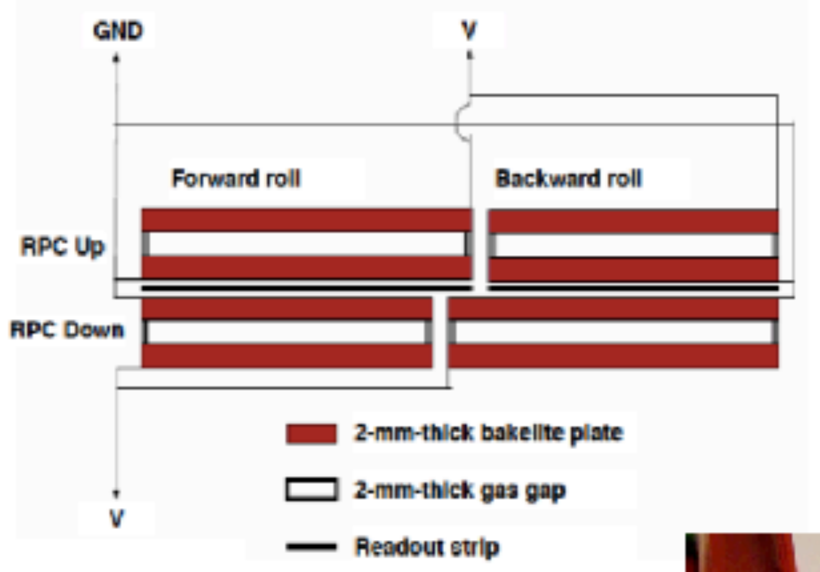
Geometry (540 chambers in total)

- 2 end-caps
- 4 disks / end-cap
- 2-3 rings / disk
- 18-36 chambers / ring



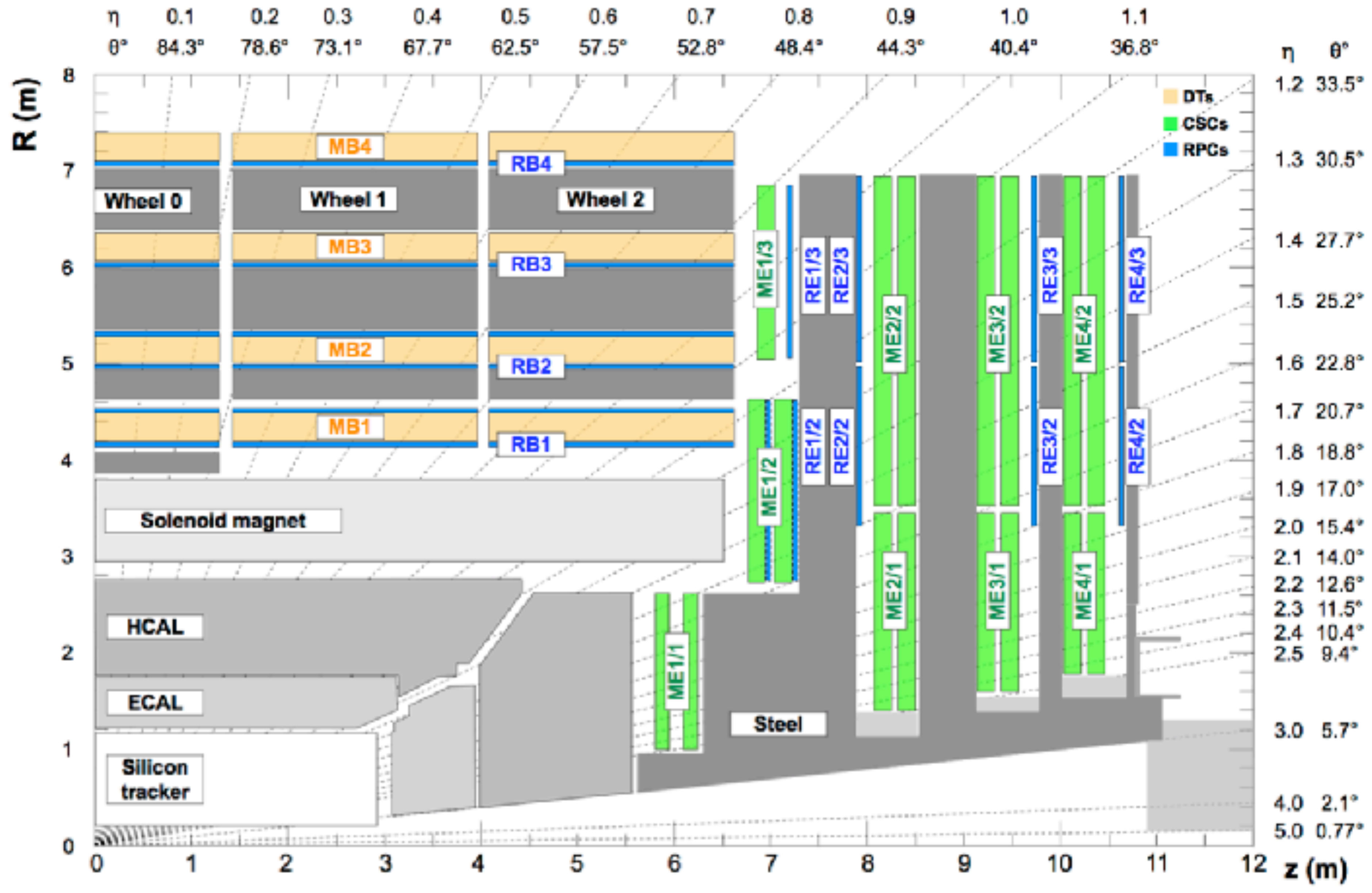
The CMS muon system: RPC

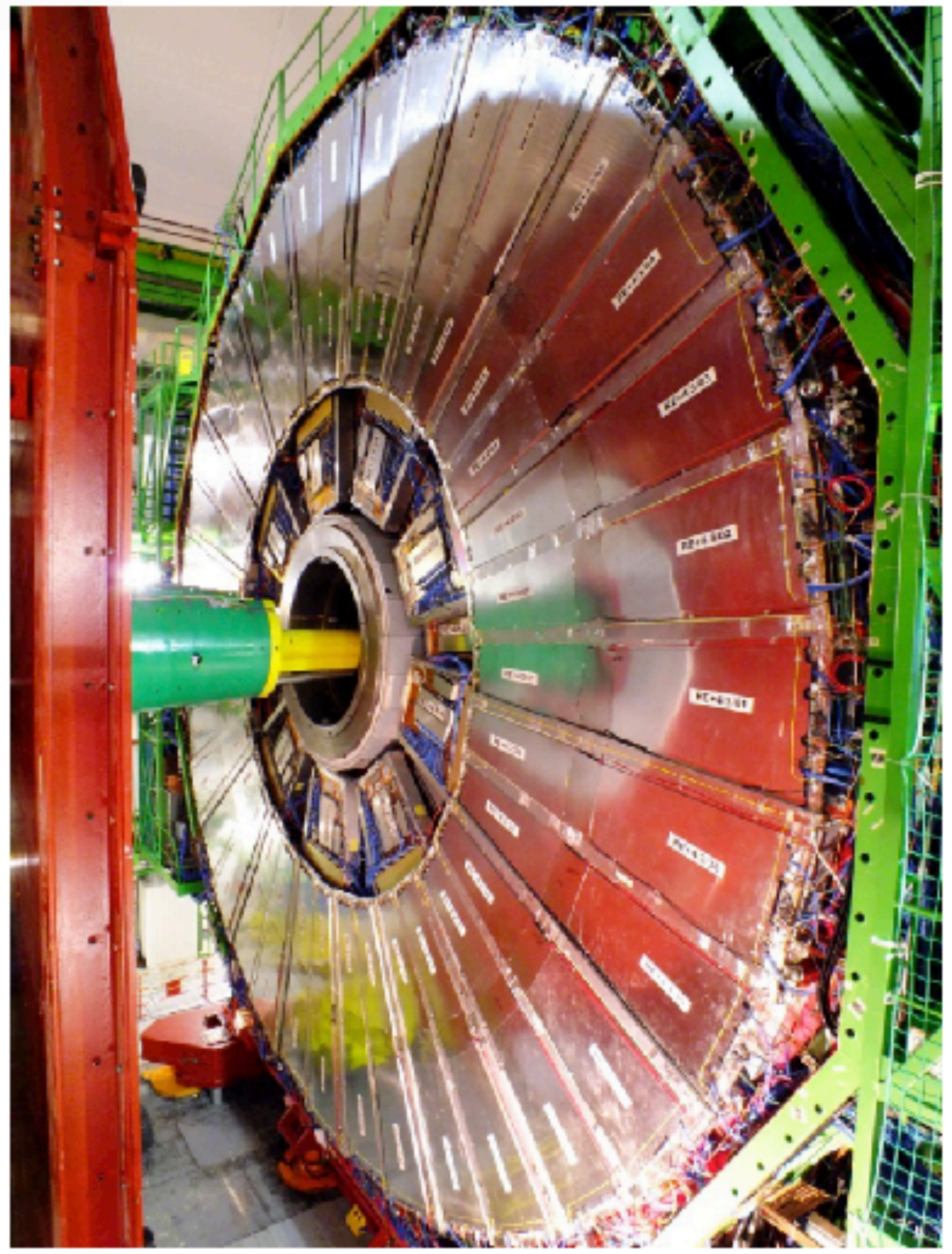
- Resistive plate chambers (RPC) cover up to $|\eta| < 1.9$
  - **Mostly used in trigger, but participate also to reconstruction**
  - Double gap RPCs operating in avalanche mode
  - Cluster spatial resolution **~1 cm** (r-φ)
  - Hit time resolution **~2 ns**



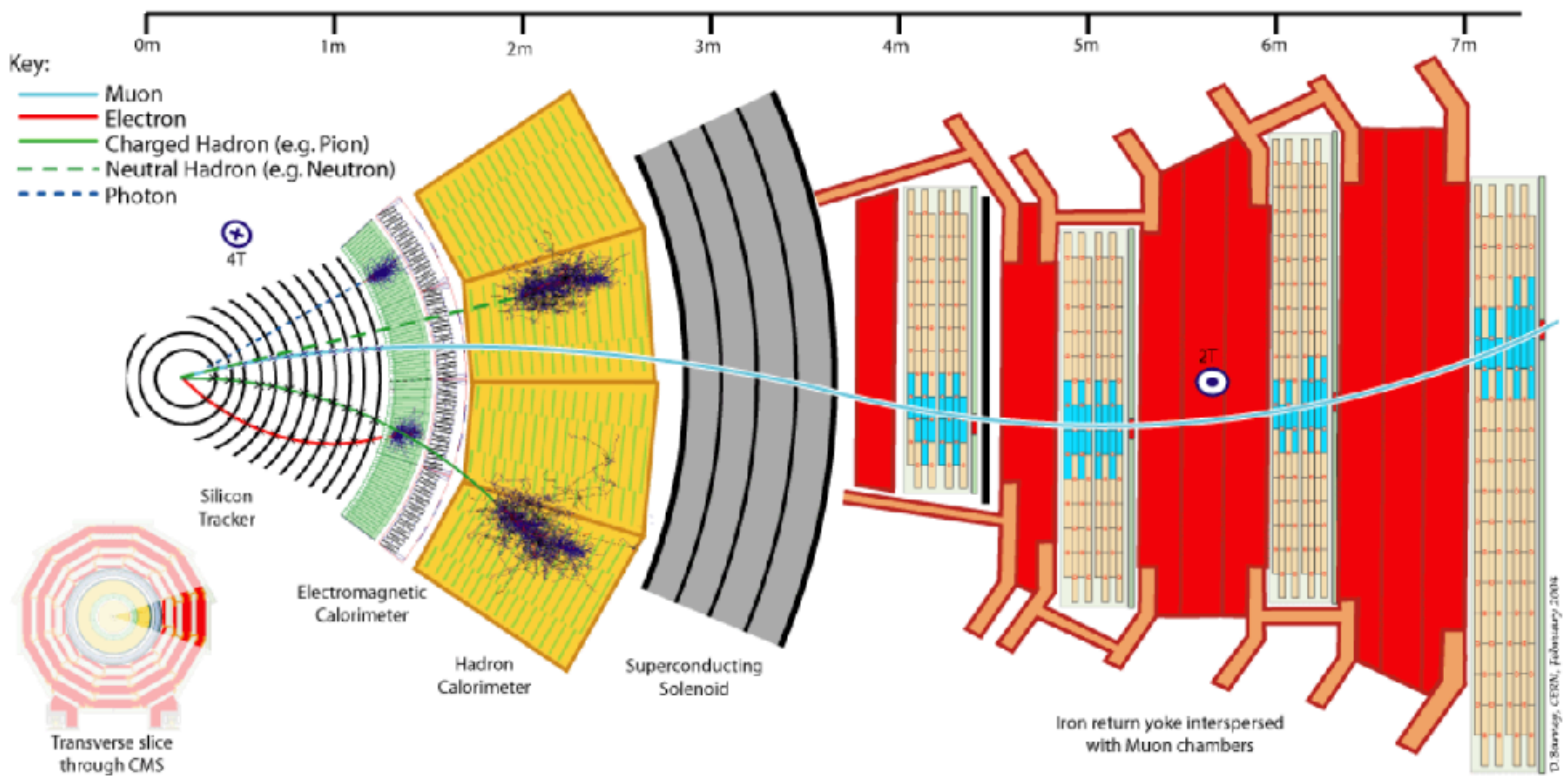
Geometry

- Segmentation similar to DT/CSC
- 480 chambers in barrel
- 576 chambers in end-caps





Muon reconstruction- quick overview



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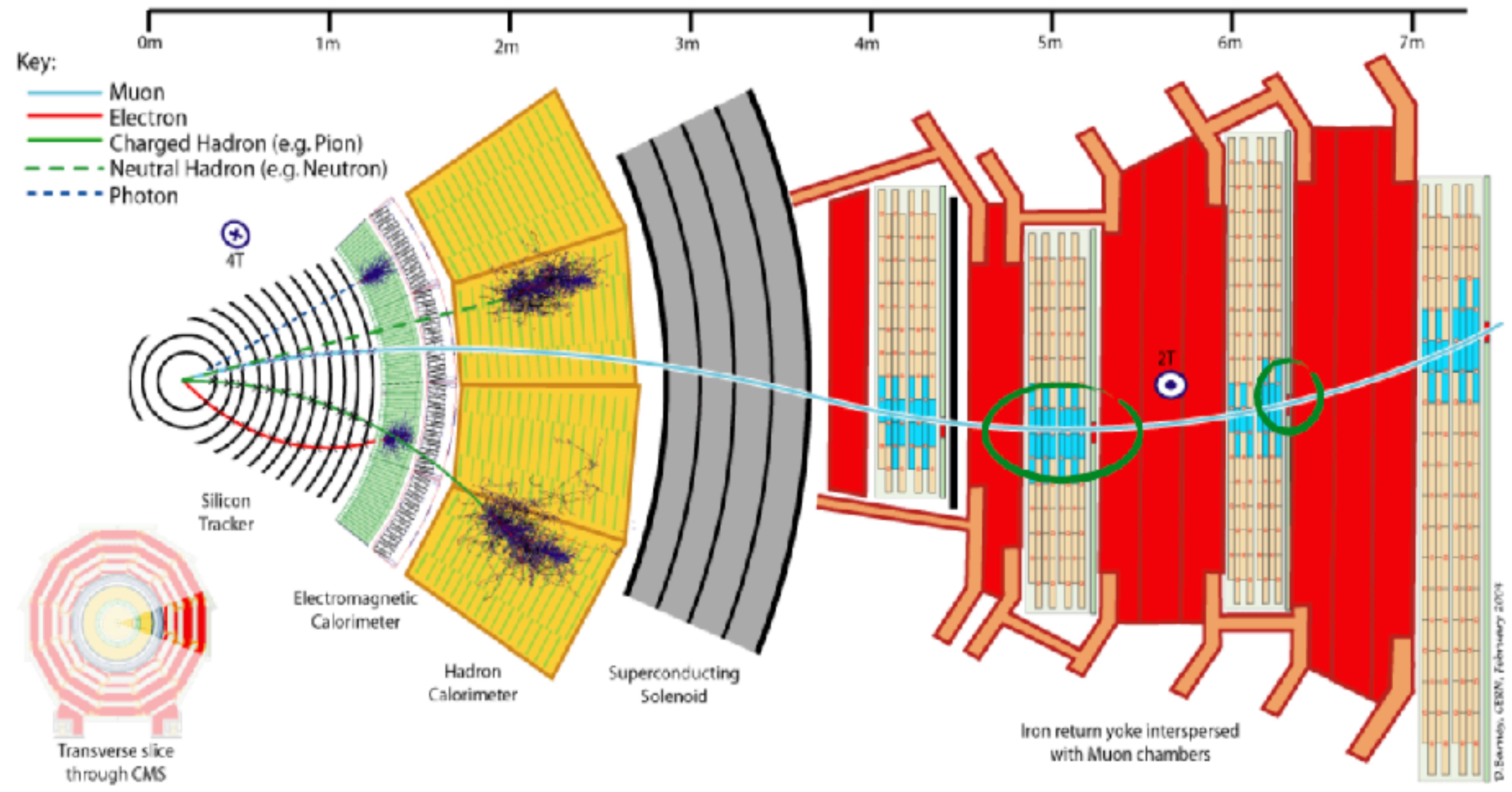

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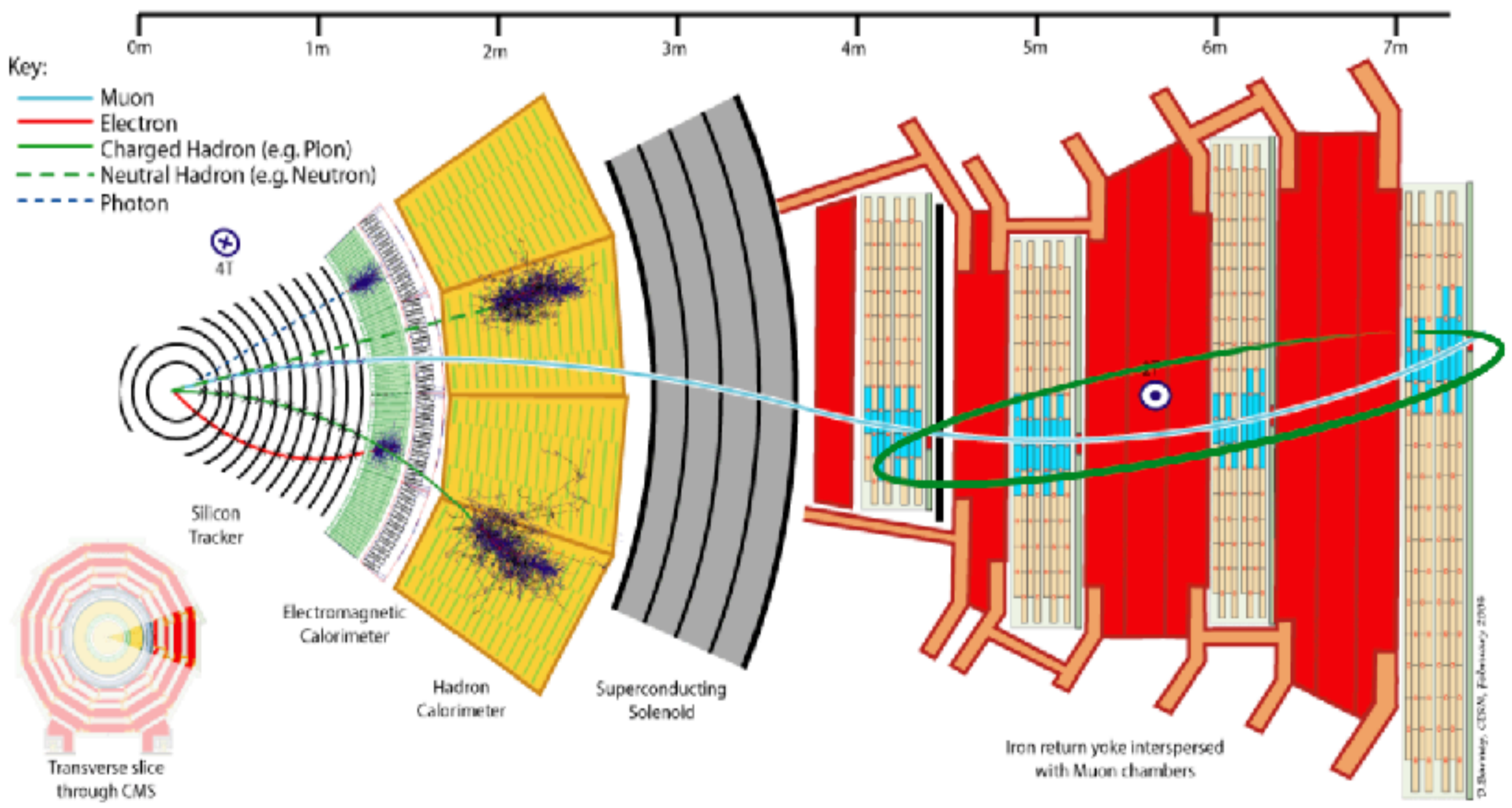

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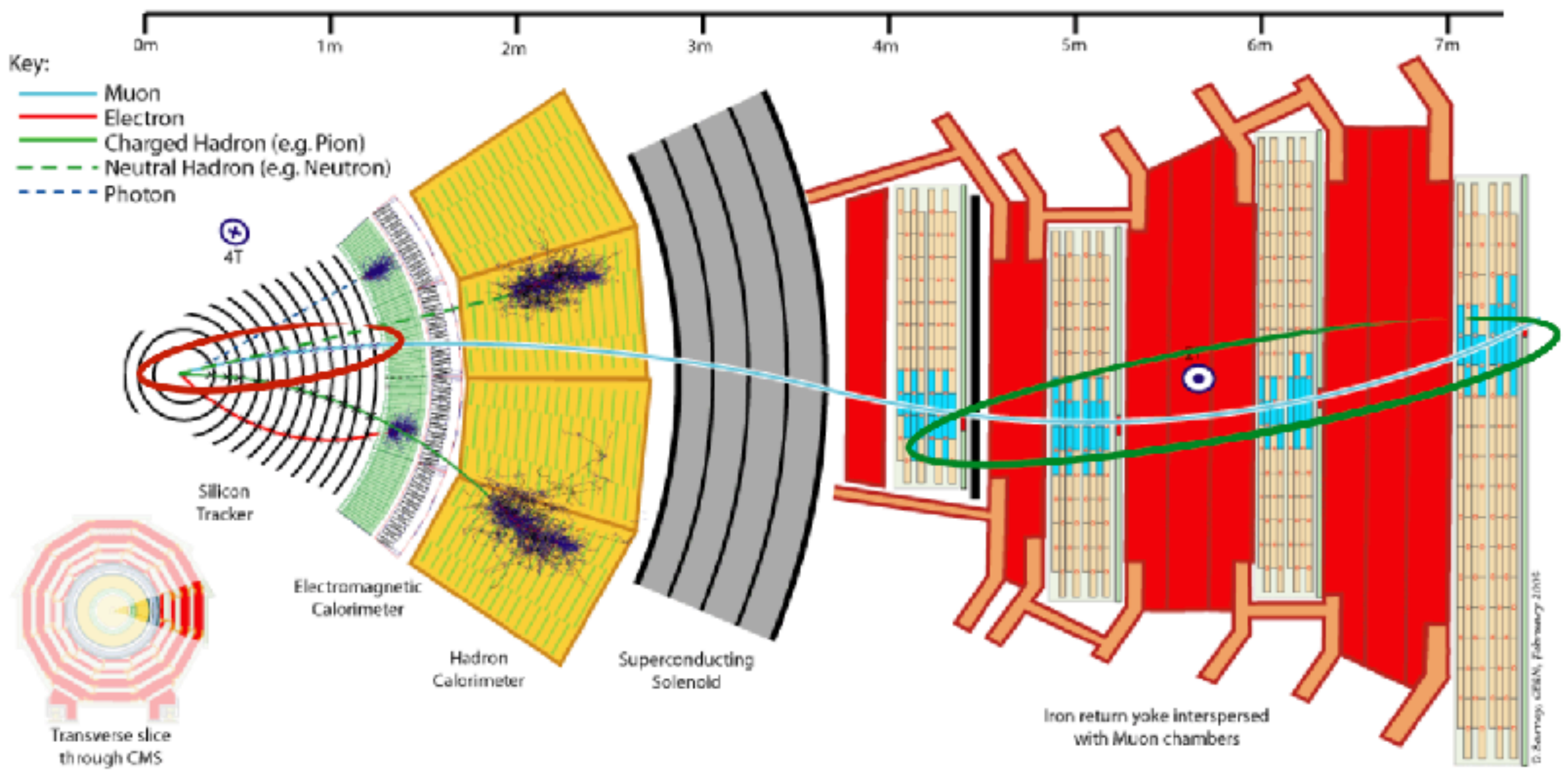

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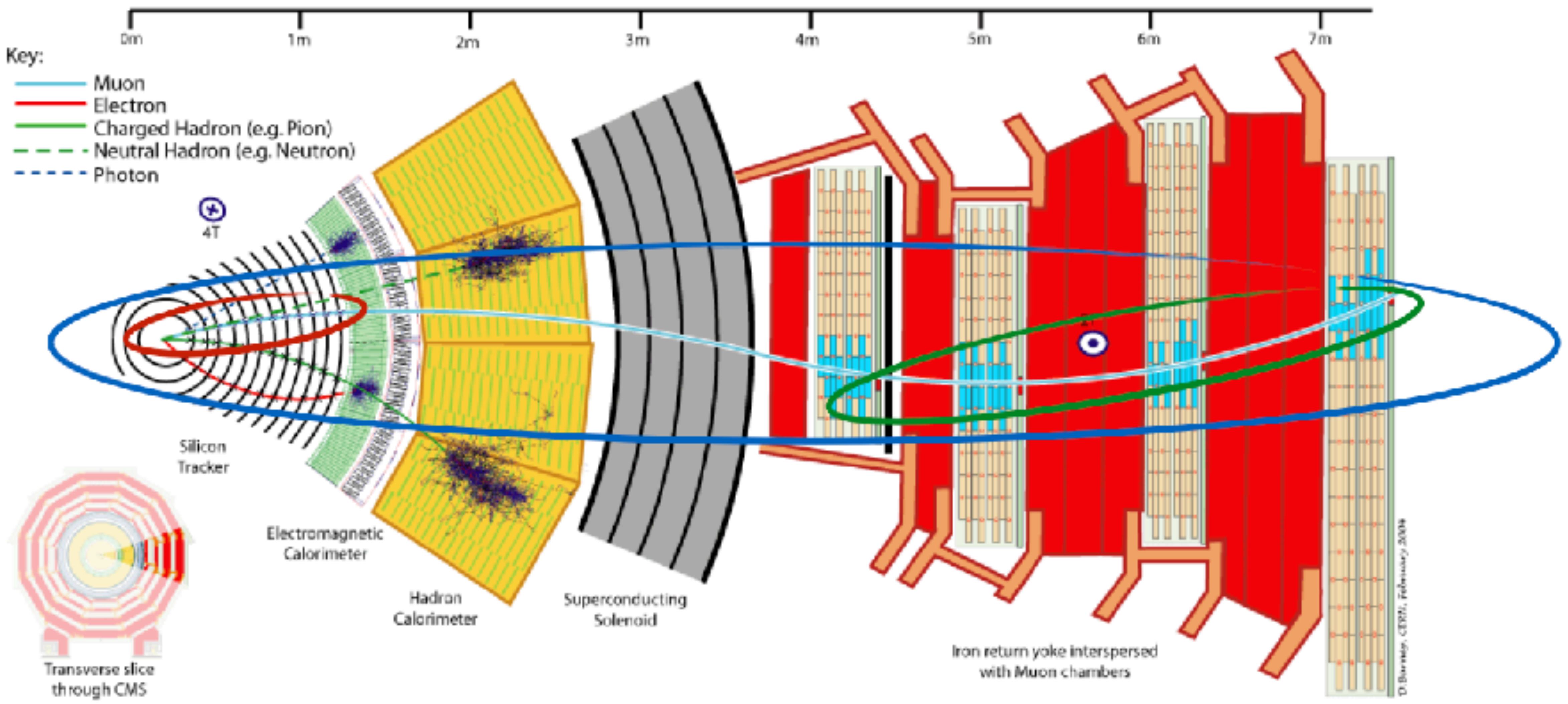

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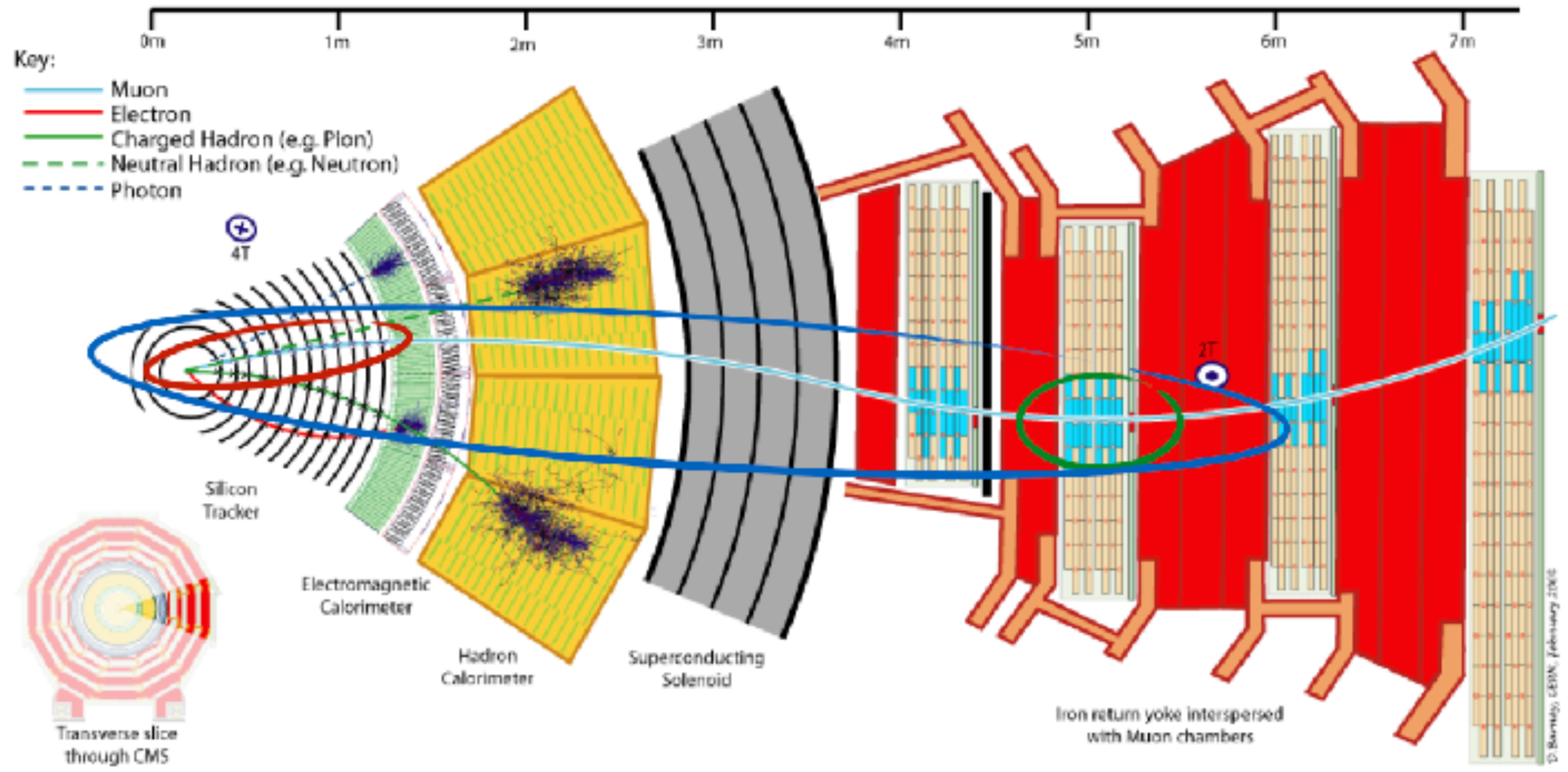

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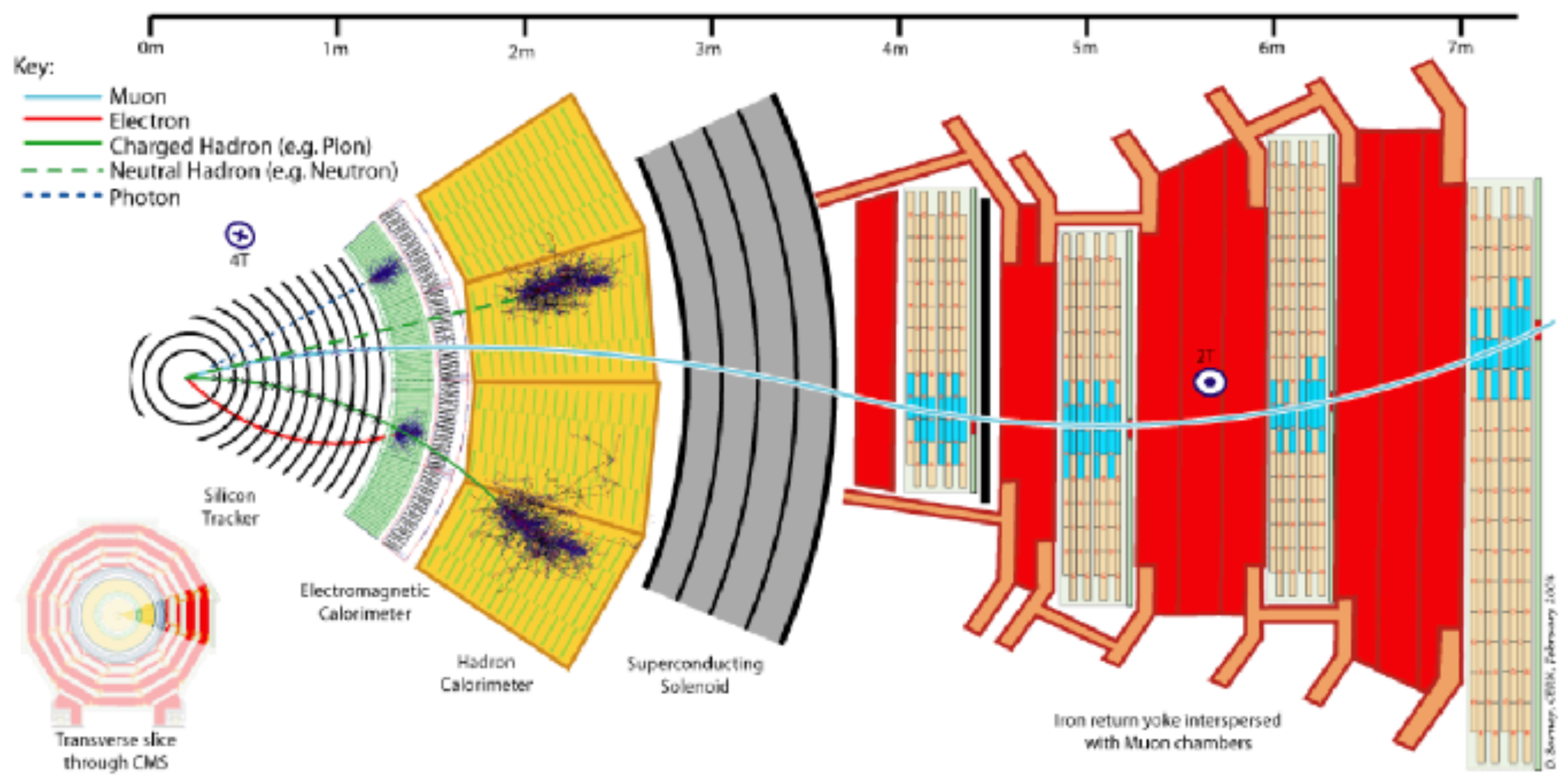

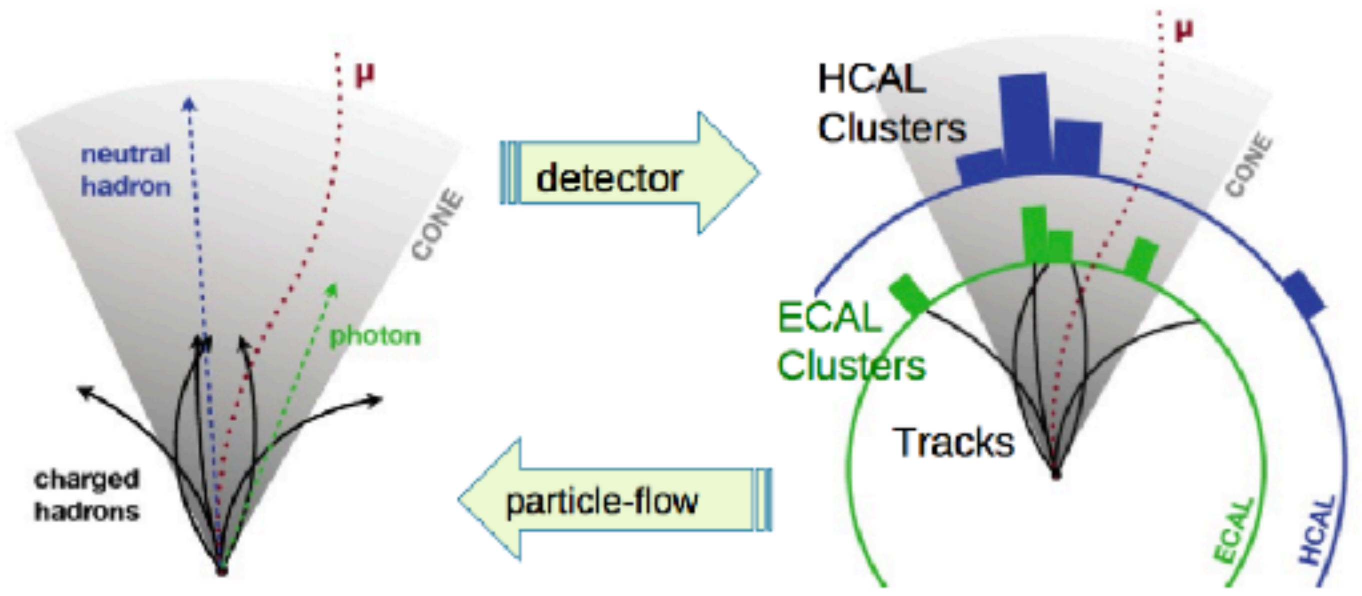

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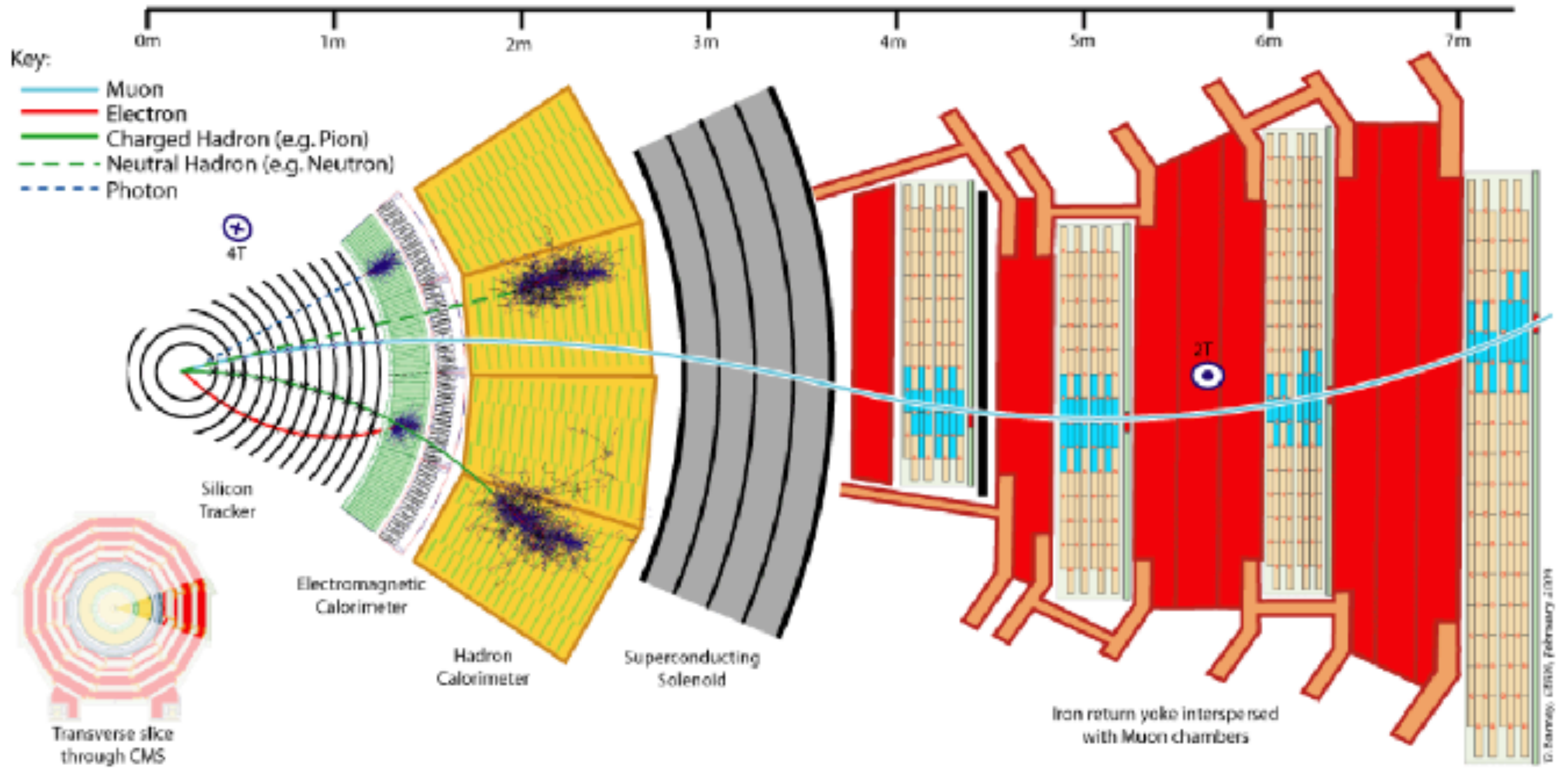

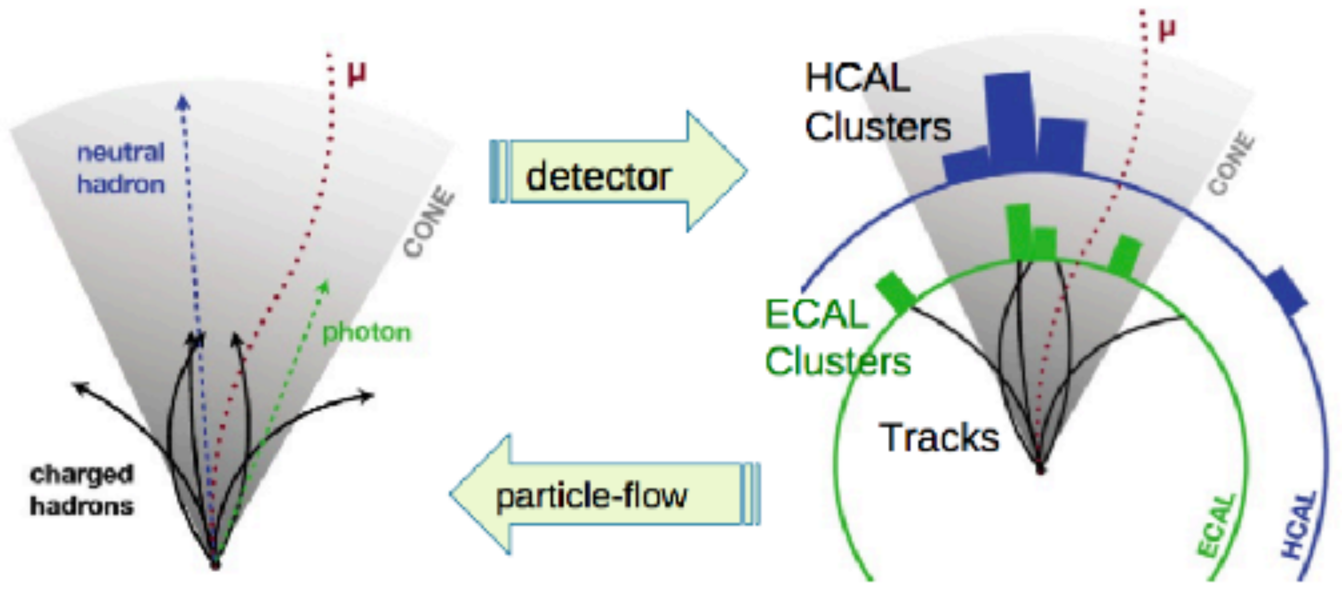

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6. Output of muon RECO further treated by Particle Flow (PF) to obtain a Global Event Description
7. And there is more "under the hood":
   a. computation of identification variables
   b. "ad hoc" high-p_T refits
   c. computation of isolation quantities around muons (based both on detector and "particle flow" quantities)

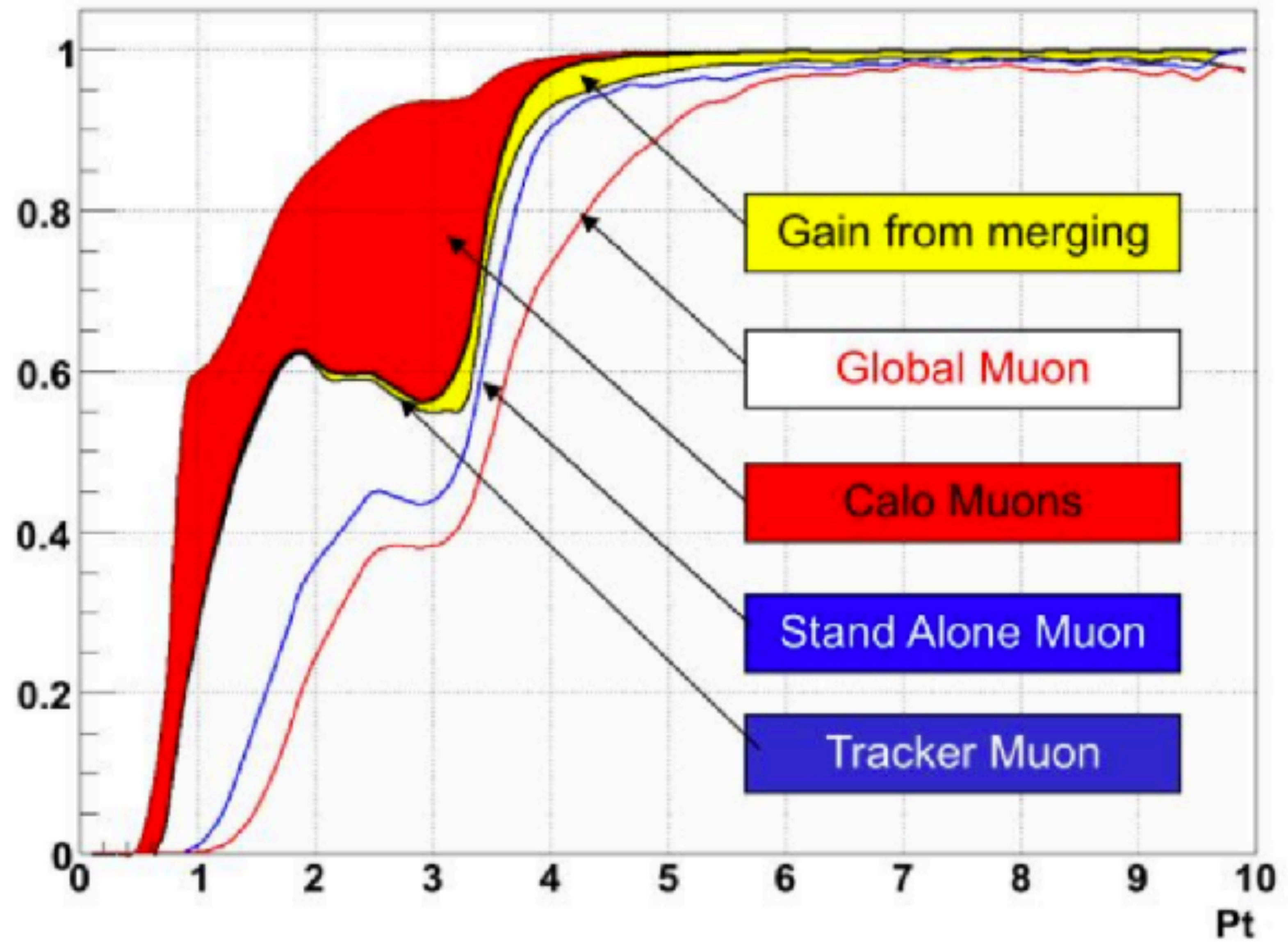
Muon reconstruction- more information (1)

- Standalone muon reconstruction:
  - Create seeds from local DT/CSC segments (HLT uses only those geometrically matched with a L1 candidate)
  - Build the track:
    - propagate seed to each station layer
    - look for the most compatible segment (on χ^2 basis)
    - update the state vector with the additional measurement (if passed compatibility requirements)
    - proceed to next station layer
  - Clean ghosts
  - Extrapolate to the PCA Point of Closest Approach
  - Potentially, update at vertex
  - Minimum requirement for a track: hits/segment in two station layers with at least one from DT or CSC

- Global muon reconstruction:
  - Muon-track matching:
    - create region-of-interest (ROI) windows around a standalone muon
    - define a common surface and propagate standalone-track and inner-tracks from ROI to the common surface
    - compare parameters of inner-tracks and standalone-track looking for compatible TRK-STA pairs
    - if more than one compatible matching is found, perform arbitration
  - Combined refit using tracker and muon hits/segments:
    - including smoothing and propagation of track parameters to the innermost point of measure

Muon reconstruction- more information (2)

- Tracker muons
  - Starting from an inner-track:
    - extrapolate it inside-out to all DT/CSC station layers
    - look for compatible DT/CSC segments on the basis of Δx OR Δx pull
  - A tracker muon is defined if at least a single match is found
    - lower p_T reach w.r.t. global muons!
  - No refit of the inner track using muon system information



- Information from all muon track types is combined into a single object
  - Provides a coherent view of a muon candidate
  - Energy deposits in the calorimeters get also associated, as well as identification and isolation variables

- Output of muon reconstruction (together with other objects) gets further processed by PF to obtain a global event description

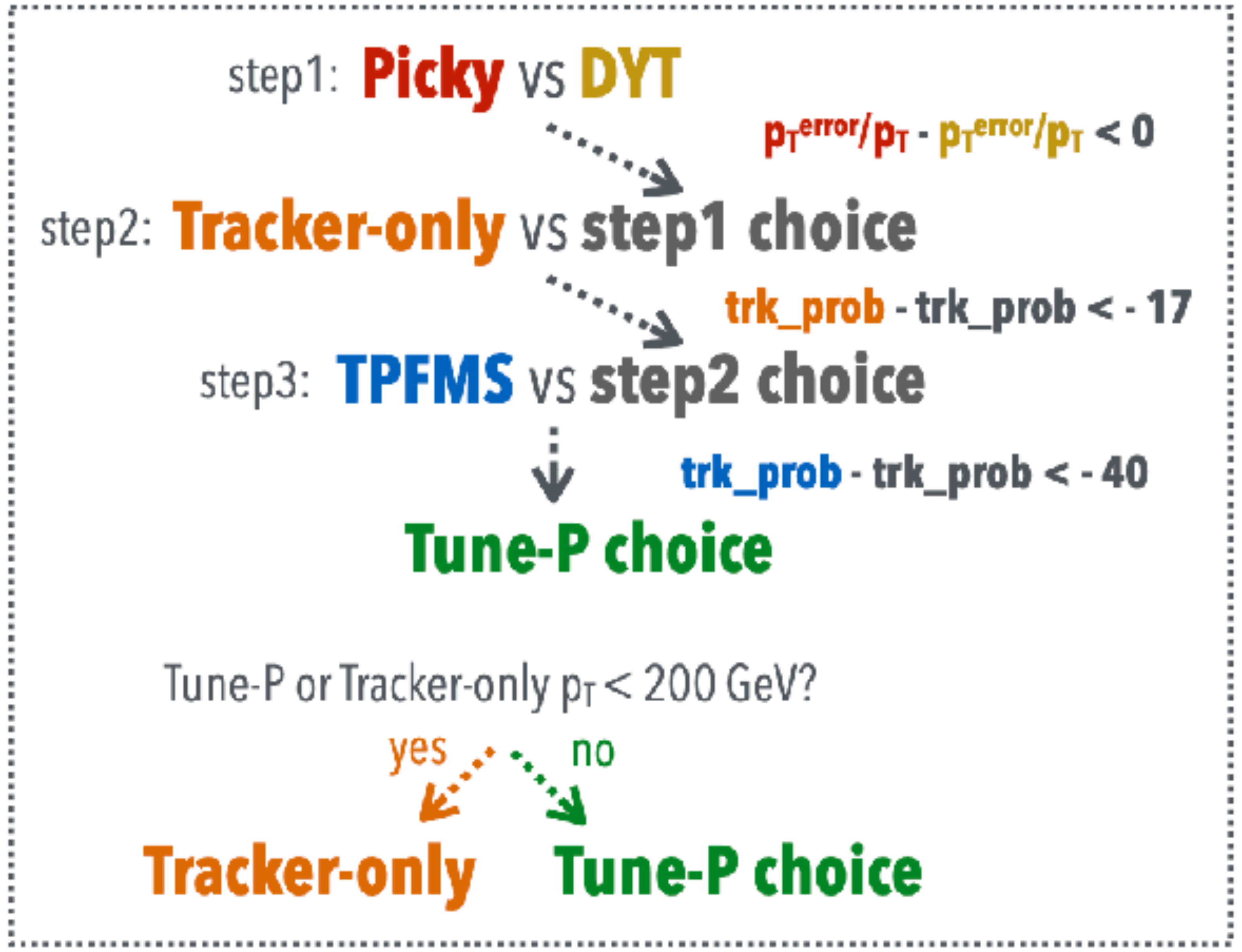
Muon momentum assignment at high-p_T

- For muons of low energy (i.e. < 200 GeV), the p_T measurement is dominated by the inner tracker
- For muons of, at least, few hundreds of GeV muon chambers contribute to the measurement

- Different track-refit strategies are used to get optimal performance:
  - **Track plus first muon station (TPFMS):**
    combined fit of tracker track and hits from innermost muon station
  - **Picky Fit:**
    in chambers with many rec-hits/layer, reject ones less compatible with muon track fit
  - **Dynamic Truncation (DYT):**
    truncate fit if extrapolated track falls "far" from segments in muon stations (i.e. because of significant energy loss in iron causing a kink)

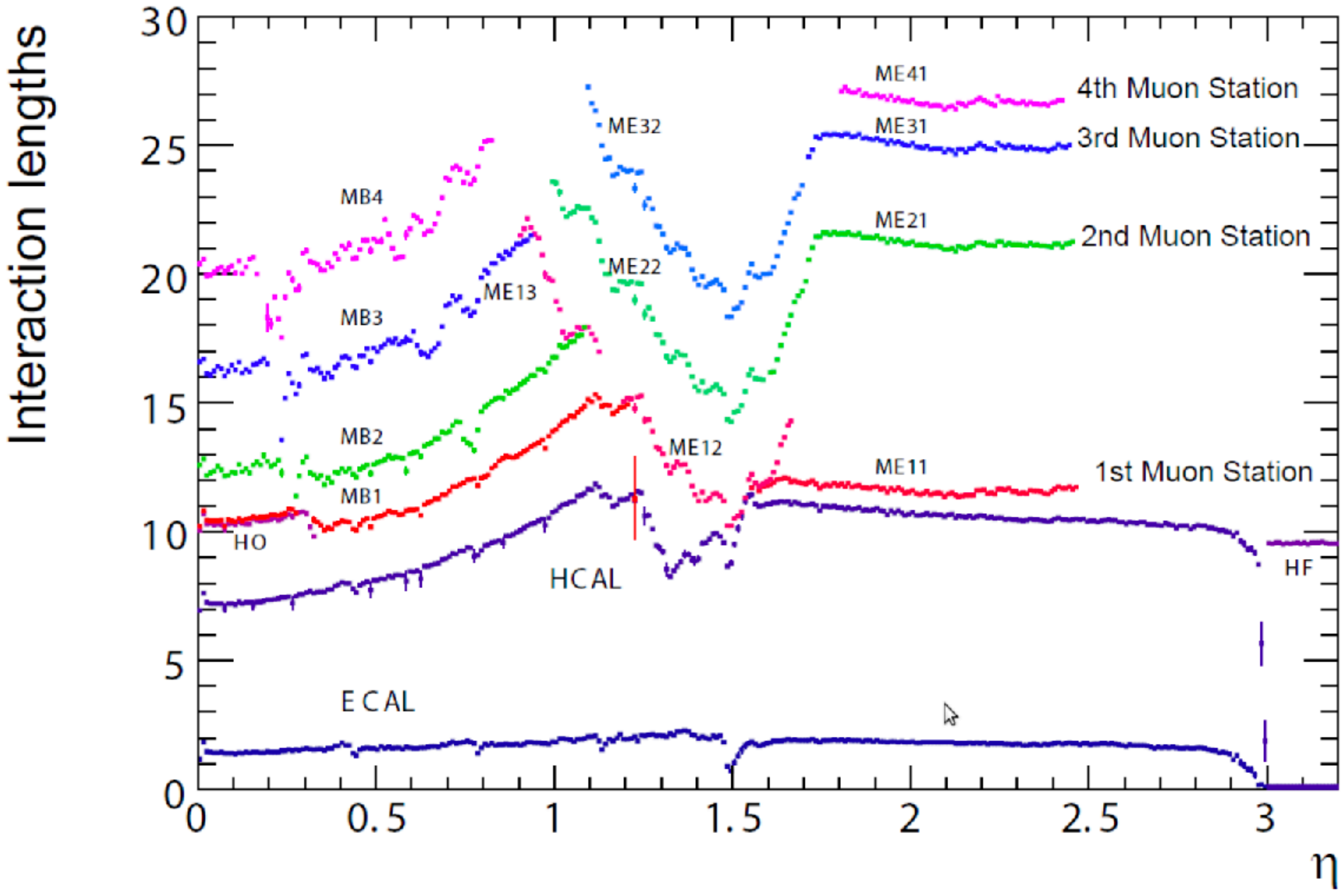
- Final track-fit type chosen by Tune-P algorithm:
  - highly favours inner-track fit at low momentum
  - at high p_T, selects among different refits based on track quality

Tune-P decision flow:



- But, based on global event perspective, PF muons may (occasionally) have a track fit choice that differs from the Tune-P one!

Why Muon identification?



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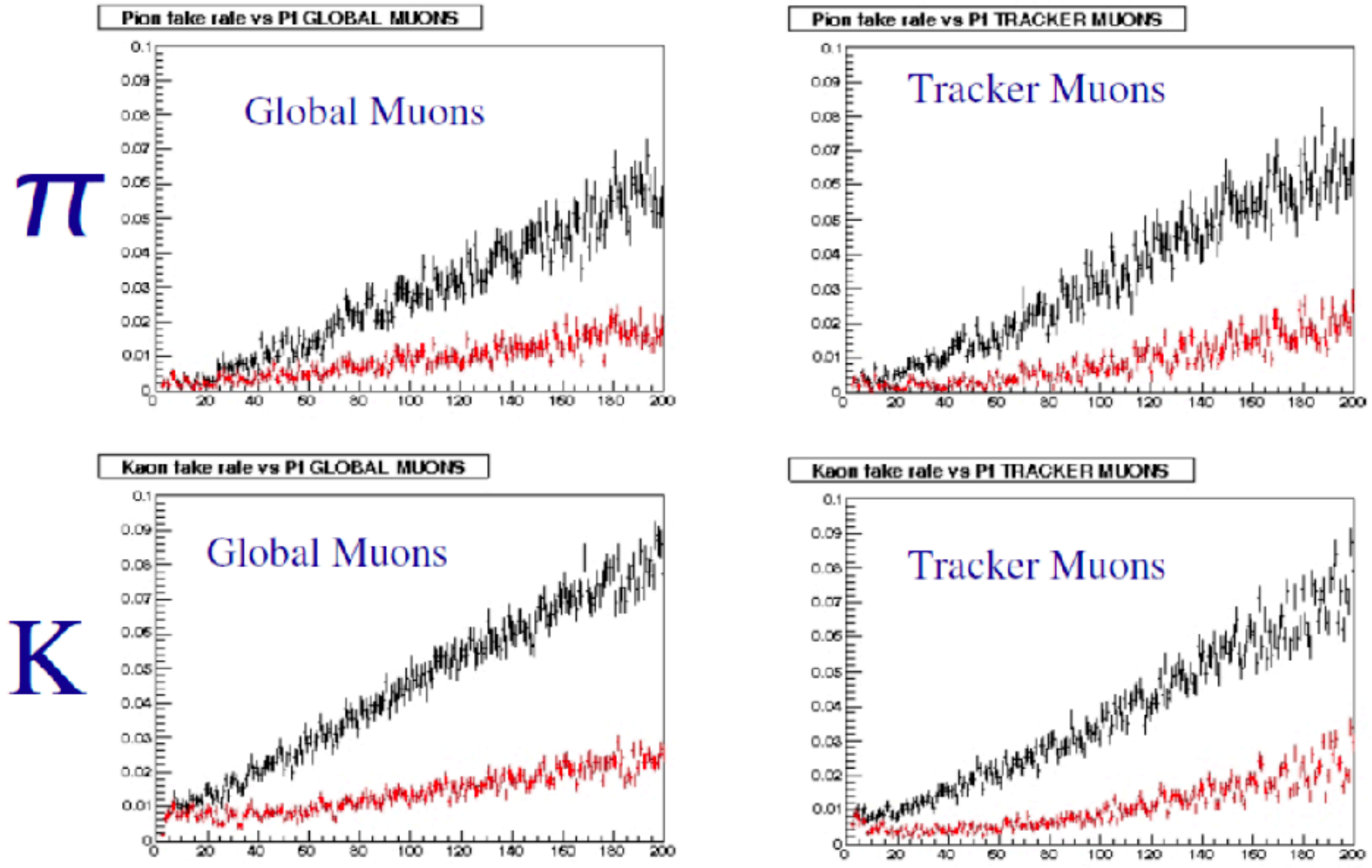
Why Muon identification?

- Out-of-the-box Global and Tracker Muon pion/kaon fake rates



Black: total contribution

Red: decays in flight
(existence of Sim-level muon)

As a function of pT (GeV)

Global Muons at 100 GeV/c

- Pion Fake rate: 3% (total) 1% (decay)
- Kaon Fake rate: 5% (total) 1% (decay)

Tracker Muons at 100 GeV/c

- Pion Fake rate: 3% (total) 0.75% (decay)
- Kaon Fake rate: 3% (total) 0.75% (decay)

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Why Muon identification?

Handles for Global Muon ID fake rejection

- Inner track information:
  - hits in pixel tracker
  - hits in strip tracker
  - quality of the track fit (χ^2/ndof)
  - kink in track?
  - impact parameters
- Calorimeter based information:
  - energy deposition in ECAL and HCAL (compatible with MIP?)
- Muon system information:
  - hits and segments in muon system
  - penetration depth in muon system
  - Stand-Alone muon quality
- Global Fit information: fit quality (χ^2/ndof)

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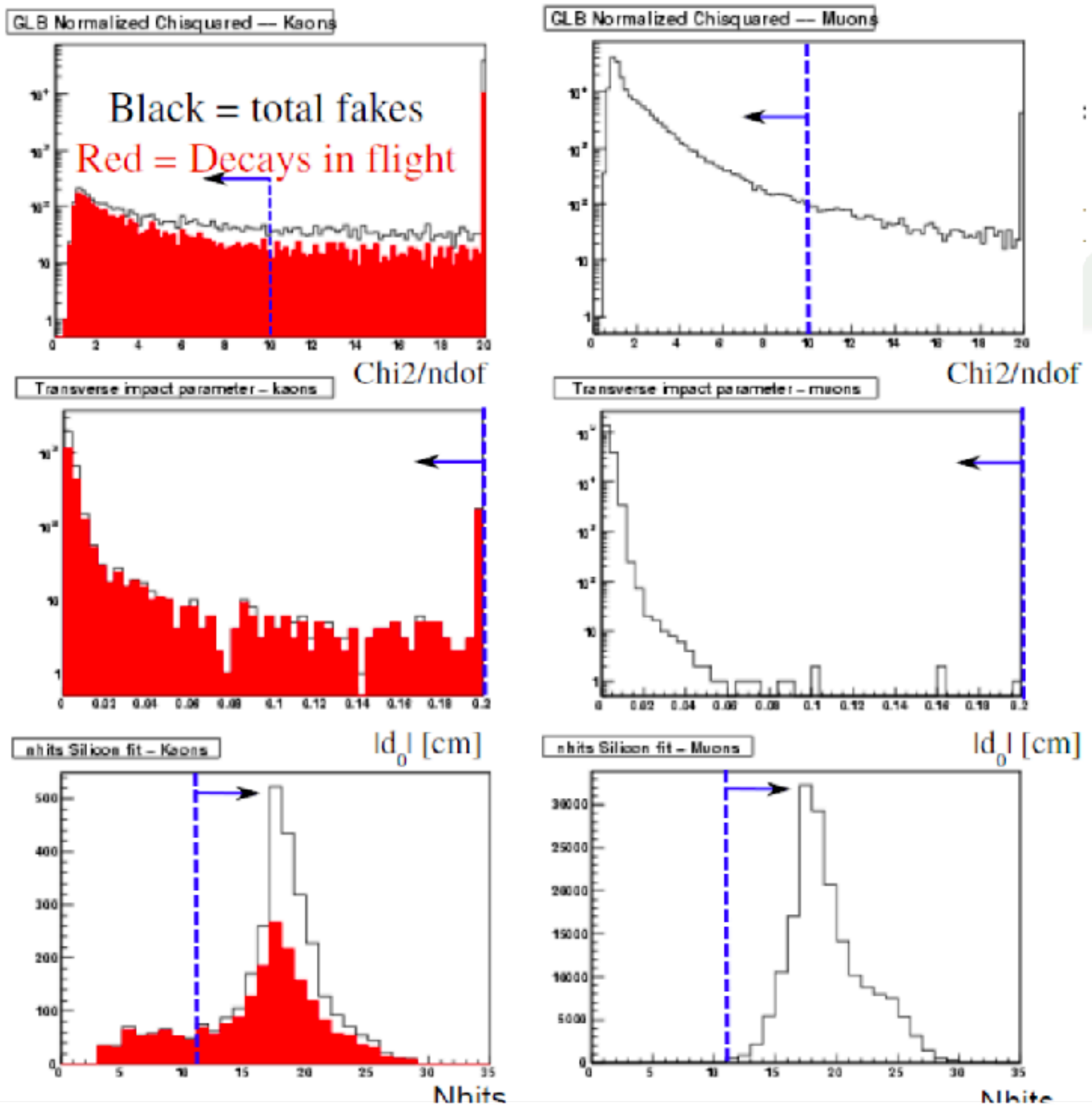

Kaons vs Muons

- **Quality of Global Muon fit ::** $\chi^2/\mathrm{ndof} < 10$
  . . . but long tails . . .
- **Inner track ::** $d_{xy} < 0.2\,\mathrm{cm}$
  . . . room for optimization
- **Inner track ::** $n_{\mathrm{hits}} > 11$
  . . . could be made as function of η

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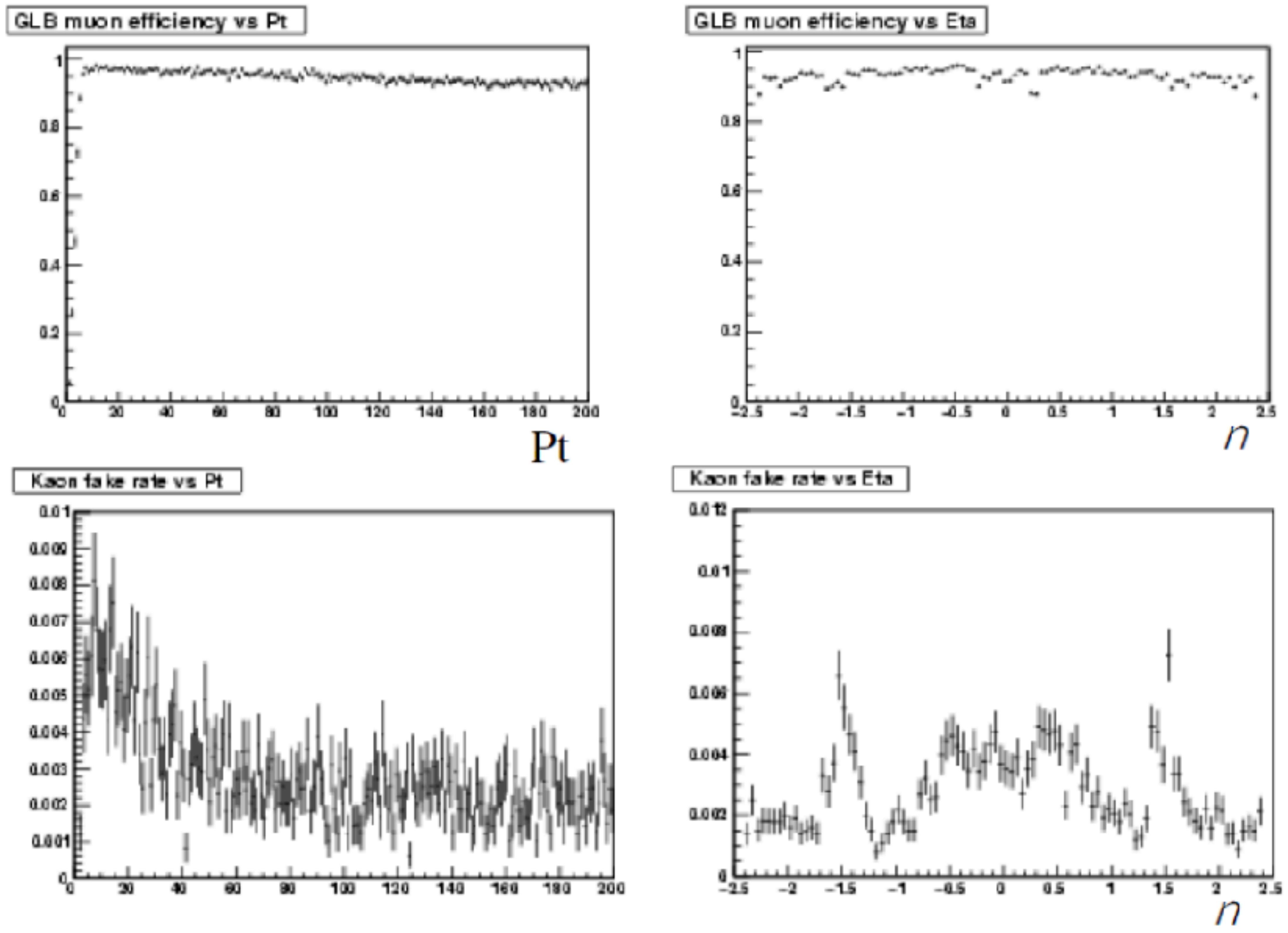
Why Muon identification?



- **Cuts used:**
- Global Muon fit: $\chi^2/\text{ndof} < 10$
- Inner track :: $d_{xy} < 0.2\,\text{cm}$
- Inner track :: $n_{\text{hits}} > 11$

- **Results:**
- Muon ID efficiency high
- Kaon Fake Rate reduced with factor 10

0.3% vs 3% (before) at 100 GeV/c

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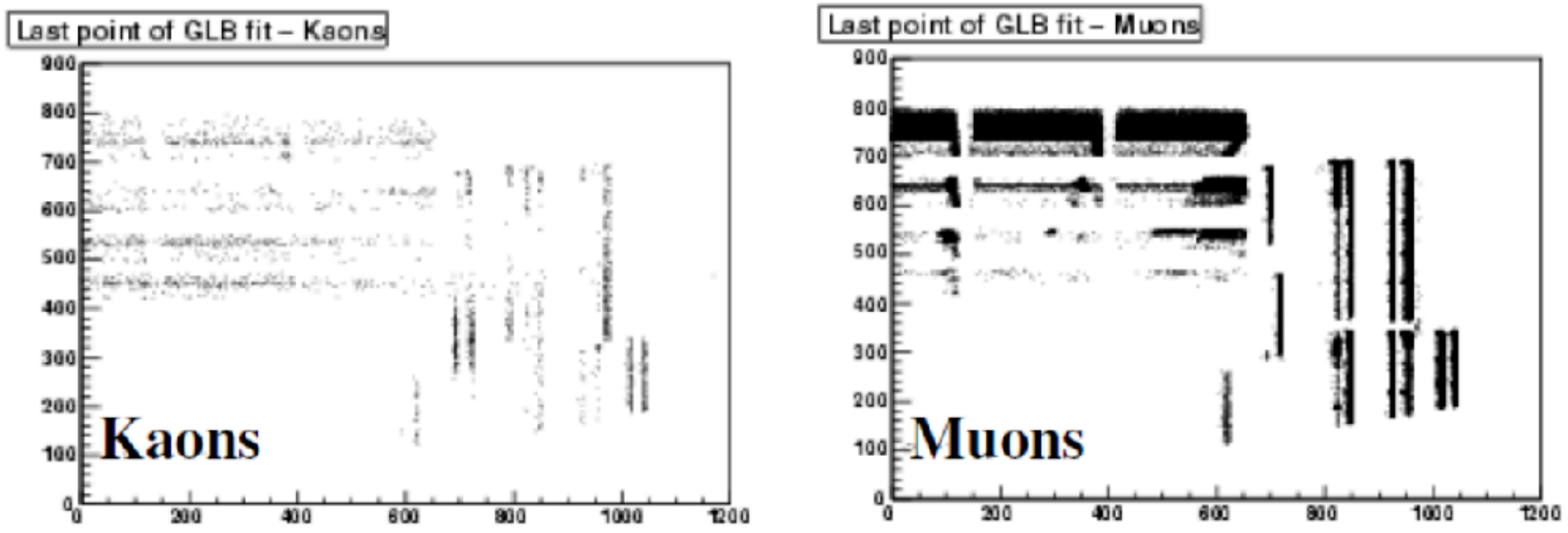
Why Muon identification?

- Reduce fakes from punch-through further by removing muons whose global fit ends in the first station of the muon detector
  - if (abs(z) < 660 && r > 400 && r < 480) keepMuon = false;
  - If (abs(z) > 600 && abs(z) < 650 && r < 300) keepMuon = false;
  - If (abs(z) > 680 && abs(z) < 730 && r < 480) keepMuon = false;



- Rejecting these muons results in a ~20% reduction in fake rate at very little cost in efficiency

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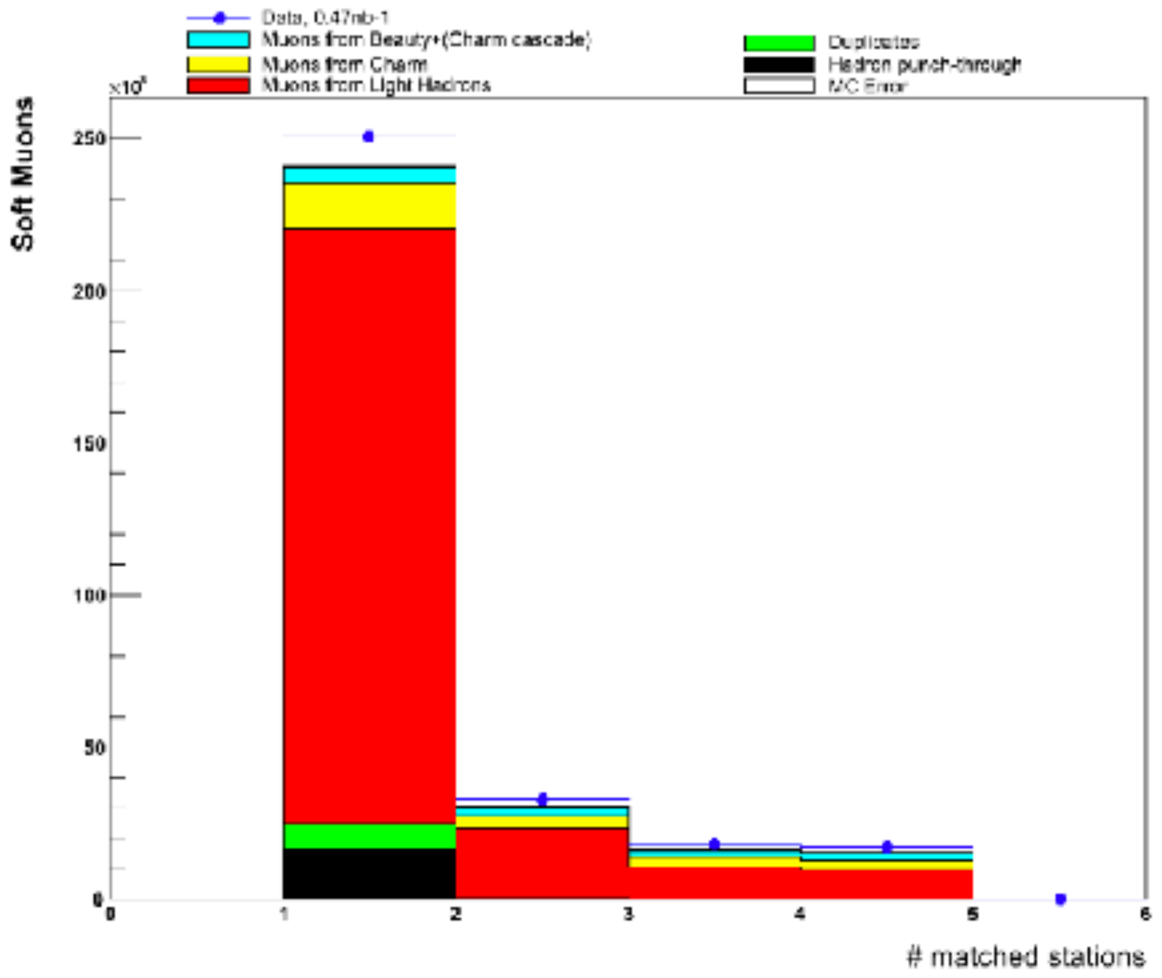
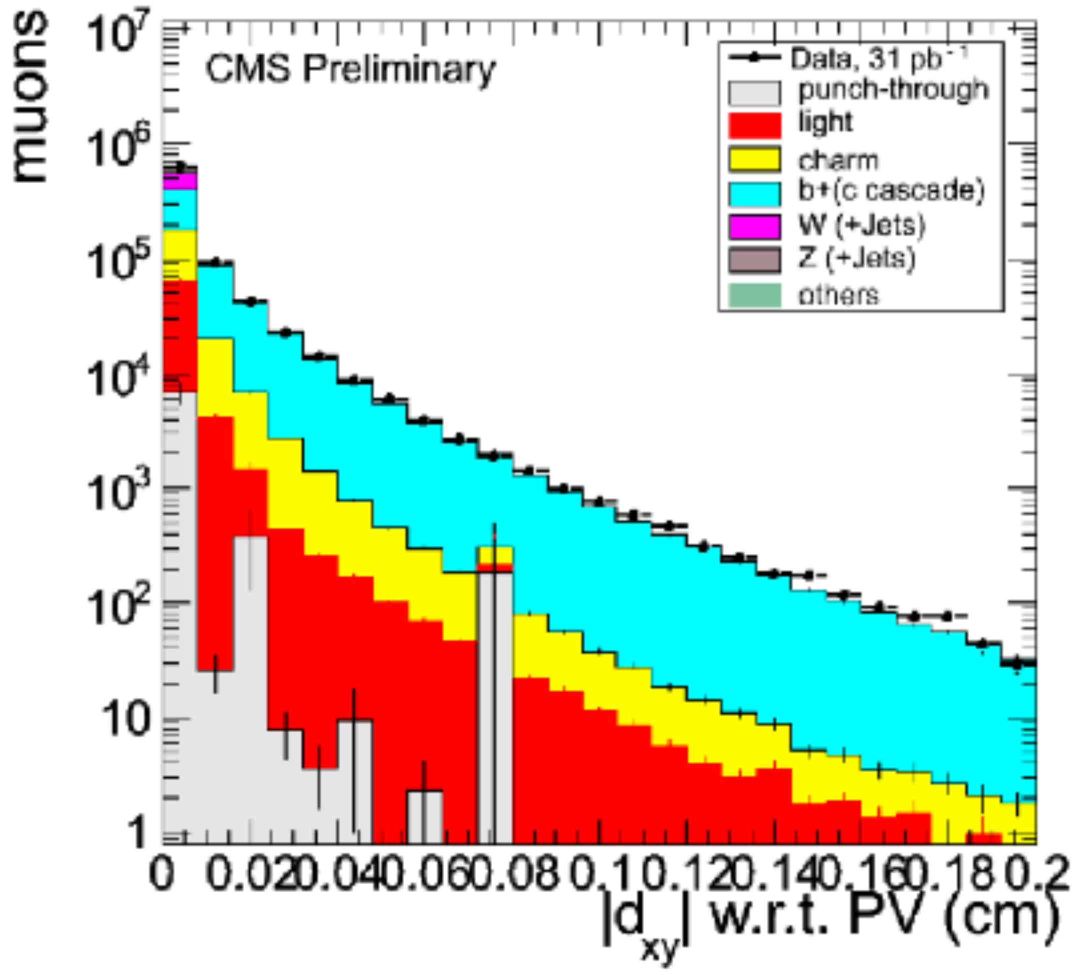
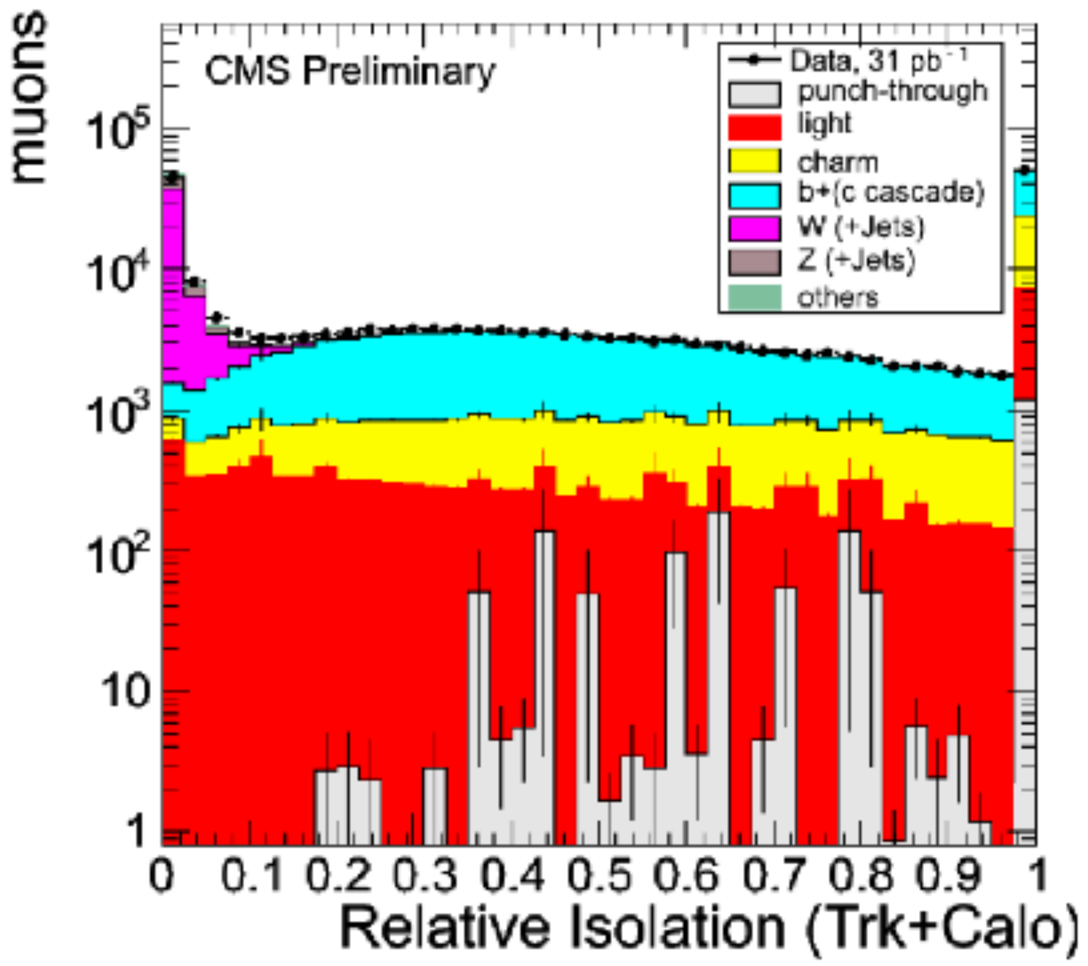
Sources of muons in CMS / need for muon identification

- CMS detects muons from many sources:
  - Prompt muons (e.g. from W/Z decays): coming from IP, isolated, long track crossing tracker and muon system …
  - Muons in jets from heavy flavour (b/c) decays: not from IP, not isolated, long track crossing tracker and muon system …
  - Muons from π/kaons from light flavour (u,d,s) decays: not from IP, not isolated, may have no hits in tracker or a kinked track …
  - Fake muons (e.g. from hadronic shower punch-through): large disagreement between hits in tracker and muon system …
  - Muons from cosmic-rays / beam-halo: displaced from IP, possibly no hits in tracker, bad crossing time w.r.t. collision …
- Muon reconstruction tuned for high efficiency, not purity
  - Also, it is aimed at reconstructing all muon types (low/high-p_T muons, exotic decays e.g. in displaced muons …)
- <u>Must optimise muon selection criteria offline, according to analysis needs</u>







Muon identification selectors

- Many different selection criteria are centrally maintained by the Muon POG
  - Information available in: https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideMuonIdRun2
- Cut based IDs include:
  - PF based IDs:
    - Loose, Medium and Tight IDs
  - Soft ID
    - Optimised for low momentum muons (e.g. used in B-physics)
  - High-pT and Tracker High-pT IDs
    - Optimised for high momentum muons
- In addition
  - MVA-based IDs for soft and prompt leptons are supported
  - Specific trigger ID and in-time muon selectors are provided

Example of a selector: the Tight muon ID

Plain-text description	Technical description
The candidate is reconstructed as a Global Muon	`recoMu.isGlobalMuon()`
Particle-Flow muon id	`recoMu.isPFMuon()`
χ^2/ndof of the global-muon track fit < 10	`recoMu.globalTrack()->normalizedChi2() < 10.`
At least one muon-chamber hit included in the global-muon track fit	`recoMu.globalTrack()->hitPattern().numberOfValidMuonHits() > 0`
Muon segments in at least two muon stations This implies that the muon is also an arbitrated tracker muon, see SWGuideTrackerMuons	`recoMu.numberOfMatchedStations() > 1`
Its tracker track has transverse impact parameter d_{xy} < 2 mm w.r.t. the primary vertex	`fabs(recoMu.muonBestTrack()->dxy(vertex->position())) < 0.2` Or `dB() < 0.2` on `pat::Muon` [1]
The longitudinal distance of the tracker track wrt. the primary vertex is d_z < 5 mm	`fabs(recoMu.muonBestTrack()->dz(vertex->position())) < 0.5`
Number of pixel hits > 0	`recoMu.innerTrack()->hitPattern().numberOfValidPixelHits() > 0`
Cut on number of tracker layers with hits >5	`recoMu.innerTrack()->hitPattern().trackerLayersWithMeasurement() > 5`

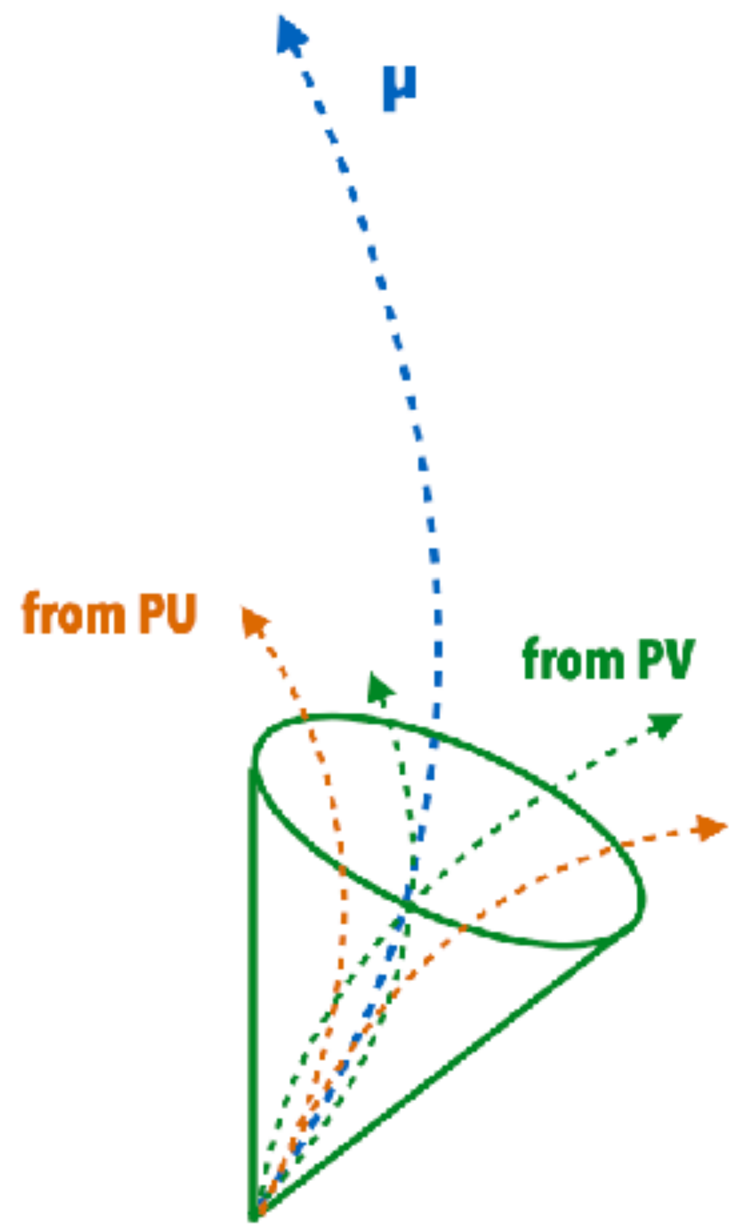
- Unless an analysis has special needs, it is suggested to stick with centrally-maintained selectors
  - Beyond muon POG, central working points are continuously used/commissioned by many analyses
  - High level calibrations (i.e. data MC scale factors - see later) centrally computed by Muon POG

Muon isolation

- Isolation is another important handle to discriminate prompt vs non-prompt muons:
  - It is computed :
    - in cones of fixed or variable size (mini isolation) around a muon track
    - summing detector (TRK, ECAL, HCAL) or PF (ch. had, neu. had, photons) based energy/momentum deposits
    - it is usually computed relative to the muon p_T
    - it may account for contribution to energy deposits from PU vertices in different ways:
      - $\Delta\beta$ corrections, ϱ corrections, PUPPI …
- An example of an isolation definition from recommendations:

$$I^{PF}_{\Delta\beta} = \left(\Sigma p_T^{\text{ch.had. PV}} + \max(0, \Sigma E_T^{\text{neu.had.}} + \Sigma E_T^{\text{ph.}} - k \cdot \Sigma p_T^{\text{ch.had. PU}}) \right) / p_T^{\mu}$$

Assume charged/neutral ratio = 2:1 → $k = 0.5$

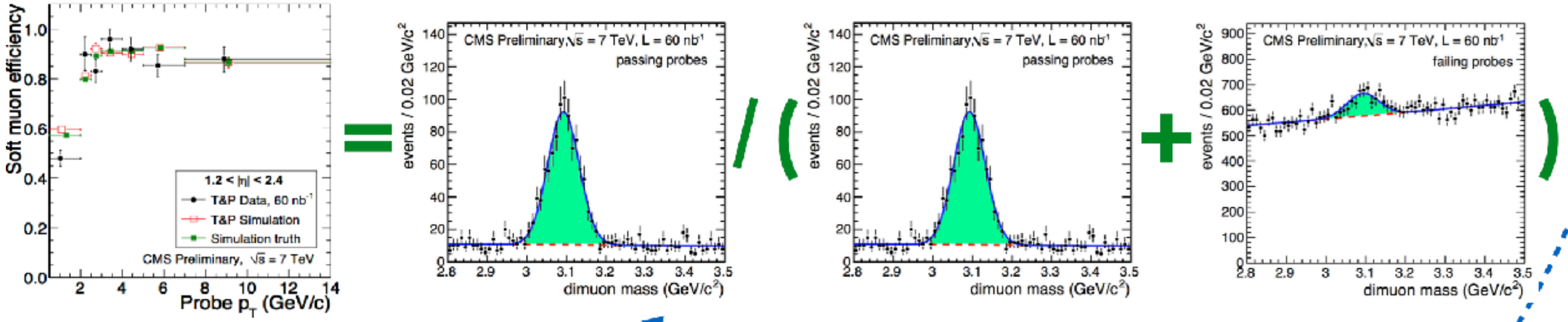


- Recommended way of accessing centrally supported isolation working points and identification criteria (for CMSSW version ≥ 9_4_X) documented here

High-level calibrations:
efficiency measurement with the tag and probe method

- The tag-and-probe method in a nutshell (more here and here):
  - Start from a sample collected with an unbiased trigger (e.g. SingleMuon for TnP with Zs)
  - Identify **tag μ**: apply tight ID/isolation cuts - match with muon from HLT
  - Identify **probe μ** (denum.): apply cuts mild enough to avoid biases (e.g. probes for RECO-ID are all TRK tracks)
  - Define **passing probe μ** (num.): probe definition AND RECO / ID / isolation / trigger selection under study
  - Reconstruct a **pair**: opposite sign - cuts (e.g. dZ) - in a **mass window around a known resonance** (e.g. J/Psi, Z)
  - Bin appropriately (e.g. in probe p_T or η, # of reconstructed PVs …)
  - For each bin, fit invariant mass for events passing and non-passing probes and compute efficiency
  - Apply the same method on DATA and MC and compute efficiency ratios (scale factors)

PROBE μ:
mild quality/isolation cuts

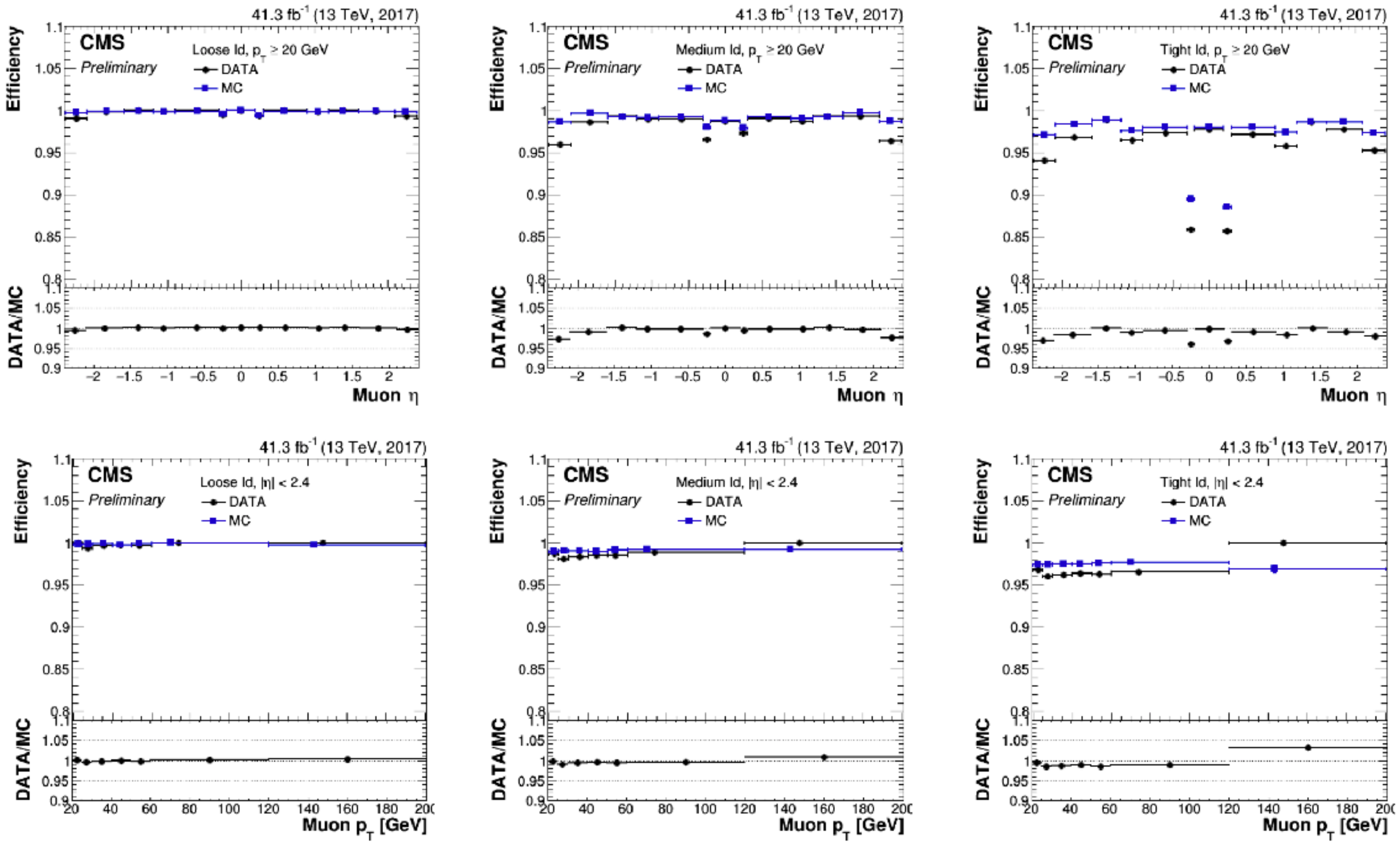


TAG μ:
tigh quality/isolation cuts
matched with HLT

PAIR:
opposite sign / dZ cut
invariant mass range

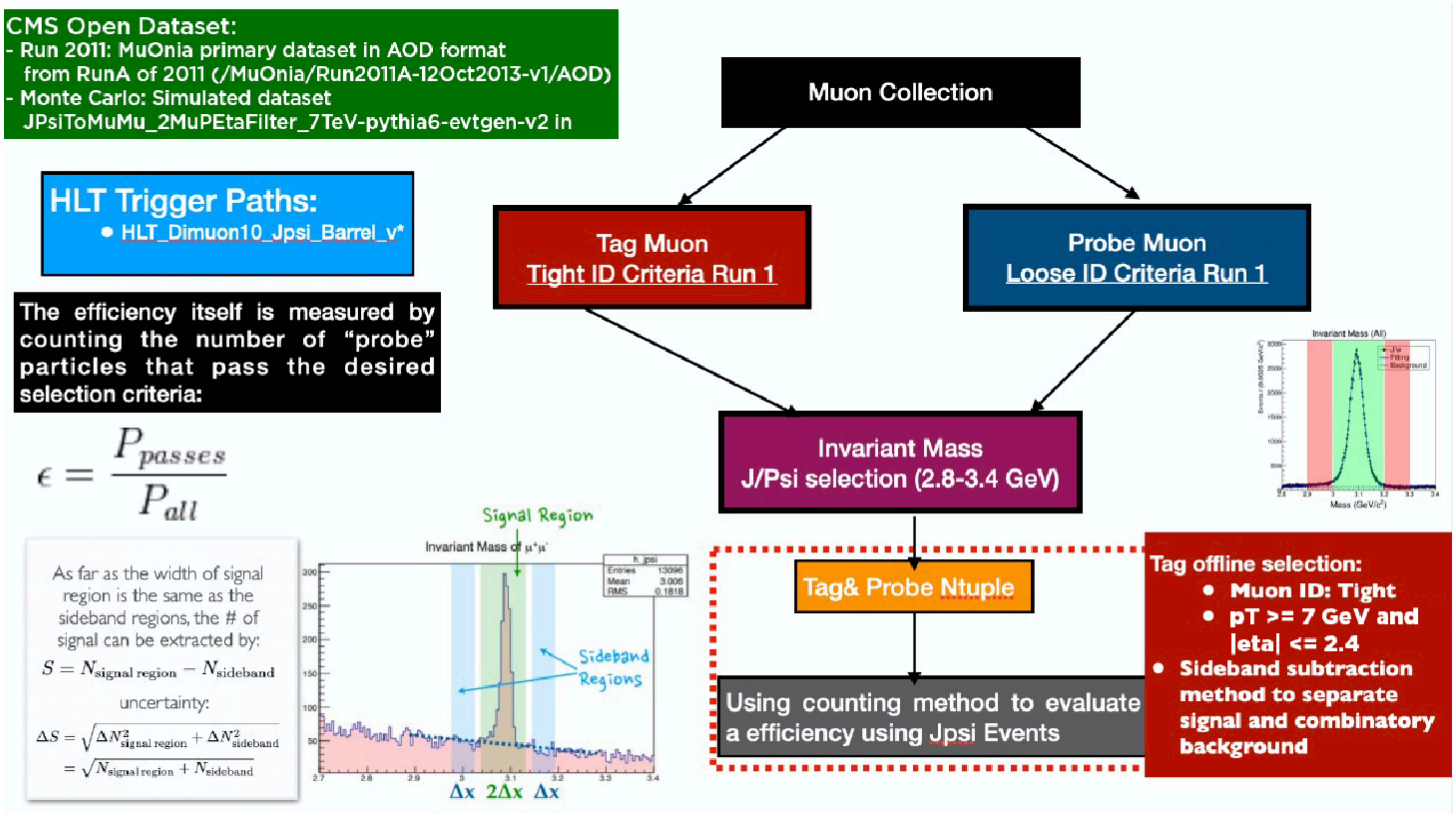
High-level calibrations: efficiency official measurement results

https://twiki.cern.ch/twiki/bin/view/CMS/MuonReferenceEffs2017



https://cds.cern.ch/record/2629364/files/DP2018_042.pdf

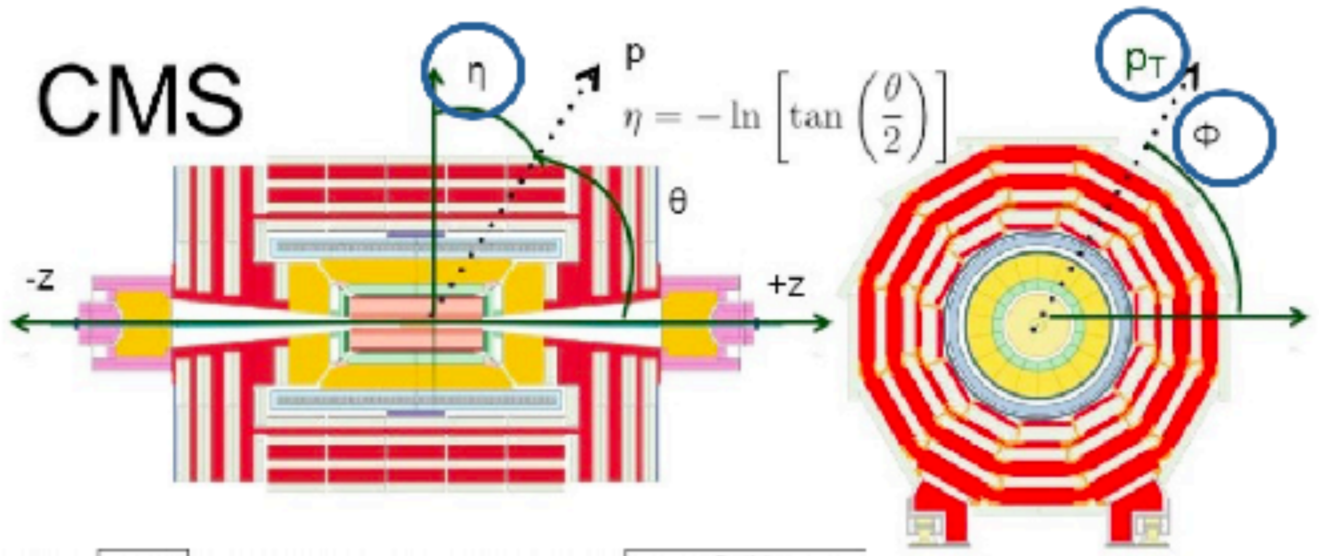
Tag and Probe Efficiency studies using JPsi Open Data



Tag and Probe Efficiency studies using JPsi Open Data

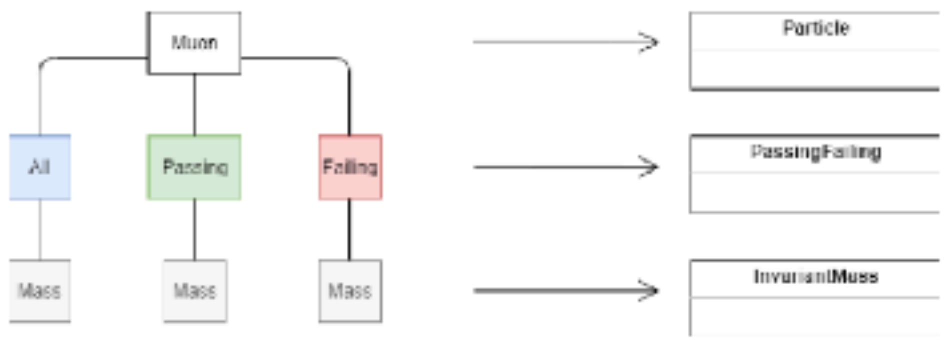
$$\varepsilon = \frac{\textit{partículas de sinal}}{\textit{todas as partículas}}$$

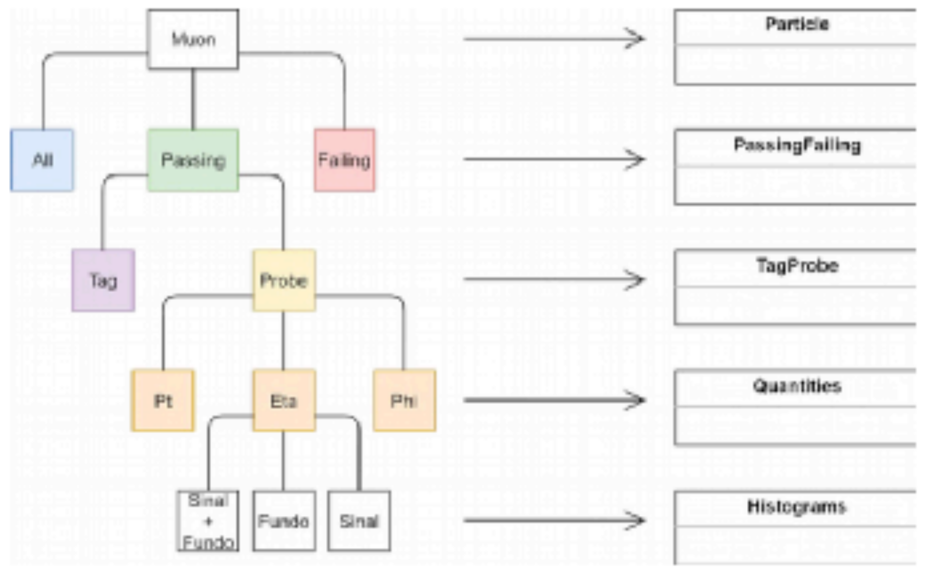
Para cada grandeza



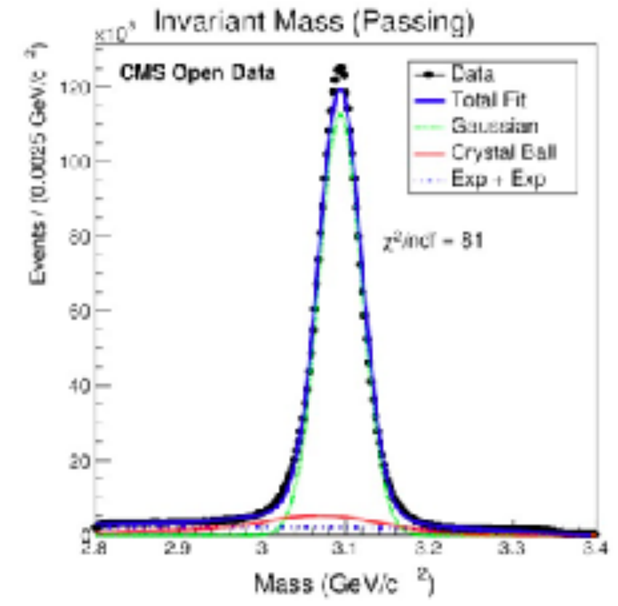
Ntupples

- Run 2011
- Monte Carlo

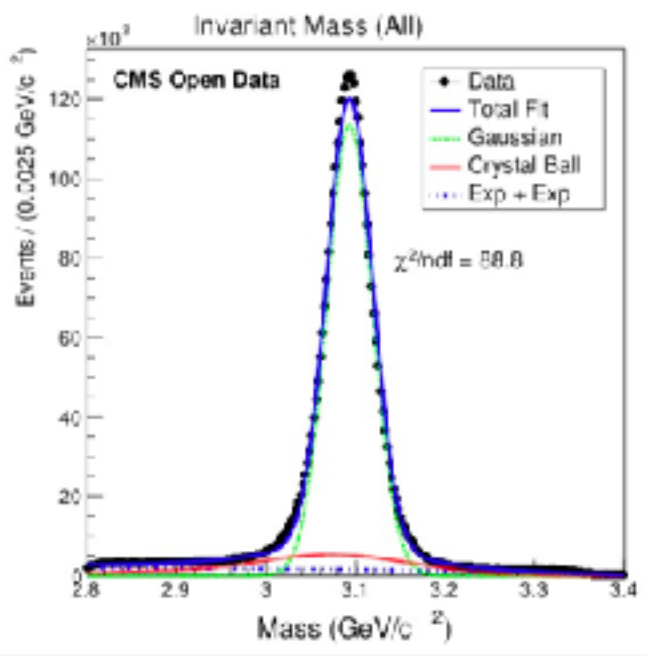




Run 2011



Run 2011



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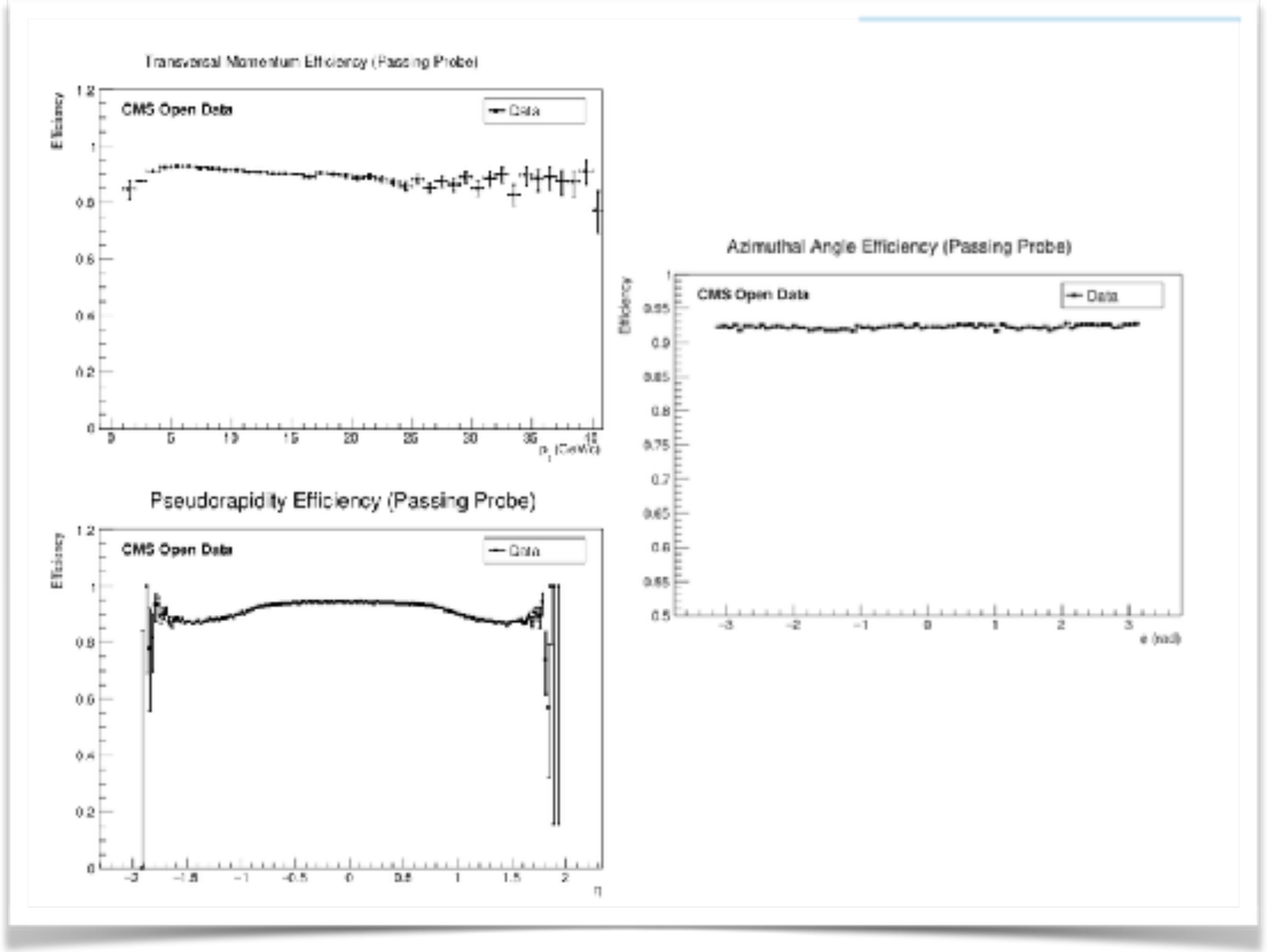

Tag and Probe Ntuples and CMS Open Datasets

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	Upsilon_Run2011A_MuOnia_DATA	···	11 July	Nuno Viegas Guerreiro Leonardo
	Upsilon1SToMuMu_MC	···	11 July	Nuno Viegas Guerreiro Leonardo

https://espace.cern.ch/cms-lip/internship/_layouts/15/WopiFrame.aspx?sourcedoc=/cms-lip/internship/summer2020/tnp/data/README.docx&action=default

CMS Open Data Primary Datasets:

MuOnia primary dataset in AOD format from RunA of 2011 - ntuple done for J/Psi

Simulated dataset JPsiToMuMu_2MuPEtaFilter_7TeV-pythia6-evtgen-v2 in AODSIM format for 2011 collision data (B-physics)- ntuple done for J/Psi

Simulated dataset Upsilon1SToMuMu_2MuEtaFilter_tuneD6T_7TeV-pythia6-evtgen in AODSIM format for 2011 collision data (B-physics)

Simulated dataset DYToMuMu_M-20_CT10_8TeV-powheg-pythia6 in AODSIM format for 2012 collision data

MuOnia primary dataset in AOD format from Run of 2012