Muon reconstruction and identification performance in CMS

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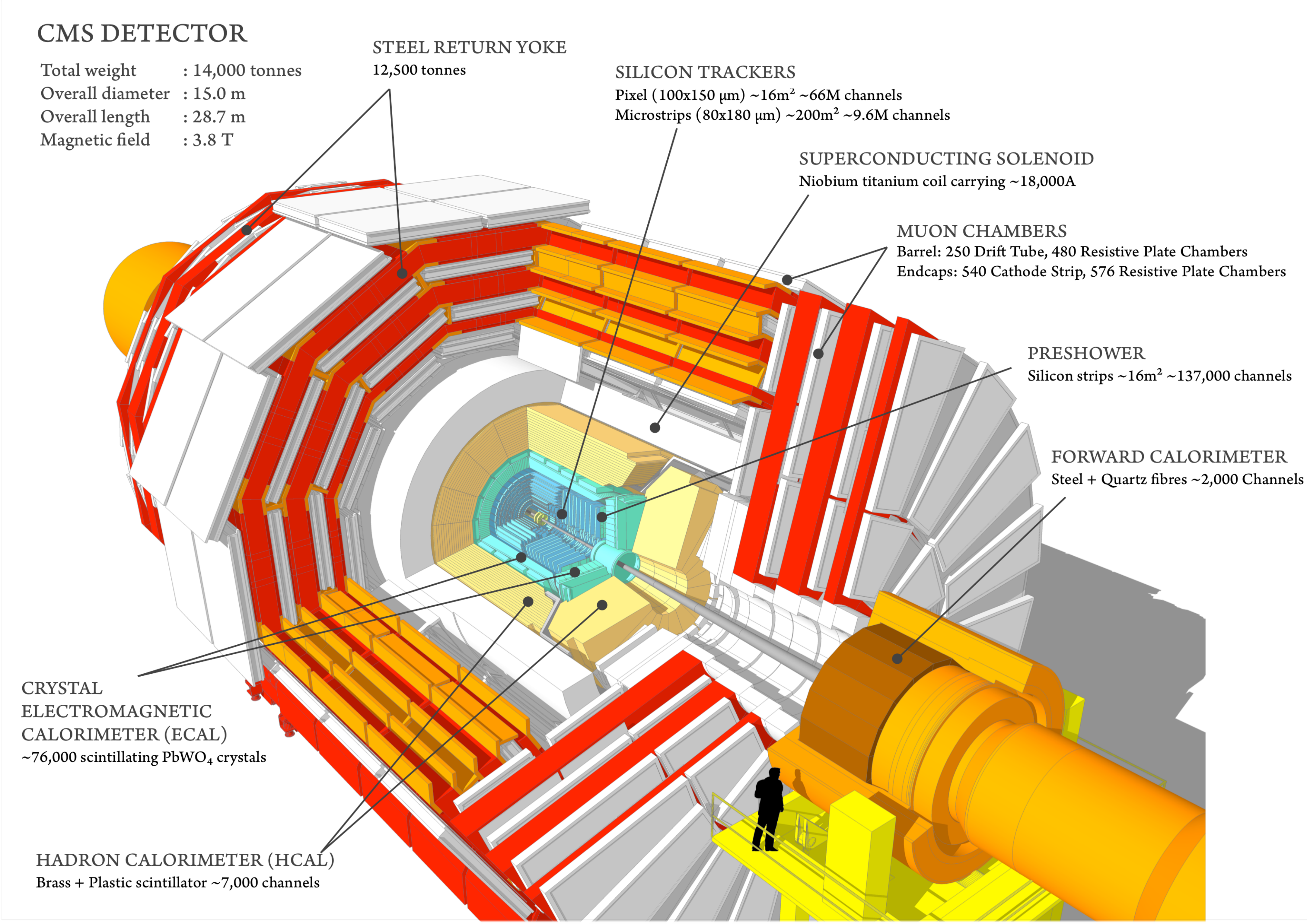
Outline

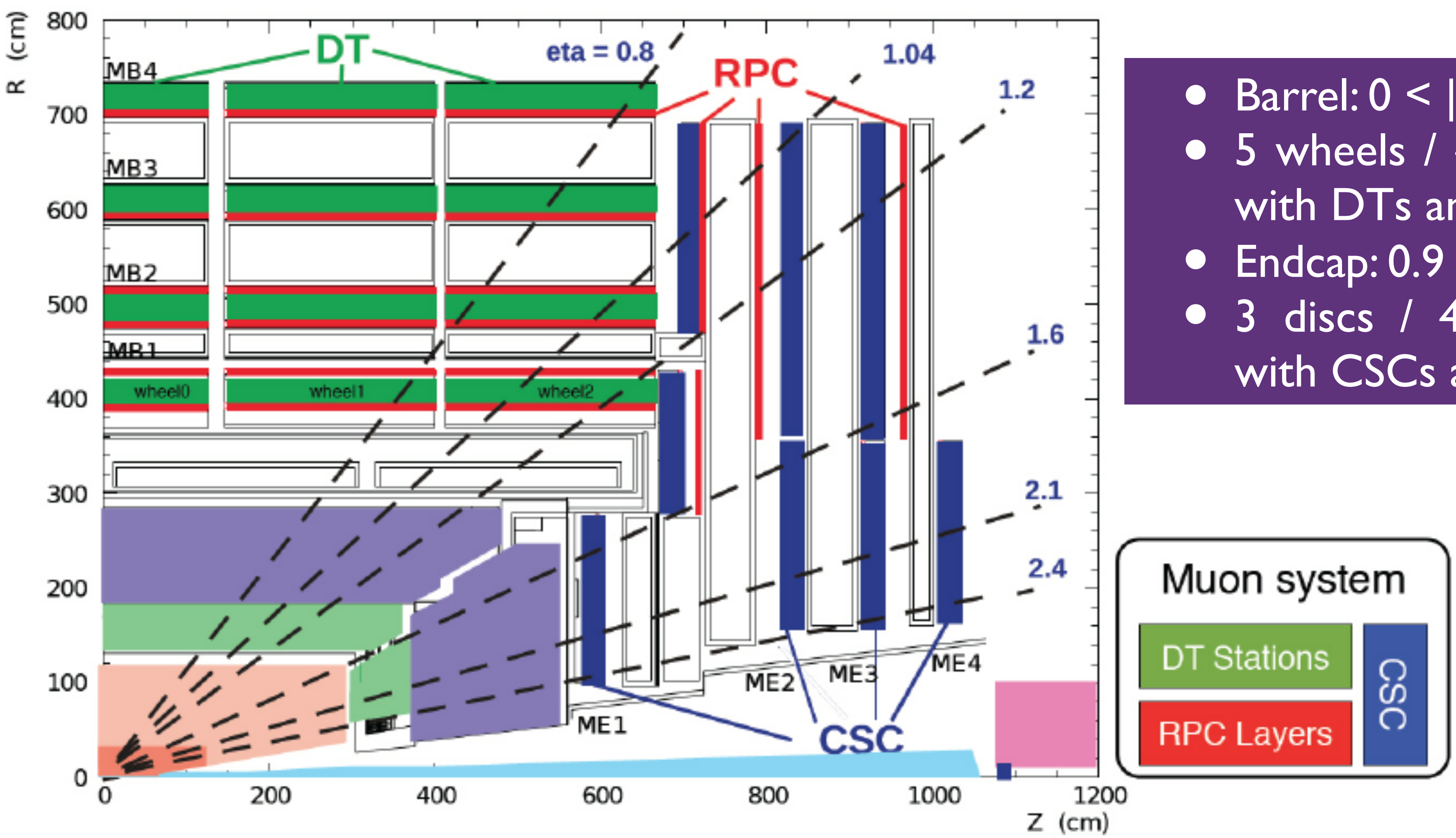
- CMS Experiment
- Review of the Muon performance with CMS detector in Run2
- Summary

CMS Experiment



Muon System: Present Status

- Three types of detector:
  - Precise position measurement and triggering by Drift Tubes (DT) in the barrel, and Cathode Strip Chambers (CSC) in the endcap
  - Redundant triggering and timing by Resistive Plate Chambers (RPC)



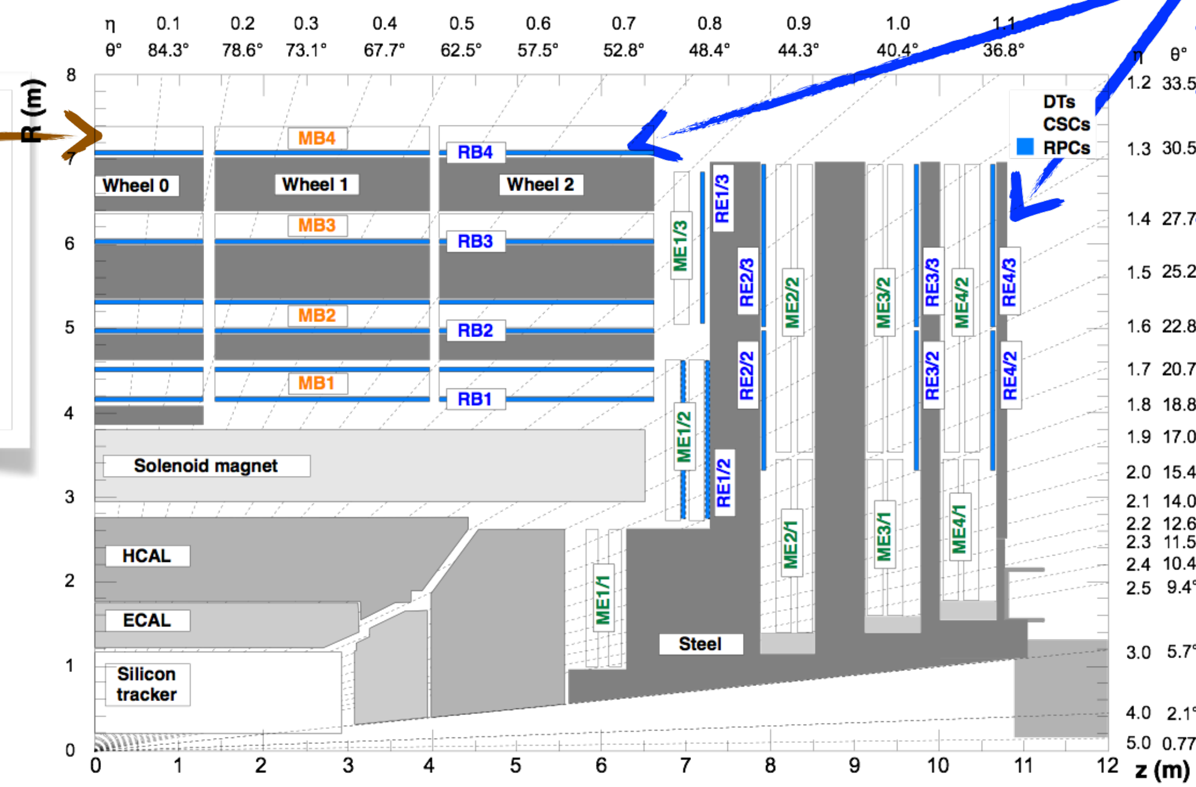
- Barrel: $0 < |\eta| < 1.2$
- 5 wheels / 4 stations instrumented with DTs and RPCs
- Endcap: $0.9 < |\eta| < 2.4$
- 3 discs / 4 stations instrumented with CSCs and RPCs

Muon system overview

Robust trigger and efficient muon reconstruction

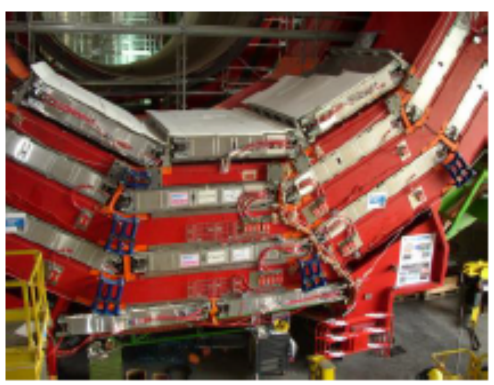
Drift Tube (DT):

- 0 < |η| < 1.2
- 250 chambers
- Spatial resolution 100 µm time resolution 2 ns



Resistive Plate Chamber (RPC)

- 0 < |η| < 1.8
- 480 (barrel) + 576 (endcap) chambers
- Spatial resolution 0.8-1.3 cm, time resolution 1.5 ns

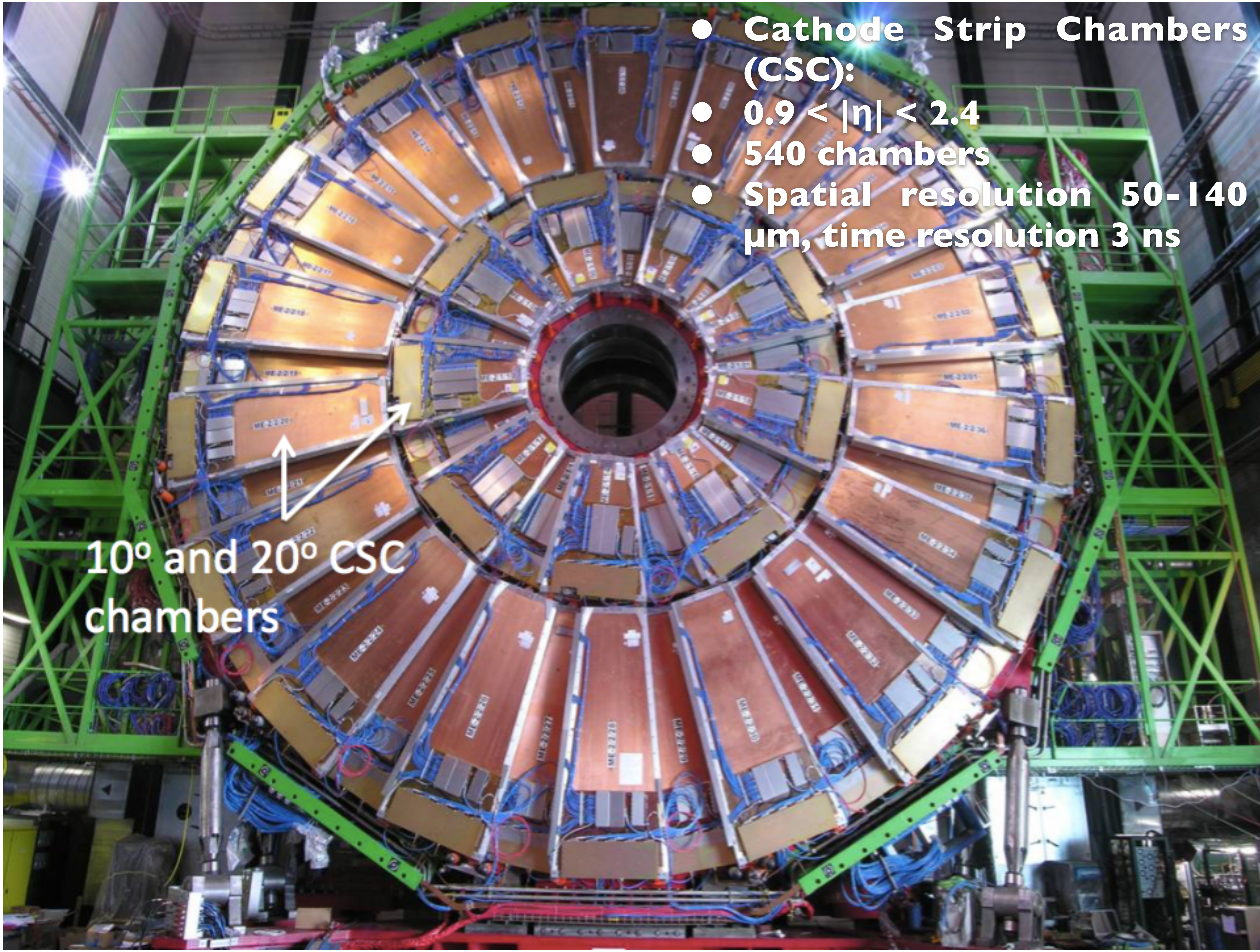


Cathode Strip Chamber (CSC)

- 0.9 < |η| < 2.4
- 540 chambers
- Spatial resolution 50-140 µm, time resolution 3 ns

All currently installed Muon detectors will be kept operational at HL-LHC


Drift Tubes Chambers (DT):
● 0 < |η| < 1.2
● 250 chambers
● Spatial resolution 100 μm time resolution 2 ns
20° DT chambers with thin barrel RPCs attached


● Cathode Strip Chambers (CSC):
● 0.9 < |η| < 2.4
● 540 chambers
● Spatial resolution 50-140 μm, time resolution 3 ns
10º and 20º CSC chambers

- **Resistive Plate Chamber (RPC):**
- **$0 < |\eta| < 1.8$**
- **480 (barrel) + 576 (endcap) chambers**
- **Spatial resolution 0.8-1.3 cm, time resolution 1.5 ns**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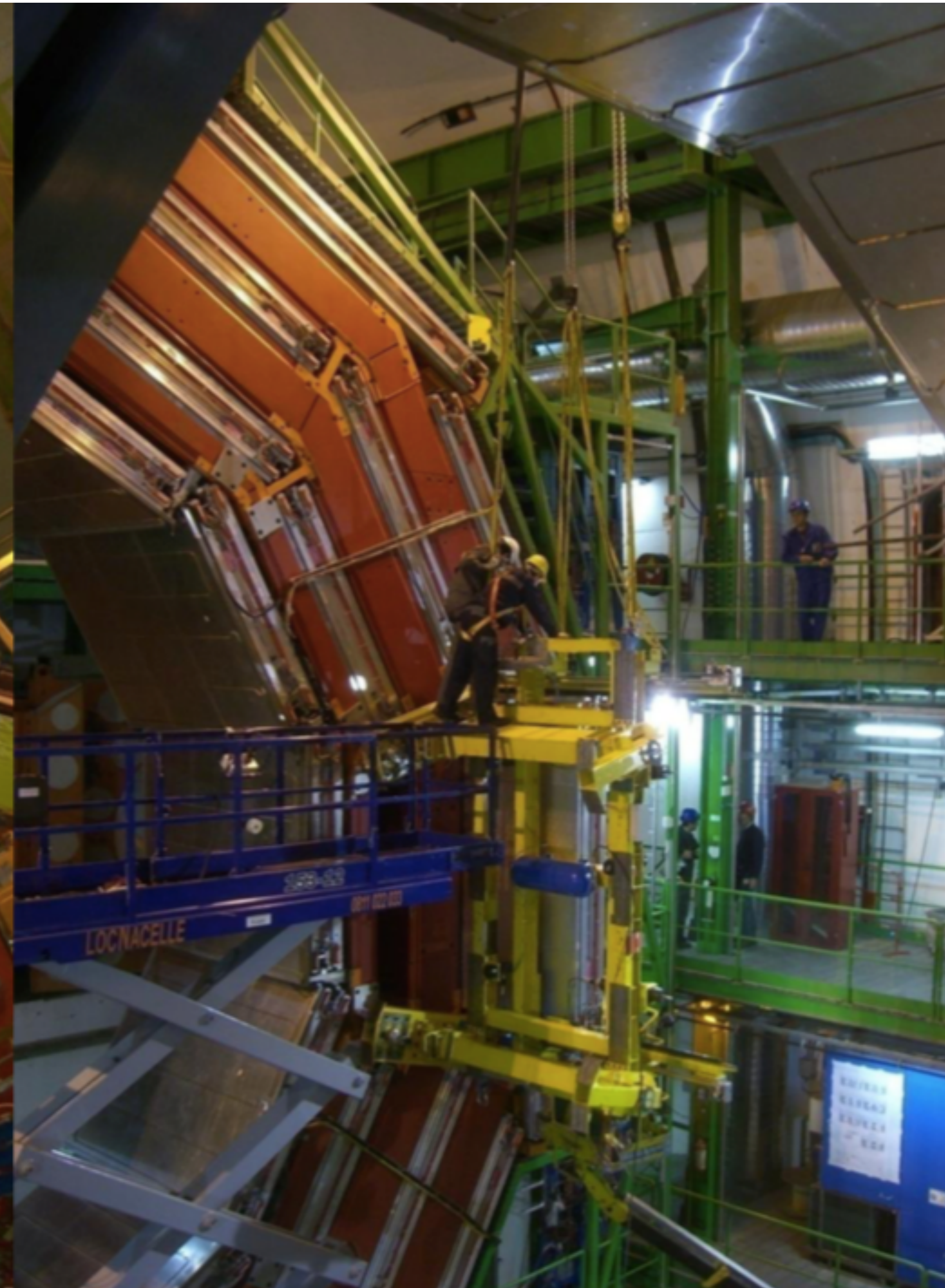
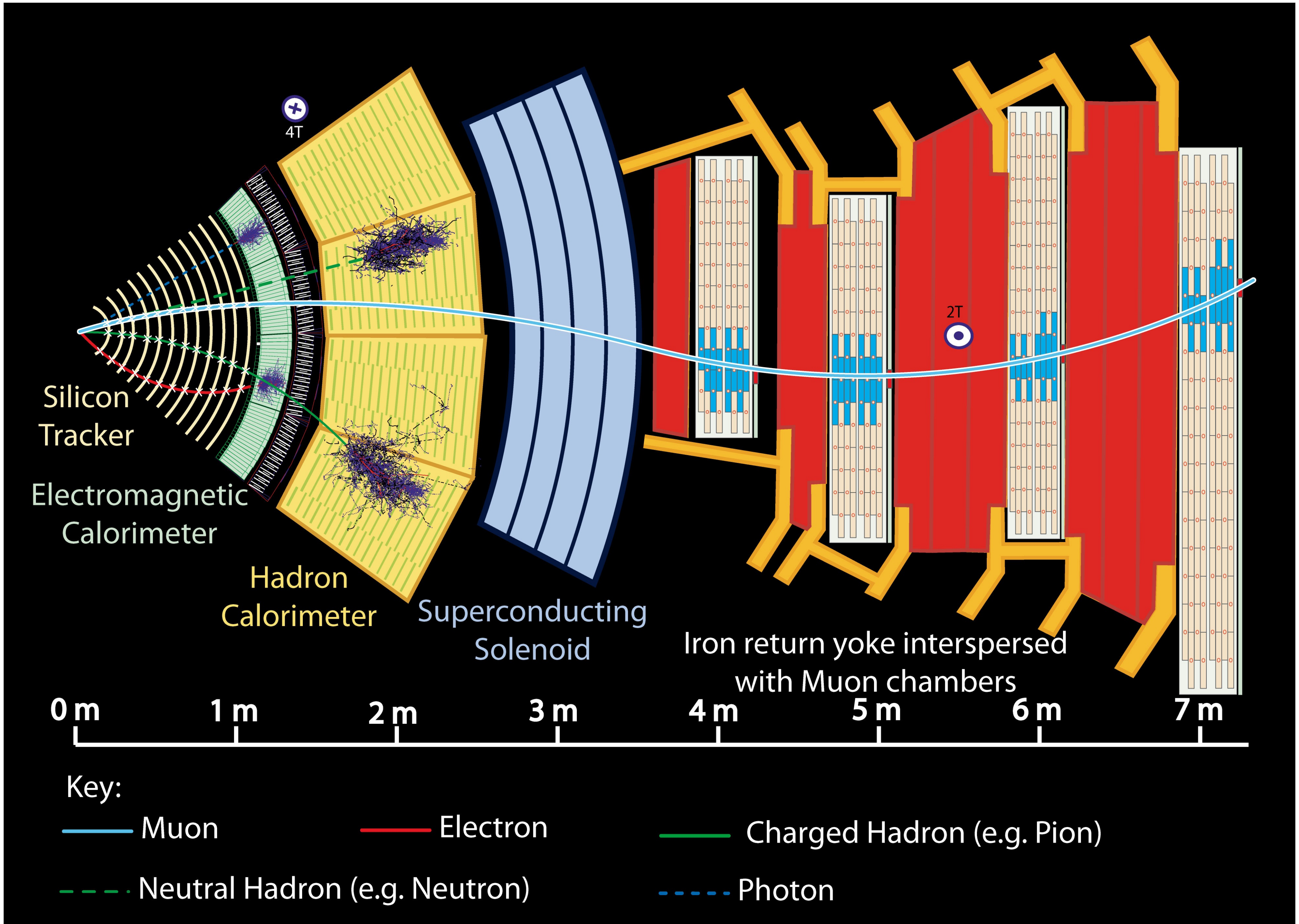

LOCNACELLE

Muons Reconstruction and Identification



Muons Reconstruction and Identification

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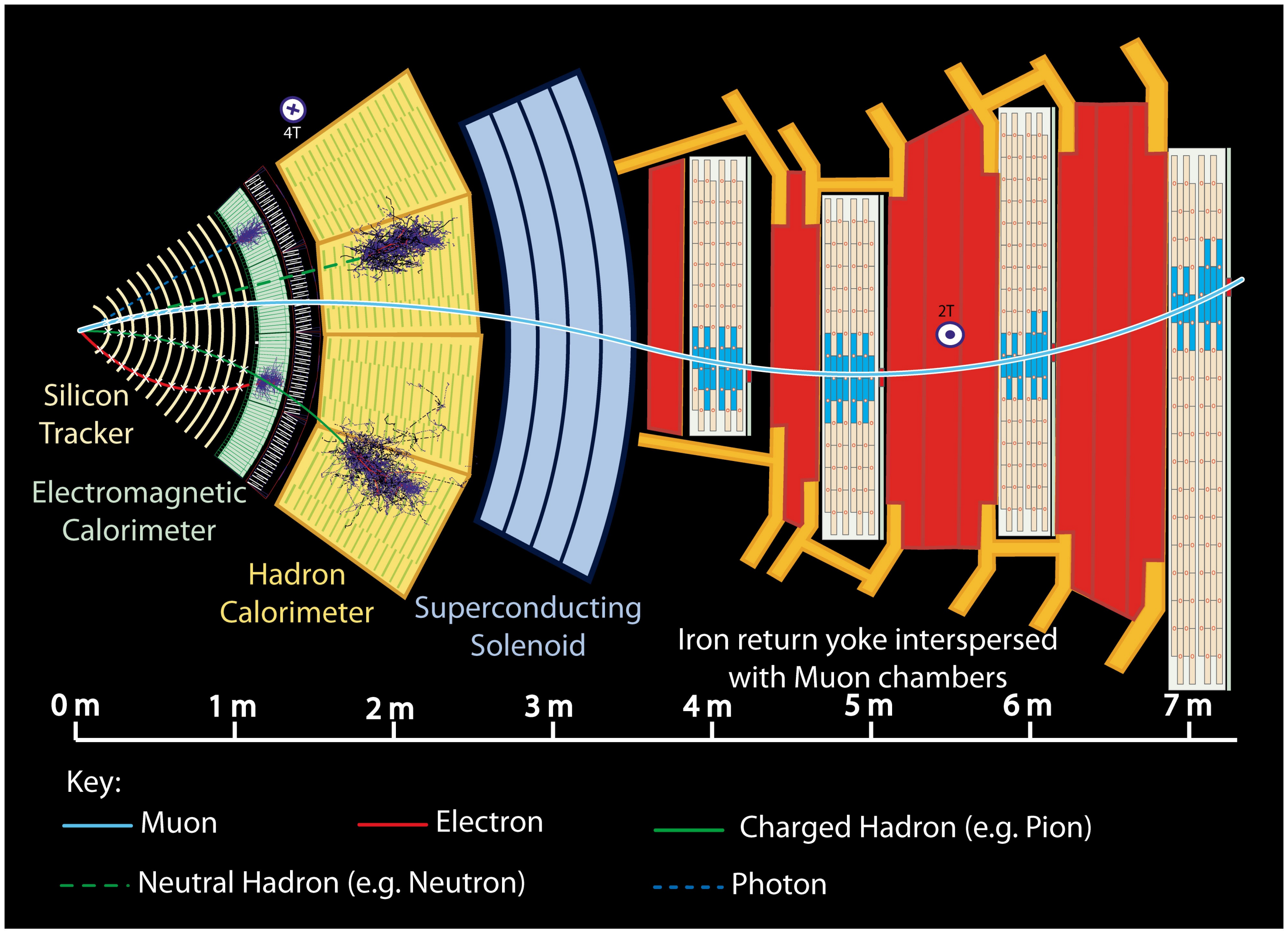

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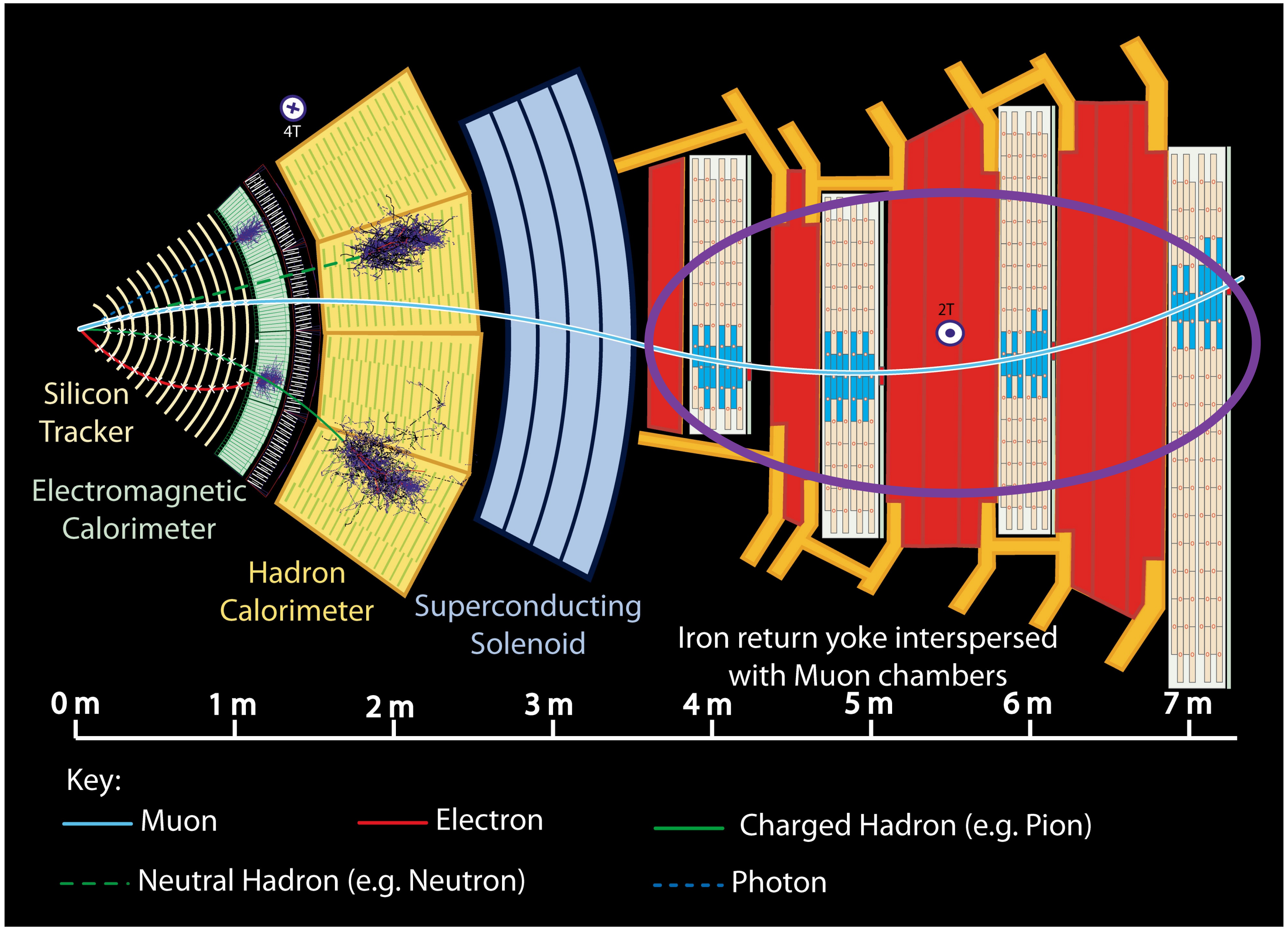
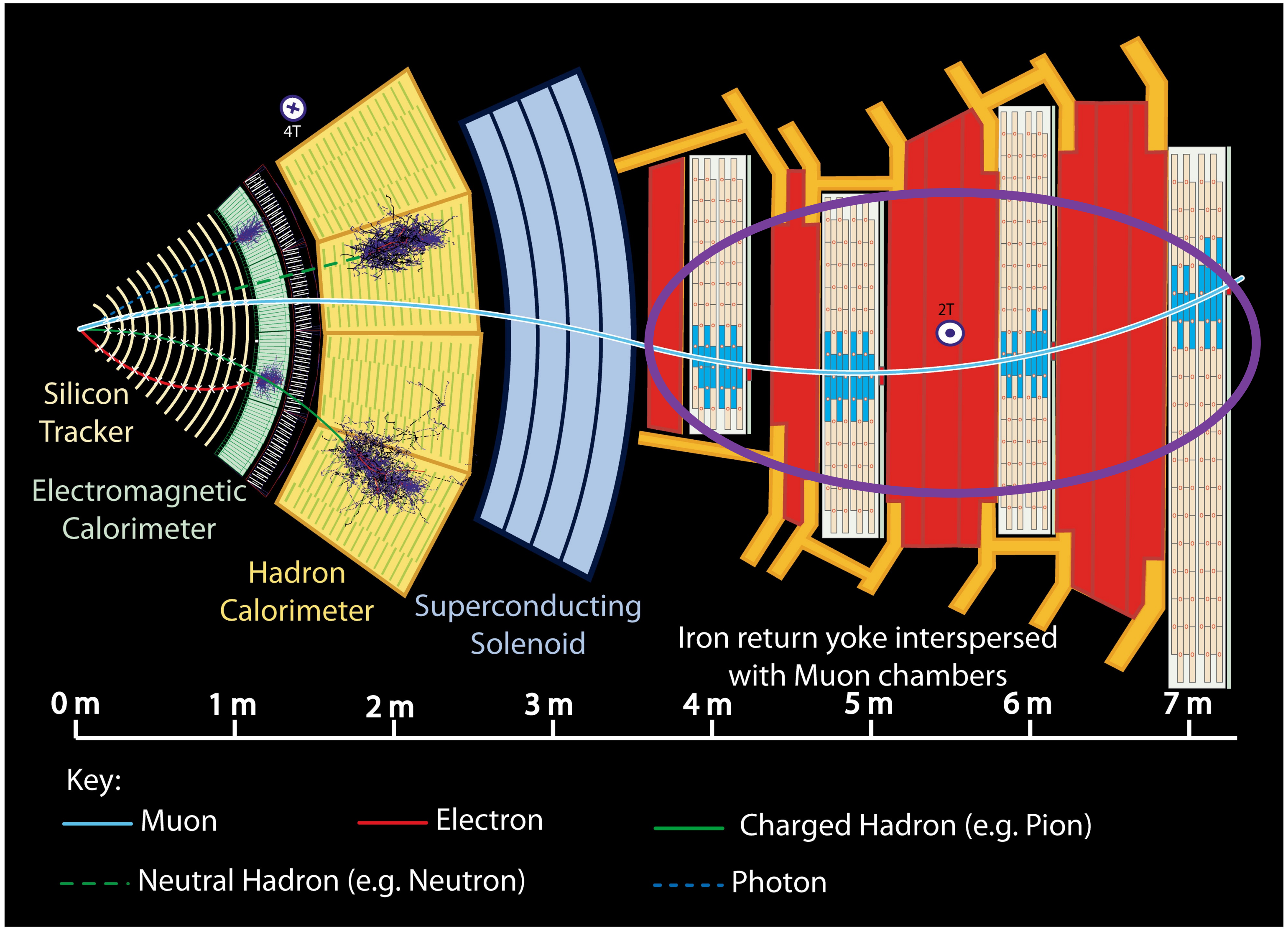


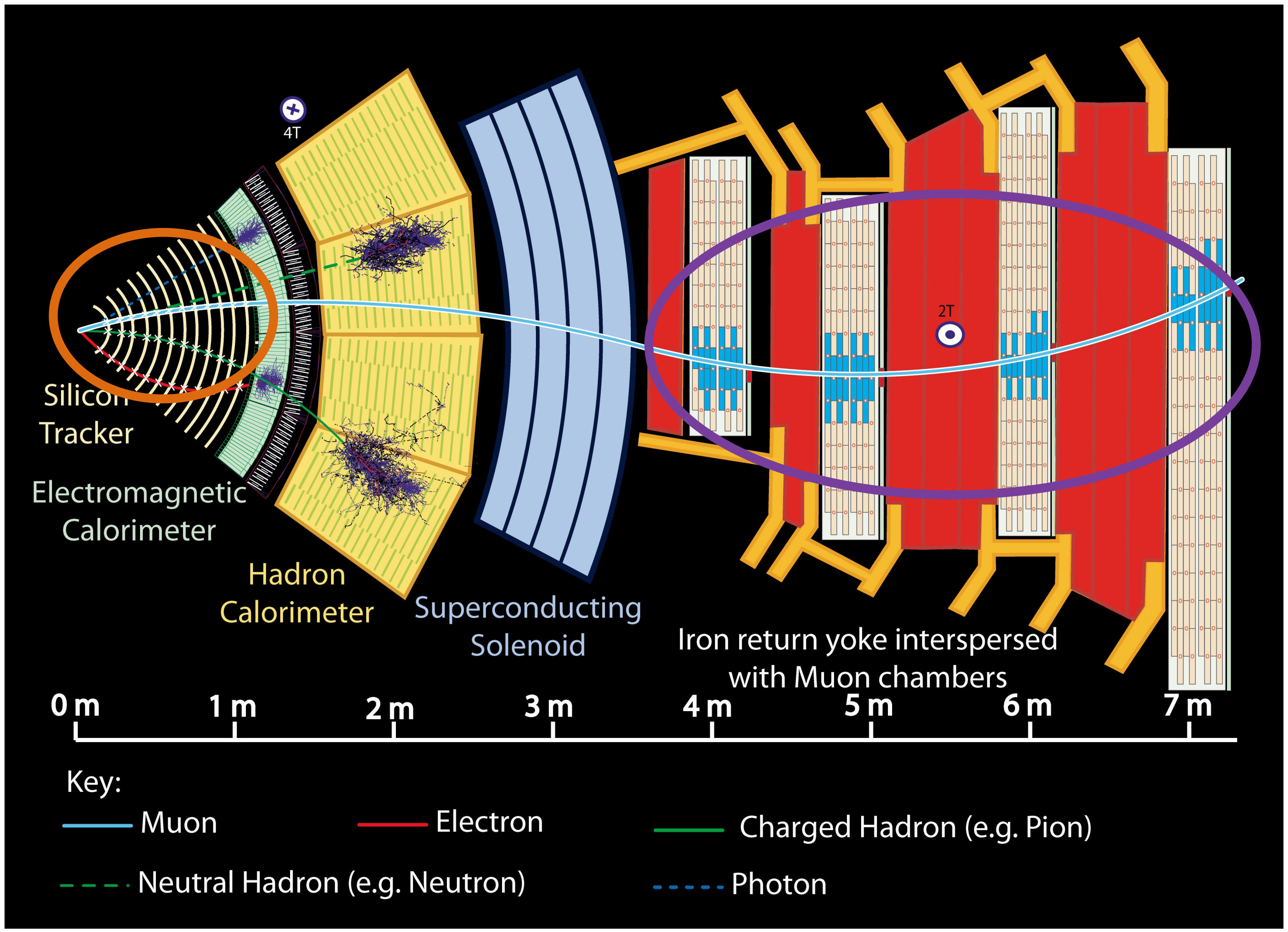
1. Local hit - segment reconstruction (RPC - DT/CSC)

Muons Reconstruction and Identification



1. Local hit - segment reconstruction (RPC - DT/CSC)
2. Reconstruction of muon spectrometer stand-alone track(s) (pT estimation)

Muons Reconstruction and Identification



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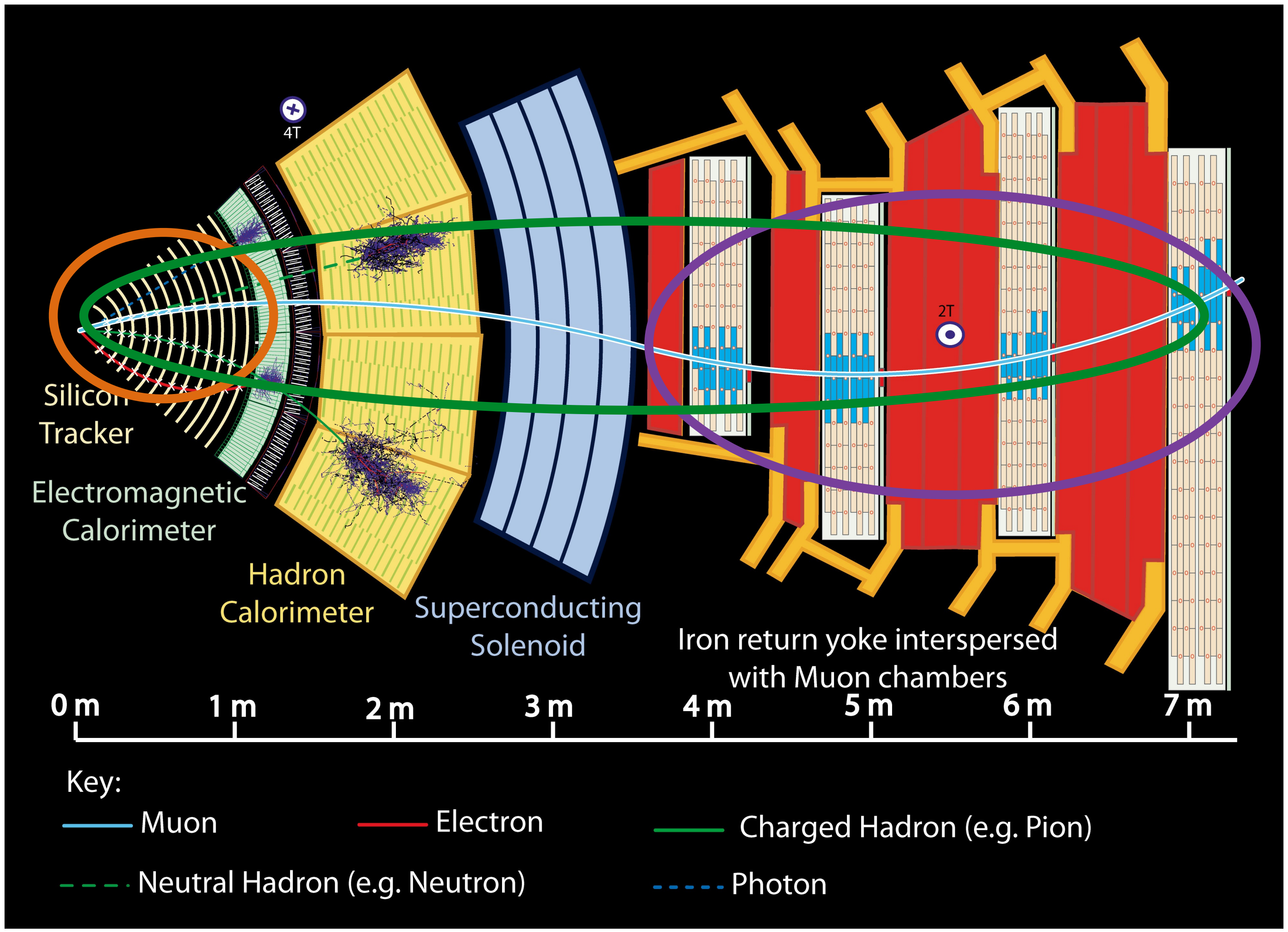

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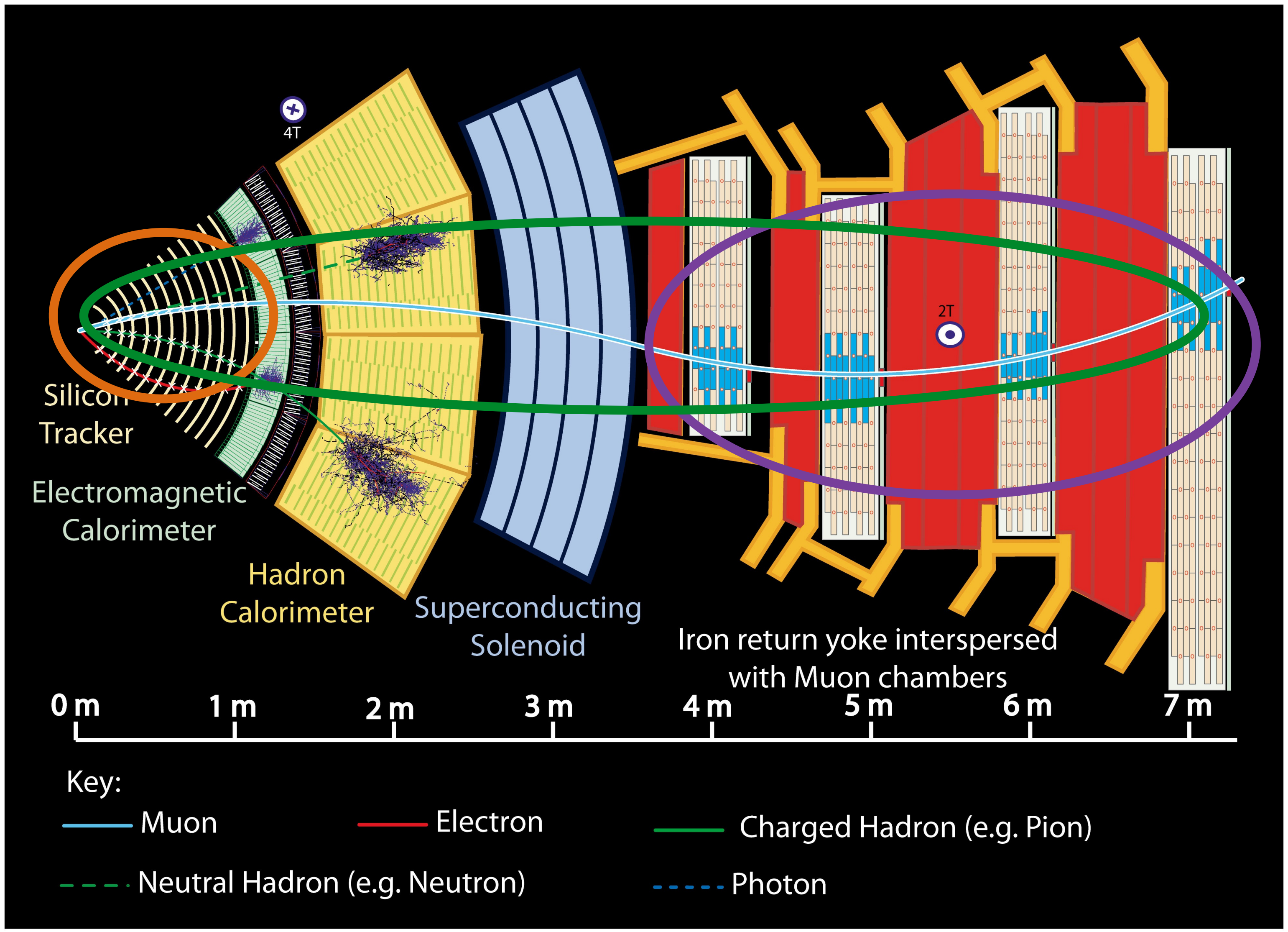
Muons Reconstruction and Identification



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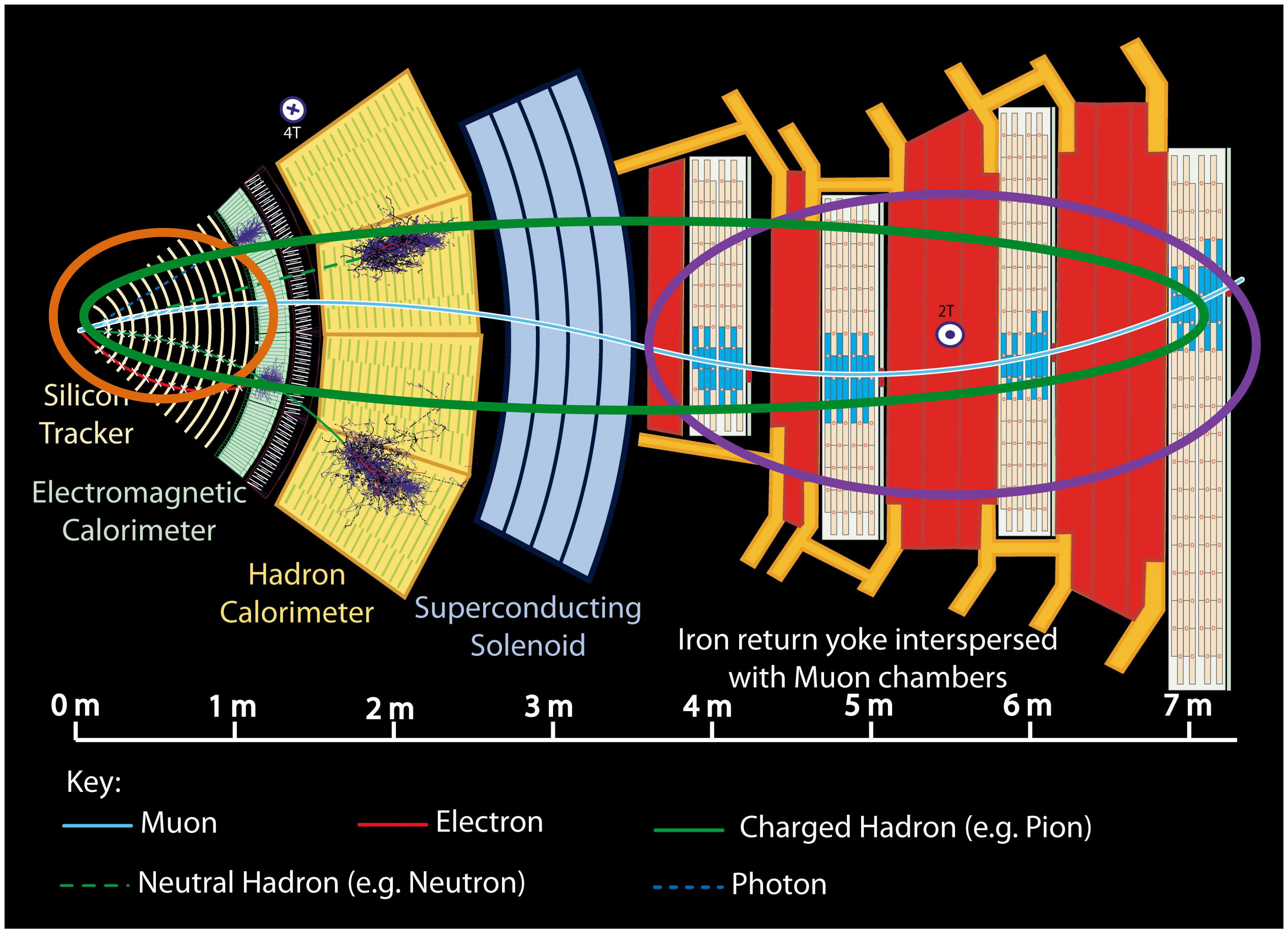
Muons Reconstruction and Identification



1. Local hit - segment reconstruction (RPC - DT/CSC)
2. Reconstruction of muon spectrometer stand-alone track(s) (pT estimation)
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4. Global Muon are defined from standalone + inner tracks (combined fit performed - pT re-evaluated: outside-in)
5. Inside-out identification of "tracker muons"(by matching inner tracks with CSC/ DT segments)
6. Plus more, e.g. :
   - "Ad hoc" high-pT refits
   - Computation of isolation quantities around muons (both based on detector quantities and "particle flow" ones)

Tag and Probe Overview

- Tag and probe is a data driven technique used to calculate efficiencies.
- In order to calculate the efficiency one needs a mass resonance (i.e. J/psi, upsilon or Z), or a well known PDF.
- The Tag is a muon or electron that has very tight selection criteria and a very low fake rate.
- The Probe has looser criteria.
- The Passing Probe has tighter criteria than the probe, but not tighter than the Tag (unless the Tag and Probe sets are mutually exclusive).

General Definition of Efficiency

Efficiency of the probe is the number of passing probes divided by the total number of probes.

$$E(Probe)=\frac{N_{passing\ probes}}{N_{all\ probes}}$$

Ideal

$$E(Probe)=\frac{2N_{TT}+N_{TP}}{2N_{TT}+N_{TP}+N_{TF}}$$

Tag and Probe

The probe efficiency calculated by tag and probe does depend depend on the definition of the tag.

Muons Identification (ID) definition

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Loose ID	**Prompt** muons + muons from **light and heavy** flavor decays
Medium ID	**Prompt** muons + muons from **heavy** flavor decays
Tight ID	**Prompt** muons + **suppress** decay-in-the-flight & hadronic punch-through
Soft ID	**Low-pT muons** for B-physics & quarkonia analysis requiring high purity on tracker-track
High-pT ID	Optimised for **high-pT muons** (pT > 200 GeV) No requirement on global fit $\chi 2$ & requirement on error(pT)/pT < 30%

Muons Identification (ID) definition

Standard ID

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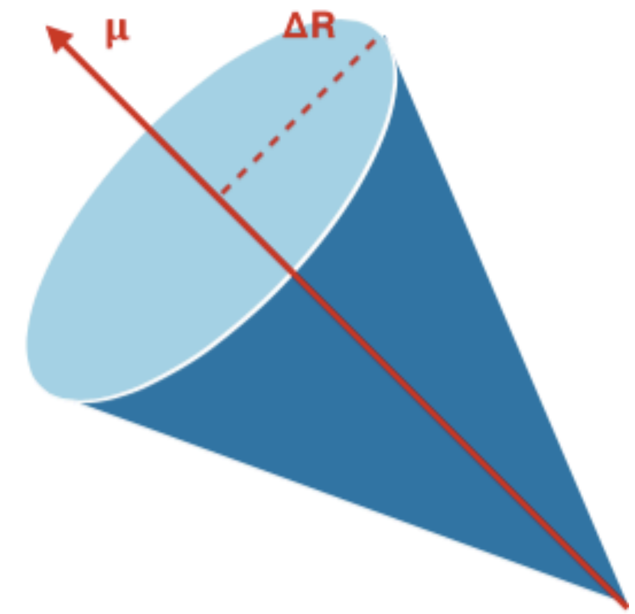
Muon Isolation definition

Powerful variable to **distinguish prompt muons from muons from jets**

Track-based isolation

- Use the sum of **reconstructed tracks** in a cone of ΔR
- **High efficiency & small dependence on pileup**



Muon Isolation definition

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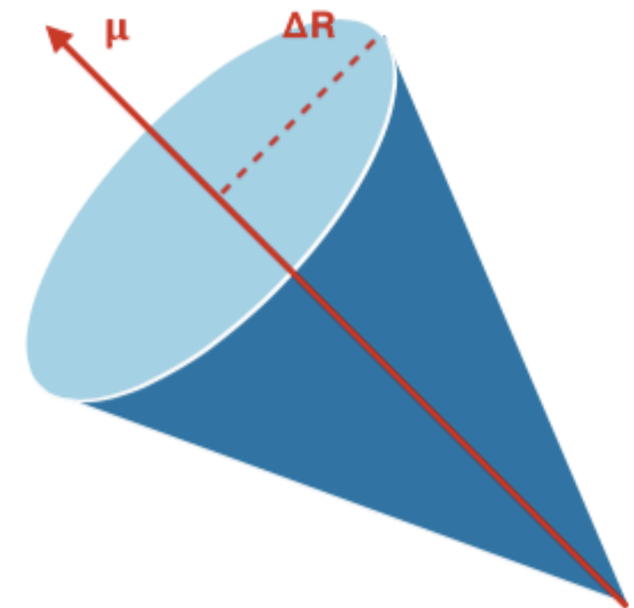
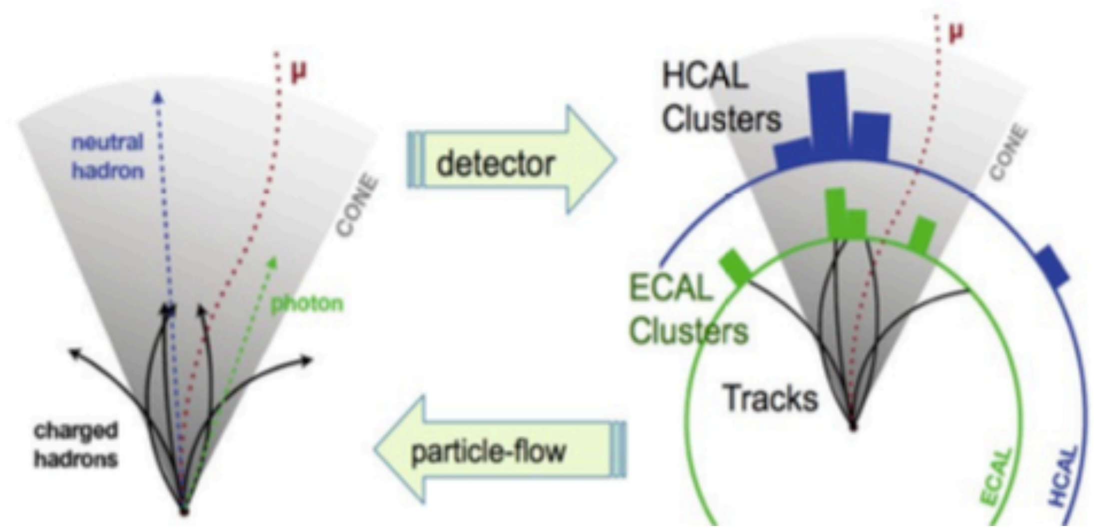


Track-based isolation

- Use the sum of **reconstructed tracks** in a cone of ΔR
- **High efficiency & small dependence on pileup**

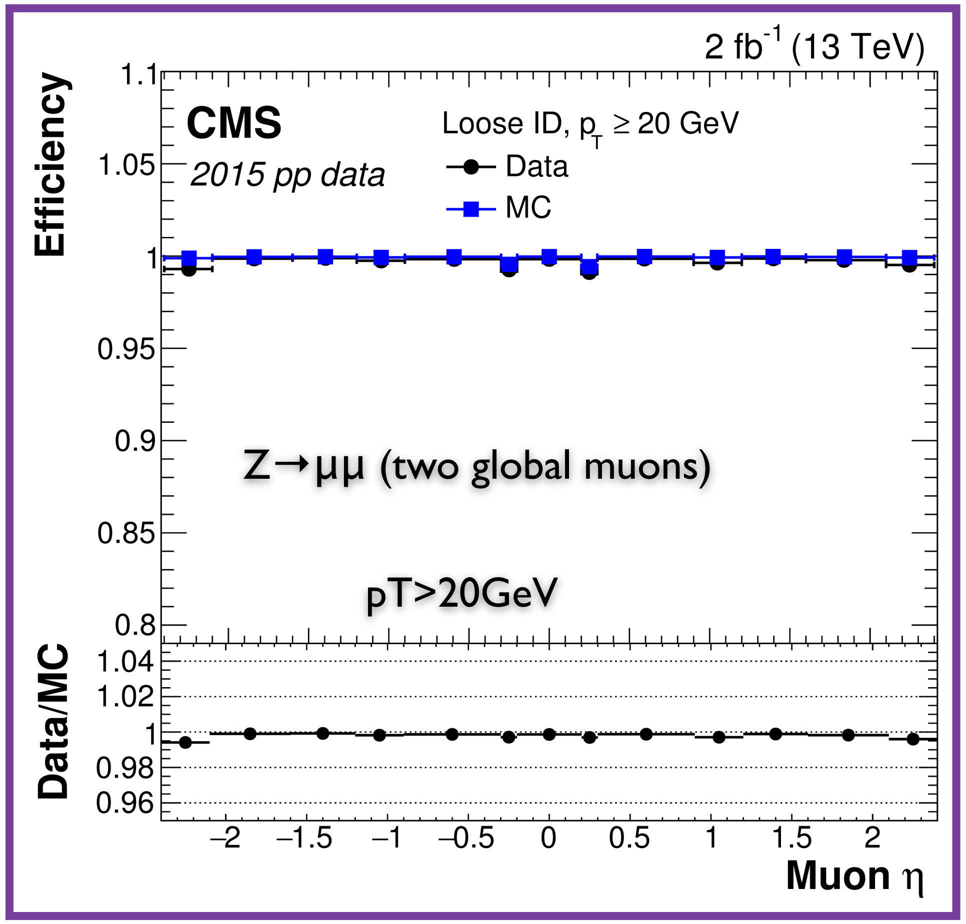
Particle-flow based isolation

- Use the sum of charged & neutral particles from **particle-flow (PF) algorithm**
- **Better suppression of muons from jets**

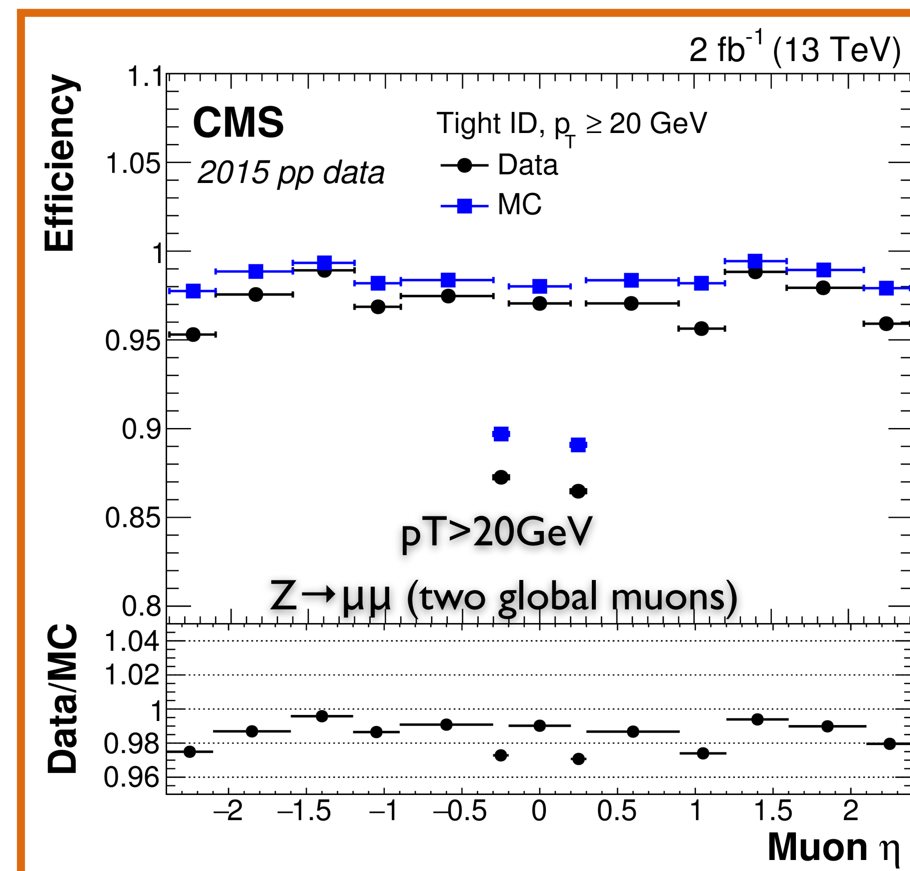


Reference: CMS-MUO-16-001 - Published - 19 June 2018 in J. Instrum.

Muons: Identification Efficiencies



The loose ID efficiency exceeds 99% over the entire range, and the agreement between data and simulation is better than 1%.

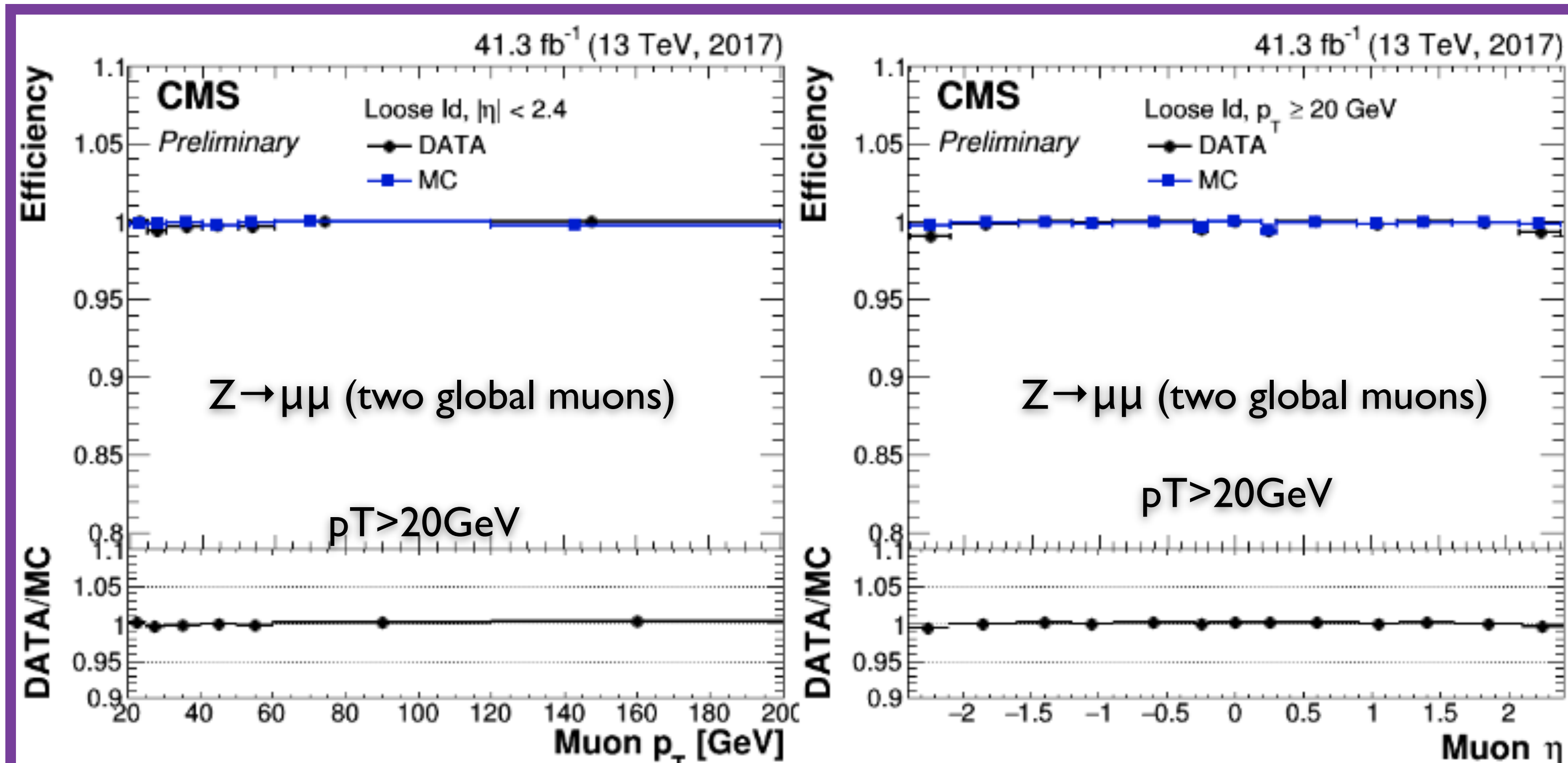


The tight ID efficiency varies between 95% and 99% and the agreement with simulation ranges from 1% to 3%.
The dips in efficiency close to |eta| = 0.3 are due to the cracks between the central muon wheel and the two neighboring wheels

"2015 data" = about 2/fb of p+p collisions collected in 2015

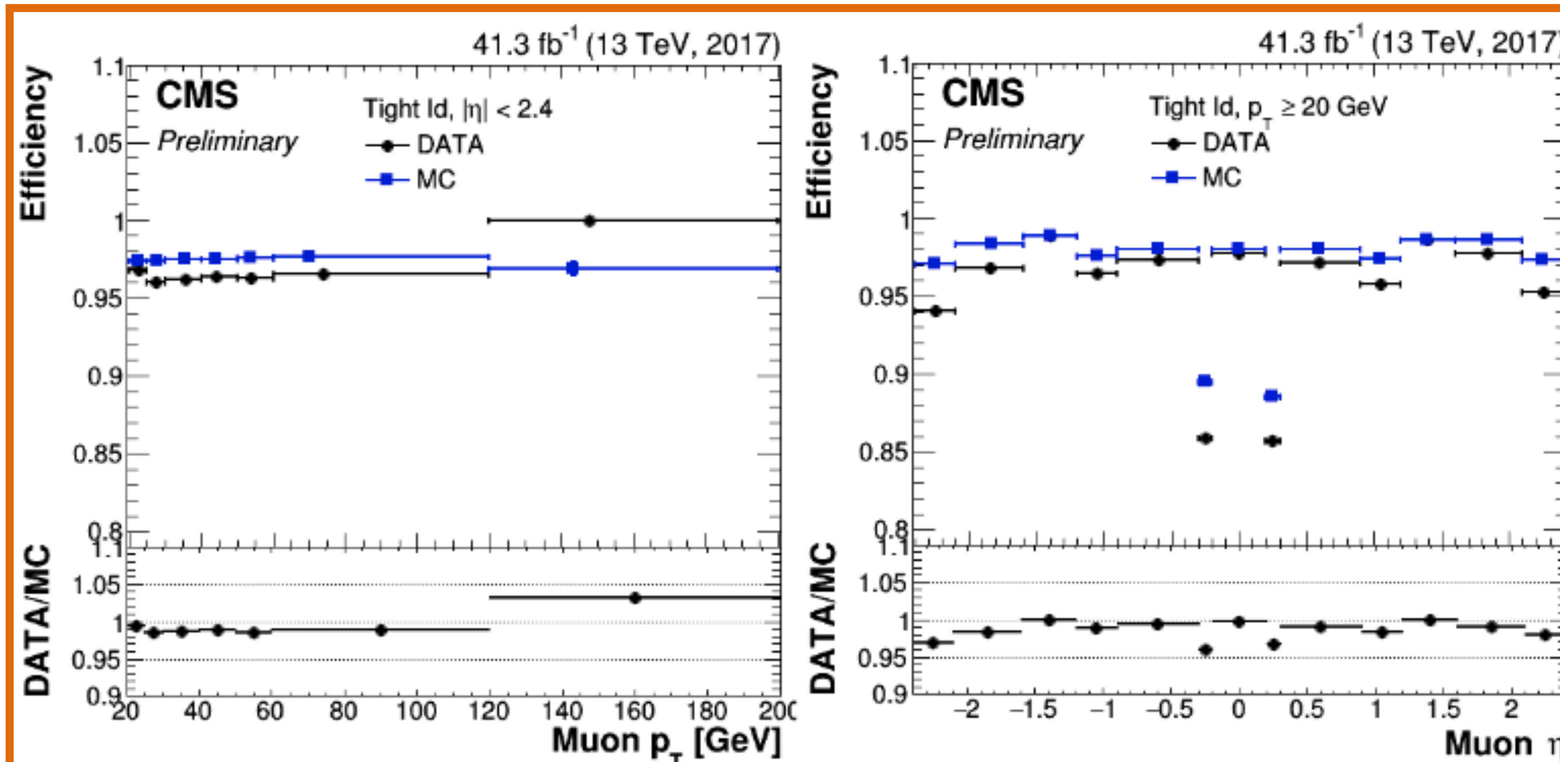
CMS DP 2018 042 was presented in ICHEP 2018

Muons: Identification Efficiencies



Loose muon Id efficiency as a function of p_T and η for 2017 data and MC. The denominator is all tracker tracks with $p_T > 20$ GeV. There is no dependency with the number of primary vertex.

Scale factor is ~99.8%. Systematic uncertainties < 0.2%.

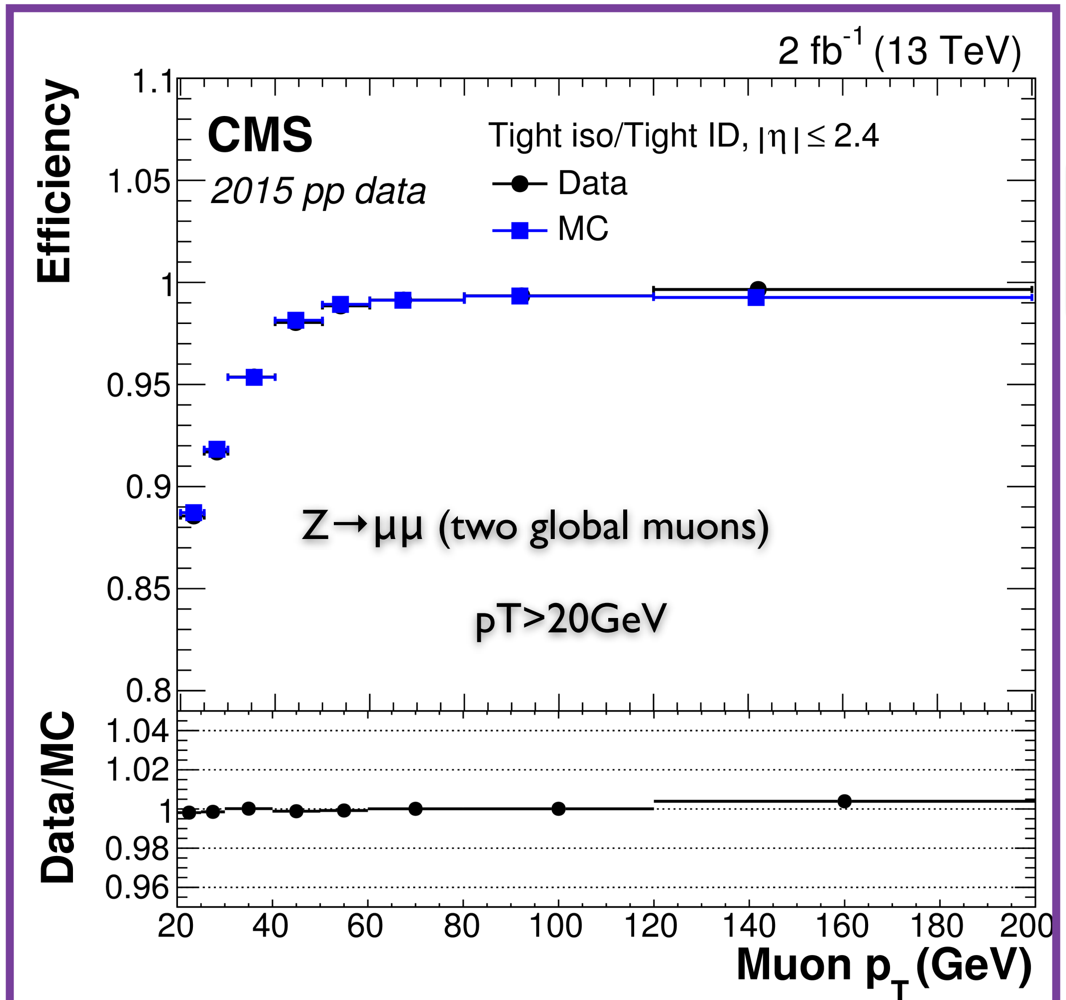


* Error bars in the plot include only statistical uncertainty

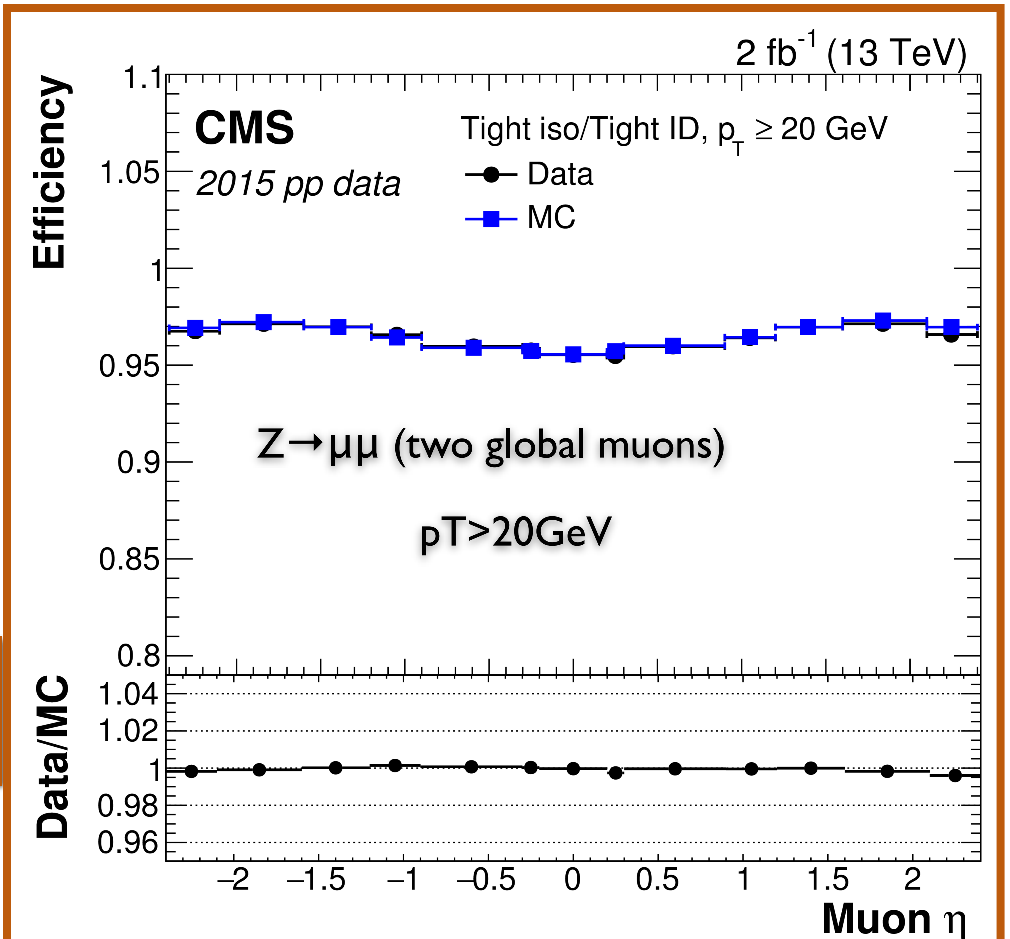
Efficiency of **2017** data (41.3 fb^{-1}) compared to Monte-Carlo (MC) simulation using LooseID and TightID.

Reference:CMS-MUO-16-001- Published - 19 June 2018 in J. Instrum.

Muons: Isolation Studies



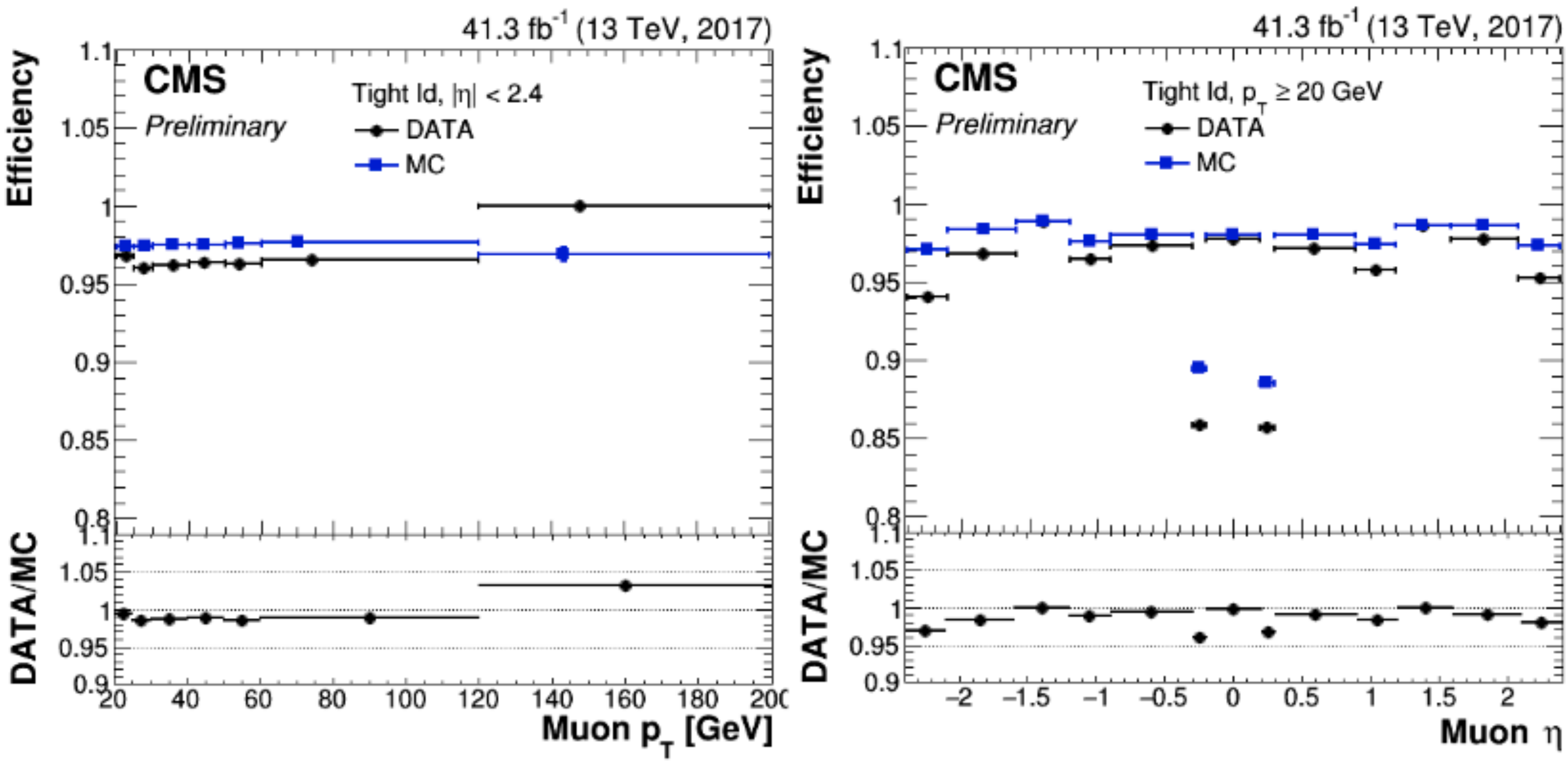
Good agreement between data and MC simulation is always ~0.5 %



The Tight Muon to also satisfy tight isolation requirements is about 5% in the barrel and goes up to about 15% in endcap

"2015 data" = about 2/fb of p+p collisions collected in 2015

Muons: Isolation Studies

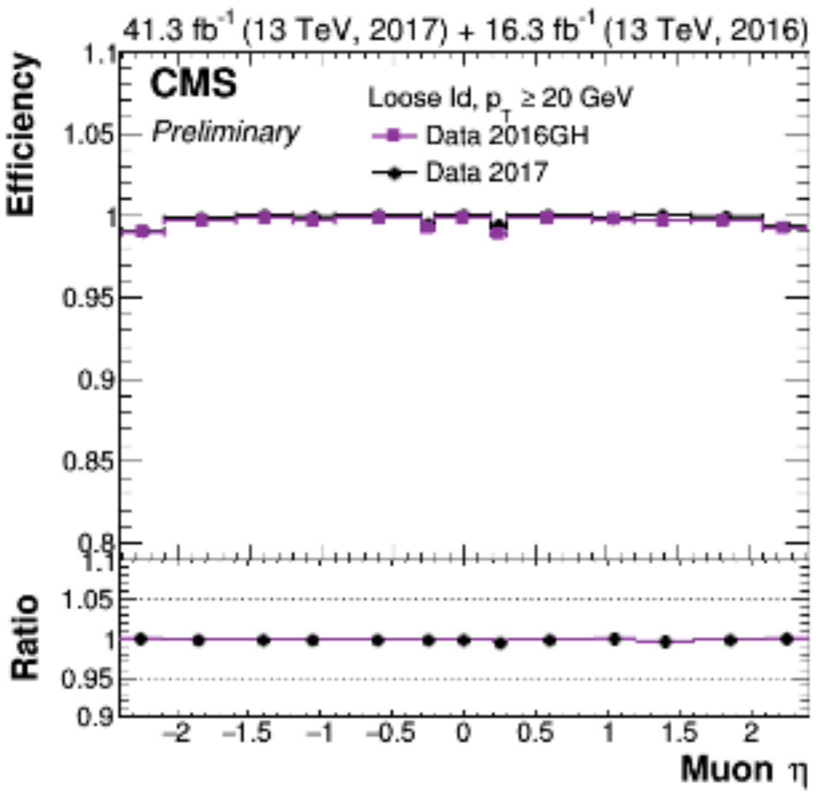


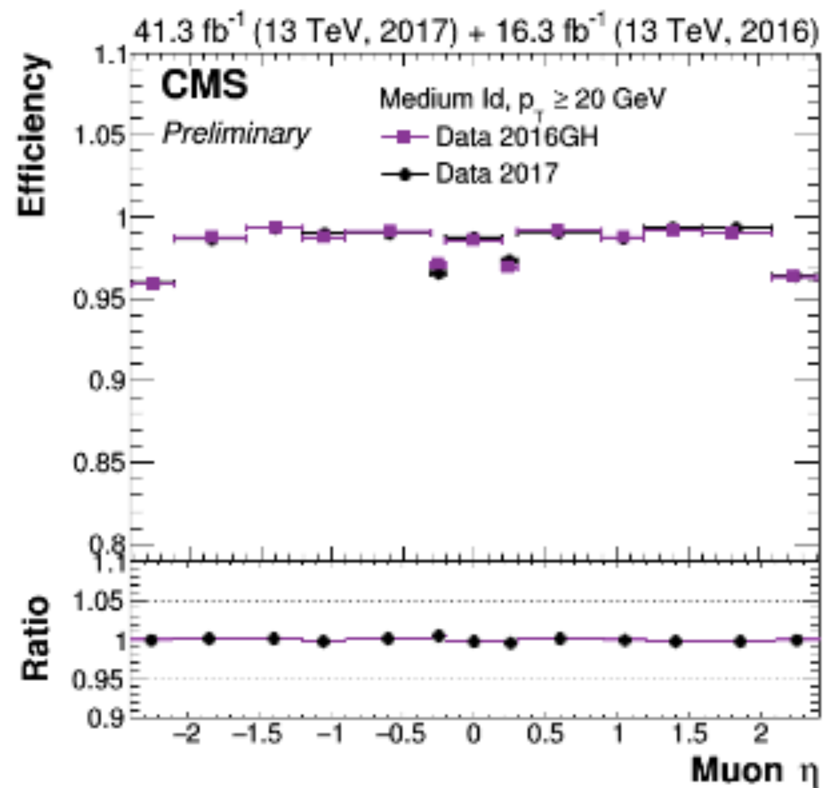
- Efficiency of **2017** data (41.3 fb^{-1}) compared to Monte-Carlo (MC) simulation using TightID.
- Overall **~96%**
- Data and MC agree within 0.5%

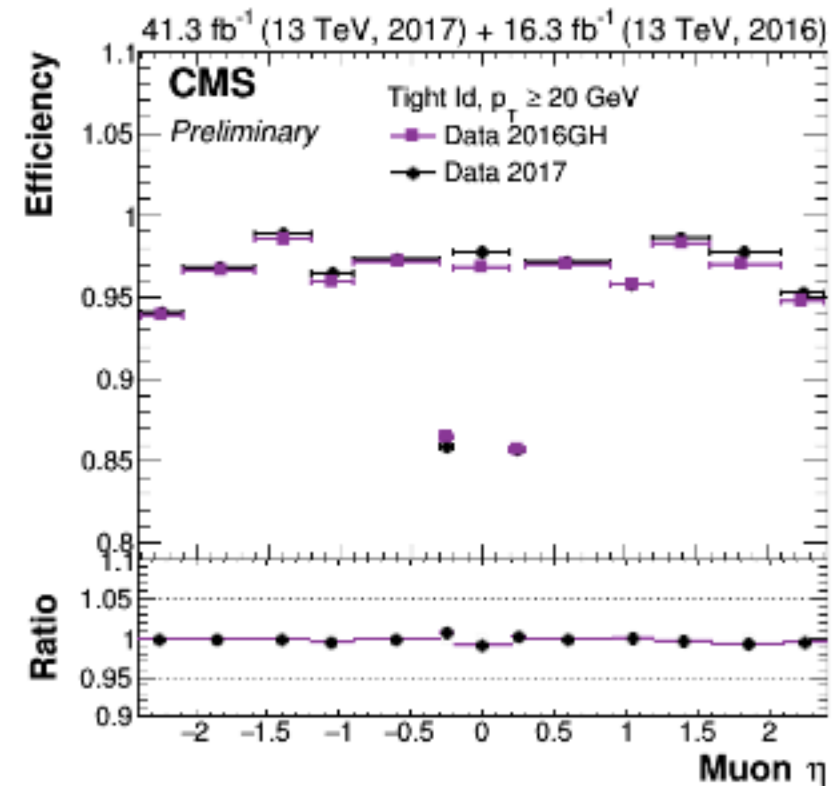
* Error bars in the plot include only statistical uncertainty

CMS DP 2018 042 was presented in ICHEP 2018

Muons: Comparison with 2016 Performance





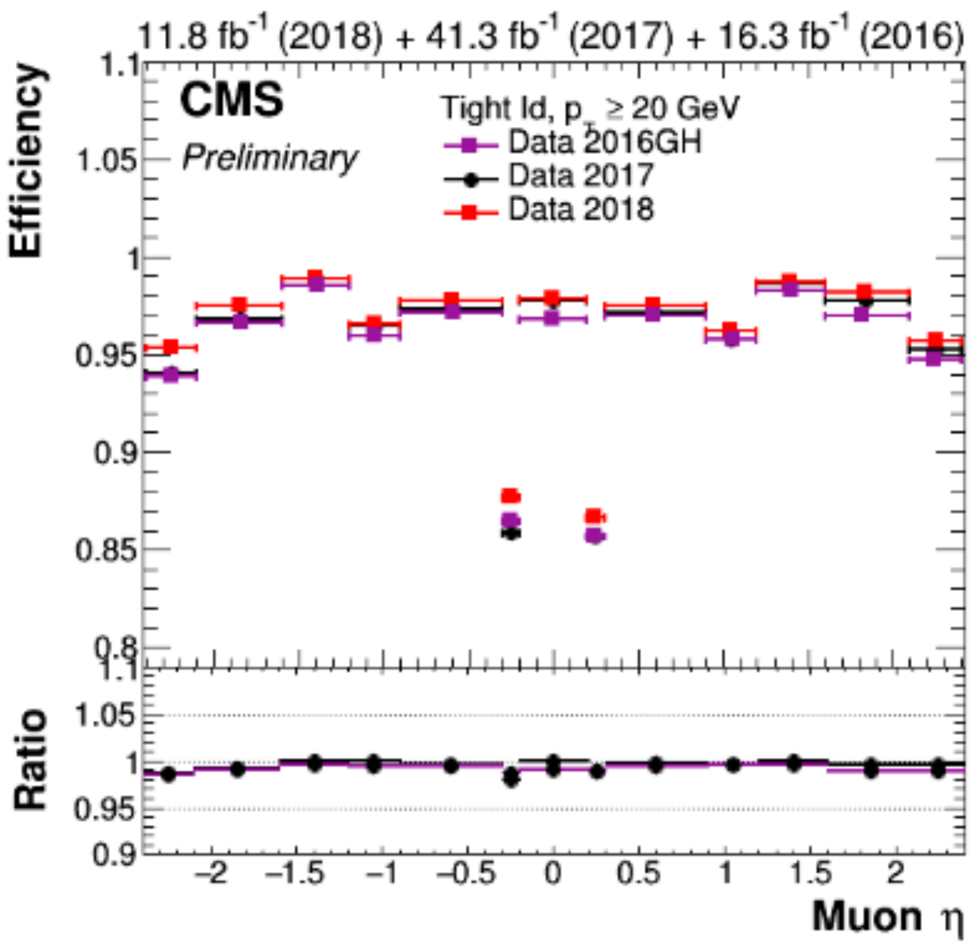


- Comparison of the efficiency of the 2016 (16.3 fb^{-1}) and 2017 data (41.3 fb^{-1}) using several Muon IDs.
- In 2017 pixel upgrade suffered upgrade with one additional layer was installed.
- We can see that there is a slight improvement for the TightIDs.

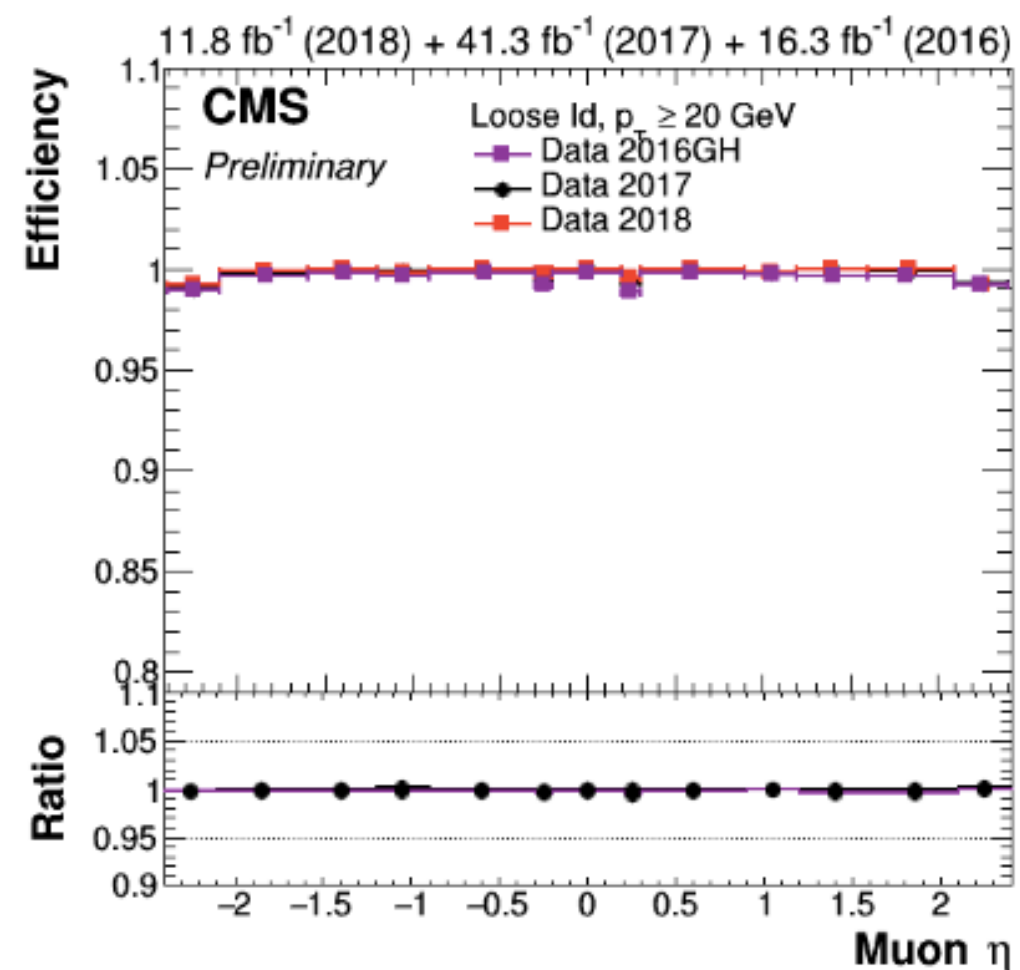
* Error bars in the plot include only statistical uncertainty

CMS DP 2018 042 was presented in ICHEP 2018

Muon Performance 2016 vs 2017 vs 2018



- Efficiency of 2016, **2017, 2018** data using TightID.
- In 2017 pixel upgrade suffered upgrade with one additional layer was installed.
- The performance of 2018 data is slightly better than 2017
-



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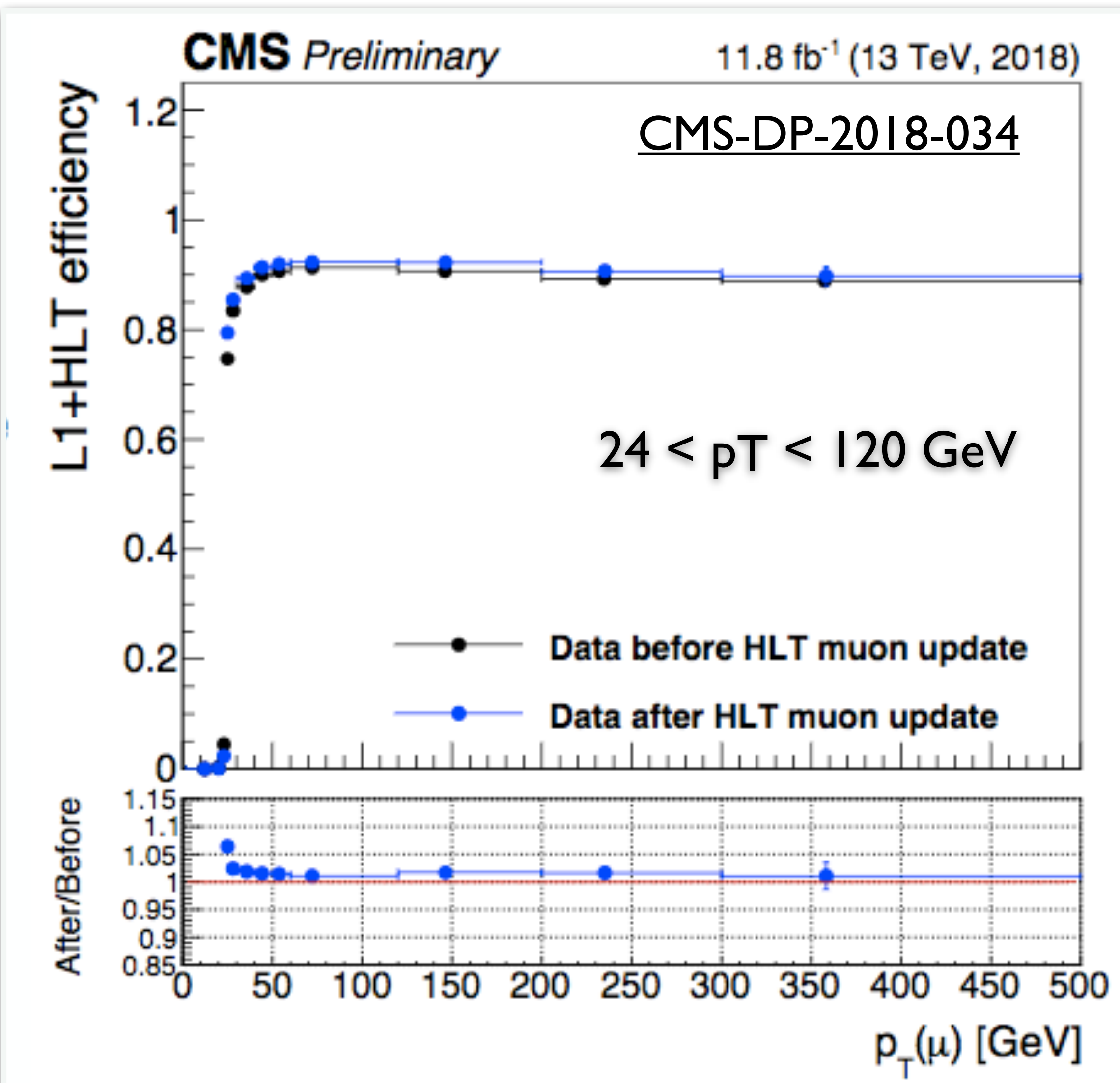
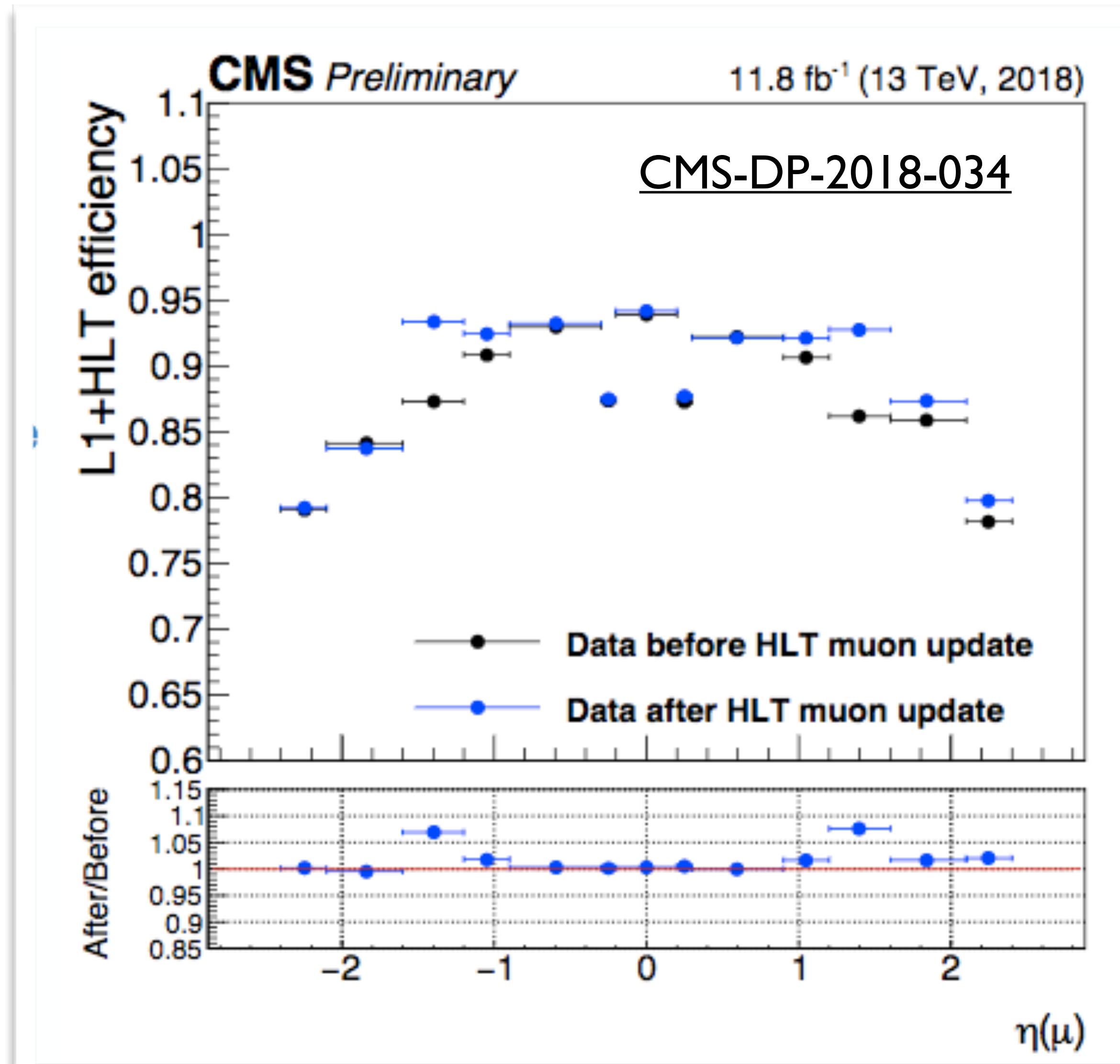
Trigger Efficiencies: Isolated Muon

The efficiency of combined L1 and high-level trigger requiring **isolated single muon** with pT > 24 GeV between after and before L3 muon update.



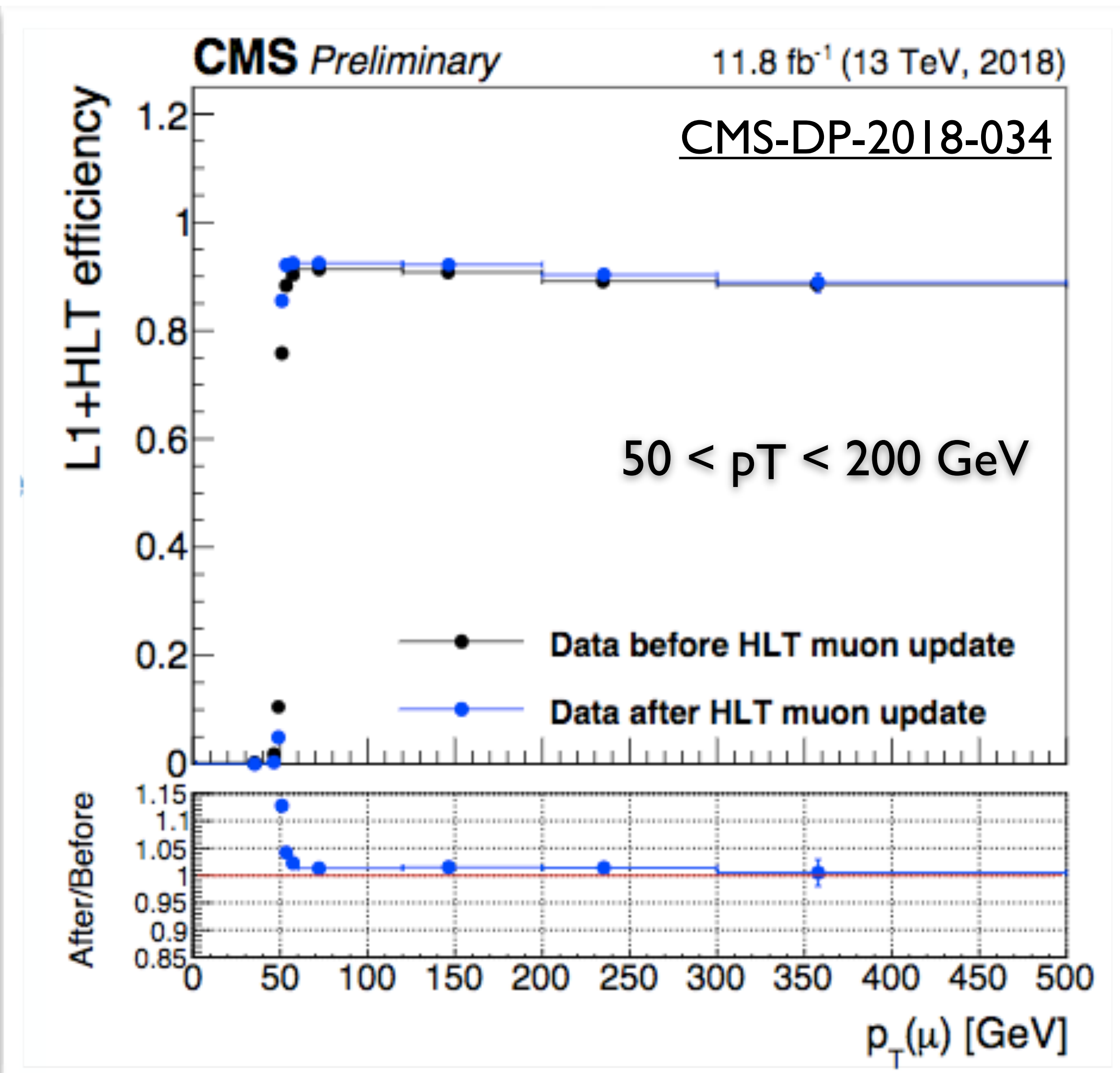


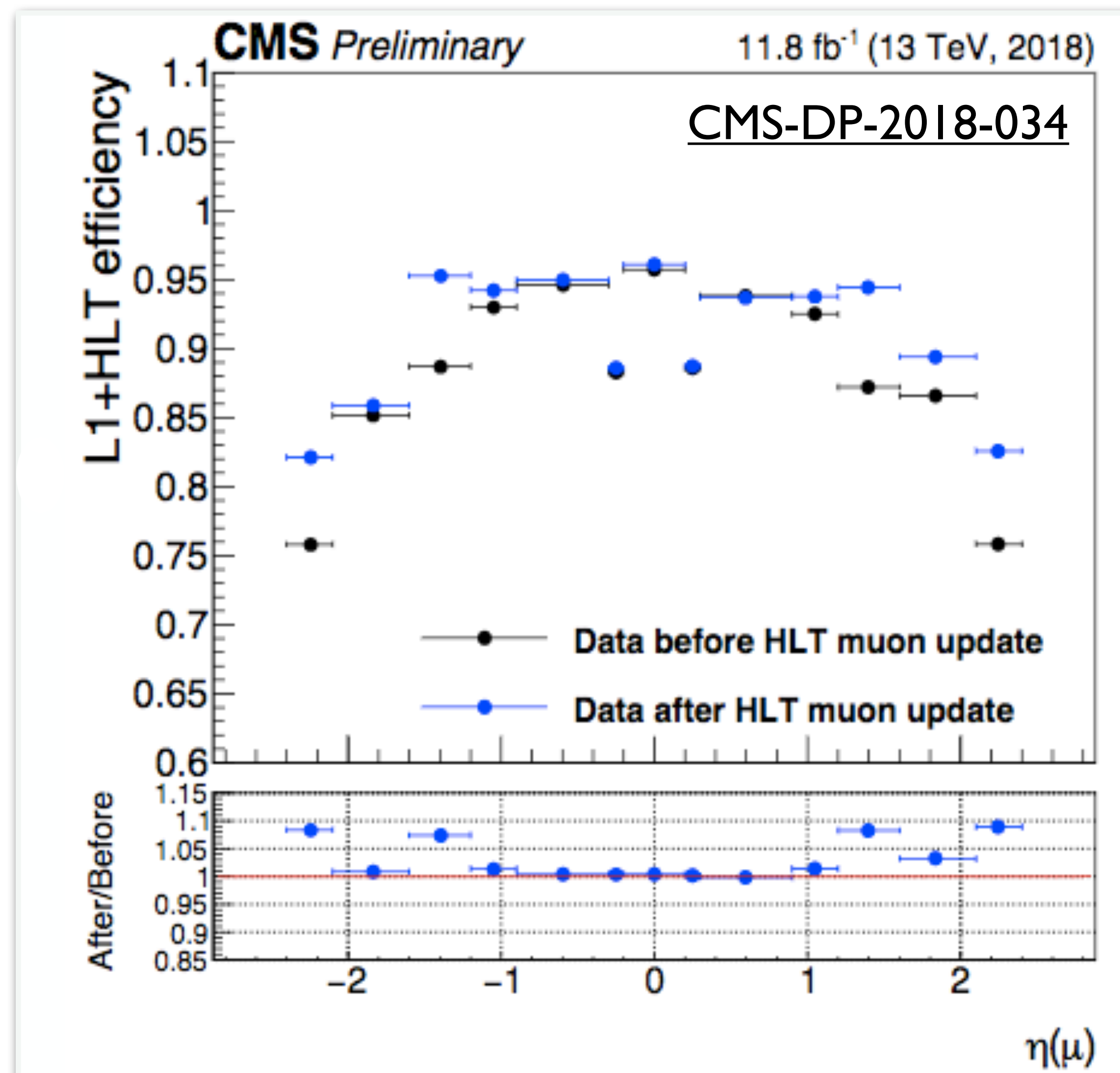
- Large improvement in 1.2 < |η| < 1.6
- Overall efficiency: 89-90 %

The errors are statistical only

Trigger Efficiencies: Non Isolated Muon

The efficiency of combined L1 and high-level trigger requiring **non isolated single muon** with pT > 24 GeV between after and before L3 muon update.





- Large improvement in $1.2 < |\eta| < 1.6$
- Overall efficiency: 89-90 %

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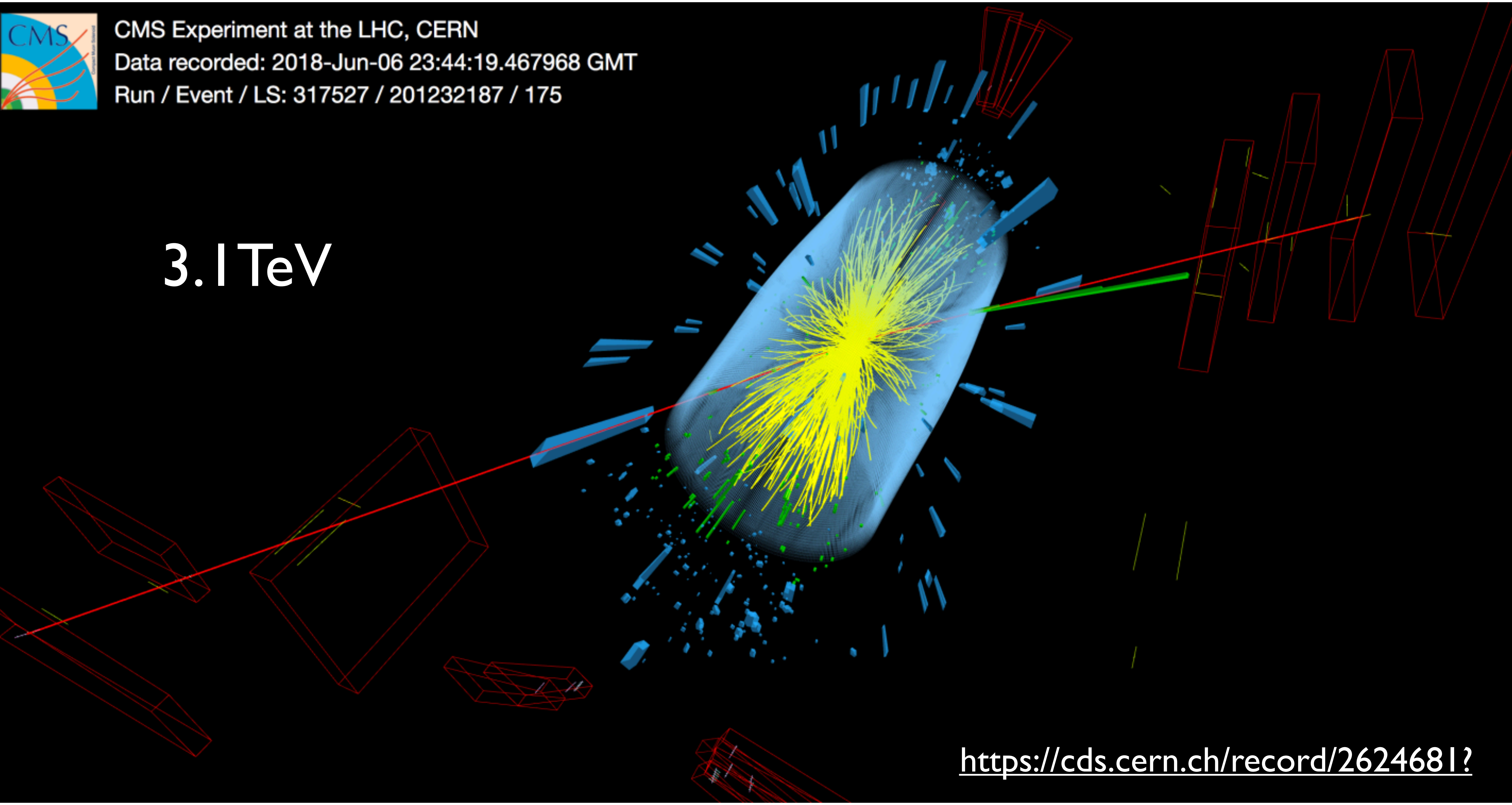
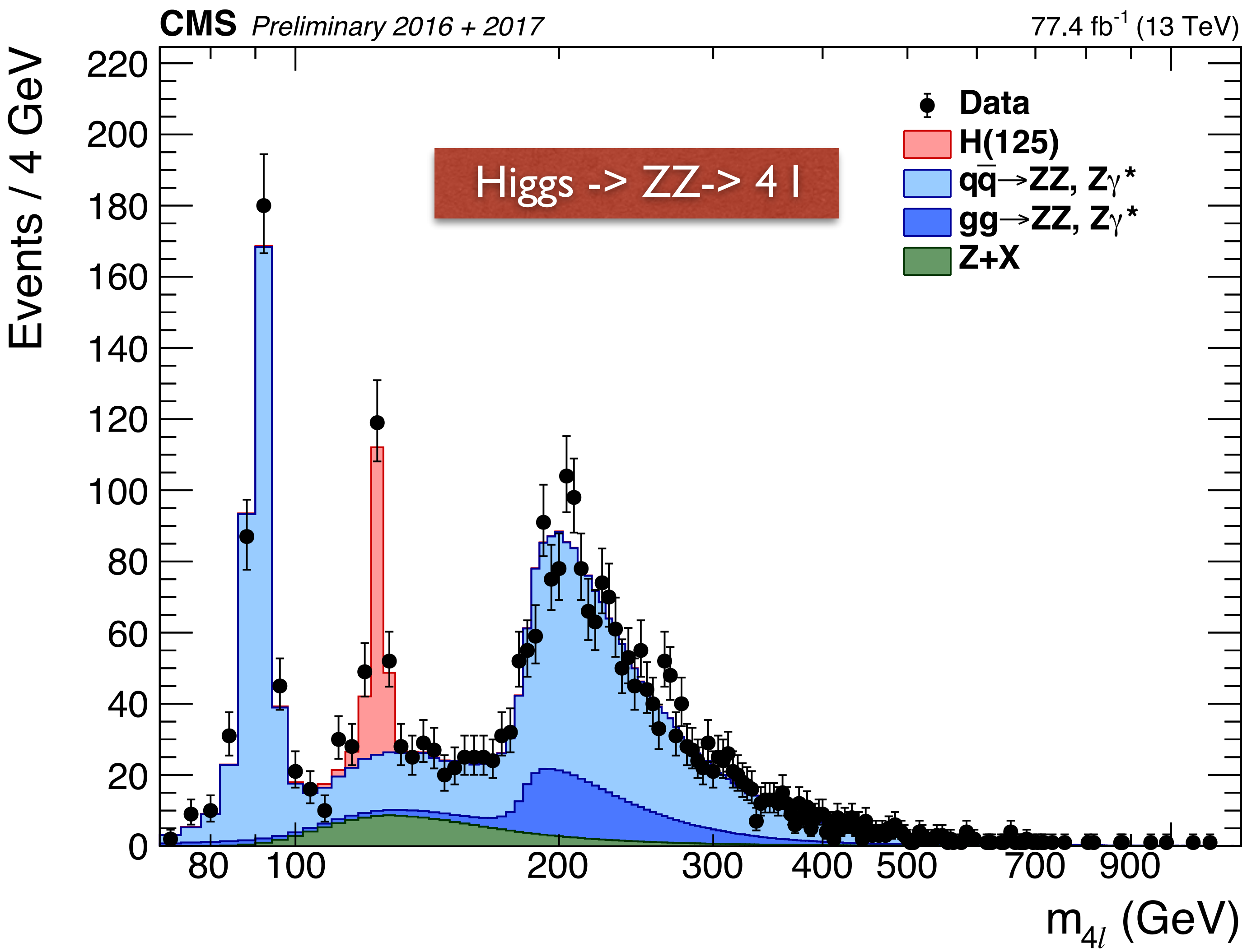
Heaviest Dimuon Mass from 2018 Data



Higgs boson results@ 13 TeV



- ✓ CMS-PAS-HIG-18-001
- ✓ 2016 + 2017 dataset
- ✓ Single/double/triple muon triggers + cross trigger with electrons
- ✓ Loose ID & customized High-PT ID + PF-based isolation
- ✓ Good agreement between data and prediction

Summary

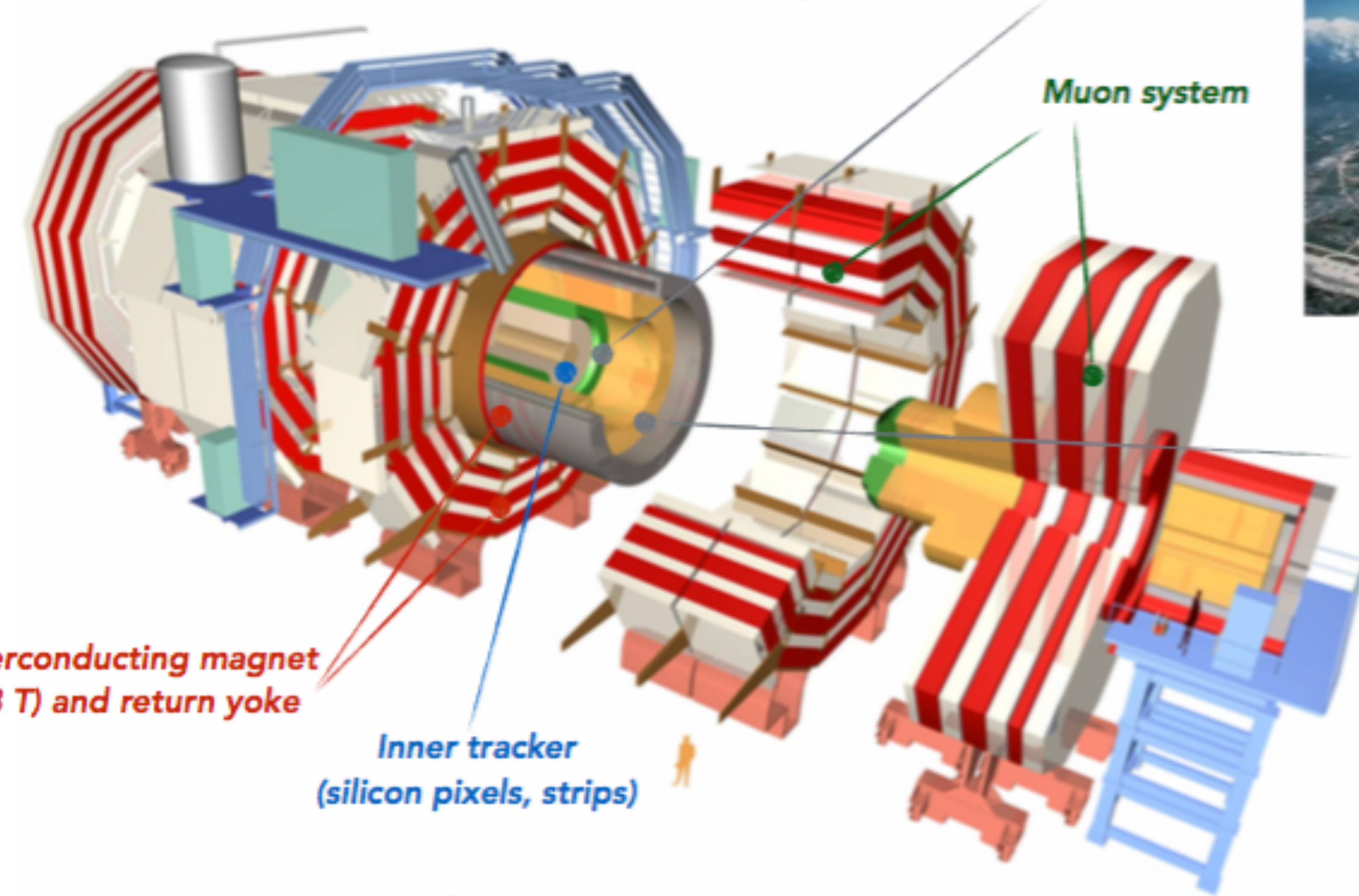
- We can observe nice reconstruction performance measurements using muon objects in CMS experiments during Run-II data taken, even with the increase of instantaneous luminosity and Pile-up events

- Therefore, this enables to explore all physics program proposed for CMS experiments for Run-II and beyond.

Thank you for your attention

Backup slides

The CMS detector



LHC collider at CERN

Size and weight:

length : 21.6 m
diameter : 14.6 m
weight : ~12500 t

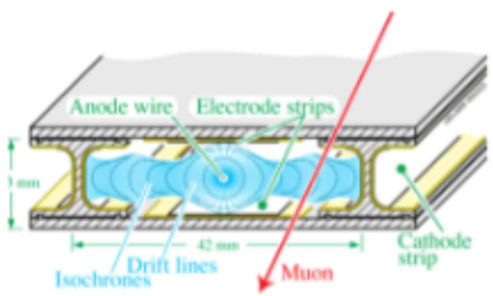
CMS muon system main goals:

1. efficient μ identification
2. improve μ momentum resolution at high p_T (above ~ 200 GeV)
3. "robust" stand-alone μ trigger (capable of bunch-crossing assignment)

CMS trigger:

1. Design machine bunch-crossing (BX) rate 40 MHz
2. Reduce collected data rate (down to $O(10^{2\text{-}3})$ Hz)
   a. Level-1 (L1) trigger: HW system (~40 MHz → <100 kHz)
   b. High Level Trigger (HLT): CPU farm (~100 kHz → $O(10^{2\text{-}3})$ Hz)

Muon system overview (DTs)



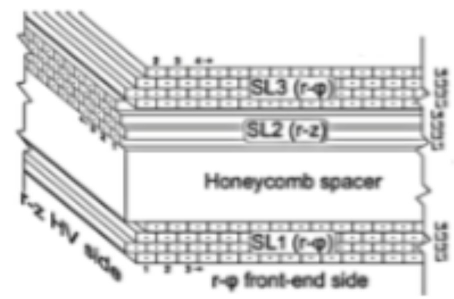
Coverage |η| < 1.2

DT chamber:

- *4 + 4 detection layers in r-φ*
- *4 detection layers in r-z (for 3 innermost stations)*
- *segment resolution: ~**100** μm in r-φ (~**2** ns time resol.)*
- ***provides segments to L1 trigger (incl. BX Id)***

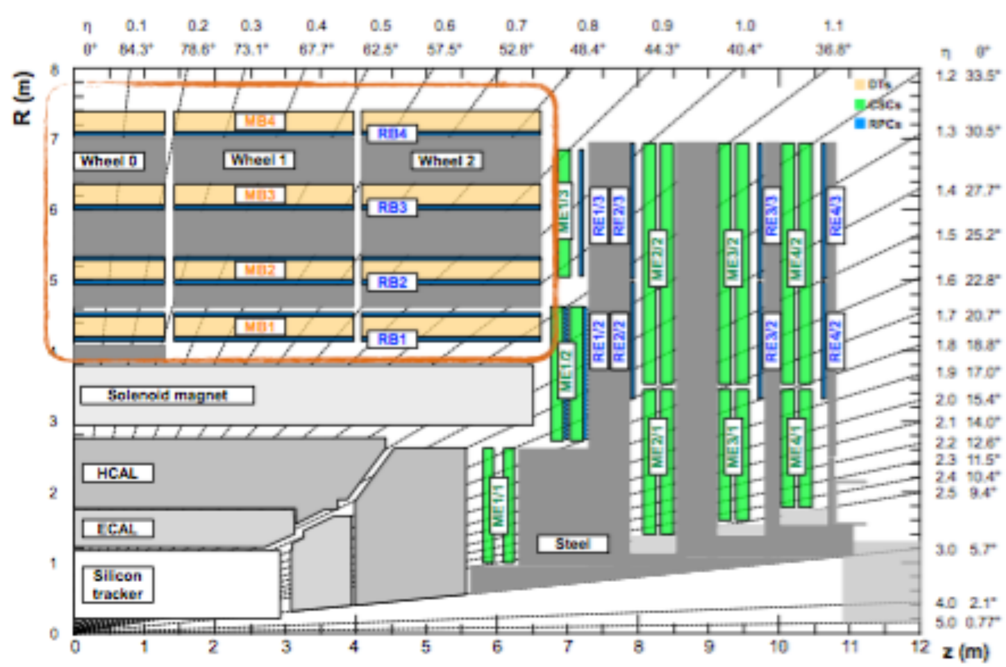
Drift cell design:

- *size: 4.2 x 1.3 mm*
- *gas mixture: 85% Ar - 15% CO_2*
- *~ const drift velocity: ~54 μm/ns (t_{MAX} ~ 400 ns)*
- *hit resolution: ~**250 μm***



Geometry (250 chambers in total) :

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



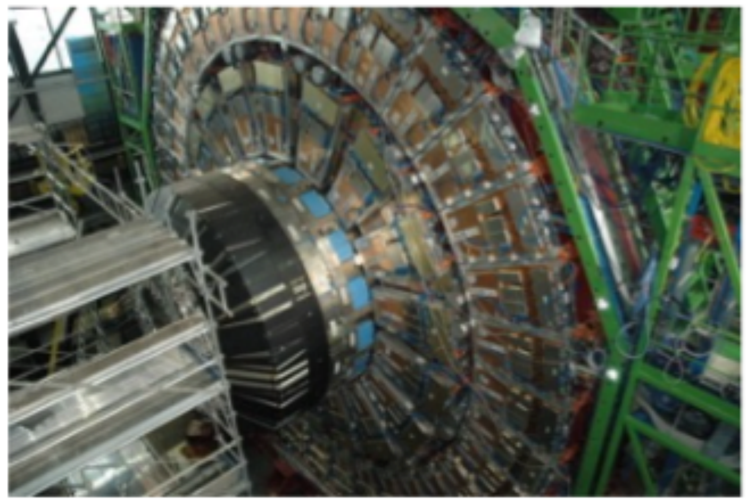
☐ ***What's new in Run-2?***

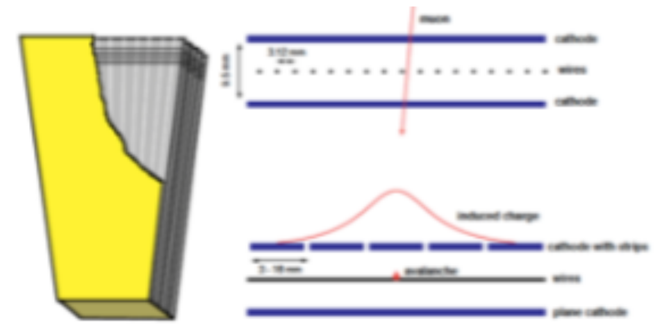
- Relocation of RO boards outside the experimental cavern *(easier access to critical components)*
- **New trigger boards** *(TwinMux)* allow combination of DT/RPC information for L1 segments
- New "on chamber" trigger boards in r-z view
- **Improved local reconstruction** algorithm
  - More details later in these slides

Muon system overview (CSCs)

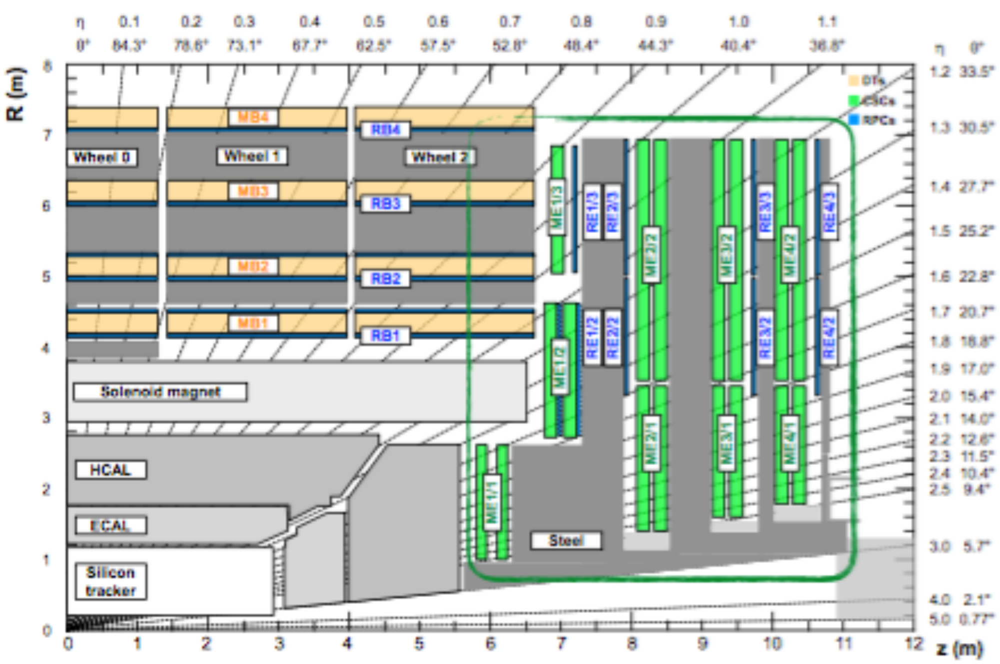
Coverage 0.9 < |η| < 2.4

Geometry (540 chambers) :
- 2 end-caps
- 4 disks / end-cap
- 2-3 rings / disk
- 18-36 chambers / ring





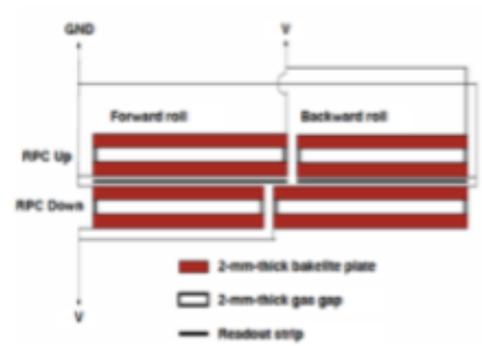
MWPC with cathode strip readout
- gas mixture: 40% Ar - 50% CO_2 - 10% CF_4
- strips width pitch: 8.4 -16 mm (meas. position in r-φ)
- wires measure radial coordinate
  (+ **perform BX identification at trigger level**)
- 6 detection layers per chamber
- segment resolution: **~75 - 150 μm** (**~3** ns time resol.)

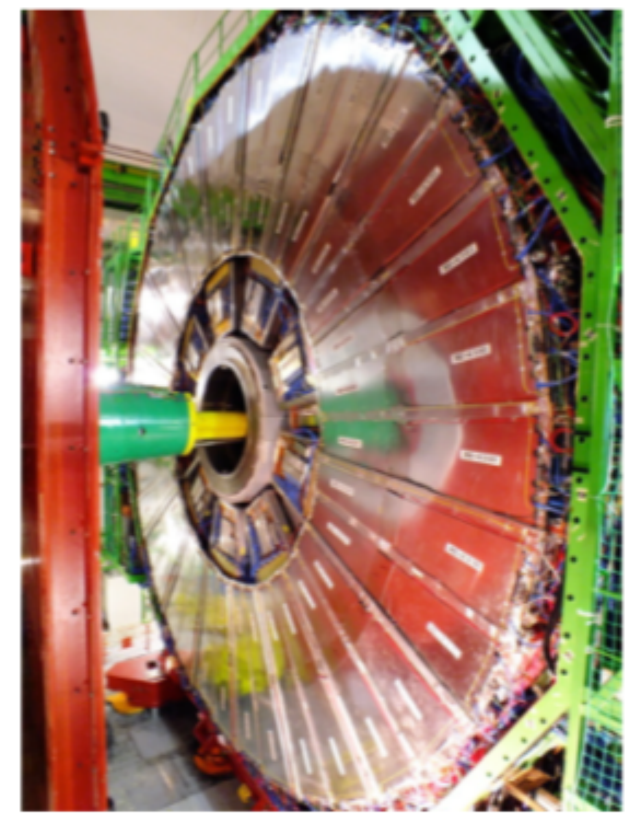


- ***What's new in Run-2?***
  - Complete installation of ME4/2 rings
    - **72 new chambers installed!**
  - **Unganged readout** of **ME1/1A** chambers
    - Run-1: 16 RO channels for 48 strips
    - Run-2: 48 RO channels for 48 strips
      - Improves resolution of offline and L1 segments

Muon system overview (RPCs)

Coverage $|\eta| < 1.8$ (1.6) readout (trigger)



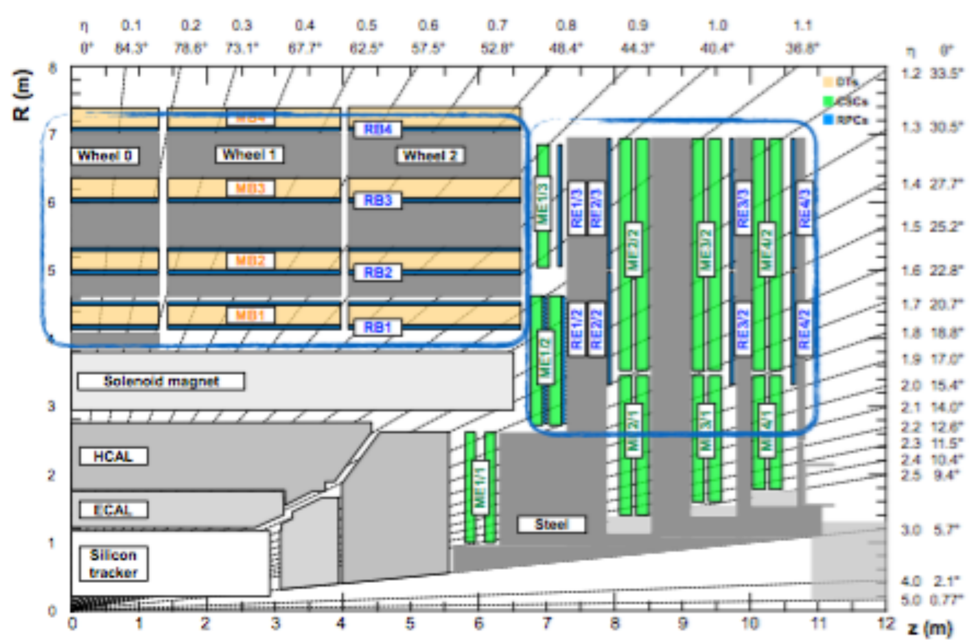


Chamber/performance details:

- *double gap RPCs operating in avalanche mode (tolerate rates up to ~ 1kHz/cm^2)*
- *gas mixture: 96.2% $C_2H_2F_4$ - 3.5% C_4H_{10} - 0.3% SF_6*
- *hit spatial resolution: **~1 cm in r-φ***
- *Fast detector, excellent hit timing resolution: **~2 ns** (add redundancy/robustness to trigger system)*

Geometry:

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



- ***What's new in Run-2?***
  - Installation of RE4 rings
    - **144 new chambers installed!**
      - Increases overall efficiency
      - More robust against failures in the long term
      - Allows tighter quality cuts at L1 *(can reduce rate as well)*

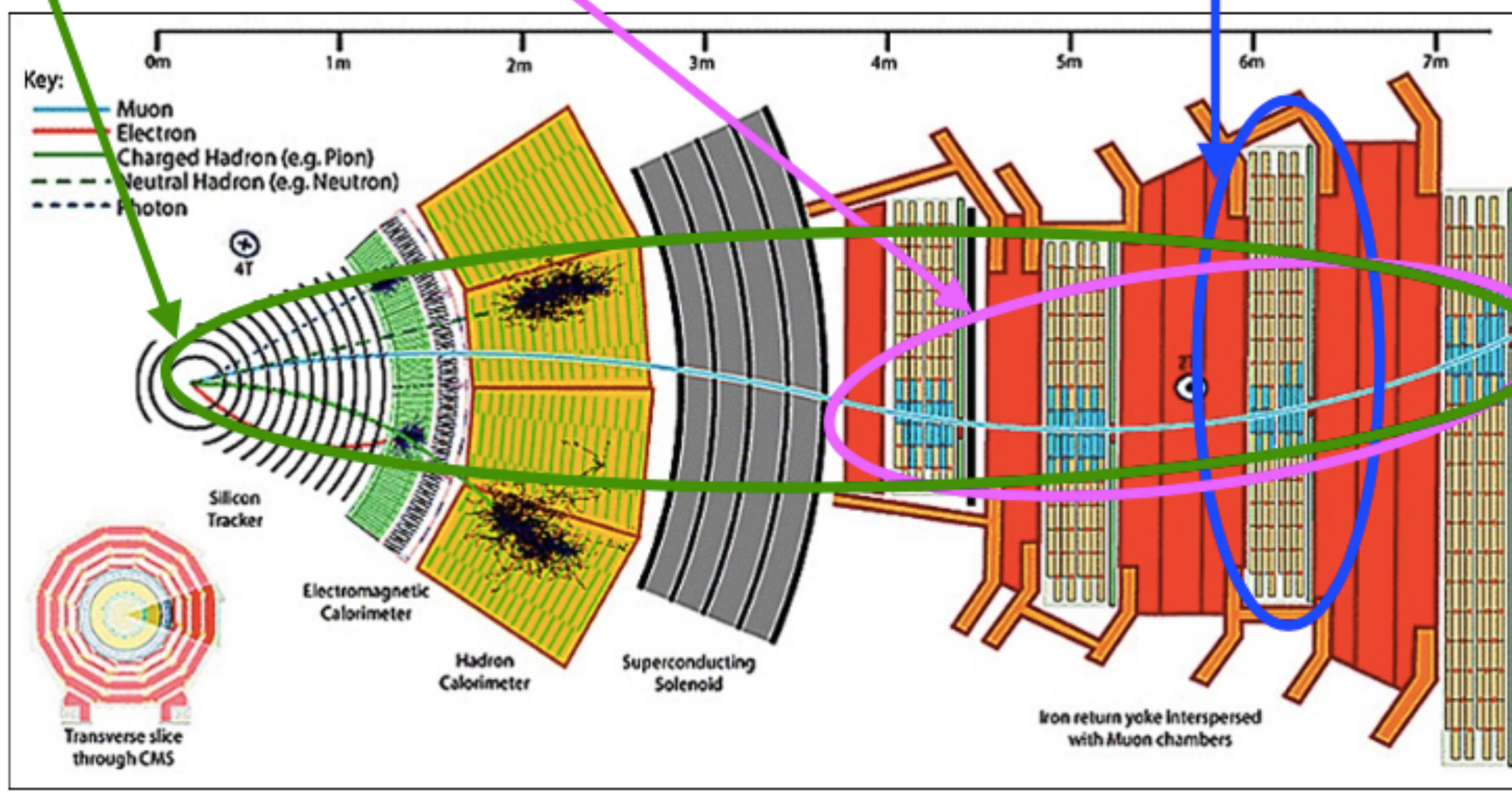
Muon Reconstruction Overview on CMS

(3) Muons are reconstructed by combining information from the tracker and muon systems. So-called global and tracker muons are reconstructed in this way.

(2) Muon tracks (standalone muons) are reconstructed by combining hits and segments from different stations.

(1) Hits and segments are reconstructed within each chamber.

- **Two complementary strategies.**
  - In both cases, tracks in tracker built w/ out muon system information.
  - Significantly improved momentum reconstruction at price of some loss of efficiency.
- **Global Muons**
  - Find compatible pairs of tracks from tracker and muon systems.
  - Refit using hits from matched tracks.
- **Tracker Muons**
  - Tracker tracks extrapolated to muon system. Compatible segments associated to these muons.
  - Improved efficiency at low p_T.



TnP method and samples used

- Efficiencies are computed by means of a **tag-and-probe method** exploiting the $Z \to \mu^+\mu^-$ resonance.
- **Data:**
  - Proton-proton collision data at 13 TeV corresponding to an integrated luminosity of 16.3 fb^{-1} (2016), 41.3 fb^{-1} (2017) and 11.8 fb^{-1} (2018)
  - Events collected using single muon triggers.
  - 2017 and 2016: reconstruction using realistic calibrations and alignment.
  - 2018: prompt reconstruction (using startup calibration and alignment)
- **Simulation**
  - Drell-Yan + jets LO sample (madgraph)
  - Events are re-weighted to match the pileup distribution in data.

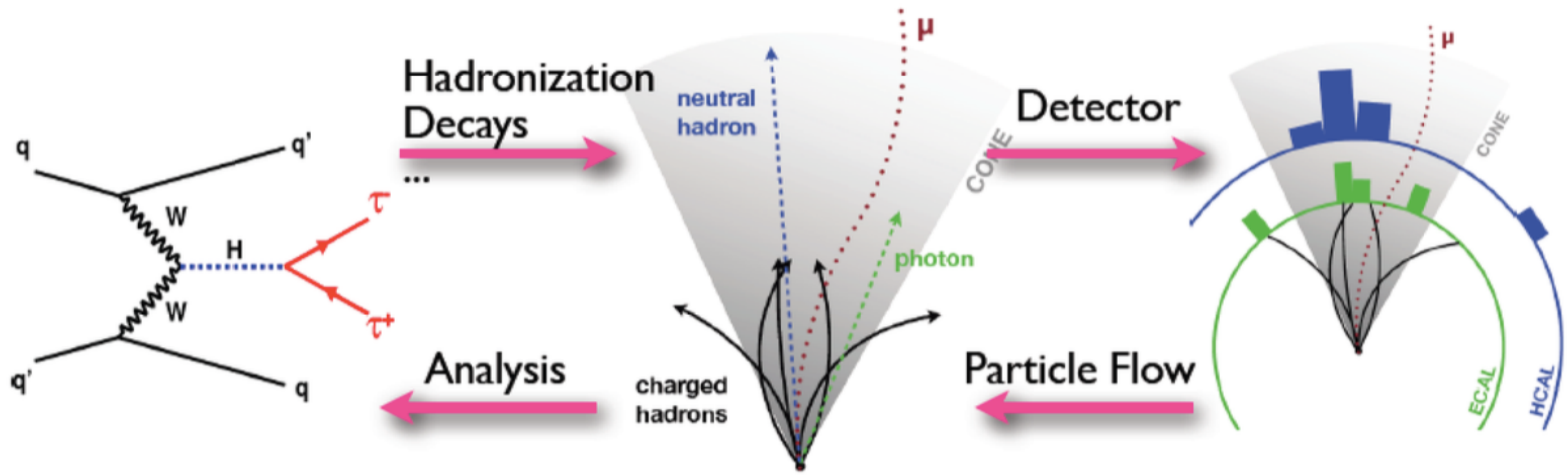
TnP Parameters for Identification

- The tag and probe method is used to extract the data-to-MC scale factors that account for the differences in identification and isolation.
- Tag selection:
  - Tight Id muon, with p_T > 29 GeV.
  - Rel. Comb. Isolation ($\Delta R = 0.4$) < 0.2
  - Matched with single isolated muon trigger (p_T > 27 GeV)
- Probe selection:
  - For ID: tracks with p_T > 10 GeV
  - For isolation: muon must pass the indicated ID requirement.
- The invariant mass distribution for signal and background is fitted using the following functions:
  - **signal:** sum of 2 Voigtians
  - **background:** CMSshape or exponential
- Z mass window:
  - For ID: [70-130] GeV
  - For isolation: [77-130] GeV

CMS Muons: Identification Efficiencies
TnP definitions

- Probe = single tracker tracks associated with tag
  - Single tracks reduce combinatorial bkgd at low pT
- Standard technique: tag + probe invariant mass fit with signal and background
  - Signal = sum of 2 Voigtians (Gaussian Lorentzian)
  - Background = exponential
- Efficiency = ratio of signal normalization factors, numerator has probes that pass selection
- Plots contain statistical errors only
- Systematic errors ~1%, dominated by backgrounds
  - Estimated by varying p_T and isolation cuts on tag muon

Particle Flow on CMS



- Particle Flow (PF) reconstruction:
  - "global event" reconstruction paradigm
  - outputs a list of particles identified across different detectors
  - identify the "primary vertex" (PV) from PU
  - uses particles from PV to build jets, compute missing-ET, lepton isolation ...

arXiv:1706.04965

L3 Muon Trigger Reconstruction Evolution

2015-2016

Two independent algorithms

- "**Cascade**" algorithm: 2 outside-in (OI) and 1 inside-out (IO) algorithm from L2
  - Has been used since Run1
  - Run sequentially from the fastest algorithm to the slowest one
  - Stop if a track is reconstructed in previous step → time saving
  - Run2: add a track quality filter in first two algorithms: improve efficiency in high-PU
- "**TkMu**" algorithm: HLT tracker muon algorithm from L1
  - Similar to the tracker muon reconstruction in offline (inside-out)
  - Optimization for processing speed

2017

Two algorithms are replaced by new algorithm: "**iterative L3**"

- Exploiting iterative tracking algorithm used in CMS
- OI from L2 + IO from L2 + IO from L1: **use both L1 and L2 seeds**
- Adapts to new pixel detector geometry
- Aim to have better performance than Cascade & TkMu

2018

Updated iterative L3 algorithm

- To improve the efficiency with rate reduction
- **OI**: generate **more seeds** in the overlap & endcap region
- **IO**: add **one more iterative tracking**
- **Apply a simple ID** to keep high purity with lower rate in harsher LHC conditions
- Deployed in May 2018

Muon Isolation

- On 15th May 2018, the muon reconstruction at high level trigger (HLT) was updated
  - More seeds for the muon track building are generated to improve the efficiency
  - One more iterative tracking is added to the muon tracking algorithm to improve the efficiency
  - A simple ID on HLT muons is applied to keep high purity with lower rate
- In these slides, the efficiency of muon triggers will be shown with 2018 data
  - Comparison of the efficiencies before and after the HLT muon reconstruction update
  - Two kinds of the triggers will be presented
    - Isolated single muon trigger with $P_T > 24$ GeV
    - Non-isolated single muon trigger with $P_T > 50$ GeV

Muon Isolation Setup

- The trigger efficiencies are measured with the data collected in 2018 corresponding to an integrated luminosity of 11.8 fb^{-1}
  - Before HLT muon update: 7.7 fb^{-1}
  - After HLT muon update: 4.1 fb^{-1}

- Efficiencies are estimated using Tag and Probe (T&P) method using $Z \rightarrow \mu\mu$ events
  - Tag is an offline muon with $P_T > 29$ GeV and $|\eta| < 2.4$ passing a tight identification criteria ensuring the high purity
  - Probe definition is different for each trigger efficiency
    - The definition will be explained in the captions
  - Tag & probe invariant mass should be within [70, 130] GeV mass range
  - The background events are subtracted by the fit on dimuon invariant mass distribution with Double Voigtian (signal) and Exponential (background) functions