Performance of the reconstruction and identification of high-momentum muons collected with CMS in 13 TeV data

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on behalf of the CMS collaboration

ICHEP2020: 40th International Conference on High Energy Physics 28/07 - 06/08 (virtual conference)

Detection of muons with the Compact Muon Solenoid (CMS)

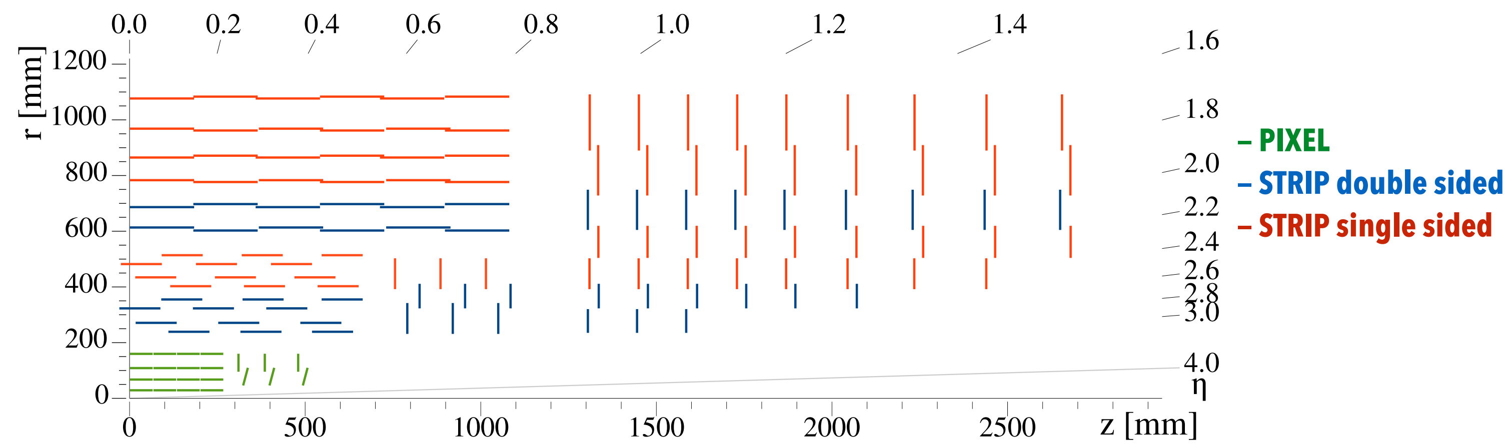
- Muon in CMS are tracks with curved trajectory, bent in radial plane by a B = 3.8 T solenoidal field
- Muon tracking is performed with:

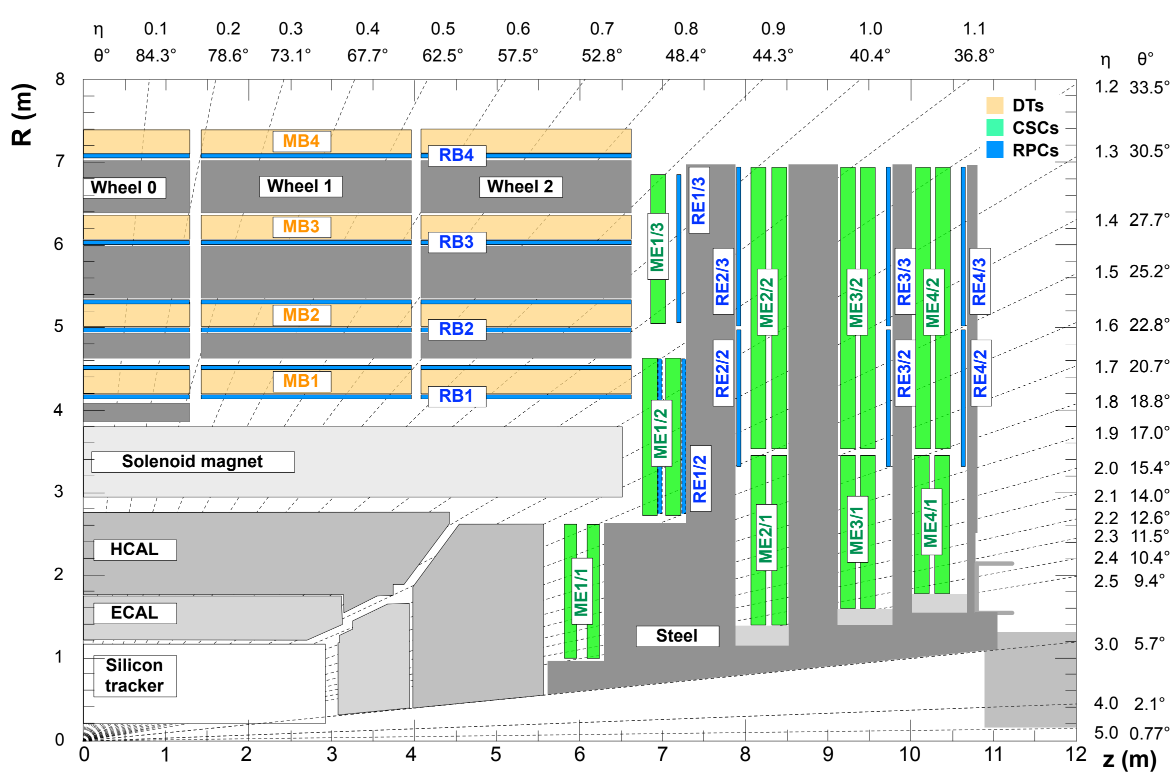
1. Silicon inner tracker:
   - **PIXEL:** 4 layers (BPix) - 3 layers (FPix) ≥ 2017

     3 layers (BPix) - 2 layers (FPix) ≤ 2016
   - **STRIP:** 4 layers (TIB) - 6 layers (TOB) barrel

     3 layers (TID) - 9 layers (TEC) endcap

Longitudinal view of a quarter of the inner tracker





Longitudinal view of a quarter of the muon system

2. Muon system (gaseous detectors):
   - **Drift Tubes** ($|\eta| < 1.2$)

     tracking detector with trigger capabilities
   - **Cathode Strip Chambers** ($0.9 < |\eta| < 2.4$)

     tracking detector with trigger capabilities
   - **Resistive Plate Chambers** ($|\eta| < 1.9$)

     mostly used in trigger

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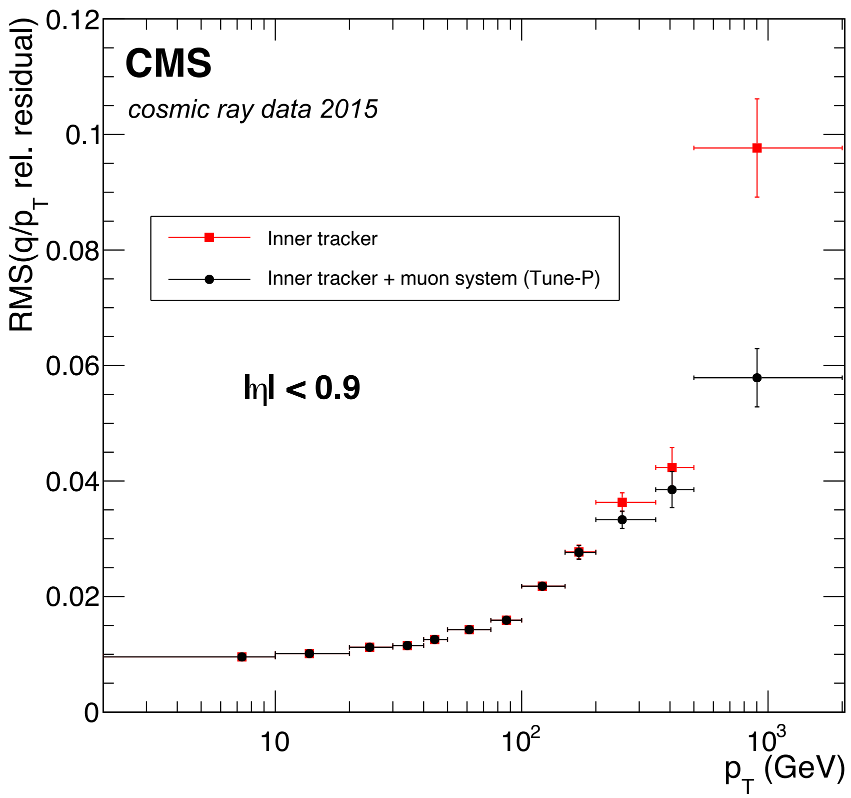

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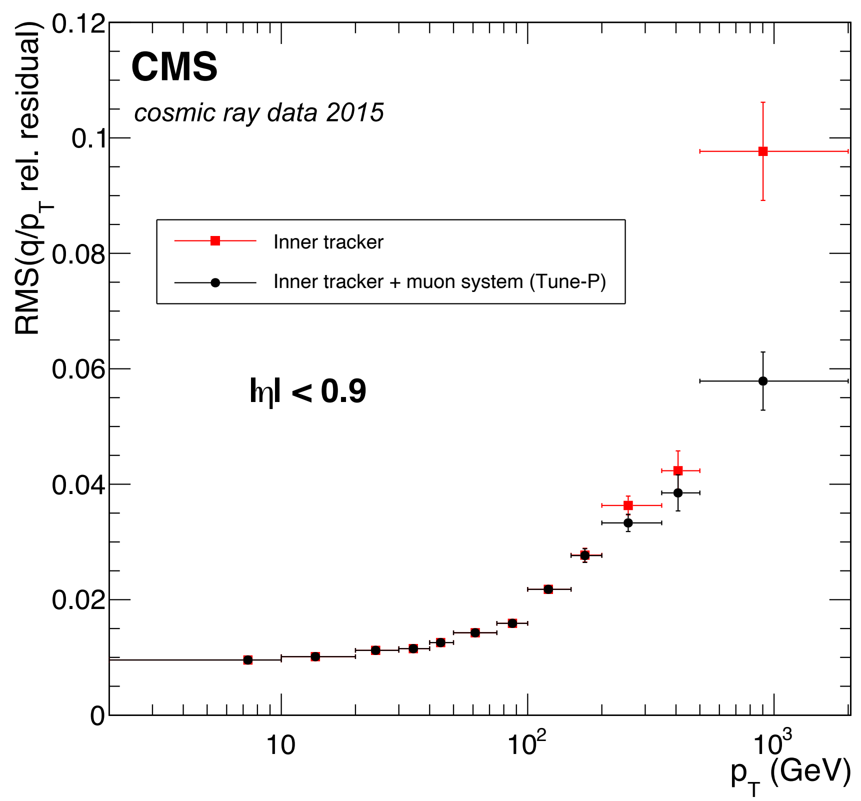

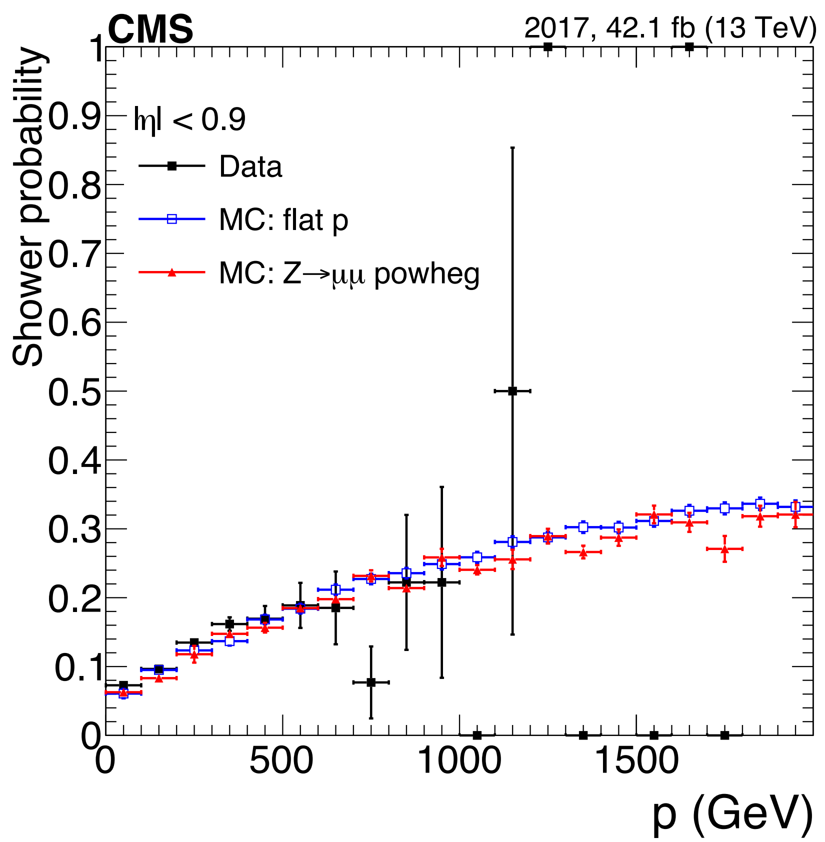

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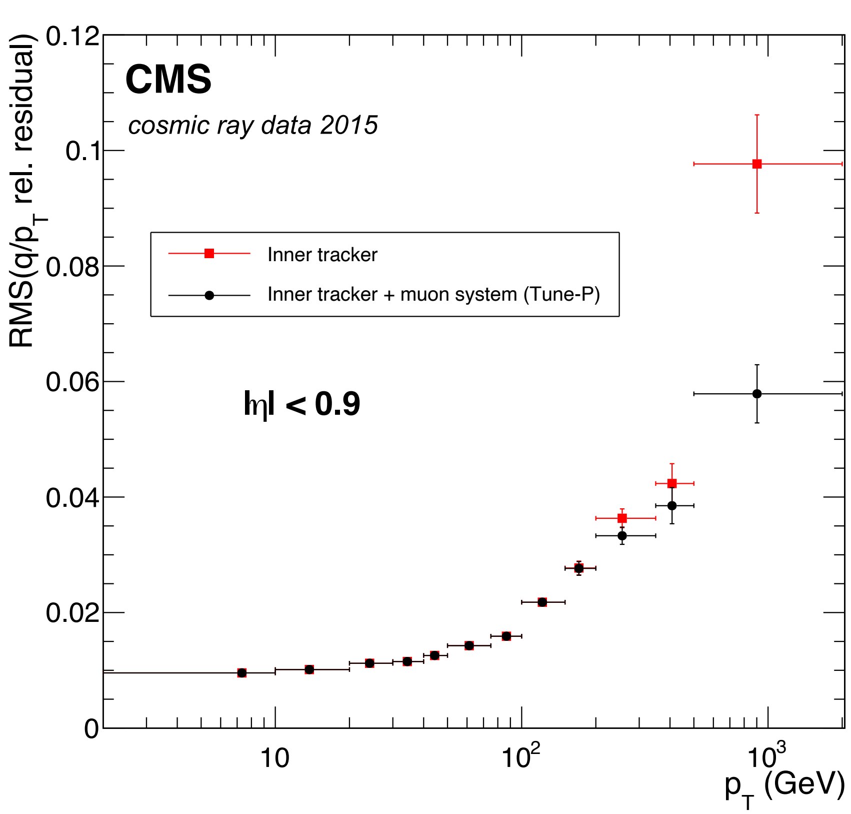
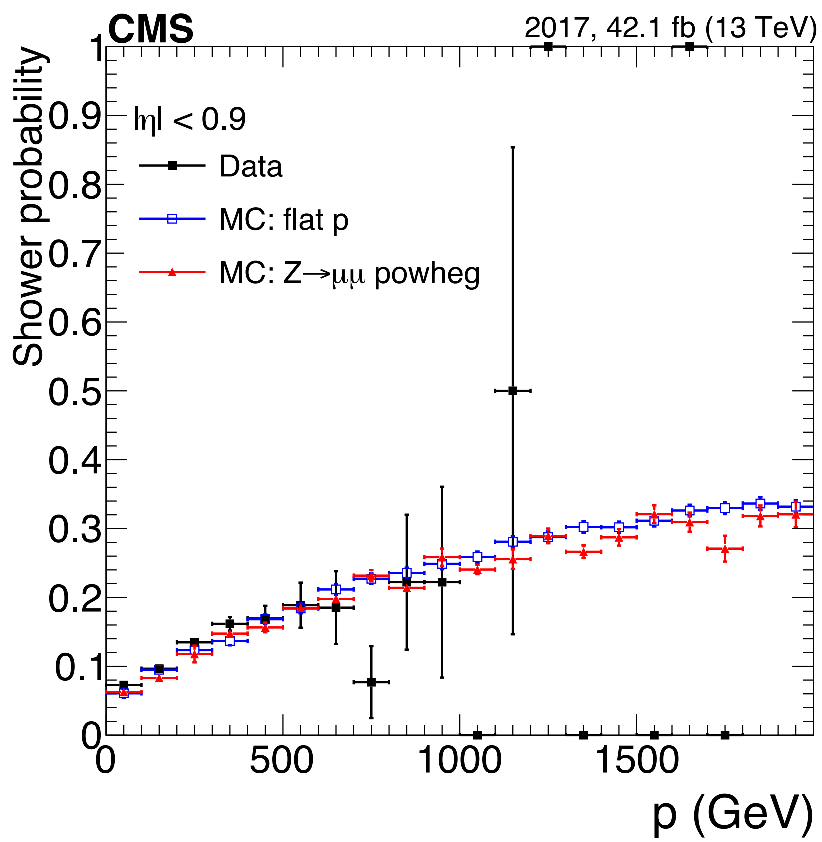


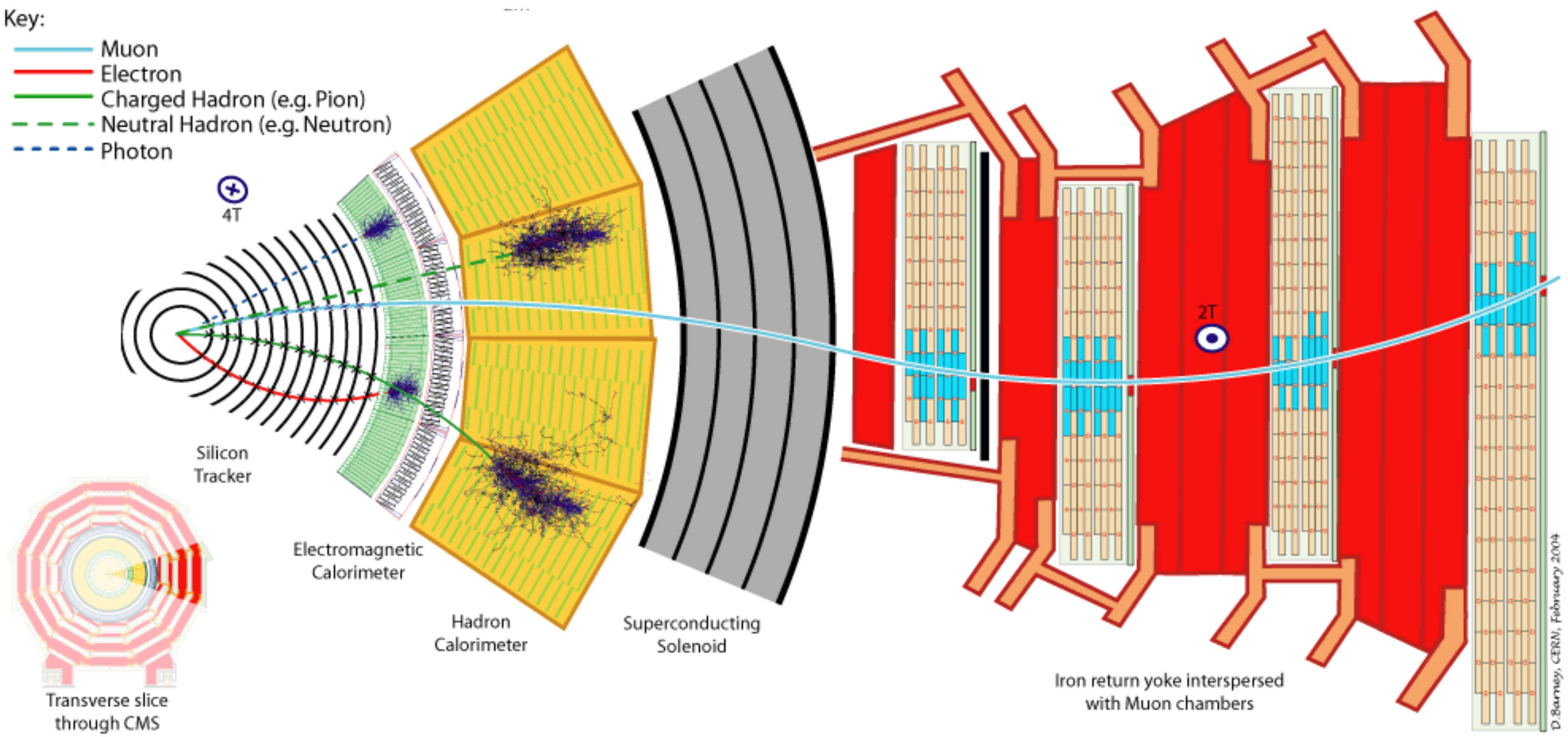


A complete study of high-energy muons with 2016 and 2017 data is documented in: JINST 15 (2020) P02027

Reconstruction of *high-momentum muons*

Muon object reconstruction overview

More details in: [JINST 13 (2018) P06015]



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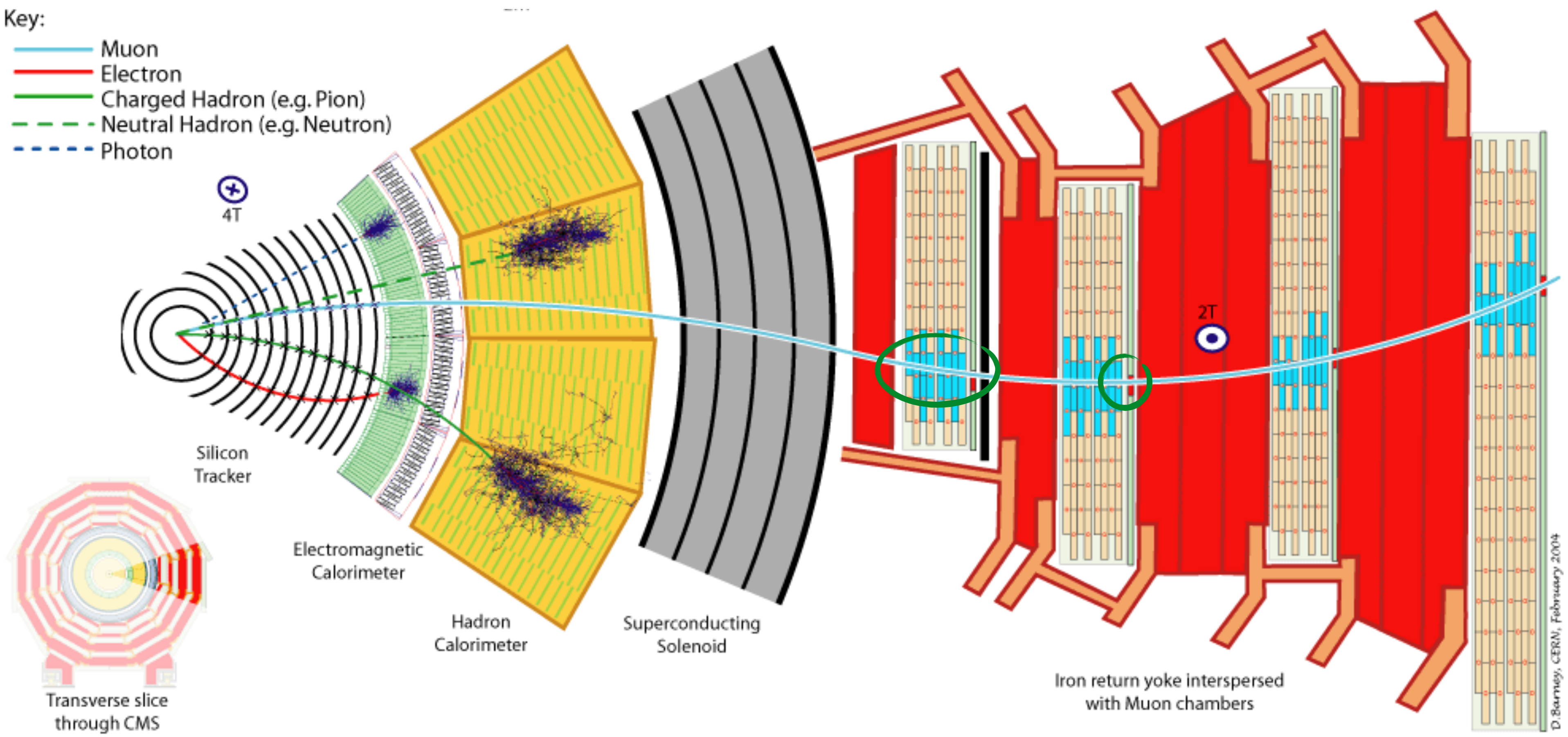

1. Local muon reconstruction:
- RPC hit clusters
- DT/CSC segments

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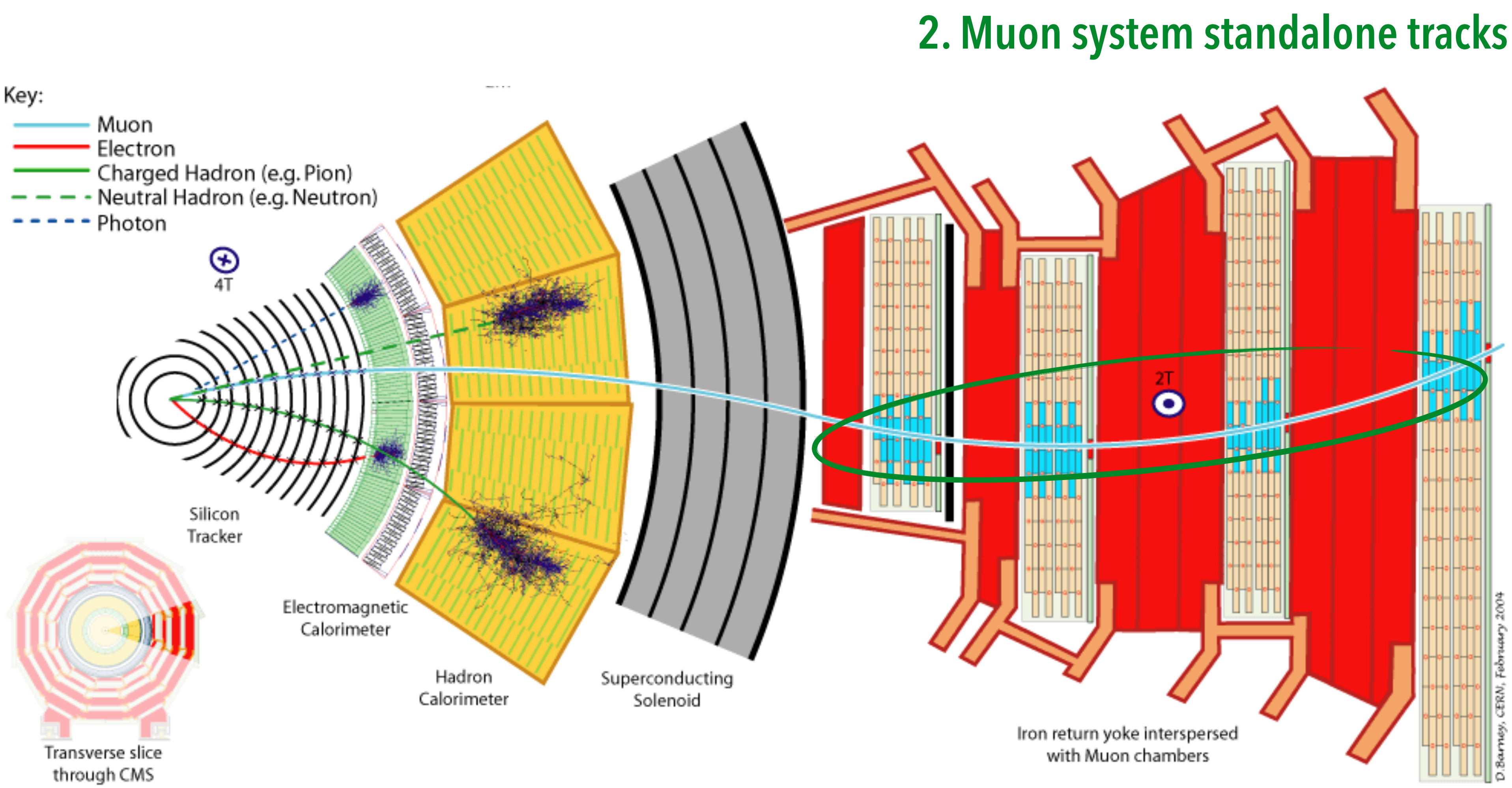

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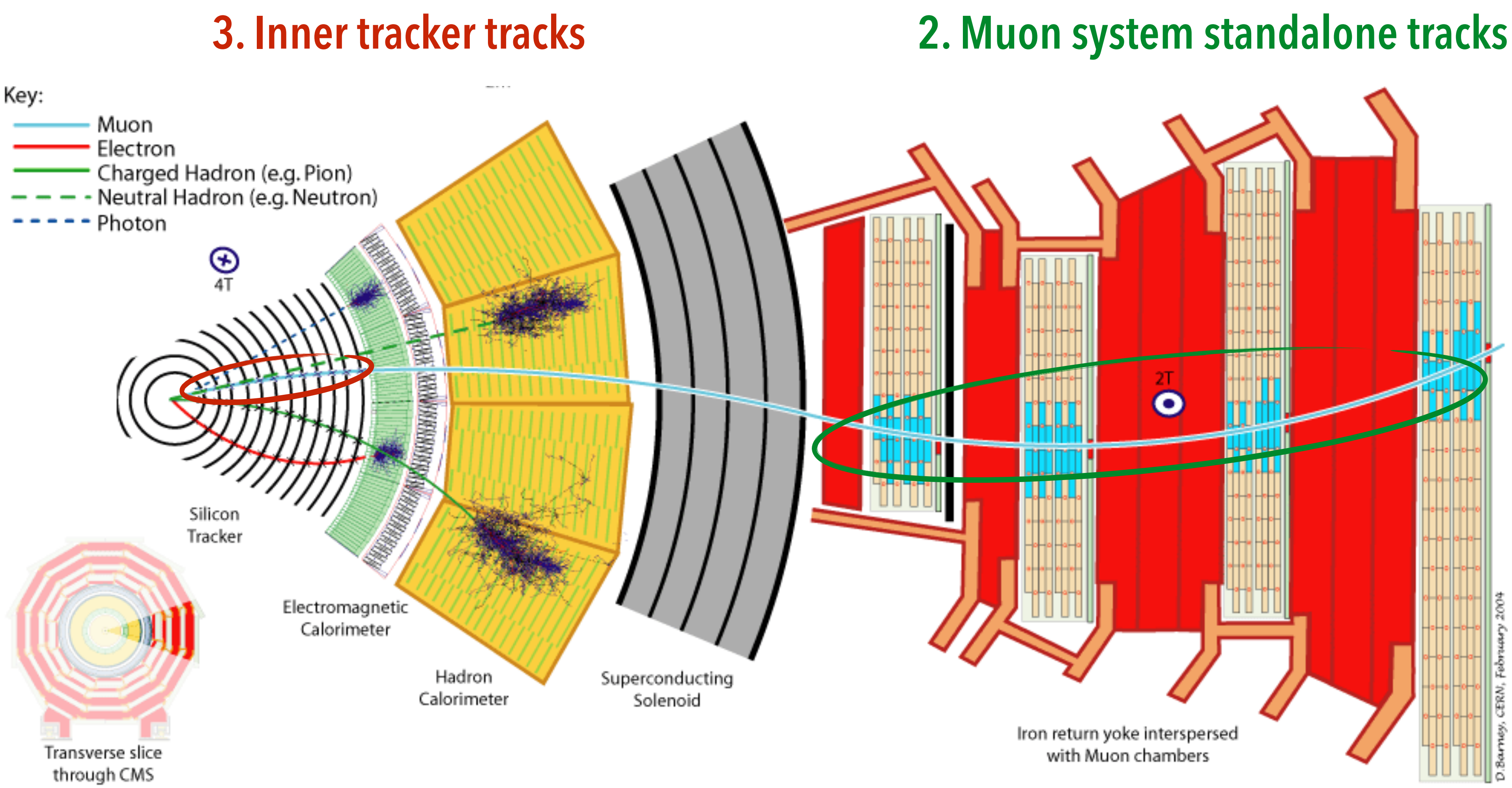

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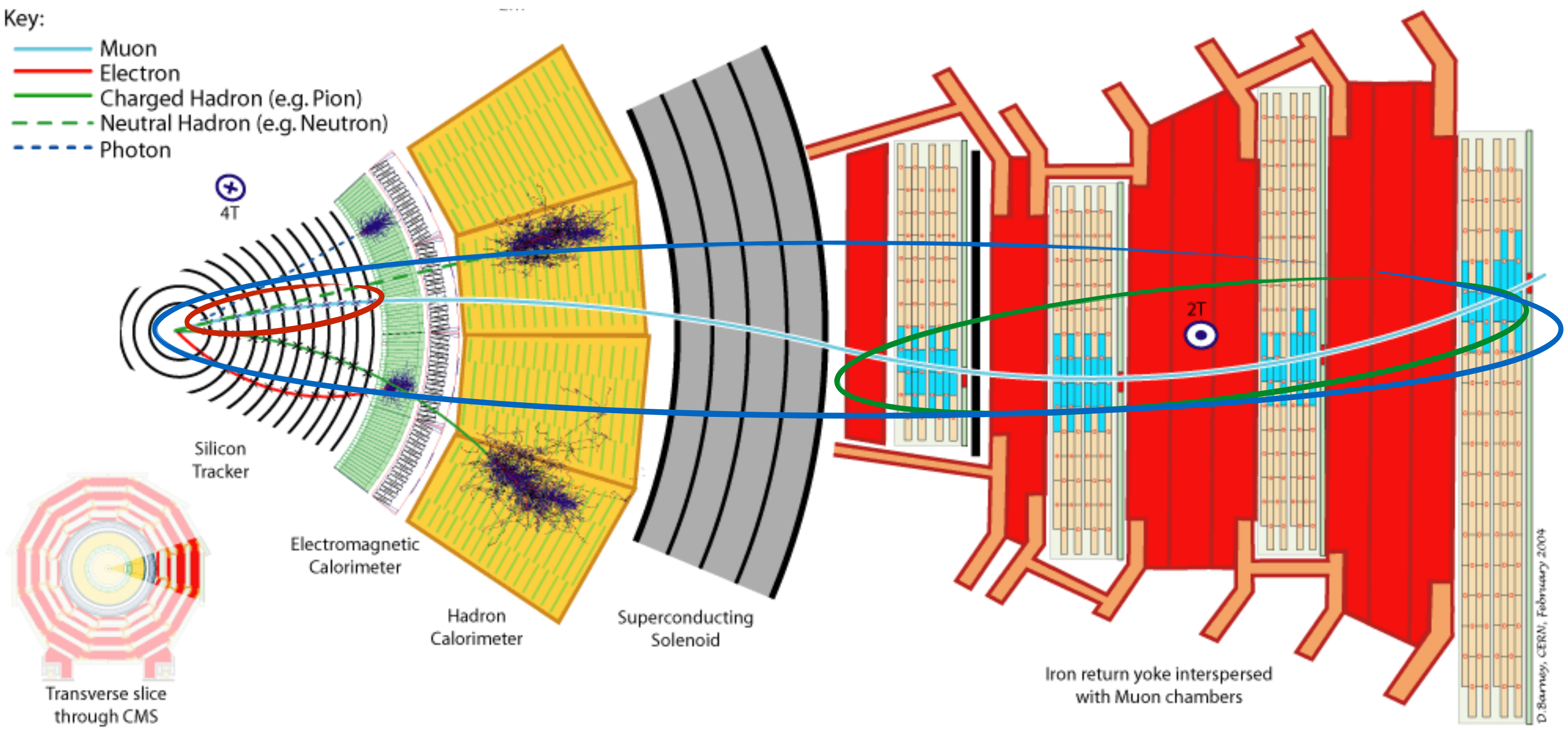
2. Muon system standalone tracks



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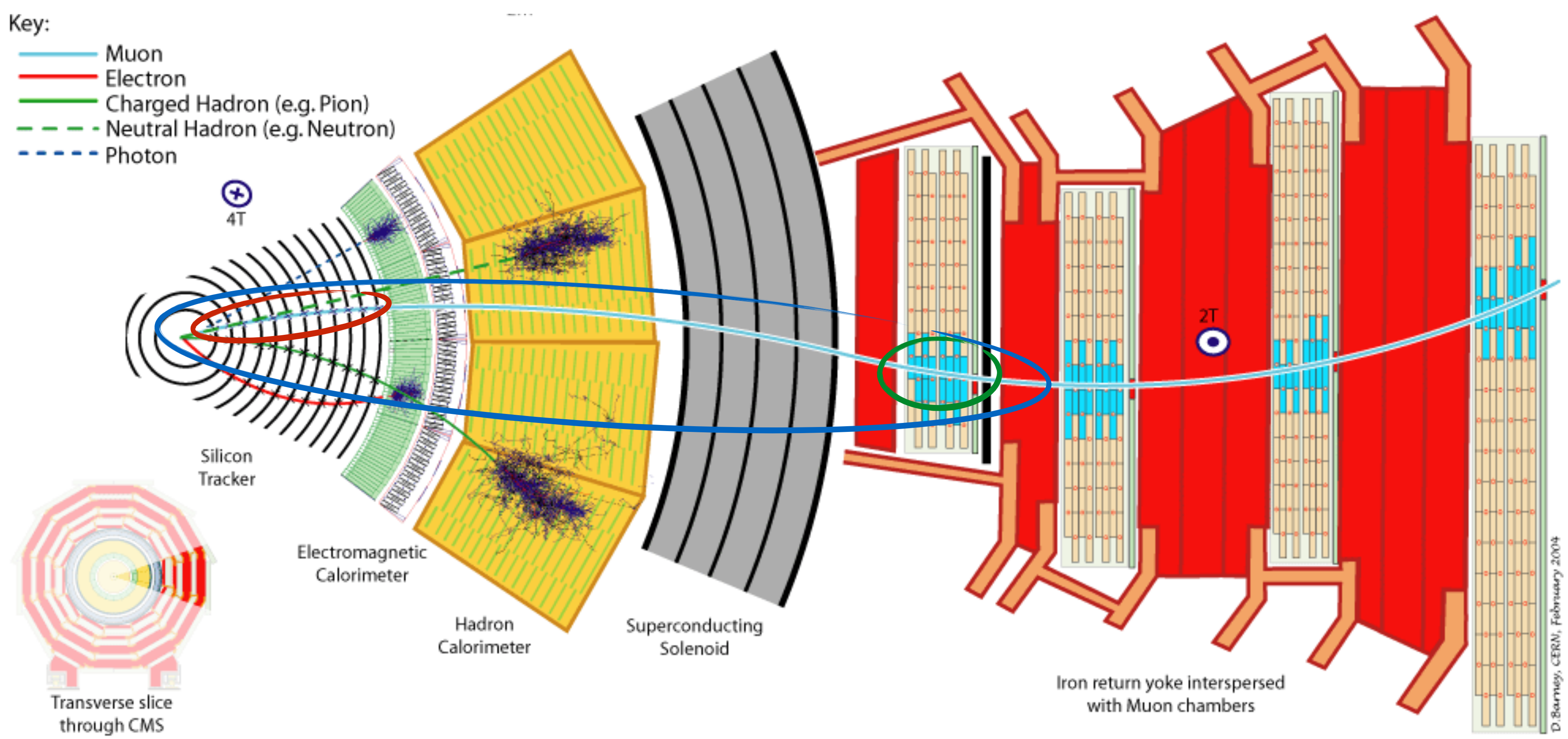

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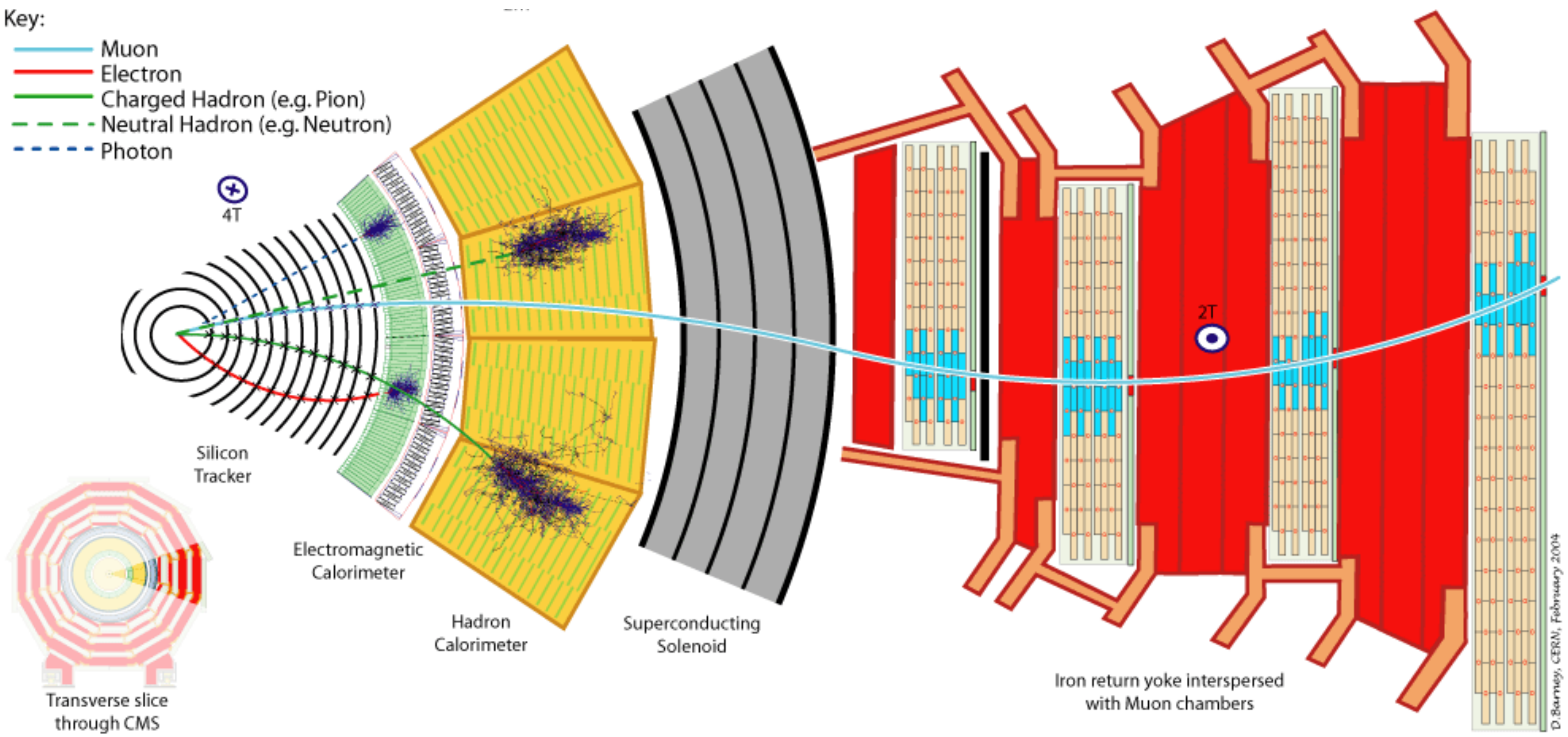

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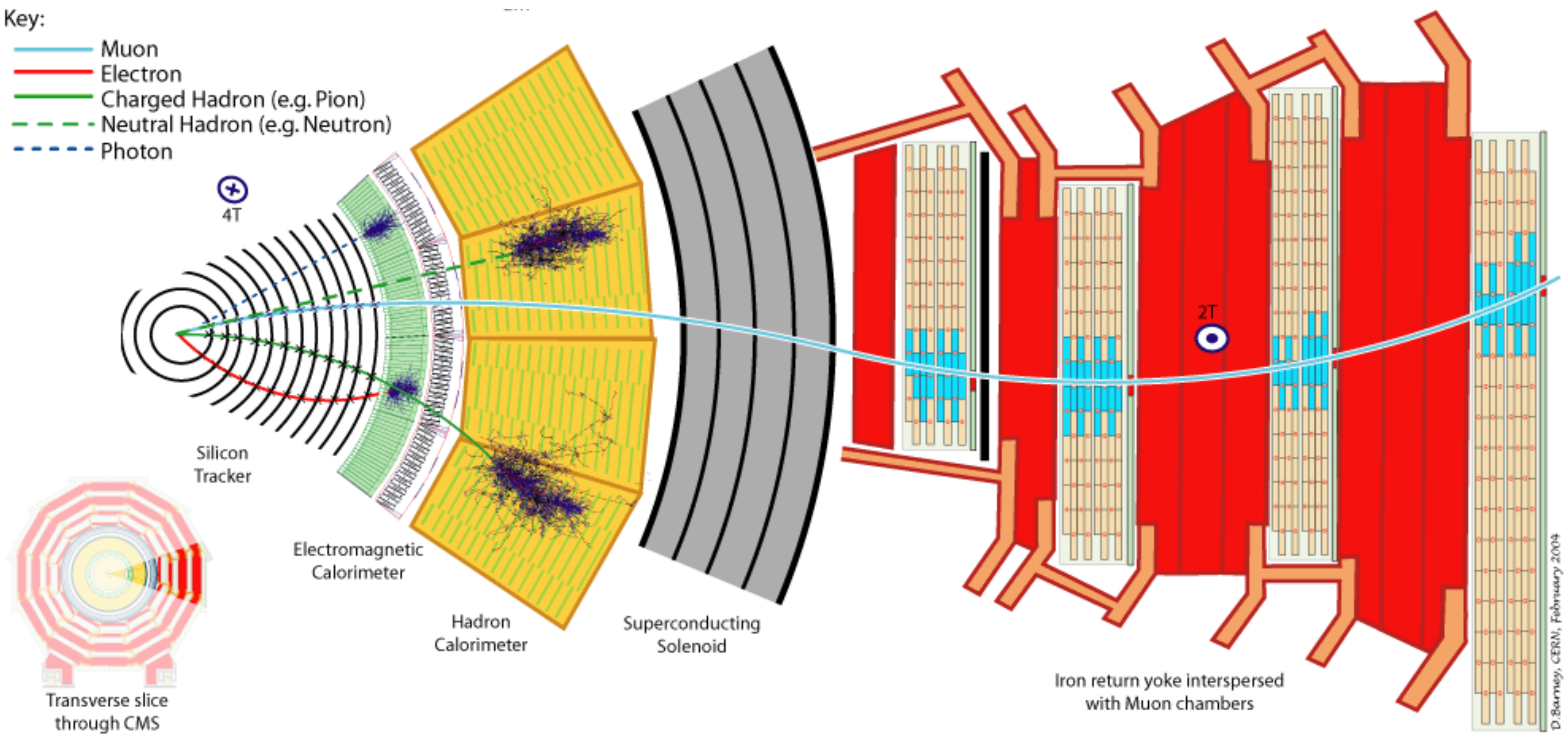

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\+ **Muons included in the CMS Particle-Flow (PF) event reconstruction** (not covered today)

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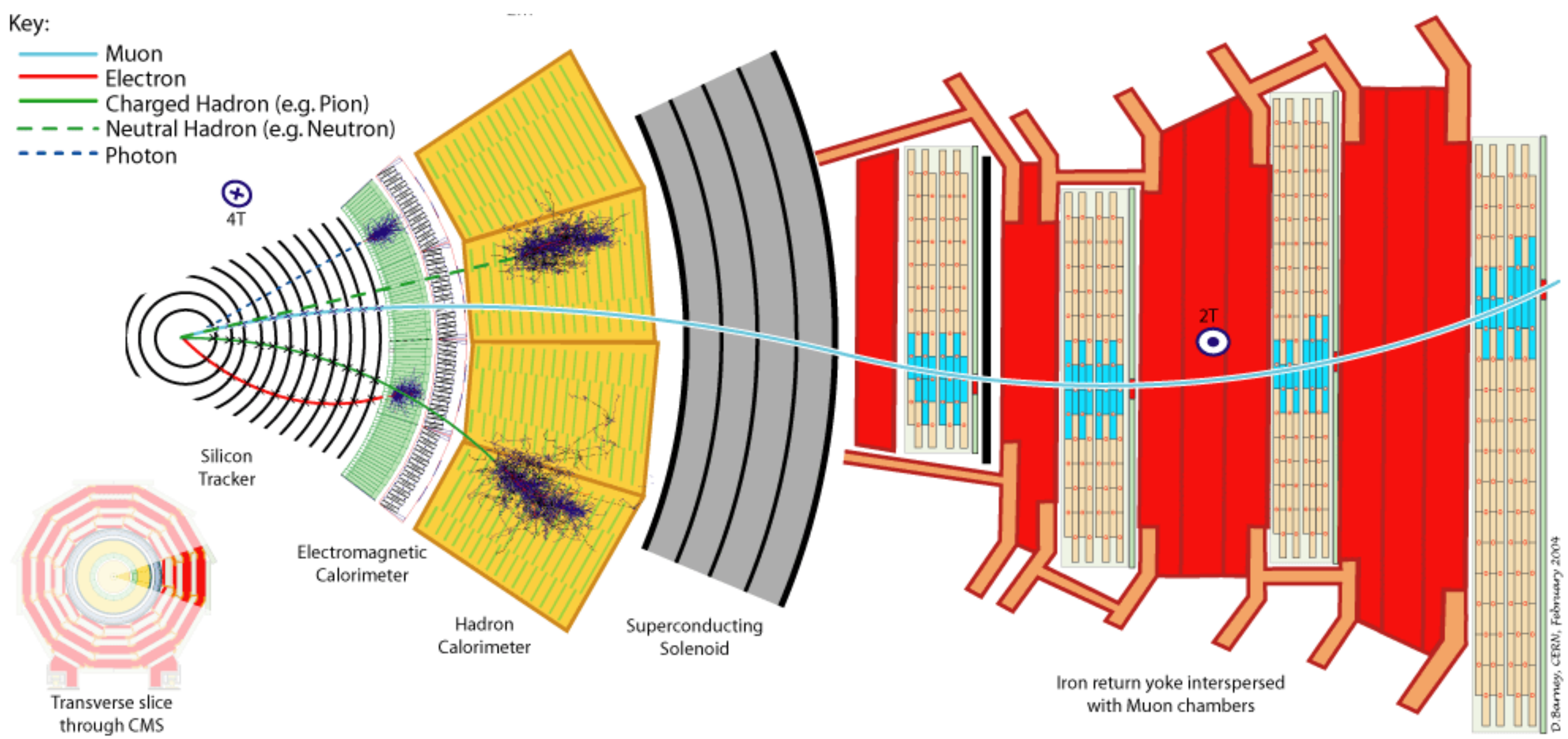

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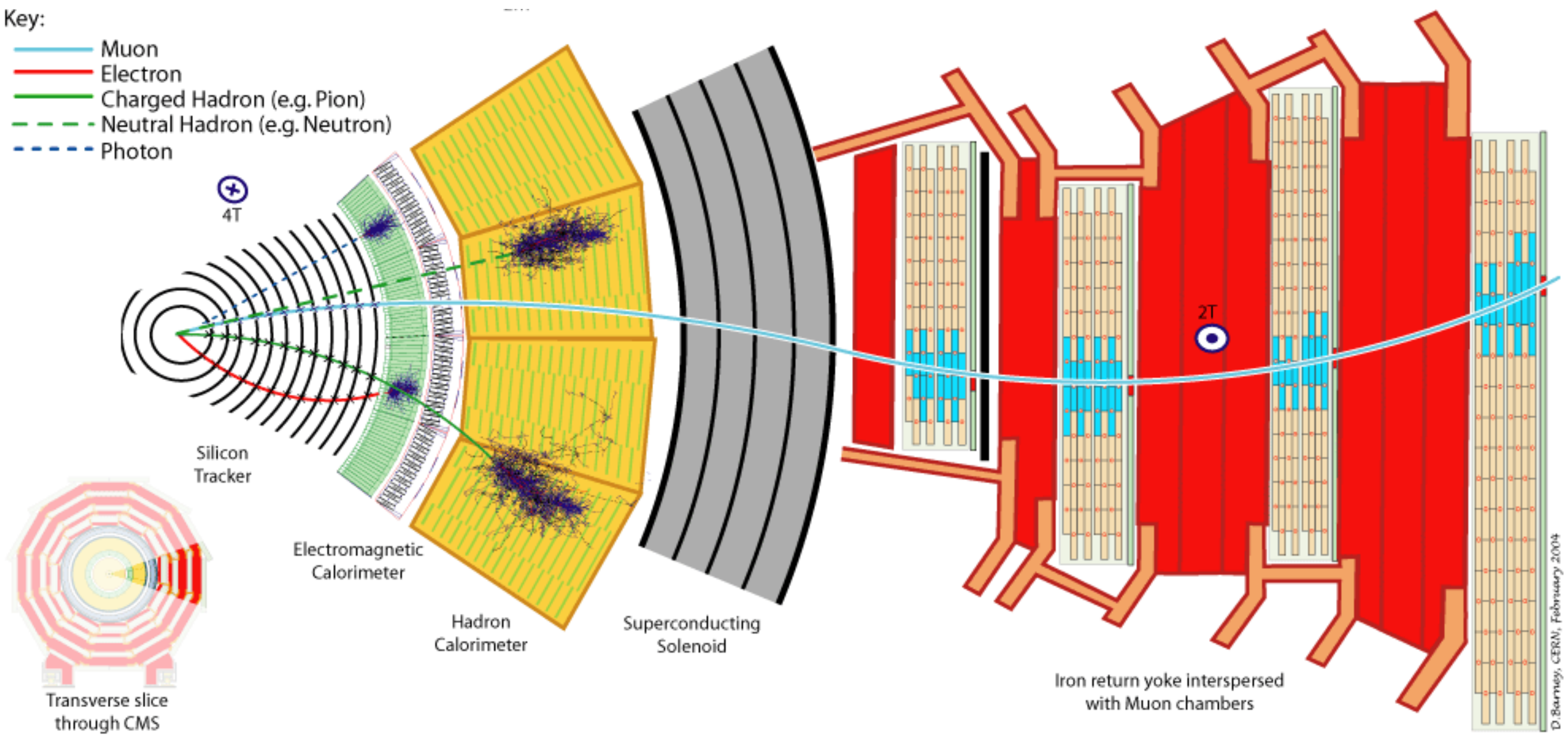

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+ Muon isolation:

- counting energy deposits in tracker and calorimeters
- based on PF quantities (charged/neutral hadrons, photons)

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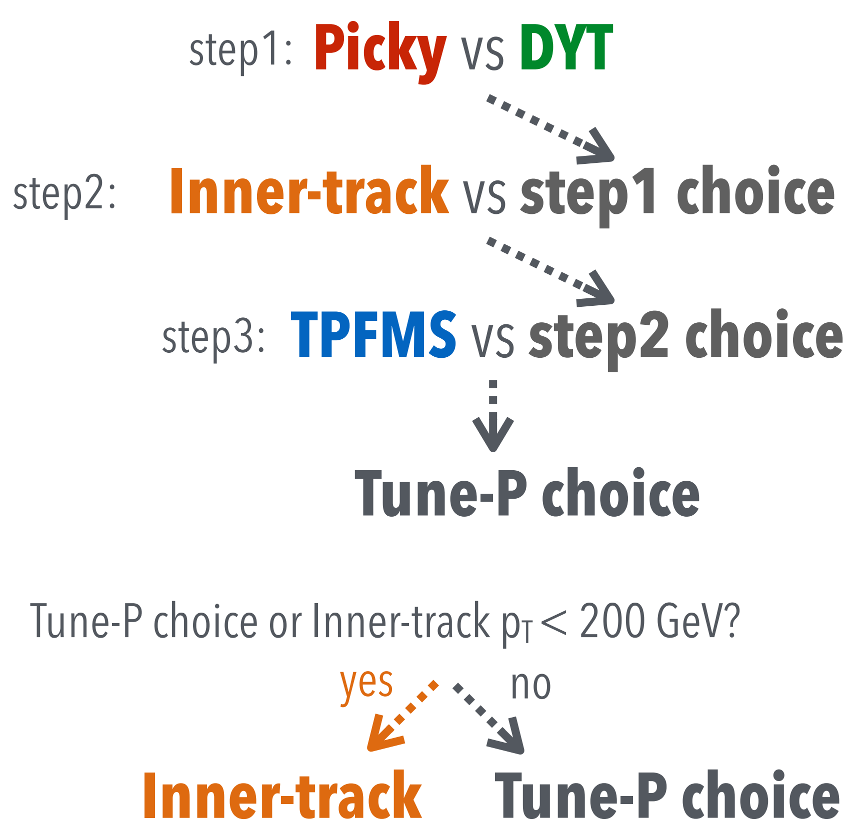
Tune-P decision strategy



- Final track-fit type chosen by **Tune-P** algorithm:
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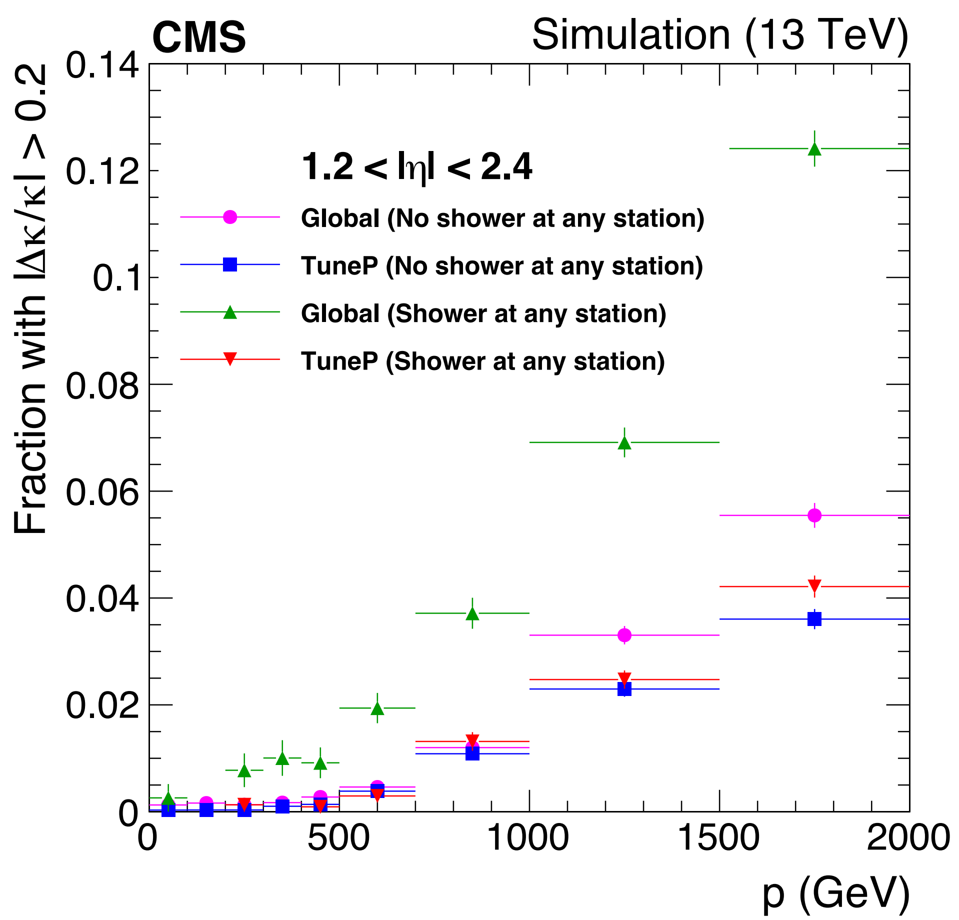

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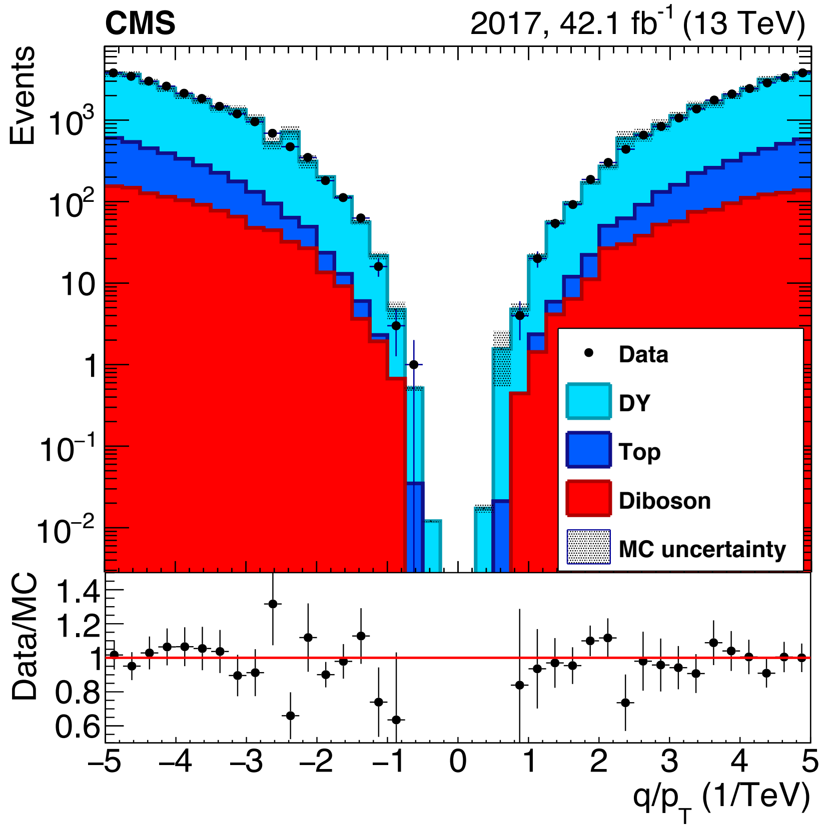
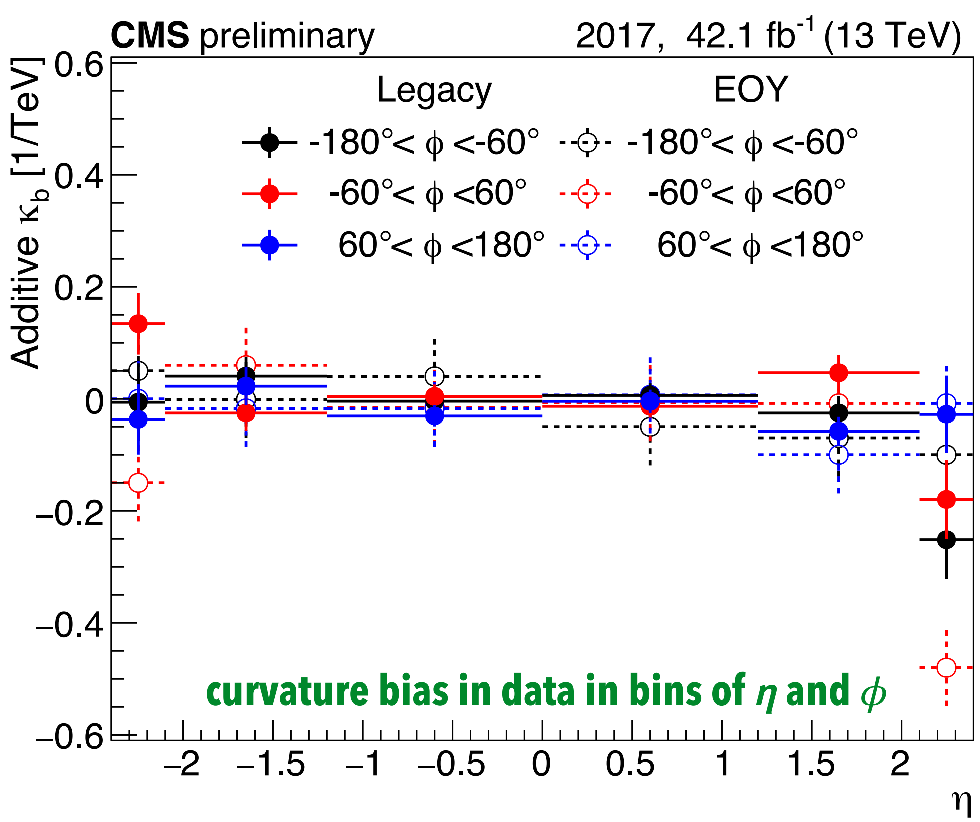
Physics object performance: *scale and resolution*

Measurement of biases in the muon p_T scale

[*] CMS DP-2020/040

- High-p_T muons have a small curvature (k) ⇢ little distortions in the estimation of k can largely bias p_T
  - At high energy, biases are **mostly due by constant shifts of k** due to residual misalignments of tracker and muon system
- Scale consistency between data and MC is measured with the **Generalized Endpoint Method**:
  1. The $k = q/p_T$ distribution of muons (from dimuon events) with $p_T > 200$ GeV is plotted for data and simulation
  2. For simulation (which has no scale bias), an artificial curvature bias k_b is injected "in steps" to the original q/p_T distribution
  3. For each injected k_b step a binned χ^2 test is performed to compare the data and (distorted) simulation q/p_T distributions
  4. The **curvature bias in data** is selected as the **value minimizing the χ^2 distribution** as function of k_b
- Bias overall less than 10% (mostly consistent with 0), with the exception of the high $|\eta|$ region





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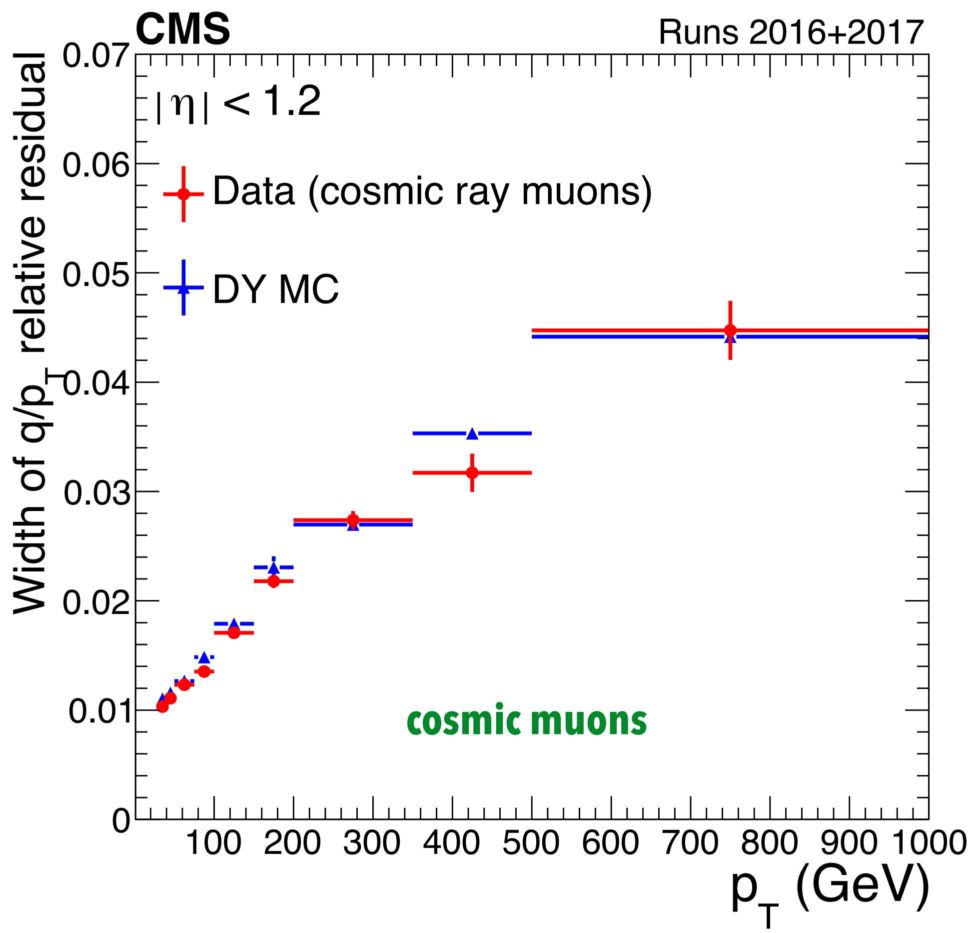
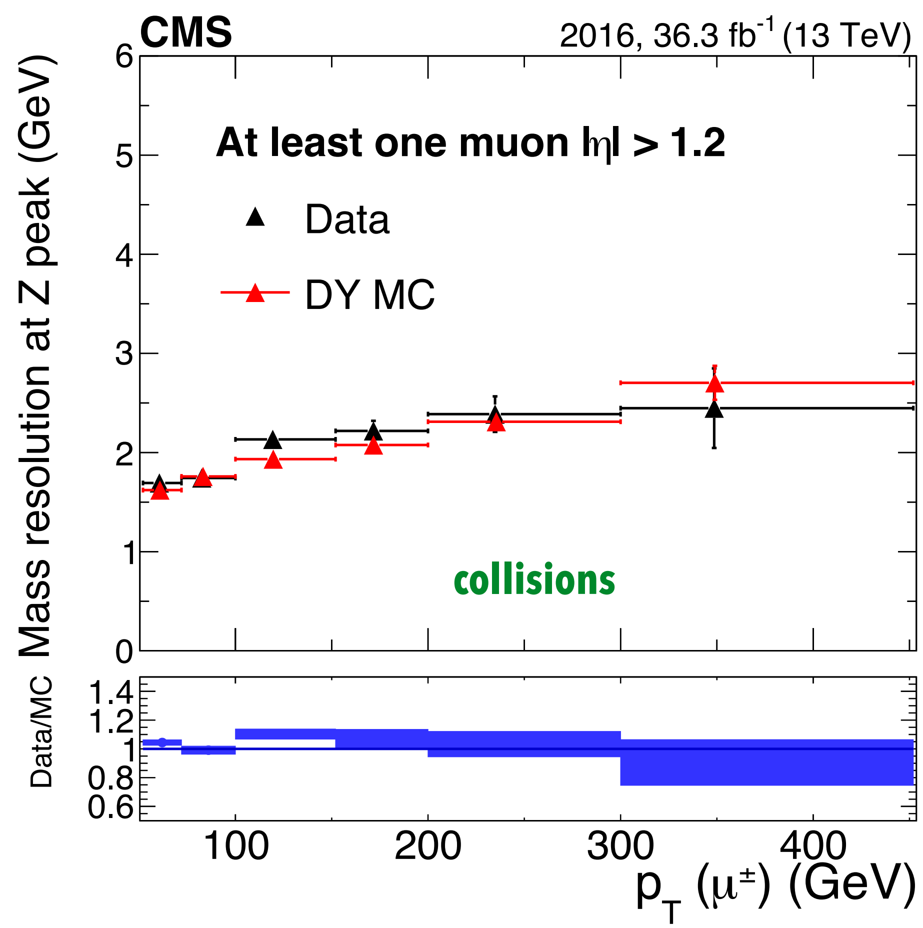
Muon momentum resolution



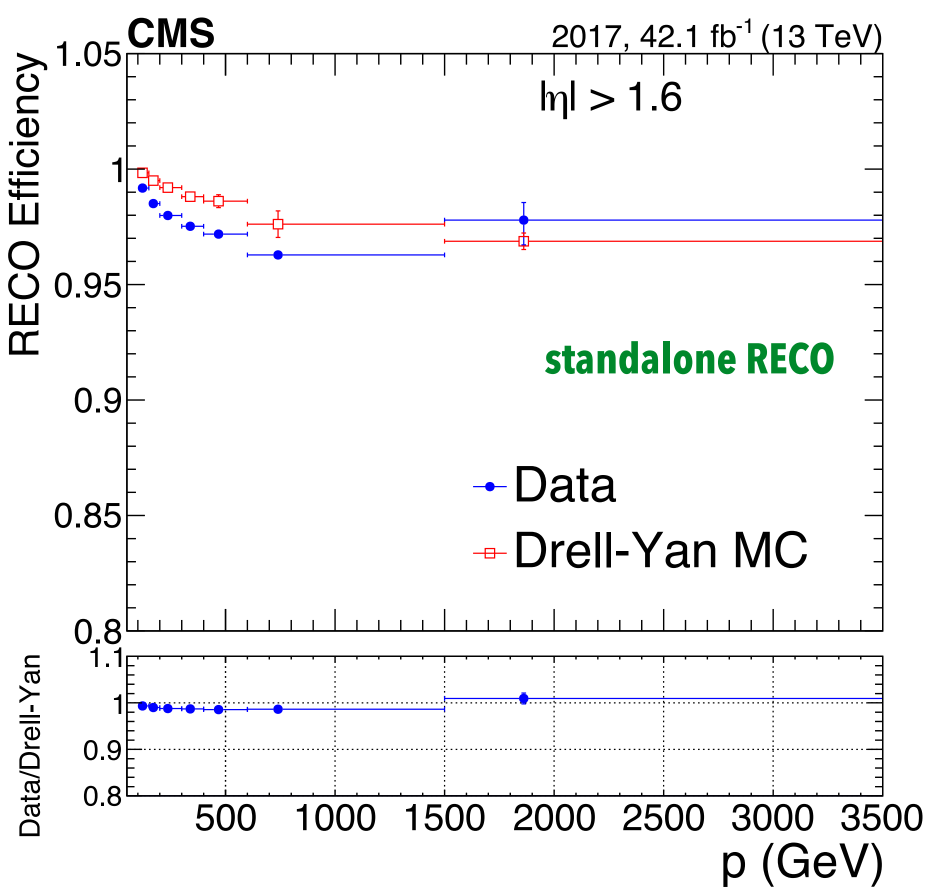


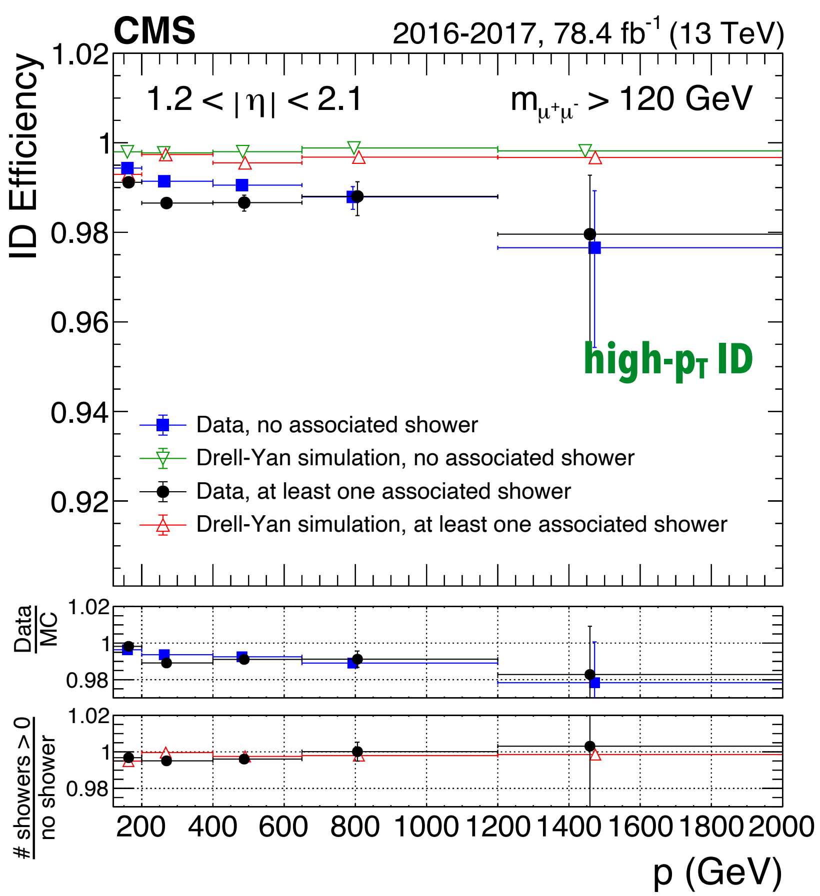
- Either evaluated using cosmic muons:
  - Muons traversing CMS close to the beamline get reconstructed separately in the *upper* and *lower* halves of CMS
  - The q/p_T relative residual between the *upper* and *lower* reconstructed muons is a measure of the momentum resolution
- Either by using pp collision events:
  - Selecting dimuons from boosted Z decays and fitting the Z invariant mass distribution
- Data/MC agreement generally good; main exception: a discrepancy around ~15% for $|\eta| > 1.6$ (2017 dataset)

Physics object performance: *efficiencies*

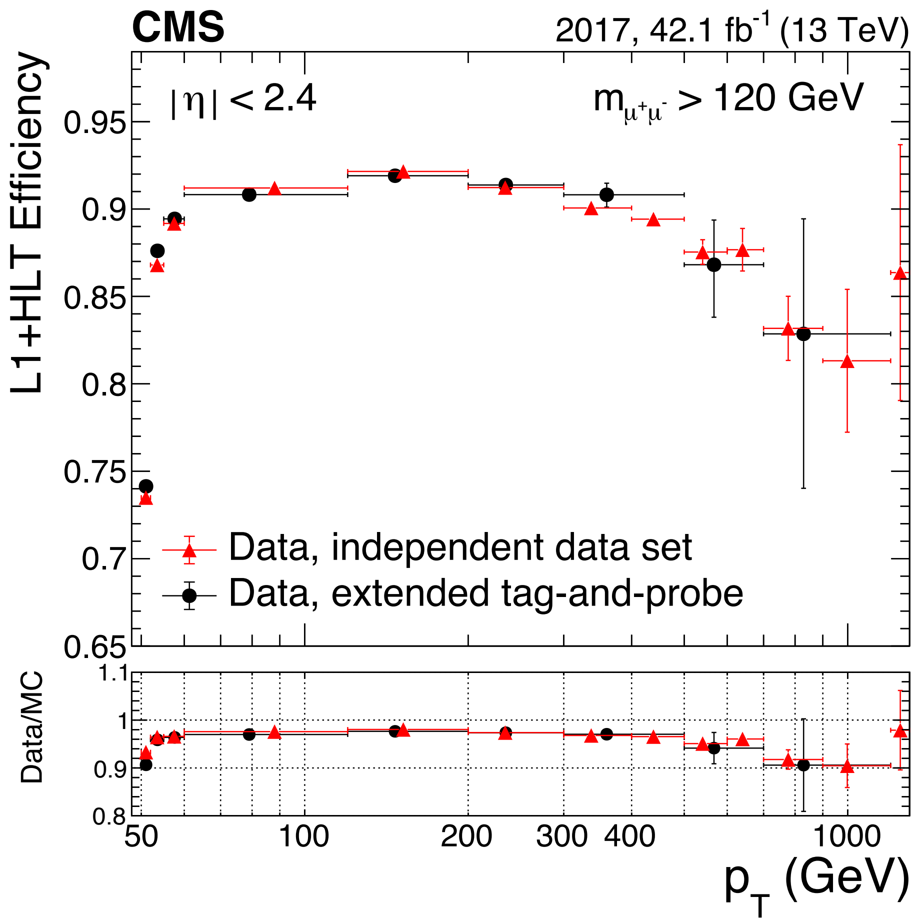
Muon reconstruction and identification efficiencies

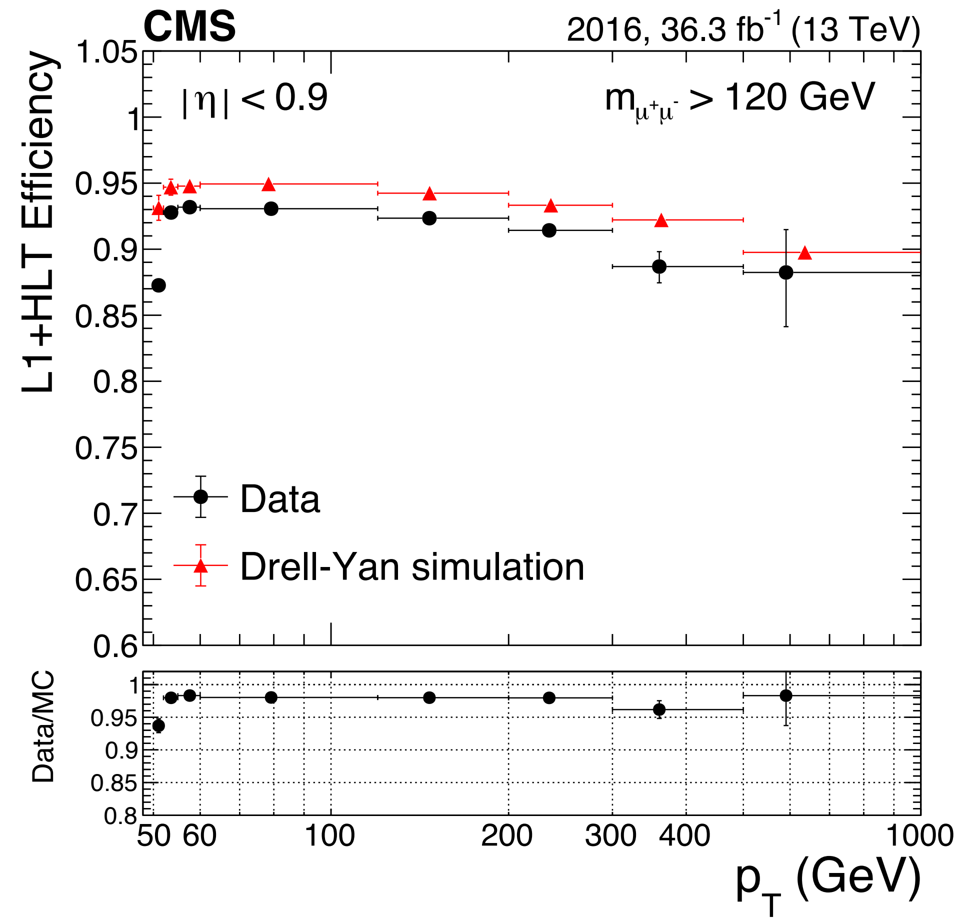
- Efficiencies are measured with a *cut and count extended tag-and-probe technique*:
  - **TAG:** muon satisfying high-p_T ID criteria and very tight isolation cut, matched with single muon trigger
  - **PROBE:** tracker muon, with very tight isolation cut (+ potentially cuts on the inner track, e.g. # of layers, vertex proximity)
  - **PAIR:** no upper cut on on invariant mass, plus add cuts (e.g. p_T balance) to select non resonant DY events
- The muon component of the reconstruction efficiency and the full high-p_T ID selection are probed
  - **RECO:** p_T dependent inefficiency for $|\eta| > 1.6$ as large as 3% - efficiency in barrel is flat vs p_T, with a data/MC SF ~99%
  - **ID:** efficiency is ~98% (data) with a ~1% data/MC discrepancy - flat as function of p_T both in barrel and endcaps





Trigger efficiency





- The trigger efficiency is measured exploiting two different strategies:
  1. With the *extended tag-and-probe method*
  2. Using datasets collected with *non-muonic* triggers (e.g. e-gamma triggers)

- Overall efficiency varies with p_T between ~92% to ~82% data/MC SFs vary between ~98% and ~90%
  - Inefficiency, data/MC SF and p_T dependence mostly due by Level-1 trigger
  - Results computed with different approaches agree well with each other

Summary

- High-momentum muons have peculiarities that make them differ from lower energy ones
  - To maximize physics performance at high p_T, dedicated algorithms are implemented in the CMS muon reconstruction
- The LHC Run-2 provided ideal conditions to probe the high-energy regime
  - Because of the $\sqrt{s}$ increase to 13 TeV, as well as because of the increased statistics
- Using Run-2 data, high-momentum muons in CMS were studied with unprecedented level of detail
  - The outcome of such studies is documented in JINST 15 (2020) P02027
- Overall very good performance was observed:
  - Efficiencies are generally high, with small p_T dependence in all the probed momentum range (but for Level-1 trigger)
  - Up to rather large $|\eta|$, no significant scale biases are observed
  - Using muon information in the p_T measurement improves the resolution w.r.t. a tracker-only measurement
  - Resolution is probed both using comics and collision data, the disagreement from simulation is 15% or (generally) less
  - Empirical methods to tag showers recorded in the muon system were developed
  - Shower tagging methods show reasonable data/MC agreement and were used to parametrize all performance figures
- All this work also highlighted areas were things can be further improved ⇢ we are working hard to prepare for Run-3 and achieve even better performance!

Thank you for your attention!

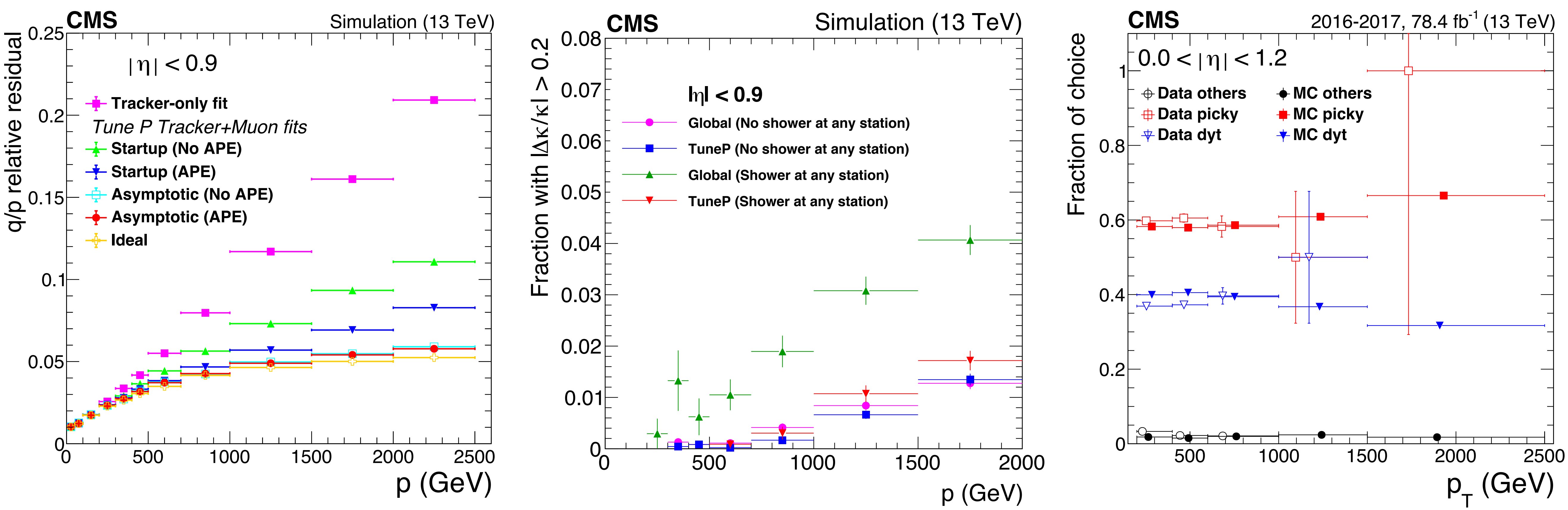
Questions?

also offline at: carlo.battilana@cern.ch

Backup

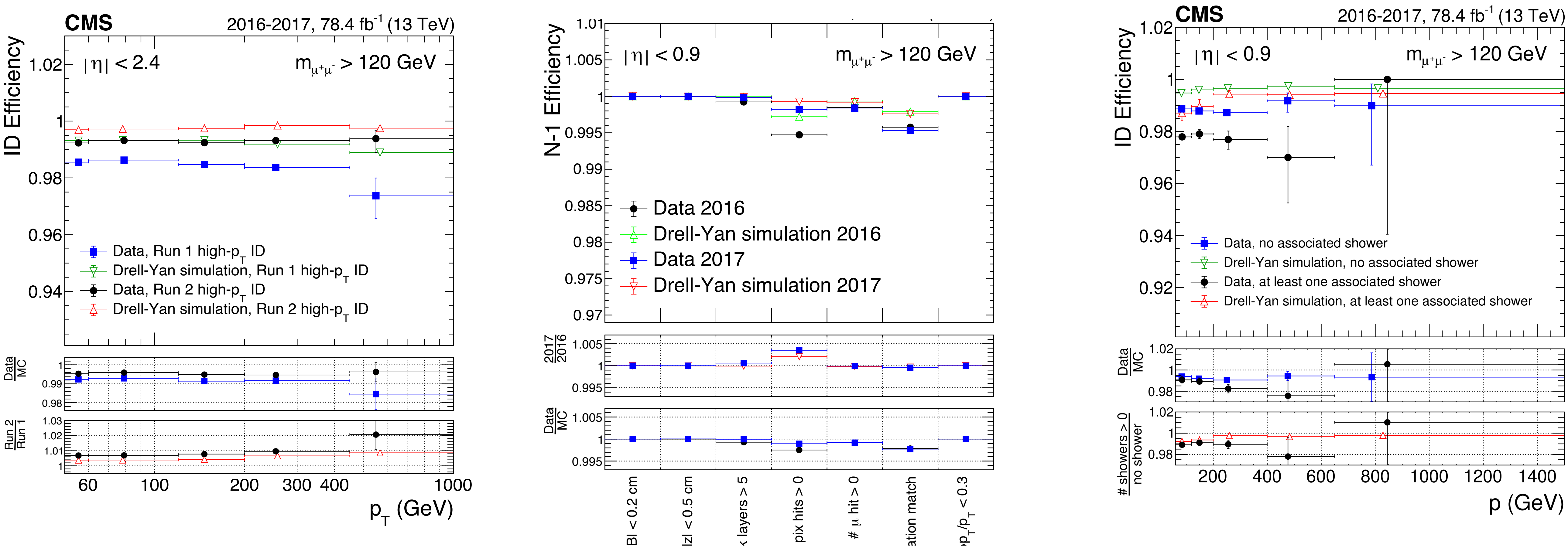
Tune-P performance in simulated samples and real data

Results shown for the muon system barrel as an example



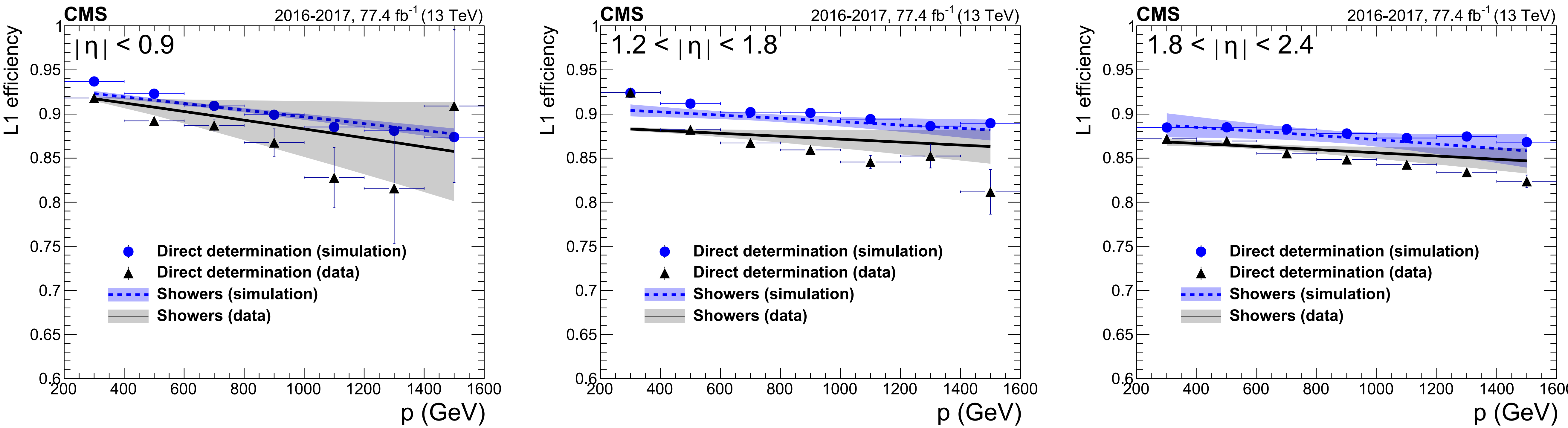
- Tune-P is optimized (and its performance is studied) with simulations:
  - Considering different alignment scenarios (and alignment errors - APE) of tracker and muon system
  - Comparing its performance with the one of different refits (e.g. inner-tracker or global), also in events "with showers"
- The consistency of the Tune-P decision choice in data and simulation is then validated
  - Using dimuon events from data which satisfy dedicated ID criteria (high-p_T ID) and have a $p_T > 200$ GeV
  - Comparing with MC events (DY, diboson, $t\text{-}\bar{t}$, single-top MC) satisfying the same selection as for data

Muon identification efficiency (more details)



- The high-p_T selection criteria was retuned over Run-2 to feature a ~1.5% (1%) increase in data (MC)
- Its efficiency was measured, with the *extended tag-and-probe method*, w.r.t. reconstructed global muons
  - Including N-1 measurement of the efficiency of single cuts
  - Studying performance in events with showers
- The selection efficiency is ~98% (data) with a ~1% data/MC discrepancy
  - In presence of showers, efficiency degrades of ~1% in barrel, and data/MC agreement worsens
  - No significant p_T dependence is observed (incl. events with showers)

Level-1 trigger efficiency (shower-based measurement)



- Trigger efficiency is measured exploiting two different strategies:
  1. With the *extended tag-and-probe method*
  2. Using datasets collected with *non-muonic* triggers (e.g. e-gamma triggers)
- In case 2., the Level-1 trigger efficiency is also computed:
  - Assuming that p dependence is only due to the increased probability of generating showers at higher momentum
  - Computing the efficiency as function of # showers and convoluting it with the shower probability vs p to get "ε vs p"