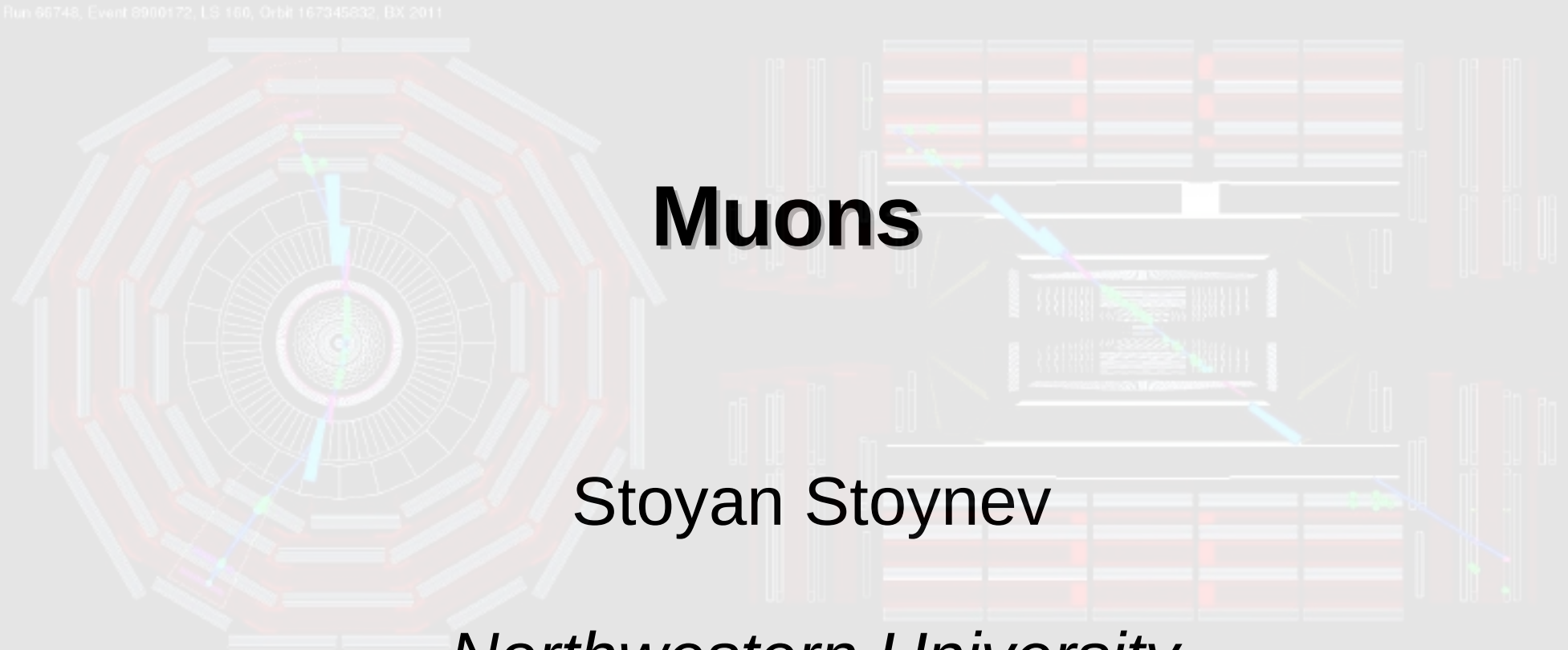
# LPC JTERM IV



## Muons

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# Outline

- Muons - Introduction
- Muon reconstruction types
  - STA muons
  - Tr muons
  - GLB muons
- Muon object and collections
- Performance
- Muon identification
- Muon isolation

# Muons - Introduction

- Muons are part of the signature for many interesting processes
- There are obvious requirements for the muon reconstruction:
  - High reconstruction efficiency at low fake and “ghost” rate
  - Precise and robust momentum measurement over large momentum range (1-$10^3$ GeV)
  - Full (uniform) coverage within the detector acceptance
- To achieve these main goals the muon reconstruction make use of essentially all the detectors
  - the redundancy of the three different muon detectors - DT, CSC and RPC
  - the tracker
  - precise knowledge of the magnetic field
  - The ECAL and HCAL systems

# The muon system in CMS

a muon:

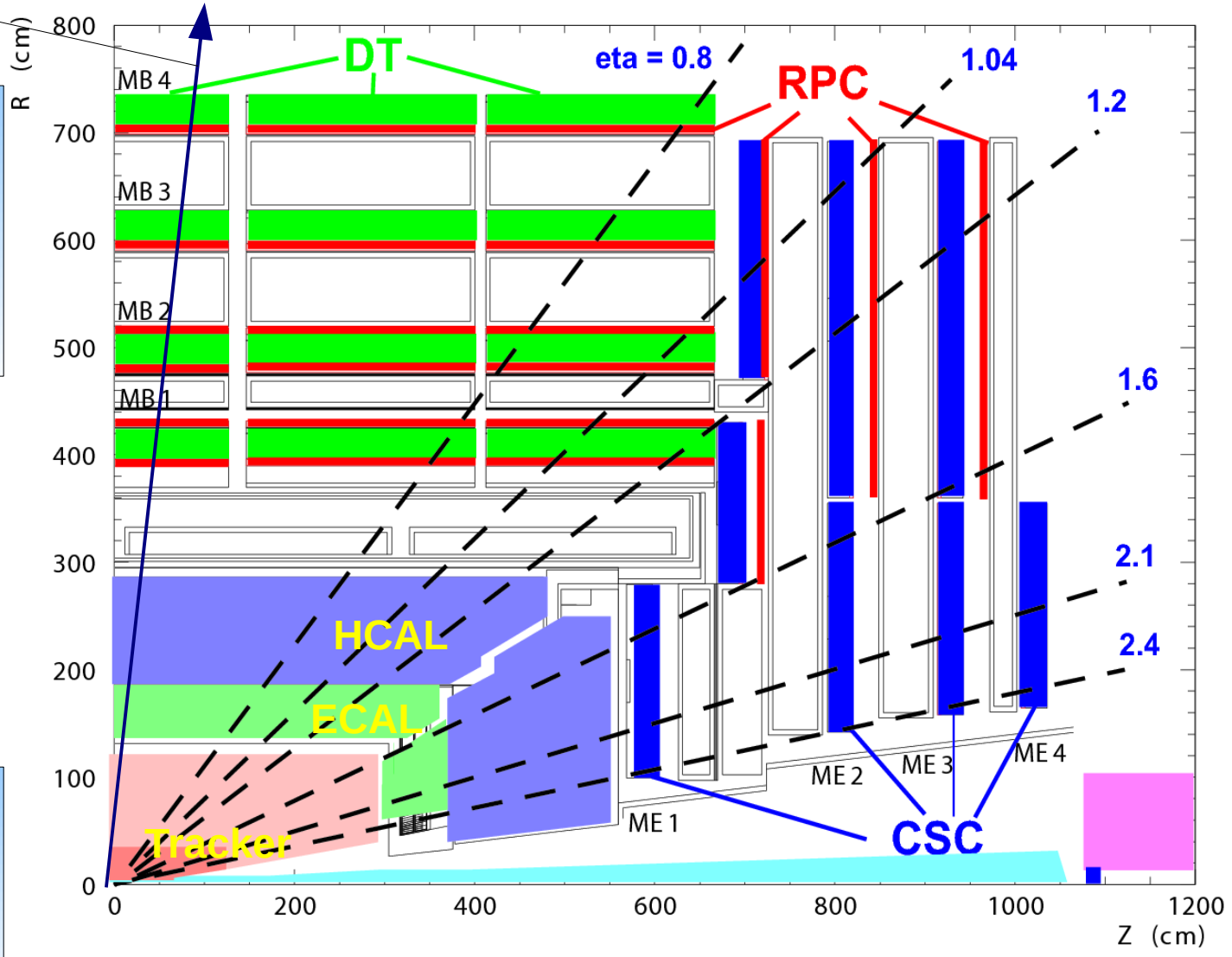
Precise signal from the muon chambers; bending mainly in first two stations (and magnetic field not so homogeneous)

Energy loss in supporting walls, yokes, coils

Only MIP signal in calorimeters

Very precise tracking signal in the silicon tracker; bended by the magnetic field

## A graphic view



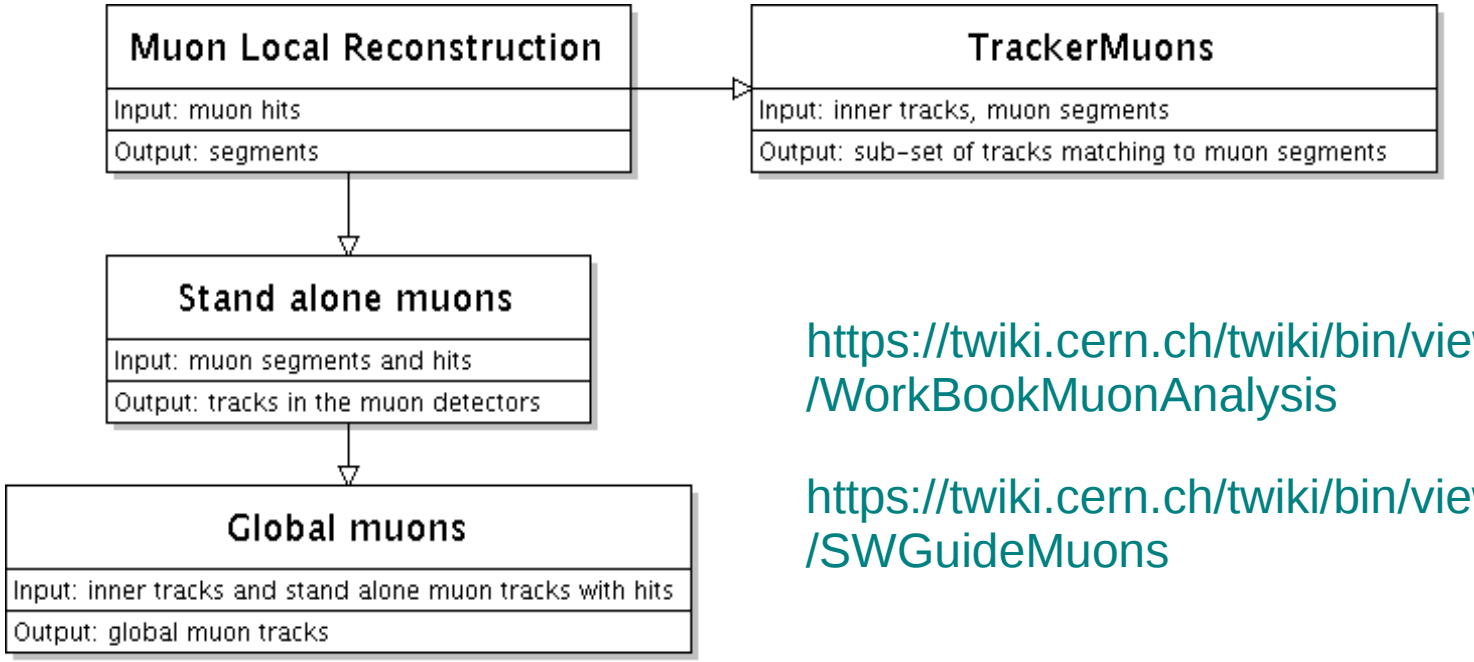
# Muons – three different reco types

- There are three main reconstruction type muons – StandAlone (STA) , Tracker (Tr) and Global (GLB) muons
- They facilitate different approaches in the muon reconstruction

  1) STA muons use information from the muon system only

  2) Tr muons are tracker tracks with “matched” muon signature in the muon system

  3) GLB muons come from a global fit over hits in the muon system and the tracker




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

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

# 1) STA muons

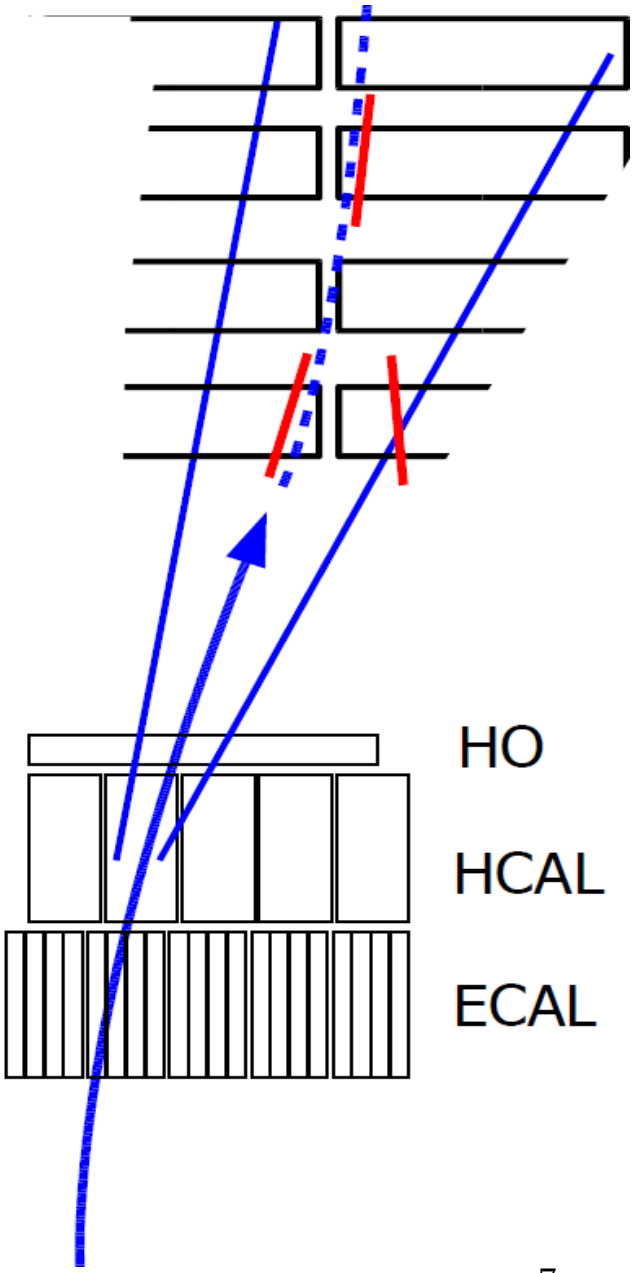
- Seed
  - This is the initial trajectory estimate
  - It is formed by a pair of segments - CSC and/or DT generally
  - It gives the initial starting point for the STA muon reconstruction and an initial pT estimate calculated by the bending of the segment pair
- Pattern recognition
  - Based on Kalman fit (filter) technique
  - Hits from the DT, CSC and RPC detectors are being collected along the Seed propagation to form a Trajectory
  - The Stepping helix propagator employed in the process includes all of the magnetic field and material effects treatment internally
- Smoothing
  - At the end an additional (“backward”) Kalman fit is applied which uses the covariance matrices of all the measurements in the already built trajectory
  - Thus the final parameters and their error estimations are more robust



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

# 2) Tr muons

- It is an "inside-out" approach
  - Seed: every tracker track is considered a Tr muon candidate
  - If a track is "matched"* to muon segments it becomes a Tr muon (new object)
  - There is no fit involved – the Tr muon kinematic parameters coincide with the tracker track parameters




Like for all the muon reco types , there is a lot of additional "muon" information stored – energy deposits in calorimeters, traversed (by propagation) muon chambers, distance to segments, etc. See later.



*Only tracks with pT > 1.5 GeV are tried, a minimum number of matched segments is required

# 3) GLB muons

- It is an "outside-in" approach
  - Seed: every STA muon is considered a GLB muon candidate
  - A muon is eventually "matched" to one or more tracker tracks*
  - After a Global (Kalman) refit of silicon and muon hits for all STA-Tr muon matched pairs, maximum one (best $\chi^2$) GLB muon is retrieved for each STA muon
  - (It is a new Trajectory that is fit and smoothed combining tracker and muon hits)

A note:

The reconstruction of STA muons make use of the convention of valid (used in the fit) and compatible (used for matching with the tracker) hits

It is possible that all the hits are invalid (due to tight $\chi^2$ requirement) but still compatible

Then the STA muon would have 0 (valid) hits – the seed parameters become STA muon parameters

Eventually the GLB muon corresponding to this STA muon will contain no muon hits!

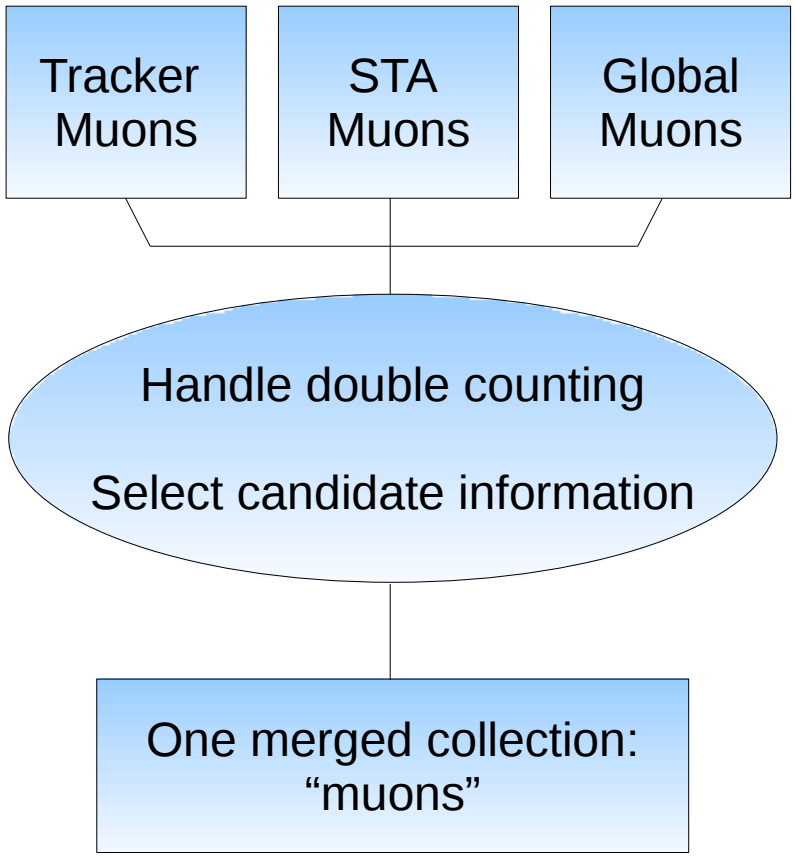


*Matching criteria are different from the ones used to find Tr muons

# Muon object and muon collection

- The three types of reconstructed muons are merged in a single muon object (reco::Muon) and the collection of these objects is named “muons”
- The muon types stored in the object are inclusive

- For each of the muon types helpful variables are being stored
  - Identification variables
  - Isolation variables
  - Energy depositions
  - Timing information
- These variables are to be used in analyses for muon selection
- As it is, the muon object is built for efficiency – additional selection is needed to get a clean muon!



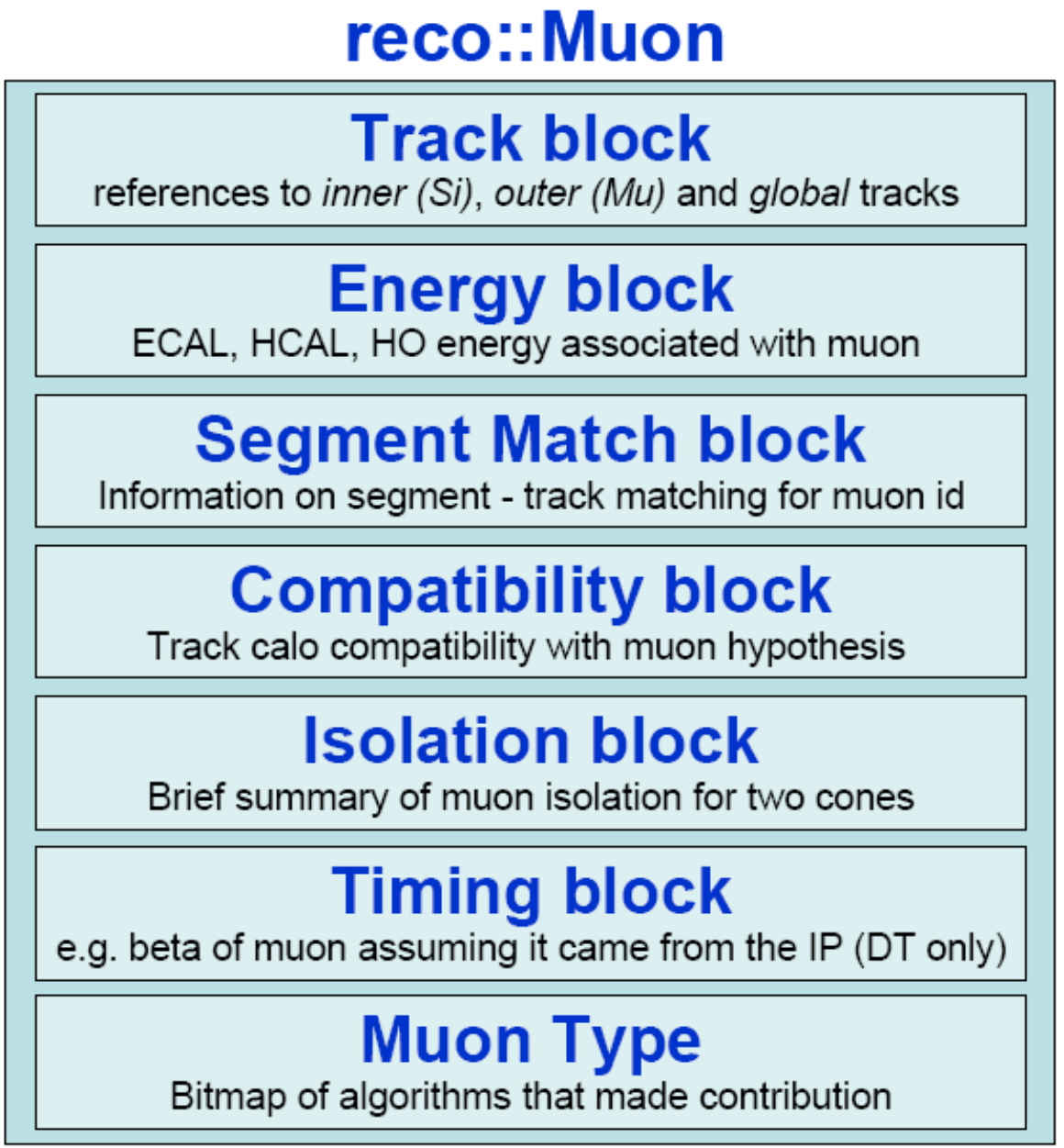



https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideDataFormatRecoMuon

# Muon object reco::Muon

- An object in the muon collection contains all the available muon information
- Currently it (directly) retrieves the information from the “best” reconstruction available (GLB -> Tr -> STA)
- However each of the (available) muon reco tracks (STA, Tr, GLB) can be retrieved by its reference in the muon object

Since Pat::Muon object inherits from reco::Muon object the same information is accessible there too






http://cmslxr.fnal.gov/lxr/source/DataFormats/MuonReco/interface/Muon.h

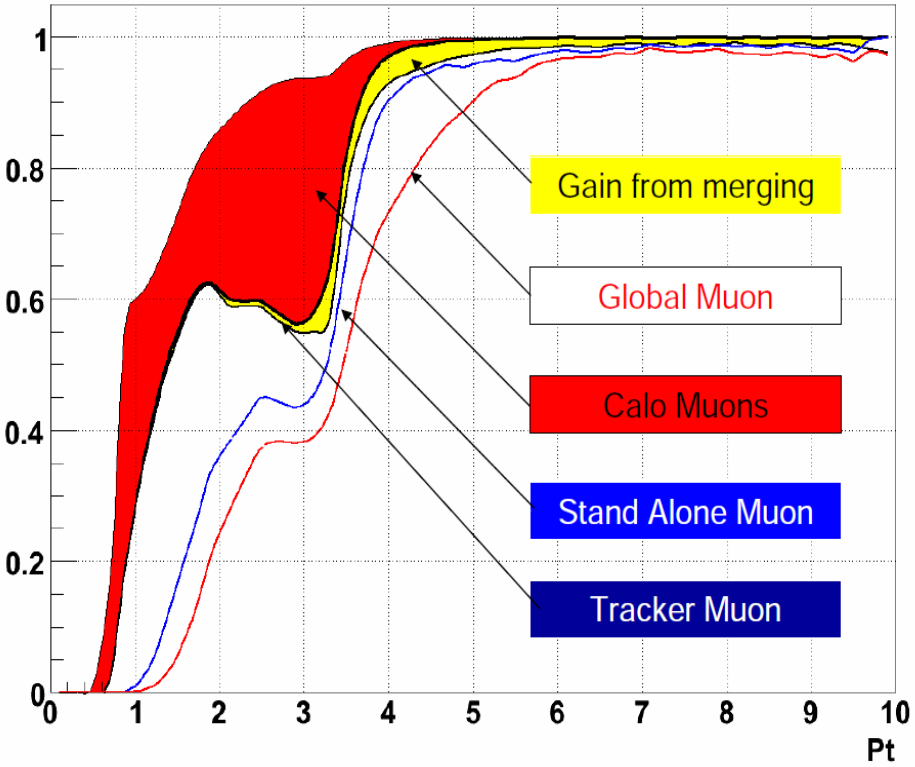
# Special muon collections

- TeV muons (OK, technically it is not a separate collection but a separate GLB refit with tracker and selected muon hits)
  - Optimized for muons with energies above few hundred GeV
  - Needed since radiation becomes leading reason for energy loses – the reconstruction quality is degraded
- Calorimeter based muons
  - A tracker track compatible with MIP energy deposition in the calorimeters (caloCompatibility ) leads to a caloMuon
  - Currently it is an exclusive collection (tracks are considered caloMuon candidates only if not reconstructed as GLB or Tr muons)
  - There is no minimum pT requirement for the track to become a caloMuon
- Cosmic muons (https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideCosmicMuonReco)
  - It is a very special collection – the muon reconstruction is DIFFERENT from the standard reconstruction which has important Interaction Point (IP) constraints!
  - Like in the standard reconstruction there are various muon types – generally put in “GLBMuons*” and “STAMuons*” collections

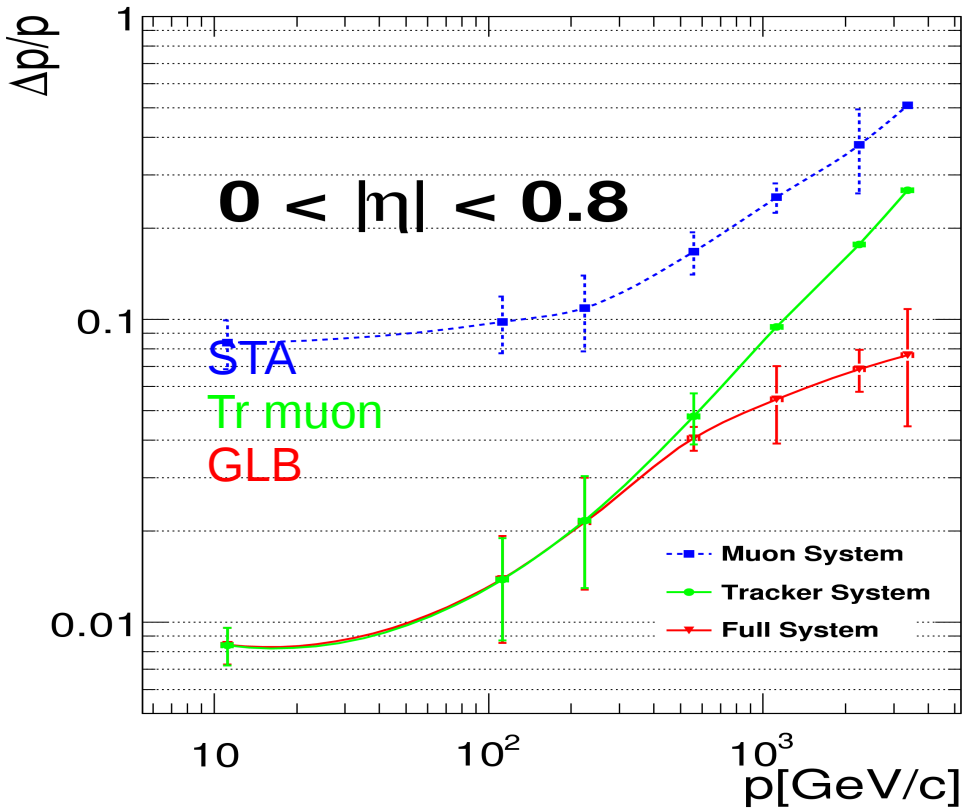
# Gains from having different reco muons

- Increased efficiency
- More options for background subtraction
- Increased momentum coverage (maintaining high efficiency)
- Improved momentum resolution at higher energies

Efficiency

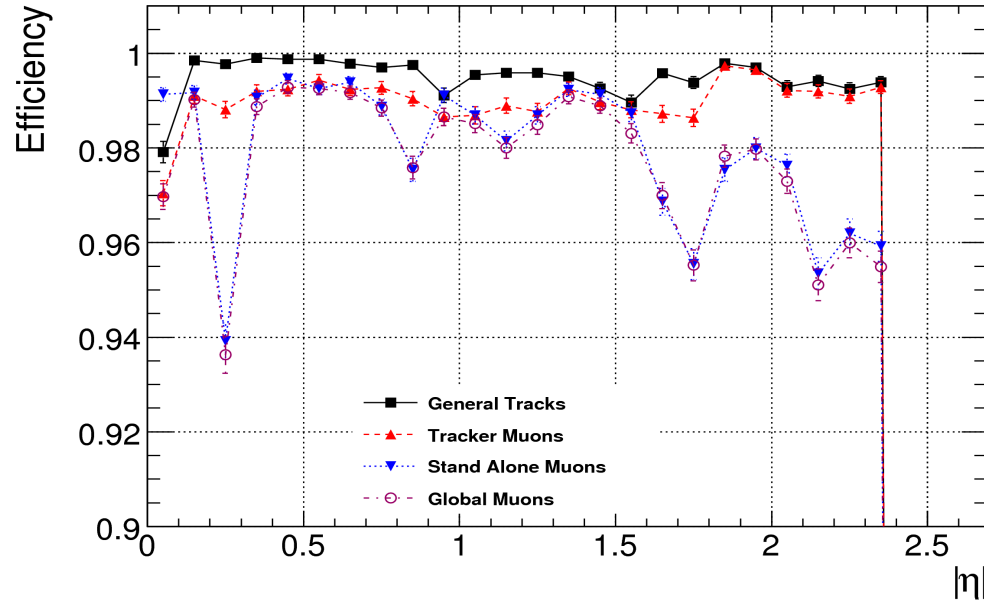


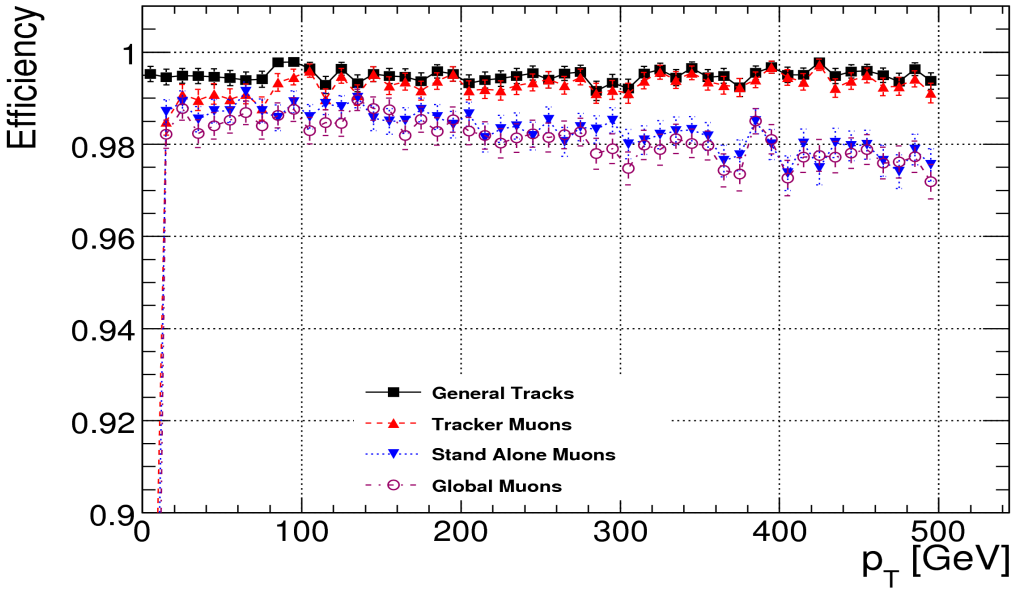

Momentum resolution



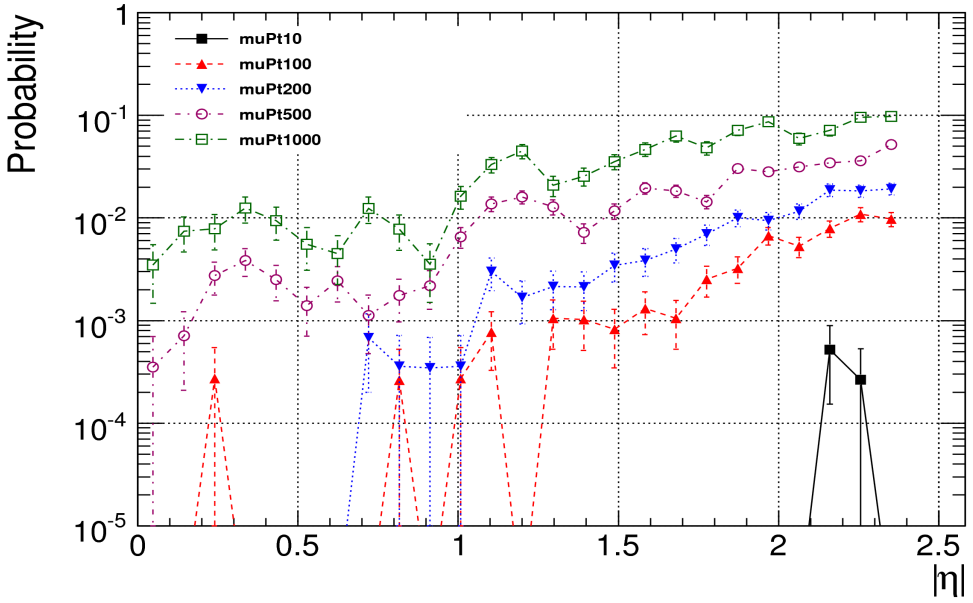
# Performance of different reco muons

## Efficiency (main muon types) in eta and pT

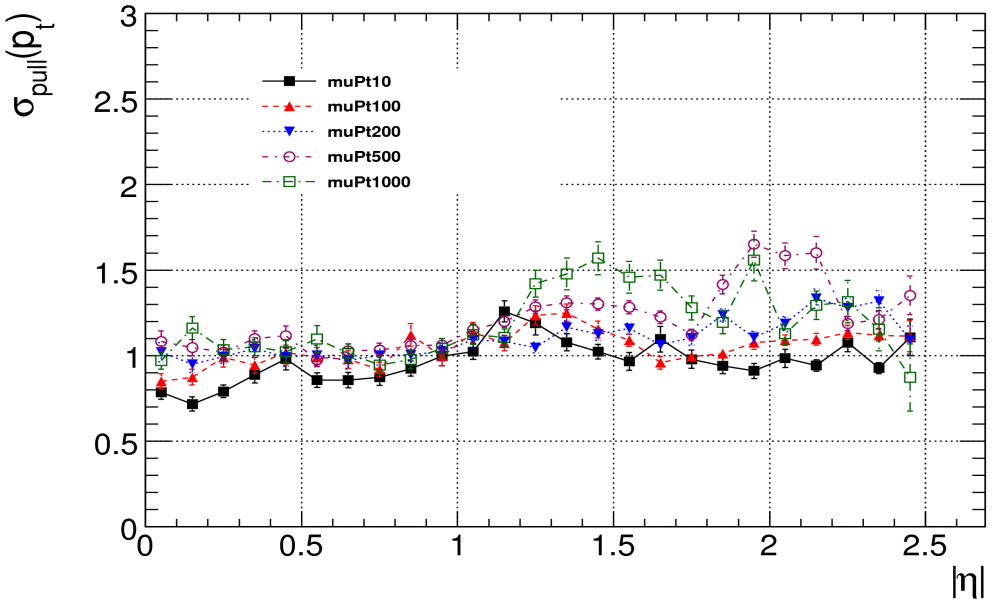



## Charge mis-ID at various momenta (GLB)




## Pulls at various momenta (GLB)



# Muon identification

- Aimed at providing discriminative variables and selection functions to help identifying the muon tracks as true muons – all accessible through the muon object
- The variables currently in use can be categorized as
  - Cut-based ID for GLB muons: they consist of GLB muon quality variables (including a tracker track variables)
  - Cut-based ID for Tr muons: related to track-penetration depth in the detector
  - Likelihood-based ID for Tr muons: use the compatibility of the calorimeter response with the muon hypothesis (caloCompatibility) and the presence of matched segments in the muon system (segmentComatibility)
- A single selection function is also available with predefined selection types which are algorithms exploring the variables above (next page)

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

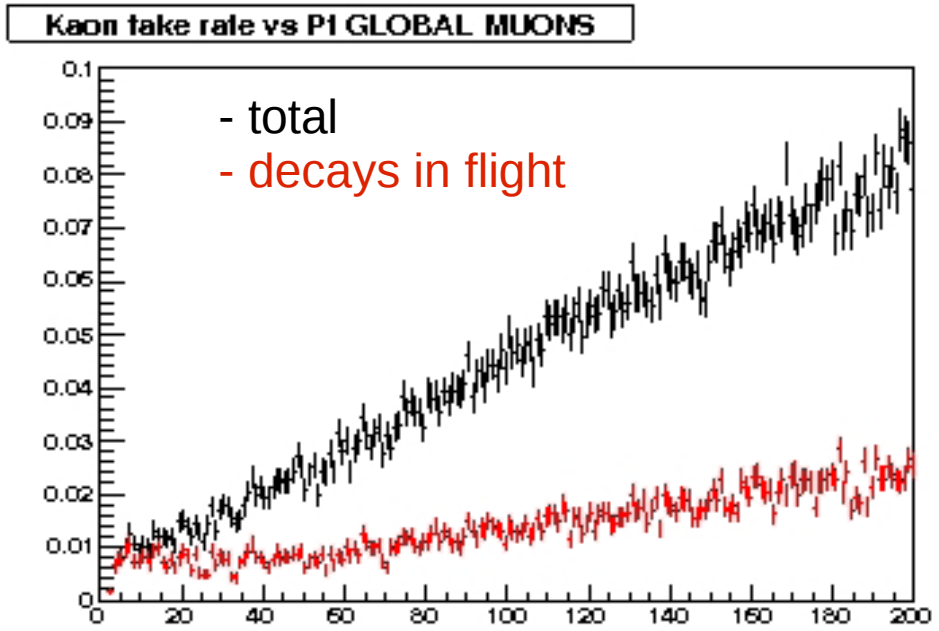
# Muon identification (2)

| ***Selection type*** | ***Action*** |
|---|---|
| **TrackerMuonArbitrated**<br>**AllArbitrated** | Resolves shared segment ambiguities |
| **GlobalMuonPromptTight** | Cuts on chi2, N hits (, d0 – not used) |
| **TMLastStationLoose**<br>**TMLastStationTight**<br>**TMOneStationLoose**<br>**TMOnetStationTight** | Cuts on maximum penetration depth (matched segments parameters) |
| **TMLastStationOptimizedLowPtLoose**<br>**TMLastStationOptimizedLowPtTight** | Efficiency-optimized for low Pt |
| **TM2DCompatibilityLoose**<br>**TM2DCompatibilityTight** | Cuts on segment and calorimeter compatibilities |

# Muon identification (3)

- To illustrate the application let's consider kaons which get reconstructed as muons
  - these will be “fake” muons
  - the fake rate would be the fraction of generated kaons reconstructed as muons

Kaon fake rate for GLB muons (similar for Tr muons)*




What selection should we apply to decrease the fake rate at no great cost for losing real muons?

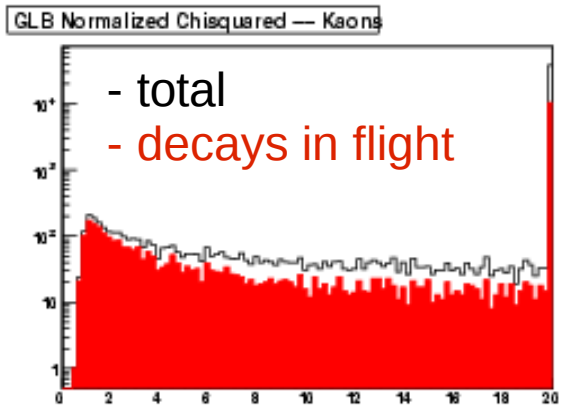
*There are indications that the decays in flight rate is actually overestimated. This will mean that the punch-through rate is underestimated (total is *const*).

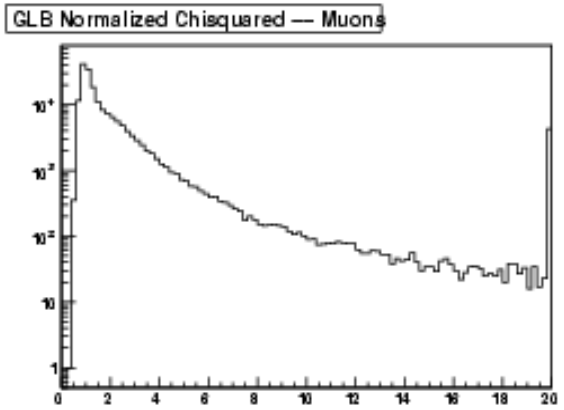
# Cut-based ID for GLB muons

"Fake" muons

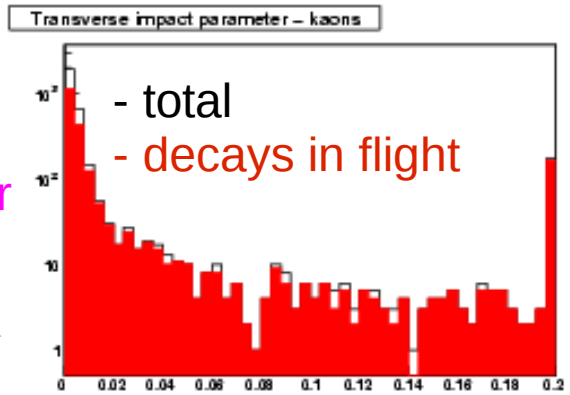
Real muons

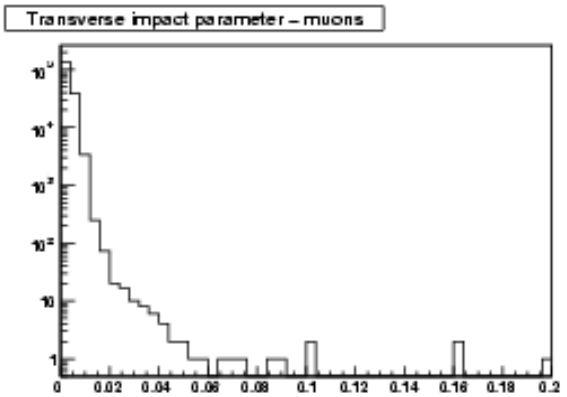
$\chi^2$/ndf




Impact parameter (d0, cm)




One can consider also the number of hits in the GLB muon (possibly es a function of eta)

- Recommended:
  - chi2/ndf< 10
  - |d0| < 2 mm
  - Nhits>10

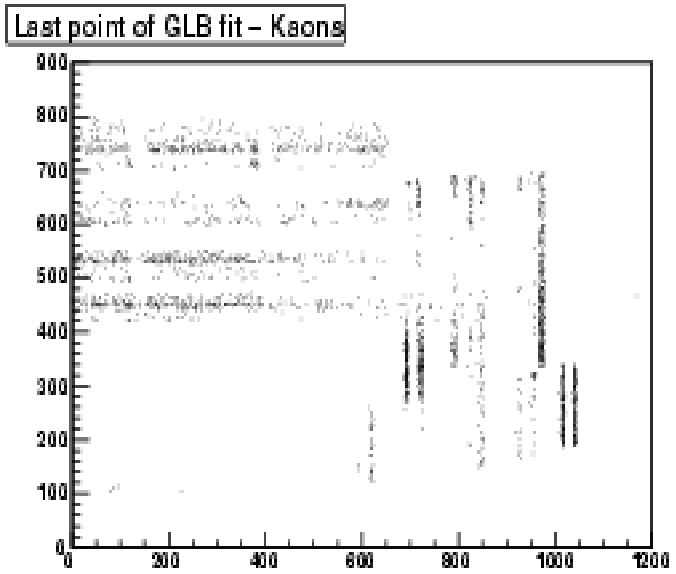
$\chi^2$ and impact parameter distributions are generally wider for fake muons

# Cut-based ID for GLB muons

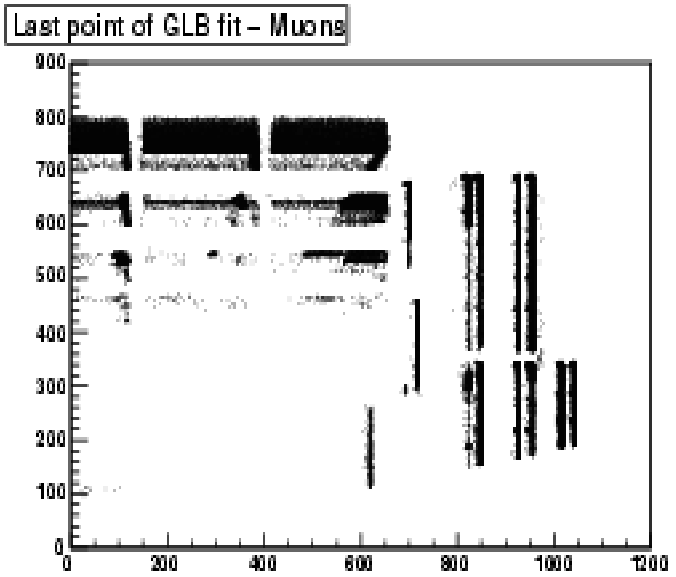
- One can directly cut on the position (Z, r) of the last measurement in the GLB fit – muons penetrate deeper
- Or/and apply tracker track penetration criteria (see later)

Last point of the GLB fit in (Z,r) plane

"Fake" muons




Real muons*

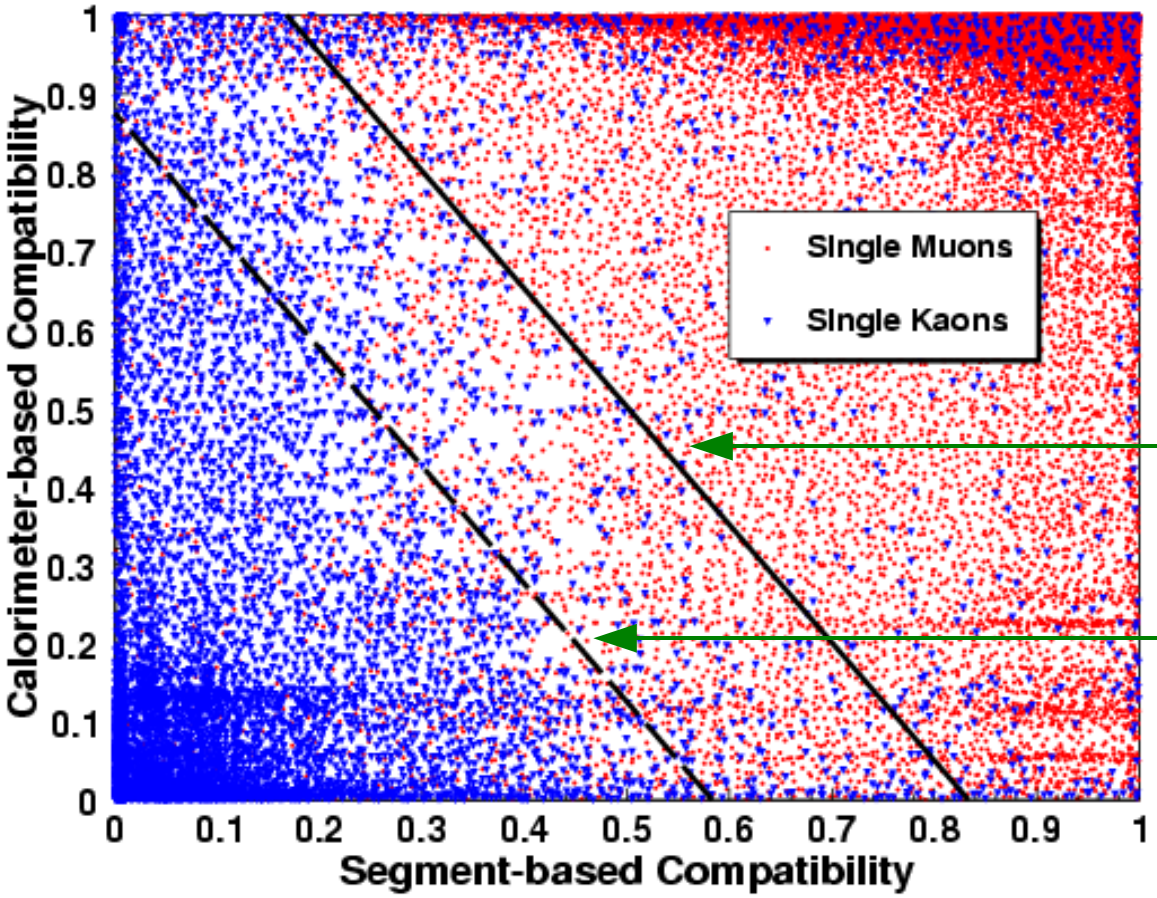



~20% reduction of the fake rate is achievable without significant loses of muons

*There was a track reconstruction problem in the CSC area (as seen on the right plot) which is already fixed

# Likelihood-based ID for Tr muons

Distribution of Calorimeter and Segment Compatibilities for real and “fake” muons (kaons)

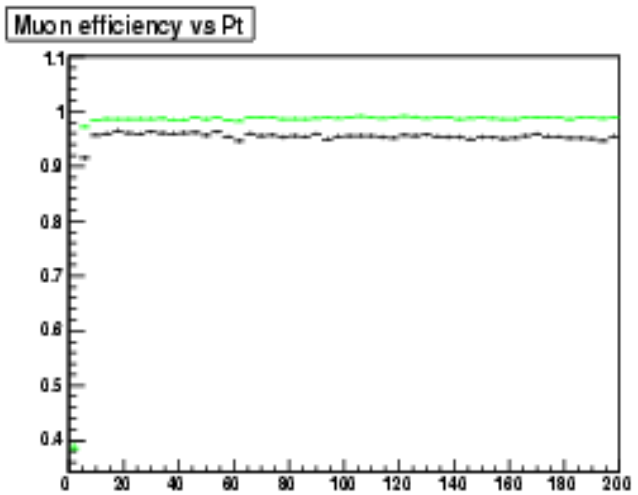



**TM2DCompatibilityTight**

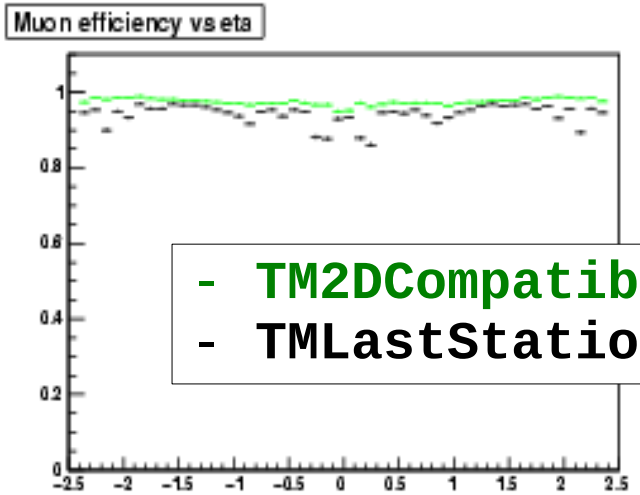
**TM2DCompatibilityLoose**

# Likelihood-based and cut-based ID for Tr muons

Efficiency (real muons)



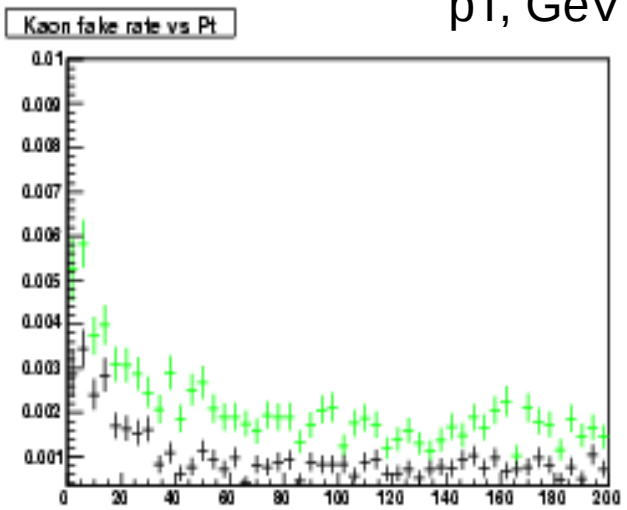

pT, GeV

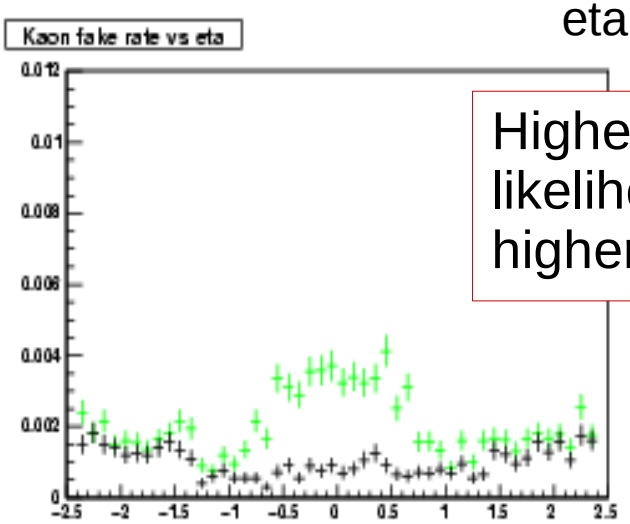



eta

- **TM2DCompatibilityLoose**
- **TMLastStationLoose**

"Fake" rate



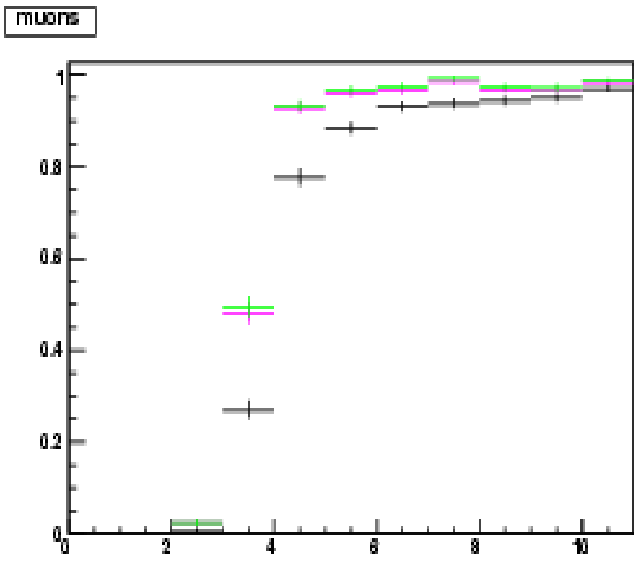




Higher efficiency for likelihood-based but higher fake rate too

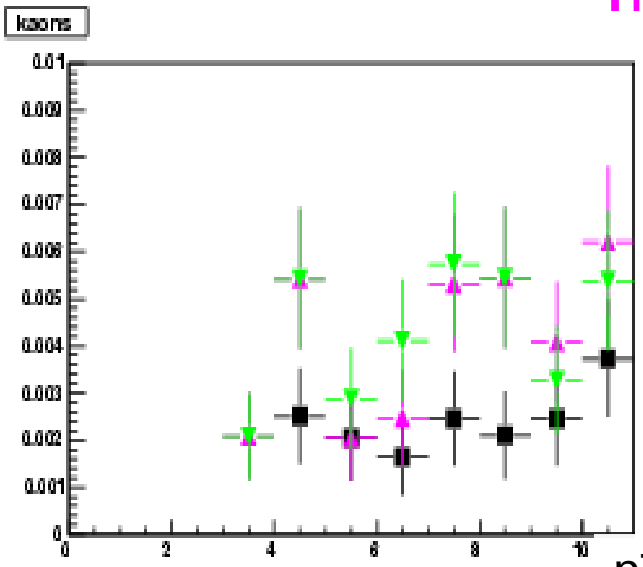
- **TMLastStation** requires at least two well matched segments (one in the last station crossed):
  $|\Delta X| < \mathrm{Max}(3\sigma, 3\ \mathrm{cm})$ (**TMLastStation [Loose | Tight]**)
  $|\Delta Y| < \mathrm{Max}(3\sigma, 3\ \mathrm{cm})$ (**TMLastStationTight**)

# Cut-based ID for Tr muons

Efficiency
(real muons)




"Fake" rate




pT, GeV

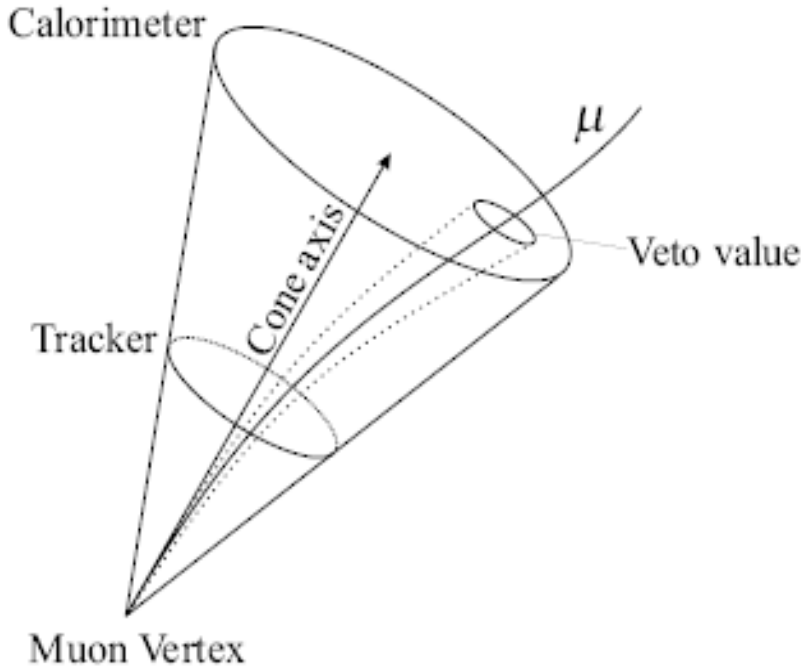
- **TM2DCompatibilityLoose**
- **TMLastStationLoose**
- **TMOneStationLoose**

- **TMOneStation** requires at least one well matched segment. It is conceived to be used in conjunction with **TMLastStation** (to recover efficiency at low pT).
- An optimized selection exists
  **TMLastStationOptimizedLowPt[ Loose | Tight ]**:
  - **TMOneStation[Loose|Tight]** for |eta| < 1.2 and Pt < 8GeV
  - **TMLastStation[Loose|Tight]** at higher eta and/or higher Pt

# Muon isolation

- Aimed at providing discriminative variables to help distinguishing isolated muons from muons embedded in jets
- There are pre-computed isolation variables defined in cones of $\Delta R = [(\Delta\varphi)^2 + (\Delta\eta)^2]^{1/2} = 0.3$ and $0.5$
- They are accessible for all the muon types:

  - number of tracks and number of jets
  - Summed pT of tracks
  - Summed Ecal, HCAL and HO energies
  - Energy and pT in veto cone

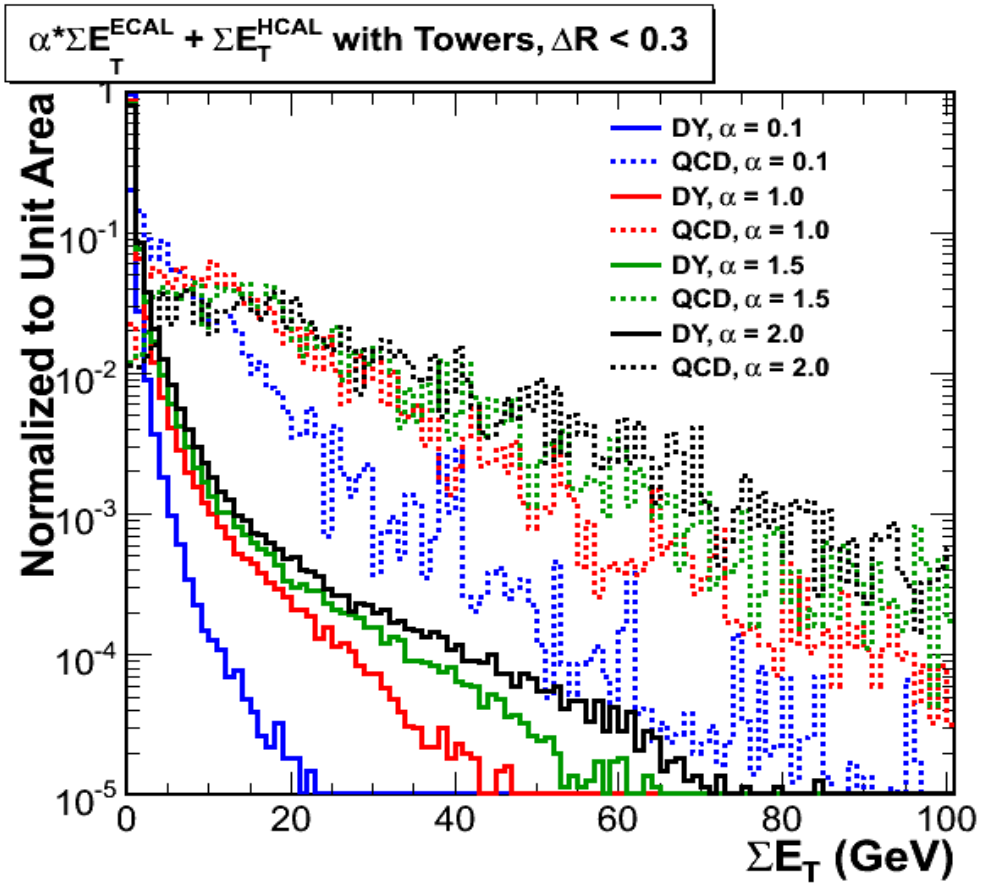


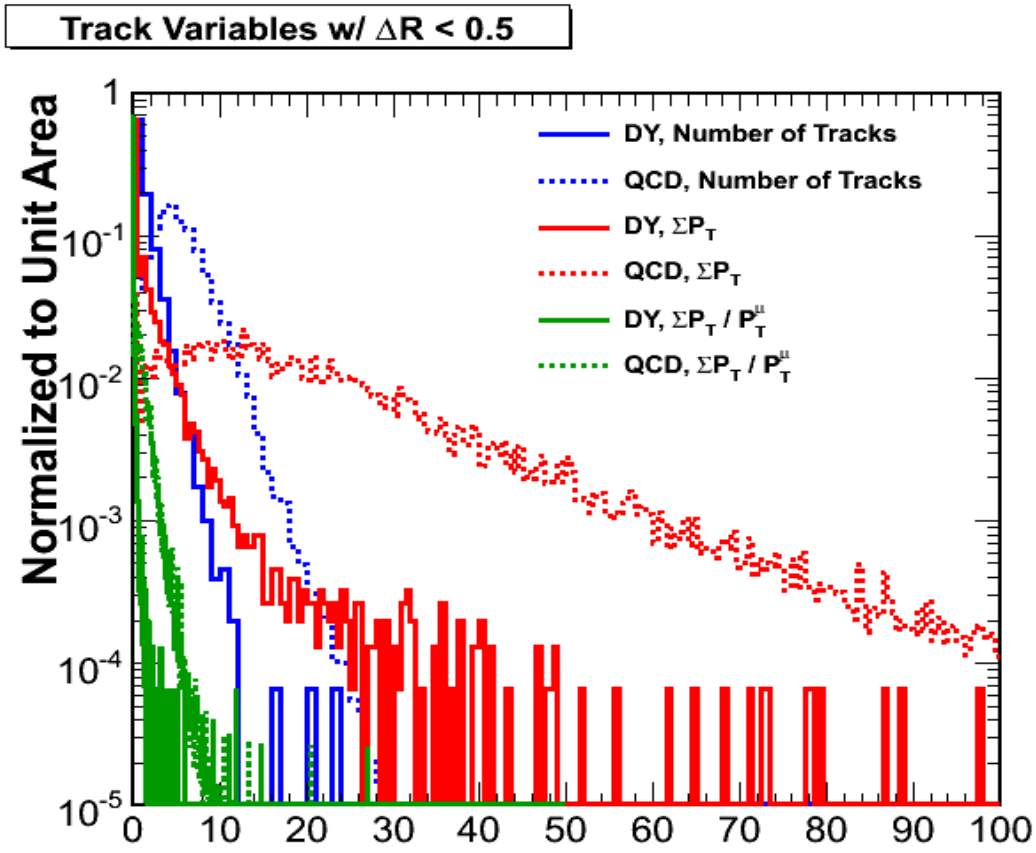

It is possible to define different cone radii or even different shapes for isolation (requires additional effort)

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

# Muon isolation (2)

- In general, the optimal isolation requirements would depend on the process under investigation and selection applied
- Here – Drell-Yan (DY) and QCD samples compared




- A suggested starting point would be (in ΔR<0.3):
  - trackIso = SumPt < 3 GeV
  - caloIso = sumEtHcal+sumEtEcal < 5 GeV
  - Or explore relIso = (trackIso+caloIso)/muonPt < *x*

# Summary

- Muons can be reconstructed (simultaneously) by three different algorithms thus producing three muon reco types
- A single muon collection “muons” contains the information about the reconstructed muons – it's virtue is “efficiency” but not “purity”
- Additional information stored in the muon object (Identification and Isolation) allows to further purify muons and reject backgrounds efficiently
- There are special muon collections (that can be) used for specific purposes
- Related CMS notes (published or being written):
  - http://cmssw.cvs.cern.ch/cgi-bin/cmssw.cgi/cmsnotes/MPOG/
  - CMS AN-2008/097 and CMS AN-2008/098
- Additional basic information not covered here:
  - PAT muons https://twiki.cern.ch/twiki/bin/view/CMS/EWKPatDefaults21X#Muons
  - HLT muons https://twiki.cern.ch/twiki/bin/view/CMS/MuonHLT

# How to access the information

Muon RECO collection
(of muon objects)

```
edm::Handle<reco::MuonCollection> muons;
event.getByLabel("muons",muons);
reco::MuonCollection::const_iterator muon;
```

Muon PAT collection
(of muon objects)

```
edm::Handle<View<pat::Muon> muons;
event.getByLabel("selectedLayer1Muons",muons);*
View<pat::Muon>::const_iterator muon;
```

Which reco type
(which algorithm found this muon)

```
bool muon::isStandAloneMuon()
bool muon::isGlobalMuon()
bool muon::isTrackerMuon()
```

Reference to the tracker,
STA and global tracks
(and their parameters)

```
TrackRef muon::track()
TrackRef muon::standAloneMuon()
TrackRef muon::combinedMuon()
```

Time

```
MuonTime muon::time()
```

*In PAT2 (CMSSW_2_2_11 onward) the label is "cleanLayer1Muons"

# How to access the information (2)

Identification by selection types

```
bool muon::isGoodMuon( const reco::Muon& muon,
                       muon::SelectionType type )
```

Identification by Likelihood variables

```
muon::caloCompatibility()
muon::segmentCompatibility()
```

Isolation

```
MuonIsolation muon::isolationR03()
MuonIsolation muon::isolationR05()
```

Isolation variables

```
float muon::isolationR03().hadEt
float muon::isolationR03().emEt
float muon::isolationR03().hoEt
float muon::isolationR03().sumPt
int muon::isolationR03().nTracks
int muon::isolationR03().nJets
int muon::isolationR03().trackerVetoPt
int muon::isolationR03().hadVetoEt
int muon::isolationR03().emVetoEt
int muon::isolationR03().hoVetoEt
```

# How to access the information (3)

TeV muons

```
edm::Handle<reco::TrackToTrackMap> tevMap;
event.getByLabel("tevMuons",refit_name,tevMap);
```

with refit_name = "default", "first hit" or "picky"*

Calo muons

```
edm::Handle<reco::CaloMuonCollection> muons;
event.getByLabel("caloMuons",calomuons);
reco::CaloMuonCollection::const_iterator calomuon;
```

Cosmic muons

```
edm::Handle<reco::TrackCollection> muons;
event.getByLabel("cosmicMuons",muons);
reco::TrackCollection::const_iterator muon;
```

Use http://cmslxr.fnal.gov/lxr/ to search for class and variable definitions and their cross-references

*https://twiki.cern.ch/twiki/bin/view/CMS/WorkBookMuonAnalysis#TevMu
https://twiki.cern.ch/twiki/bin/view/CMS/WorkBookMuonAnalysis#CaloMu