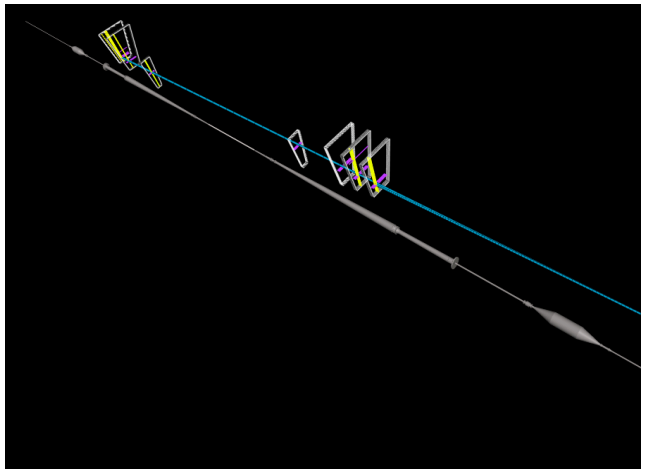
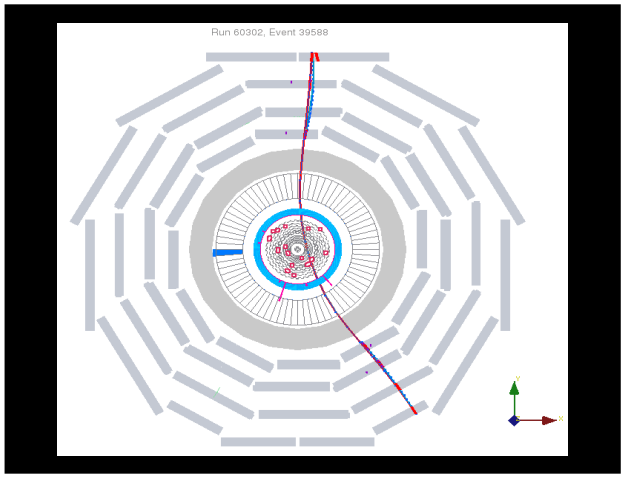
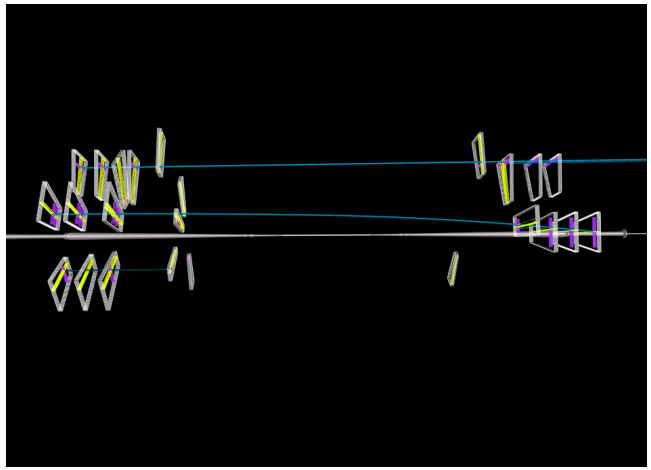
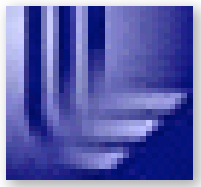






Introduction to muons

Jonathan Hollar (end user)
for the Muon POG (the developers)



The standard muon object

reco::Muon

- Data format is defined in

  DataFormats/MuonReco/interface/Muon.h

- The standard collection for offline analysis is simply "muons"

- So typical usage in an EDAnalyzer is something like:

```
edm::Handle<reco::MuonCollection> muons;

event.getByLabel("muons",muons);

reco::MuonCollection::const_iterator muon;
```

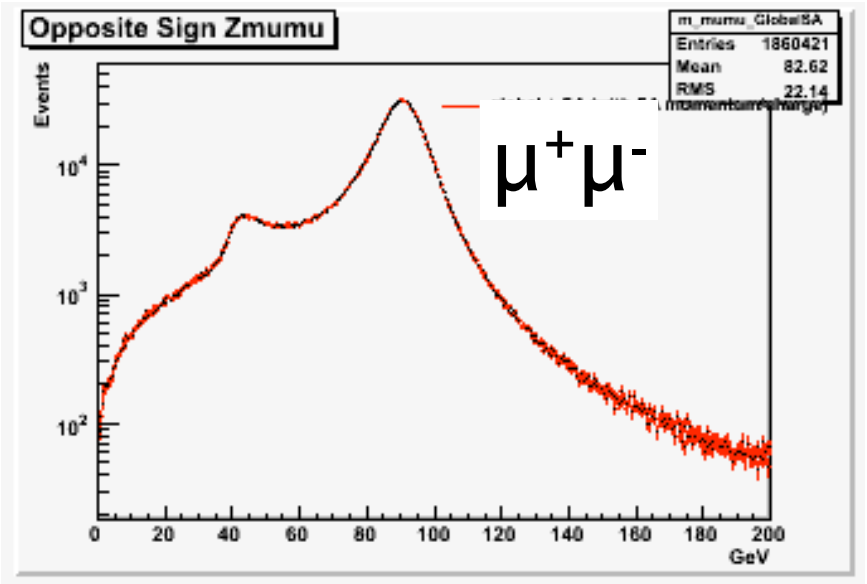
- As of CMSSW_1_7_X, three different muon reconstruction algorithms are merged in the "muons" collection: GlobalMuons, TrackerMuons, StandaloneMuons

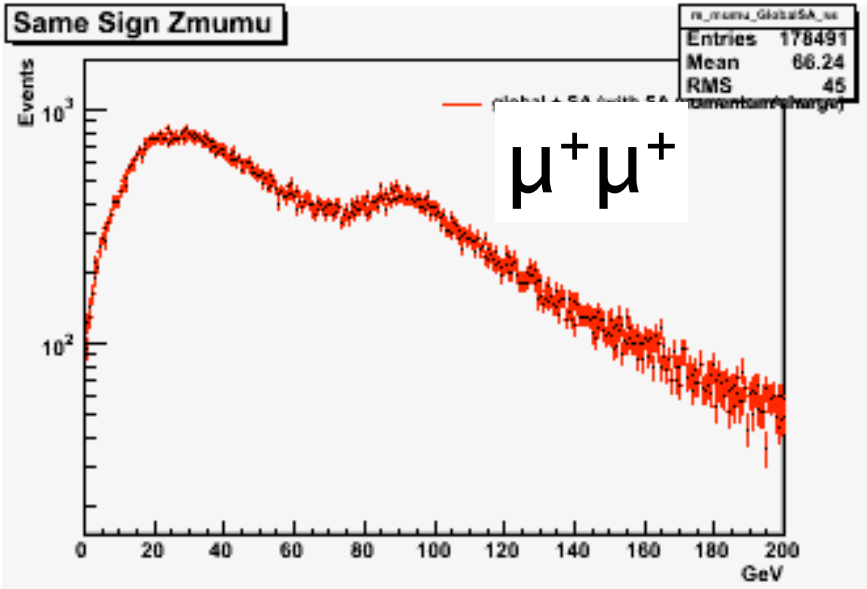
```
bool muon::isStandAloneMuon()
bool muon::isGlobalMuon()
bool muon::isTrackerMuon()
```

- Important concepts:
  - The three algorithms are not mutually exclusive - one muon can be in all 3 categories!
  - TrackerMuons are not a subset of GlobalMuons (or vice-versa)!

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

Standalone muons



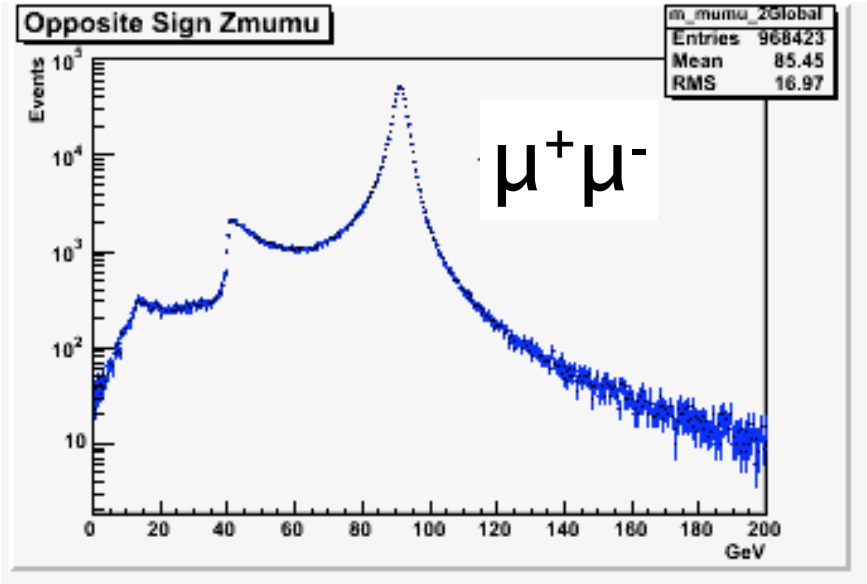


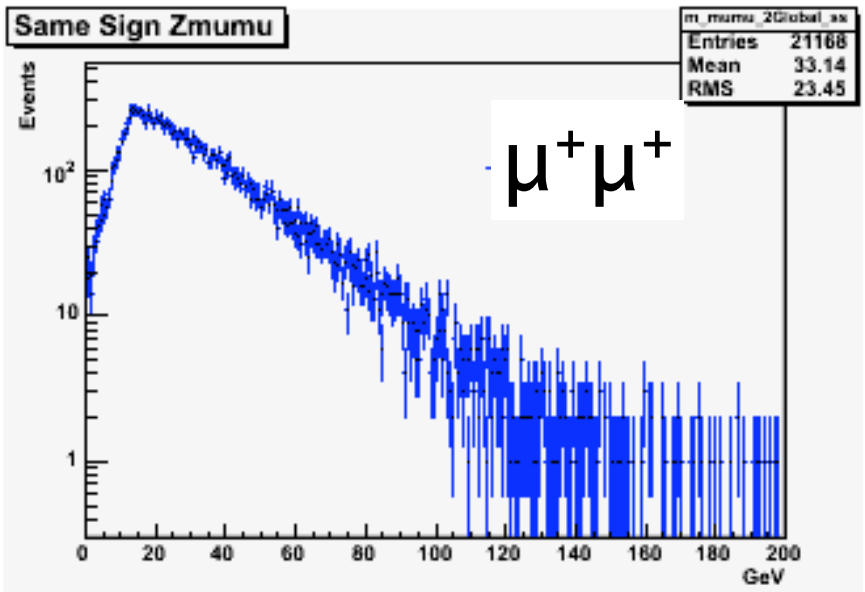
2_1_7 Z→μμ MC samples
(all plots by A. Fanfani)

- Muon chamber reconstruction only (no tracker information), requiring at least 2 muon segments

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

Global muons

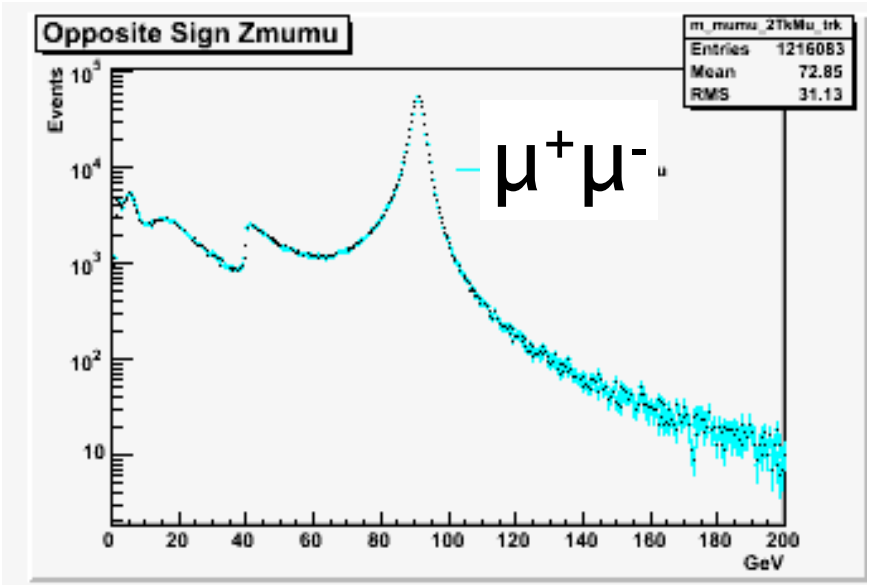


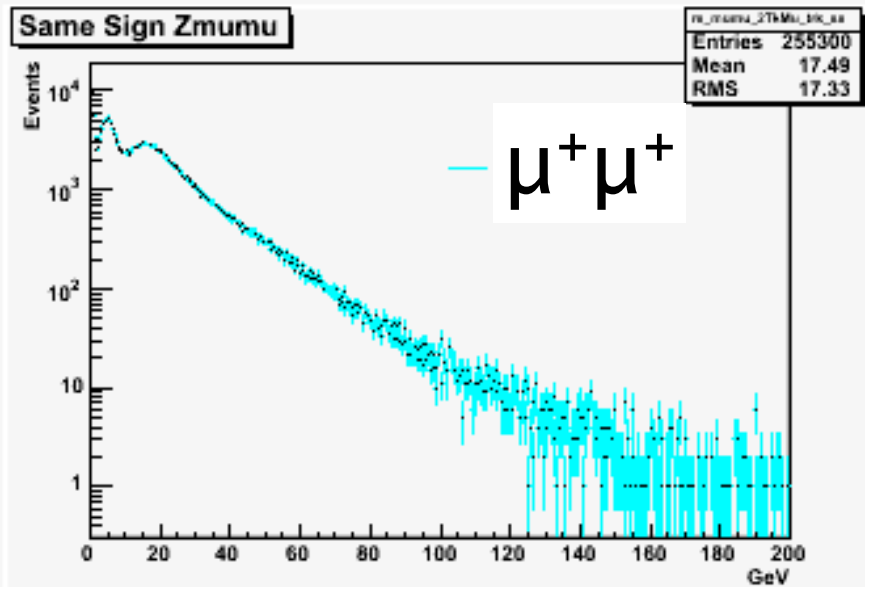


- Match a StandaloneMuon to a track in tracker, then perform a global refit using hits from both
- Generally should give the best performance (efficiency/fake-rate/resolution/ charge assignment) for muons from ~10GeV to ~1TeV

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

Tracker muons





- Match a track to at least 1 segment in the muon chambers - no global refit
- Best efficiency for low p_T muons ($J/\Psi \rightarrow \mu\mu$, $\gamma\gamma \rightarrow \mu\mu$, etc.), but also highest fake rate and ambiguities in matching multiple tracks to one muon segment - use only with additional selections/constraints

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

Muon kinematics

- reco::Muon inherits from RecoChargedCandidate - access to all the "usual" kinematic variables: pt(), eta(), phi(), etc.
- But one muon may be reconstructed by >1 algorithm → currently, the parameters returned by the muon object will be from the "best" reconstruction available
- Three possibilities (using p_T as an example)

1. GlobalMuon : muon→pt() returns the p_T from the global refit
2. TrackerMuon and not a GlobalMuon: muon→pt() returns the p_T from the tracker track
3. StandaloneMuon and not a TrackerMuon or GlobalMuon: muon→pt() returns the p_T measured in the muon chambers

- To be sure of getting a particular fit, the tracker only, muon system only, and global fit muons can be retrieved explicitly:

```
TrackRef muon::innerTrack()
TrackRef muon::outerTrack()
TrackRef muon::globalTrack()
```

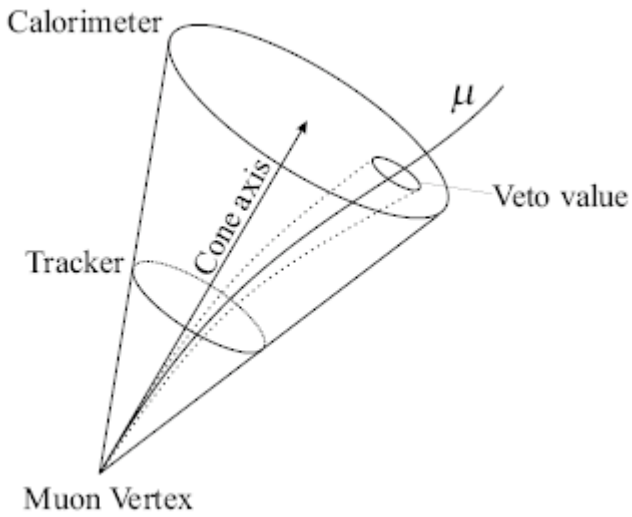
Isolation, selectors, and other variables

Muon isolation (I)

- No isolation is applied by default
- Pre-computed isolations in ΔR cones of 0.3 and 0.5 are accessible from the reco::Muon object
  - Can be used with "muons" reconstructed with any of the three algorithms
- Defined in

  DataFormats/MuonReco/interface/Muon.h

  DataFormats/MuonReco/interface/MuonIsolation.h



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

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

Muon isolation (II)

- For a given isolation cone, several calorimeter and track-based variables are available
  - Sum of HCAL E_T
  - Sum of ECAL E_T
  - Sum of H0 E_T
  - Sum of p_T of tracker tracks
  - Number of tracker tracks
  - Number of jets (sisCone Calo5Jets)

Accessible from the isolation object (using $\Delta R = 0.3$ for example):

float muon::isolationR03().hadEt

float muon::isolationR03().emEt

float muon::isolationR03().hoEt

float muon::isolationR03().sumPt

int muon::isolationR03().nTracks

int muon::isolationR03().nJets

Muon selectors (I)

- Further selections are available to clean up the reconstructed muons
  - These are especially important for low-purity muons (e.g. TrackerMuons)
  - Results of the selector decisions are accessible from the reco::Muon object:

```
bool muon::isGood(SelectionType type);
```

  - Where "type" is the name of the muon selector algorithm
  - These are defined in:

DataFormats/MuonReco/interface/Muon.h

DataFormats/MuonReco/interface/MuonSelectors.h

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

Muon selectors (II)

- The selector "type" can be one of 11 different options:

Alternative way to select Global/ Tracker/Standalone muons	reco::Muon::All reco::Muon::AllGlobalMuons reco::Muon::AllStandaloneMuons reco::Muon::AllTrackerMuons
Resolves shared segment ambiguities in TrackerMuons	reco::Muon::TrackerMuonArbitrated reco::Muon::AllArbitrated
Cuts on DOCA, X^2, and N(hits)	reco::Muon::GlobalMuonPromptTight
Cuts on maximum penetration depth	reco::Muon::TMLastStationLoose reco::Muon::TMLastStationTight
Cuts on 2-D segment/calorimeter compatibility likelihood	reco::Muon::TM2DCompatibilityLoose reco::Muon:TM2DCompatibilityTight

Muon timing

- Muon time-of-flight information is available from the DT's
  - Useful for rejection of non-collision backgrounds, "exotic" heavy charged particle searches, etc.
- Defined in

  DataFormats/MuonReco/interface/MuonTime.h

MuonTime muon::time()

Several variables are accessible from "time()" for both inward and outward going particles:

float muon::time().inverseBeta

float muon::time().inverseBetaErr

float muon::time().freeInverseBeta

float muon::time().freeInverseBetaErr

float muon::time().timeAtIpInOut

float muon::time().timeAtIpInOutErr

float muon::time().timeAtIpOutIn

float muon::time().timeAtIpOutInErr

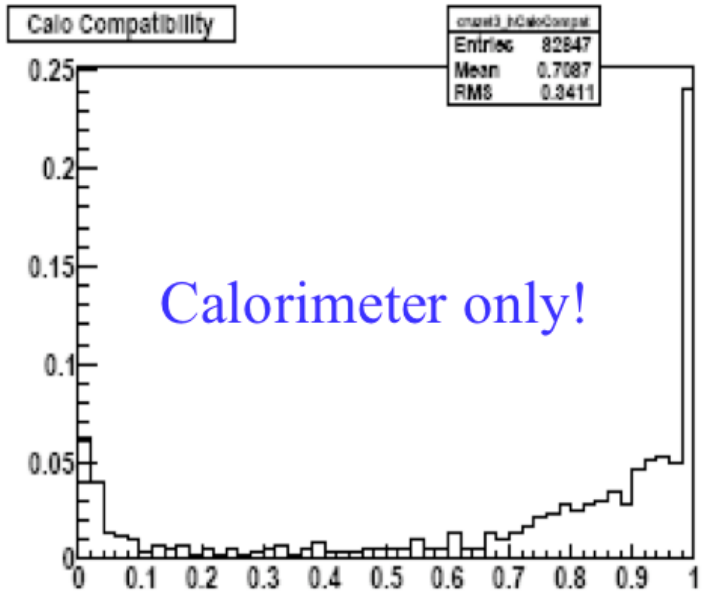
Muons in the calorimeter

- Calorimeter compatibility - use energy deposited in ECAL, HCAL, and HO to check for compatibility with a minimum ionizing particle (MIP)
  - Complementary to information from tracker & muon system
- Defined in

  RecoMuon/MuonIdentification/interface/MuonCaloCompatibility.h
- Result is summarized in a likelihood variable

$$L_\mu/(L_\mu+L_{not\ \mu})$$

float muon::caloCompatibility()



(J. Ribnik)

- Validated on real cosmics data

Special cases

TeV muons

- Special treatment is needed for very high p_T muons ($Z' \rightarrow \mu\mu$, etc.)
  - Muon system contributes to the resolution, must deal with showering muons
- Maps stored in RECO/AOD link global muons to refits done with altered hit content
  - Improves resolution & non-Gaussian tails
- Typical usage:

```
edm::Handle<reco::TrackToTrackMap> tevMap;

event.getByLabel("tevMuons","refit_name",tevMap);
```

"refit_name" can be one of three refit algorithms:

1. "default"
2. "first hit"
3. "picky"

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

CaloMuons

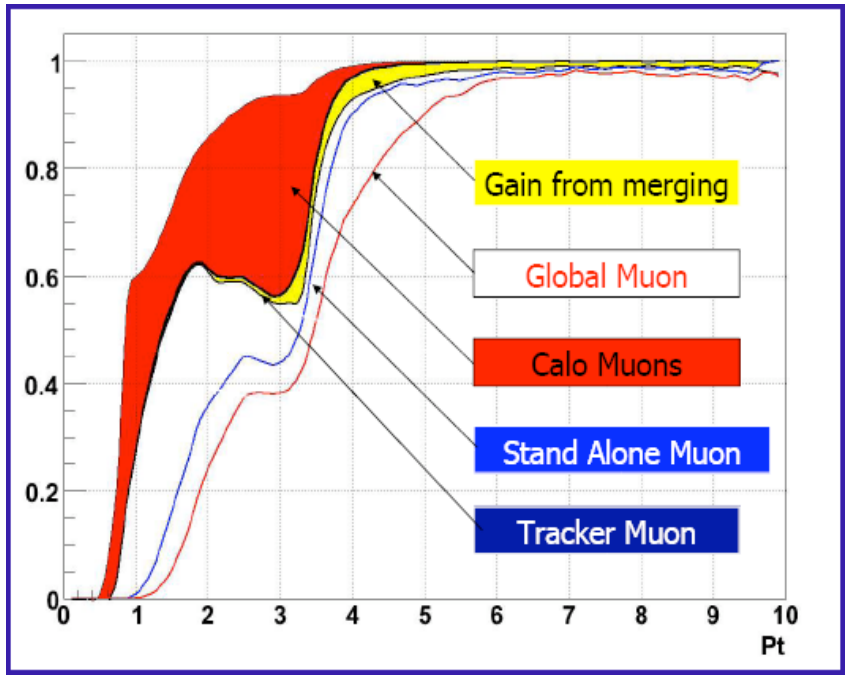
- New algorithm for CMSSW_2_X - not included in reco::Muon objects
- Tracker track (that was not reconstructed by any other muon algorithm) matched to MIP signature in the calorimeter - no muon system information at all!
- Defined in:

  DataFormats/MuonReco/interface/CaloMuon.h
- Typical usage:

```
edm::Handle<reco::CaloMuonCollection> muons;

event.getByLabel("caloMuons",calomuons);

reco::CaloMuonCollection::const_iterator calomuon;
```



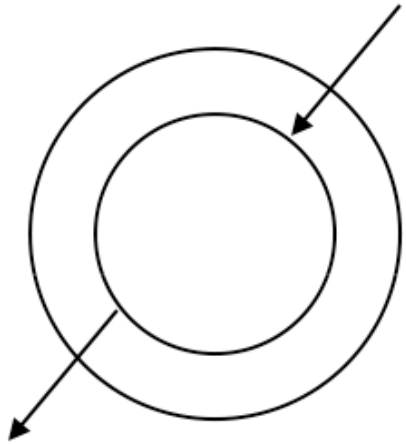
(D. Kovalskyi)

- Extremely high efficiency/low purity for low p_T muons

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

CosmicMuons

- Dedicated reconstruction is used for muons not originating from the IP
  - Momentum direction for all muons is set as downward, two legs are found if the muon crosses upper & lower hemispheres



- Can be reconstructed either with tracker + muon system ("globalCosmicMuons" collection) or with muon system only ("cosmicMuons" collection)
- Typical usage:

```
edm::Handle<reco::TrackCollection> muons;

event.getByLabel("cosmicMuons",muons);

reco::TrackCollection::const_iterator muon;
```

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

Summary

- The reco::Muon object provides access to a large number of standard and muon-specific variables
  - The RECO/AOD data format has largely been stable since CMSSW_1_7_X
  - Many more details in the muon SWGuide & Workbook
- The basic "muons" list plus selectors/isolation should cover most analysis use cases (for collision data!)
  - For special cases, other algorithms are easily accessible (TeV muons, CaloMuons, CosmicMuons)
- For some closely related topics not covered here:
  - PAT muons (https://twiki.cern.ch/twiki/bin/view/CMS/EWKPatDefaults21X#Muons and PAT tutorial this week)
  - HLT muons (https://twiki.cern.ch/twiki/bin/view/CMS/MuonHLT)