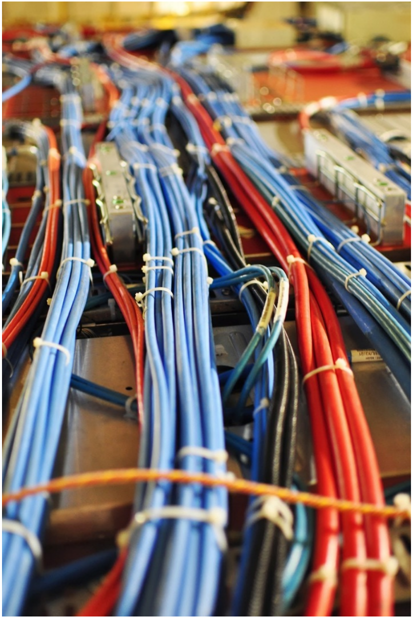
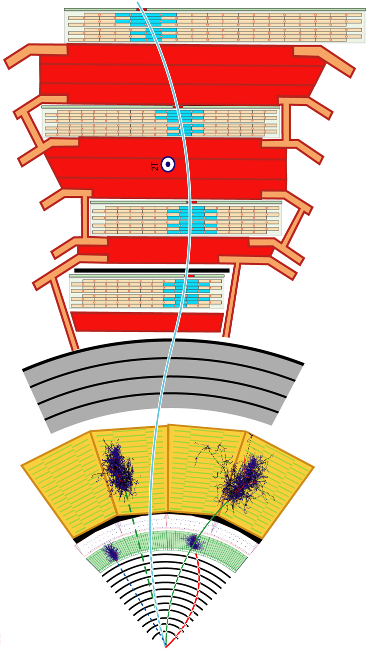


3. Muon reconstruction and triggering

Piet Verwilligen

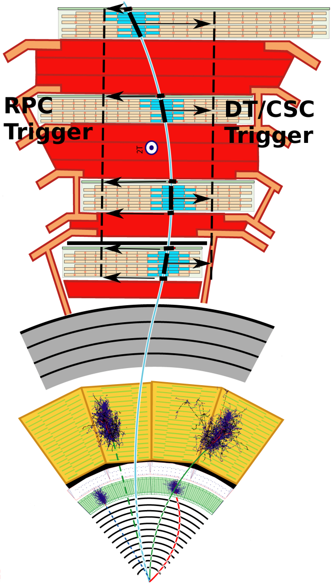
INFN Sezione di Bari

Capita Selecta in HEP
Vrije Universiteit Brussel
April 9-10, 2014



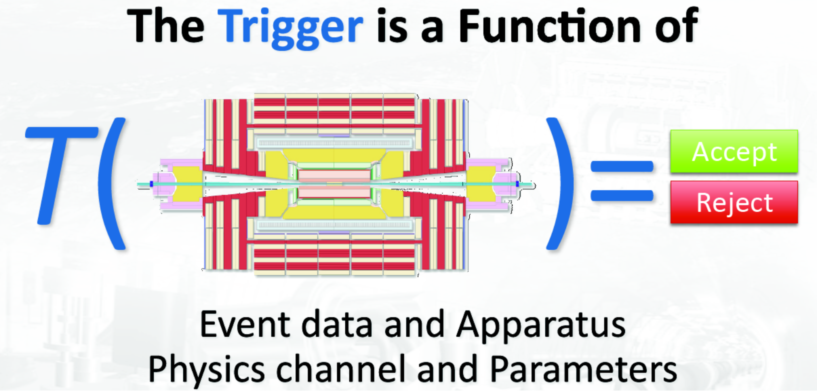
Overview

- CMS L1 Trigger
  - DT Trigger
  - CSC Trigger
  - RPC Trigger
  - Global Muon Trigger
- CMS Muon Reconstruction
  - Local Reconstruction
  - Stand Alone Muon Reconstruction
  - Global Muon Reconstruction
  - Tracker Muon Reconstruction



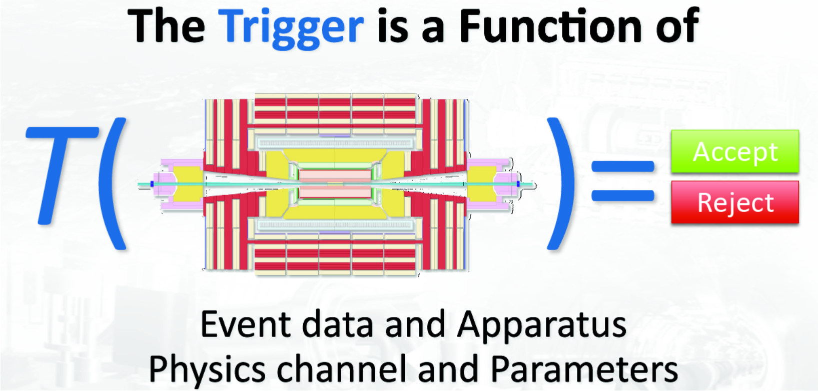
Muon Trigger

What is a Trigger?



A **Trigger** is a function that based on the **electronic signals** generated by a *pp*-collision, and limited by the **experimental setup**, and for given **physics priorities** results in an **Accept** or **Reject** decision.

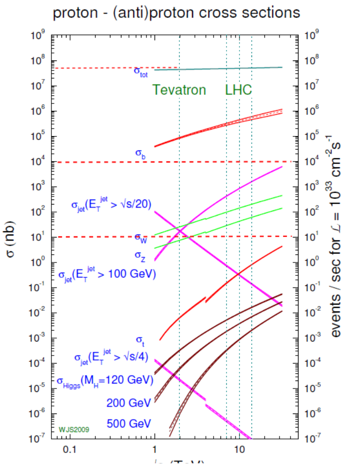
What is a Trigger?

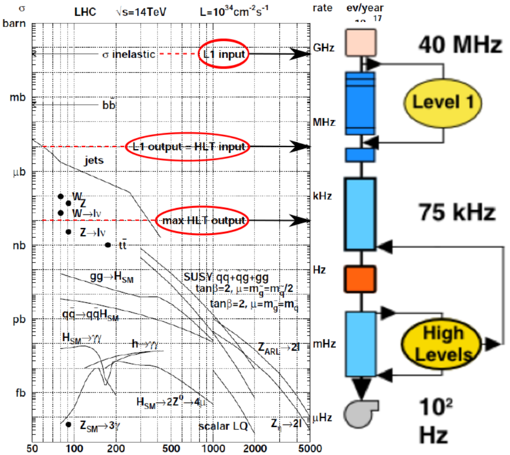


A **Trigger** is a function that based on the **electronic signals** generated by a *pp*-collision, and limited by the **experimental setup**, and for given **physics priorities** results in an **Accept** or **Reject** decision.

The trigger is the start of the physics event selection process!

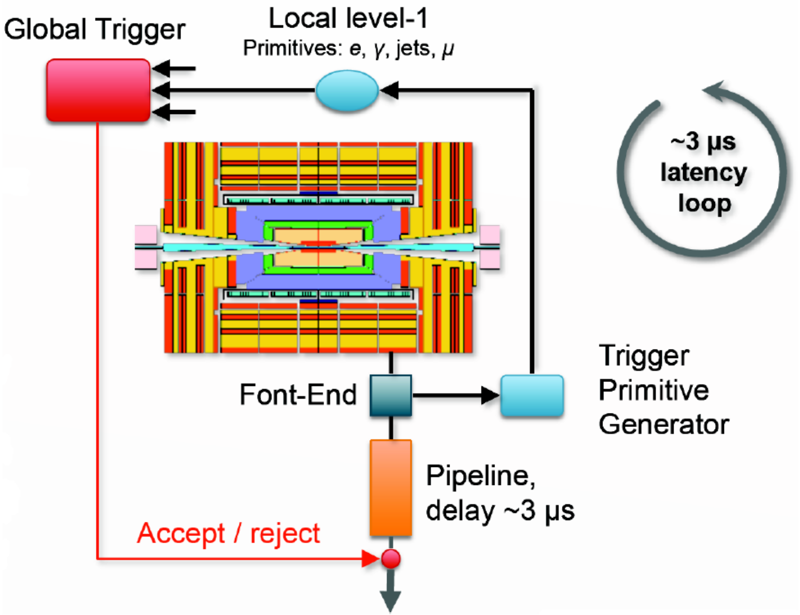
Why do we need a Trigger?



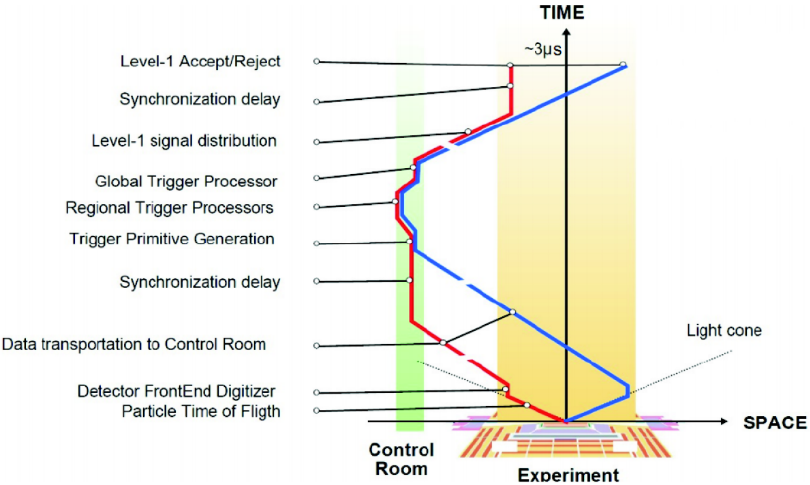


Required rejection power of 10^5 cannot be obtained in a single step. CMS opted for a two-step system: the L1-trigger based on custom hardware (dead time-less) and a High Level Trigger (HLT) based on a computing farm. 40 MHz → L1-trigger → 75 kHz → HLT → 400 Hz → T0 CERN.

How to trigger every 25 ns?



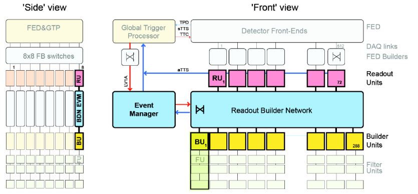
How to trigger every 25 ns?



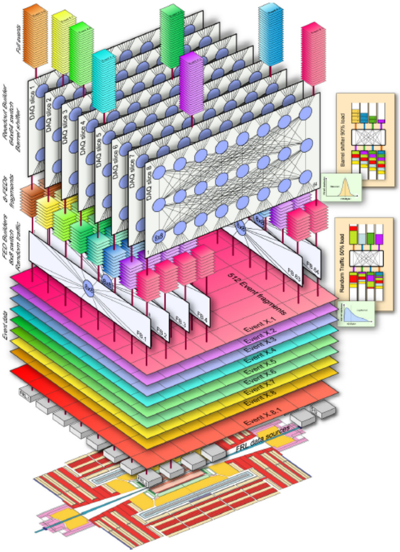
Most of the 3.2 μs used for data transport from UXC to USC and L1A from USC to UXC + delays

The CMS High Level Trigger

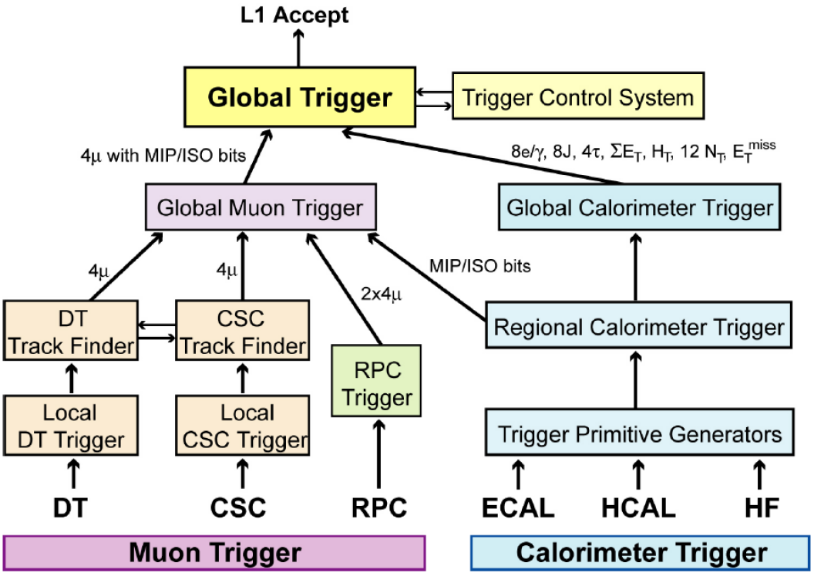
HLT Builder Network



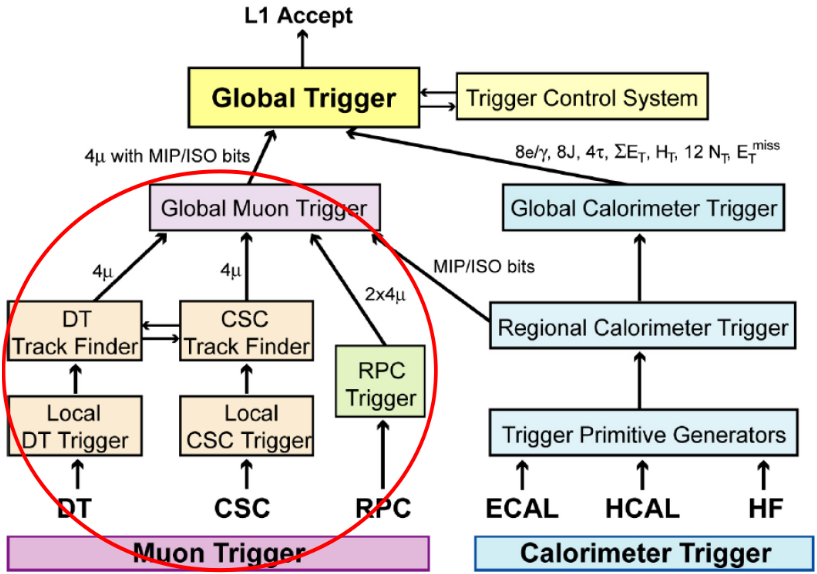
- Upon **Level-1 Accept** (L1A) signal the **Data** is read out from the detector **Front Ends (FEDs)** and stored in buffers of the **Readout systems**
- These buffers are connected to the processors in the HLT farm by a large switch (**Builder Network**)
- The **HLT algorithms** are run on the processors once a “full” event is provided by the readout
- The **HLT algorithms** have to process the event in 50–100 ms. **Filters** at the end decide to keep or reject the event.



The CMS L1 Trigger



The CMS L1 Trigger

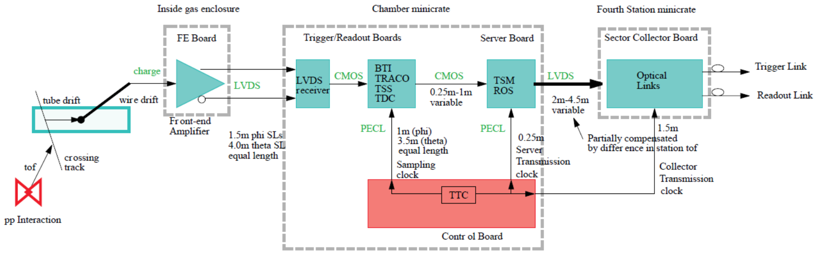


The Local DT Trigger

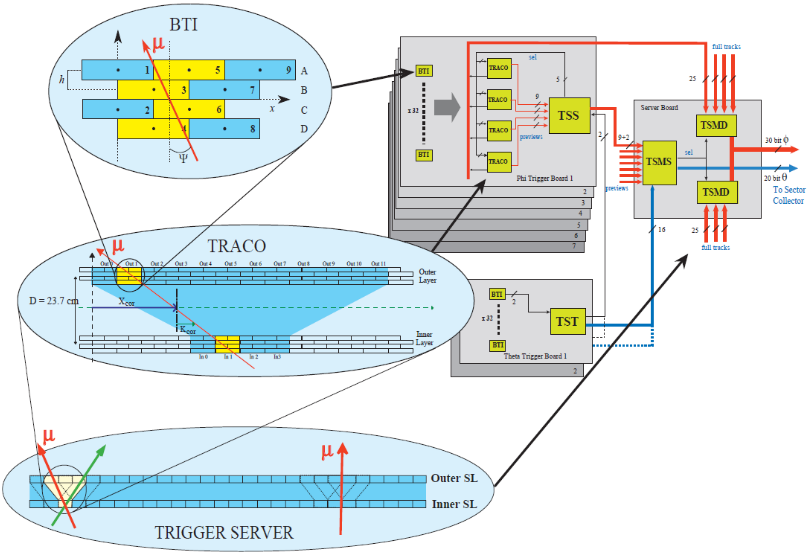
Goal :: max 2 **Triggers** at chamber level: i.e. one **segment** in the r–ϕ projection and one in the r–z projection + *a Bunch Crossing (BX) ID*.

Realized :: by complex on-chamber electronics: **Mini Crate** containing
7 TSϕ (containing 32 BTI, 4 TRACO, 1 TSS), 2 TSθ (containing 32 BTI and 1 TST), 1 SB.

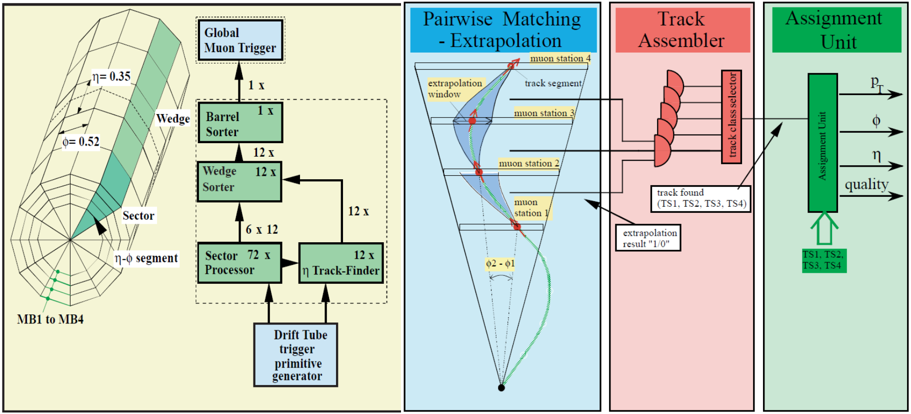
Overview



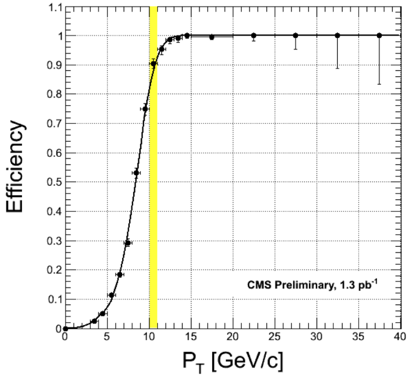
The Local DT Trigger

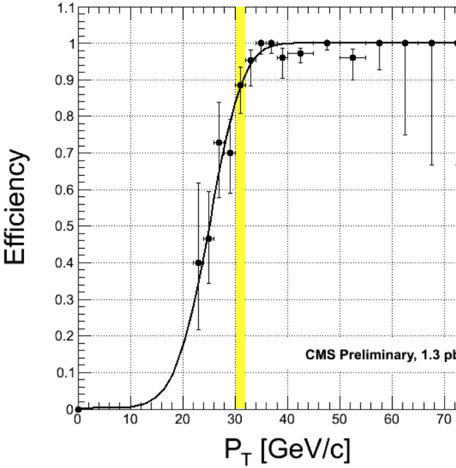


The DT Track Finder

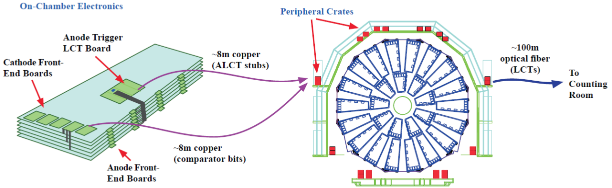


The DT Track Finder Efficiency

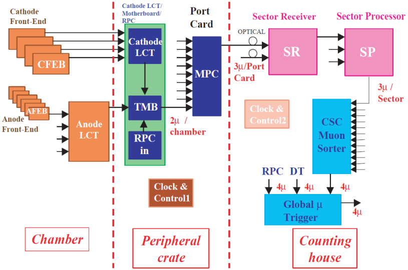




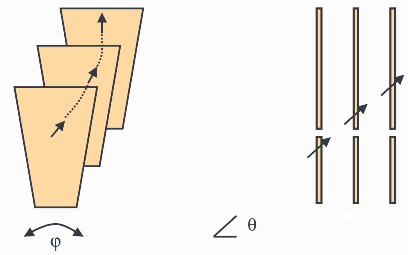
The CSC Trigger



CSC Local Trigger

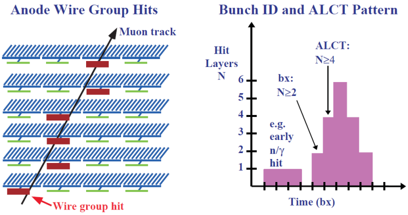


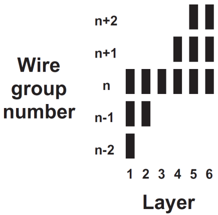
CSC Track Finder



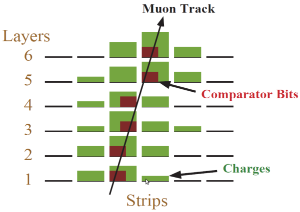
The CSC Local Trigger

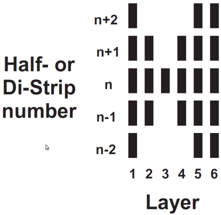
Anode Local Trigger (ACLT)



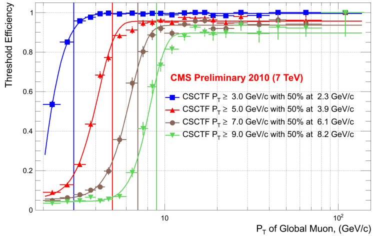


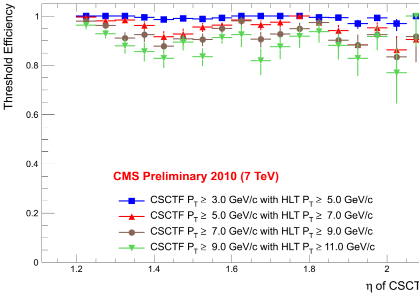
Cathode Local Trigger (CLCT)





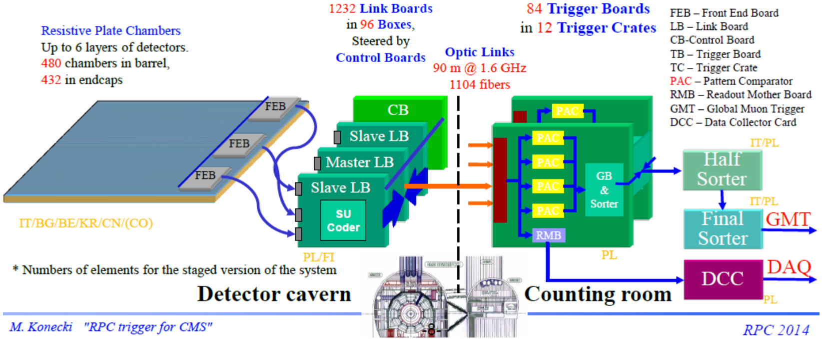
The CSC Track Finder Efficiency





The RPC Trigger

- The RPC trigger system – part of CMS Level-1 muon trigger.
- Designed and build by Poland, Finland and Italy.
- The system is composed of link system, fibers, splitters, trigger and readout system and a set of sorters. Uses RPC data
- It compares muon hit pattern with the predefined set of patterns.



M. Konecki —

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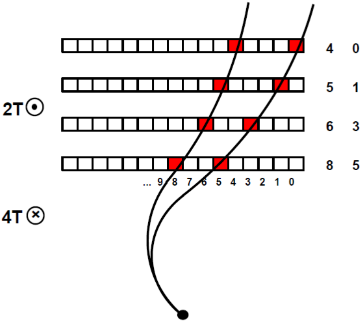
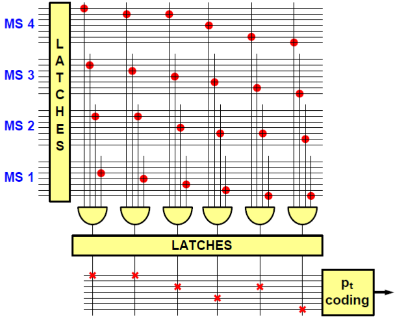
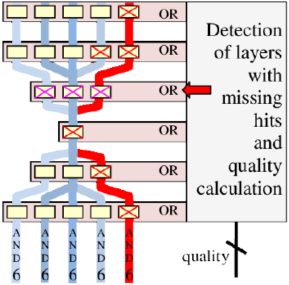
The RPC Trigger





The RPC Trigger

- **The chamber signals (fired strips) are compared with the predefined set of patterns every 25 ns (BX)**
- Each pattern has assigned a transverse momentum (p_T) and sign (depending on the track banding by the magnetic filed).



A pattern is a set of AND gates connected to selected strips

- A candidate is produced even though not all layers have hits.The minimum required number of fired layers is 3 (out of 3, 4, 5 or 6 layers available – depending on a detector region).
- In this way the trigger efficiency does not suffer from the limited geometrical acceptance and inefficiency of the chambers.
- The number of fired planes defines the candidate quality.
  The quality is used for the candidates sorting and "ghost busting" (cancellation of duplicated candidates).
- The patterns are generated based on the simulated muon track. Advanced algorithms are used to create the patterns from the simulated chamber hits, assign the p_T, and then select optimal set of patterns.

The goal is to achieve best possible trigger efficiency and purity with a patterns set that can be fit into the PAC FPGAs.

M. Konecki —

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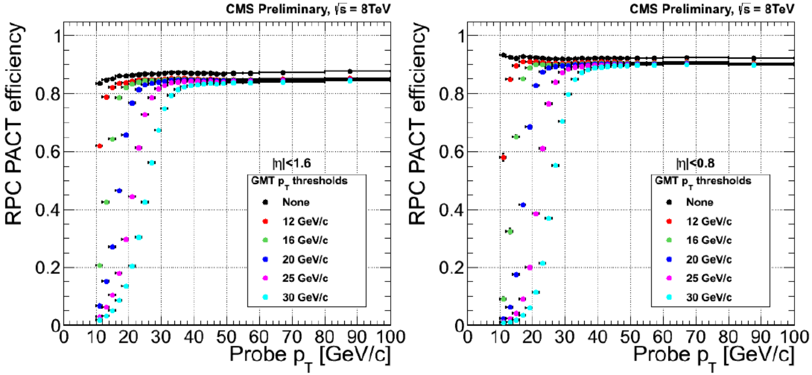
The RPC Trigger Efficiency

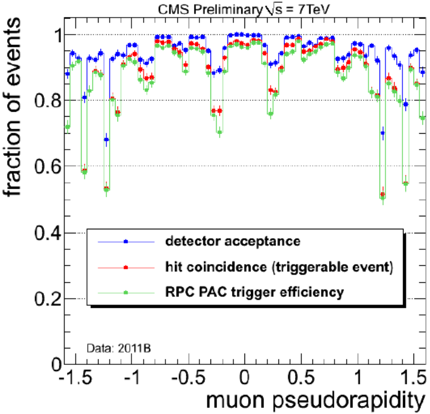


The Tag&Probe efficiency of the RPC Trigger as a function of probe pT for tight muon probes, for **the total RPC acceptance |η|<1.6 (left),** and for the **barrel region |η|<0.8 (right).** Calculated using Z boson sample. Small irregularities in the curves for different η regions come from muon η-pT dependence.

The RPC Trigger Efficiency Breakdown

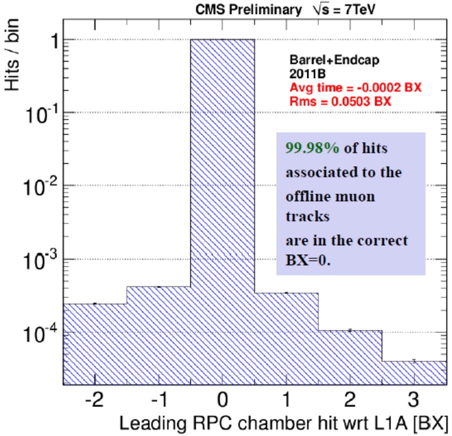
The trigger efficiency is a convolution of geometrical acceptance of RPCs, chamber intrinsic efficiency and the efficiency of the trigger algorithm itself.

- The **"detector acceptance"** indicates fraction of events where a reconstructed muon crosses number of RPC chambers sufficient to provide a trigger candidate.
- The **"hit coincidence"** gives fraction of events with sufficient number of hits to start trigger algorithm. This component is obtained by emulation (on data) of a trigger algorithm with dedicated pattern covering full geometrical region of trigger decision.
- The **"RPC PAC trigger efficiency"** is the obtained efficiency of the RPC trigger



Fraction of events in coincidence is normalised w.r.t. reconstructed offline muons of $p_T > 10$ GeV/c, from vtx. In the selected events the number of hits from detectors other than RPCs is sufficient for muon reconstruction. The RPC PAC result matches the global muon at the 2nd muon station.

The RPC Trigger BX Identification



Distribution of chamber hits BXs w.r.t. the event BX for all 1232 Link Boards (LBs).

The RPC data synchronisation is defined by programmable delay and width parameters of a LB "synchronisation window" (accuracy of ~100 ps, one delay dedicated for each LB).

The initial setting from simulation, corrected with LHC data.
Link Board synchronization has been tuned 7 times 2010-2011. Good precision after 2-3 corrections. Last one - a few LB corrected only. No correction in 2012.

RPC hits must agree with the propagated reconstructed muon trajectory. Only good muons, compatible with vertex are considered.

The residual out-of-time hits originate from: cosmics, muons from other bunch crossings or chamber noise

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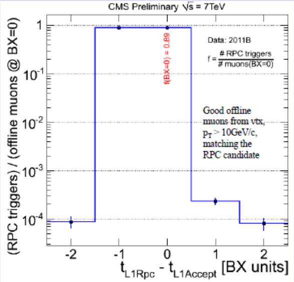
The RPC HSCP Trigger

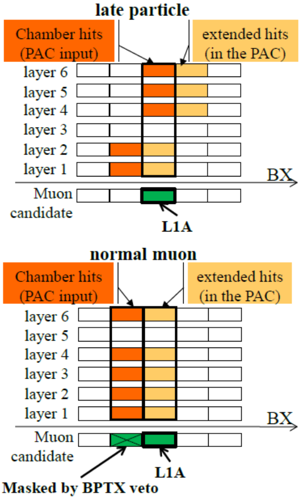
- Some supersymetry models foresee **Heavy Stable Charged Particles**
- In the CMS they will look like **“slow muons”**: (some) hits in muon chambers can be later than the hits of the muons
  → no trigger candidate
- **PACT for HSCPs triggering**

In the PAC logic the detector signals are extend in time to 2 BXs to allow HSCP hits for a proper time-coincidence of in PACT resulting in possible trigger candidate

(Normal) muons trigger twice.
The fake (pre-muon) candidate is masked by BPTX veto



Significant increase of the efficiency to trigger on lower momentum, slower moving HSCPs e.g. **for gluino 800 GeV: from 24 to 32%.**



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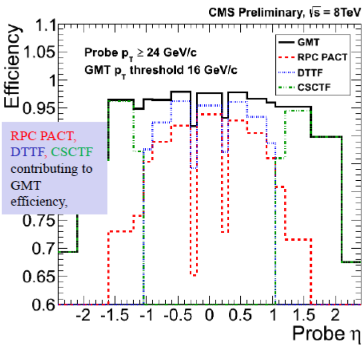
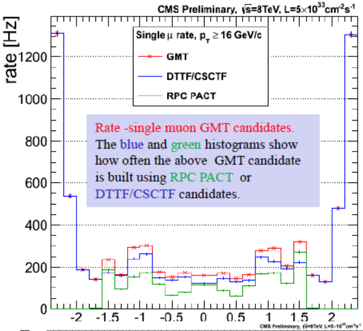
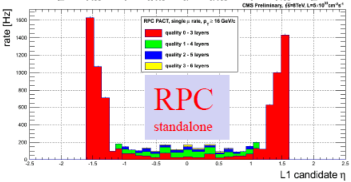
The Global Muon Trigger (GMT) Efficiency





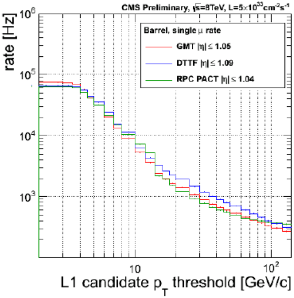


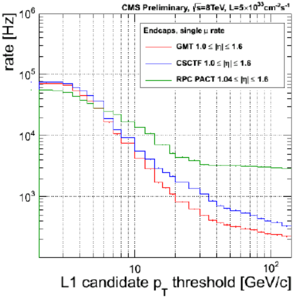
The Level-1 p_T defined by minimal p_T of candidates from sub-systems (baseline) and quality (esp. endcap). Stronger GMT requirements in case of candidate from one sub-system candidates.
Trigger redundancy - better efficiency and rate.

M. Konecki —

http://166.111.32.59/indico/getFile.py/access?contribId=18&sessionId=10&resId=0&materialId=slides&confId=1

The Global Muon Trigger (GMT) Efficiency





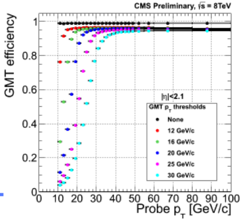
GMT: efficiency and rate vs momentum threshold.

RPC: The solid performance in barrel

RPC: Lack of selectivity in endcap for approx. $p_T > 20$ GeV

For the GMT the quality cut used for single muon trigger algorithms was applied. This cut reject low quality CSCTF candidates (from selected eta regions) not matched with the RPC PACT candidates. Therefore the resulting GMT rate (red) is significantly lower then the CSCTF rate (black).

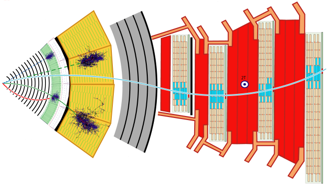
Trigger redundancy - better efficiency and rate.



M. Konecki "RPC trigger for CMS"

M. Konecki —

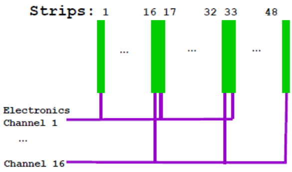
http://166.111.32.59/indico/getFile.py/access?contribId=18&sessionId=10&resId=0&materialId=slides&confId=1

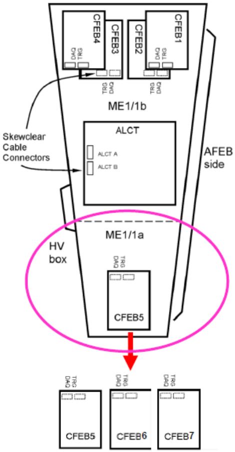


Muon Activities during LS1

Motivation for CSC Upgrade ME11

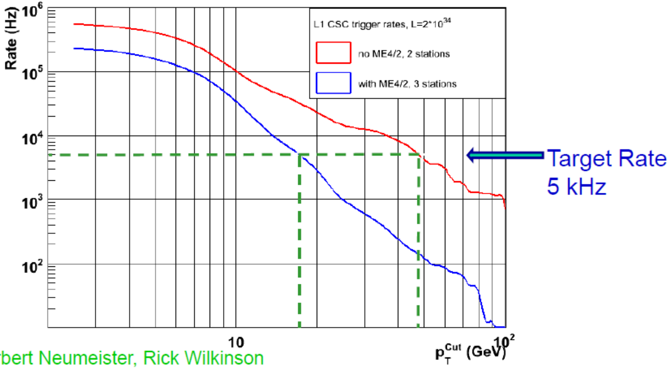
- Highest-rate chambers, with troublesome 3:1 strip ganging in η 2.1-2.4
  - Easily handle HL-LHC rates by replacing CFEBs with Digital CFEBs (DCFEBs) containing Flash ADCs
  - Add more DCFEBs to remove the strip ganging





Motivation for CSC Upgrade ME42

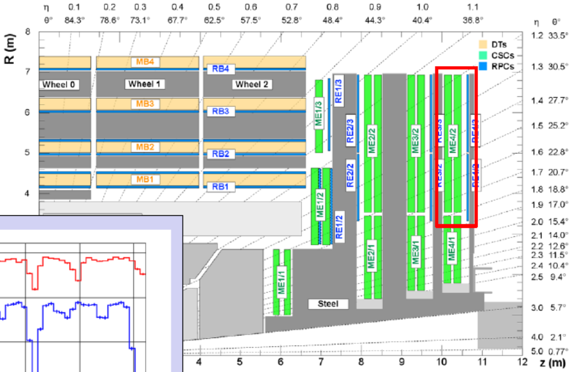
- Adding 4th station allows to tighten L1 trigger criteria
  - L1 trigger rates at 2 E34
  - Threshold reduced from 48 to 18 GeV

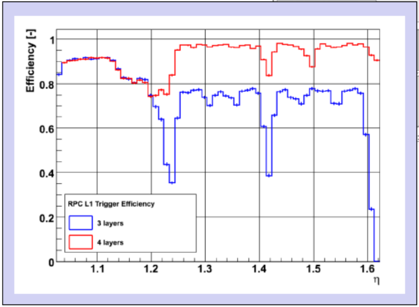


Ingo Bloch, Norbert Neumeister, Rick Wilkinson

Motivation for RPC Upgrade RE4

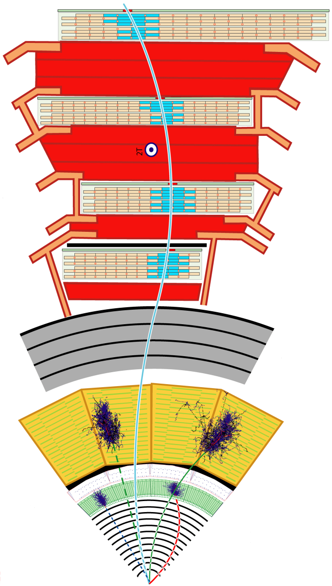
LS1: Restore disk4 (incl. RPC RE4/2, 4/3); Large improvement of RPC RPCT efficiency. No significant increase of rate expected (ongoing)



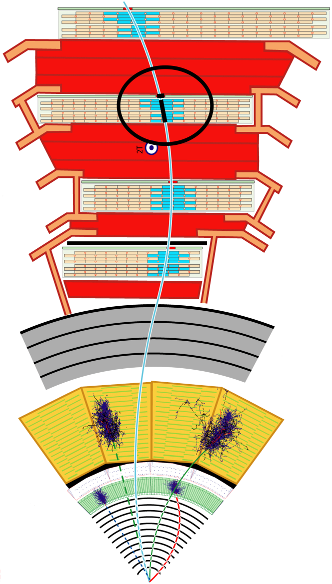


- 144 new LinkBoards, 24 ControlBoards.
- No new Trigger Boards.
- Prepare and optimize patterns

"Technical proposal for the upgrade of the CMS detector through 2020"
CERN-LHCC-2011-006 (CMS-UG-TP-1)

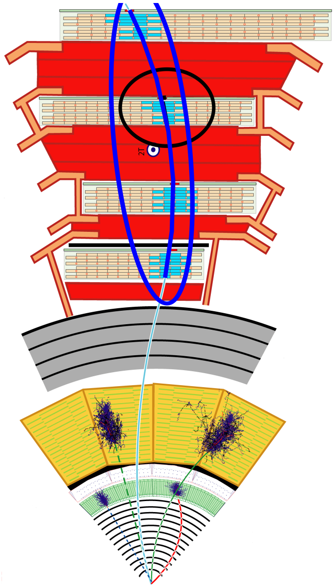


Muon Reconstruction



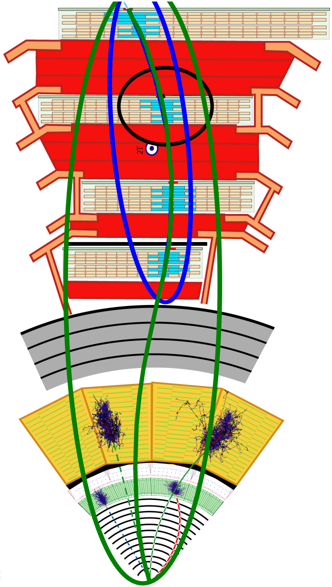
Overview of Muon Reconstruction

- Local Reconstruction
  - Reconstruction of **hits** and **track segments** inside the muon chambers



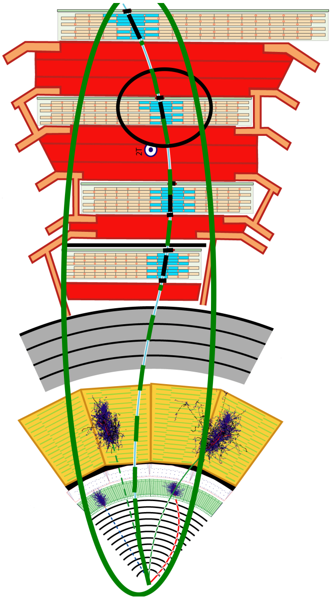
Overview of Muon Reconstruction

- Local Reconstruction
  - Reconstruction of **hits** and **track segments** inside the muon chambers
- Stand-Alone Reconstruction
  - Reconstruction of the **muon track** inside the **Muon System**



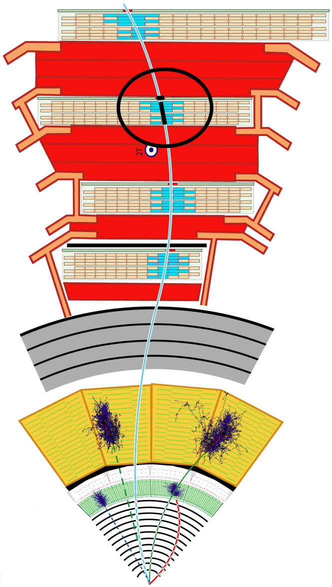
Overview of Muon Reconstruction

- Local Reconstruction
  - Reconstruction of **hits** and **track segments** inside the muon chambers
- Stand-Alone Reconstruction
  - Reconstruction of the **muon track** inside the **Muon System**
- Global Reconstruction
  - Reconstruction of the **muon track** combining information from the **Muon System** and the **Tracker**



Overview of Muon Reconstruction

- Local Reconstruction
  - Reconstruction of **hits** and **track segments** inside the muon chambers
- Stand-Alone Reconstruction
  - Reconstruction of the **muon track** inside the **Muon System**
- Global Reconstruction
  - Reconstruction of the **muon track** combining information from the **Muon System** and the **Tracker**
- Tracker Muon Reco
  - Tagging of a **Tracker track** as a muon using information from the **MuonSystem**



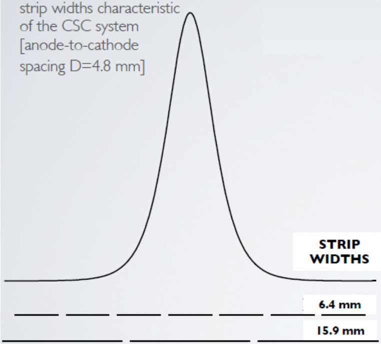
Local Muon Reconstruction

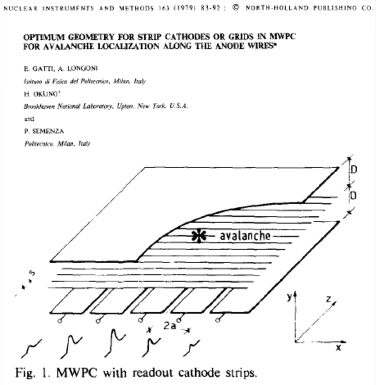
Local Reconstruction in CSC

- The Gatti et al. distribution is a semi-empirical function that describes the induced charge distribution on cathode strips: $\Gamma(\lambda) = k_1[(1 - \tanh^2(k_2\lambda))/(1 + k_3\tanh^2(k_2\lambda))]$

$\lambda = x/D$

Here it is compared to strip widths characteristic of the CSC system [anode-to-cathode spacing D=4.8 mm]




NUCLEAR INSTRUMENTS AND METHODS 163 (1979) 83-92 ; © NORTH-HOLLAND PUBLISHING CO.

OPTIMUM GEOMETRY FOR STRIP CATHODES OR GRIDS IN MWPC FOR AVALANCHE LOCALIZATION ALONG THE ANODE WIRES*

E. GATTI, A. LONGONI
Istituto di Fisica del Politecnico, Milan, Italy
H. OKUNO†
Brookhaven National Laboratory, Upton, New York, U.S.A.
and
P. SEMENZA
Politecnico, Milan, Italy

Fig. 1. MWPC with readout cathode strips.

E. Gatti, A. Longoni, H. Okuno, P. Semenza – Nucl. Instr. and Meth., 163 (1979), 83–92
http://www.sciencedirect.com/science/article/pii/0029554X79900351

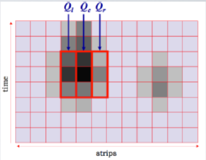
The strip widths in the system are in the range 6.6 mm innermost ME1/2 to 16.0 mm outermost ME234/2 chambers. ME1/1 has smaller widths, 3.2–7.6 mm and a-to-c spacing 3.5 mm

Local Reconstruction in CSC

THE U. FLORIDA ALGORITHM

- Suggested in 2007 as a 'fast' rechit builder for use in HLT. But it was so good that we switched to using it for everything!

$$r = \frac{1}{2}\frac{Q_r - Q_l}{Q_c - min(Q_r, Q_l)}$$



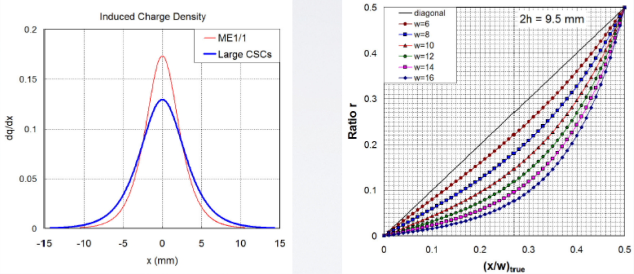


Figure 14: **Left:** Induced charge distribution calculated according to Gatti et al. [19] for large and ME1/1 chamber geometries. The Gatti parameter K_3 was taken to be 0.334 for large chambers and 0.379 for ME1/1 according to the empirical approximations in Ref. [20]. **Right:** Ratio r versus a local coordinate x for large chambers calculated for variety of strip widths in the assumption of the Gatti charge distribution for large chambers (see plot on the left).

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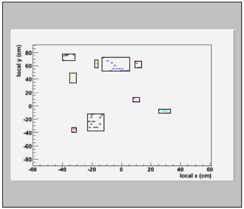
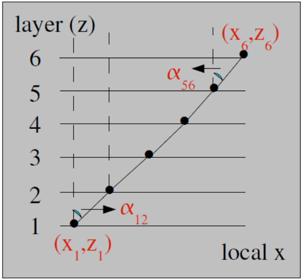
Local Reconstruction in CSC

General aims and strategy for muon stubs/segments:

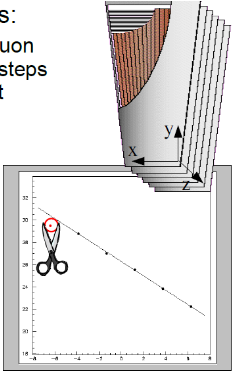
→ match groups of hits that are likely due to passing muon across layers to reduce combinatorics in later reco steps
→ used to seed SA muons and in the initial SA muon fit
→ used for tracker muons



Pre-cluster hits using local x, y coordinates
→ new: also z coordinate, see later



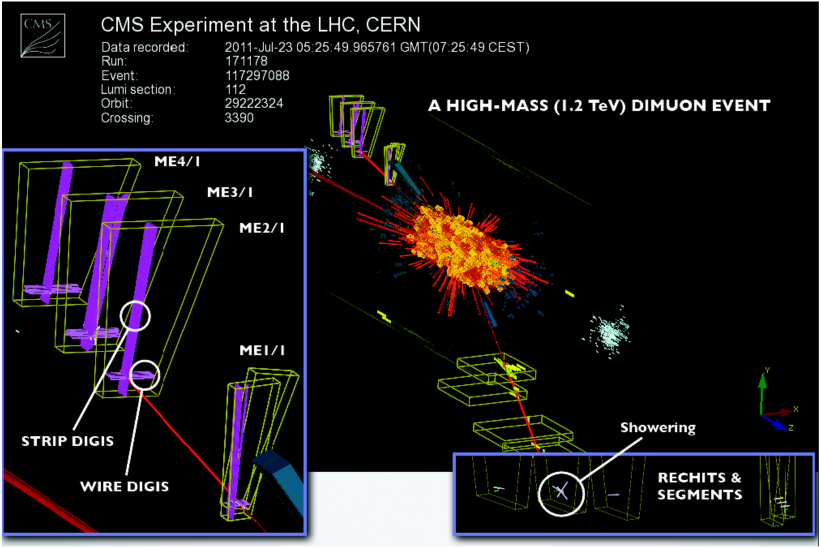
Compare all hit combinations within pre-cluster and find straightest segment candidates



Prune single bad hit from the "best" candidates

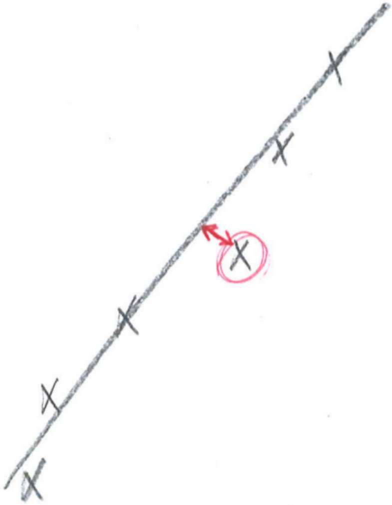
Ingo Bloch — https://indico.cern.ch/event/54180/

Local Reconstruction in CSC



Tim Cox — https://indico.cern.ch/event/210563/

CSC Spatial Resolution



Method

- Take Segment with 6 hits
- Remove one hit from the segment
- Refit 5 hits to form a segment
- Measure residual between hit and "fit-5"

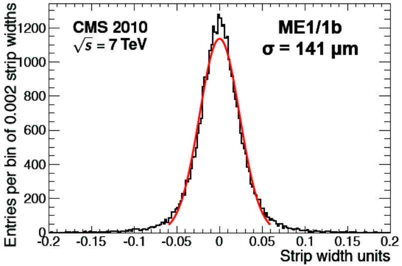
Bias

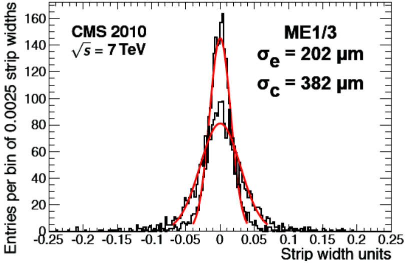
- both "fit-5" and "fit-6" are biassed
- "fit-6" $\rightarrow$ includes the hit
- "fit-5" $\rightarrow$ segment extrapolation uncertainty performed after fit
- Bias can be removed by

$$\sigma_i = c_i \sigma_{R_i}$$

- σ_{R_i} = width of distribution for layer i
- $c_i \sim$ distance to middle of segment
- σ_i =actual resolution

CSC Spatial Resolution





- if muon passes through the edge of a strip charge is shared between neighbours
  $\Rightarrow$ better position resolution at the edge
- $\Rightarrow$ split staggered layers: σ_e and σ_c

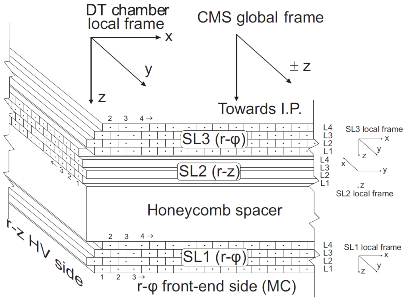
$$\sigma_{\text{chamber}} = \left(\frac{3}{\sigma_e^2} + \frac{3}{\sigma_c^2} \right)^{-1/2}$$

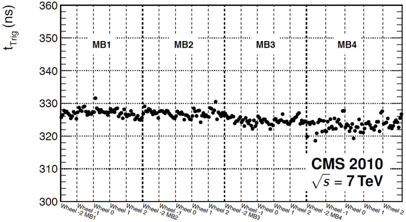
- ME11 has no staggered strips)

$$\sigma_{\text{chamber}} = \frac{\sigma_{\text{layer}}}{\sqrt{6}}$$

Ring	Strip Width $\langle w \rangle$ [mm]	Resolution req. [μm]	Resolution meas. [μm]
ME1/1	6.0	75	58
ME1/2	8.5	75	92
ME1/3	13.0	150	103
ME2/1	11.2	150	126
ME2/2	12.2	150	132
ME3/1	11.7	150	126
ME3/2	12.2	150	136
ME4/1	12.1	150	131

Local Reconstruction in DT





$$x = v_{\text{drift}} \cdot t_{\text{drift}}$$

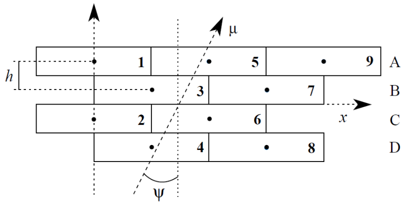
TDC readout of wires:

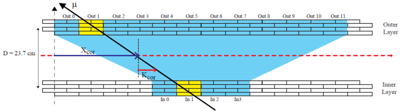
contains:

- Time of flight (tof) of muon to center of DT chamber (t_{tof})
- Propagation time along anode wire (t_{prop})
- Delays due to cable length and electronics (t_0^{wire})
- Latency of L1 Trigger (t_{L1})

$$t_{\text{TDC}} = t_{\text{drift}} + t_0^{\text{wire}} + t_{\text{tof}} + t_{\text{prop}} + t_{\text{L1}}$$
$$= t_{\text{drift}} + t_0^{\text{wire}} + t_{\text{trig}}$$

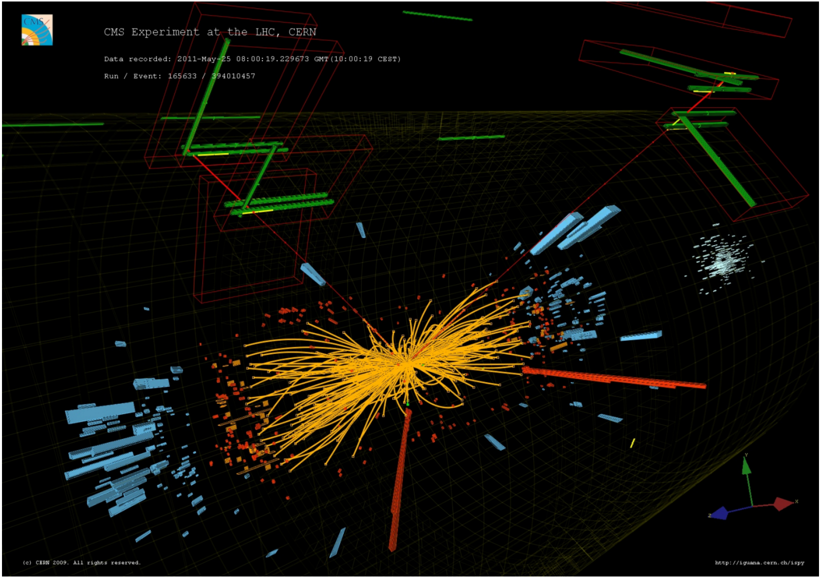
- t_0^{wire} determined by test pulses
- t_{trig} extracted from data
- t_{tof} and t_{prop} corrected offline after obtaining 3D hit position





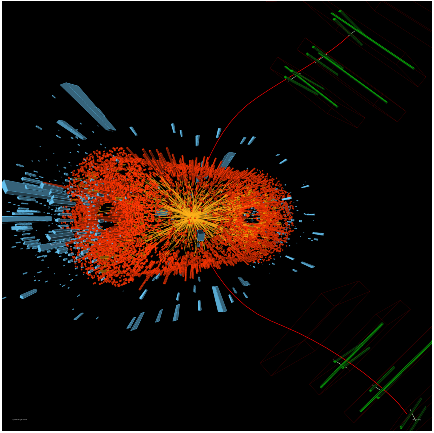
- Hits in each layer are analyzed by Mean Timer Algorithm
- Algorithm finds a segment in every Super Layer (SL)
- segments of two r–ϕ SL are combined by Track Correlator
- r–z superlayer gives measurement of θ
- Combined in 3D segment

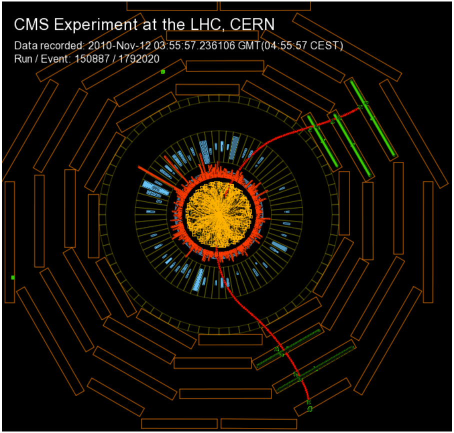
Local Reconstruction in DT



Candidate $H \to ZZ \to e^+e^-\mu^+\mu^-$ event recorded at 7 TeV (2011)

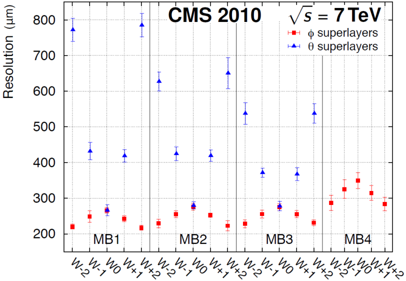
Local Reconstruction in DT

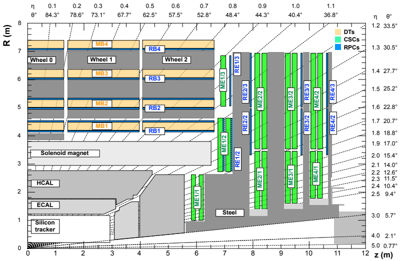




Candidate $Y \rightarrow \mu^+\mu^-$ decay in a Pb-Pb collision

DT Spatial Resolution





Method

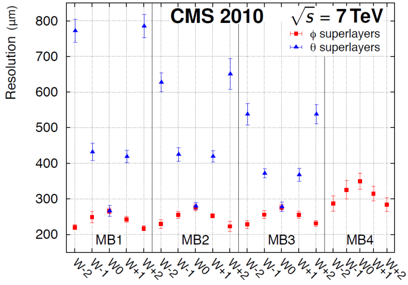
- r–ϕ measurement in 8 layers
- r–z measurement in 4 layers
- Segment hits > 3 (r–z) or > 7 (r–ϕ)

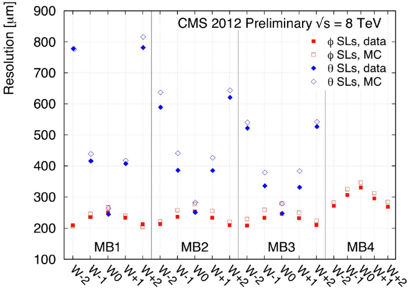
- r–ϕ and r–z resolution are the same in W0
- Resolutions are similar for W+1 vs W-1 and W+2 vs W-2

Angle of incidence θ

- $\Rightarrow$ r–z resolution worse for W$\pm$1, W$\pm$2
- $\Rightarrow$ r–ϕ resolution better for W$\pm$1, W$\pm$2
- r–ϕ resolution worse for MB4 since no correction for drift time because of missing measurement in r–z plane

DT Spatial Resolution





SL Type	Station	W−2	W−1	W0	W+1	W+2
r-ϕ	MB1	78±2	88±6	94±3	86±3	77±2
	MB2	81±4	90±3	98±3	89±2	79±5
	MB3	81±4	90±4	97±4	90±4	82±3
	MB4	101±7	115±9	123±8	111±7	100±7
r-z	MB1	386±16	216±12	133±8	209±9	393±17
	MB2	314±13	212±9	140±5	210±8	325±22
	MB3	269±15	186±7	139±7	184±9	269±14

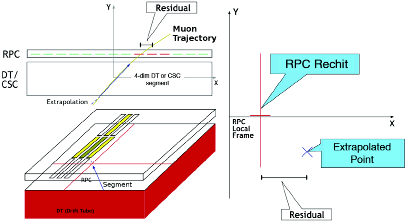
req. resolution: r–ϕ : 100 μm; r–z : 150 μm.
for perpendicular tracks (e.g. W0)

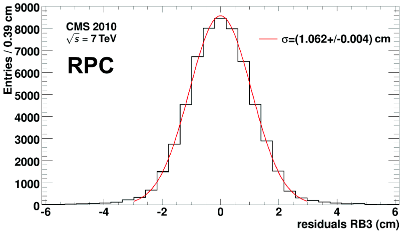
Note that

- Higher statistics in 2012 → more accurate calibration constants
- Improved Reconstruction Algorithm (application of Mean Timer Algorithm at level of pattern recognition)
- (crossing angle θ as additional free parameter in the fit)

Local Reconstruction in RPC

RPC Spatial Resolution





RPC Clustersize and Efficiency

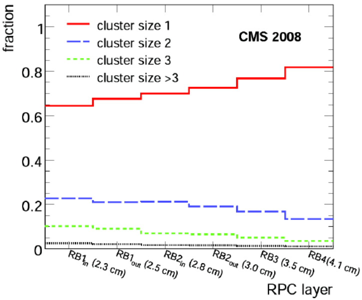


Figure 5.19: Fraction of the reconstructed clusters with size equal to 1, 2, 3 and 4 and more strips for each RPC layer in the barrel as measured during the cosmic run at the end of 2008 [233].

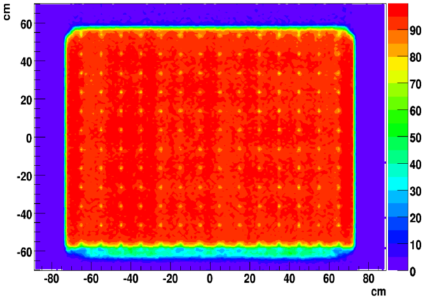
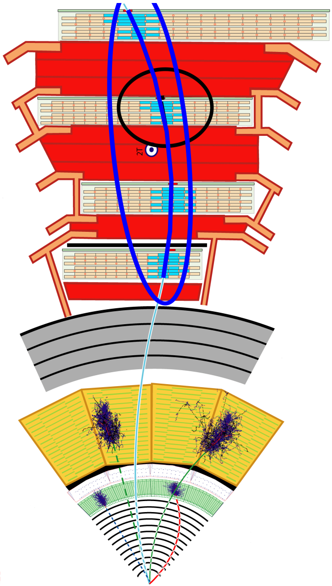


Figure 5.20: Local efficiency map during LHCs first run in 2010, for all RB3 backward rolls (in the barrel). The low efficiency points correspond to the location of spacers in the gas gap [153].



Stand-Alone Muon Reconstruction

Stand Alone Reconstruction

Muon Tracking

- In a magnetic field, the trajectory is a helix $\rightarrow$ 5 parameters

  x = (charge/momentum, position and direction on a given surface)

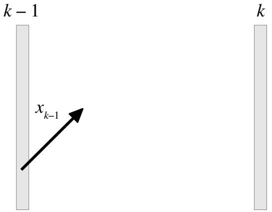
- It is reconstructed using hits and segments in the muon chambers
  - pattern recognition: set of hits compatible with track hypothesis
  - best estimation of track parameters (i.e. minimum χ^2)

- Requirements
  - account for energy loss and multiple scattering
  - handle different formats of RecHits (DT and CSC segments and hits, RPC hits)
  - be as fast as possible, to be used in both offline and HLT recontruction

- To fulfill all these requirements, the Kalman filter technique is used

Stand Alone Reconstruction

Kalman Filter (I)

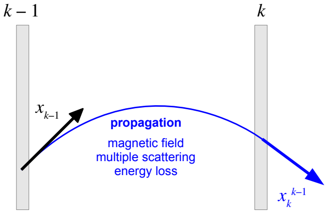


Iterative method:

- starts from an intial state (seed)

Stand Alone Reconstruction

Kalman Filter (I)



Iterative method:

- starts from an intial state (seed)
- the seed state is propagated to the next layer

Predicted state and covariance:

$$x_k^{k-1} = F_{k-1}\, x_{k-1}$$

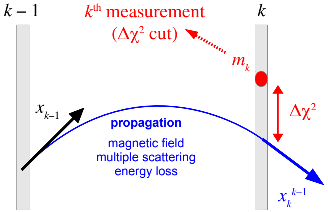
$$C_k^{k-1} = F_{k-1}\, C_{k-1}\, F^T_{k-1} + M_{k-1}$$

F_{k-1} ↓ magnetic field, energy loss

M_{k-1} ↓ multiple scattering

Stand Alone Reconstruction

Kalman Filter (I)



Iterative method:

- starts from an intial state (seed)
- the seed state is propagated to the next layer
- on this layer, the *most compatible* measurement is found on a χ^2 basis

Predicted state and covariance:

$$x_k^{k-1} = F_{k-1} x_{k-1}$$

$$C_k^{k-1} = F_{k-1} C_{k-1} F^T_{k-1} + M_{k-1}$$

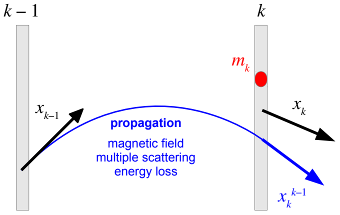
Measurement:

$$m_k = H_k x_k^{true} + \varepsilon_k$$

noise

Stand Alone Reconstruction

Kalman Filter (I)



Iterative method:

- starts from an intial state (seed)
- the seed state is propagated to the next layer
- on this layer, the *most compatible* measurement is found on a χ^2 basis
- the new measurement is used to update the track parameters

Predicted state and covariance:

$$x_k^{k-1} = F_{k-1} x_{k-1}$$

$$C_k^{k-1} = F_{k-1} C_{k-1} F^T_{k-1} + M_{k-1}$$

Measurement:

$$m_k = H_k x_k^{\text{true}} + \varepsilon_k$$

Filtered state and covariance:

$$x_k = x_k^{k-1} + K_k (m_k - H_k x_k^{k-1})$$

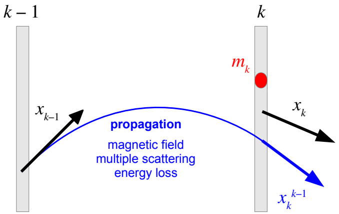
$$C_k = (1 - K_k H_k) C_k^{k-1}$$

↓ Kalman gain matrix

10/04/12 D. Trocino – Muon Reconstruction Workshop 8

Stand Alone Reconstruction

Kalman Filter (I)



Iterative method:

- starts from an intial state (seed)
- the seed state is propagated to the next layer
- on this layer, the *most compatible* measurement is found on a χ^2 basis
- the new measurement is used to update the track parameters
- starting from the new state, the procedure is repeated on each reachable layer

Predicted state and covariance:

$$x_k^{k-1} = F_{k-1} x_{k-1}$$

$$C_k^{k-1} = F_{k-1} C_{k-1} F^T_{k-1} + M_{k-1}$$

Measurement:

$$m_k = H_k x_k^{\text{true}} + \varepsilon_k$$

Filtered state and covariance:

$$x_k = x_k^{k-1} + K_k (m_k - H_k x_k^{k-1})$$

$$C_k = (1 - K_k H_k) C_k^{k-1}$$

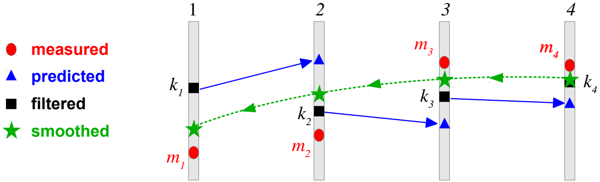
Stand Alone Reconstruction

Kalman Filter (II)

On the k^{th} layer, the *filtered state* x_k contains information only from the first k *measurements*

Once all the n *measurements* have been collected, the *smoothing* is performed

→ each x_k is updated with the information from the last $n-k$ layers



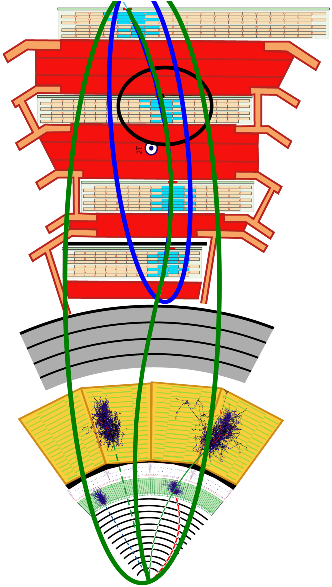
Smoothed state and covariance:

$$x_k^n = x_k + A_k (x^n_{k+1} - x^k_{k+1})$$

$$C_k^n = C_k + A_k (C^n_{k+1} - C^k_{k+1}) A^T_k$$

↓ smoother gain matrix

The smoothed trajectory represents the best estimate (least χ^2) for a given set of measurements



Global Muon Reconstruction

Global Muon Introduction

- Reconstructing muons with the best possible precision is necessary for analyzing many physics signatures
- Muon reconstruction uses information from silicon tracker, calorimeters, and dedicated muon chambers
- Global muon reconstruction: Reconstruction of the muon track combining the information from the tracker and the muon system
- The goal is to reconstruct the full trajectory of a muon using position measurements of all sub-detectors
- Same algorithms used for offline reconstruction used for online trigger reconstruction
- Reconstruction must be robust to deal with misalignment, mis-calibration, and beam conditions and flexible to adapt to changing conditions

Norbert Neumeister — https://indico.cern.ch/event/210563/

Global Muon Reconstruction

- Start from standalone reconstructed muon
- Use tracker tracks from *standard track reconstruction* (generalTracks)
  - Assume tracker tracks are already reconstructed
- Propagate all tracker tracks (including error matrix) within (large) region around STA track to the surface of the first muon hit
  - Calculate compatibility between the STA trajectory state and the extrapolated tracker track trajectory state on that surface
  - Define matching criteria based on χ^2, distance, etc.
- Refit combined trajectory for all matches
  - In case of more than one match use χ^2 of global fit to decide on best match
- Design objective: reconstruct all muons (not just prompt)

Norbert Neumeister — https://indico.cern.ch/event/210563/

Global Muon Reconstruction

- Design based on CMS core tracking software
- Outside-In approach:
  - Standalone muon (used as seed) defines a region of interest (ROI) in the silicon tracker
  - Standalone muon are propagated to match tracker tracks
  - A matching tracker track is found
  - Global-muon track is fitted combining all hits
- Two different strategies are available
- Track matching
  - It is used in the offline reconstruction
  - Tracker tracks are built independently in the whole tracker and the ones in the ROI are selected
- Prompt reconstruction
  - It is used in the L3 trigger reconstruction
  - Tracker tracks are reconstructed only inside the ROI
  - Crucial point is track seeding

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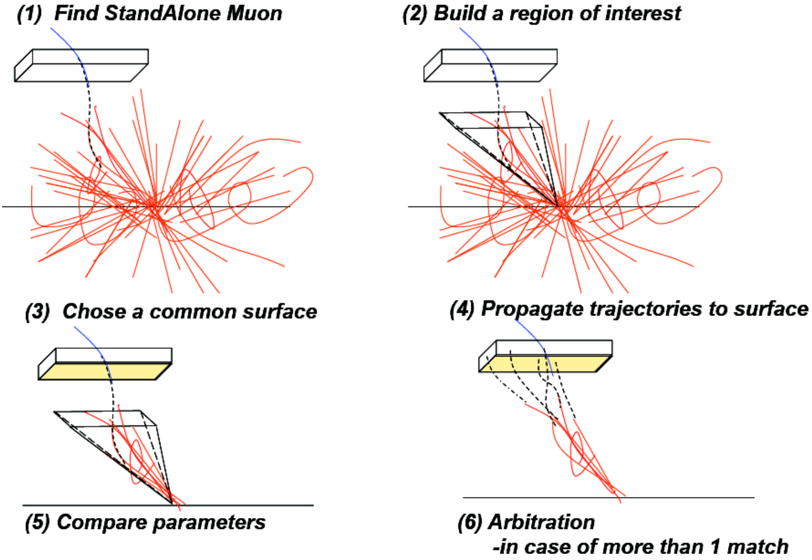
Global Muon :: Algorithm



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Global Muon :: Propagation

- Transportation of muon state vector (+ covariance matrix) accounting for magnetic field and material effects
  - Magnetic field, mean energy loss (Bethe-Bloch) → state vector
  - Multiple scattering, energy loss fluctuations → covariance matrix
- Runge-Kutta used inside the Tracker volume
  - State vector is propagated from layer to layer
  - Material effects are introduced in the endpoints
- Stepping-Helix (mainly outside the Tracker)
  - 2nd order Runge-Kutta method → uniform magnetic field
  - The CMS volume is mapped in cells with uniform magnetic field
  - Inside each cell the trajectory is a helix
  - At each step, the magnetic field is updated and the material effects are introduced

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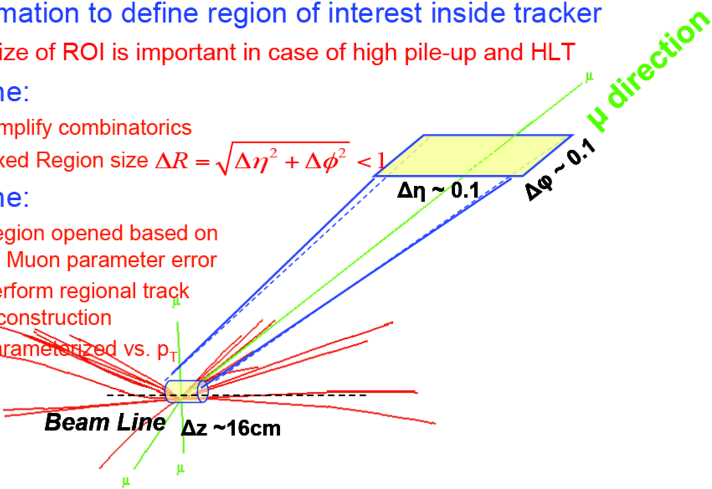
Global Muon :: Region of interest

- Use StandAlone track parameters and primary vertex information to define region of interest inside tracker
  - Size of ROI is important in case of high pile-up and HLT
- Offline:
  - Simplify combinatorics
  - Fixed Region size $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 1$
- Online:
  - Region opened based on L2 Muon parameter error
  - Perform regional track reconstruction
  - Parameterized vs. p_T



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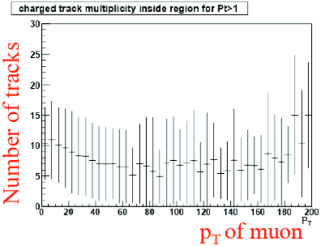
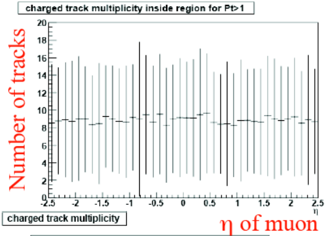
Global Muon :: Tracker tracks

Number of reconstructed tracks inside the offline region with p_T>1GeV

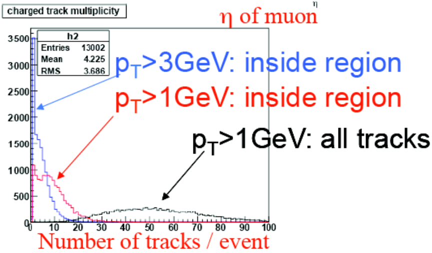
TTbar sample





Number of tracks per event
in the tracker for p_T > 1GeV

- p_T >1 GeV ~ 50 tracks
- p_T >1 GeV inside region ~ 8 tracks
- p_T >3 GeV inside region ~ 4 tracks



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Global Muon :: Track matching

- Test compatibility of tracker track with Standalone muon track
- Objectives
  - Efficient, fast, robust
- Matcher selects the correct match among the candidates
- Narrow down the number of candidates per standalone/L2 muon
- Algorithm is used *Online* and *Offline*
- High efficiency in case of multiple muons close to each other
- Allow for tracker–muon system misalignment

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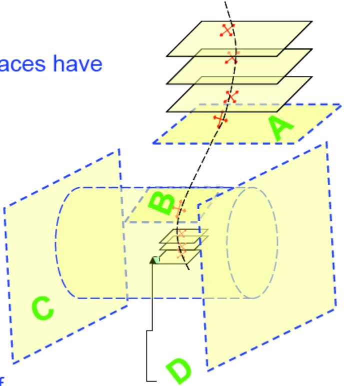
Global Muon :: Track matching

- The following (unbound) geometrical surfaces have been considered
  - (A) Inner-most Muon surface
    - - surface of the first muon hit
  - (B) Outer-most Tracker surface
    - - surface of the last tracker hit
  - (C) Tracker-envelope surface
    2 planes & cylinder
  - (D) Vertex point
- Option *C* was used in the past
  - both STA & TK tracks need to be propagated
- The current implementation makes use of surface *A* and Vertex point D
- Surface B can also be configured
  - surfaceOption == 1 in GlobalMuonTrackMatcher.h



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Global Muon :: Refit

- After the muon track matching a complete track fit is performed for all compatible combinations
  - Fitting: inside-out
  - Smoothing: outside-out
  - χ^2 of global fit to decide on best match
- Finally the track parameters with their covariance matrix at the innermost measurement is provided
  - Define p_T, eta, phi of muon
- The inclusion of all position measurements provided by the detector does not necessarily result in the best possible parameter estimation

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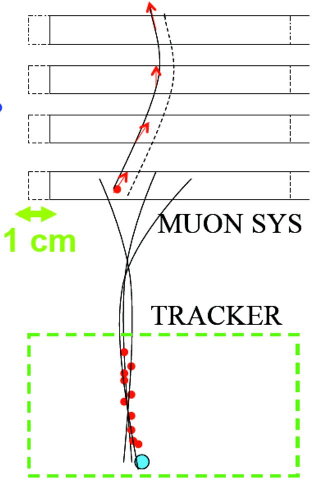
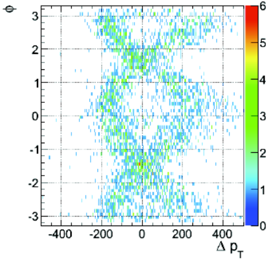
Global Muon :: Misalignment

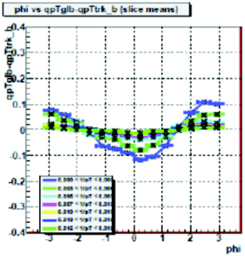
- How sensitive is the matching to misalignment of the first muon station (tracker-muon system misalignment)?
  - The matching criteria are very robust and allow for a misalignment of the order of centimeters
- Apply a systematic misalignment of the Muon system by 1cm along the beam line.
  - This is worst case scenario
  - StartUp conditions use a random misalignment with $\sigma_z \sim 0.2$ cm



Global Muon :: Misalignment

- The displacements and rotations for all tracking devices in CMS (misalignment) have a direct impact on the global muon reconstruction
- START misalignment scenario shows a dependency of the p_T residuals on phi; observed in data ("phi-mode")
  - The "phi-mode" makes up to 50% of the p_T resolution at TeV scale
  - The muon system introduces a bias in the global fit, which is pronounced at TeV energies





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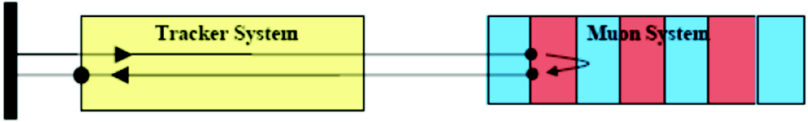
TeV Muons

- TeV muon reconstruction is affected by large energy losses from bremsstrahlung and/or the presence of severe electromagnetic showers in the muon chambers
- Muon trajectory *after* hard bremsstrahlung is problematic
- In the presence of severe EW showers in a muon chamber local pattern recognition may be affected
  - large hit multiplicity in muon chamber; pick wrong segment
- In order to improve muon momentum resolution, especially for high-momentum muons, various fit options were introduced ("TeV refits")
- Along with various refit options, there is a "cocktail" algorithm – which uses these refits as an input and aims at providing the best momentum resolution
- Currently following refit options are available:
  - TPFMS, Picky, DYT, Cocktail (Tune P)

TeV Muons :: Tracker + First Muon Station

- At high p_T, the muon momentum resolution is dominated by ~$1/(BL^2)$
- As the muon traverses the iron yoke, however, multiple scattering and/or showers will corrupt the measurement of the muon, so using multiple stations worth of muon hits is not always the best choice.
- Algorithm: use tracker and hits from the 1st muon station containing hits
  - large lever arm of first muon station



- This algorithm is referred to as tracker-plus-first-muon-station (TPFMS)
- If the muon brems before it reaches the muon system, or if there is large multiple scattering in the iron (lower-energy muons), the lever arm advantage of TPFMS can be wiped out, and it may not be as good.
- For each muon either tracker-only fit or TPFMS is selected based on goodness-of-fit criteria

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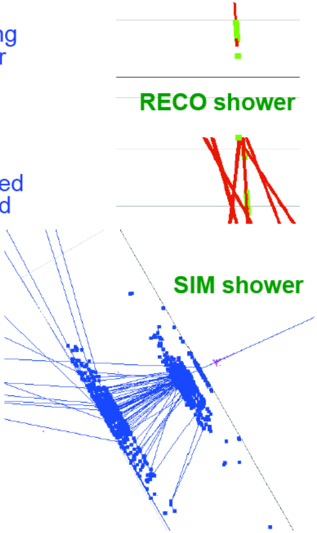
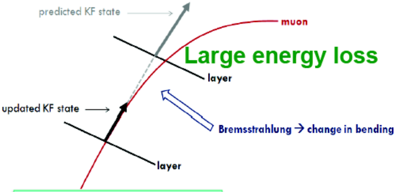
Global Muon :: Picky

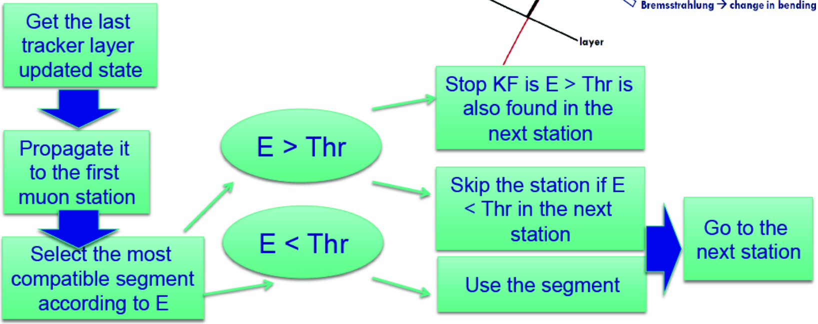
- The probability of electro-magnetic showering in the muon system (in the detector layers or in iron yoke) is relatively high
- An EM shower manifests itself by a large hit and segment occupancy of the muon chambers
- In cases of large energy loss, the extrapolated track state is incompatible with the measured segments
- Given the number of reconstructed segments is large, there is a high risk to pick up a wrong segment
- Algorithm: count segment in the cone around a muon track per chamber, skip station if the number of segments is below threshold
- Skipping an entire muon station where an electromagnetic shower is detected in the track fit improves the momentum resolution



Global Muon :: Dynamic Truncation

- How to approach the case when the radiative process happens entirely in inactive material (iron yoke)?
- In such case, a predicted track state is incompatible with muon segments, but a shower will not be identified





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Global Muon :: Cocktail = TuneP

- The idea of Tune P is to approach mis-reconstruction problems at the level of muon momentum assignment
- Algorithm: at the beginning, check the $\Delta p_T/p_T$ for each TeV refit
  - Mark refits with $\Delta p_T/p_T > 0.25$ as invalid
  - If all refits become invalid, raise the cut threshold to the value of the lowest $\Delta p_T/p_T$ available + 0.15
  - The algorithm then proceeds as usual, but picking an invalid track is forbidden
- Evaluate the tail probability P of the χ^2 of the fit, given the number of degrees of freedom to pick the best refit option

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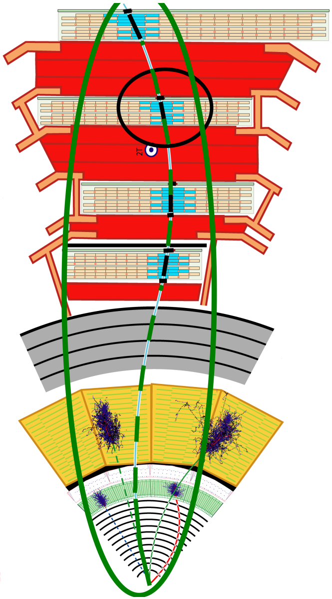

Tracker Muon Reconstruction

Tracker Muon

- A **tracker muon** is a type of reco::Muon which is produced by the muon ID algorithm
- Basic input are muons that have **Si-track**
- **Extrapolate Si-track through detector** and store traversed sub-detector information:
  - Energy deposits
  - Traversed (and nearby) chamber information
    - i.e. distances between extrapolated track position and chamber edges in X and Y of local coordinate system
  - Segment matching information
    - i.e. extrapolated track position - segment position

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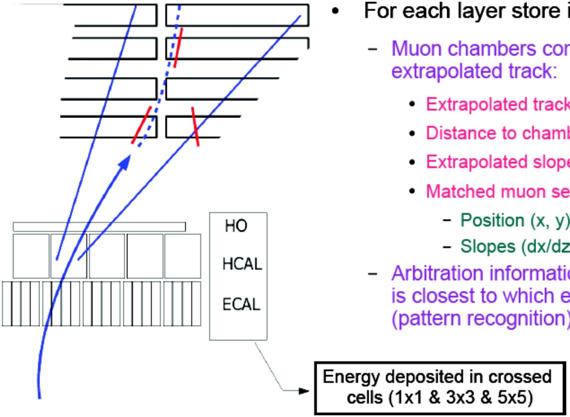
Tracker Muon

- In a nutshell: extrapolate Si-track through detector and store traversed subdetector deposits



- For each layer store information about:
  - Muon chambers compatible with the extrapolated track:
    - Extrapolated track position (x, y) + errors
    - Distance to chamber edge (x, y) + errors
    - Extrapolated slopes (dx/dz, dy/dz) + errors
    - Matched muon segments in chamber:
      - Position (x, y) + errors
      - Slopes (dx/dz, dy/dz) + errors
  - Arbitration information, i.e. which segment is closest to which extrapolated track (pattern recognition)

- All information accessible directly from muon object (see backups)

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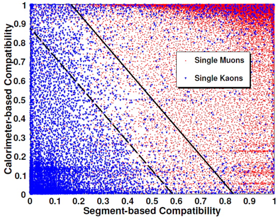
Tracker Muon :: TMOneStationTight

- **TMLastStation** :: Reduce hadron contribution (punch-through and decay-in-flight)
  - requires 2 tightly matched segments:
    - $|\Delta X| < \max(3\sigma_X, 3\,\mathrm{cm})$
    - $|\Delta Y| < \max(3\sigma_Y, 3\,\mathrm{cm})$
    - $|\Delta X|$ and $|\Delta Y|$ are the distances between the extrapolated silicon track and the segment in local X and Y coordinates (in cm)
    - σ_X and σ_Y are the uncertainties on $|\Delta X|$ and $|\Delta Y|$
  - one of the segments must belong to the last station crossed by the muon (fiducial volume)
  - Inefficiency in Barrel for low p_T
- **TMOneStationTight** :: requires single tightly matched segment:
  - $|\Delta X| < \max(3\sigma_X, 3\,\mathrm{cm})$
  - $|\Delta Y| < \max(3\sigma_Y, 3\,\mathrm{cm})$

Compatibility

- Continuous variables to quantify the compatibility with the *muon hypothesis*
- Segment Compatibility :: give higher weight to segments in last station
- Calorimeter Compatibility :: Low energy deposits (MIPs)



Tracker Muon :: Segment Matching

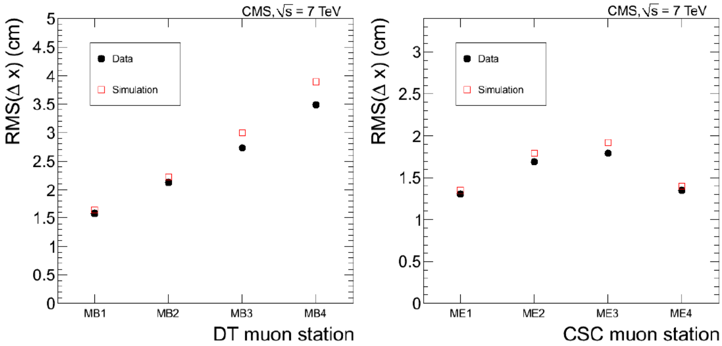
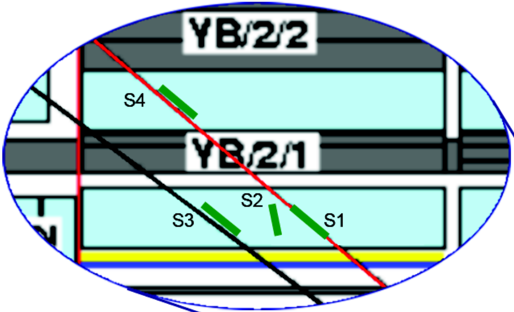


Figure 8. RMS width of residuals of the local x position, given by the position of the muon segment with respect to the extrapolated tracker track, as a function of the muon station, for DT chambers in the barrel region (left) and CSCs in the endcap regions (right). Data are compared with MC expectations.

Tracker Muon :: Arbitration



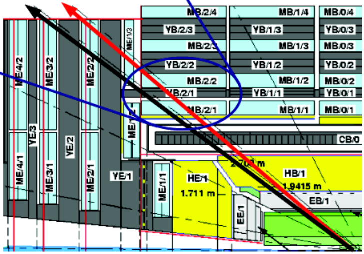
What is arbitration?

Before arbitration:

Red Track { S1 S2 S3 S4 }
Black Track { S1 S2 S3 }

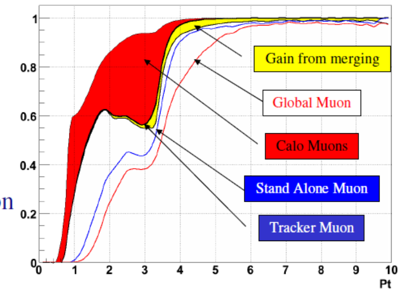
After arbitration:

Red Track { S1 S2 S4 }
Black Track { S3 }



Why Tracker Muons?

- Simple
  - No need to fit a track through a non-uniform magnetic field, accounting for large multiple scattering and dE/dX
- More efficient at low Pt in the barrel, where the Stand Alone Muon fails
  - Important for b-tagging!
- More handles to reject backgrounds
  - Layer-by-layer track-segment matching quality information accessible directly from muon object



- Demonstration of the gain in efficiency achieved by merging the various muon reconstruction algorithms products into a single collection.
- An aside: A Calo Muon is a tracker-track that was not reconstructed as a Global Muon or a Tracker Muon, and passes a minimum calo-compatibility requirement

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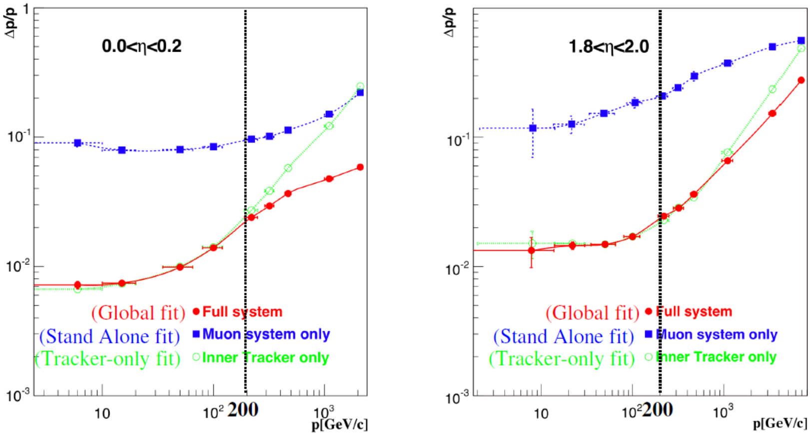
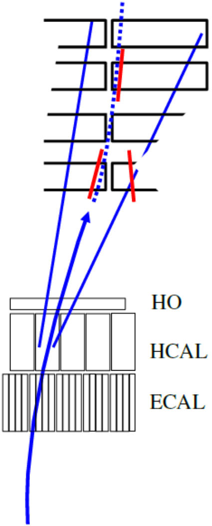
Why not only Tracker Muons?

- At high momentum (> 200 GeV), the global fit has better resolution in MC
  - But be careful about radiative effects at high momentum (global fits have more non-Gaussian tails) ==> Special selection can be applied



The Muon Object



- Track fits
  - Stand alone muon track
  - Tracker track (+ matched information)
  - Global track + TeV muon refits:
    - using only first muon station
    - 'picky' muon reconstructor
- MuonID
  - Matched muon chambers + segments
  - Deposited energy in ECAL, HCAL, HO
  - Compatibility with muon signature
  - Flag a Track with an "inclusive label": **trackerMuon**, **globlaMuon**, **standAloneMuon**
- Isolation information
- Muon time and velocity

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Sources

- CMS Muon TDR — http://cds.cern.ch/record/343814
- CMS Trigger TDR — http://cds.cern.ch/record/706847
- The CMS experiment at the LHC — http://iopscience.iop.org/1748-0221/3/08/S08004
- The performance of the CMS muon detector in proton-proton collisions at $\sqrt{s} = 7$ TeV at the LHC — http://iopscience.iop.org/1748-0221/8/11/P11002
- Marcin Konecki — CMS RPC Trigger performance — http://166.111.32.59/indico/getFile.py/access?contribId=18&sessionId=10&resId=0&materialId=slides&confId=1
- Tim Cox — CSC Local Reconstruction — https://indico.cern.ch/event/210563/
- Ingo Bloch — Muons in CMS — https://indico.cern.ch/event/54180/
- Riccardo Bellan — Introduction to the Muon Reconstruction Workshop — https://indico.cern.ch/event/210563/
- Daniele Trocino — Stand Alone Muon Reconstruction — https://indico.cern.ch/event/210563/
- Norbert Neumeister — Global Muon Reconstruction — https://indico.cern.ch/event/210563/
- Dmytro Kovalskyi — Tracker Muon Reconstruction — https://indico.cern.ch/event/210563/