High-Mass Resonances Decaying to Muon Pairs

Experimental Aspects in the CMS Experiment

Adam Everett

PURDUE UNIVERSITY

Outline

High Mass Dimuon Spectrum

Experimental Aspects

- **CMS Detector**
- **Muon Reconstruction**
  - Resolutions and Efficiencies
- **Measuring Efficiencies from Data**

Discovery potential and reach

- **Extra dimensions**
- **Z'$\rightarrow\mu^+\mu^-$**

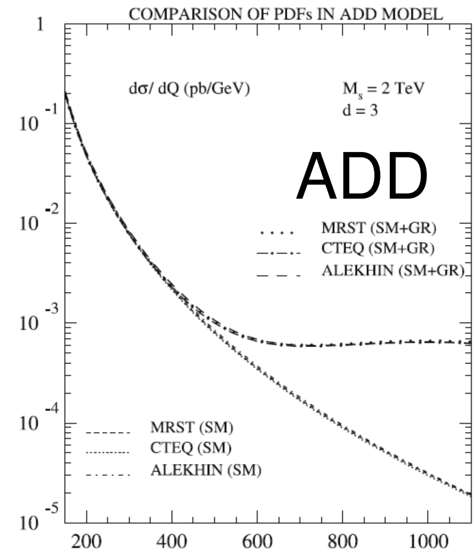
Motivation: Dimuon Physics Signals

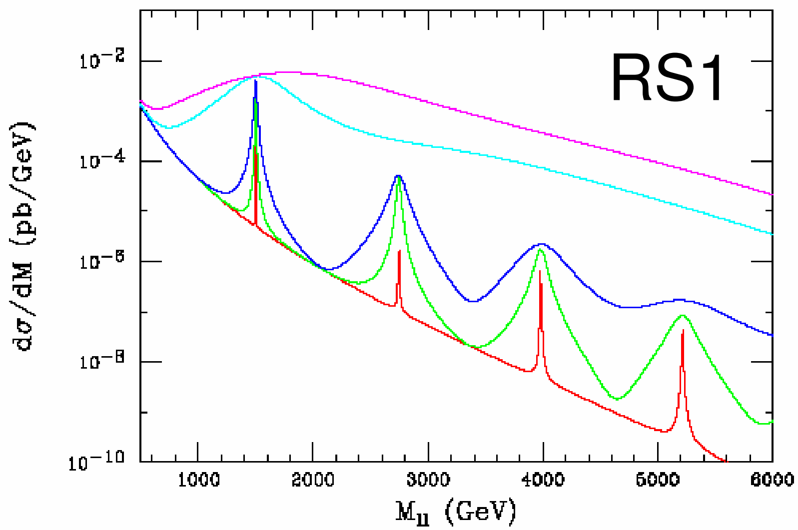
Many scenarios beyond the Standard Model are expected to manifest themselves through modifications in the mass spectrum of high-mass dimuon pairs.

- **Dimuon final states predicted in two classes of large extra dimension models**
  - ADD (*Phy. Lett.* **B429** 263-272)
    - **Observed via non-resonant modifications of the dimuon spectrum**
  - RS (*Phys. Rev. Lett.* **83** 3370-3373, 4690-4693)
    - **Observed via relatively narrow resonances**
- **Discover dimuon decays of a new heavy neutral gauge boson**

•Backgrounds

- **Drell-Yan, vector boson pair production, ttbar, etc.**





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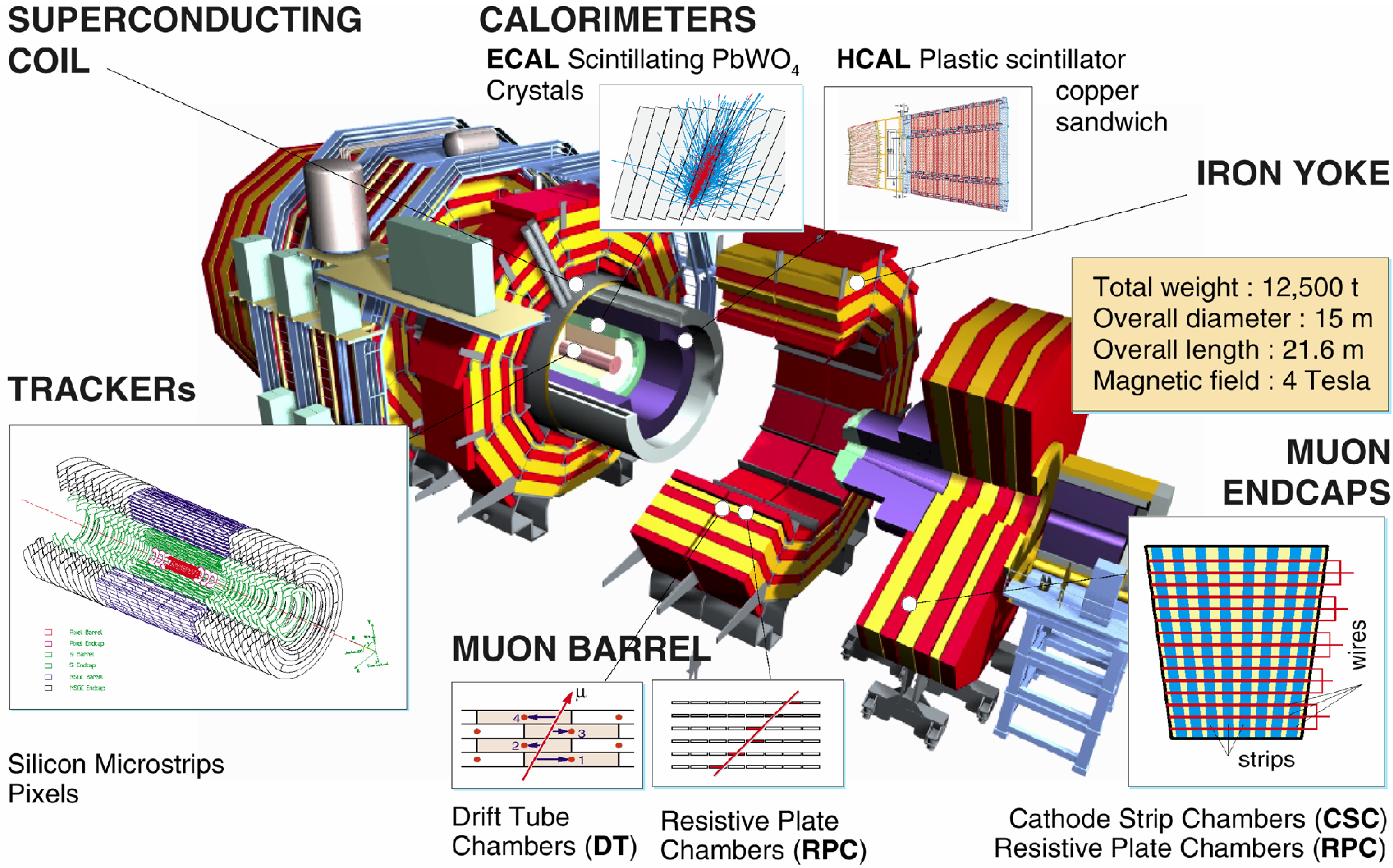
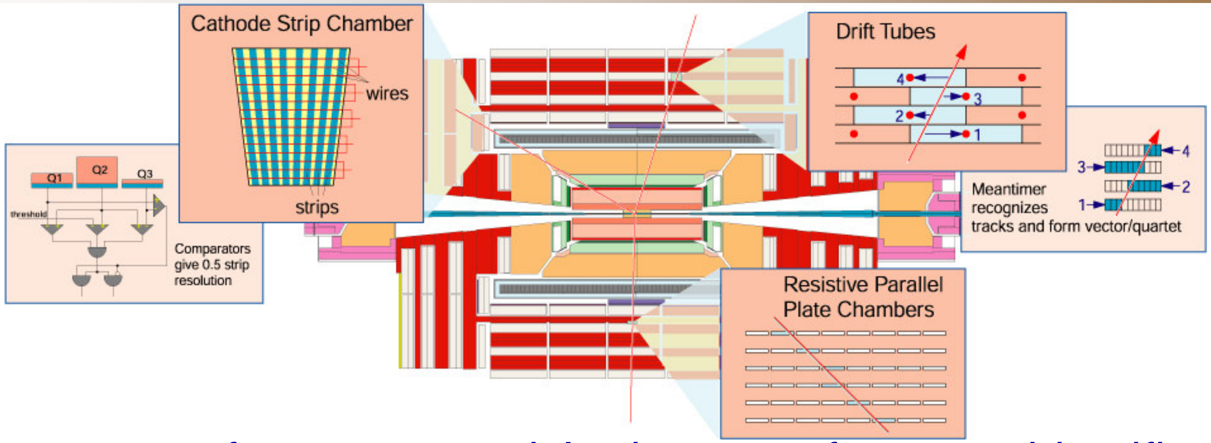
CMS Detector



Muon Detectors



CMS uses three types of gaseous particle detectors for muon identification

Drift Tubes (DT): central barrel region ($|\eta|<1.2$)

- 4 layers per superlayer; 2-3 superlayers per station
- Precise measurement of position and momentum:
  - **Offline: 250 – 100 µm; Online: ~2 mm**

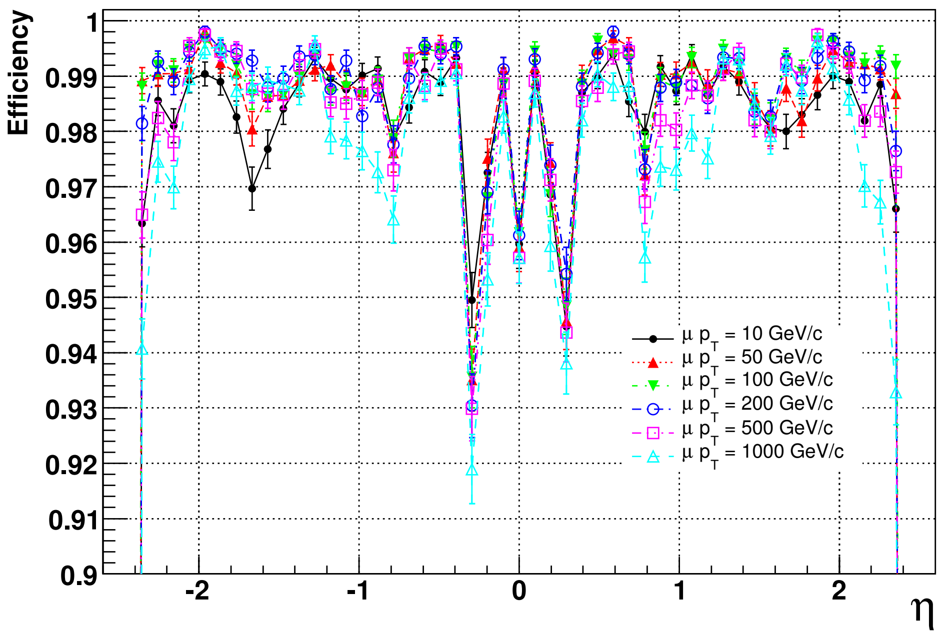
Cathode Strip Chambers (CSC): endcaps ($0.8<|\eta|<2.4$)

- 1 wire plane and 1 cathode plane with strips per gap; 6 gaps per chamber
- Precise measurement of position and momentum:
  - **Offline: 100 µm; Online ~2mm**

Resistive Parallel Plate Chambers (RPC): barrel and endcaps

- 1-2 PC per DT; 1 RPC per CSC
- Good spatial and time resolution: ~1 cm; ~2 ns

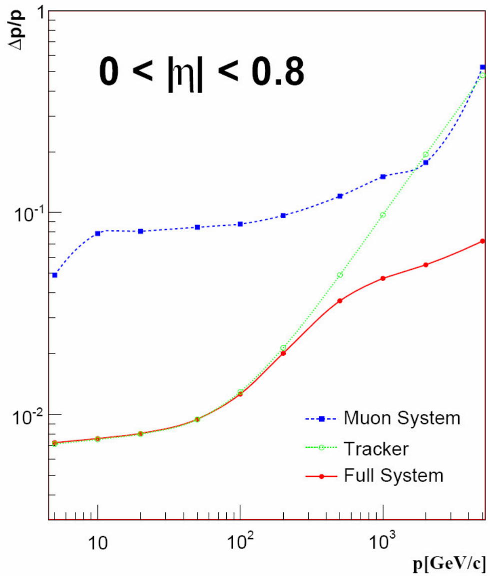
Muon Reconstruction Efficiency

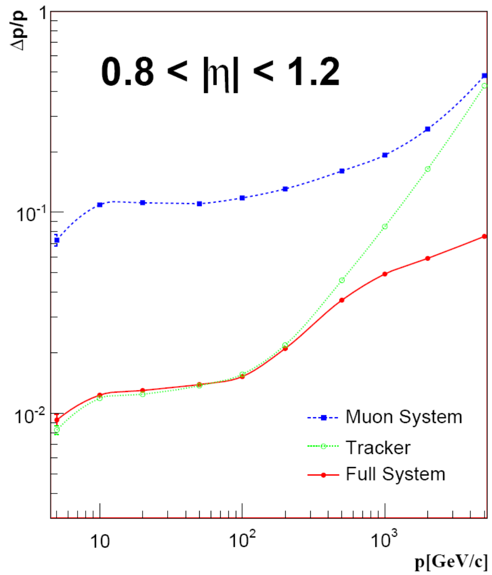


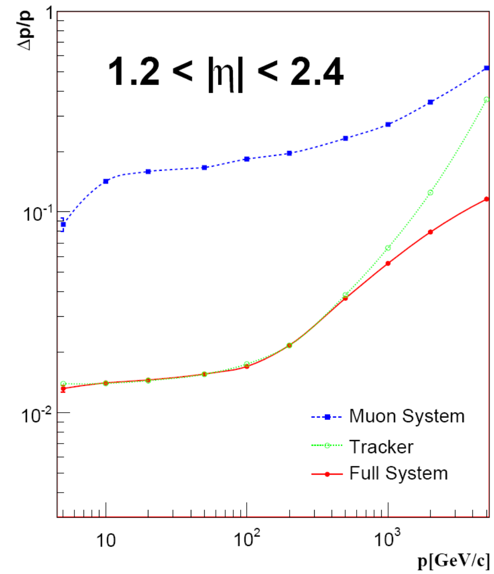
Reconstruction of muons as a function of pseudorapidity as measured from Monte Carlo studies

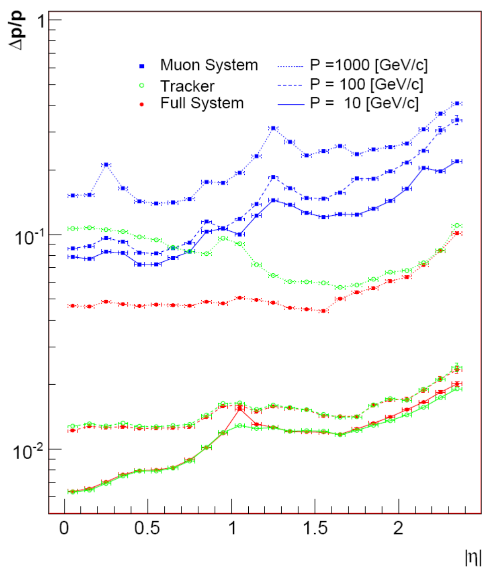
- **Efficiency is uniform over pseudorapidity**
- **Efficiency is uniform over energy of muons**
- **Some special optimization developed for high-energy muon reconstruction**

Muon Reconstruction Resolution







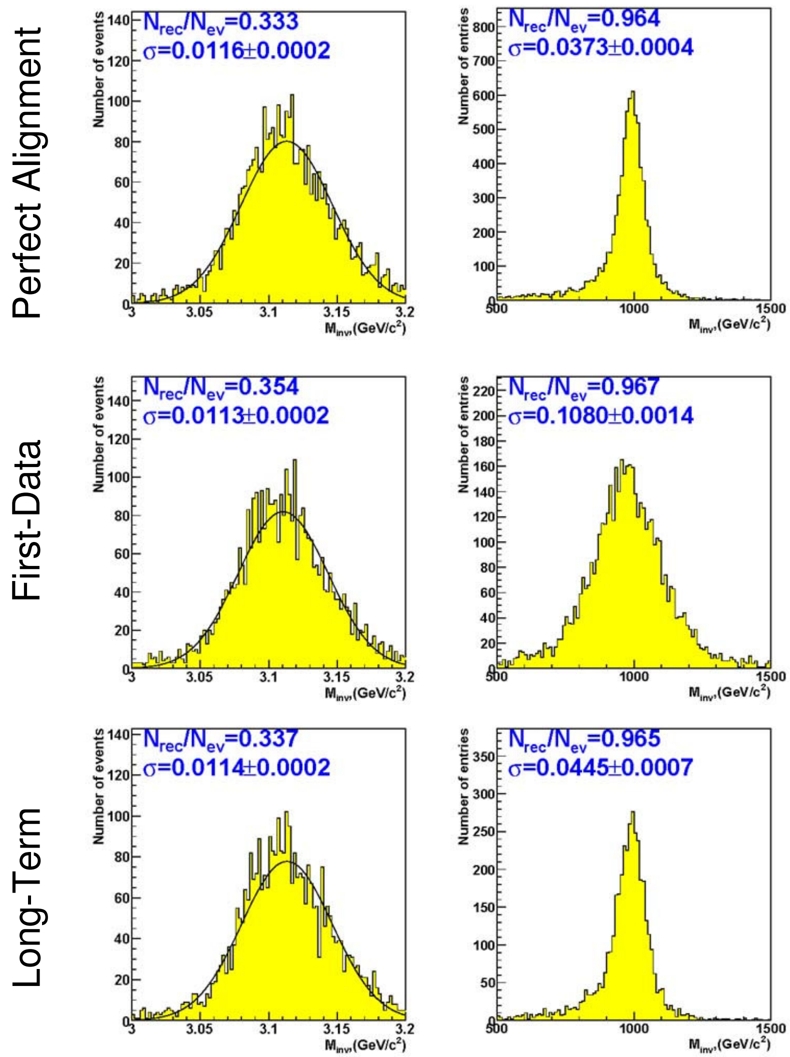


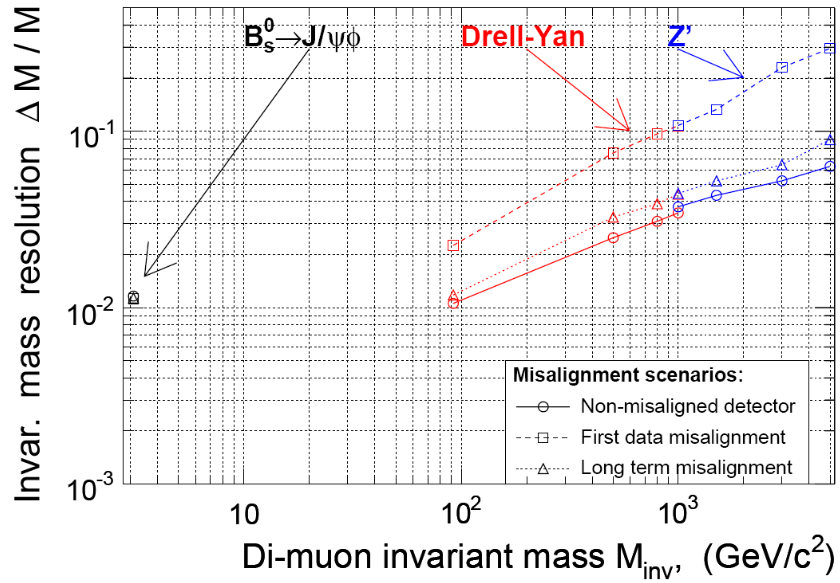
Muon p_t resolution as a function of momentum and pseudorapidity

- **At low energy, central tracker dominates resolution**
- **At high energy, using the full detector improves resolution**

Dimuon Reconstruction Resolution

$J/\psi \rightarrow \mu^+\mu^-$ $Z' \rightarrow \mu^+\mu^-$





Dimuon invariant mass distributions and resolutions for different channels and misalignment scenarios

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General Search Procedure

Search for new physics is performed by comparing the observed distribution of an opposite-sign muon pair with that expected from standard model processes

  - Bump search, cross section measurement, etc.

- DY muon pair production is the dominant and irreducible background
  - Essential to measure and understand DY mass spectrum over a large range
- Event Selection
  - Online:
    - Each event must pass a single OR double muon path (L1 and HLT)
      - L1: pt > 7 GeV; pt > 3, 3 GeV
      - HLT (non-isolated): pt > 16 GeV; pt > 3, 3 GeV
  - Offline
    - At least two opposite-sign muons reconstructed

Efficiency Measurements

The overall dimuon efficiencies of the measurement are assumed to be the product of several parts

$$\varepsilon = \varepsilon_{\text{trigger}} \times \varepsilon^{2}_{\text{offline}}$$

$$\varepsilon_{\text{trigger}} = \varepsilon_{\text{L1}} \times \varepsilon_{\text{HLT}}$$

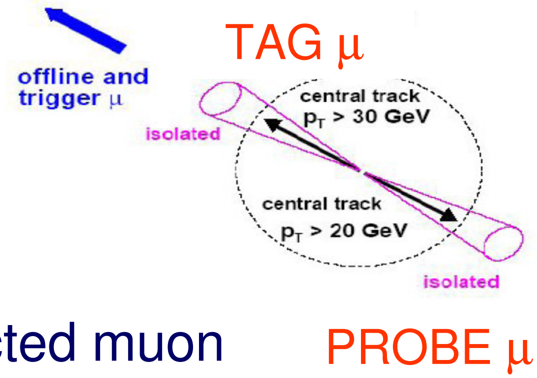
$$\varepsilon_{\text{offline}} = \varepsilon_{\text{global}} \times \varepsilon_{\text{isolation}} \times \varepsilon_{\text{id}}$$

$$\varepsilon_{\text{global}} = \varepsilon_{\text{standalone}} \times \varepsilon_{\text{tracker}} \times \varepsilon_{\text{matching}}$$

Methodology

Tag-And-Probe method is a method to determine reconstruction efficiencies from physics processes

- GOAL: Efficiency table as a function of η and p_t
- used by electron/photon analyses; extensively used in CDF and D∅



- **Choose a reference process: $Z \to \mu^+ \mu^-$**
  - Choose a *tag* muon: "high quality" reconstructed muon
  - Choose a *probe* track: probable muon based on criteria to study
- **Requiring $M_{\mu\mu}$ consistent with M_Z yields a high-purity and almost unbiased sample of *probe* muons**
  - Several different strategies for handling background
    - **Side band subtraction, signal + bkgd. fit, etc.**

Description of TAG and PROBE

Tag Type	Description
Reconstruction	Global muon p_t > 30 GeV
Isolation	Isolated Global muon p_t > 20 GeV

Probe Type	Description
Golden	Global muon that is also a TAG
Matched	Global muon that is not a TAG
Unmatched	Tracker track AND Standalone muon found, but they are not associated with a Global Muon
Tracker Only	Only a tracker track
Stand Alone Muon	Only a standalone muon
Isolated	Isolated muon
Non-isolated	Non-isolated muon

Efficiency Calculations

- Standalone, Tracking, Matching, and Isolation efficiencies calculated with simple event counting

$$\varepsilon_{\text{standalone muon}} = \frac{2N_{GG} + N_{GM} + N_{GU}}{2N_{GG} + N_{GM} + N_{GU} + N_{GT}}$$

$$\varepsilon_{\text{tracker track}} = \frac{2N_{GG} + N_{GM} + N_{GU}}{2N_{GG} + N_{GM} + N_{GU} + N_{GS}}$$

$$\varepsilon_{\text{matching}} = \frac{2N_{GG} + N_{GM}}{2N_{GG} + N_{GM} + N_{GU}}$$

$$\varepsilon_{\text{isolation}} = \frac{2N_{II}}{2N_{II} + N_{IN} + N_{NI}}$$

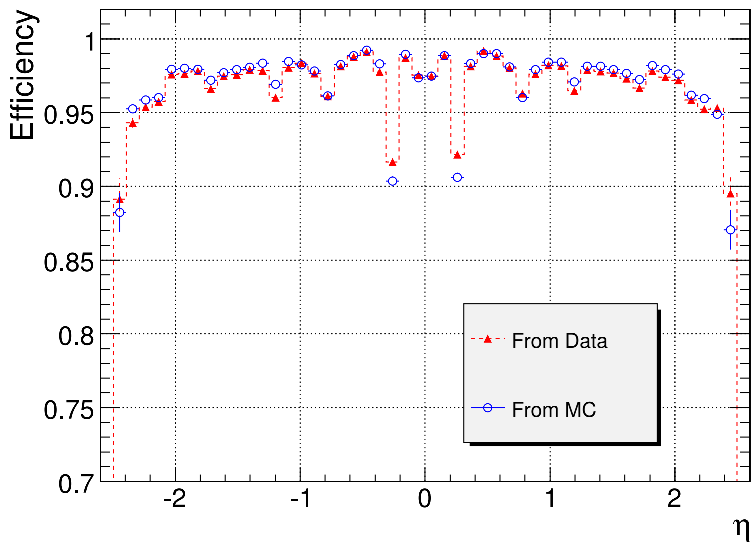
TAG and PROBE Selection

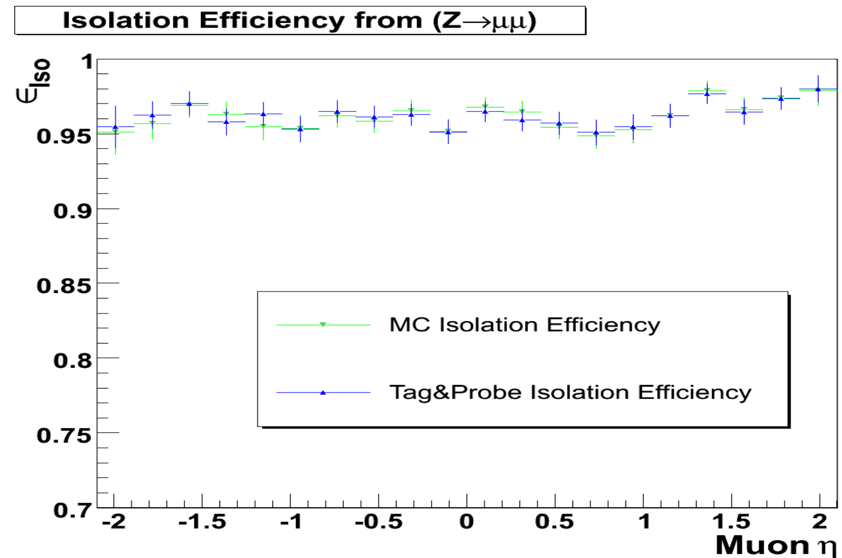
Tag: Global muon with pt > 30 GeV

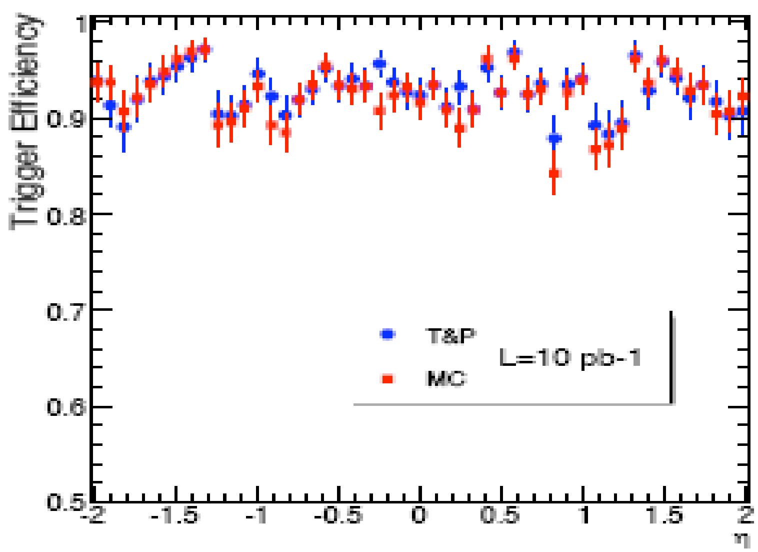
Probe: additional cuts minimize background

- **Global muon (isolated)**
  - $p_T > 10$ GeV
  - $\Delta\phi_{Tag,Probe} > 1.5$
- **Standalone muon (isolated)**
  - $p_T > 10$ GeV
  - $\Delta\phi_{Tag,Probe} > 1.5$
- **Tracker track (isolated)**
  - $p_T > 15$ GeV
  - $\Delta\phi_{Tag,Probe} > 1.5$
- **Isolation Study**
  - $P_t > 20$ GeV, $|\eta|<2.0$, $M_{\mu\mu} \in (70,110)$GeV

Tag and Probe Results (Reco)







Efficiencies from Tag-and-Probe method are compatible with efficiencies calculated from Monte Carlo studies

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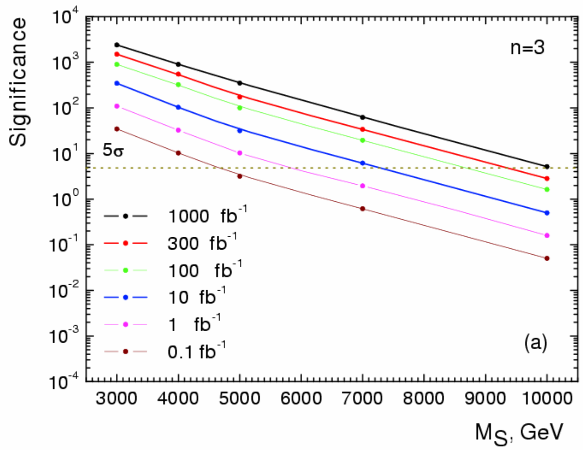
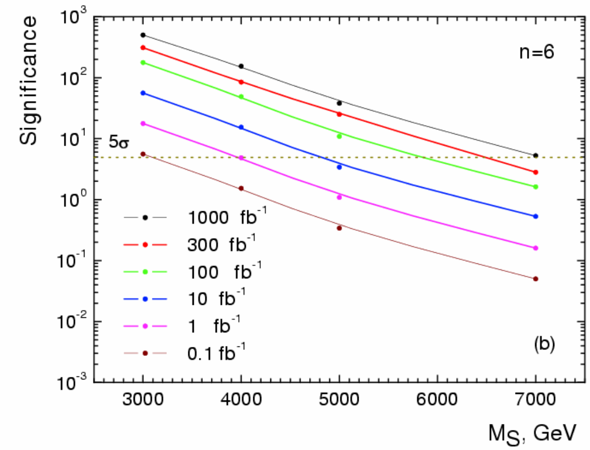
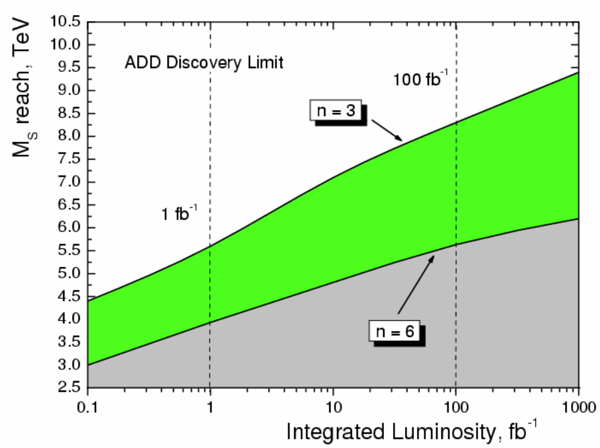
- **$Z' \to \mu^+\mu^-$**

Discovery Potential (ADD)



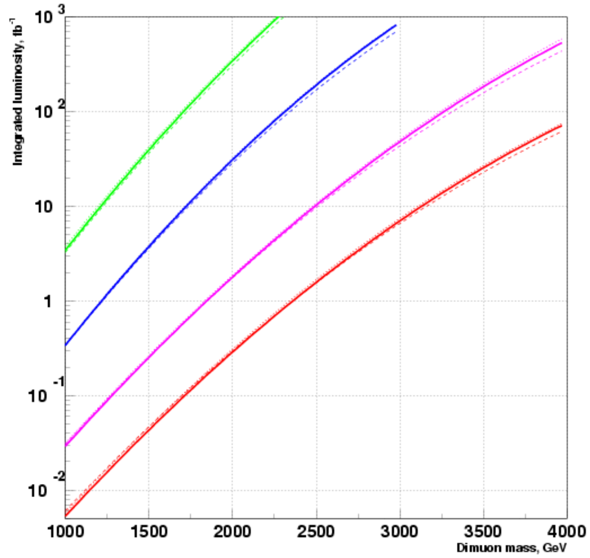




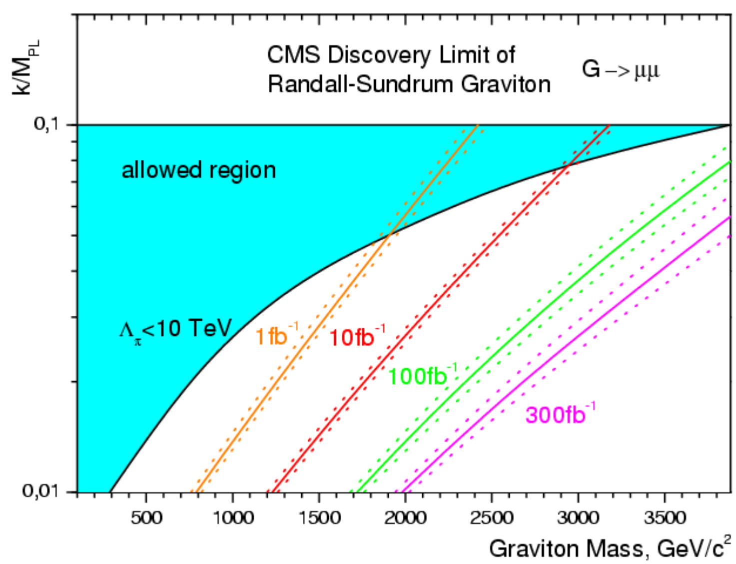
Significance as a function of the mass scale for 3 and 6 extra dimensions

Discovery reach on M_s as a function of luminosity

Discovery Potential (RS)

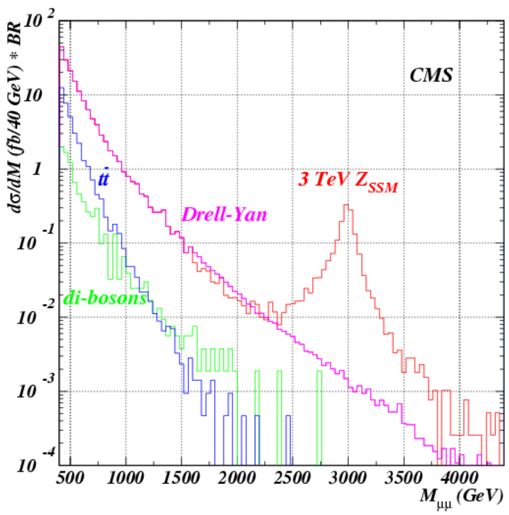


Integrated luminosity required for a discovery
for various values of the coupling c= 0.01, 0.02, 0.05 and 0.1 (from top to bottom)

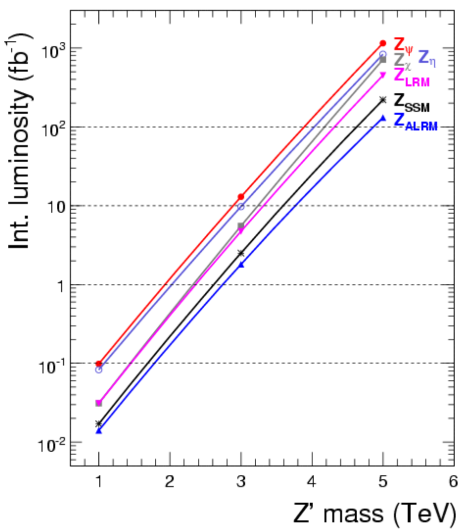


Discovery reach for various luminosities.

Discovery Potential (Z')



Cross section times the branching ratio for 3 TeV Z' of the Sequential Standard Model (red) as a function of the $\mu+\mu-$ invariant mass $M\mu\mu$, compared with the production of muon pairs in a few main background sources.



Integrated luminosity required for a 5-sigma discovery as a function of the Z' mass for various Z' models.

Conclusion

CMS Detector optimized for muon detection

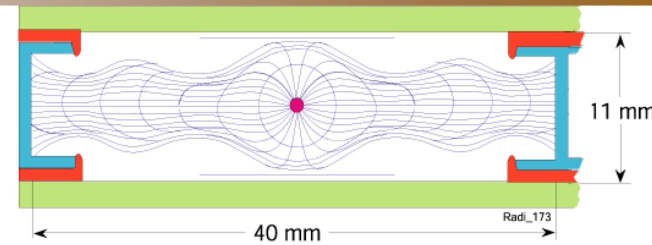
New Physics signals in high-mass resonances

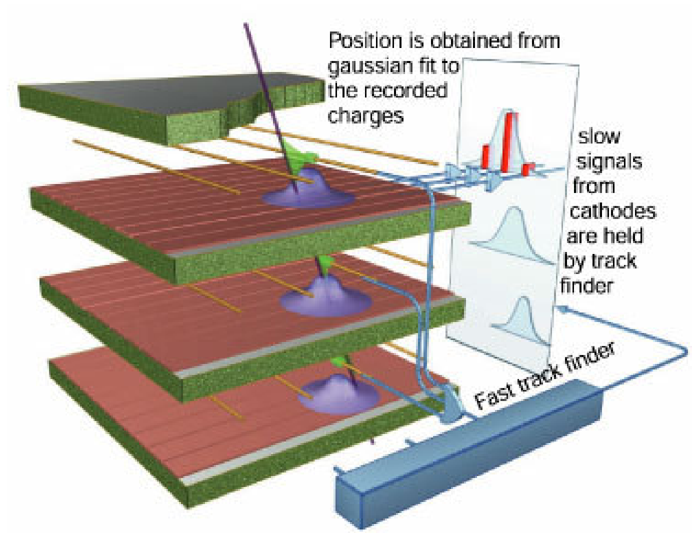
- **New bosons**
- **Extra dimensions**

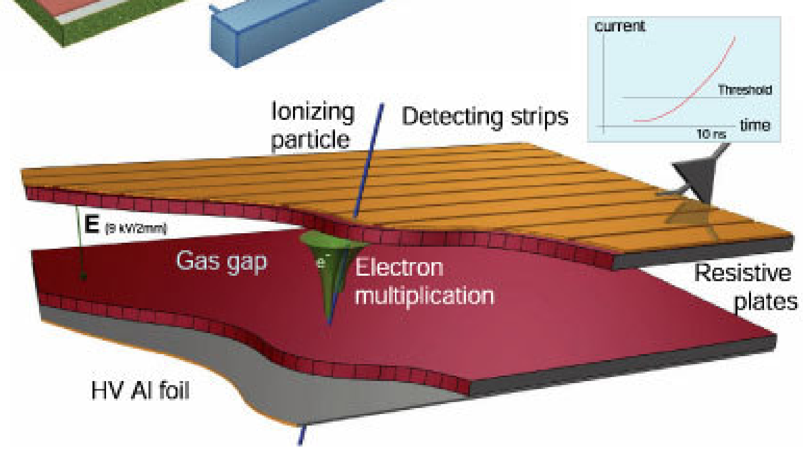
Special Optimization and Methods developed for detecting high energy muons and measuring efficiencies and resolutions from data

Backup Slides

Local Reconstruction







DT Local Reconstruction

Single cell: drift time is converted to position with respect to the wire

R-ϕ and R-θ views reconstructed independently

In superlayer R-ϕ: $\sigma \approx 146\ \mu m$

CSC Local Reconstruction

Build 2D points:

- ϕ measured by strips
- R measured by wires

Build segment: fit 2D points from 6 layers

Position resolution: $\sigma \approx 100 \div 200\ \mu m$

RPC Local Reconstruction

Strips in double gap measure ϕ

Primarily for trigger use, but still used in reconstruction

Muon Reconstruction Stages

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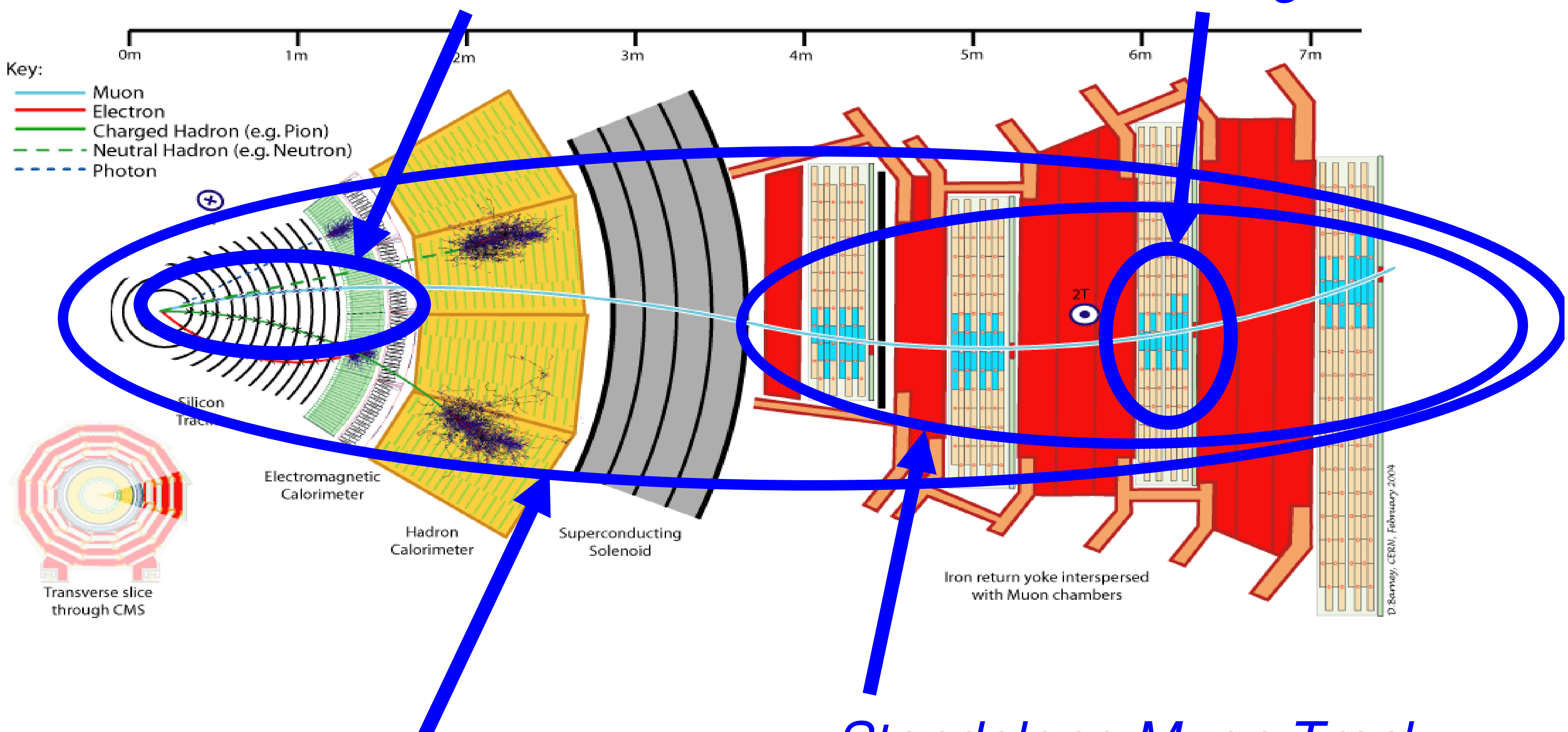
Muon in Silicon Tracker *Hits and Track Segments*



Global Muon Track *Standalone Muon Track*

Software Design

Level-1 Trigger

- **The only CMS hardware trigger**
- **Level-1 Trigger gives us a physics object (pt, direction, etc.)**

Offline and High-Level Trigger (HLT)

- **Reconstruction software: reusable for offline and HLT**
- **Require seeds – initial values of 5 trajectory parameters**
  - Level-1 Trigger provides seed for HLT
  - Segments chambers provide offline seed
- **Offline reconstruction makes use of complete calibration, alignment, etc.**

Requirements

- **Object-Oriented design**
- **Flexibility to adapt to unforeseen conditions and cope with imperfect detector**
- **Scheduled Reconstruction: reject events as soon as possible**
- **Regional reconstruction**
  - Use data in a region around a seed
  - Reconstruction/selection applied to seed regions only

Standalone Muon Reconstruction

All muon detectors (DT, CSC and RPC) are used

Seed generation:

- **Online: Level-1 trigger → Level-2 reconstruction**
- **Offline: patterns of muon system segments**

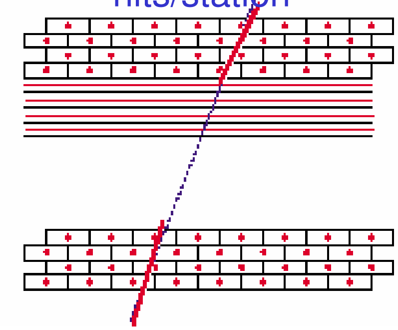
Fit:

- **Kalman filter technique applied to DT/CSC/RPC measurements**
  - Use segments in barrel and 3D hits in endcaps
- **Trajectory building works from inside out**
- **Apply χ^2 cut to reject bad hits**
- **Track fitting works from outside in**
- **Fit track with beam constraint**

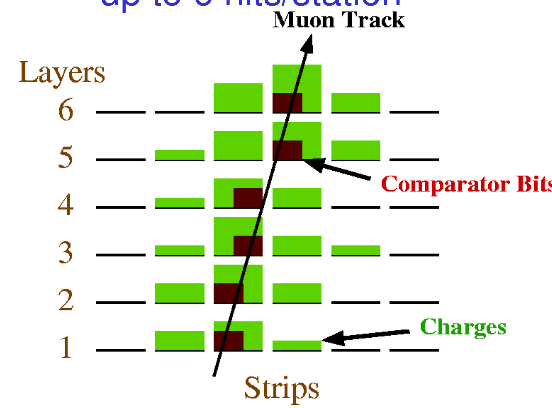
Propagation:

- **Non constant magnetic field**
- **Propagation through iron between stations**

Barrel: Drift Tubes up to 12 hits/station



Endcap: Cathode Strip Chambers up to 6 hits/station

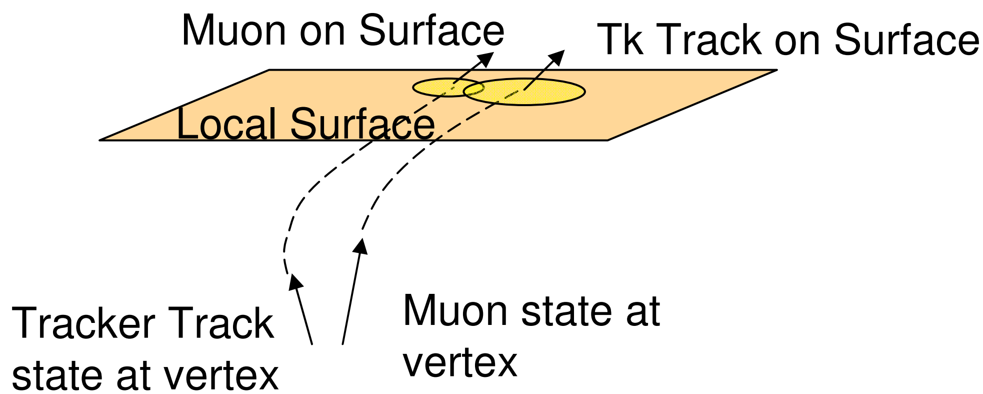


Global Muon Reconstruction

- **Start from standalone reconstructed muon**

Online

- **Tracker Seed based on Level-2 standalone muon**
- **Regional Tracker track reconstruction from Seed**
  - Propagate from innermost layers out
  - Resolve ambiguities
  - Final fit of trajectories



Offline

- **Tracker tracks already reconstructed**
- **Match best tracker track to standalone muon**
- **Refit of both tracks' information**