Online Event Selection at the LHC

Part III: Reconstruction of Physics Objects

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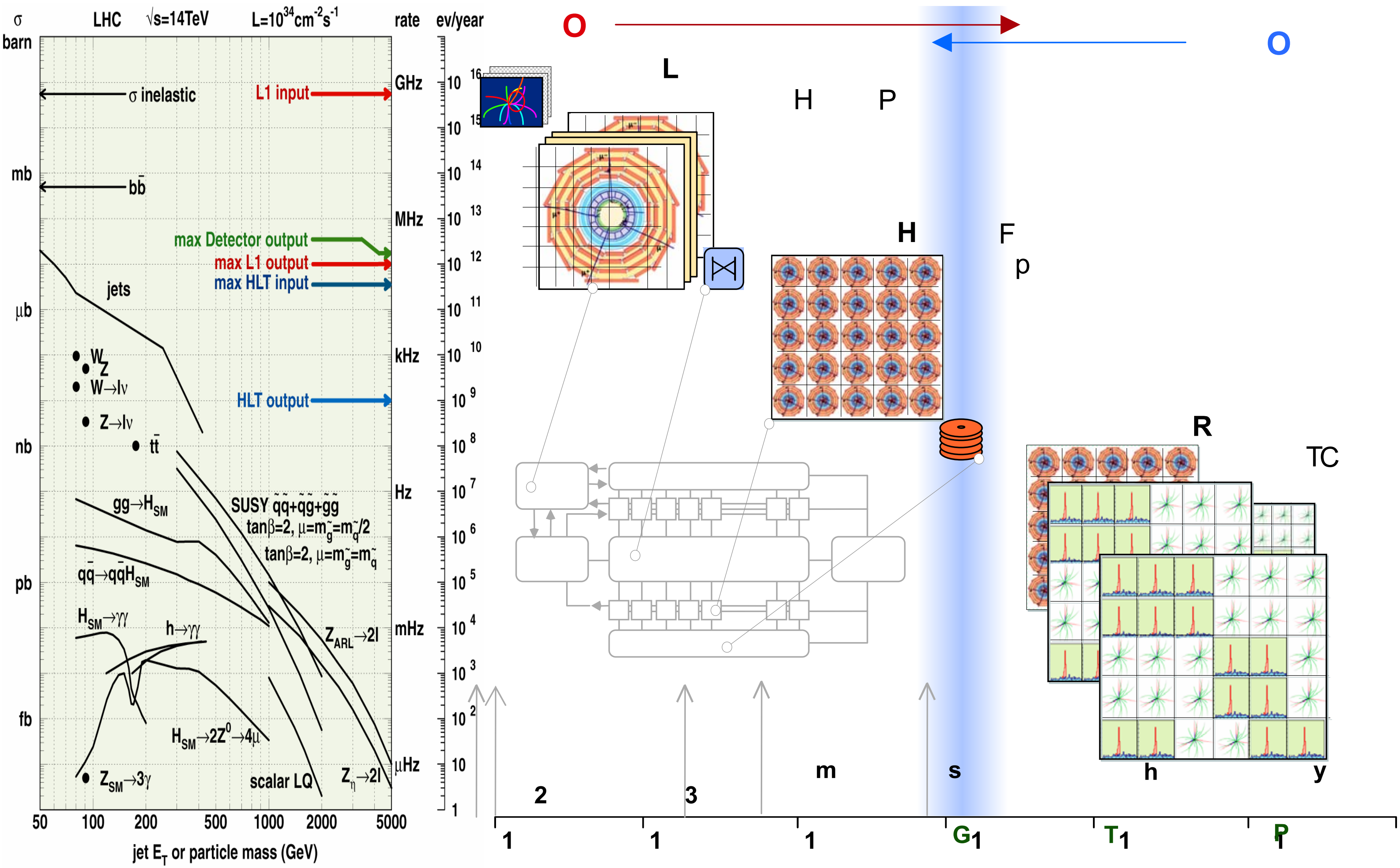
Event Selection Stages



Outline

- **Physics Objects**
- **Reconstruction of Physics Objects**

- **Muons**
  - Detectors
  - Level-1 algorithms
  - Reconstruction algorithms
  - High-Level Trigger selection strategy
- **Electrons, Photons**
  - Detectors
  - Level-1 algorithms
  - Reconstruction algorithms
  - High-Level Trigger selection strategy
- **Jets/Taus**
  - Level-1 algorithms
  - Reconstruction algorithms
  - High-Level Trigger selection strategy

- **Trigger Table Determination**

Physics Objects

Object	Examples of Physics Coverage
Muon	Higgs (SM, MSSM), extra gauge bosons, extra dimensions, SUSY, W, Z, top
Electron	Higgs (SM, MSSM), extra gauge bosons, extra dimensions, SUSY, W, Z, top
Photon	Higgs (SM, MSSM), extra dimensions, SUSY
Jet	SUSY, compositeness, resonances
Tau + missing E_T	Extended Higgs models, SUSY
Jet + missing E_T	SUSY, leptoquarks

Reconstruction Algorithms

- Muons
  - Level-1 background:
    - K, π, b, c decays - real muons!
    - Low p_T muon promotion
  - Successive refinement of momentum measurement + isolation

1) Reconstructed in muon system; must have valid extrapolation to collision vertex
2) Calorimeter isolation
3) Full track match, tracker isolation

- Electrons and Photons
  - Level-1 background:
    - π^0s from profusely produced QCD jets

1) Better isolation, π^0/γ rejection - full granularity calorimeter
2) Matching track stub in pixel detector
3) Full track match, bremsstrahlung and pair conversion identification

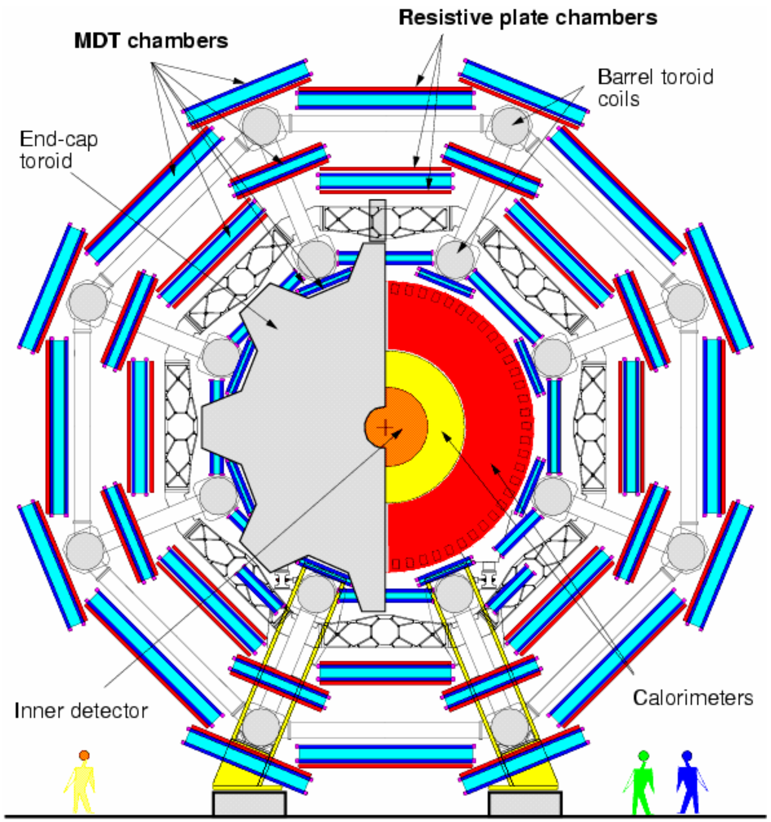
Reconstruction Algorithms

- Jets and E_T^{miss}
  - Level-1 background:
    - Real Jets
  1) Better energy resolution, multi-jet topology
  2) Primary vertex identification
  3) Secondary vertices to identify b-jets
  - Jet reconstruction with iterative cone algorithm
  - E_T^{miss} reconstruction (vector sum of towers above threshold)

- τ-jets
  - Level-1 background:
    - Jet fluctuations that cause narrow jets
  1) Calorimetric reconstruction and isolation (full calorimeter granularity)
     - Very narrow jet surrounded by isolation cone
  2) Pixel stub matching and isolation
  3) Track match and tracker isolation

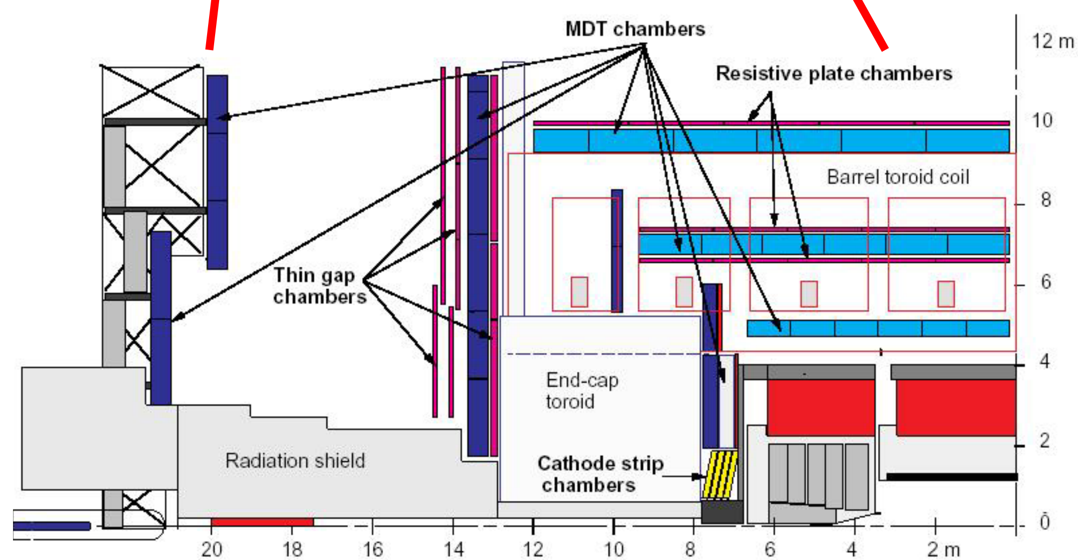
Muons

The ATLAS Muon Spectrometer



End-cap: $1 < |\eta| < 2.7$
Tracking with MDTs & CSCs
Triggering with TGCs

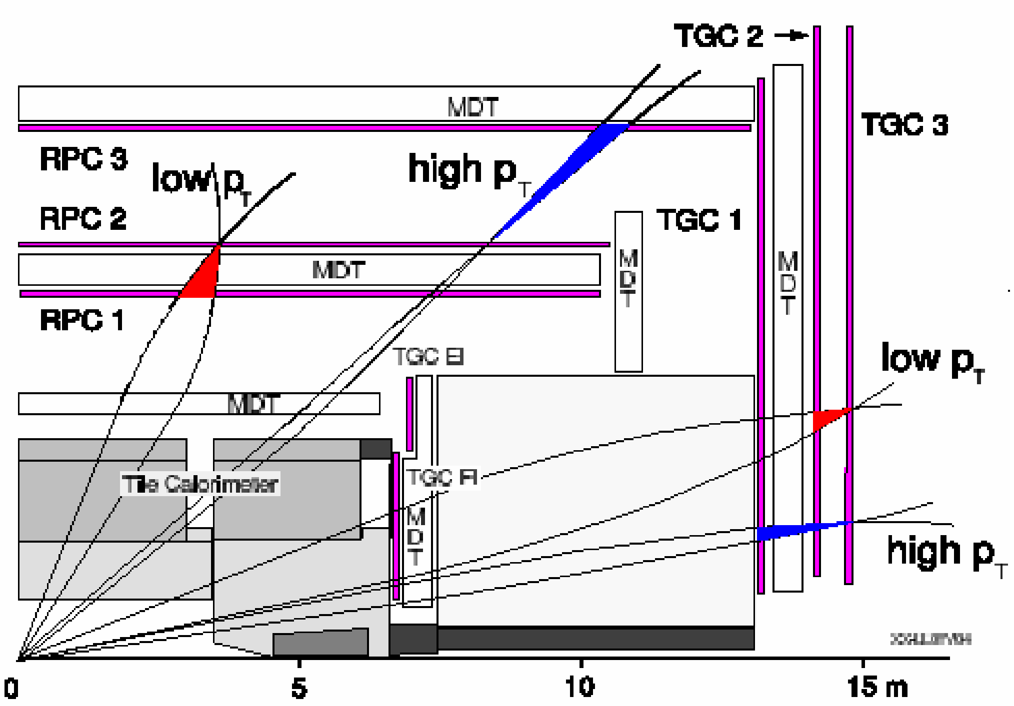
Barrel: $|\eta| < 1.0$
Tracking with MDTs
Triggering with RPCs



Acceptance: $|\eta| < 2.7$

P_T Resolution: ~10% @ 1 TeV
< 3 % P_T < 250 GeV

ATLAS: Level-1 Muon Trigger



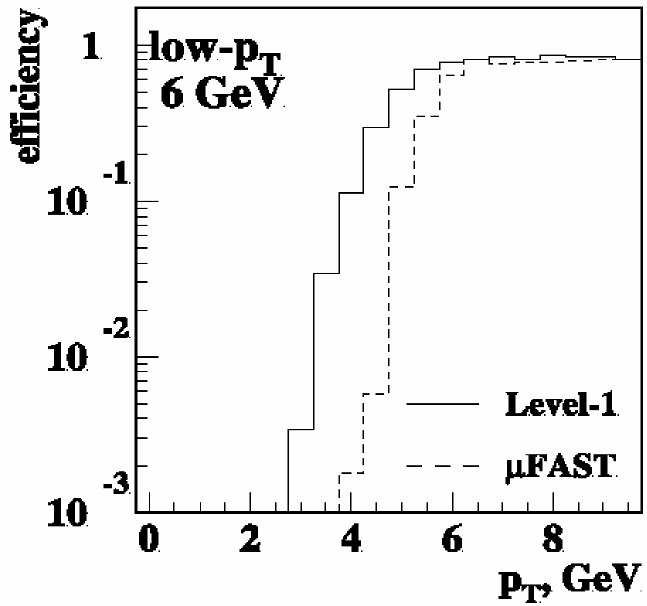
- RPC in barrel regions
  - 3 stations
  - 430,000 channels
- TGC (Thin Gap Chambers) in end-cap regions
  - 3 stations
  - 800,000 channels
- Coincidence logic (η and φ)
- Two p_T threshold ranges

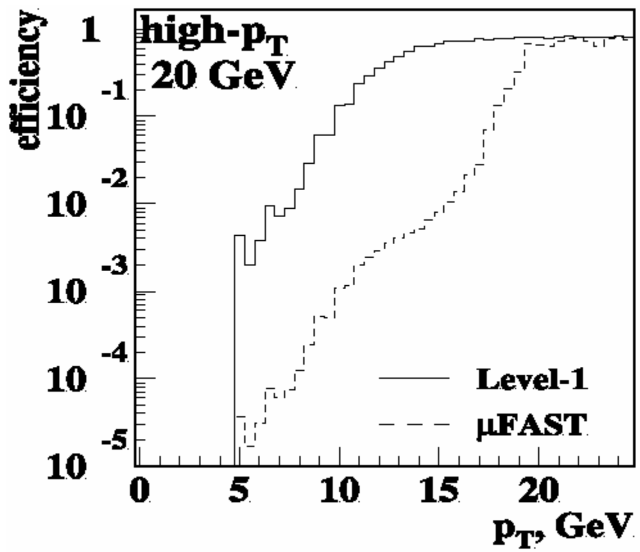
- **Low p_T (6 – 10 GeV):**
  - Require hits in 3 out of 4 layers in inner two stations
- **High p_T (8 – 35 GeV):**
  - Require hits in 3 out of 4 layers in inner two stations
  - Require hits in 1 out of 2 layers of the outer station (2 out of 3 in the end-caps)

The Level-1 trigger logic is almost fully programmable; this flexibility will allow to optimize carefully the signal trigger efficiency vs. the background rejection.

ATLAS: Muon HLT (I)

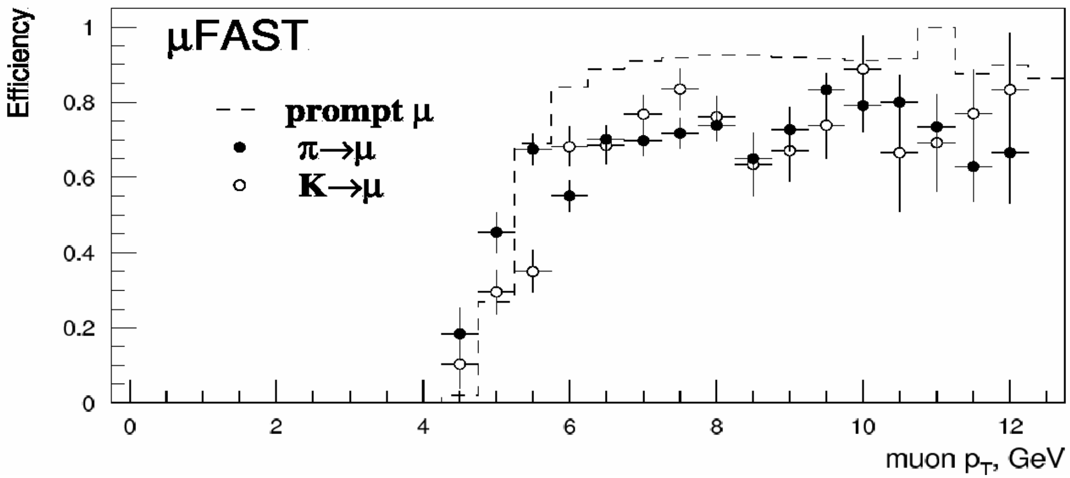
- High rate of low-p_T muons accepted by Level-1: π, K decaying in flight
- Confirm Level-1 muon and reject fakes
- Uses MDT in addition to RPC
- p_T resolution
  - 5.5 % at low p_T, 4 % at high p_T
- Efficiency: ~ 90 % above trigger threshold
- Reduces Level-1 rate by a factor of
  - ~2 at low p_T, ~10 at high p_T

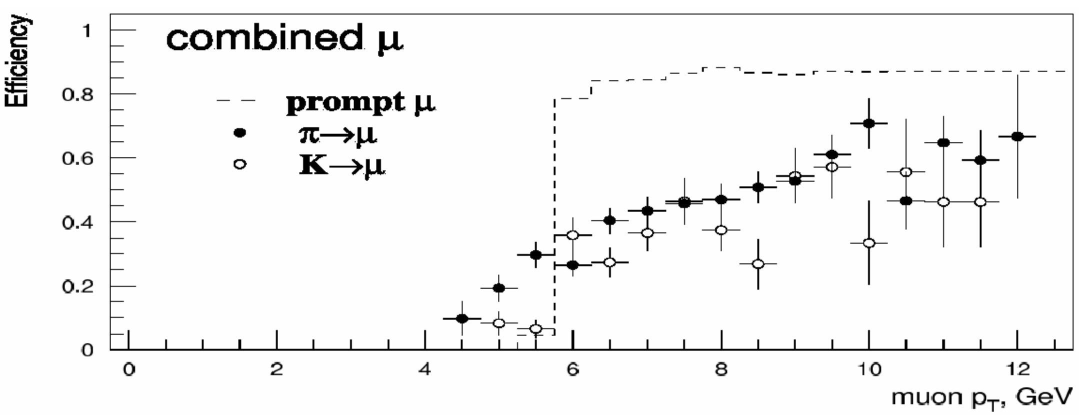




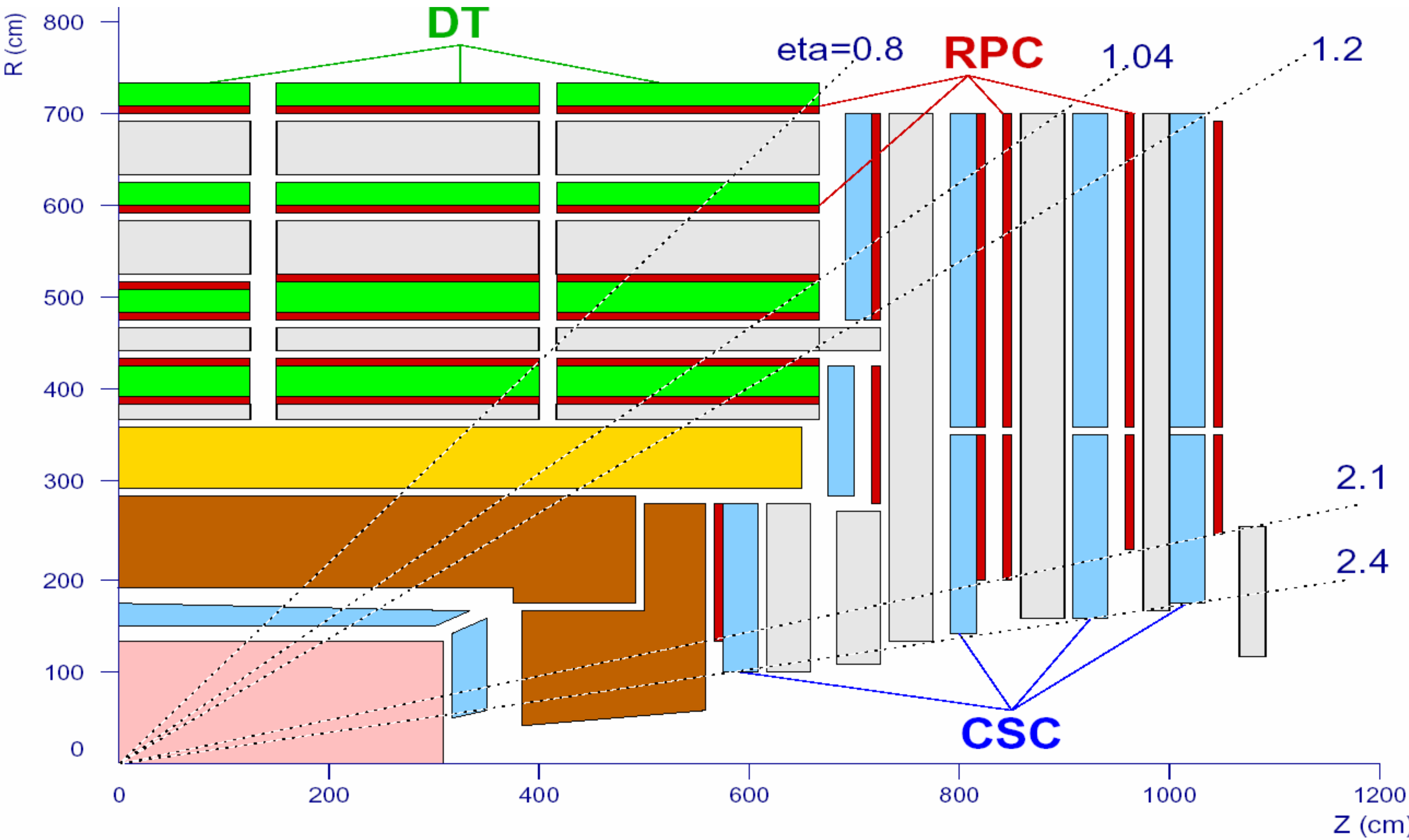
ATLAS: Muon HLT (II)

- **Combine Level-2 muon with precision tracker info**
- **Rejection of non-prompt muons from π and K decays**
  - Makes use of different p_T in Inner Detector and Muon Detectors
- **Factor 3 vs. muon algorithm alone**
- **Further improvements:**
  - Isolation in calorimeter to reject b and c's



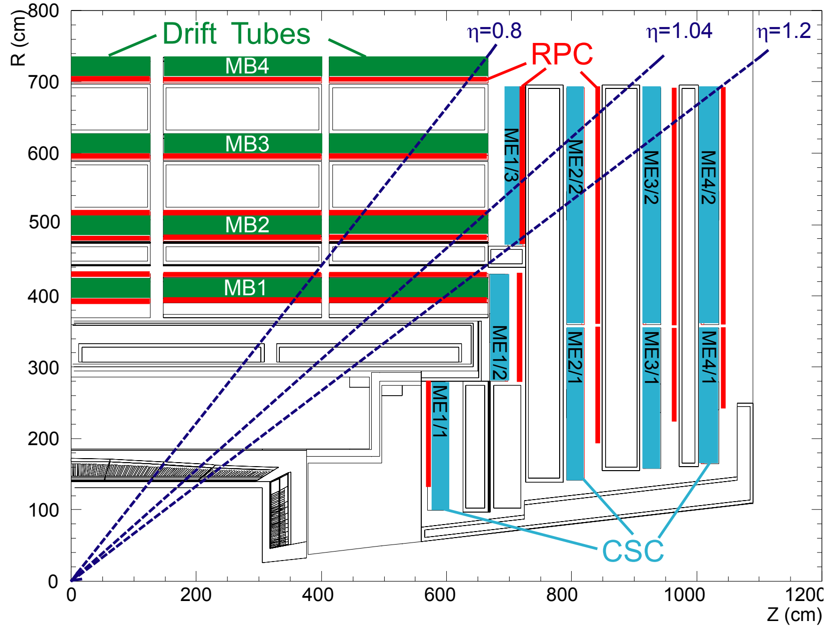


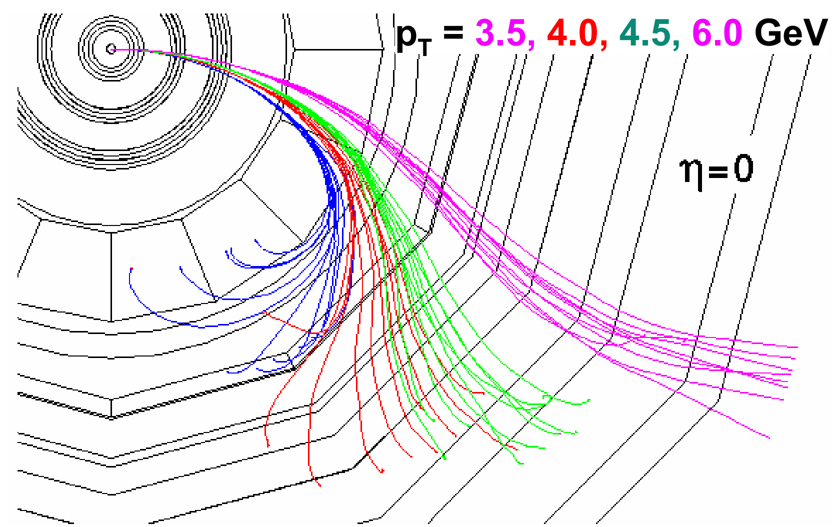
CMS Muon System



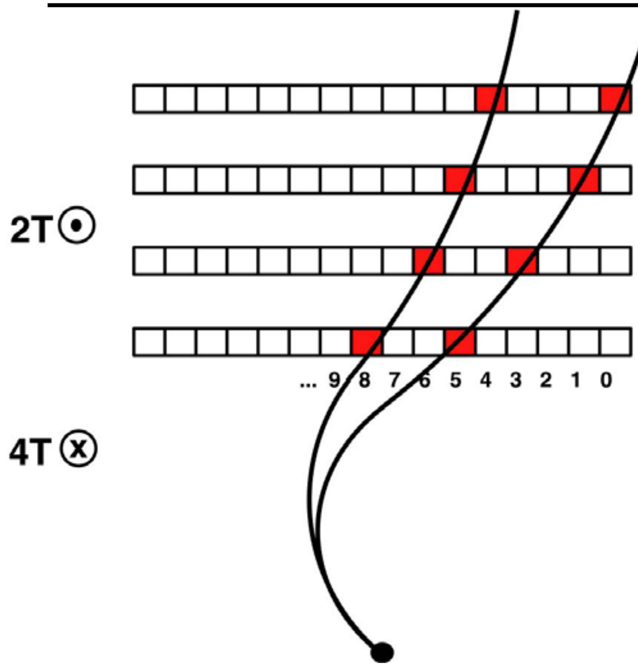
CMS: Level-1 Muon Trigger

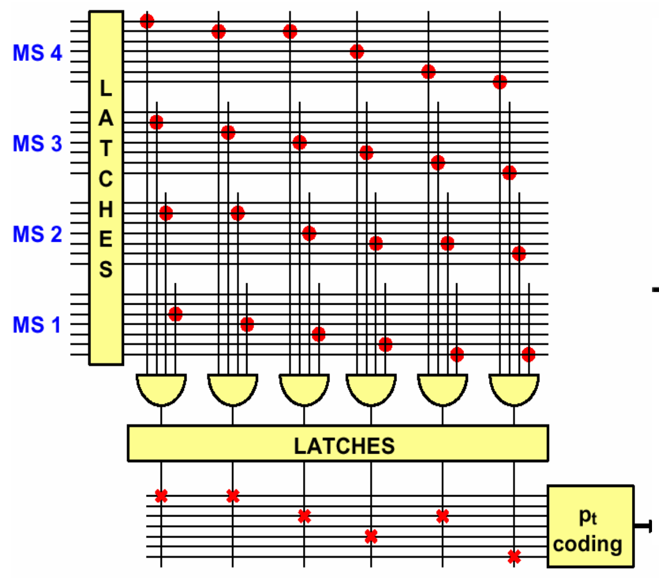
- Level-1 μ-trigger info from:
  - Dedicated trigger detectors: RPCs (Resistive plate chambers)
    - Excellent time resolution
  - Muon chambers with accurate position resolution
    - Drift Tubes (DT) in barrel
    - Cathode Strip Chambers (CSC) in end-caps
  - **Bending in magnetic field ⇒ determine p_T**

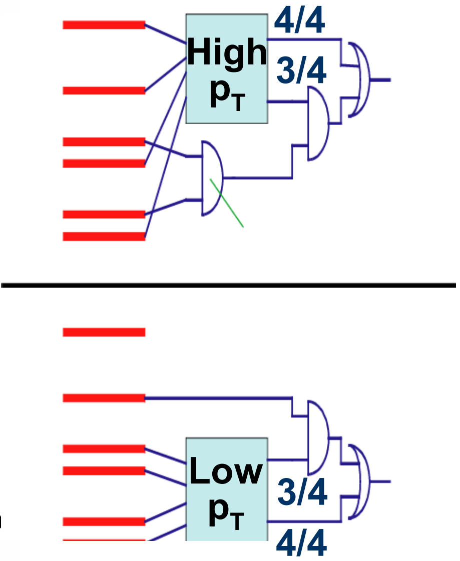




CMS: Level-1 RPC Trigger







Principle: Based on spatial and time coincidence of hits in RPC chambers. Pattern of hit strips is compared to pre-calculated patterns corresponding to various p_T values. For improved noise reduction algorithm requiring coincidence of at least 4/6 hit planes has been designed. Number of patterns is high.

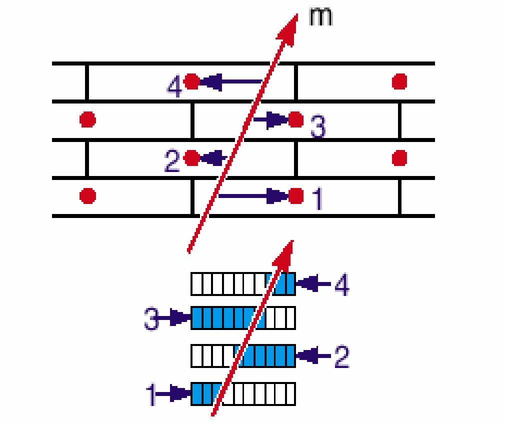
Trigger primitives: Hits from RPC chambers

Output: 8 muon candidates : 4 from barrel region and 4 from endcaps (p_T, charge, η, φ, quality)

CMS: Level-1 Local Muon Trigger

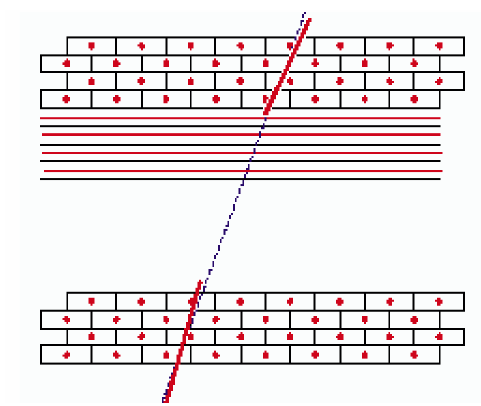
Super Layer

Drift Tube Chambers



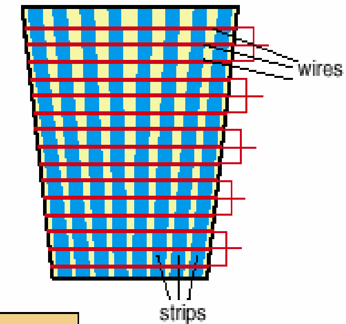
Meantimers recognize tracks and form vectors

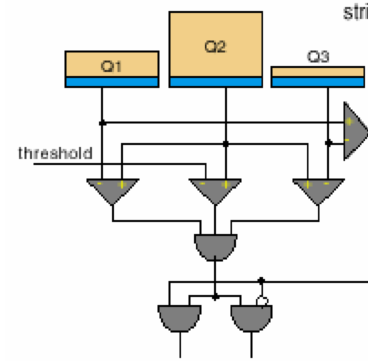
Muon Station



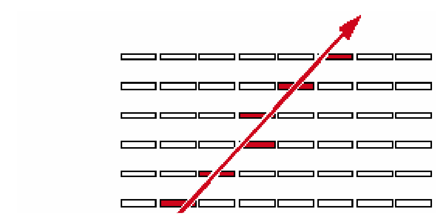
Correlator combines vectors to track segment

Cathode Strip Chambers



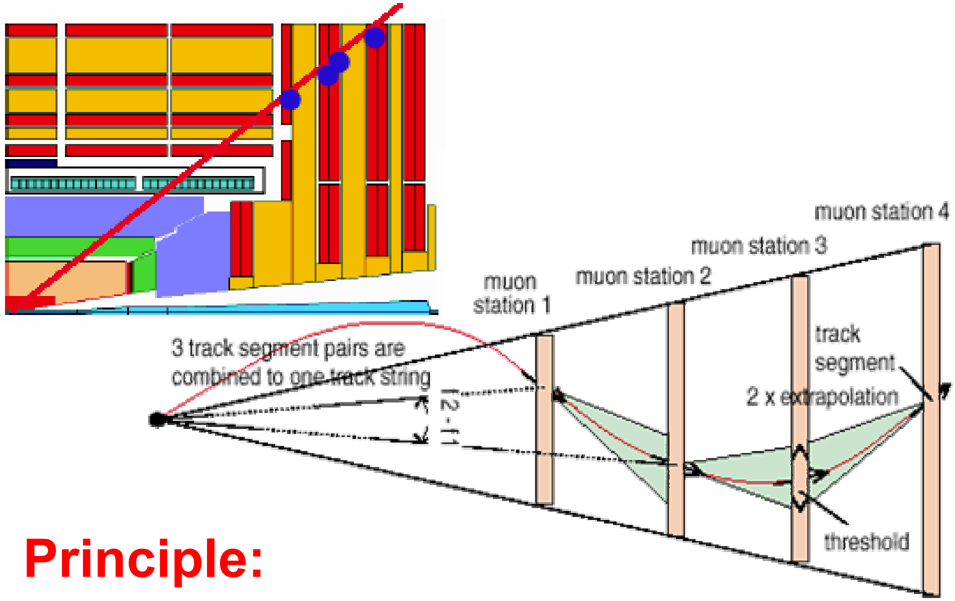


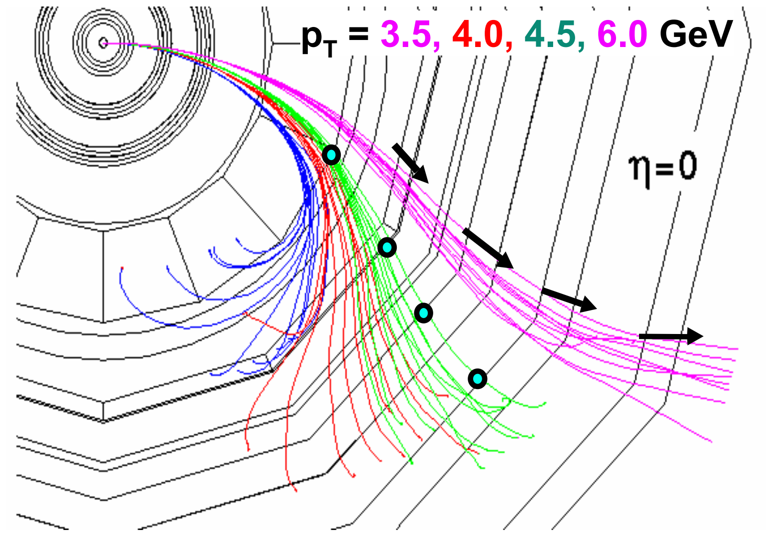
Comparators allow resolution of 1/2 strip width



6 hit strips form track segment

CMS: Level-1 Regional Muon Trigger





Principle:

Trigger relies on track segments pointing to the vertex and correlation of several detector planes

- Tracks with small p_T often do not point to vertex (magnetic deflection, mult. scattering)
- Tracks from decays and punch-through do not point to vertex in general
- Punch-through particles seldom transverse all muon detector planes

- **Extrapolation:**
  - using look-up tables
- **Track Assembler:**
  - link track segment-pairs to tracks
  - cancel out fakes
- **Assignment:**
  - p_T, charge, η, φ, quality

CMS: Level-1 Global Muon Trigger

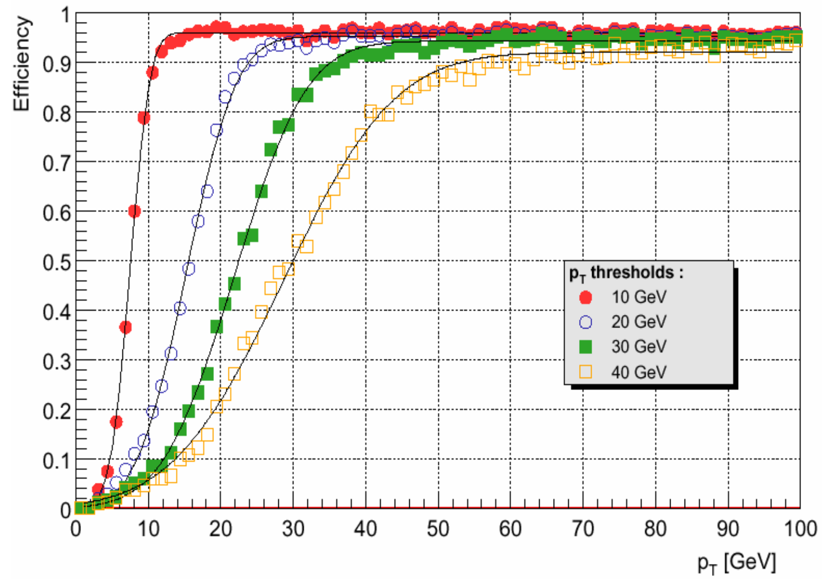
Task:

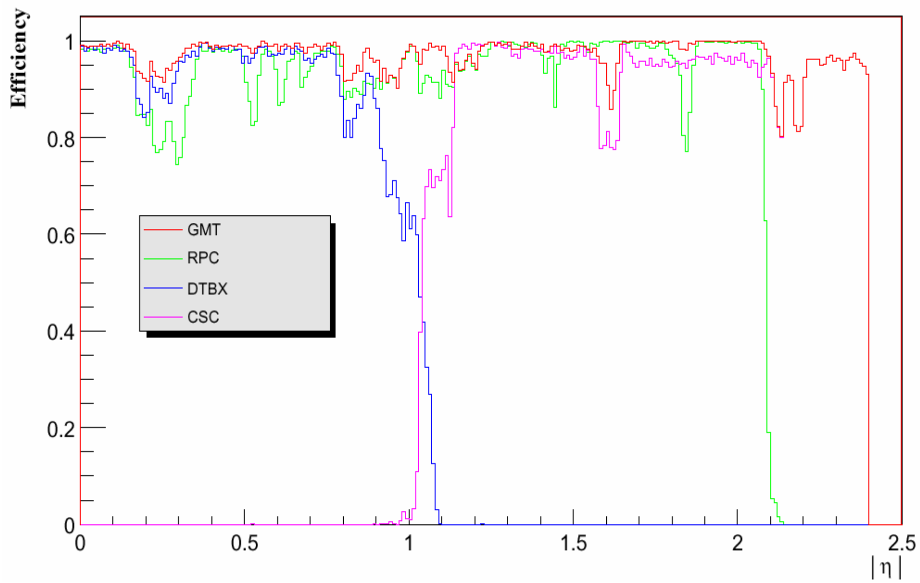
- Combine RPC, CSC and DT trigger information
- Match muon candidates from different trigger systems
- Make use of complementarity of the 3 sub-systems
- Improve overall trigger efficiency and rate capability
- Identify 4 "best" muons and pass them on to the Global Trigger

P_T resolution:

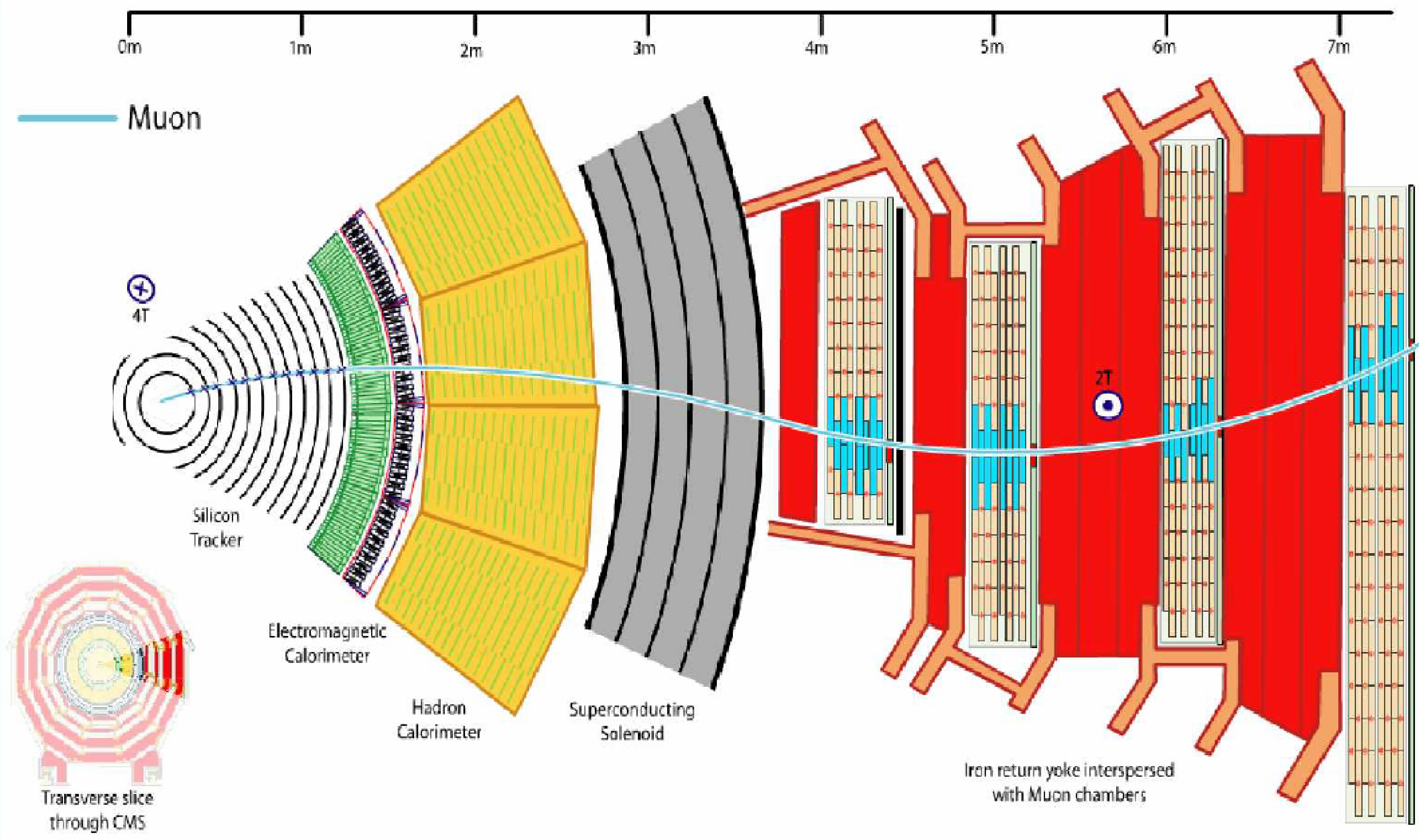
- 18% barrel
- 35% endcaps

Efficiency: ~ 97%

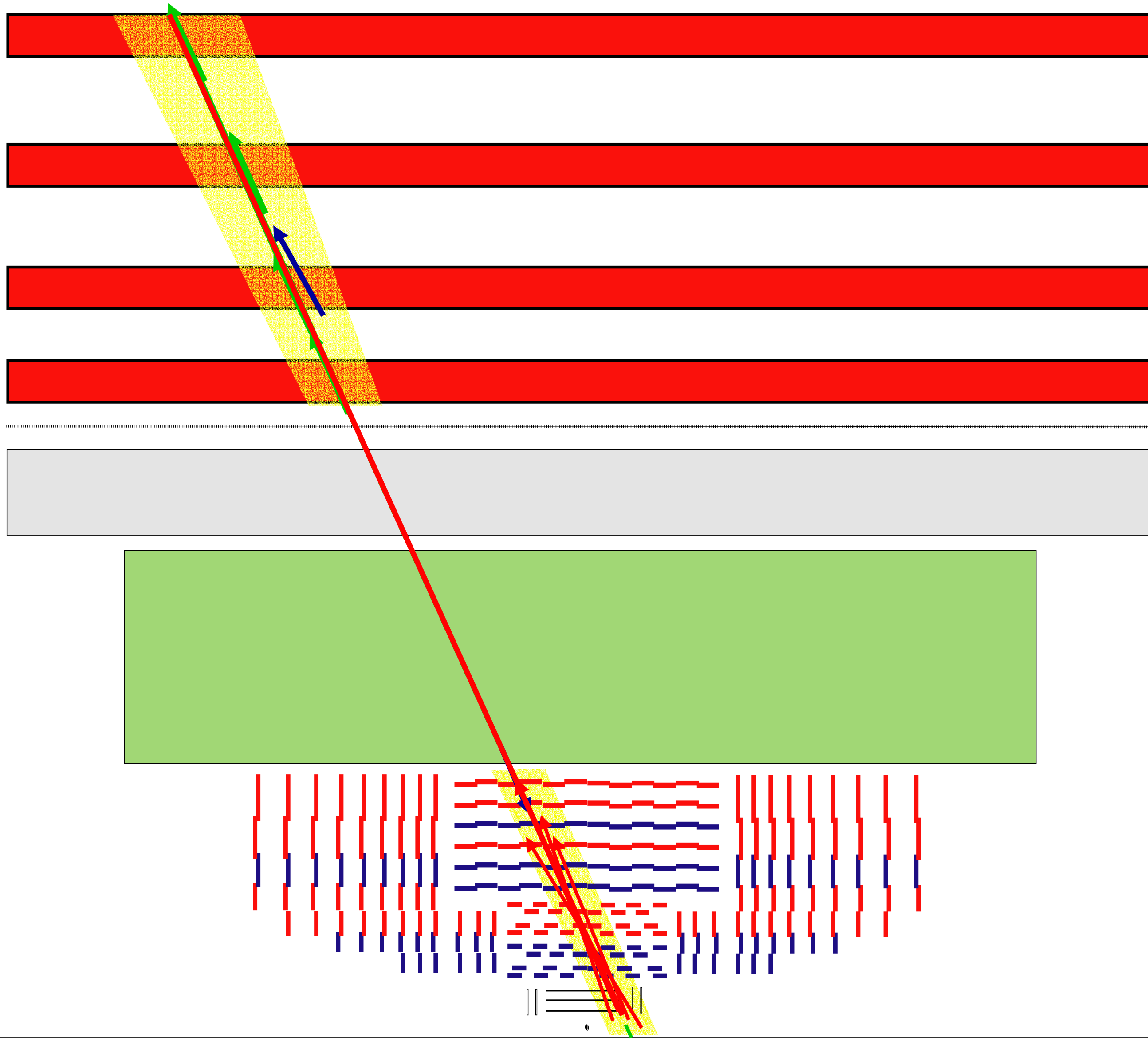




CMS Muon Reconstruction



Muon Reconstruction

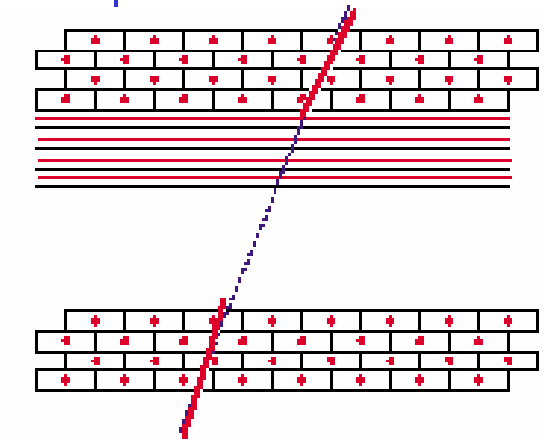


Muon Reconstruction (I)

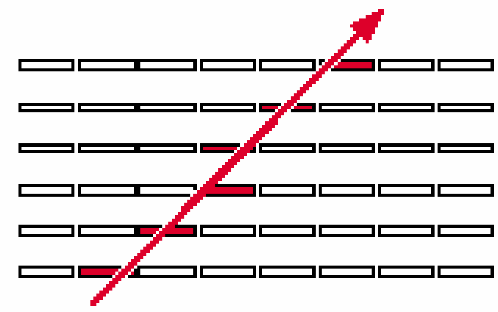
Local Pattern Recognition (Level-2)

Reconstruct track segments in the DT and CSC detectors

- Barrel:
  - Reconstruct ϕ super-layer hits (time-space conversion)
    global resolution (r-ϕ) position ~ 100 μm,
    direction ~ 1 mrad)
  - Cluster hits (linear fit): 2D segment
  - Same for *z* super-layer
  - Associate the two projections to build a 3D segment
  - Apply impact angle correction on time-to-distance relation and refit
  - Calculate position (center of gravity) of the track-segment and its angle in the super-layer



- Endcaps:
  - Reconstruct 3D hit
  - Associate hits with linear fit (only one hit per layer)



Muon Reconstruction (II)

Standalone Muon Reconstruction (Level-2)

- All muon detectors (DT, CSC and RPC) are used
- Seed generation:
  - Level-1 trigger (vector at 2^{nd} station)
- Fit:
  - Kalman filter technique applied to DT/CSC/RPC track segments
  - Use segments in barrel and 3D hits in endcaps
  - Trajectory building works from inside out
  - Apply χ^2 cut to reject bad hits
  - Fit track with beam constraint
- **Propagation:**
  - Non constant magnetic field
  - Iron between stations, propagation through iron (more difficult than in tracker!)

Muon Reconstruction (III)

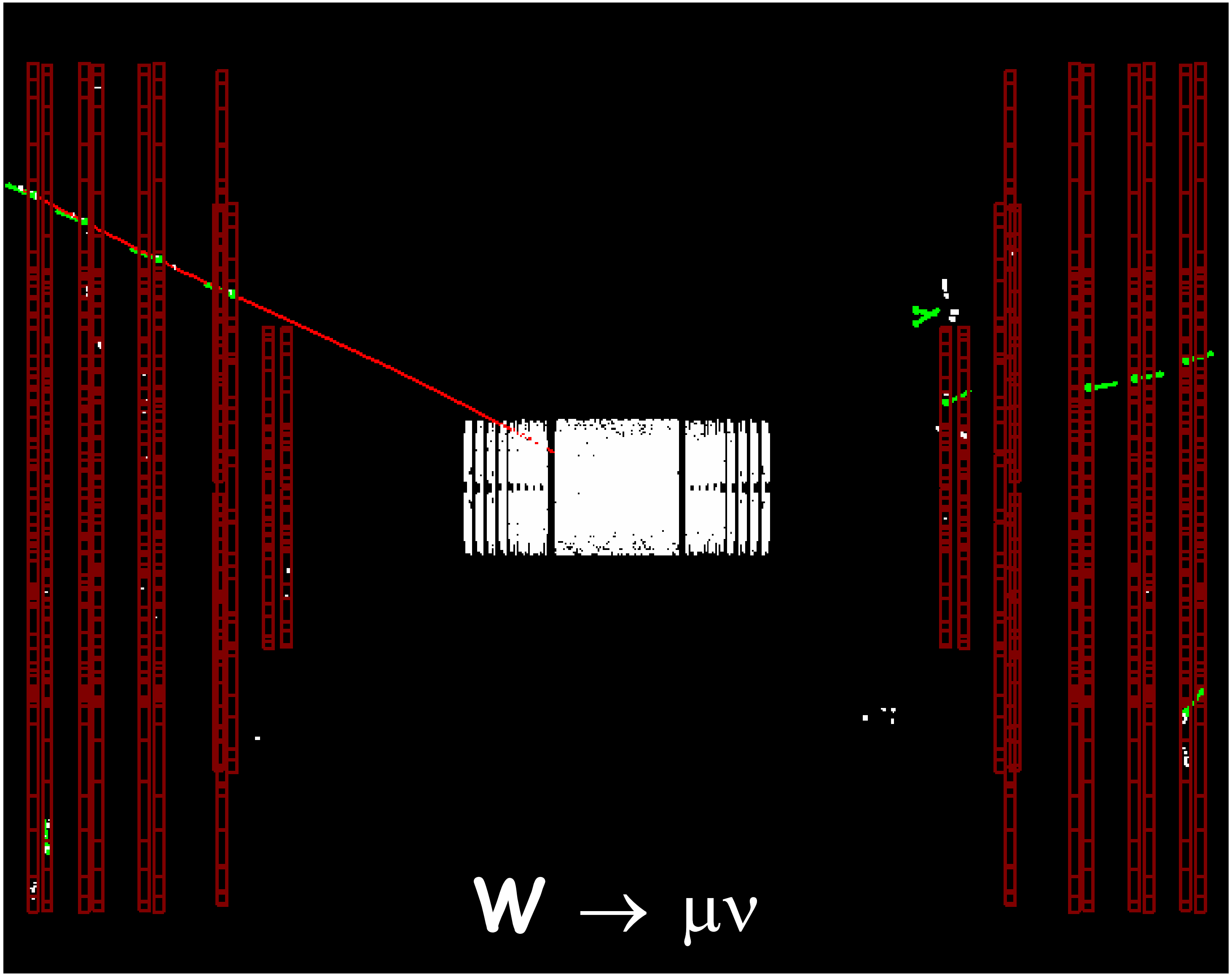
Inclusion of Tracker Hits (Level-3)

Start from Level-2 reconstructed muons:

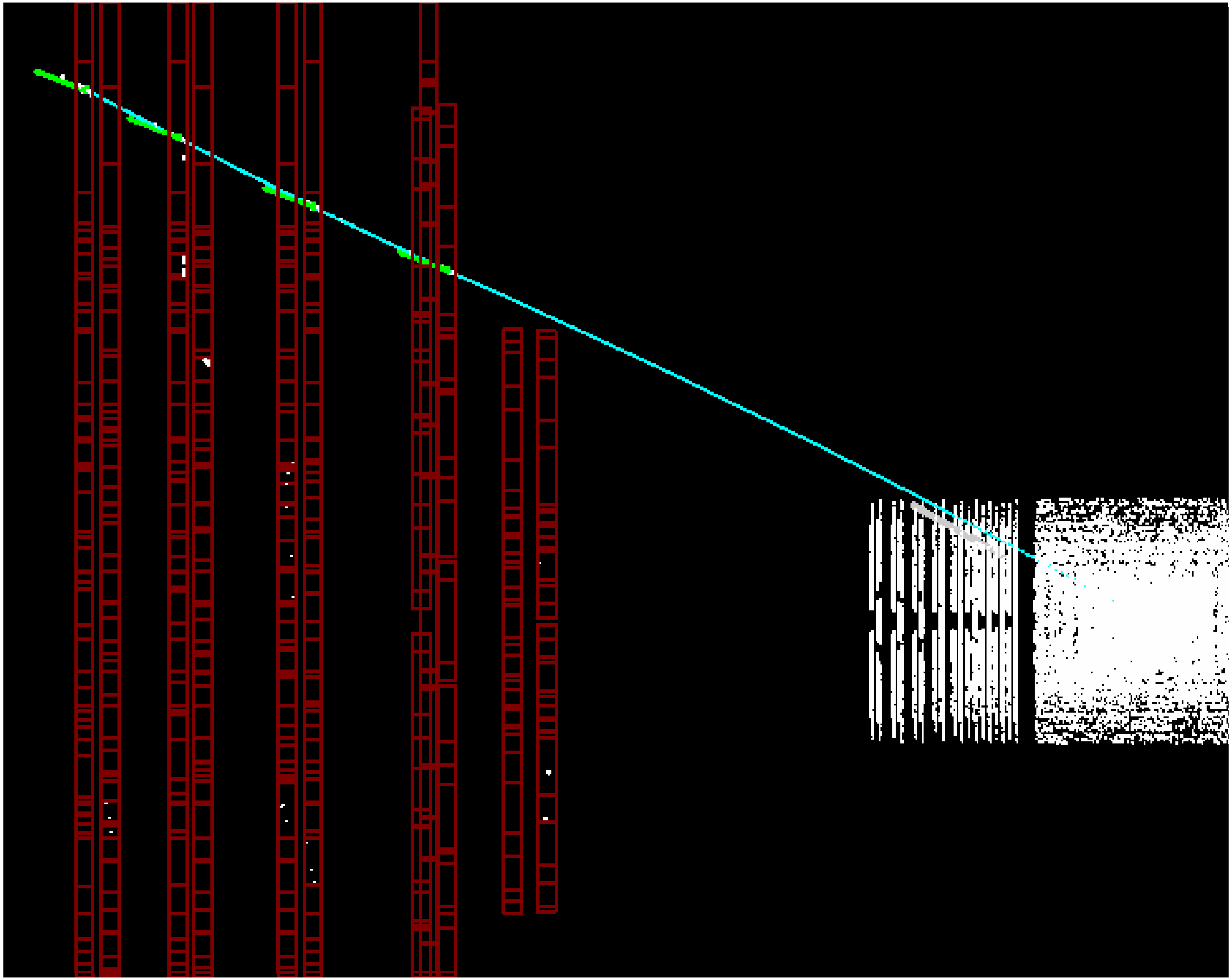
- Seed generation
  - Get muon trajectory at innermost muon station
  - Propagate to outer tracker surface and to interaction point
  - Open window for track reconstruction
    - define *region of interest* through tracker based on L2 track with parameters at vertex
    - fixed/dynamic region
  - Create one or more seeds for each L2 muon
- Construction of trajectories for a given seed
  - Propagate from innermost layers out, including hits in muon chambers
  - Resolve ambiguities
  - Final fit of trajectories

➢ tremendous gain in resolution

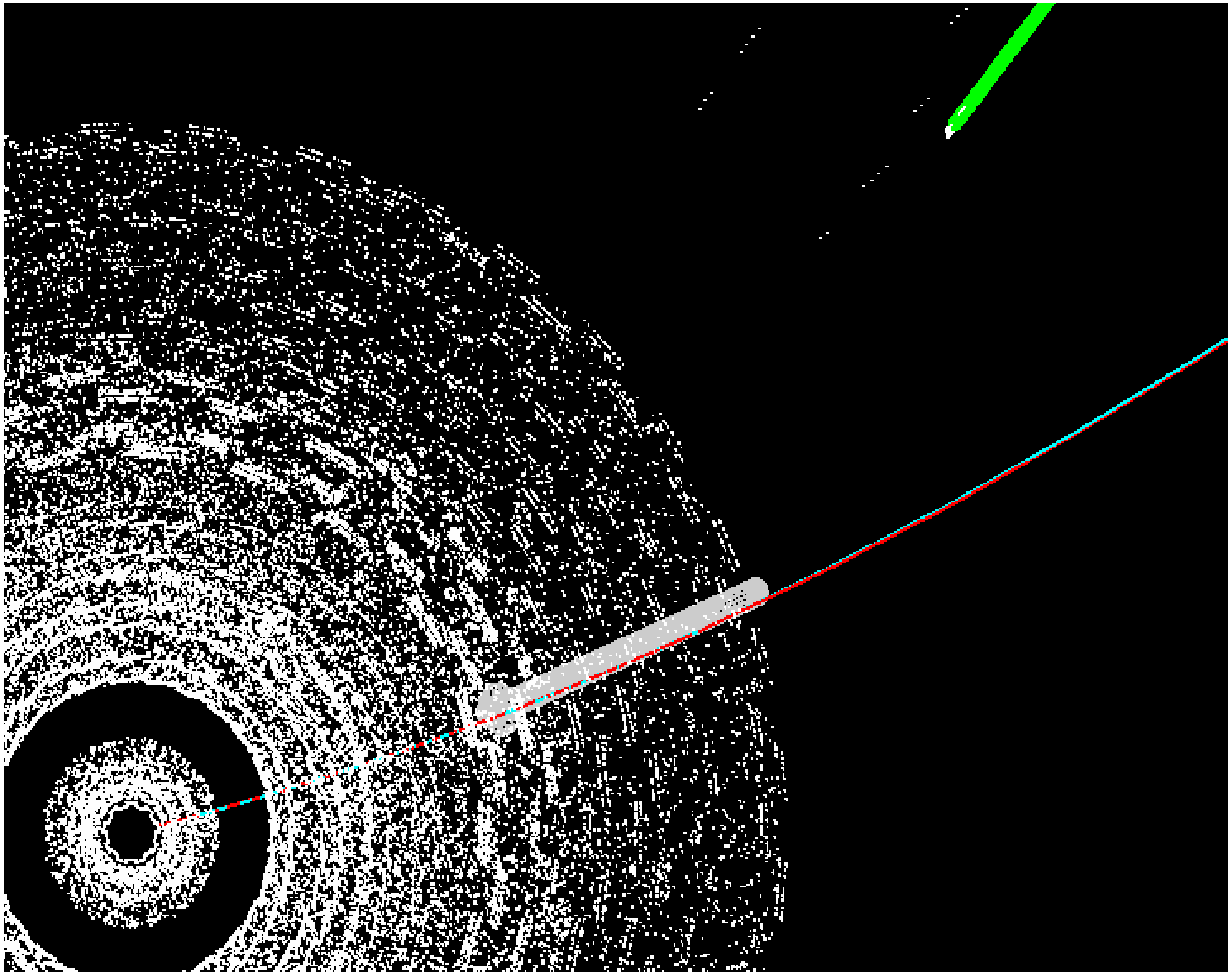
Muon Reconstruction @ high ℒ



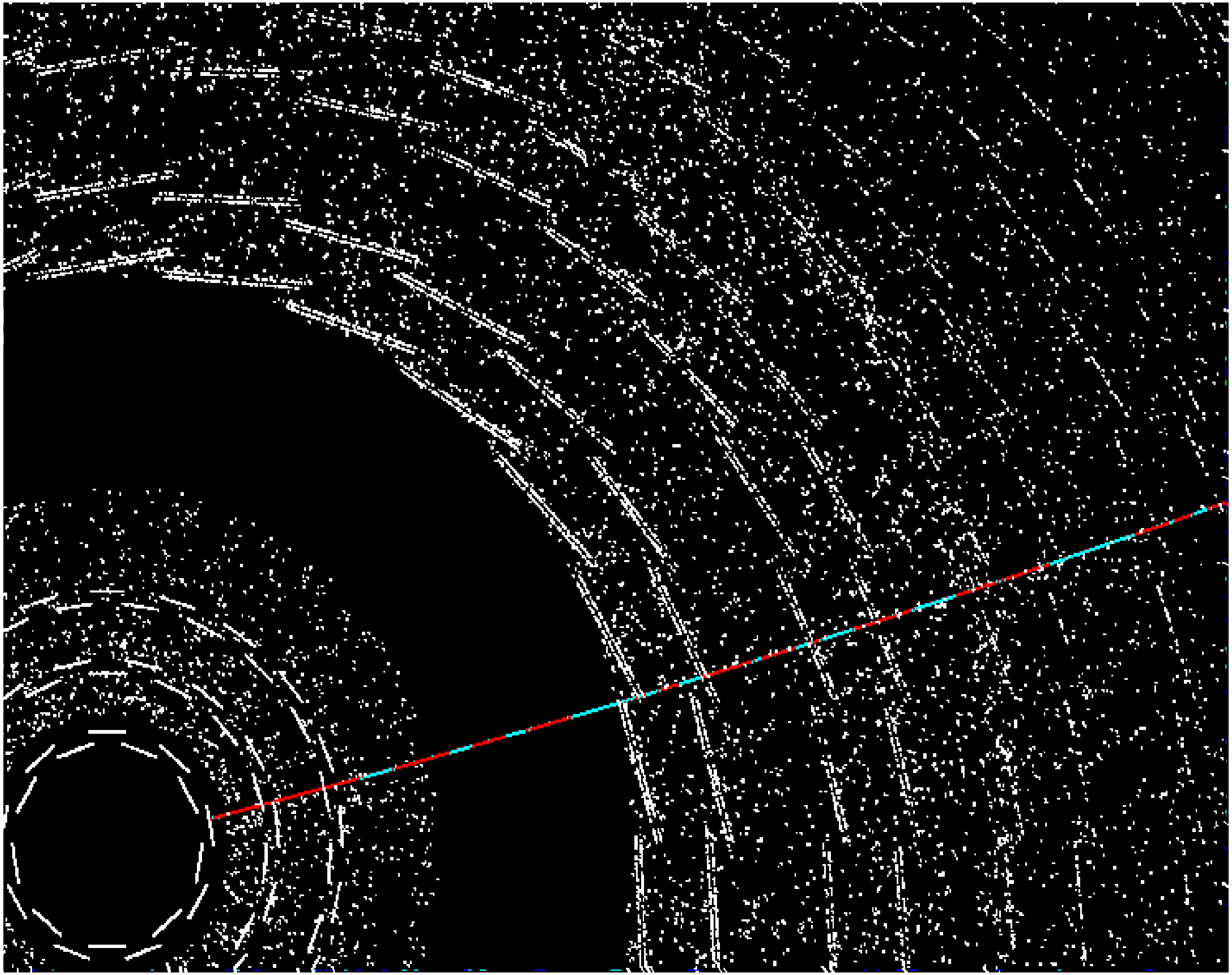
Muon Reconstruction @ high ℒ



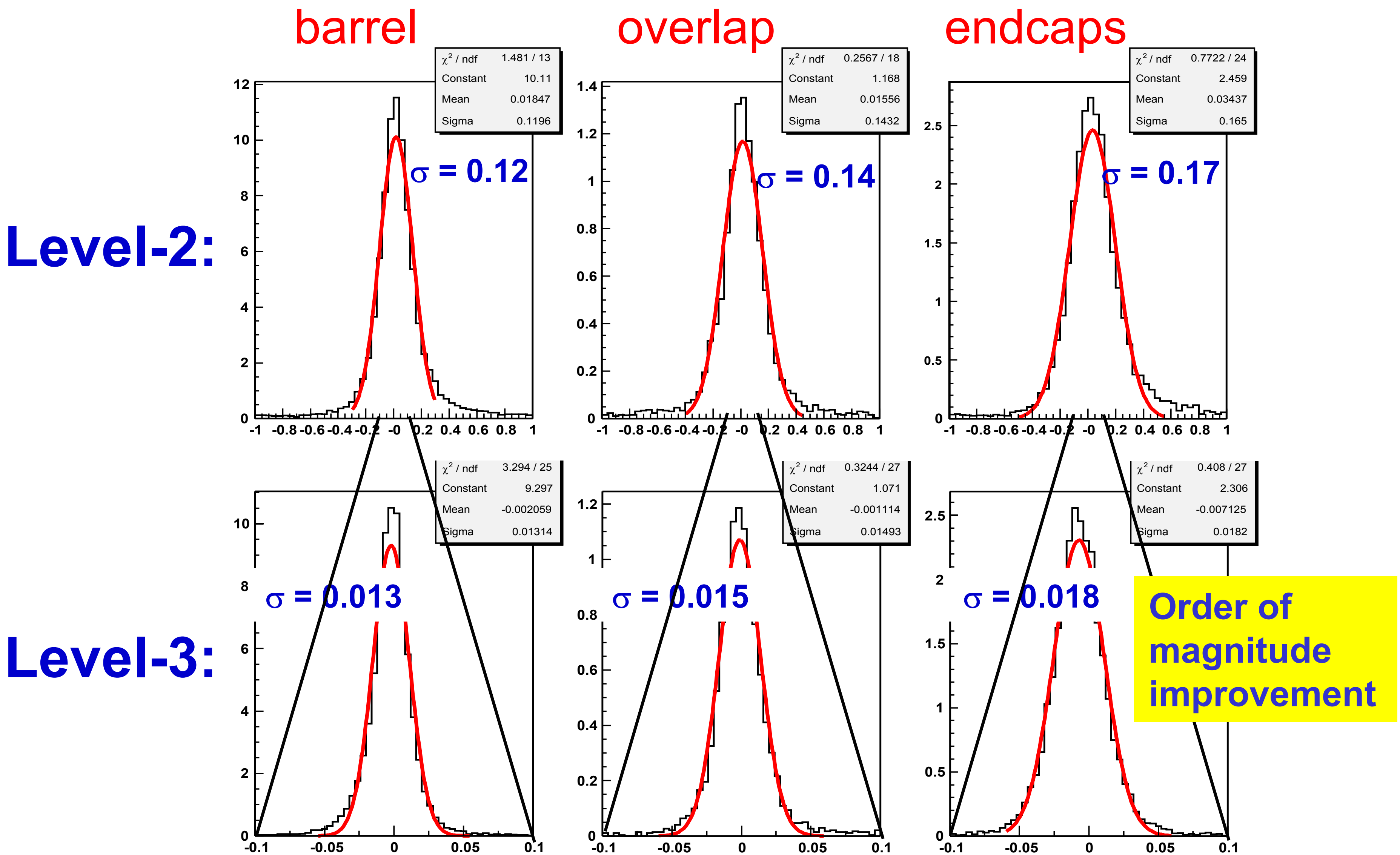
Muon Reconstruction @ high $\mathcal{L}$



Muon Reconstruction @ high $\mathcal{L}$

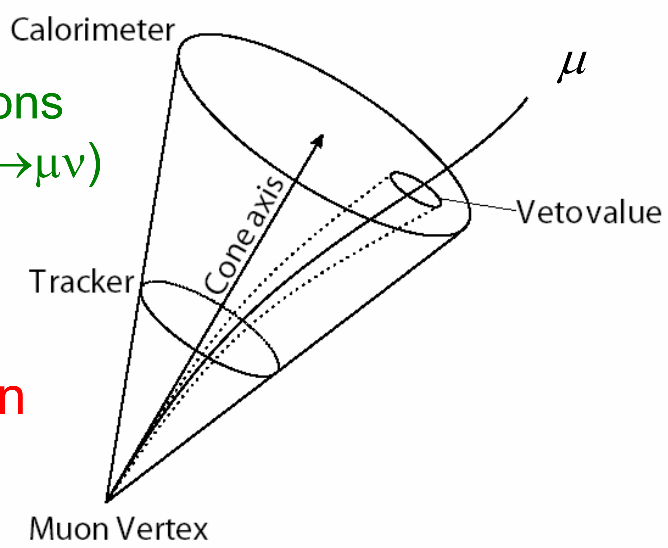


Muon p_T Resolution



Muon Isolation

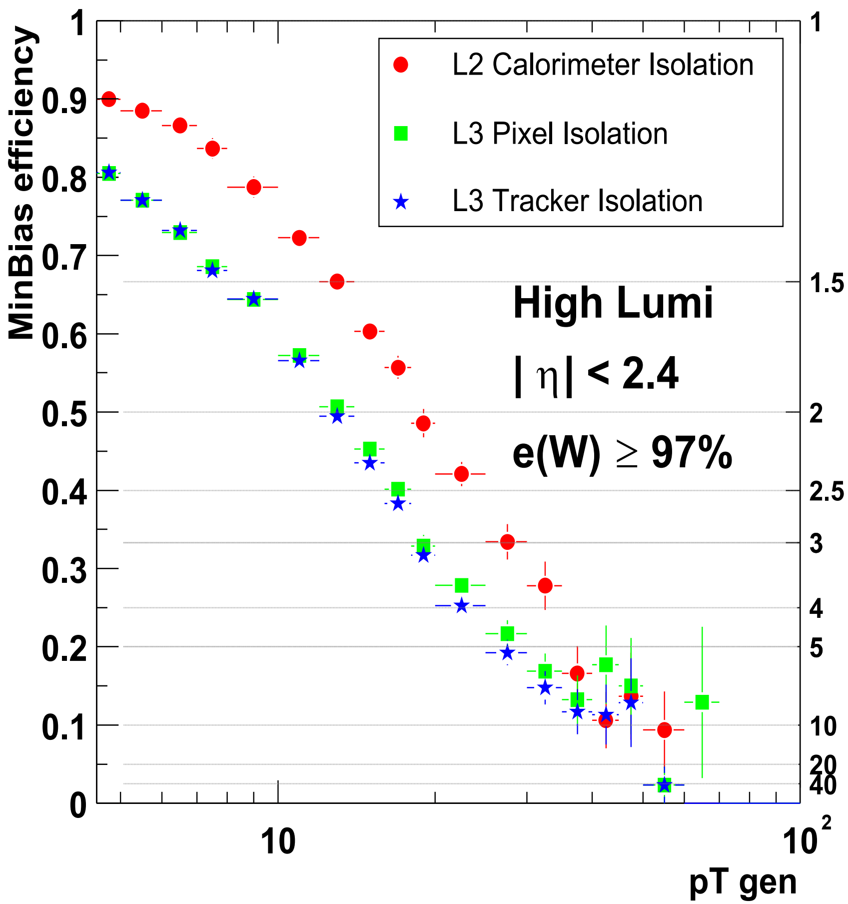
- K, π, b, c $\rightarrow \mu$ decays are accompanied by jets
  - Discard muons with high "activity" in their neighborhood
  - Based on ΣE_T or ΣP_T in cones around the muon
  - Cone sizes and thresholds are optimized
    - To get maximal rejection on background muons for a given efficiency on reference signal ($W \rightarrow \mu\nu$)
    - Flat $\varepsilon(\eta)$ on signal by construction



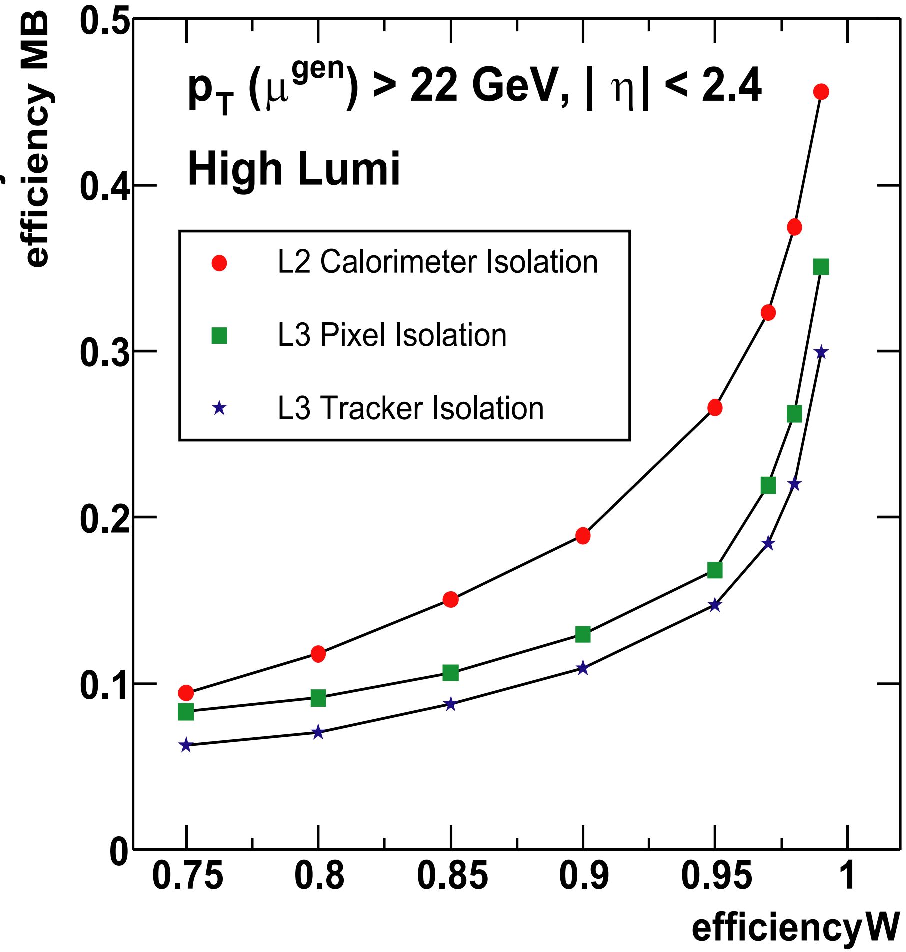
- Calorimeter Isolation
  - ΣE_T from calorimeter in a cone around muon
  - Can be applied already at Level-2
  - Sensitive to pile-up
- Tracker Isolation
  - ΣP_T of tracks in a cone around Level-3 muon, exploiting:
    - Regional reconstruction in the tracker
    - Conditional tracking

Muon Isolation

Efficiency on minbias events as a function of p_T^{gen} for 97% efficiency on signal



Efficiency on minbias events as a function of efficiency on W signal



Muon Selection

Sensitive to entire inelastic cross section at LHC, since every π/K/b/c can decay into a muon and multiple-scatter to appear as high p_T

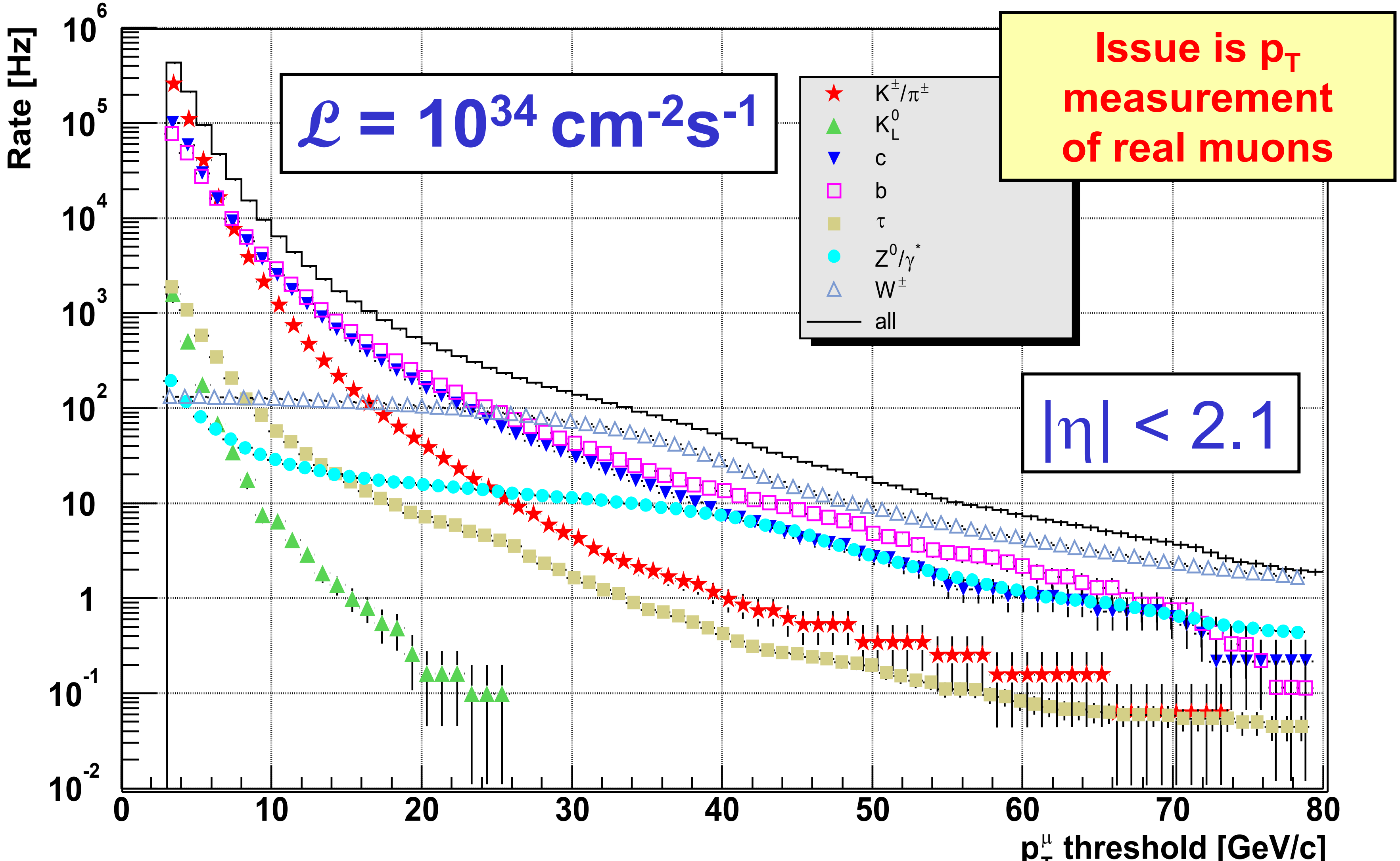
Muon candidates from Level-1 can be:

- prompt muons
  - decays of W, Z, top, Higgs, etc.
  - b and cquark decays
- non prompt muons (from $\pi^{\pm}$, $K^{\pm}$, K^0_L decays, etc.)
- fake muons (from Level-1 Trigger)
- punchthrough of hadronic showers
- cosmic muons
- beam halo muons

at the end we only want to keep prompt muons

A priori: rate is not too high if one can measure the momentum (p_T)

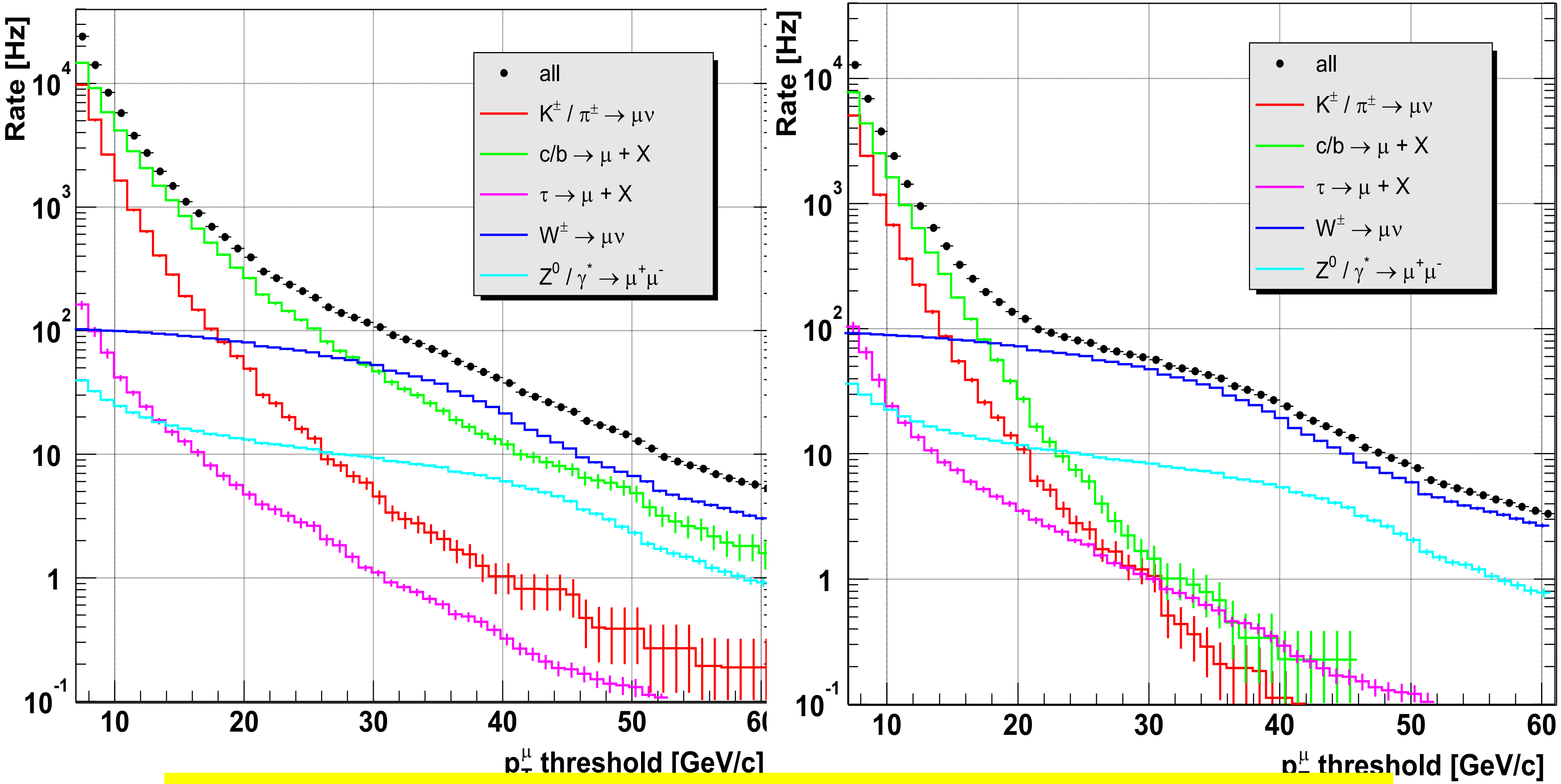
Muon Rate



rate is dominated by π, K decays up to 5 GeV and by b-, c-quark decays from 5 to 25 GeV

Physics Content after Level-3

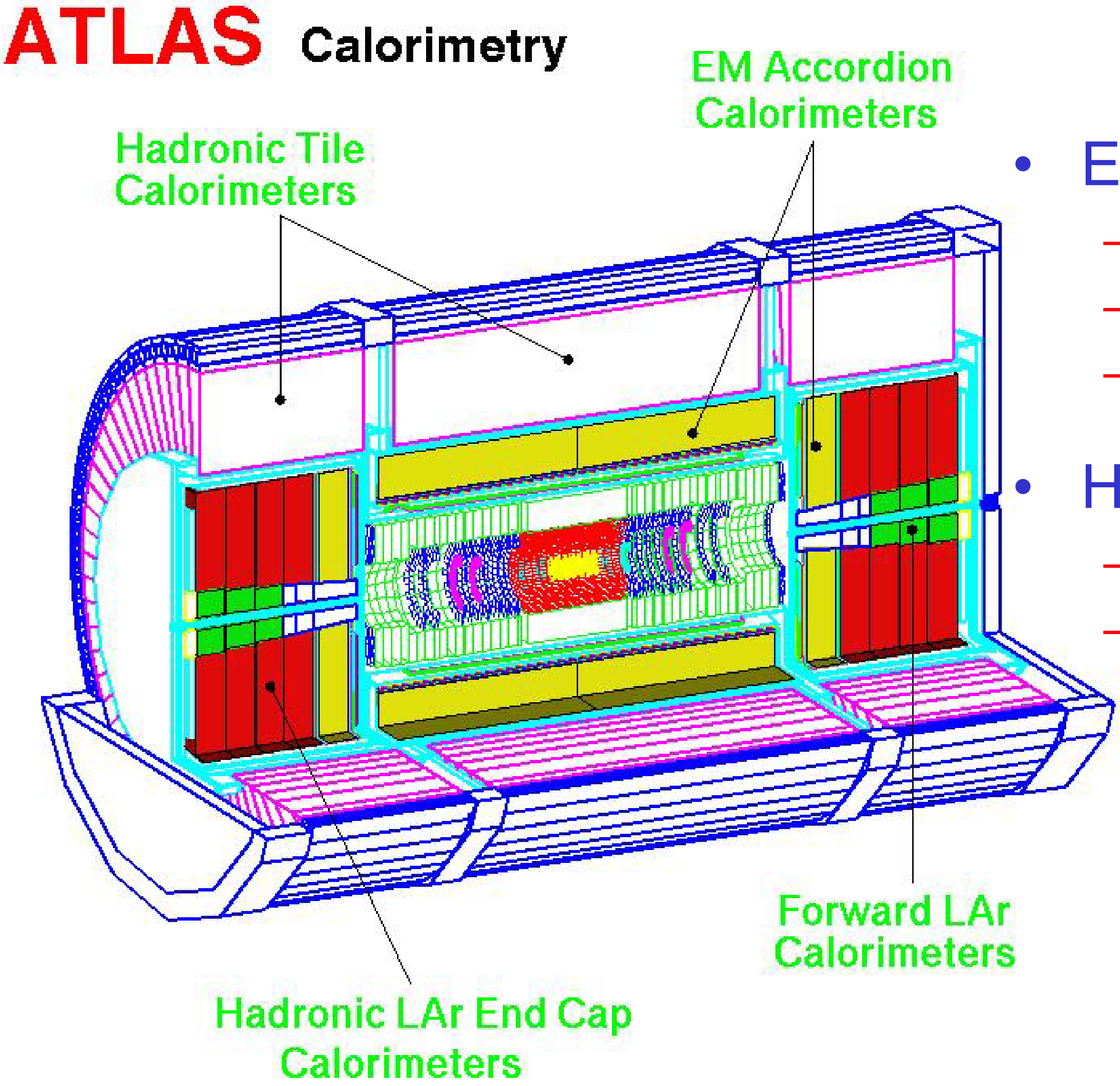
before isolation **$L = 10^{34}\ cm^{-2}s^{-1}$** after isolation



π/K/b/c strongly suppressed $\to$ dominated by W rate

Electrons/Photons

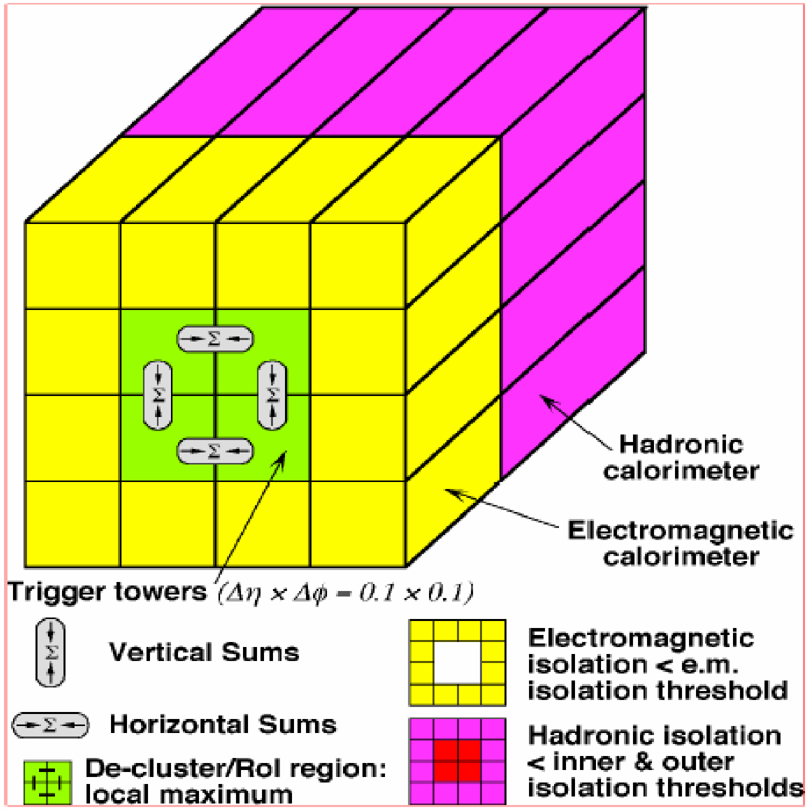
ATLAS Calorimetry



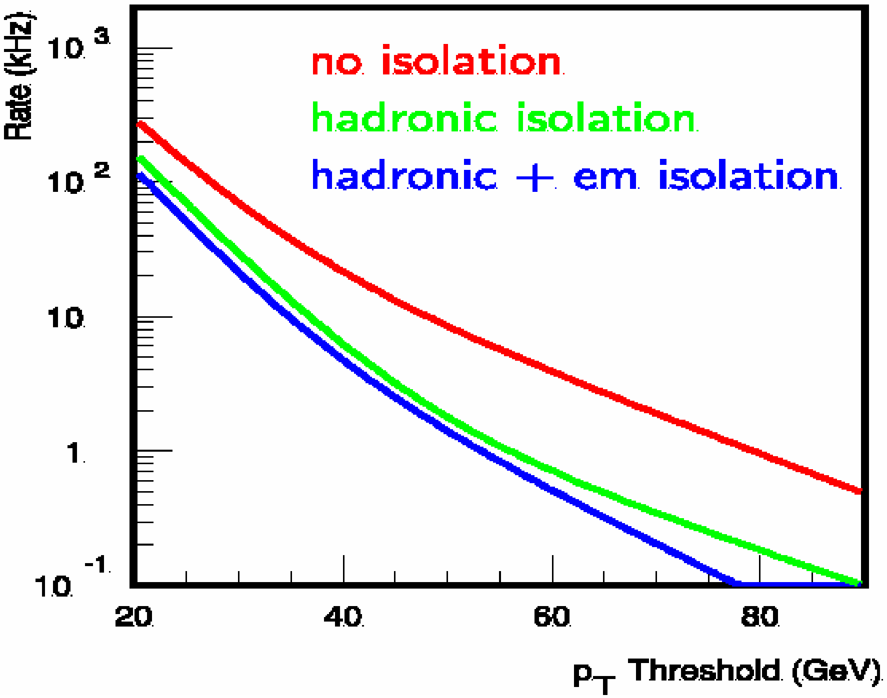
- EM Calorimeter:
  - LArg technology
  - Coverage: $|\eta|<3.2$
  - High granularity up to $|\eta|=2.5$
- Hadronic Calorimeter:
  - Fe-Scintillating tiles in $|\eta|<1.5$
  - LArg EC ($|\eta|<4.9$)
    - HEC: Cu/LAr
      $1.5 < |\eta| < 3.2$
    - FCAL: Cu/Tungsten/LAr
      $3.2 < |\eta| < 4.9$

ATLAS: Level-1 EM Trigger

Electron/Photon Algorithm



- 4 × 4 window
- 0.1 × 0.1 elements
- step by 1 element
- $|\eta| < 2.5$



Inclusive EM trigger rate vs. p_T at 10^{34} $cm^{-2}s^{-1}$

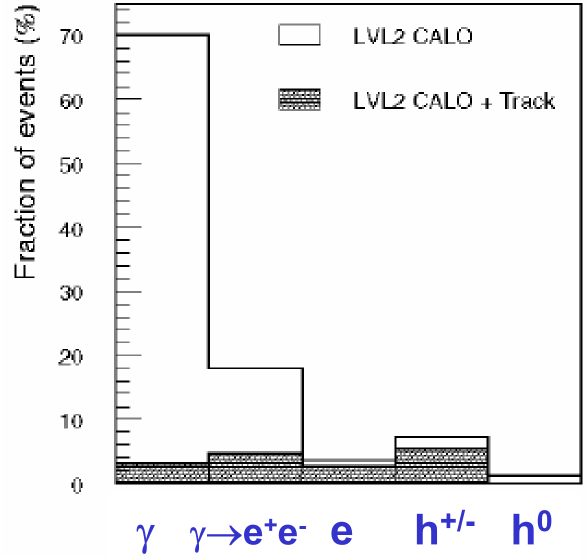
To throttle rate: increase E_T thresholds

Isolation criteria reduce rate by up to one order of magnitude

ATLAS: Electron HLT (I)

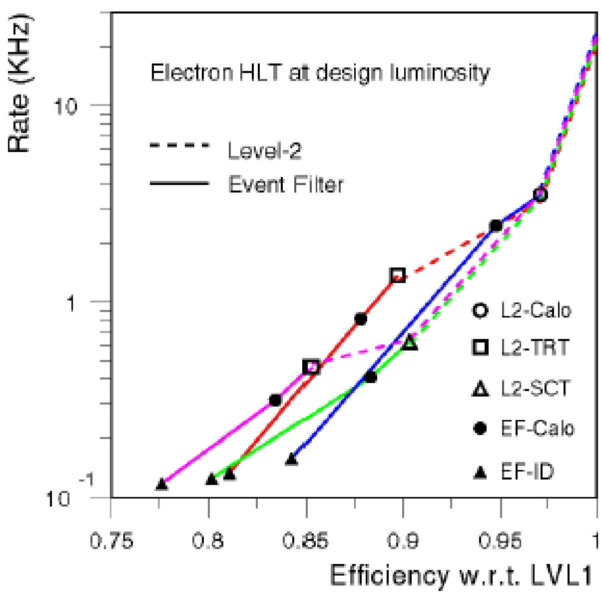
Level-2:

- Level-1 EM ROIs
- Identify e/γ clusters by calorimeter E_T and shower shape
- Electron: search for inner detector track in region, match cluster
- Improve electron identification with transition radiation



Event Filter:

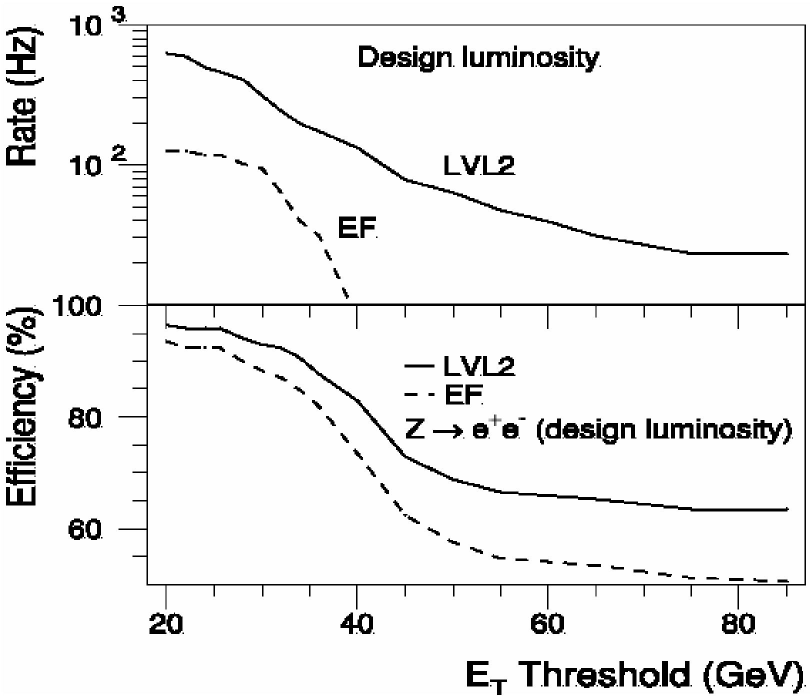
- Shower shape analysis from calorimeter
- **Photon:** possible conversion recovery
- **Electron:** track search and match
- Bremsstrahlung recovery for electrons



Different rate reduction paths:

- Optimize order for fast rejection
- Flexible boundary between Level-2/EF
- Optimize both physics performance and system performance together

ATLAS: Electron HLT (II)



At high luminosity, rate reduced from 21.7 kHz (Level-1) to 114 Hz (HLT)

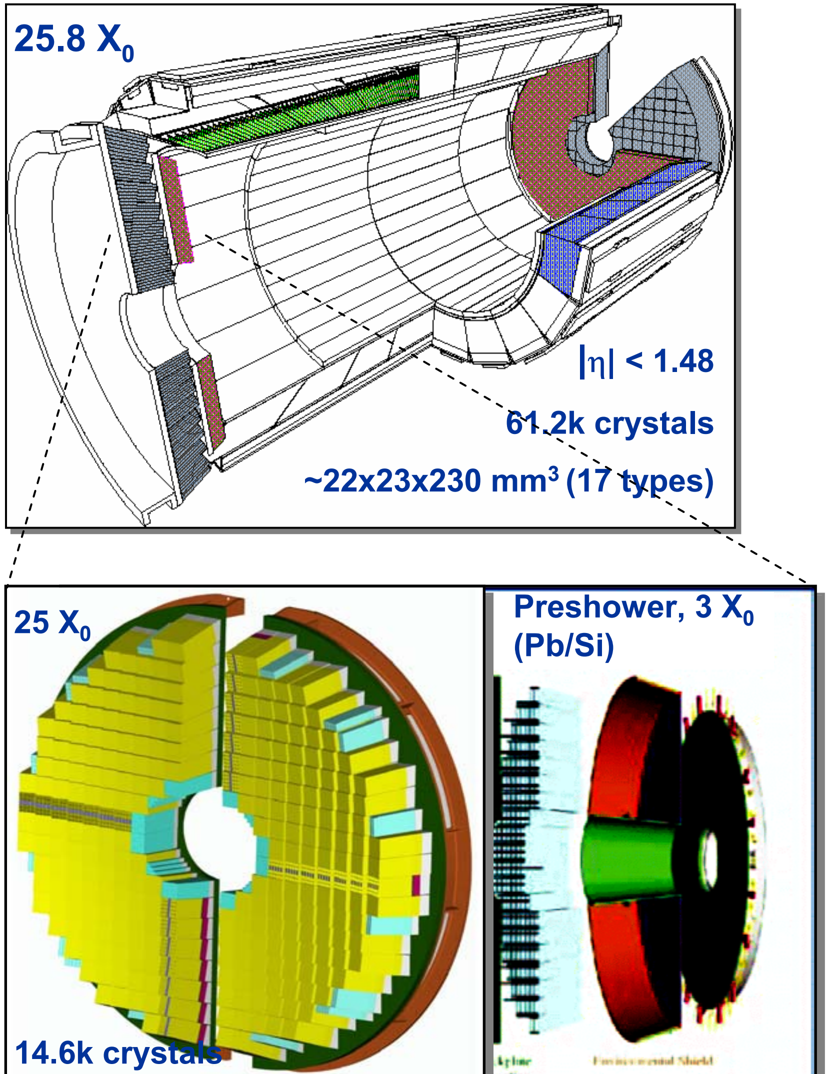
- **Composition of accepted events:**
  - **40% W → eν**
  - **13% b, c → eν**
  - **47% fakes and conversions**

Example algorithm performance

- Extrapolated to 2006
- Level-2 Calorimeter: ~ 0.03 ms
- Level-2 Tracking: ~ 1 ms
- EF calorimeter: ~ 50 ms
- EF tracking: ~ 1 s

- These numbers do not include:
  - Data Access Time
  - Network access in case of Level 2
  - Data Preparation Time
  - Conversion of front-end data into format suitable for algorithm

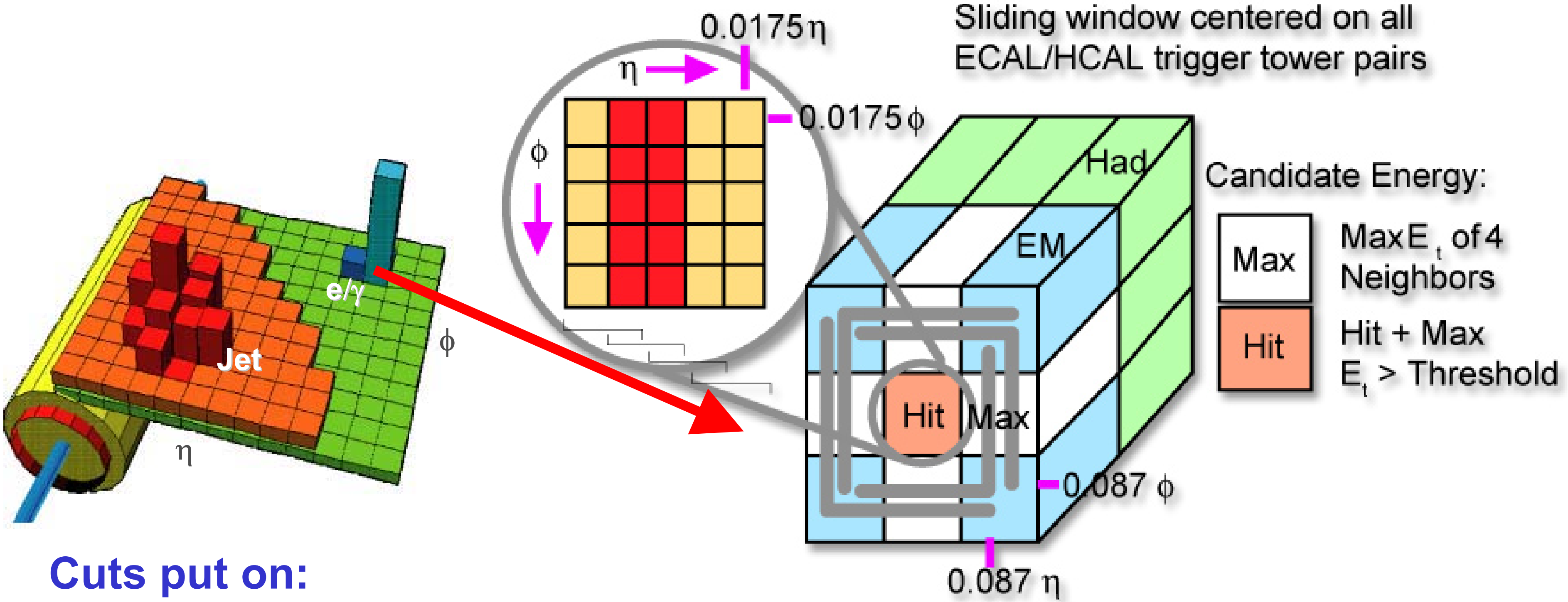
CMS: Electromagnetic Calorimeter



- Choice of crystals:
  - Excellent energy resolution
  - Structural compactness
  - Tower structure facilitates event reconstruction (cluster algorithms)
- Choice of $PbWO_4$:
  - LHC rate (25 ns)
  - Radiation hardness
  - Longitudinal containment (X_0)
- Choice of Photodetectors (APD, VPT)
  - |B| = 4 T
  - Intrinsic gain (low light yield)
  - Radiation level

CMS: Level-1 e/γ Trigger

- Electromagnetic trigger based on 3 × 3 trigger towers
  - Each tower is 5 × 5 crystals in ECAL (barrel; varies in end-cap)
  - Each tower is single readout tower in HCAL



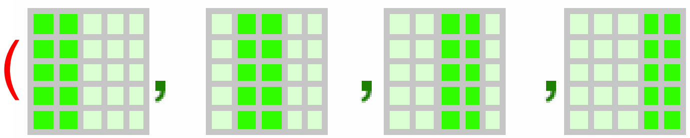
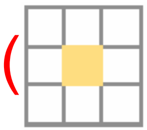
Cuts put on:

- e/h fraction
- Fine shape in ECAL (acts as local isolation)
- Isolation in both ECAL and HCAL sections

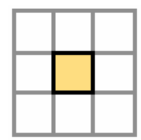
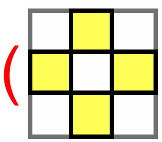
Trigger threshold on sum of two towers

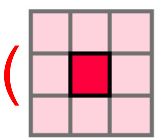
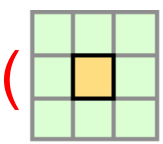
CMS: Level-1 e/γ Trigger

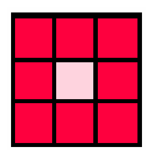
Trigger Primitive Generator

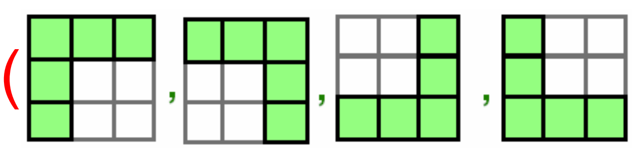
Fine-grain: Max Flag of () & Sum E_T ()

Regional Calorimeter Trigger

E_T cut: E_T() + max of E_T() > E_T threshold

H/E cut: E_T() / E_T() < 0.05

Isolation hadronic & EM: E_T() < 2 GeV

At least one E_T() < 1 GeV

⬇

Electron / Photon

HLT Selection: Electrons/Photons

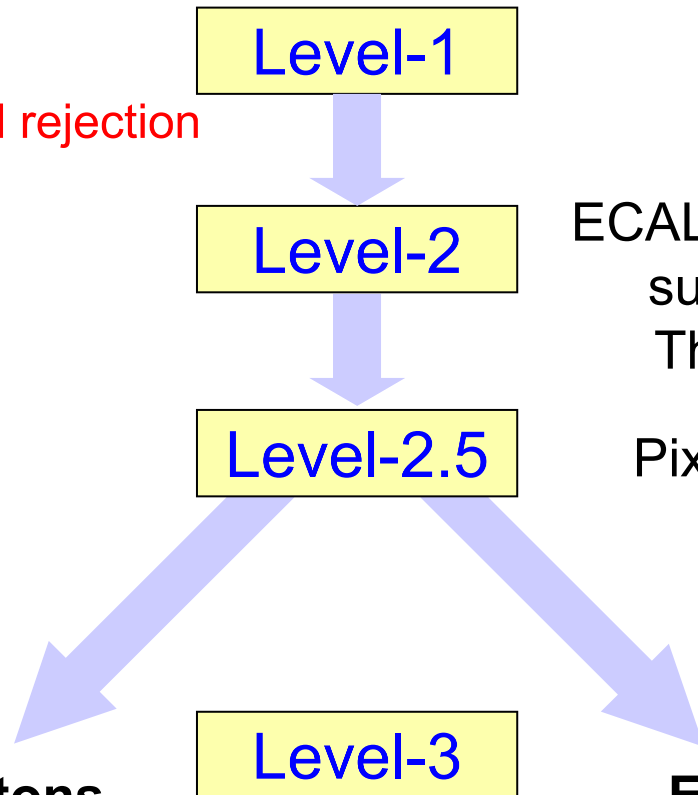
- Signal = electrons/photons
- Background = jets (dominated by jets where a single π^0 takes a large fraction of the jet E_T)

– Issue is electron reconstruction and rejection

– Higher E_T threshold on photons

– Electron reconstruction
  - key is recovery of radiated energy

– Electron rejection
  - key tool is pixel detector

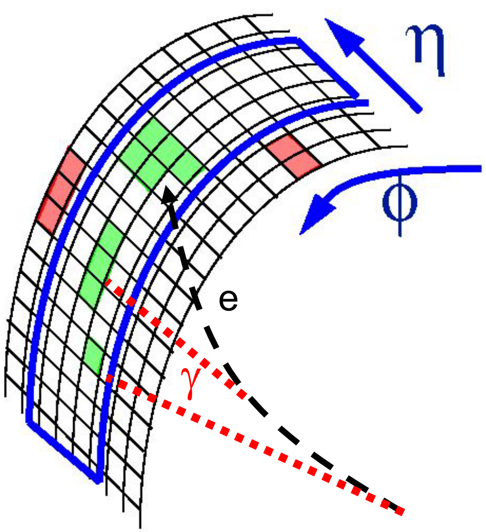


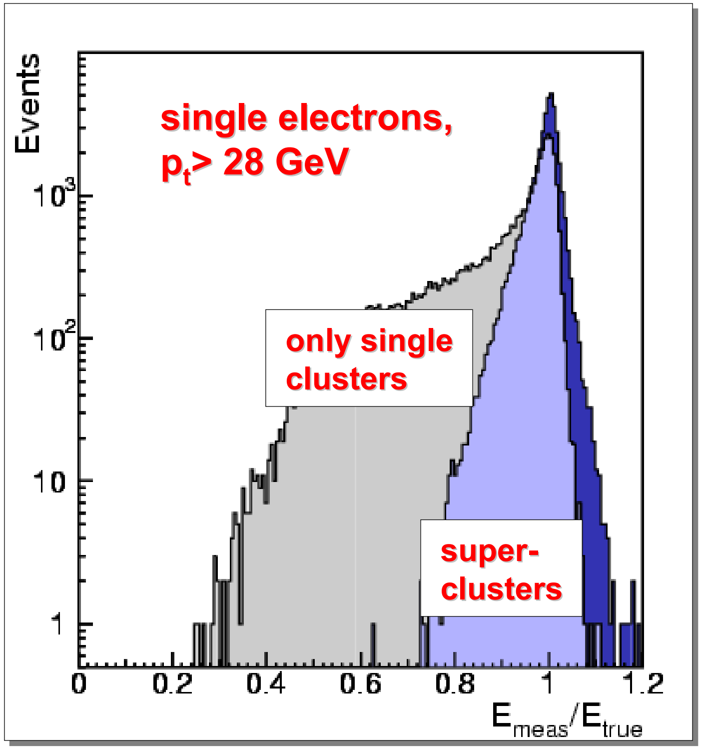
Electron Reconstruction

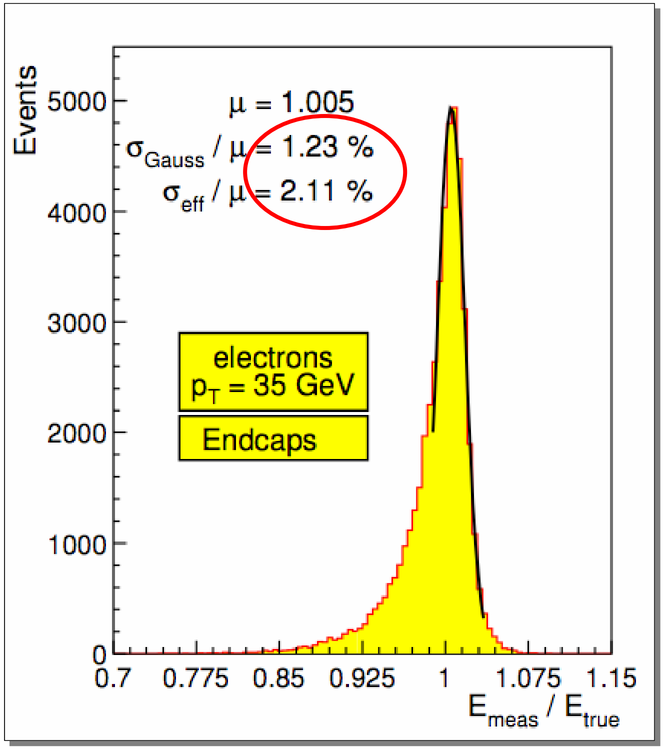
- **Main difficulty**: tracker material $\Rightarrow$ **bremsstrahlung**

  $\langle E_{breams}/E \rangle = 43.6\ \%$, $P_T = 35$ GeV, $|\eta| < 1.5$

- Recover by reconstructing clusters of clusters (**super-clusters**)
- Essential for $Z \rightarrow ee$ and $W \rightarrow e\nu$ reconstruction, find compromise between statistics and little bremsstrahlung-loss





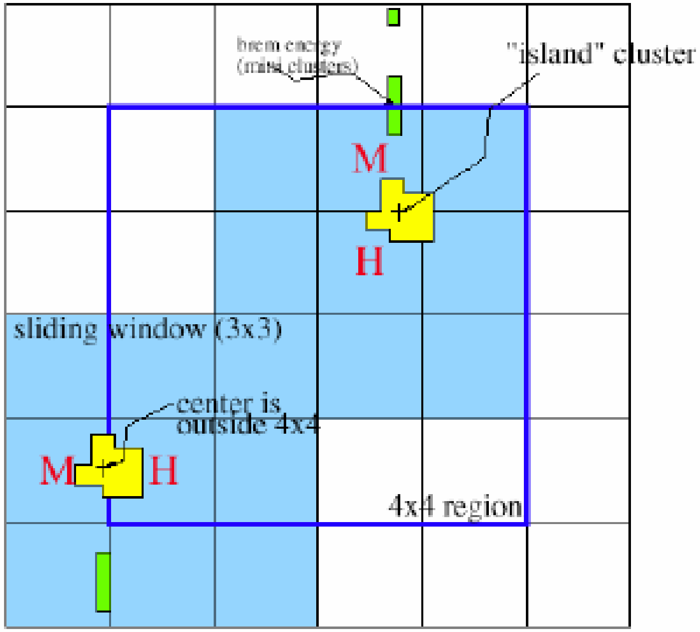


Clustering

- Collection of energy resulting from an electromagnetic shower in a fine grained calorimeter
  - can be approached as a pattern recognition procedure

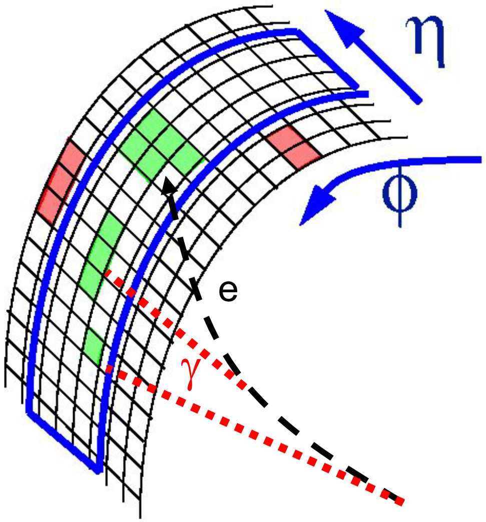
- The shower appears as a local maximum (bump) in a spatial array of energy deposits

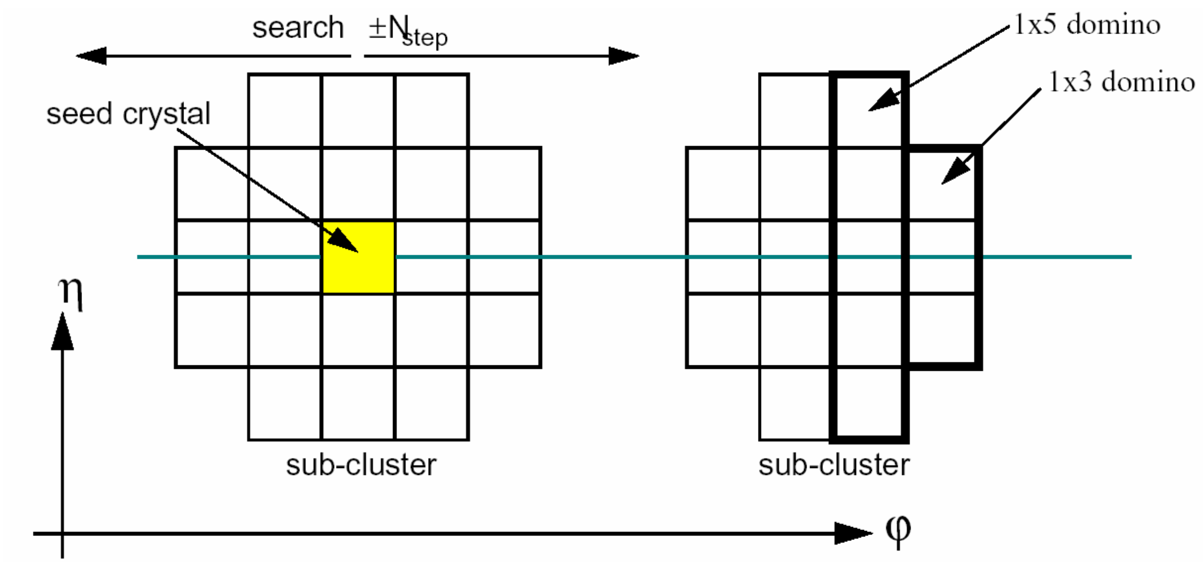
- Looking for local maxima ("seeds"), which are then extended to collect as large a fraction of the original shower energy deposition as possible, while avoiding the collection of energy depositions from nearby particles and noise

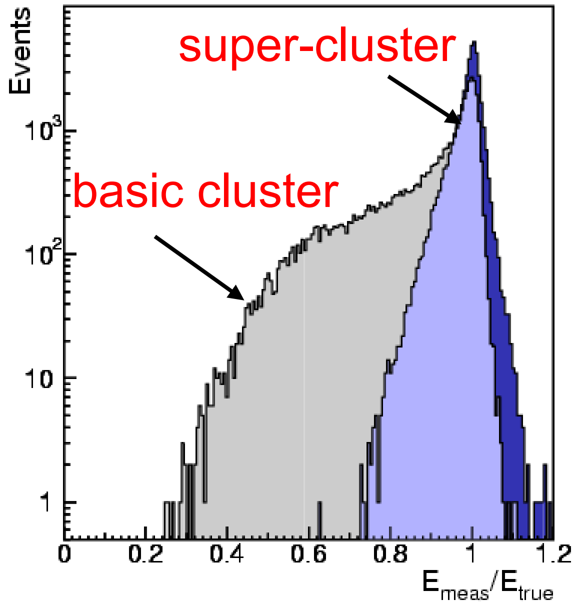


Electron Selection: Level-2

- Level-2 electron:
  - Search for match to Level-1 trigger
    - Use 1-tower margin around 4×4-tower trigger region
  - Bremsstrahlung recovery "super-clustering"
  - Select highest E_T cluster
- Bremsstrahlung recovery:
  - Road along ϕ — in narrow η-window around seed
  - Collect all sub-clusters in road → "super-cluster"

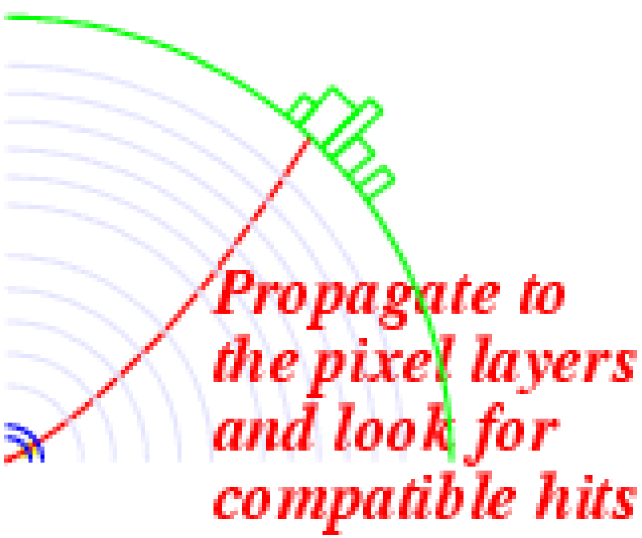


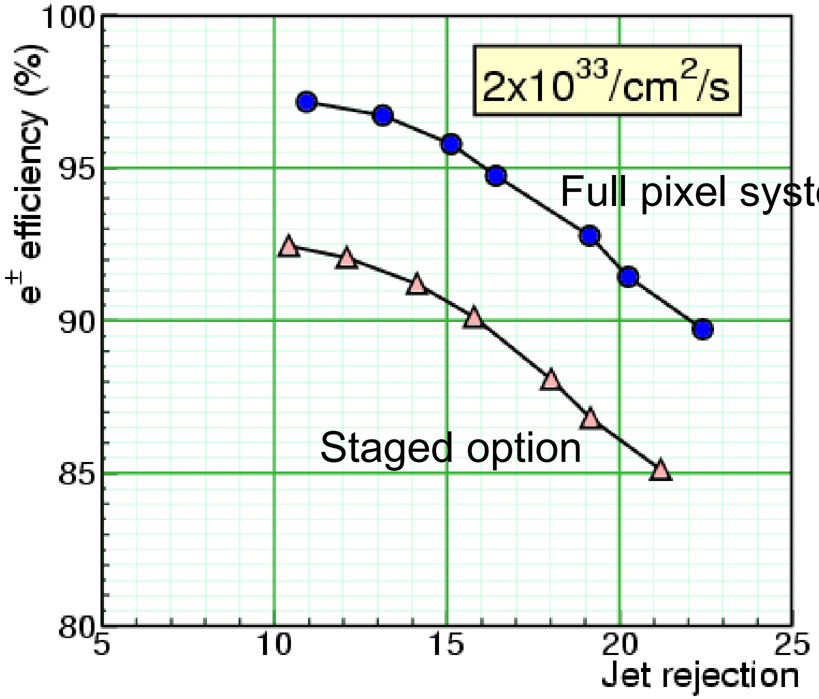




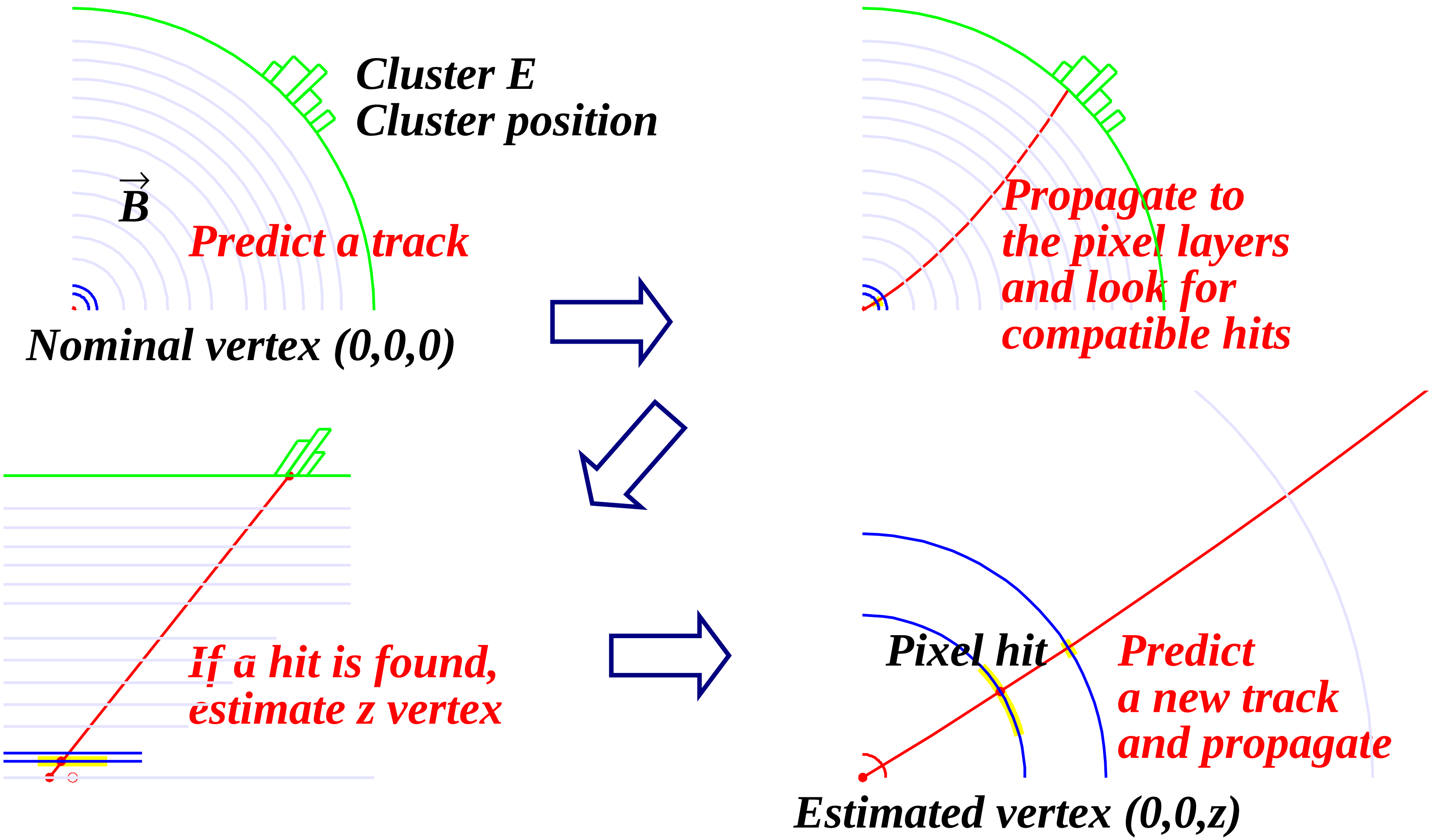
Electron Selection: Level-2.5

- Level-2.5 selection: use pixel information
  - Very fast, large rejection with high efficiency (>15 for ε=95%)
    - Before most material $\Rightarrow$ before most bremsstrahlung, and before most conversions
    - Number of potential hits is 3: demanding $\geq$ 2 hits quite efficient



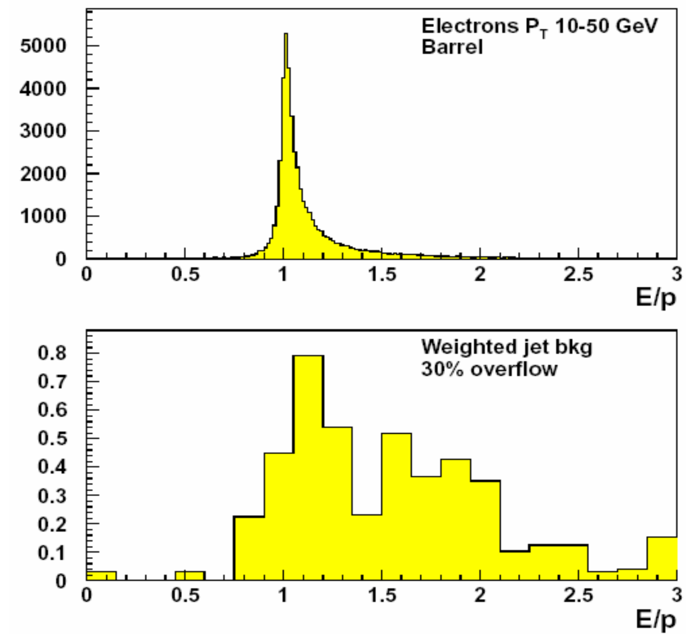


Pixel Matching



Electron Selection: Level-3

- Level-3 selection
  - Full tracking, loose track-finding (to maintain high efficiency)
  - Cut on E/p everywhere, plus
    - Matching in η (barrel)
    - h/e (end-cap)
  - Optional handle (used for photons): isolation

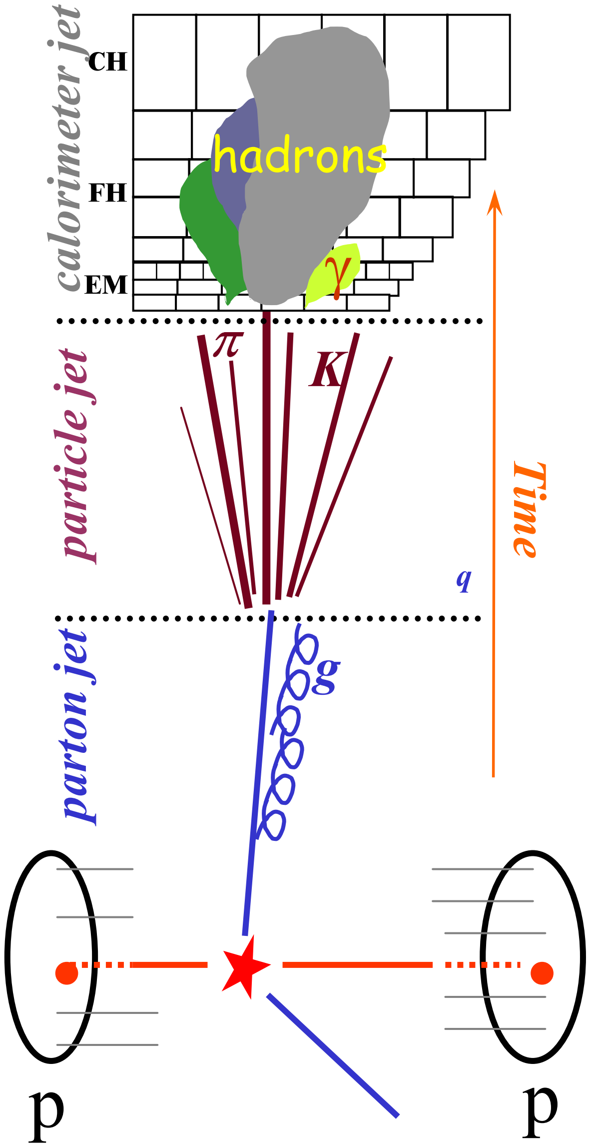


2×10^{33} cm^{-2}s^{-1}

	Signal	Background	Total
Single e	$W \rightarrow e\nu$: 10 Hz	$\pi^{\pm}/\pi^{0}$: 5 Hz π^{0} conversion: 10 Hz $b/c \rightarrow e$: 8 Hz	33 Hz
Double e	$Z \rightarrow ee$: 1 Hz	~0	1 Hz
Single γ	2 Hz	1 Hz	4 Hz
Double γ	~0	5 Hz	5 Hz

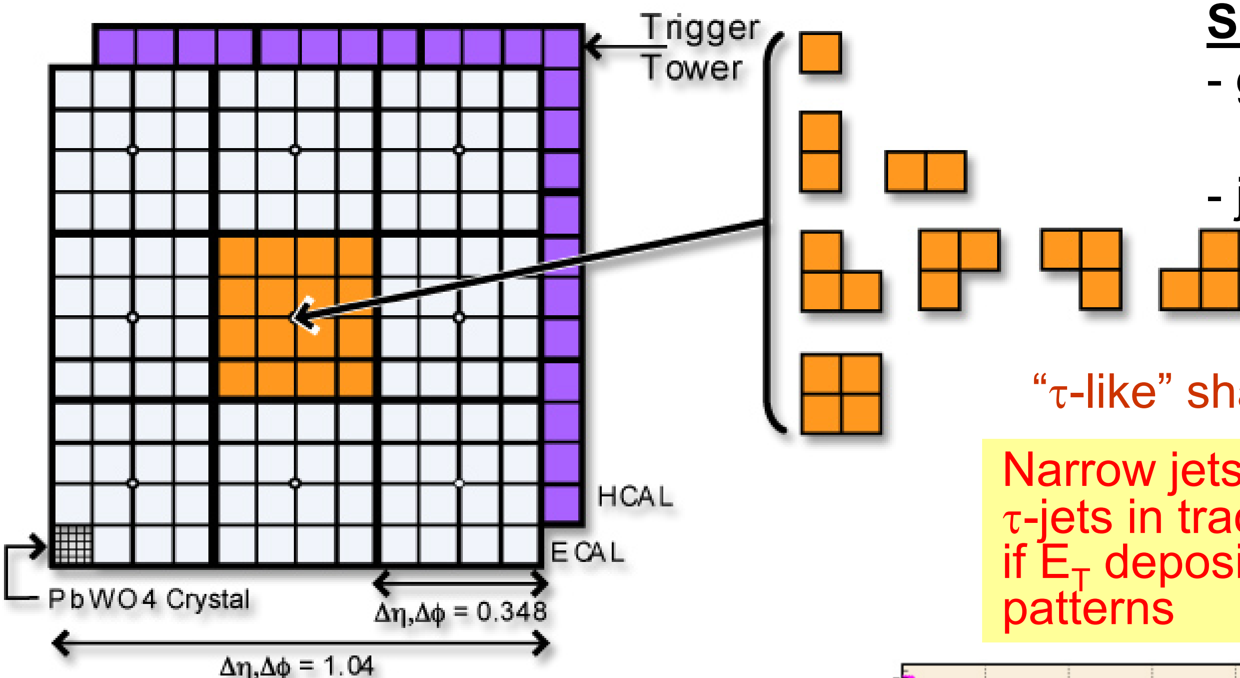
Jets/Taus

Jet Definition



- Calorimeter jet:
  - Measured object (after calorimeter shower)
  - A jet is a collection of hit cells within a region
  - Jet reconstruction algorithm:
    - Grouping hit cells by tower, cluster or cone
    - Cone direction maximizes the total E_T of the jet
  - Various cone/clustering algorithms
- Particle jet:
  - Final state (after hadronization)
  - A spray of particles running roughly in the same direction as the initial parton
  - Correct for finite energy resolution
  - Subtract underlying event
- Parton jet:
  - q and g (before hadronization)
  - Parton hard scattering and parton showers well described by pQCD

CMS: Level-1 Jet and Tau Trigger

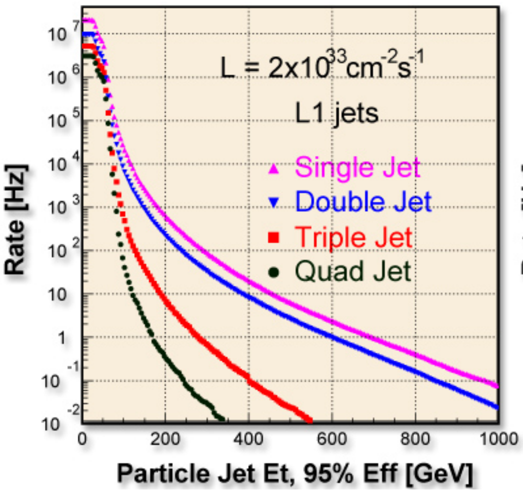


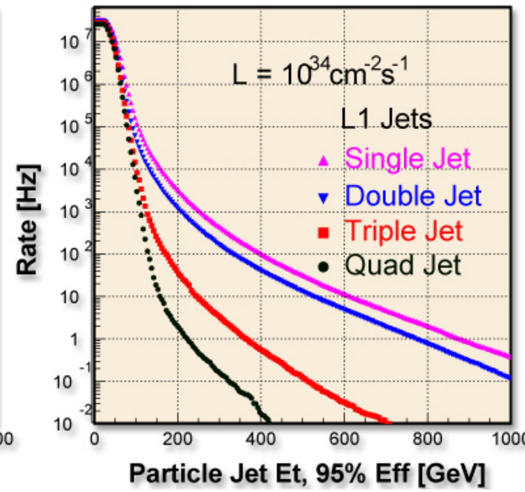
Sliding window:
- granularity is 4x4 towers = trigger region
- jet E_T summed in 3x3 regions $\Delta\eta,\Delta\phi = 1.04$

"τ-like" shapes identified for τ trigger

Narrow jets are tagged as τ-jets in tracker acceptance ($|\eta| < 2.5$) if E_T deposit matches any of these patterns

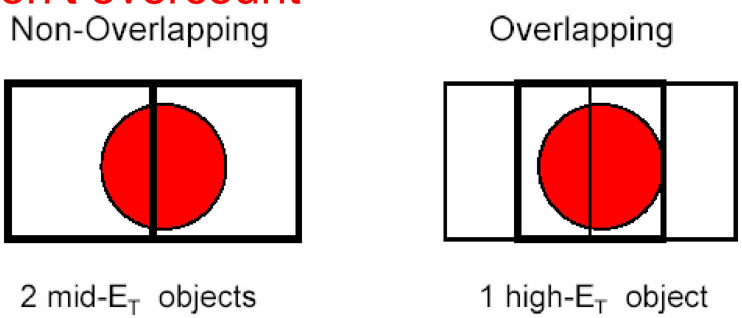
- Single, double, triple and quad thresholds possible
- Possible also to cut on jet multiplicities
- Also E_T^{miss}, ΣE_T and ΣE_T(jets) triggers



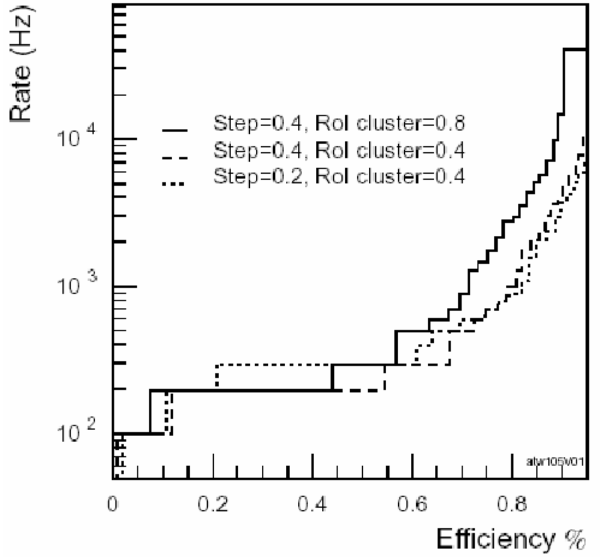


HLT Selection: Jets

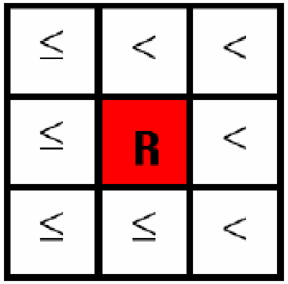
- Very useful (compositeness, extra dimensions, SUSY decays) but also very abundant
  - Background to jets is jets; and QCD makes lots of them
  - Main issue is instrumental: don't split jets, don't overcount
    - Overlapping windows: efficient, but need additional "declustering" logic to remove multiple counts



  - Jet reconstruction with iterative cone algorithm



- **ATLAS:** use ROI clusters, defined as maximum found in sliding window by half jet window width



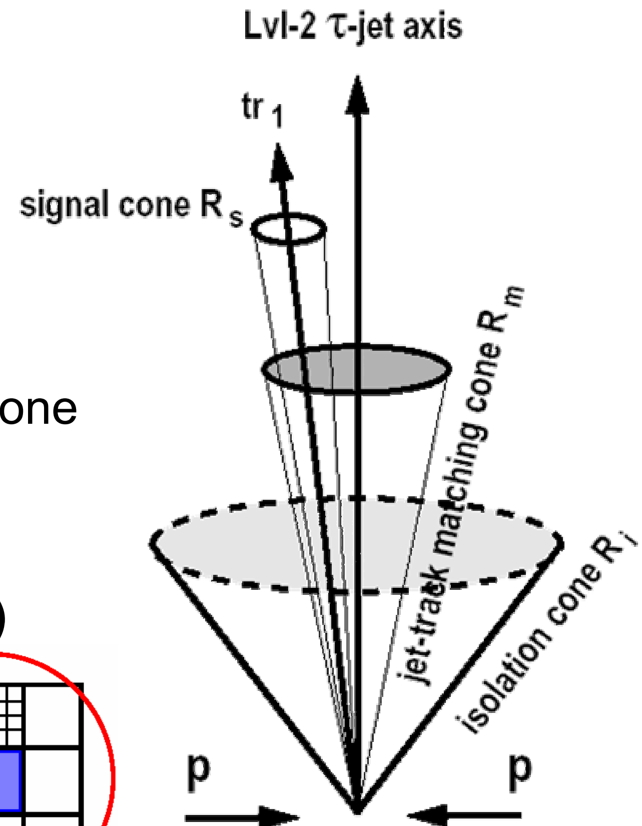
HLT Selection: Taus

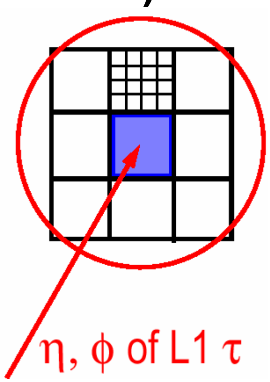
- τ-leptons
  - Important signature for SUSY
  - Reconstruct jet and require isolation
  - Level-2: calorimetric reconstruction and isolation
    - Very narrow jet surrounded by isolation cone

    1. reconstruct a jet
    2. calculate EM isolation :

       $$P_{isol} = E_T^{ecal}(R < 0.4) - E_T^{ecal}(R < 0.13)$$

    3. accept event if $P_{isol} < P_{cut}$
  - Level-3: tracker isolation





Jet is reconstructed at the location of the Level-1 highest E_T tau with an iterative cone of size of 0.6 and ECAL+HCAL towers as input

Jet Reconstruction Algorithms

Jet algorithms are employed to map final states, both in QCD pert. theory and in the data, onto jets. The motivating idea is that these jets are surrogates for the underlying energetic parton.

Variety of Jet algorithms:

- JADE algorithm
- Durham algorithm
- Cambridge algorithm
- Iterative Cone algorithm
- Successive combination algorithm
- KT jet algorithm

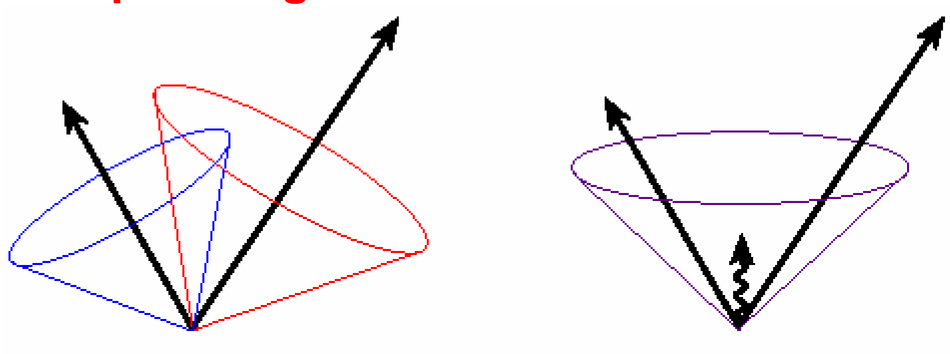
Historically hadron collider use cone algorithms: easier calibration

Jet reconstruction using:

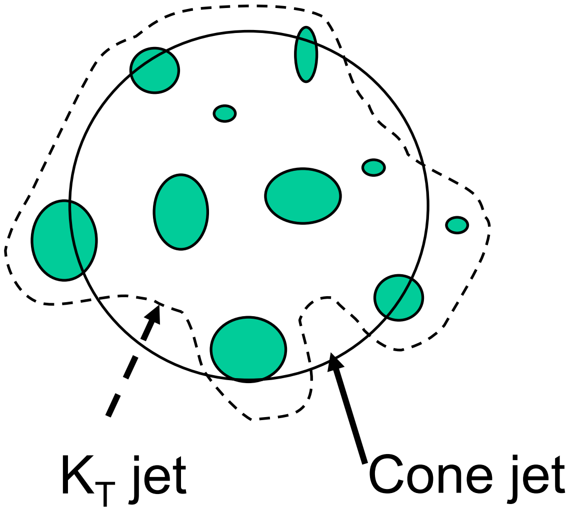
- Calorimeters
- Tracker: regional reconstruction!
- Combined (Calorimeters + Tracker)

Jet Algorithms

- **Cone Algorithm:**
  - Draw a cone of fixed size around seed
  - Compute jet axis from E_T-weighted mean and jet E_T from ΣE_T's
  - Draw a new cone around the axis and recalculate axis and E_T
  - Iterate until stable
  - Algorithm is sensitive to soft radiation
  - Split/Merge criteria invoked



- **K_T Algorithm:**
  - Recombination algorithm based on relative transverse momentum between 'particles'
  - Theoretically favored, no split-merge; Infrared safe to all orders in perturbation theory
  - To reduce computation time, startwith 0.2 x 0.2 preclusters



Trigger Table Determination

Trigger Table Determination

How to allocate the Trigger budget: CMS example

Physics startup assumptions:

- **$L = 2\times10^{33}\ cm^{-2}s^{-1}$**
- **Machine conditions non-optimal**
- **Don't need 100 kHz on day 1**
- **DAQ with a 50 kHz throughput**

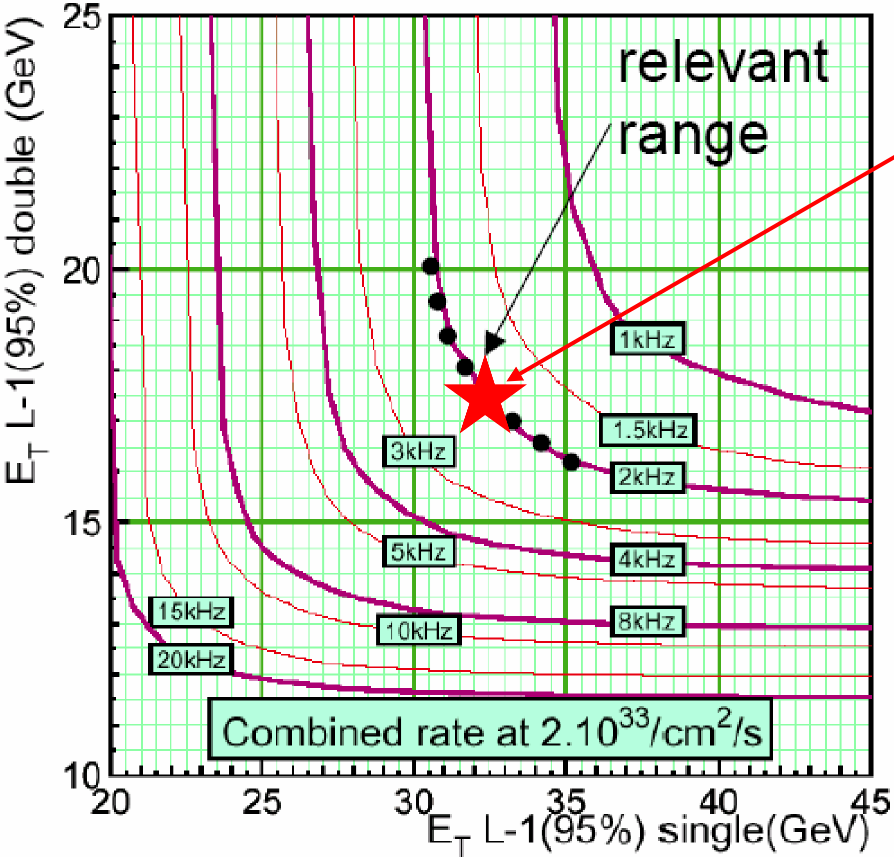
Starting point: 50 kHz/3 $\rightarrow$16 kHz to allocate

- Factor 3 is safety: accounts for all processes that have not been simulated, uncertainties in generator/simulation and beam conditions
- Initial step: equal allocation across (1&2e/γ), (1&2μ), (1&2τ) and jets/cross channels (e&τ, μ&jet, etc.)
- Get thresholds, efficiencies; look at physics cost; iterate
- **Guarantee discovery physics**
  - It fits within very small trigger requirements

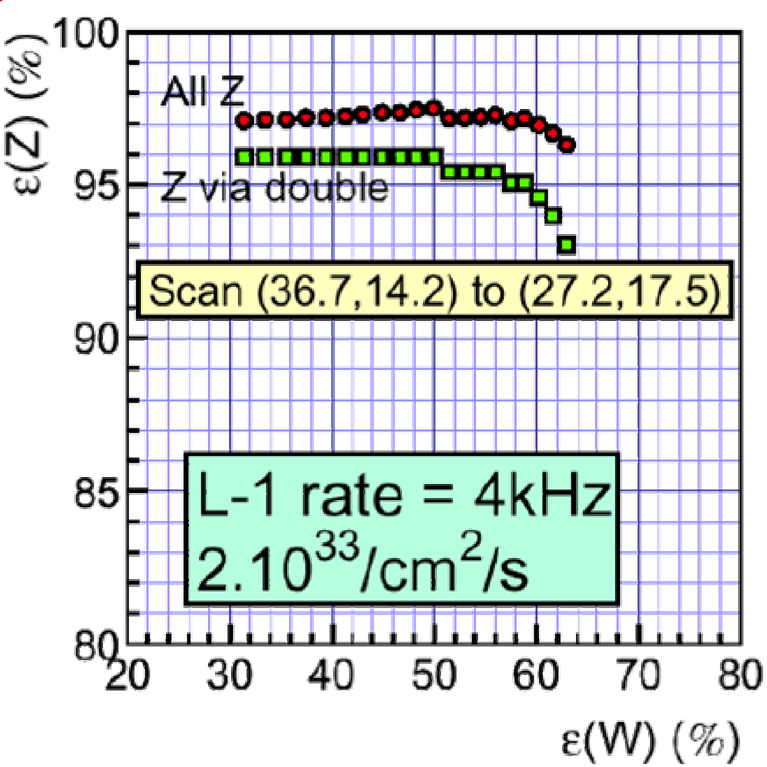
Choice of Operating Point

Deciding thresholds: 1e/γ vs 2e/γ, 1μ vs 2μ, 1τ vs 2τ

- Create iso-rate plot (contours of "equal cost")
- For each contour (in relevant range, e.g. 2 kHz, 3 kHz, 4 kHz) get efficiency of physics channel in 1-obj vs 2-obj requirement



operate at point of rapid slope change



HLT Table Issues

- Purity of streams is not the same (e.g. electrons vs. muons)
  - Kinematic overlap provides **redundancy**
  - To answer the sort of question, when a problem is under investigation in $W \rightarrow e\nu$: do we see this in the muons?
- Comparison of unlike things:
  - How much more bandwidth should go to lower-p_T muons than to electrons?
  - How should one share the bandwidth between jet*E_T^{miss} and di-electrons?
- Only final guidance is efficiency to all the known channels
  - While keeping the selection **inclusive**
  - For this is online: **Events rejected are lost forever**

Level-1 Trigger Table 2×10^{33} $cm^{-2}s^{-1}$

Total rate: 40 kHz, factor 3 safety, allocate 16 kHz

Trigger	Threshold [GeV] or [GeV/c]	Rate [kHz]	Cumulative Rate [kHz]
Isolated e/γ	*29*	*3.3*	*3.3*
Di-e/γ	*17*	*1.3*	*4.3*
Isolated muon	*14*	*2.7*	*7.0*
Di-muon	*3*	*0.9*	*7.9*
Single tau-jet	*86*	*2.2*	*10.1*
Di-tau-jet	*59*	*1.0*	*10.9*
1-jet, 3-jet, 4-jet	*177, 86, 70*	*3.0*	*12.5*
JetE_T^{miss}*	*88*46*	*2.3*	*14.3*
*Electron*jet*	*21*45*	*0.8*	*15.1*
Min-bias		*0.9*	*16.0*
TOTAL			*16.0*

HLT Table 2×10^{33} $cm^{-2}s^{-1}$

Total rate: 105 Hz

Trigger	Threshold [GeV] or [GeV/c]	Rate [Hz]	Cumulative Rate [Hz]
Inclusive electron	*29*	*33*	*33*
Di-electron	*17*	*1*	*34*
Inclusive photon	*80*	*4*	*38*
Di-photon	*40, 25*	*5*	*43*
Inclusive muon	*19*	*25*	*68*
Di-muon	*7*	*4*	*72*
Inclusive tau-jet	*86*	*3*	*75*
Di-tau-jet	*59*	*1*	*76*
*1-jet * E_T^{miss}*	*180 * 123*	*5*	*81*
1-jet OR 3-jet OR 4-jet	*657, 247, 113*	*9*	*89*
*Electron * jet*	*19 * 45*	*2*	*90*
Inclusive b-jet	*237*	*5*	*95*
Calibration etc		*10*	*105*
TOTAL			*105*

CMS: HLT performance

- With previous selection cuts

Channel	**Efficiency** (for fiducial objects)
H(115 GeV) $\rightarrow\gamma\gamma$	*77%*
H(160 GeV) $\rightarrow$ *WW** $\rightarrow 2\mu$	*92%*
H(150 GeV) $\rightarrow$ *ZZ* $\rightarrow 4\mu$	*98%*
A/H(200 GeV) $\rightarrow 2\tau$	*45%*
SUSY (~0.5 TeV sparticles)	*~60%*
With R_P*-violation*	*~20%*
W $\rightarrow e\nu$	*67% (fid: 60%)*
W $\rightarrow \mu\nu$	*69% (fid: 50%)*
Top $\rightarrow \mu X$	*72%*

HLT CPU Time Usage

- All numbers for a 1 GHz, Intel Pentium-III CPU

Physics object	CPU time [ms/Level-1]	Level-1 rate [kHz]	Total CPU time [s]
Electrons/photons	*160*	*4.3*	*688*
Muons	*710*	*3.6*	*2556*
Taus	*130*	*3.0*	*390*
Jets and E_T^{miss}	*50*	*3.4*	*170*
Electron + jet	*165*	*0.8*	*132*
b-jets	*300*	*0.5*	*150*

- Total: 4092 s for 15.1 kHz → 271 ms/event
  - Therefore, a 100 kHz system requires 1.2×10^6 SI95
- Expect improvements, additions. Time completely dominated by muon extrapolation – this will improve
- This is “current best estimate”, with ~50% uncertainty.

ATLAS HLT Table

Selection	2×10^{33} cm^{-2}s^{-1}	Rates (Hz)
Electron	e25i, 2e15i	~40
Photon	γ60i, 2γ20i	~40
Muon	μ20i, 2μ10	~40
Jets	j400, 3j165, 4j110	~25
Jet & E_T^{miss}	j70 + xE70	~20
tau & E_T^{miss}	τ35 + xE45	~5
b-physics	2μ6 with m_B /$m_{J/\psi}$	~10
Others	pre-scales, calibration,	~20
Total		~200

Mostly physics signal, some thresholds already rather high (j70 + xE70)

Summary

- Reduction of 1 GHz of interactions to ~10^2 Hz with high efficiency for discovery physics
- Event selection based on presents of physics objects
- Reconstruction/Selection performed in stages:
  - Level-1: 1 GHz to 50 - 100 kHz
  - Higher Levels: 50 - 100 kHz to 100 Hz archival rate
  - Regional/partial event reconstruction
  - Region of Interest and seeds provided by Level-1 trigger
- Allocate bandwidth $\rightarrow$ Trigger Table
  - Example trigger table for LHC startup
  - Meets target rates for Level-1 and for final output to permanent storage
  - While maintaining high efficiency for signal events and wide inclusive selection (open to the unexpected)