Vertex reconstruction and tracking in the trigger algorithm for CMS

M. Konecki
University of Warsaw

on behalf of the CMS Collaboration

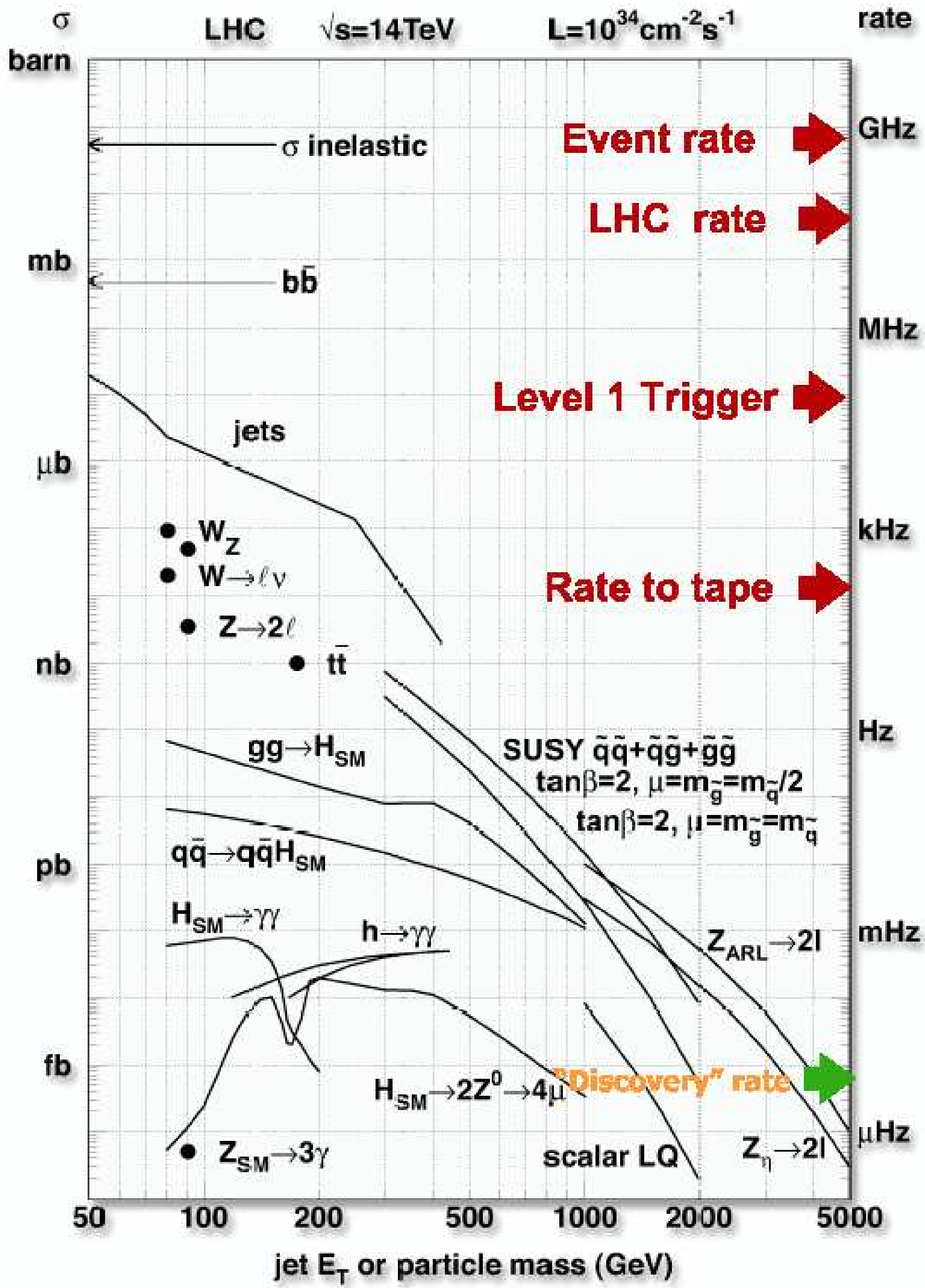
Outline:

- CMS trigger and DAQ Architecture
- General Track and Vertex reco for HLT
  - regionality
  - pixel-based reconstruction and seeding
  - full track reconstruction
- HLT application
- Summary

HLT = High-Level Trigger

"Level-1 TDR" - CERN/LHCC 2000-038
"DAQ & HLT TDR" - CERN/LHCC 2002-26
"PHYSICS TDR1" - CERN/LHCC 2006-001

+ CMS notes



CMS at LHC

LHC

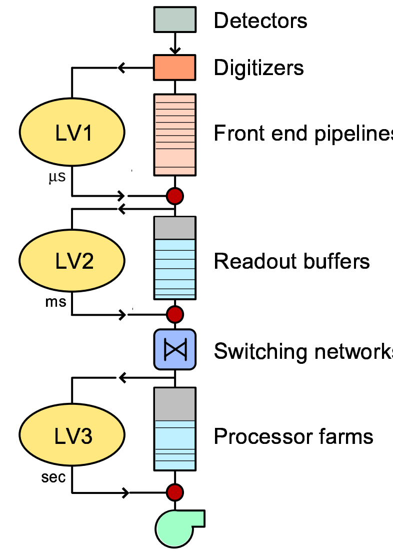
- 7+7 TeV protons
- bunch crossing rate: 40MHz
- High Luminosity: $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  Low Luminosity: $2 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  Initial Luminosity: $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

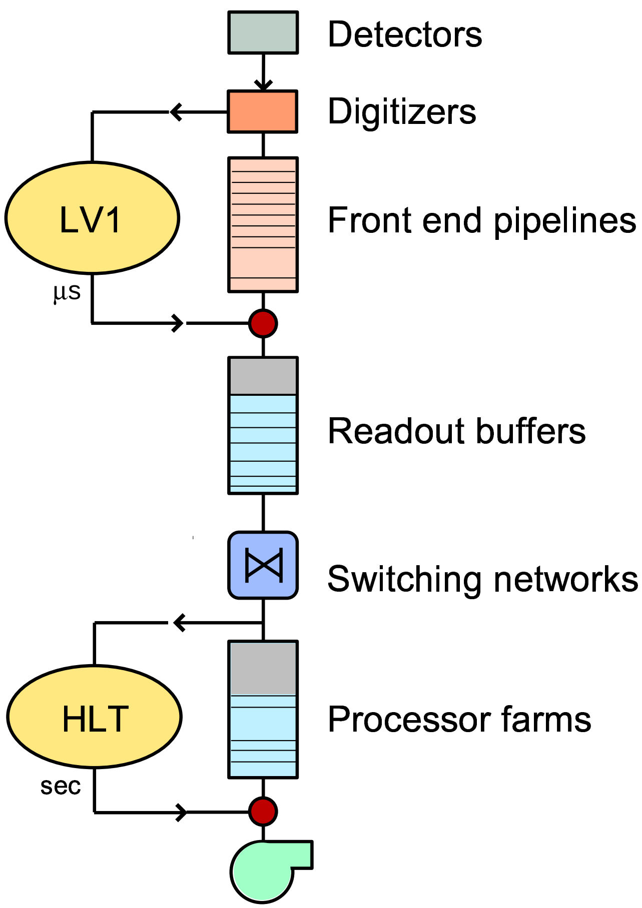
CMS: General purpose experiment

- 2 trigger levels
  - Max Level-1 output: 100kHz
  - High-Level Trigger output: O(100 Hz)
- Event selection 1 in $10^{\sim 13}$

CMS trigger principles

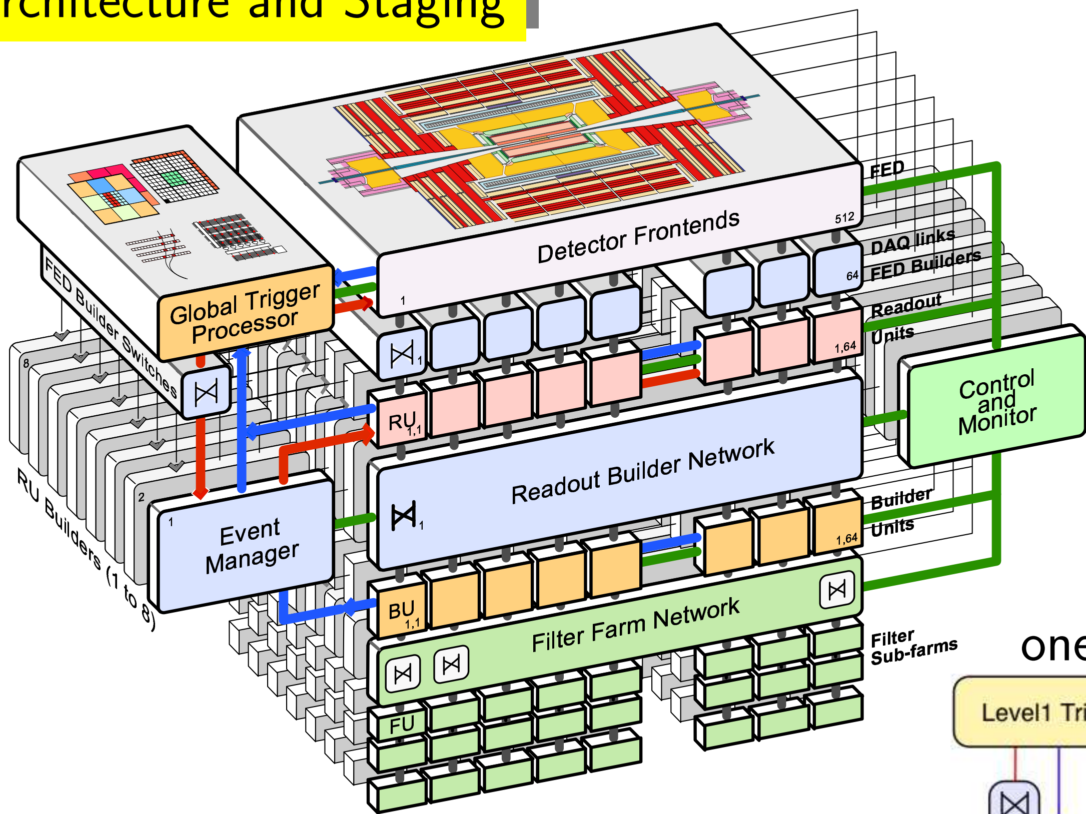
Traditional approach: Dedicated L2 hardware. Does not benefit from full granularity.



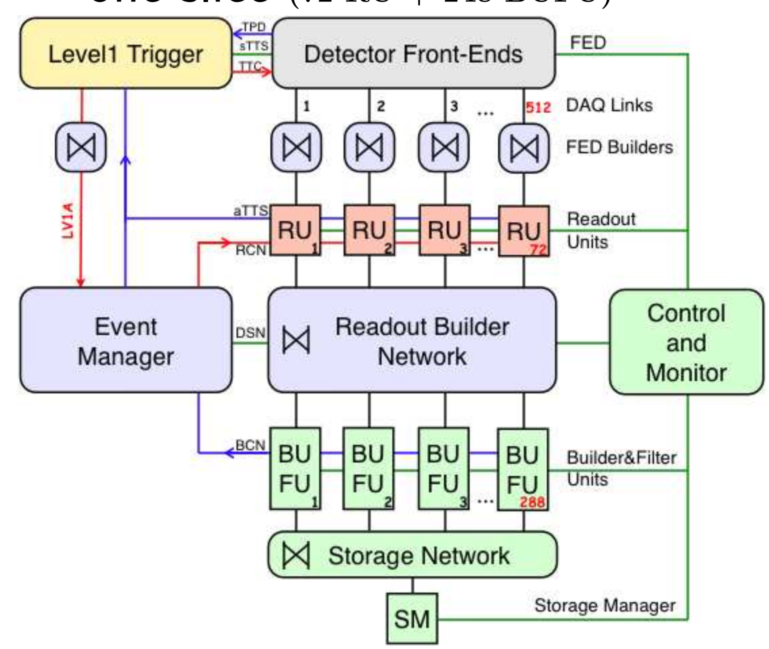


CMS Approach: do without dedicated L2 hardware. After Level-1 there is a High-Level Trigger running on a single processor farm.
Advantage: The only limitation is available CPU. Maximal Flexibility. Full granularity and resolution.
Caveats: A lot of data to handle. Challenging.

DAQ Architecture and Staging



one slice (72 RU + 248 BUFU)



- DAQ designed to accept Level-1 rate of 100 kHz
- Modular DAQ: 8×12.5 kHz DAQ units. 4 Slices at startup (50 kHz).
- HLT output O(10^2) Hz - rejection of 1000.

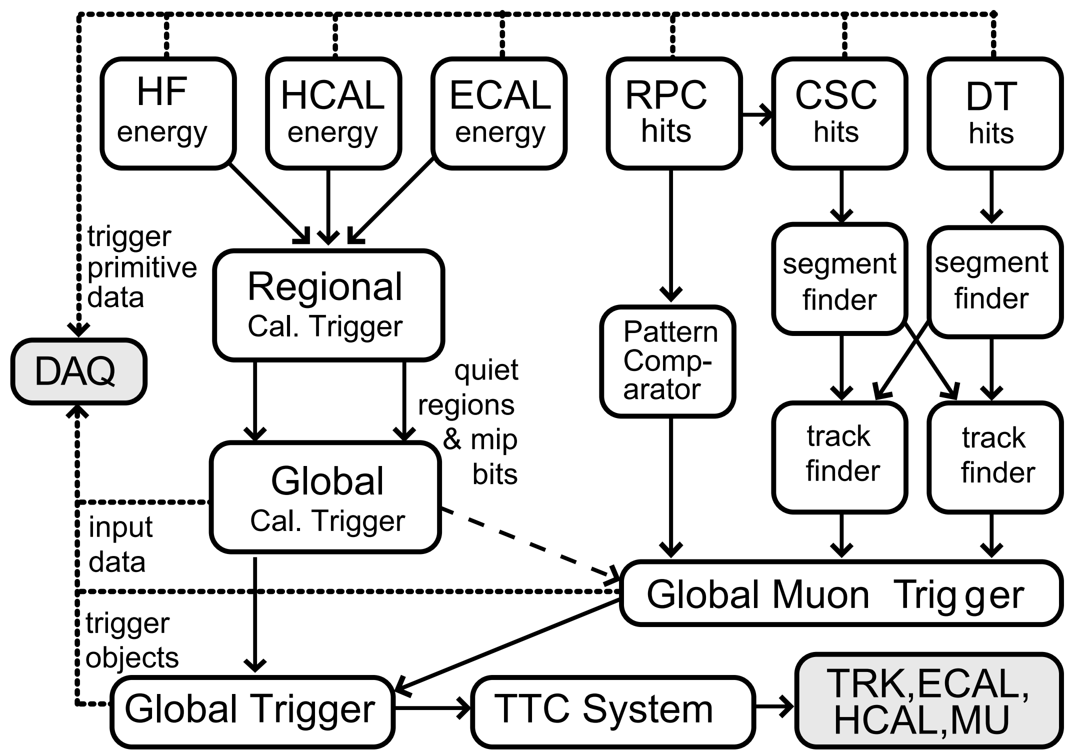
Level–1

Overview

Requirements driven by LHC discovery physics:

- Identify high-p_T leptons (including taus) and photons. Single and Combined triggers.
- All trigger thresholds and conditions must be programmable (large uncertainties in backgrounds and signals)
- Need to include overlapping and min-bias triggers to well understand efficiencies
- Large rejections factors needed: 40MHz ($\times \sim 20$ ev/bx) $\rightarrow$ 100 kHz.

- Level-1 uses muon and calorimeter detector data only
- Special-purpose hardware (ASICS) but also FPGAs
- Data stored on detector during fixed Level-1 latency. 128BX $= 3.2\mu$s
- Data read on Level-1 accept. Proceed via event builder switch to HLT



Example L1 trigger table ($2 \cdot 10^{33}$cm^{-2}s^{-1}, DAQ TDR)

Safety factor of three is superimposed for simulation uncertainties, beam conditions,... Thus output rate: $50\ \mathrm{kHz} \Longrightarrow 16\ \mathrm{kHz}$ at startup ($2 \cdot 10^{33}$cm^{-2}s^{-1}). Bandwidth is allocated in equal parts to electron/photons, muons, taus, and jet+combined triggers. Priority: discovery physics.

Trigger	Threshold (ε=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate (kHz)
1e/γ, 2e/γ	29, 17	4.3	4.3
1μ, 2μ	14, 3	3.6	7.9
1τ, 2τ	86, 59	3.2	10.9
1-jet	177	1.0	11.4
3-jets, 4-jets	86, 70	2.0	12.5
Jet * Miss-E_T	88 * 46	2.3	14.3
e * jet	21 * 45	0.8	15.1
Min-bias		0.9	16.0

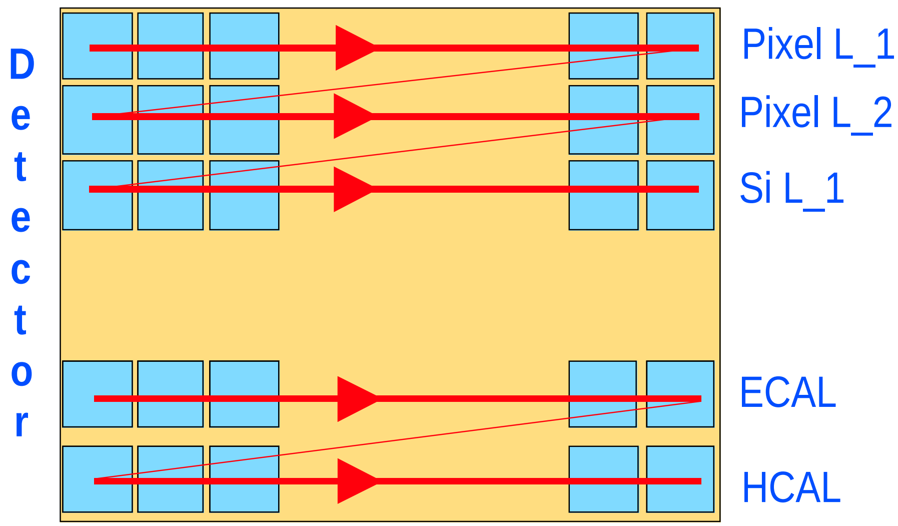
- Object provided by L1 seed HLT reconstruction!
- 50 kHz $\oplus$ 2000 CPU $\Longrightarrow$ 40 msec/event

HLT Principles

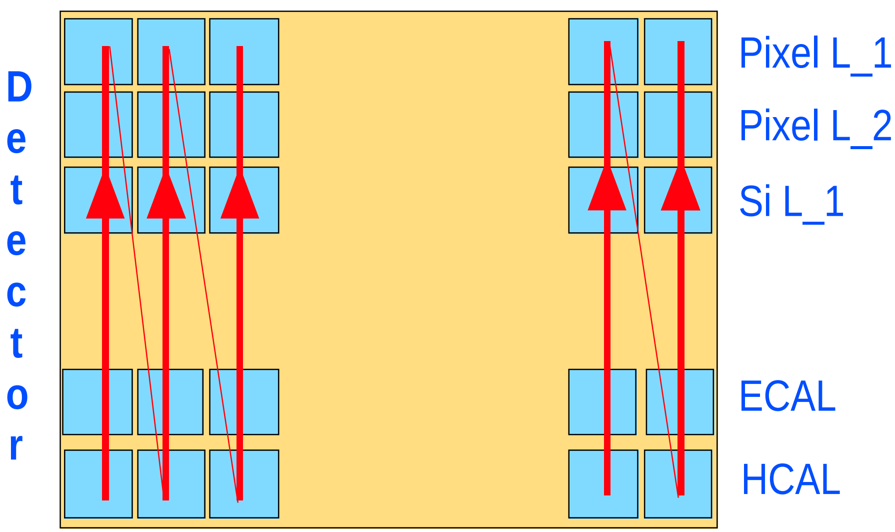
- Runs on CPU farm (1 ev/processor at a time). Available CPU is a limitation ($\rightarrow$ timing). Uses full granularity and resolution. C++.
- Must provide sufficient rate reduction 100(50) kHz $\Longrightarrow$ O(10^2) Hz. Selection 1 ev in ~1000.
- Must satisfy physics requirements: inclusive selection, high efficiency.
- Two strategies:
  - Fast but not accurate reconstruction
  - Use minimal amount of precise information.

  Both ways used to optimize event rejection speed. Second is preferred when performance comparable - code as close as possible to offline reconstruction.
- Reconstruction on demand, regional, partial.
- HLT (CMS traditional) steps: L2: calo, muon, L2.5 += pixel , L3 += strips

Global and Regional reconstruction

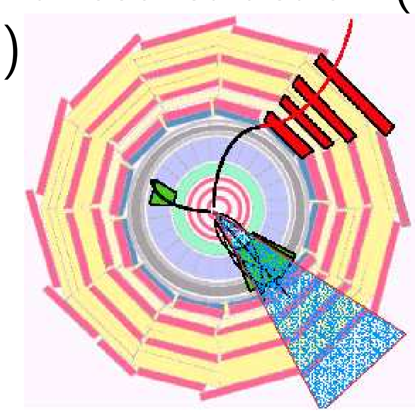


GLOBAL: Reconstruct raw data detector by detector, link detectors to make objects. Needed when no seed given. Also: global tracking, ΣE_T, Missing E_T, "other side of lepton"



REGIONAL: Reconstruct data only where it is needed. Slices of appropriate size. Need to know where to start reconstruction (seeds from Level-1, Level-2)

example: Track in the region of interest defined by a jet. Typical cone size: $\Delta R = 0.2 - 0.5$



General purpose tracking

Preparation for track reconstruction

- Read out of detector data (raw to digi)
  Detector data provided by FEDs is coded. It must be interpreted (digi) and attached to software objects representing hardware modules.
- Hit reconstruction
  Strip and pixel digis are grouped (clustering) and hit positions are evaluated (with corresponding errors)

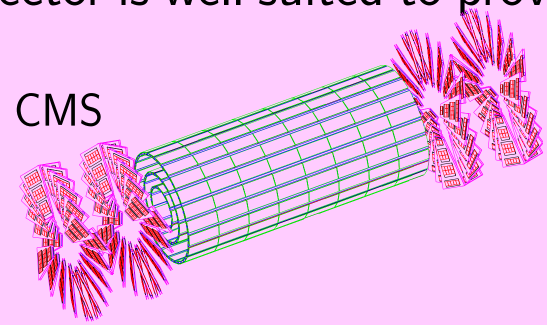
Reconstruction of tracks:

- Seed finding
  Finding a set of hits compatible with track kinematics. Seed provide a rough estimate of track's kinematics necessary for further track reconstruction
- Pattern Recognition
  Collect hits compatible with unique track. It is iterative procedure that starts from seed parameters.
- Final Fitting
  The positions of collected hits associated to the same track are used to provide best estimate of track's kinematics including errors

Pixel based reconstruction dedicated for HLT and seeding

The current CMS default scenario of track reconstruction for HLT is Combinatorial Track Finder (CTF) with Pixel based seeding. Pixel detector is well suited to provide hits for seeding and simplified reconstruction:

- the pixel reconstructed hits (RecHits) are the most precise in CMS
- both $r\phi$ and r or z coordinates are measured
- layers close to beam line - minimal multiple scattering, etc.
- low occupancy



Track candidates ("proto tracks") based on 2 or 3 hits (hit pairs, hit triplets) allow us to do seeding, vertex reconstruction and define simple analysis algorithms dedicated for HLT.

hit pair based proto tracks - low purity, precise enough to define direction (seed)

hit triplet based proto tracks - relatively high purity but not fully efficient in Pixels only; limited momentum estimation, can be used for analyses where efficiency is not crucial

Seed generation, Reconstruction of Pixel based proto tracks, PV finding to be applied for online event selection. Must be fast (and as fast as possible). Whenever possible have to avoid ***global*** algorithms, work only in the region of interest (***regional seeding, reconstruction, vertexing***).

TrackingRegion definition of region of interest with kinematic constraints

Concrete implementations:

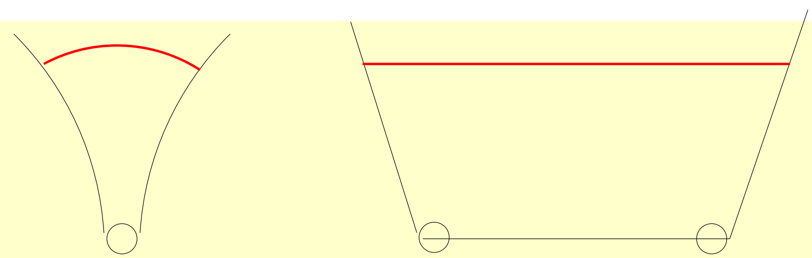
- GlobalTrackingRegion
  - vertex point from which tracks are expected to originate,
  - range of inverse pt (or minimal pt of interest)
  - maximal allowed closest distance from beam in transverse plane
  - maximal allowed distance from vertex along beam line
- RectangularEtaPhiTrackingRegion

  additional constraints:
  - direction around which the region is defined,
  - allowed η tolerance around the direction (at vertex)
  - allowed φ tolerance around direction (at vertex)

Finding of Compatible Hits, Hit Pairs and Hit Triplets

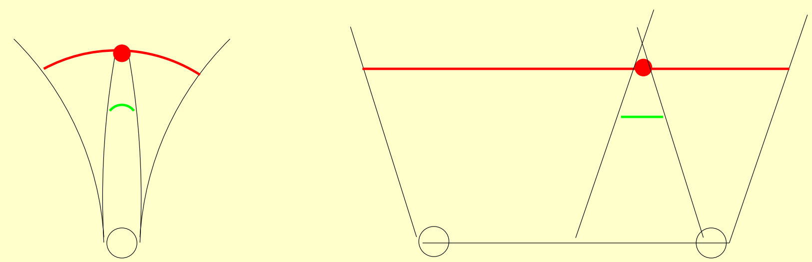
First (outer) hit

RectangularEtaPhiTrackingRegion predicts analytically range of $\varphi, r/z$ for a given layer.



Second (inner) hit

Analytical prediction, independent for φ and $r - z$ errors, mult. scatt., bending are taken into account.



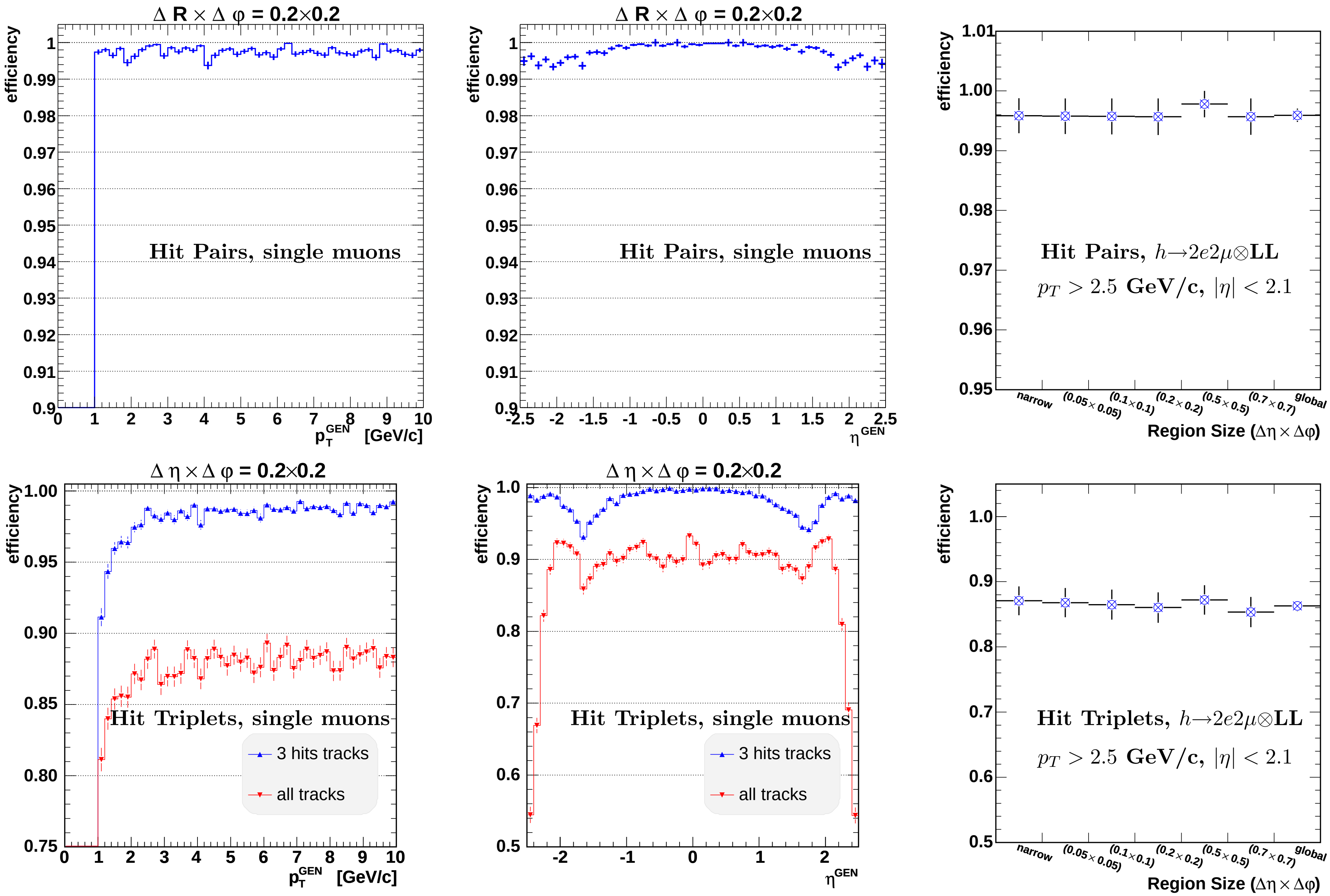
Third hit

- Full efficiency cannot be reached $\longrightarrow$ no track uncertainties mandatory at LHC
- r/z defined by hit pair direction extrapolation
- the φ checked using the prediction from circle approximated by parabola in inverted coordinates **M.Hansroul, H.Jeremie, D.Savard NIM A270 (1998) 490.**

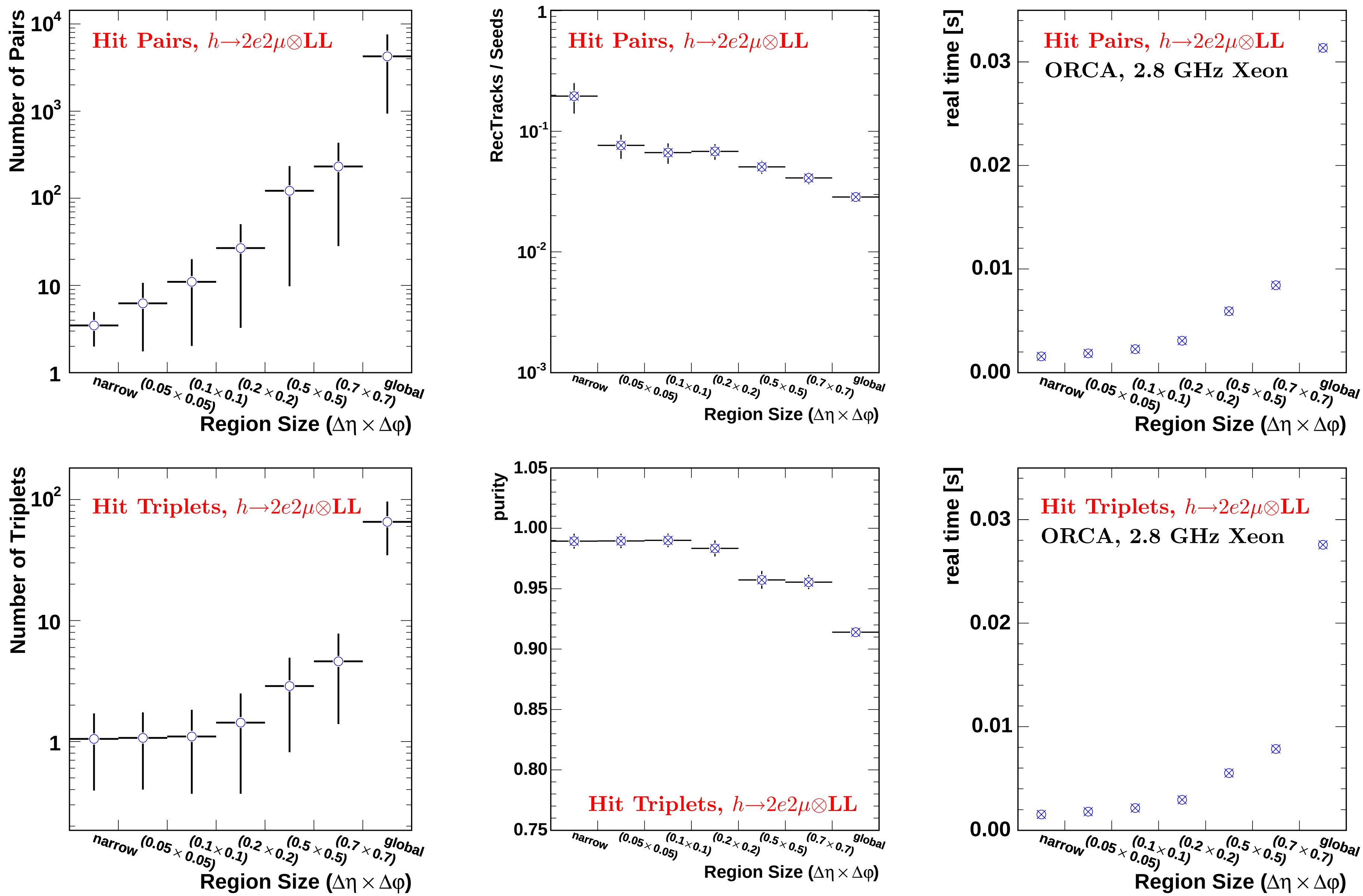
$$v = A + Bu + Cu^2, \qquad \text{where}: \quad \mathrm{u} = \frac{\mathrm{x}}{\mathrm{x}^2 + \mathrm{y}^2} \quad \mathrm{v} = \frac{\mathrm{y}}{\mathrm{x}^2 + \mathrm{y}^2}$$

Then ($\pm$): $A = \frac{1}{R \cdot \cos\alpha}$, $B = \tan\alpha$, $C = \frac{d}{\cos\alpha^3}$, **with** $1/R$ **– curvature,** α **– direction at vertex,** d **- impact parameter.**

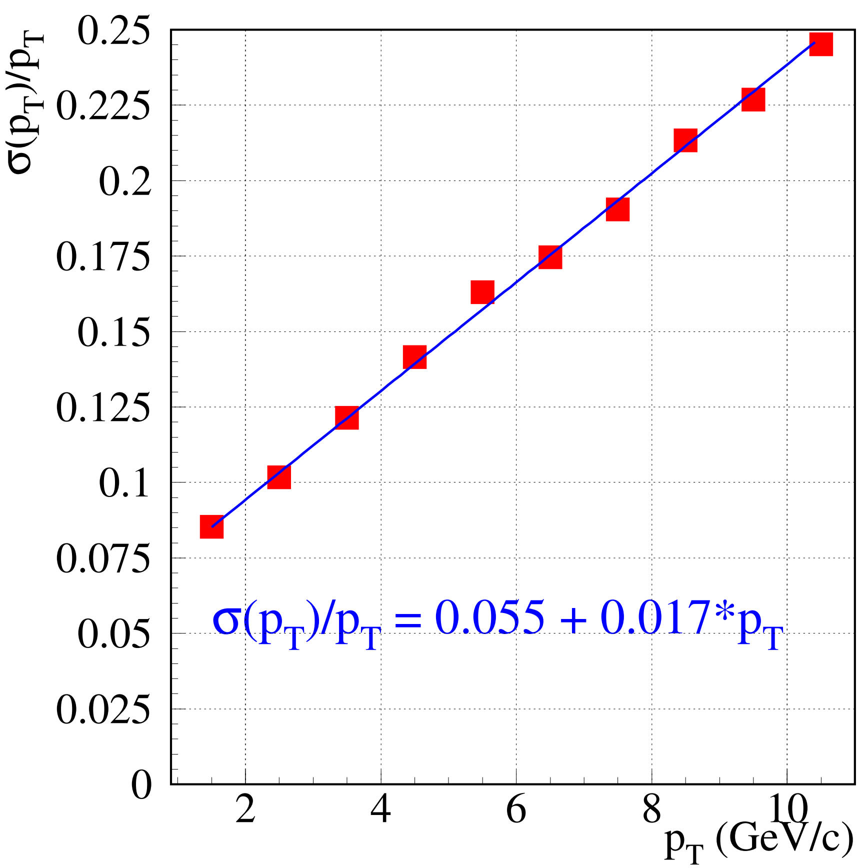
Hit Pairs and Triplets - performance

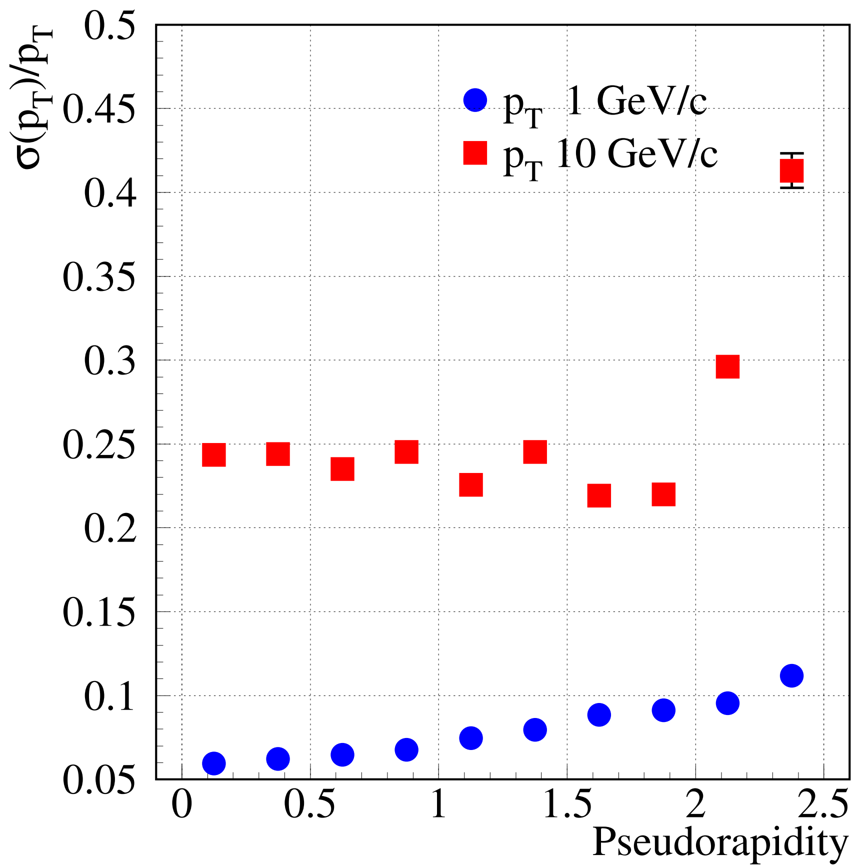


Hit Pairs and Triplets - performance



- Track parameters are computed from Helix projections to xy (transverse) plane and rz (longitudinal) plane The quality of p_T fitting does not depend on the approximation used.
- In the case of p_T calculation from Hit pair the beam line constraint is used.
- Pixel detector provides good p_T resolution for low energetic tracks. Poor p_T assignment for particle above 10 GeV.

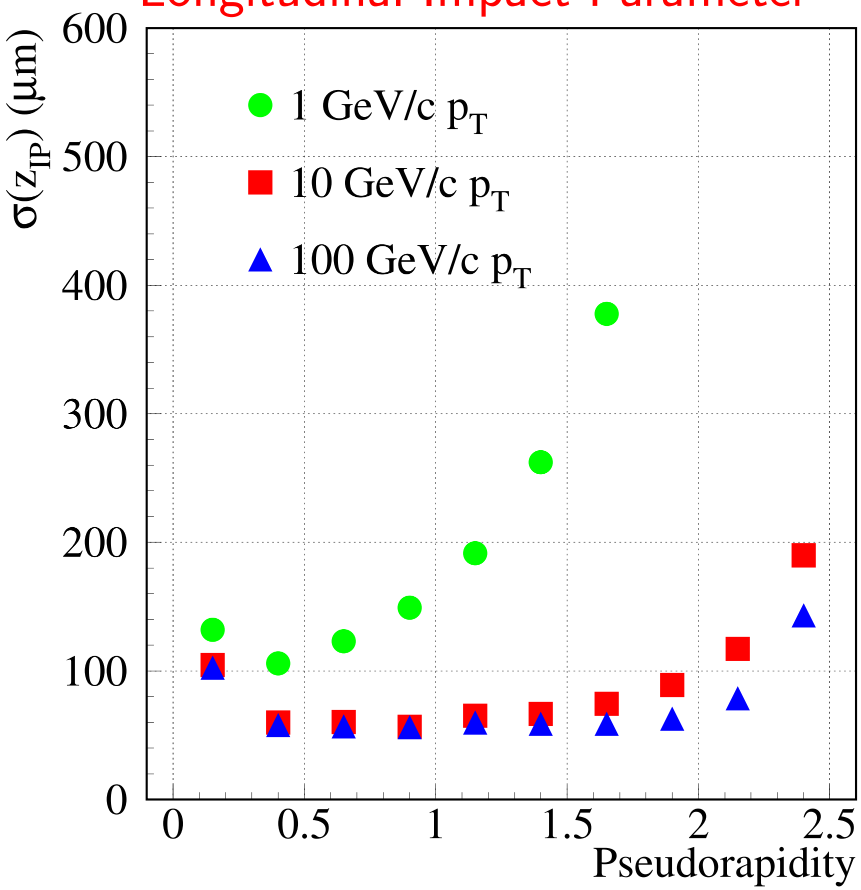




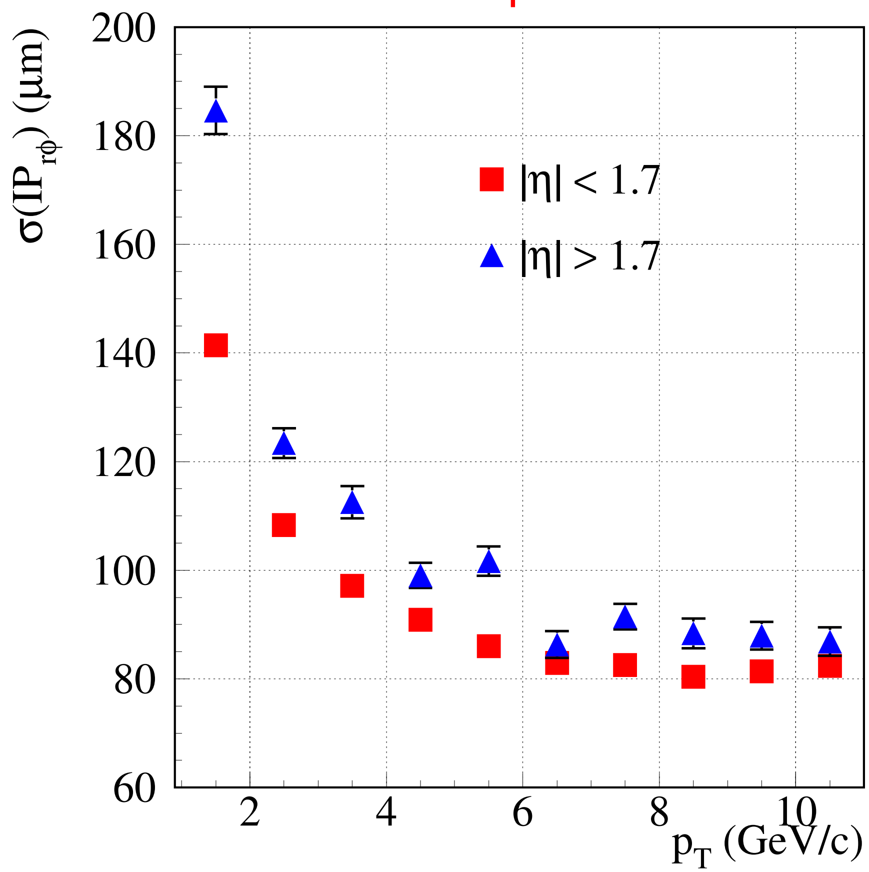
Impact Parameter resolutions

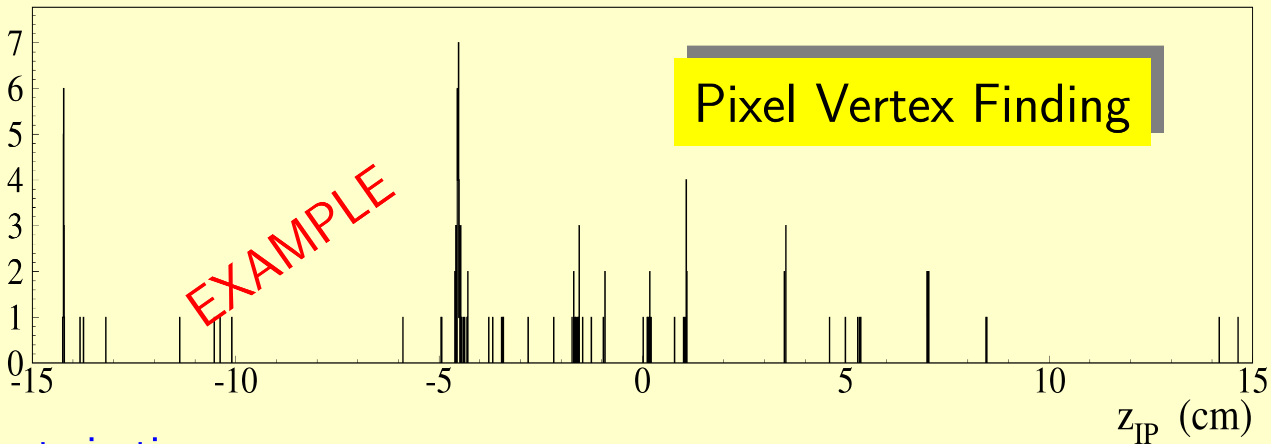
- No TIP (0. assigned) for Tracks based on Hit Pairs only
- The impact parameters resolutions significantly degrades for low p_T tracks.
- Small TIP resolution dependency vs pseudorapidity. Important dependency for ZIP.

Longitudinal Impact Parameter



Transverse Impact Parameter





- **Initial clusterisation**

  Divide luminosity region into clusters separated by more than $z_{SEP}(\sim 0.5mm)$. Cluster center is average z_{IP} of tracks belonging to given cluster.

- **Cleaning**

  An iterative procedure to discard tracks not compatible with PV. Tracks are discarded according to their distance from cluster center ($|z_{IP} - z_{PV}| < z_{offset} \cdot \sigma_{z_{IP}}$).

- **Recovering**

  Discarded tracks are recovered to form a new PV cluster. Iterative procedure (Recovering-Cleaning) stops when number of remaining discarded tracks is smaller than $N^{MIN}(\sim 2)$.

- **Sorting**

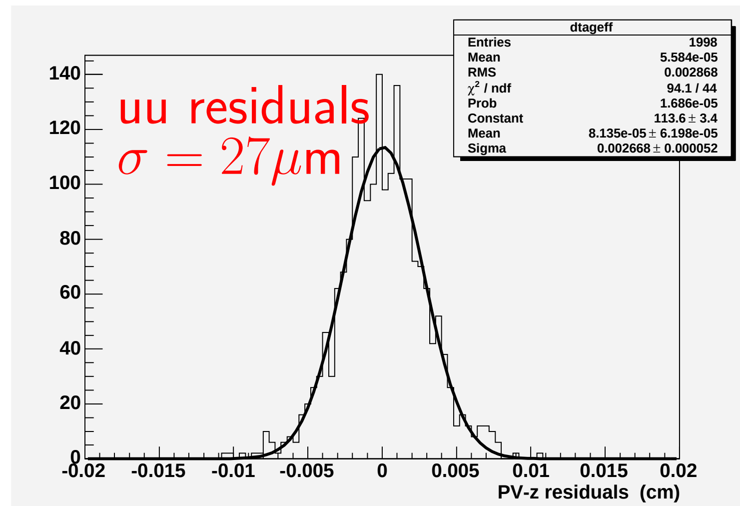
  sort PV candidates by $\sum p'_T$:

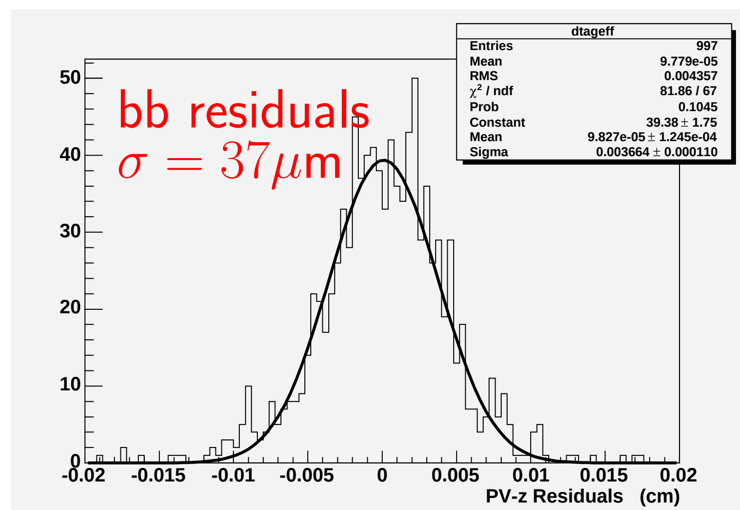
$$p'_T = \begin{cases} 0 & \text{if } p_T < 2.5\,\mathrm{GeV}/c, \\ p_T & \text{if } 2.5\,\mathrm{GeV}/c < p_T < 10\,\mathrm{GeV}/c, \\ 10 & \text{if } p_T > 10\,\mathrm{GeV}/c. \end{cases}$$

(to avoid vertices with low p_T tracks and to take into account poor evaluation of high p_T).

Among primary vertex candidates the ***found*** PV is defined as the closest in z to the simulated signal primary vertex. The ***tagged*** vertex is the one with largest p_T sum. The efficiency to find primary vertex ($\varepsilon_{found}, \varepsilon_{tag}$) is defined with respect to vertices closer that $500\mu m$ from the generated signal PV.

	Divisive	
	ε_{found}	ε_{tag}
u-jets; $E_T = 100GeV$	1.00	0.99
u-jets; $50 < E_T < 100GeV$	0.99	0.94
b-jets; $E_T = 100GeV$	0.99	0.99
b-jets; $30 < E_T < 50GeV$	1.00	0.96
$H(115GeV/c^2) \rightarrow \gamma\gamma$, g fusion	0.94	0.80
$H(150GeV/c^2) \rightarrow ZZ \rightarrow 2e2\mu$	1.00	1.00
$B_s^0 \rightarrow J/\psi\phi$	0.97	0.78
$t\bar{t}$	1.00	1.00
$t\bar{t}H$, $H(120GeV/c^2) \rightarrow b\bar{b}$	1.00	1.00





Customization of seeding

Functionality of pixel-based reconstruction

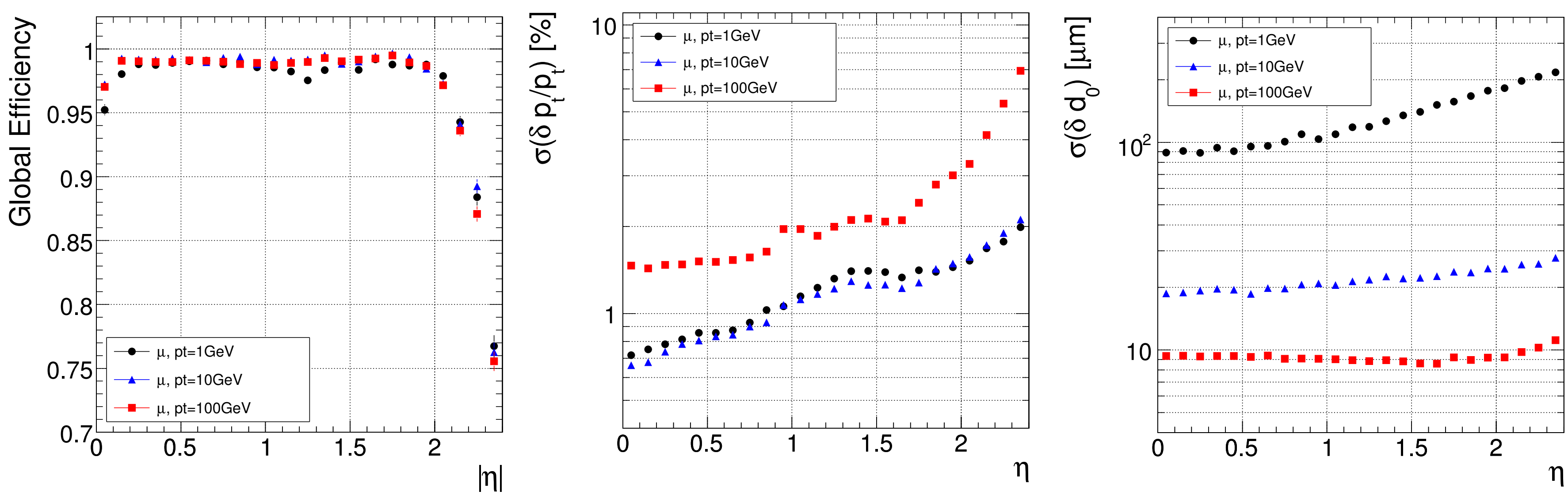
- search for hit pairs (regional)
- search for hit triplets (regional)
- reconstruction of PV from triplets (usually global)
- search for hit pairs compatible with PV's
- reconstruction of proto tracks based on hit pairs and/or triplets with/without PV; allow fast but simplified analysis
- filtering and cleaning mechanisms are provided (using proto track kinematics)
- after each step of pixel-based reconstruction seeds for CTF may be created

Combinatorial Track Finder tracks

- seeding with innermost tracker layers (pixel, mixed, pixel-less)
- the pattern recognition uses a following approach: every time a new hit is associated to the track the "partially reconstructed" trajectory parameters are re-evaluated and the search window on the next tracker layer is narrowed as the uncertainty on the track parameters is decreasing
- the final set of hits is fitted using Kalman-Filter fitting/smoothing logic

Combinatorial Track Finder tracks - performance

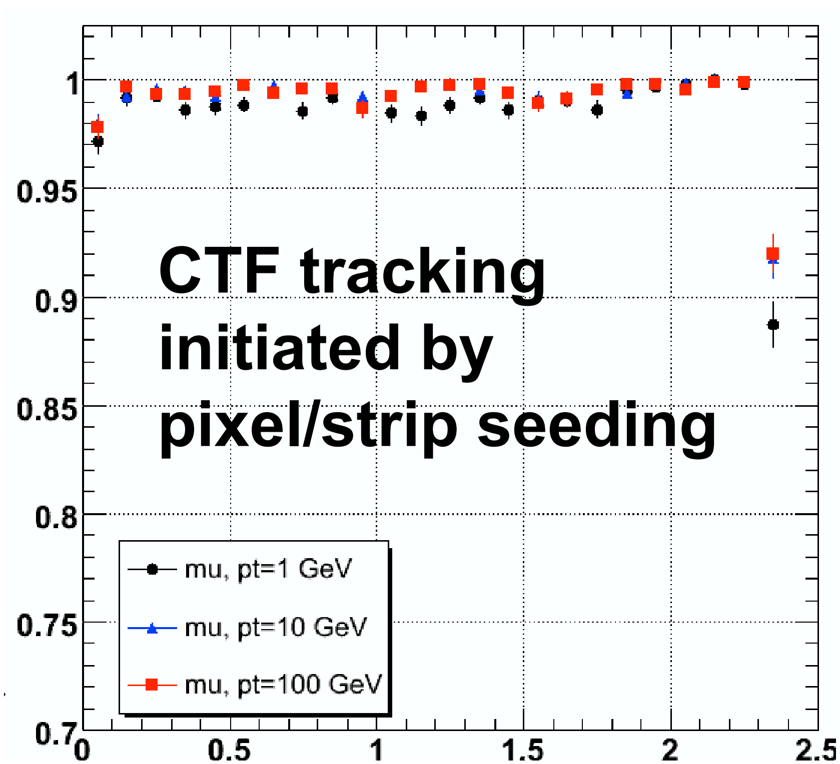
- efficiency close to 99% up to $|\eta| < 2.0$
- transverse momentum resolution 0.5-2 %
- resolution on impact parameter $10 - 100 \mu m$

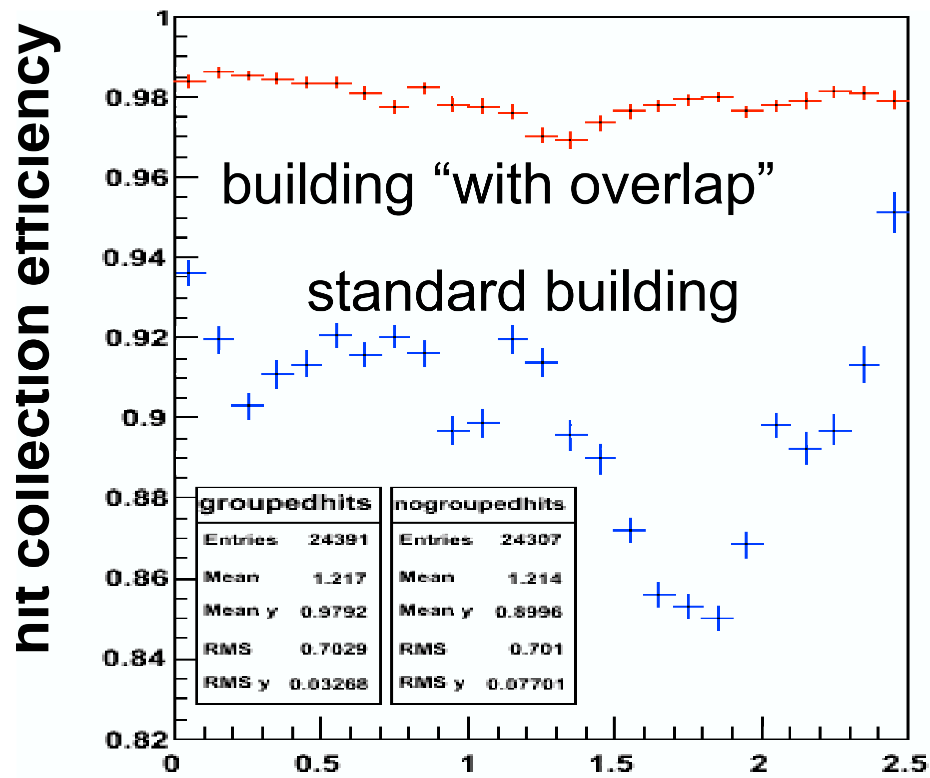


Combinatorial Track Finder tracks - customization

The CTF can be optimized for offline/online.

- seeding with mixed (pixel+strip) seeds instead of pixel only
- trajectory building with recovery of hits in overlapping sensors
- Runge-Kutta propagation instead of faster but less accurate (slightly varying magnetic field) Analytical one





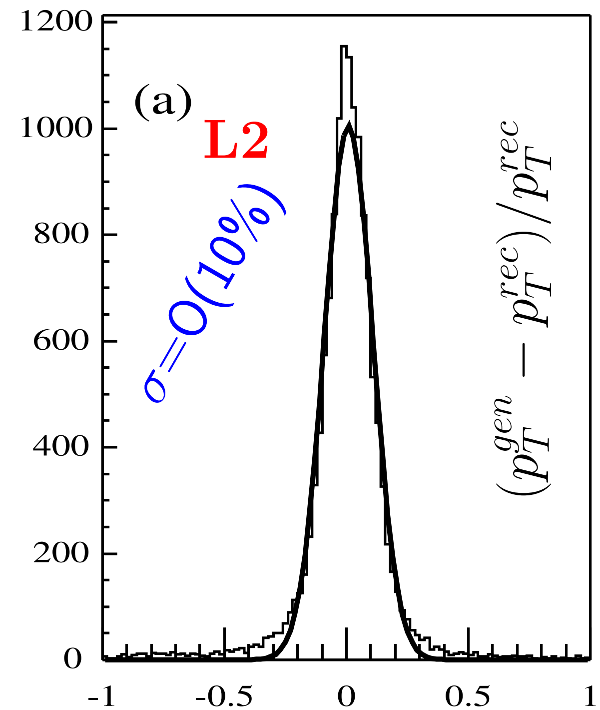
Road Search Algorithm

- the seeding is based on hits from modules on inner and outer layers of tracker
- the pattern recognition initially uses a set of pre-calculated tracjctory's $\boldsymbol{roads}$ to collect groups of hits ($\boldsymbol{clouds}$) along the seed's diretion hypothesis. The final set of compatible hits is then obtained after a subsequent cleaning of the hit collection
- The final fit is identical to the one used by CTF

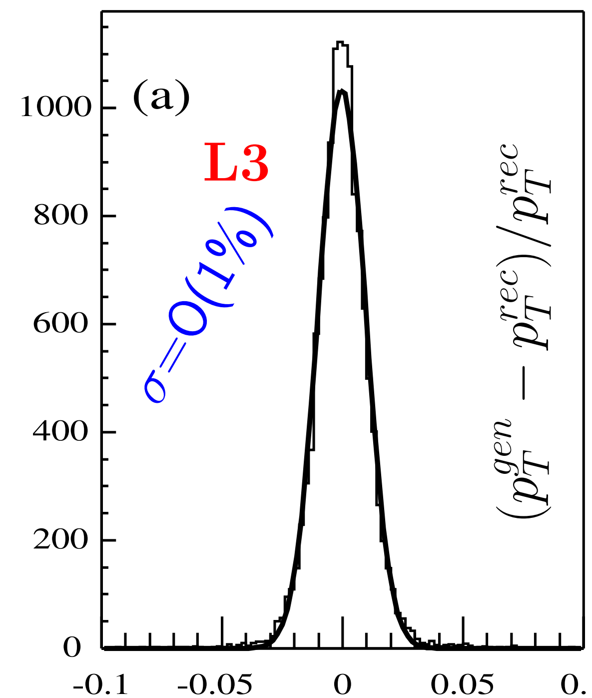
It has been demonstrated that RS reconstruction can be used at HLT (muon reconstruction) Still under active development.

Muons – reconstruction

- L2: Reconstruction in Muon System Only
  - Regional reconstruction seeded by Level-1 muon,
  - Kalman Filter Fit collecting DT/CSC/RPC segments/hits; RK-based propagation through CMS,
  - Add beam spot constraint to the fit.



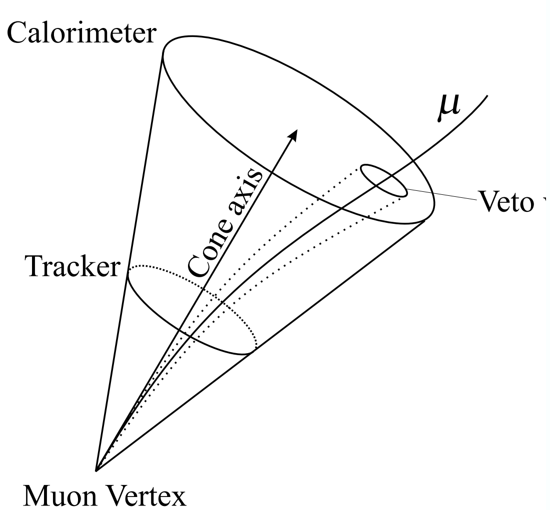
- L3: Inclusion of Tracker Data
  - Define a region of interest around L2 muon,
  - Find seeds compatible with L2 kinematic requirements; Seeds are formed by pairs of pixel hits,
  - Kalman Filter Fit in the tracker,
  - Update trajectory with hits from Muon Detector.



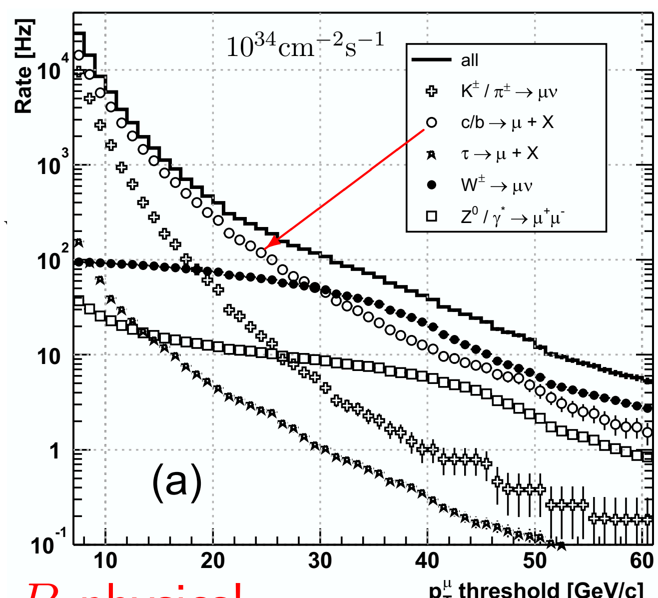
Muons – Isolation

A tool to reject muons from K, π, b, c decays which are often a background for discovery physics. Isolation is based on the ΣE_T or Σp_T in a cone around the muon.

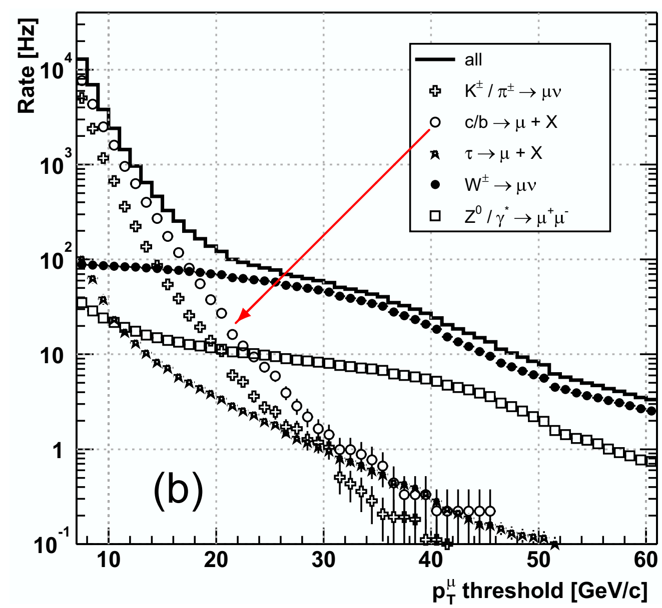
- Calorimeter Isolation
  E_T in calorimeter towers. Can be applied already at L2. Sensitive to pile-up
- Tracker Isolation
  Σp_T of tracks around L3 muon. Tracks from simplified Pixel Detector based reconstruction or Full Tracker reconstruction (regional and partial)



Before Isolation



After Isolation

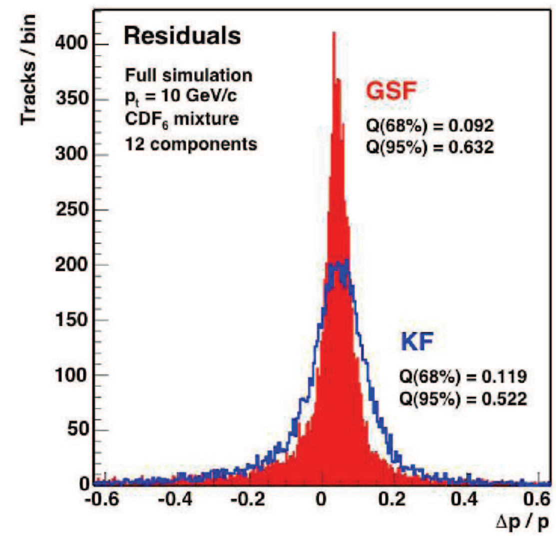


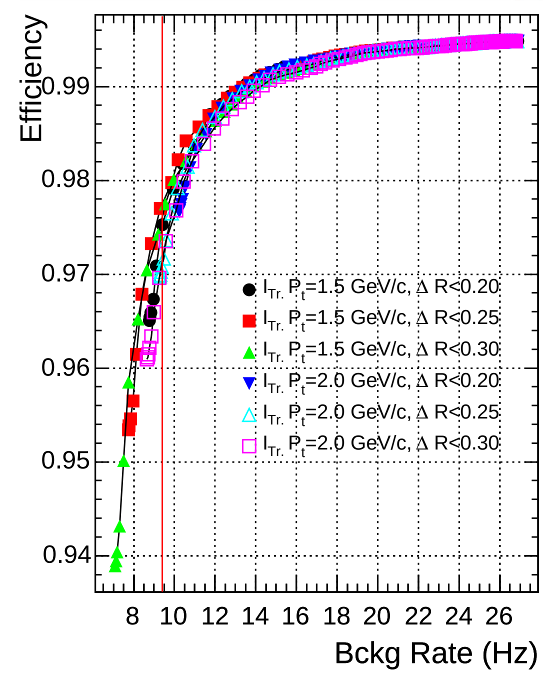
Isolation cuts are against B physics!

electron tracking for HLT

- L2.5: energy deposit (super-cluster) and its position in Calorimeter ($\rightarrow \eta, p_T$) are used to propagate electron state towards vertex. Hits found in first pixel layer constraint prediction in second one. If two hits are found the L2 e/γ object is identified as electron. non-standard hit pair finder

- L3: full electron track reconstruction with KF at HLT.
  For offline Gaussian Sum Filter (GSF) is used. GSF is a nonlinear generalization of KF in which distribution of all state vectors and errors are Gaussian mixtures. (→ W. Adam, Vertex 2006)
  Furthermore tracker (and HCAL) isolation cuts are added to find isolated electrons. Regional KF track reconstruction is used.
  isolation: $\Delta R > 0.2$, $p_T^{track} > 1.5GeV$, $\sum p_T^{cone}/p_T^{ele} < 0.06$,
  $\Rightarrow effic(W \rightarrow e\nu) \approx 0.97 - 0.98$

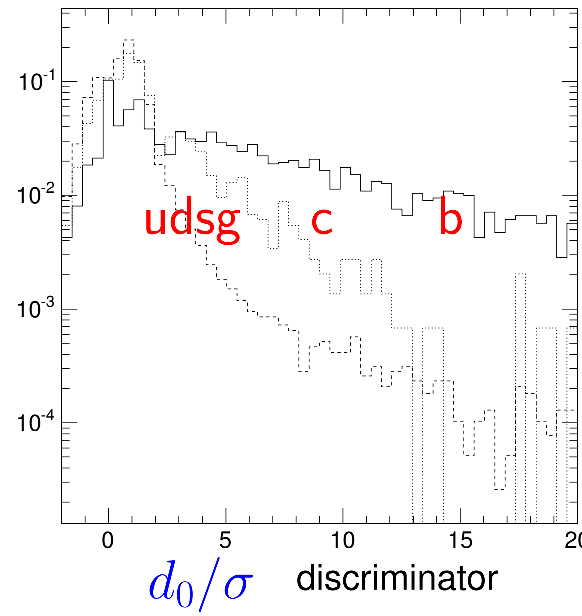




track based b-tagging for HLT

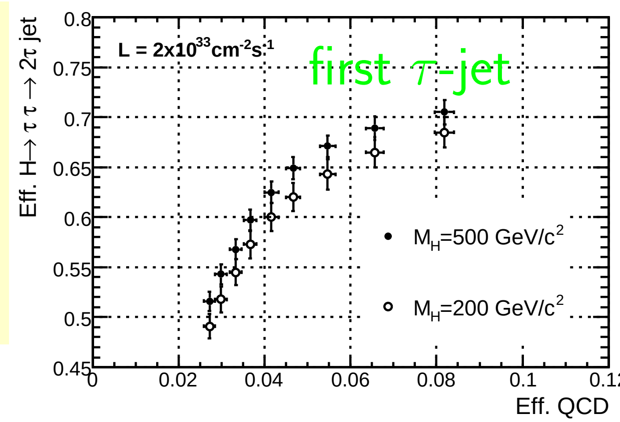
several b-tagging techniques (***track counting b-tag, probability b-tag,*** $b \to \mu$ ***tag, SV b-tag***) developed. All are based on precise measurements of 3D signed impact parameter (d_0). The candidate for HLT is ***track counting b-tag***:

- L2.5 proto tracks (3 hits) are found with PV reconstruction. Jet is tagged as b-jet if it has associated at least two track from PV with $d_0/\sigma > 3.5$. (approx. 18 ms/ev)
- L3 tracks are reconstructed with $\Delta R = 0.25$ around L2.5 jets. Stop partial track rec after 8 hits. Event is selected it at least one jest is found with two tracks with $d0/\sigma > 6$ (approx 300 msec/ev).



track based τ-tagging for HLT

- (Calo-Pixel) L2.5 proto tracks (3 hits) are found with PV reconstruction. Select leading track ($p_T > 3GeV$) compatible with jet direction ($\Delta R < 0.1$). Check for tracks in signal ($\Delta R < 0.07$) and isolation cone ($\Delta R < 0.2 - 0.6$).
- L3 track isolation with leading track $p_T > 6GeV$.



Final comments and conclusions

- Tracking algorithms are used for muon, electron, b-tag and τ-tag analysis.
- The baseline track reconstruction for HLT is using seeding from fast pixel-based reconstruction
- The pixel-based reconstruction provides not only seeds for CTF but also primary vertex reconstruction for HLT and proto tracks for simplified analysis.
- Work is ongoing to improve regionality of track reconstruction (hit reconstruction and detector data unpacking) and thus full track reconstruction timing.

- HLT algorithms and example trigger tables are prepared; The timing estimated for initial luminosity matches required 40 ms/ev
- CMS is actively preparing for data taking

I would like to thank the Organizers for invitation to VERTEX 2007