Simulating the performance of a p_T tracking trigger for CMS

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CMS Collaboration

Workshop on Intelligent Trackers, 2010

Introduction

A fair overview has been presented this morning...

By now you know,

- The CMS detector was designed for ∼10 years operation at a luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$.
- The majority of the detector will perform well at the sLHC upgrade luminosity (up to $10^{35}\text{cm}^{-2}\text{s}^{-1}$).

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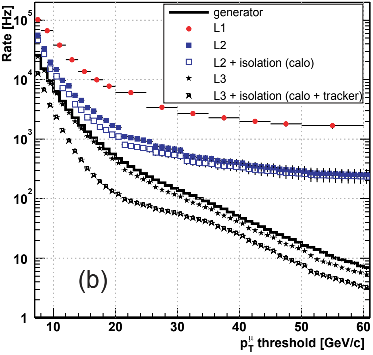
- The CMS detector was designed for ∼10 years operation at a luminosity of $10^{34}cm^{-2}s^{-1}$.
- The majority of the detector will perform well at the sLHC upgrade luminosity (up to $10^{35}cm^{-2}s^{-1}$).
- **Complete replacement of the tracking system will be required to survive the increased radiation environment and occupancies.**
- **Online trigger (L1) must continue to operate with a maximum 100 kHz rate.**

Triggering at the sLHC

L1 trigger must offer similar or better background rejection even with increased pileup, but

- Single μ rate cannot be constrained by increasing reconstructed track transverse momentum (p_T) threshold.
- A transverse energy (E_T) cut of at least 50 GeV is required to constrain the single isolated e/γ trigger.



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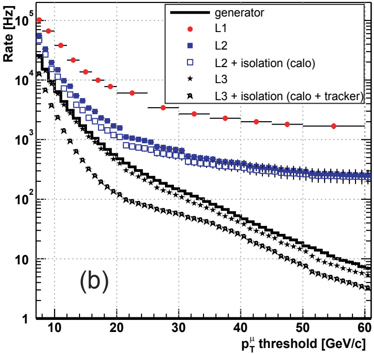

And physics performance must not be sacrificed. . .

Higher L1 thresholds will degrade sensitivity to LHC low mass discoveries.

Combined triggers risk biasing trigger strategy or important decay channels.

Stacked Tracking Concept

Solution (of course!)...

Replacement tracker should provide basic hit information to the trigger.

But how?

Enormous power requirements and limited space for cabling and cooling.

- Present tracker draws almost as much as the CMS superconducting solenoid ($\sim$15 kA)!

Constrained by huge bandwidth requirements to read out hits at 40 MHz.

- Data rates $\sim$10-20 Gbcm^{-2}s^{-1} to read out a layer at 10 cm.

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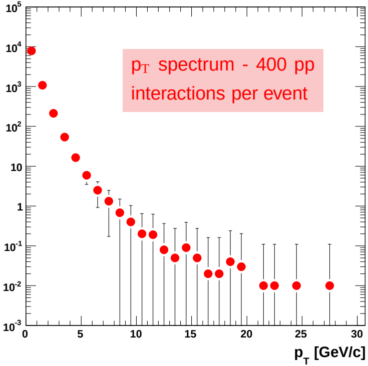
Replacement tracker should provide basic hit information to the trigger.

Tracks with transverse momentum less than 1 GeV/c are considered 'uninteresting' for physics.

- Around 85% charged tracks reaching a layer of 25 cm have p_T<1 GeV/c.
- An intelligent tracker could reduce the data bandwidth by a factor of $\sim$10 by rejecting these hits.



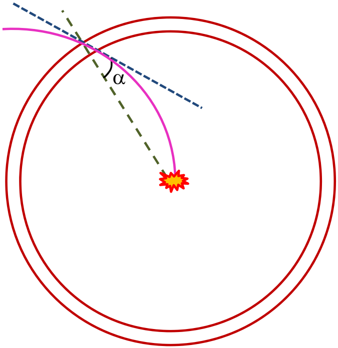
Stacked Tracking Concept

Solution (of course!). . .

Replacement tracker should provide basic hit information to the trigger.

Idea is to correlate hits between closely separated pixel sensors (**stacks**) using a simple matching algorithm

- Correlated hits can provide an effective **geometrical cut** on track p_T.
- Multiple stacks of pixels sensors allows for **track reconstruction** if correlated hits can be combined.



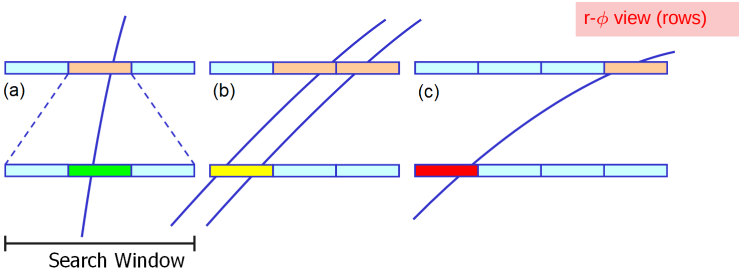
Correlation

Concept

Comparison between hit pixels on upper and lower sensors.

A successful correlation is identified as a **stub**.

- High p_T tracks can be identified if hits lie within a search window in r-ϕ (rows).
- Assumes binary readout.
- Stubs from two separate p_T layers can be correlated to obtain **tracklets**.



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Keep in mind

Correlation over a minimal number of rows (as well as columns) will permit a simpler and lower power correlation scheme.

Detector Geometry

Important to perform **realistic simulations** including material effects, interactions etc. Modifications to the current CMS geometry software allows detailed simulations of events at SLHC based on **GEANT** (or a parametrised simplification of GEANT)

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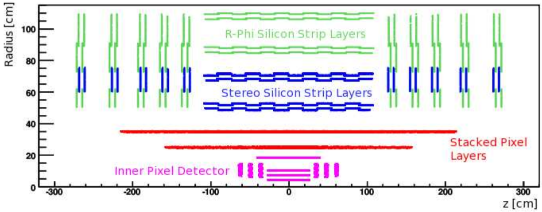
Concept geometry

Opting for the more conservative two stack layer geometry to help characterise the triggering performance of a p_T layer.



Full η coverage, layers as close as possible to IP without interfering with tracking.

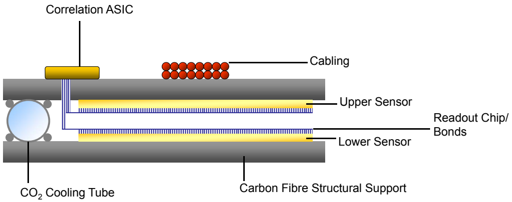
p_T Module

No definite design yet - more later this afternoon (G.Hall)

Concept design

A basic design for simulations including realistic estimates of material implemented.

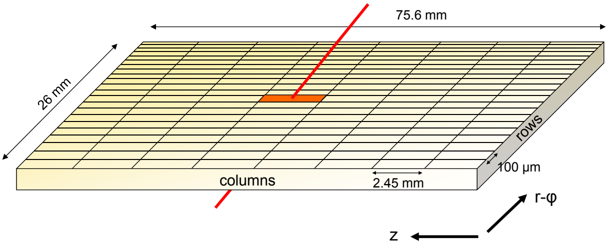
Includes provisions for cabling, cooling and structural support so that material interactions and impact on tracking performance is taken into account.



p_T Module

Sensor granularity will be constrained by power/bandwidth limitations.

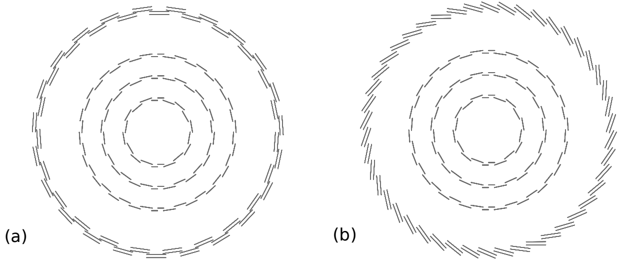
- r-ϕ pitch of less than **100 μm** is unlikely while wider pixels reduce p_T discrimination ability.
- z pitch can be increased (macro-pixels) but lower limit is determined by luminous region; **2.45 mm** for a sensor separation of 2 mm and layer radius of 25 cm. Occupancy remains less than 1%.



p_T Module

Should also consider,

- **Sensor Tilt** - can reduce the effect of Lorentz drift hence smaller clusters. . . better correlation? lower data rates?



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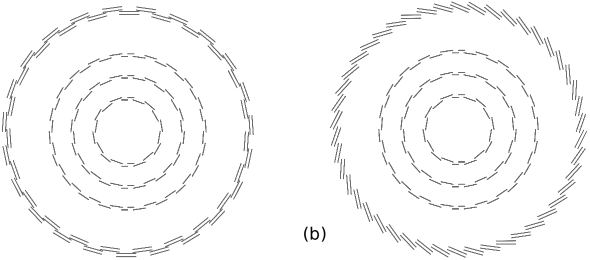

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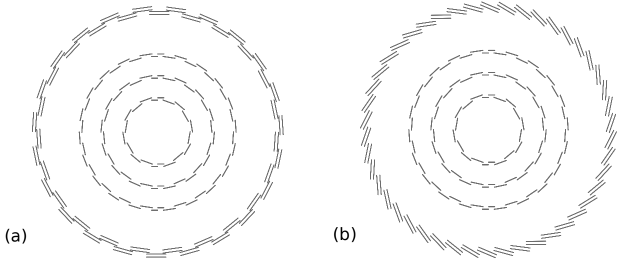

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- **Sensor Offsets** - can help match pixels in z at large η

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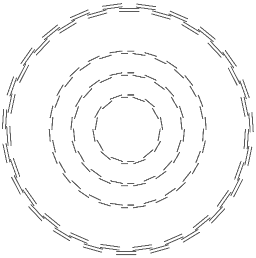

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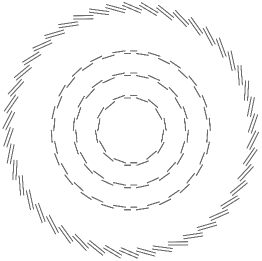

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Only a selection of the results of these simulations will be shown in the following slides...

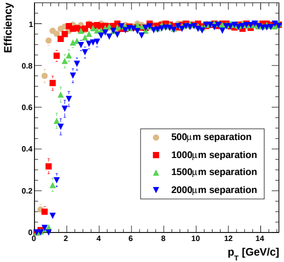
Sensor Separation vs. Correlation Window

Single $\mu^{\pm}$ efficiencies

Sensor separation allows continuous selection of cut on track p_T.

Increasing inter stack separation increases p_T threshold.

- Also increases transition region where tracks may or may not pass.
- Region width depends on pixel charge sharing, pitch, sensor thickness, sensor separation and the track impact point.



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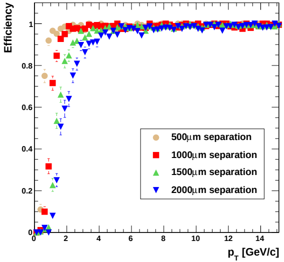
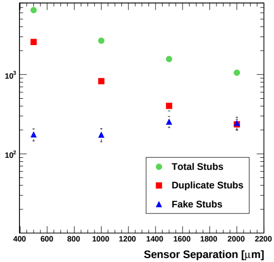
By increasing sensor separation, the p_T threshold is increased and fewer stubs are generated under SLHC pileup conditions.





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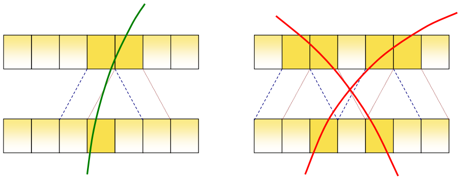
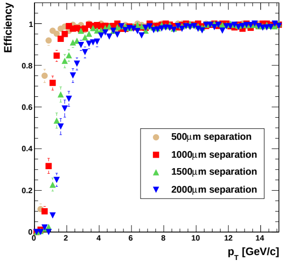
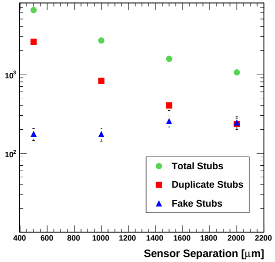
|Row Window| ≤ 1



(a) (b)

Without clustering, stubs may be duplicated (a). Incorrectly matched hits give rise to fakes (b).





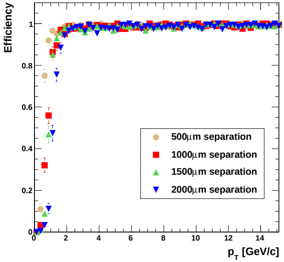
Sensor Separation vs. Correlation Window

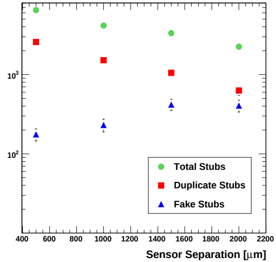
Single $\mu^{\pm}$ efficiencies

Size of correlation window can also be adjusted.
Allows discrete selection of cut on track p_T.

Window size is increased with sensor separation

- Transition region width is minimised
- Efficiency is well defined above threshold.





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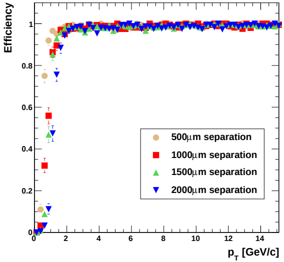
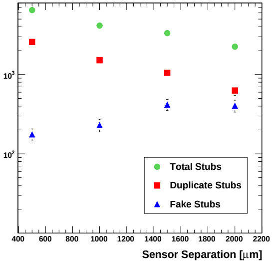
But. . .

Increasing the correlation window size increases number of generated stubs and hence data rate under SLHC pileup conditions.





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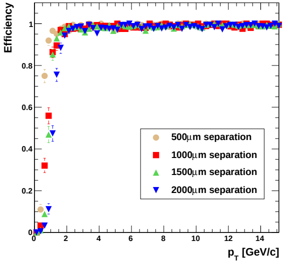
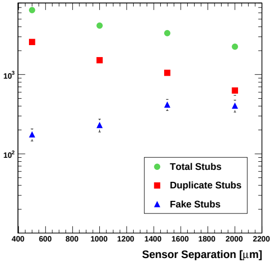
Even so,

an adjustable correlation window would be useful to change p_T cut (and control trigger data rate) during operation.





Sensor Separation vs. Correlation Window

Summary of a few results...

The table below highlights some of the important numbers from the simulations.

Sensor Separation (μm)	Row Window (pixels)	ε_{muon} $p_T>2$ GeV/c (%)	N_{Stubs}	Fake (%)	Duplicate (%)	Rate Reduction
1000	3	99.2	2670.5	6.6	30.9	22.0
1000	4	99.2	4150.9	5.6	36.6	14.2
2000	3	97.1	1054.1	23.3	22.4	54.4
2000	5	98.7	2248.3	18.1	28.0	25.5

ε_{muon} describes the efficiency of all muon tracks reaching the stacked layer with $p_T>2$ GeV/c to generate a stub.

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Tilted vs. Untilted Modules

Effect of sensor tilt

Sensors can be tilted to reduce Lorentz drift and minimise cluster size.

Tilting sensors also increases transition width

- Correlation induces small track charge bias.
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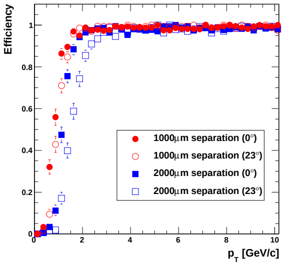

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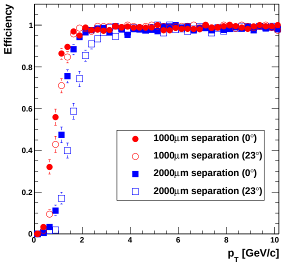

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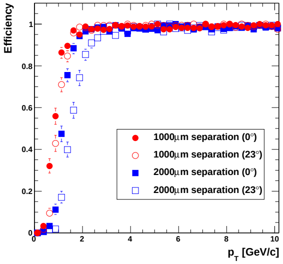


Untilted sensors probably better. . .

Unless lowest possible rate is of extreme importance, an untilted layout should be easier to implement.

- Less complex mechanics, correlation over fewer pixels.
- Offers better hit position resolution for higher level track reconstruction.
- Basic clustering on trigger data to eliminate duplicates could be possible.

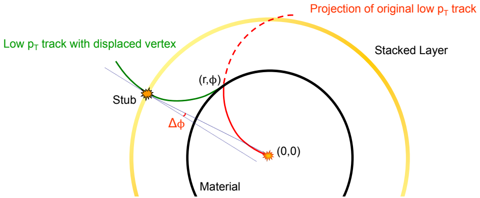
Pions, Electrons...

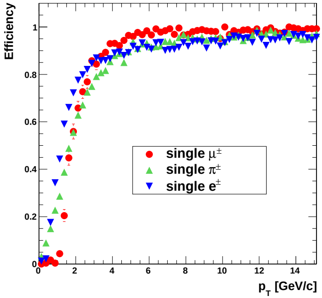
Single $\pi^{\pm}$,$e^{\pm}$ efficiencies

p_T resolution worsens for interacting particles

Inner tracker material contributes to mis-measurement of transverse momentum.

- Low p_T tracks come from secondary interactions with displaced vertex.
- High p_T electrons can radiate in material so p_T at the stack is lower.





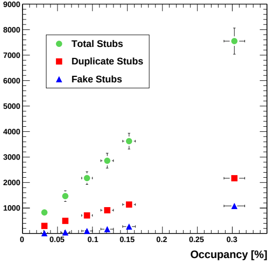
Minimum Bias Pileup

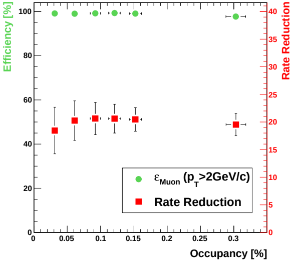
Effect of occupancy

Important to ensure correlation algorithm is robust to the range of occupancies possible at SLHC.

Simulations so far indicate that a stacked layer could operate,

- Efficiently up to an occupancy of at least 0.3%.
- With a fairly consistent rate reduction.





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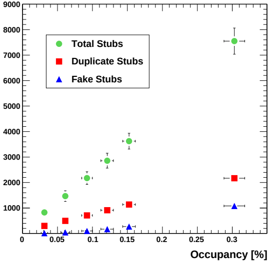
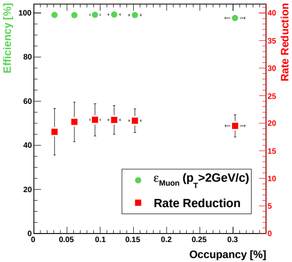
Requires further simulations for occupancies up to worst case.





Single Layer Summary

Simulations show that a stacked layer could discriminate against low p_T tracks

- Efficiently (better than 90%) up to an occupancy of at least 0.3%.
- With an adequate data rate reduction of $\sim$20.

For better operation,

- Sensors should be untilted and would benefit from simple clustering (preferably on detector).
- Material before the stacked layers should be minimised.

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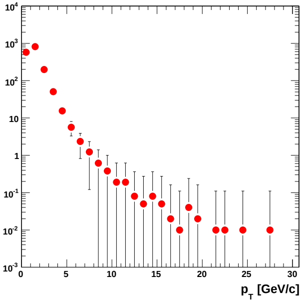


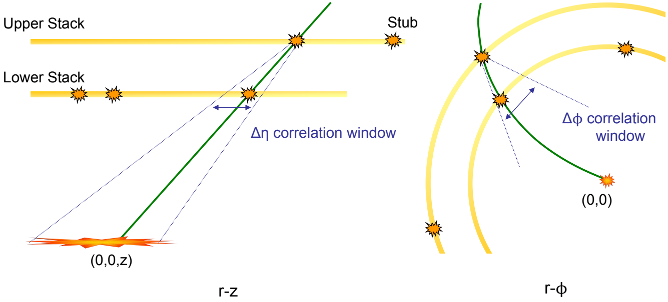
However,

A single stacked pixel layer with such a rate reduction would not be useful for a L1 trigger. With over 1000 stubs per event, every trigger tower would be matched to a tracker stub due to poor stub vector resolution. Stub p_T spectrum indicates why.

Correlation

Using two stacked layers

Correlate stubs in upper layer with stubs in lower layer to form tracklets off-detector.



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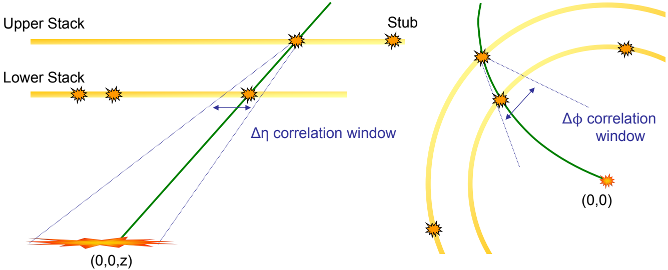

r-z

r-ϕ

Apply a cut in $\Delta\eta$ large enough to account for vertex smearing.

Apply a cut in $\Delta\phi$ large enough to allow for low p_T tracks and multiple scattering.

Correlation

Using two stacked layers

Correlate stubs in upper layer with stubs in lower layer to form tracklets off-detector.

then...

Track transverse momentum can be measured - assuming (x,y) interaction vertex is (0,0).

$$p_T = \frac{0.6\sqrt{r_1^2 + r_2^2 - 2r_1r_2\cos(\Delta\phi)}}{\sin(\Delta\phi)} \qquad (1)$$

where r_1 and r_2 are the radii in metres of the inner stack layer and outer stack layer respectively and $\Delta\phi$ is the angular separation in ϕ between the two stubs. p_T is in GeV/c.

Efficiency

Single $\mu^{\pm}$, $\pi^{\pm}$, $e^{\pm}$ efficiencies

After calculating track transverse momentum, a secondary p_T cut can be applied.

Flexibility in choice of p_T threshold in L1 firmware

- Can be trigger algorithm specific when matching to other subdetectors, e.g. electrons

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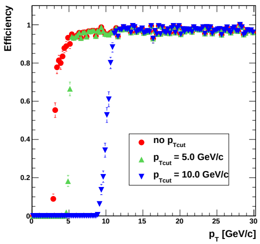
- Can be trigger algorithm specific when matching to other subdetectors, e.g. electrons

Muons



Efficiency

Single $\mu^{\pm}$, $\pi^{\pm}$, $e^{\pm}$ efficiencies

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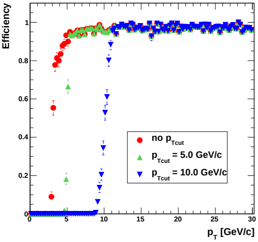
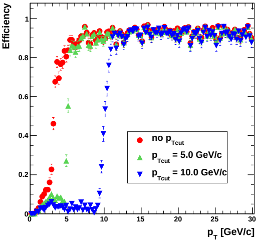


Pions



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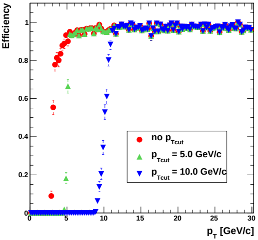

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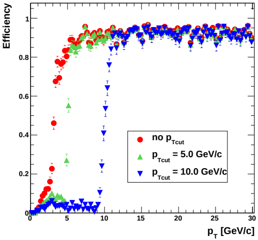
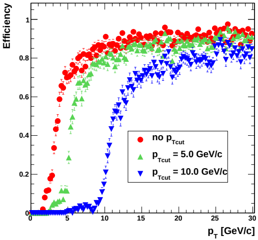


Electrons



Fake Rate

Combinatorial fakes

Matching uncorrelated stubs in each layer to form tracklets with random p_T.

Dependent on occupancy, layer correlation windows and inter-stack correlation window.

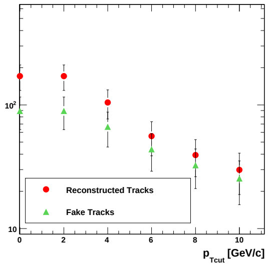
- $\sim$25 fake tracks per event after a 10 GeV/c p_T cut.

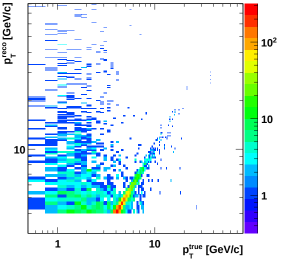
Mis-reconstructed fakes

Measurement of p_T is over-estimated due to secondary displaced vertices.

Irreducible without a third point in the reconstruction.

- $\sim$2 fake tracks per event after a 10 GeV/c p_T cut.





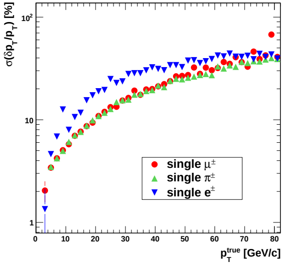
Track Reconstruction

p_T resolution

Track p_T resolution using two stack plus assumed beam spot worsens with p_T.

Performance is reasonable,

- $\sim$20% for pions and muons up to 50 GeV/c.
- Slightly worse for electrons.

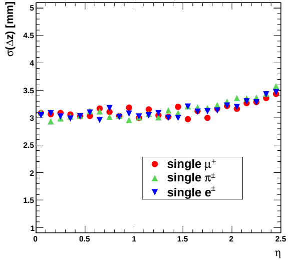


z vertex resolution

Track z vertex resolution is constant with η.

Primary vertex hard to identify,

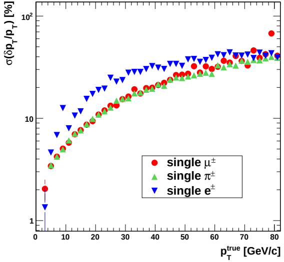
- A 3 mm resolution would include over 3 vertices every crossing.
- Determined by the pixel pitch in z.



Track Reconstruction

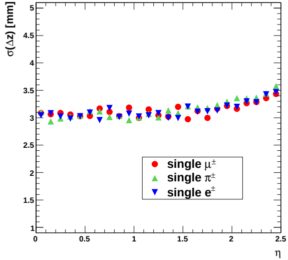
p_T resolution

Transverse momentum measurement could be used for E_T/p_T cut.
Increasing distance between layers would improve p_T resolution.



z vertex resolution

Can be improved by bringing the layers closer to the IP.
May be enough to identify a region of interest for combined trigger vertex cuts.



Track Reconstruction

$\Delta\phi$ resolution at ECAL

At the Electromagnetic Calorimeter surface, phi track resolution is better than a trigger tower.

Important so that matching of track candidates is similar to that of calorimeter trigger objects.

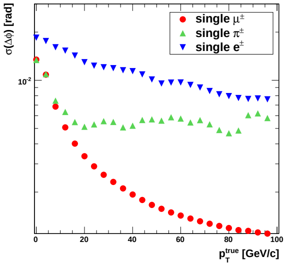
- $\sim$0.02 compared to the L1 ECAL trigger tower of $\Delta\phi$=0.087
- Worse for electrons and pions than muons.

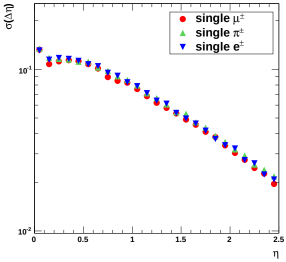
$\Delta\eta$ resolution at ECAL

At the ECAL surface, eta track resolution is worse than that of a trigger tower.

But resolution is still less than two trigger towers,

- Improves with increasing η
- Similar performance for all particles.





Summary

A realistic trigger layer has been implemented within the CMS simulation software package. The layer is also configurable. It has demonstrated that,

- On detector hit correlation is a non trivial process.
- Effects such as Lorentz drift, multiple scattering etc. are important considerations when defining the layer, e.g. tilting the sensors to reduce clusters reduces the rate but increases the algorithm complexity.

Single layer performance is good and demonstrates the viability of the stacked tracking concept but probably not viable for a L1 trigger at SLHC.

Two layers provide a good estimate of the track p_T,

- Track p_T resolution is better than 20% for $p_T < 20$ GeV/c.
- Track $\Delta\phi$ and $\Delta\eta$ resolutions for matching to ECAL trigger objects is sufficient.
- Fake background appears to be under control.

Matching with other subdetector primitives for viable L1 triggers remains to be demonstrated.