

tracking at high level trigger in CMS

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on behalf of the CMS collaboration

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introduction

CMS has a wide physics goal for Run2 [$\sqrt{s}=13$ TeV, $L \sim O(10^{34}) \text{cm}^{-2}\text{s}^{-1}$, 25 ns]

➤ BSM searches, Higgs sector (SM and BSM), SM measurement, b-physics ➡

- different physics objects
- different energy regime
- different phase-space

CMS plan for **Run2 at High Level Trigger (HLT)**

➤ **keep interesting events for physics analyses** [maximize efficiency]

➤ **keep rate under control**

➤ gain in signal efficiency and background rejection

➤ improves physics objects performance to match the offline ones
[b-tagging, lepton, object isolation, tau and jet/MET]

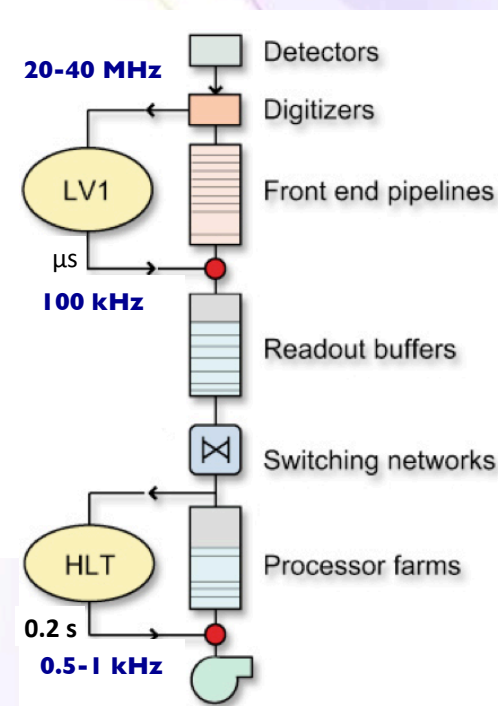
➤ **extend the usage of Particle Flow technique**
which implies **efficient** and more **precise tracking**

➤ challenge (luminosity/pileup): ➡ hits multiplicity : > 60k

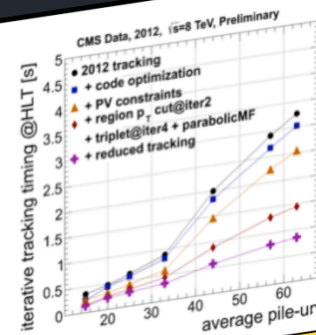
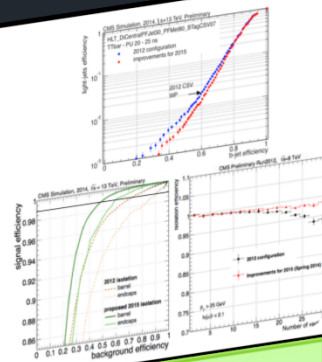
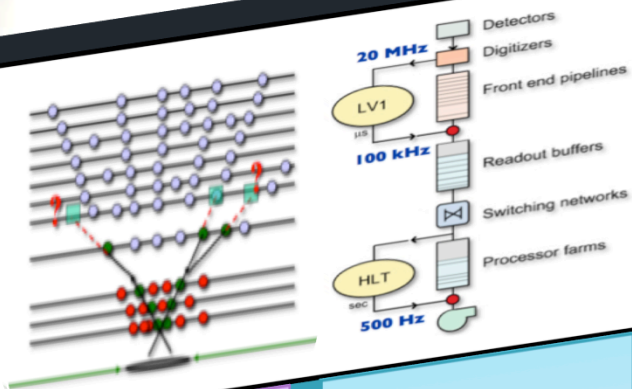
➤ **dramatic combinatorics and timing increase at very high PU**

⚠ offline reconstruction does not fit
the **online timing constraints** [200ms]

➤ technical solution:
still **keeping the same algorithm as offline**
drastically reduce tracking timing



outline



tracking

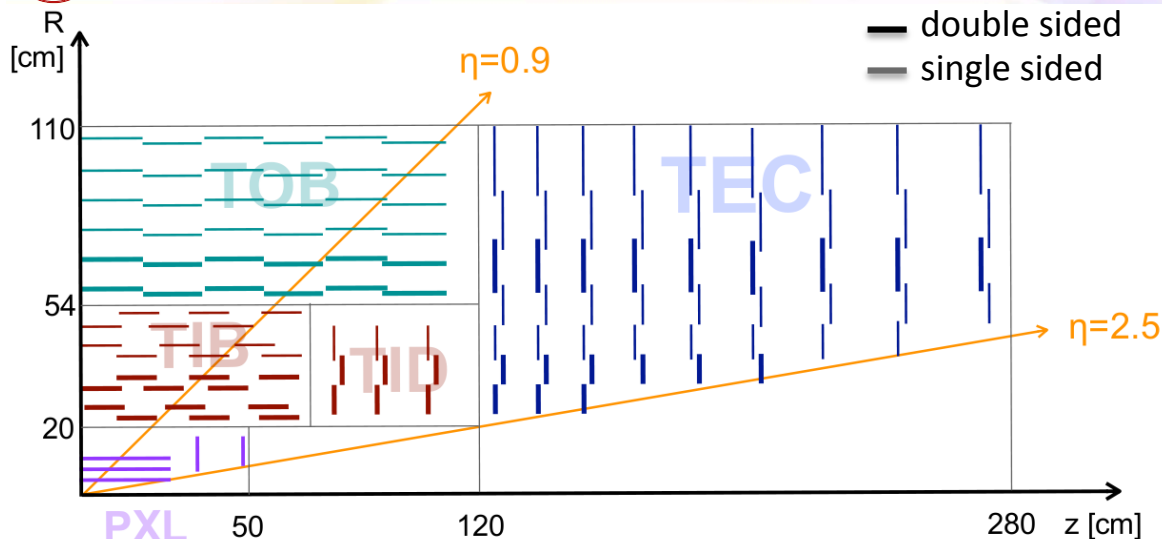
tracking and
vertexing
@HLT

physics
objects
performance

the challenge
towards
2015:
reduce timing

conclusions

CMS tracking system



largest silicon tracker ever built

- active area: $\sim 200 \text{ m}^2$
- acceptance: $|\eta| < 2.5$

Pixel detector [$100 \times 150 \text{ } \mu\text{m}^2$]:

- 3 barrel layers [$R=4.4 \text{ cm} \rightarrow 10.2 \text{ cm}$]
- 2 endcap disks
- 66M readout channels

Strip detector [pitch: $80\text{-}180 \text{ } \mu\text{m}$]:

- 10 barrel layers [$R=25.5 \text{ cm} \rightarrow 110 \text{ cm}$]
- 12 endcap disks
- 9M readout channels

pixel hits resolution: $10 \times (20, 40) \text{ } \mu\text{m}$

strip hits resolution: $(10, 40) \times (230, 530) \text{ } \mu\text{m}$

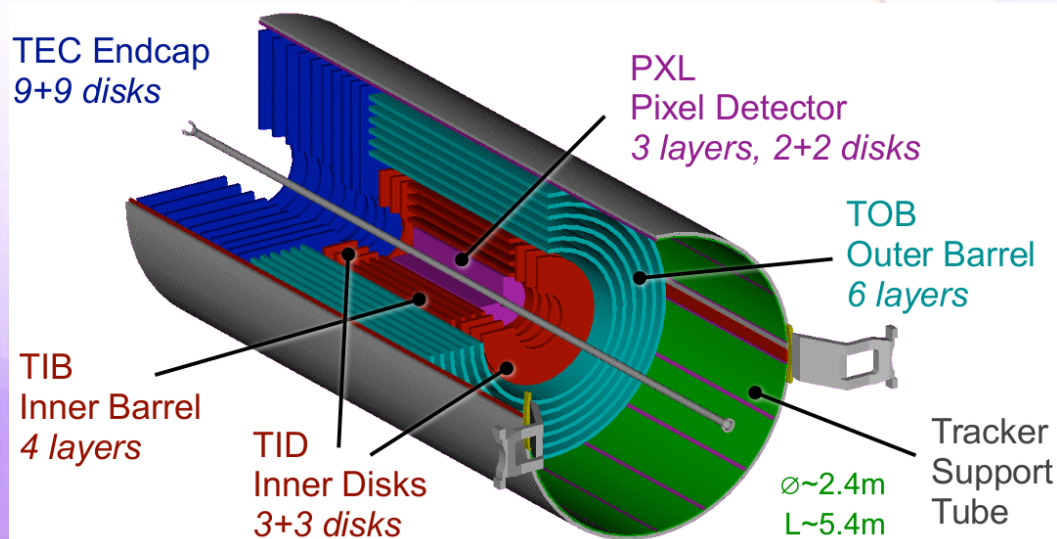
immersed in a 3.8 T magnetic field

performance:

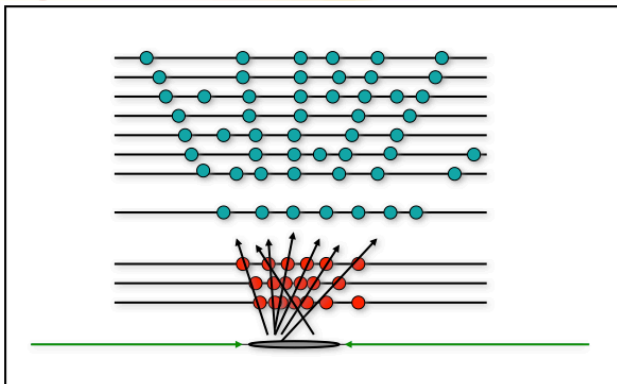
[typically ~ 15 hits per track]

$\sigma(p_T)/p_T \sim 1\text{-}2\% \text{ @ } 100 \text{ GeV}/c$

$\sigma(IP) \sim 10\text{-}20 \text{ } \mu\text{m} \text{ @ } 10\text{-}100 \text{ GeV}/c$

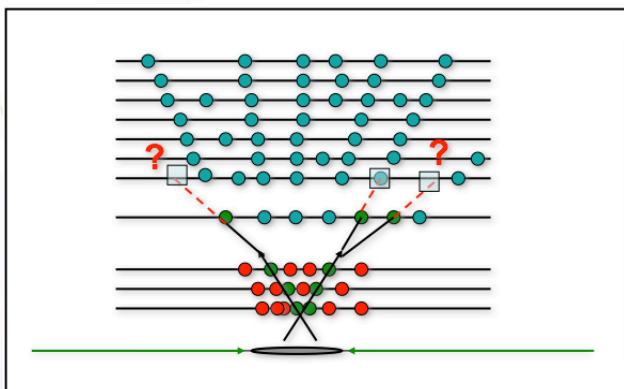


track reconstruction



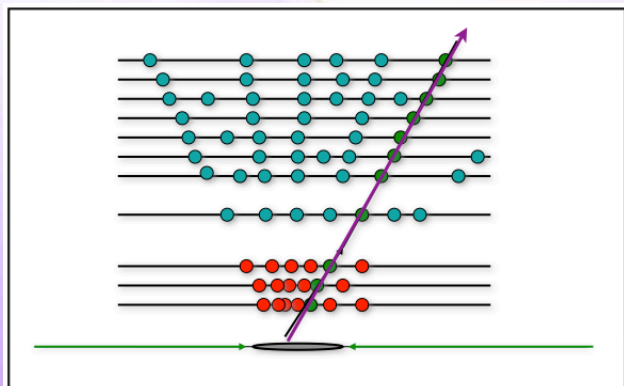
SEEDING

- starts from the pixel tracks or pixel/strip hits (triplets or pairs)
- seeds not compatible w/ the beamspot or PV are discarded



TRAJECTORY BUILDING

- each seed is propagated to the successive layers, using **Kalman Filter** or **Gaussian Sum Filter** technique [allowing for missing hits in a layer]
- propagation continues until there are no more layers or there's more than one missing hit [material effects + multiple scattering taken into account]



TRAJECTORY FITTING

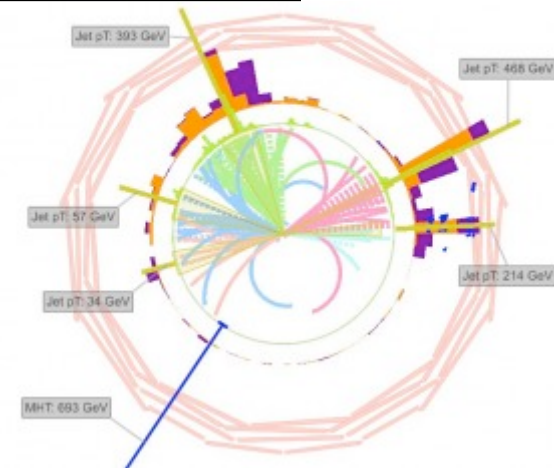
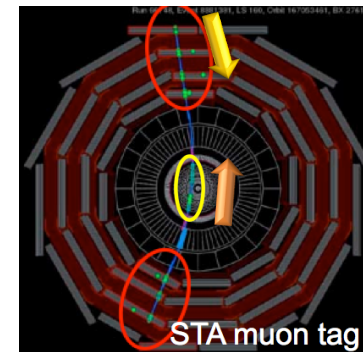
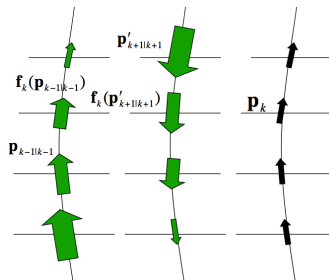
- more hits are added and the track parameters estimation is updated every time a new hit is found
- a final fit [Kalman Filter in-out+out-in] is performed to obtain the track parameters at the interaction point

tracking for trigger

several use cases for tracking at **High Level Trigger** (software)

Kalman Filter

- efficient and robust pattern recognition
- high efficiency, low fake-rate
- low contamination from spurious hits
- good track parameter resolutions
- ➔ **improve p_T resolution of muons**
hence their turn on curves [reduce fake, keeping low threshold]
- ➔ applied in a *recursive procedure* [iterative tracking]
for reconstructing the **largest number of tracks** w/in a region
 - is one of the key ingredients of the Particle Flow reconstruction
 - improves **jet/tau/MET** resolution,
 - lepton** and **photon isolation** efficiency, **b-tagging** performance

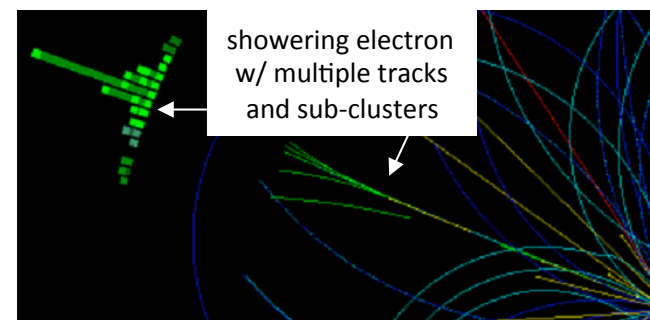
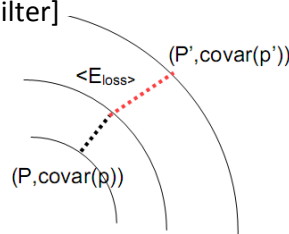


the **Iterative Tracking** reduces the combinatorics and improves both the efficiency and the fake rate

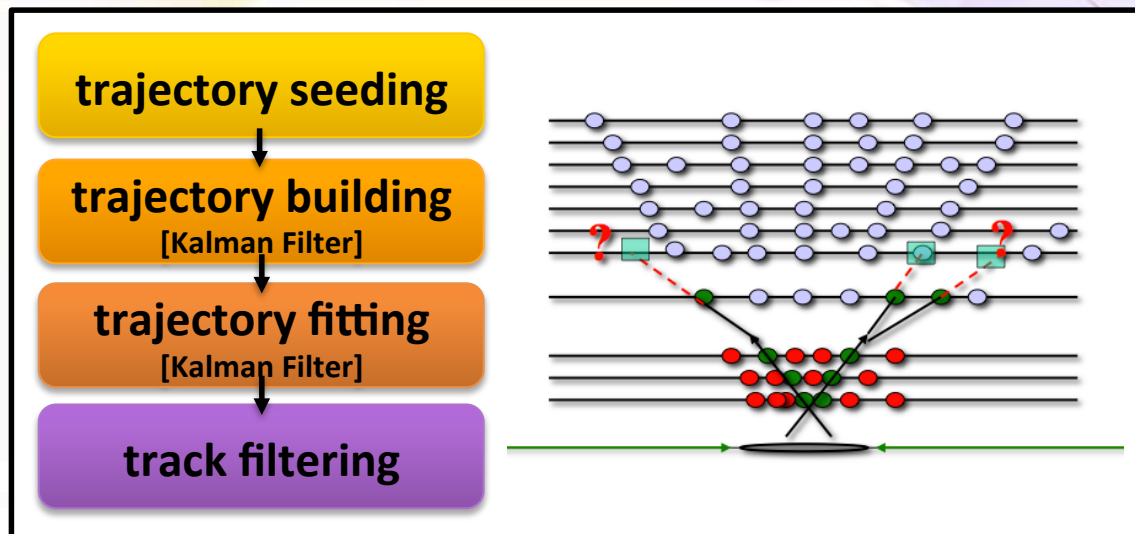
- ➔ **helps in reducing the event rate while keeping signal efficiency**

Gaussian Sum Filter [non-linear generalization of Kalman Filter]

- efficient and robust pattern recognition
- high efficiency, low fake-rate
- good track parameter resolutions
[takes into account effect of interaction w/ tracker material]
- ➔ **improve p_T resolution of electrons**
hence their turn on curves [reduce fake, keeping efficiency]



iterative tracking overview



ITERATIVE TRACKING :=

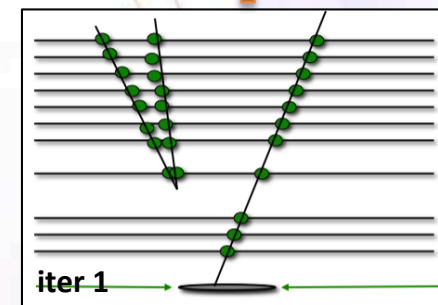
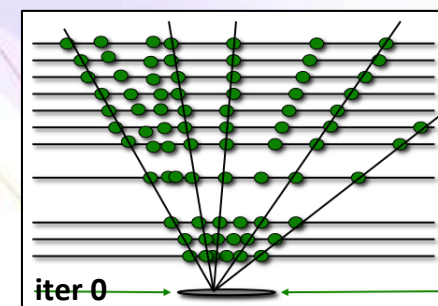
track reconstruction procedure done **iteratively**

where **each step** is meant for **reconstructing a specific subset of tracks**

(prompt, low/high p_T , displaced, ...)

- reconstruct the most energetic tracks [starting from the high p_T seeds]
- remove hits associated to reconstructed tracks
- repeat the pattern recognition w/ looser set of cuts

offline algorithms are too slow to be used online: $O(10\text{ s})$
online version have to be much faster: $O(0.2\text{ s})$



...

tracking at HLT is run only on a fraction of events in order to match the timing constraint $O(100\text{ ms})$

iterative tracking at HLT

main **differences** between **HLT** and **offline** tracking:

- **considered only region of interest**

- **Regional** \leftrightarrow **Global**

- strip clustering **OnDemand** \leftrightarrow **!OnDemand**

- **fewer iterations**

iter0: prompt tracks high p_T w/ pixelTracks [78%]

iter1: prompt tracks low p_T w/ pixel triplets [15%]

iter2: recover prompt tracks high p_T w/ pixel pairs [5%]

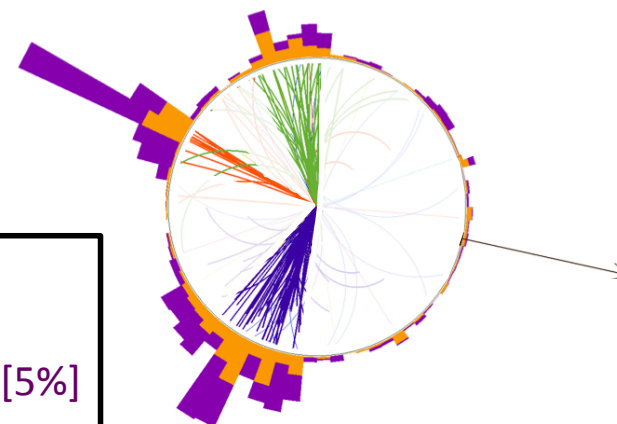
iter4(*): displaced tracks w/ strip triplets [2%]

- **seeding**

iter0 seeded by pixelTracks [instead of pixel triplets]

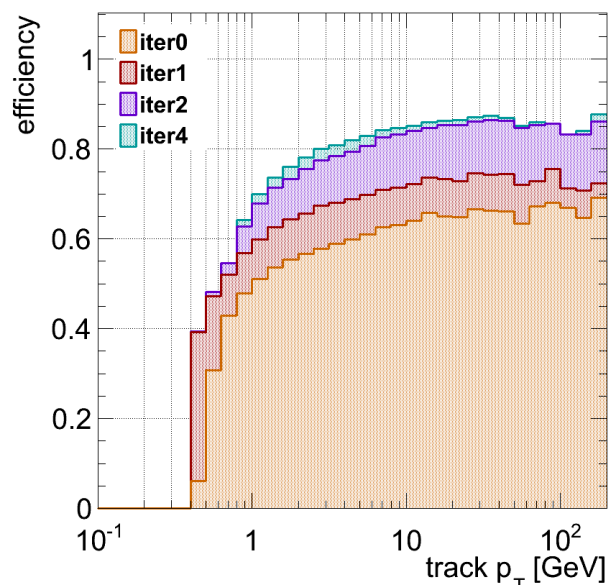
smaller number of strip layer combinations, tighter cut)

- **different builder**

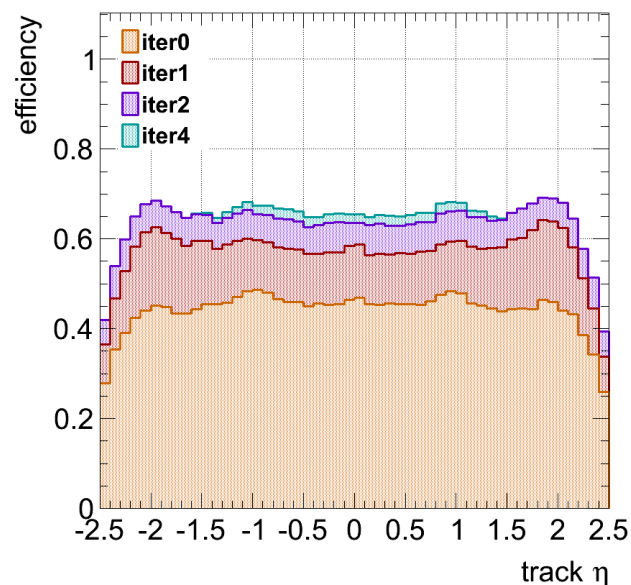


(*) iter4 in 2015 will be run only in a sub set of trigger paths where displaced tracks are needed

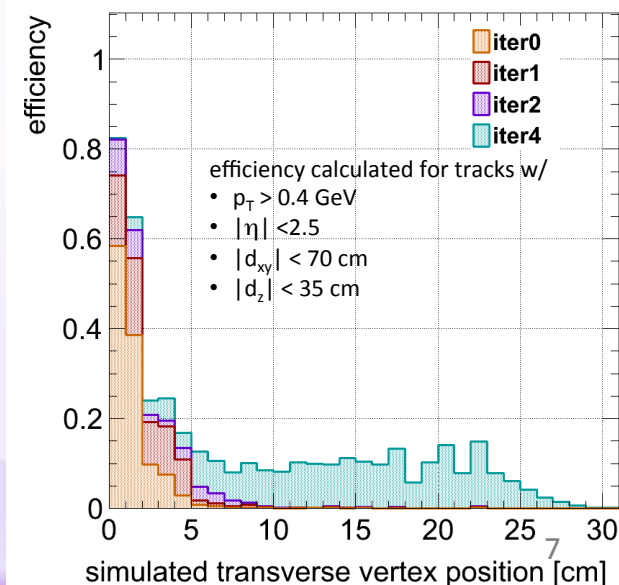
CMS Simulation, 2014, $\sqrt{s}=13$ TeV, Preliminary



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CMS Simulation, 2014, $\sqrt{s}=13$ TeV, Preliminary



effects on physics object performance

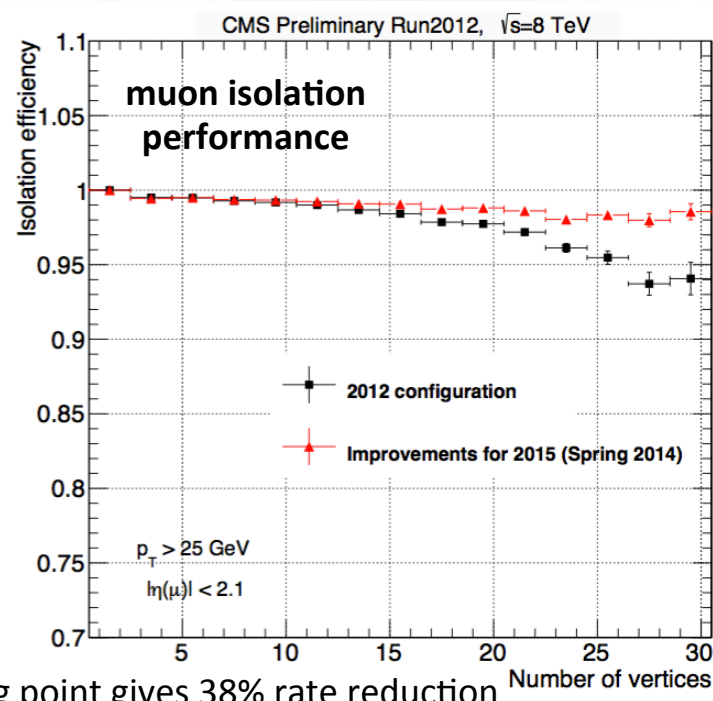
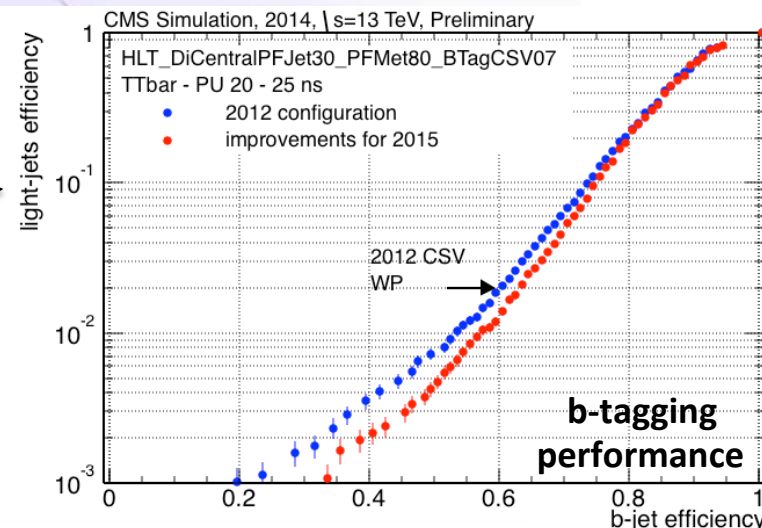
in Run2 all physics objects will exploit the iterative tracking approach

in both lepton isolation and b-tagging, **iterative tracking**

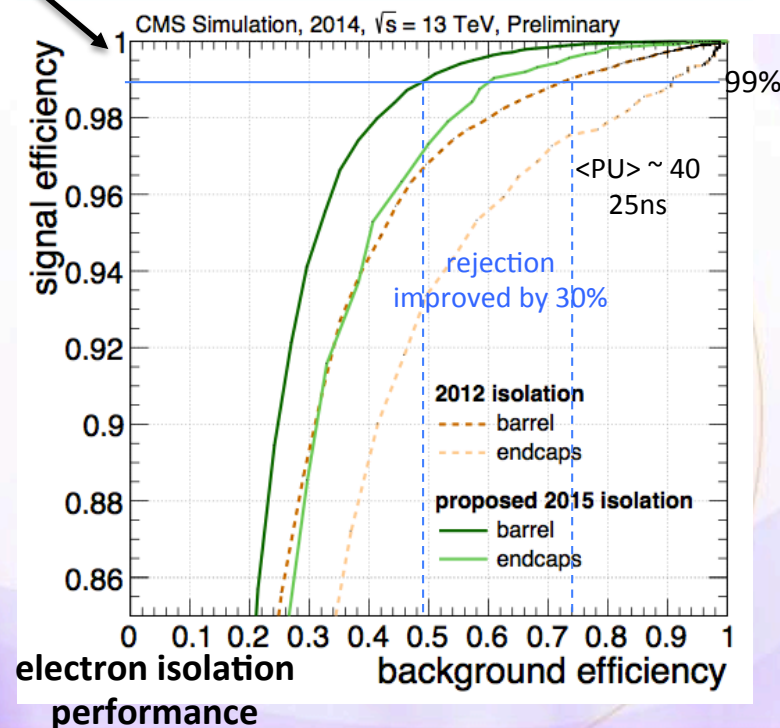
- ✓ improves signal efficiency
- ✓ improves background rejection
- ✓ improves efficiency vs PU
- ✓ reduces timing

muon isolation path gain: 40%

b-tagging path timing gain: 15%



working point gives 38% rate reduction

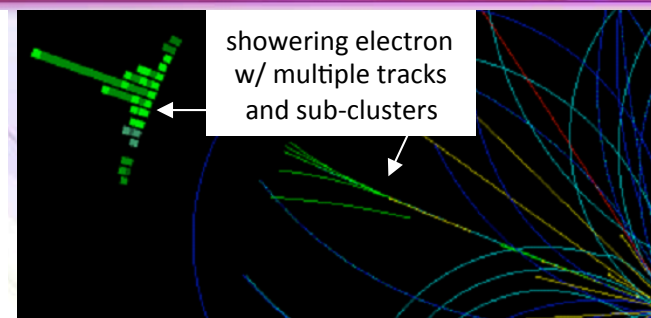
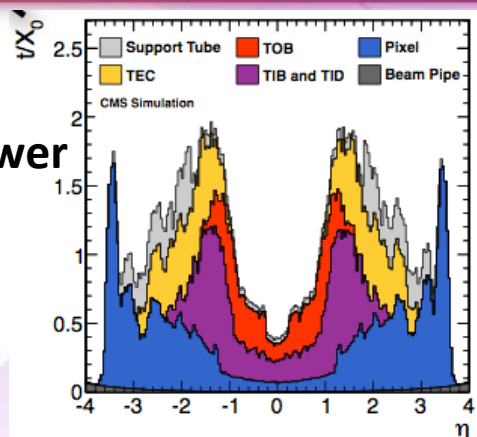


GSF tracking

at CMS

electrons frequently initiate an EM shower in the tracking system (= 0.5 to 2 X_0)

- ➡ complicating both clustering and tracking
- ➡ suffer large backgrounds from jet mis-identification

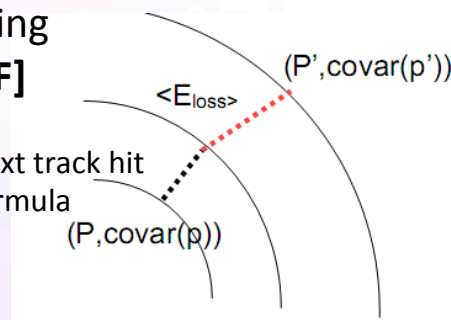


➤ take into account effect of the particle interaction

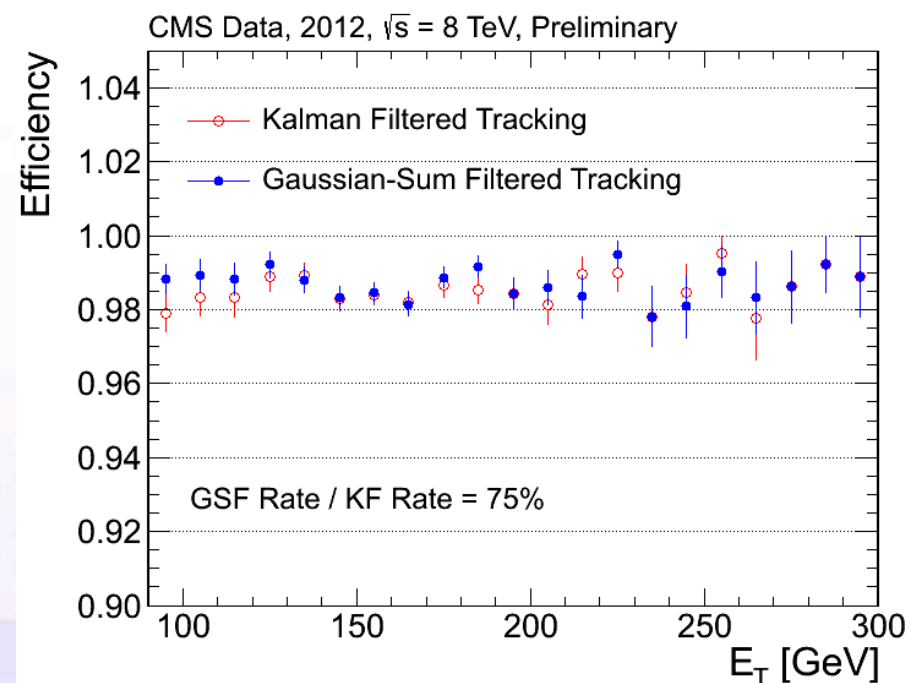
w/ tracker material by applying the **Gaussian Sum Filter [GSF]**

at each layer of material, re-estimate window to look for the next track hit based on Bethe-Heitler energy loss formula (approximated by a sum of gaussians)

- ➡ resulting GSF fit on candidate hits has track parameters varying vs R



in electron reconstruction
GSF tracking gives a **25% rate reduction** and **~0 efficiency loss w.r.t. KF** tracking

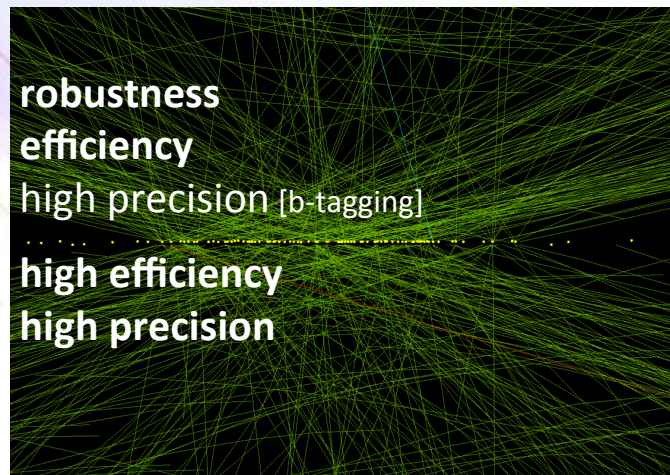


vertexing at HLT

vertexing performance crucial for physics objects performance

- **identification of the primary interaction** [primary vertex (PV)]
 - reference point for track reconstruction
 - check compatibility w/ reconstructed objects [muons, taus, jets, ..]
- **reconstruction of secondary vertex** [SV]
 - precise measurements of decay lengths/time [b-tagging]
- **estimate number of PU interactions**
- ⚠ **timing constraints**

robustness
efficiency
 high precision [b-tagging]
 high efficiency
 high precision

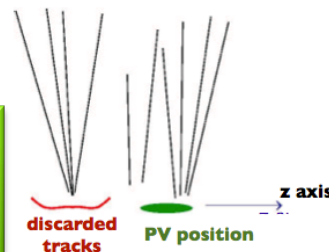


vertexing algorithms used at HLT

- **Divisive Vertex Finder 1D (z)**

clustering tracks along z

- **fast** reconstruction algorithm : ~ O(1ms)
- separation along z ~ O(0.5 mm)
- high efficiency



- **Vertex from Lepton Track**

used only for b-tagging

- **Adaptive Vertex Fitter 3D**

tracks reconstructed by the iterative tracking

w/in interesting jets

by using appropriate weights to avoid finding local minima,

annealing is performed applying a Temperature on the $\sigma(d_z)$ of tracks

$$p_{ik} = \frac{\rho_k \exp \left[-\frac{1}{T} \frac{(z_i^T - z_k^V)^2}{\sigma_i^2} \right]}{\sum_{k'} \rho_{k'} \exp \left[-\frac{1}{T} \frac{(z_i^T - z_{k'}^V)^2}{\sigma_i^2} \right]},$$

- needs full reconstructed tracks [slow]
- **mildly fast** reconstruction algorithm
- **robust** performance
- **high precision : ~O(20-30 μm)**
- **high efficiency**

vertexing at HLT: pixel PV

pixelPV **divisive vertex finder 1D (z)**

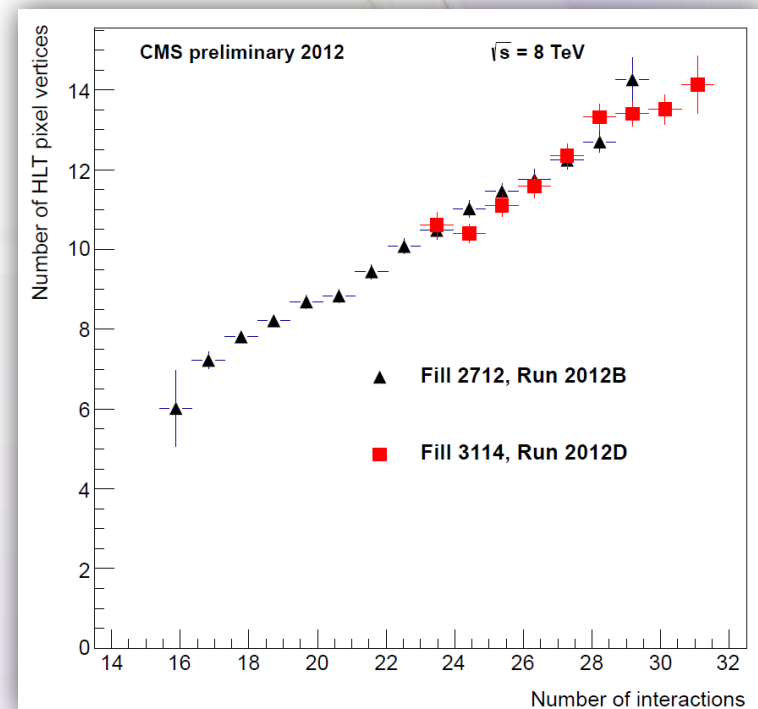
clustering pixel tracks along z

[w/ required criteria: impact parameter significance w.r.t. beam spot, number of hits, χ^2]

- **fast** reconstruction algorithm : $\sim O(1\text{ms})$
- **linearity** preserved during 2012 data taking
- separation along z $\sim O(0.5\text{ mm})$
- **robust performance** of the reconstruction **at HLT**

for further speed-up, precision and efficiency

- only **sub-set of pixel tracks** are considered
[around the already reconstructed object]
- a **constraint** is applied
 - **jet/tau/MET/photon** \rightarrow **beam spot**
 - **leptons** \rightarrow **lepton vertex**
[lepton track w/ beamspot constraint]
 - **central jet** \rightarrow **FastPV** [next slide]

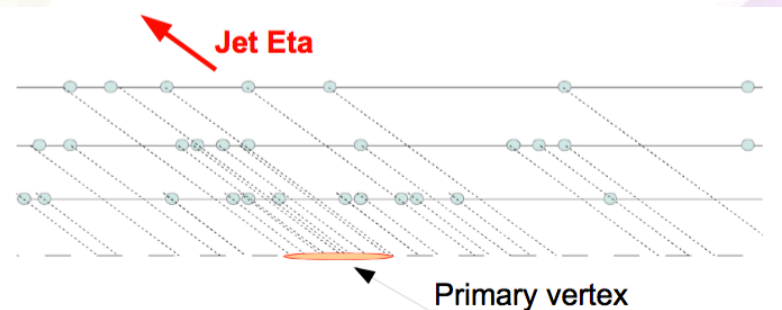


FastPV → central jet

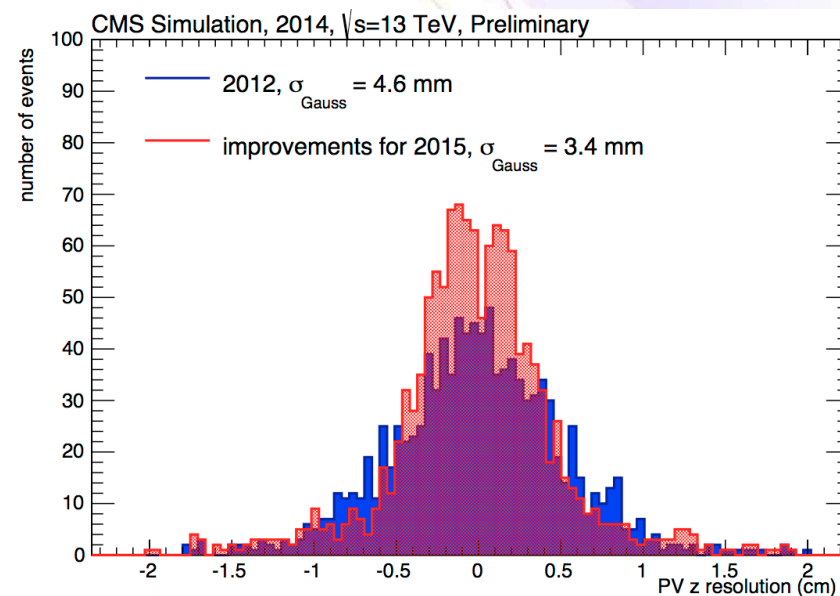
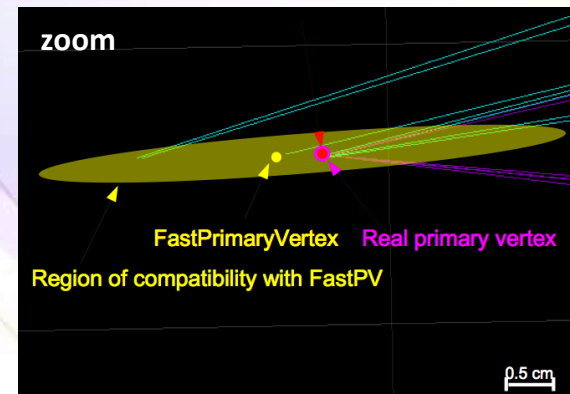
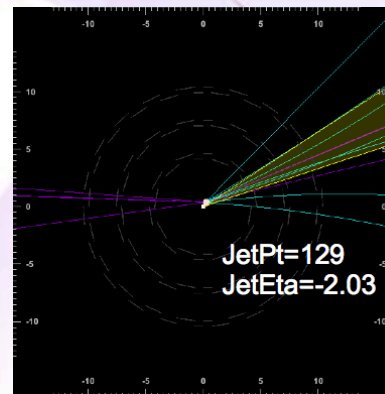
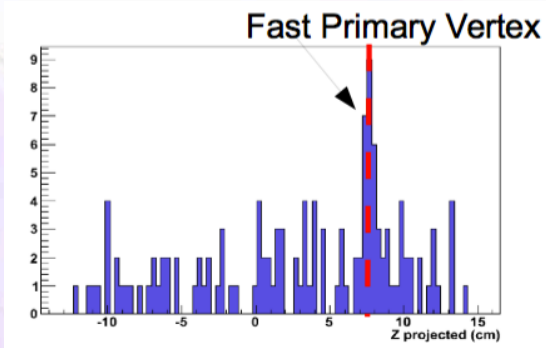
given a jet

w/in the acceptance of the tracking system $|\eta| < 2.5$

- select compatible pixel clusters along jet direction



- clusters are projected along jet direction onto z-axis
- the peak in the z position is the FastPV



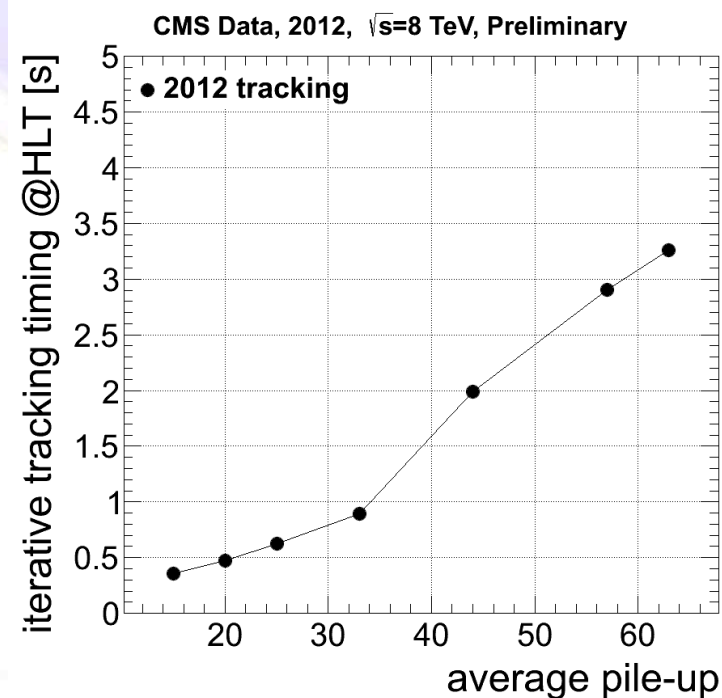
FastPV algorithm has been improved w.r.t. 2012

[extended jet acceptance, pixel end-cap clusters, regional pixel tracking]

- **very fast algorithm**
- **increase primary vertex efficiency !**
[up to 92%]

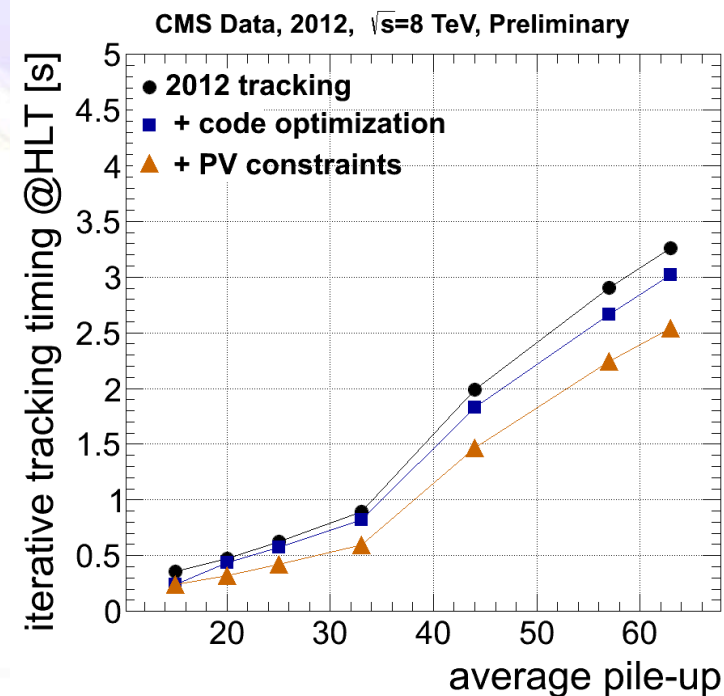
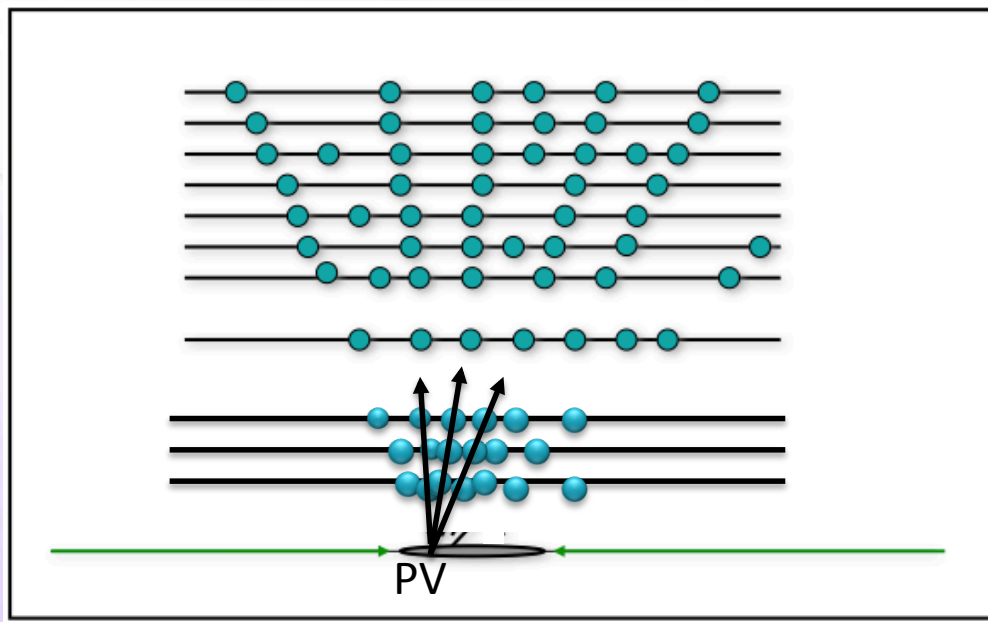
tracking timing improvements

- ✓ Iterative Tracking is the main ingredient of Particle Flow
- CMS plans to **extend the usage of Particle Flow at HLT in Run2** and to **use the iterative tracking also in lepton isolation and b-tagging**
- ⚠ there is a **large increase of timing at very high PU**
- ➡ many studies and improvements have been developed during LS1 in order to mitigate the track reconstruction timing
 - **2012 tracking**



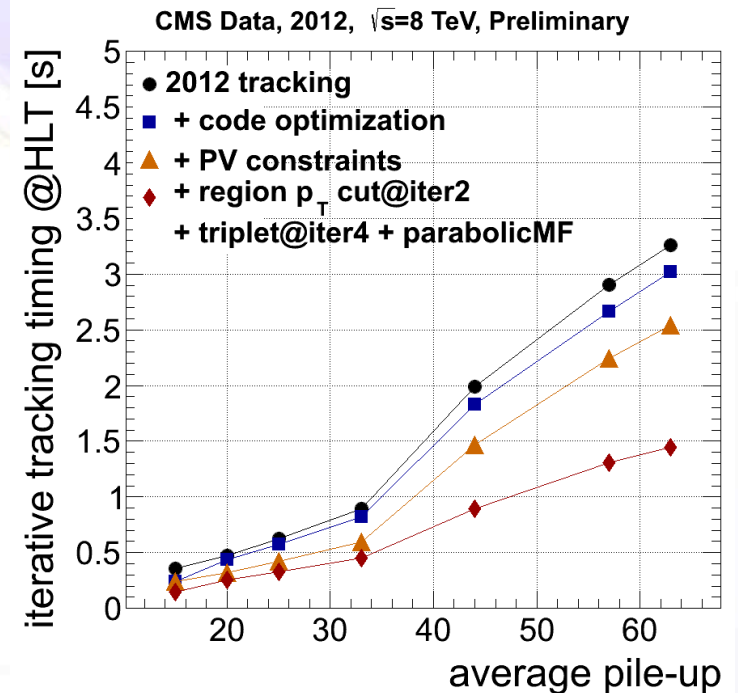
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 - **2012 tracking**
 - **code optimization** [redesign and speed up reconstruction code]
 - **PV constraint** : PV constraint also at iter0
[only pixelTracks (seed) compatible w/ PV are considered]



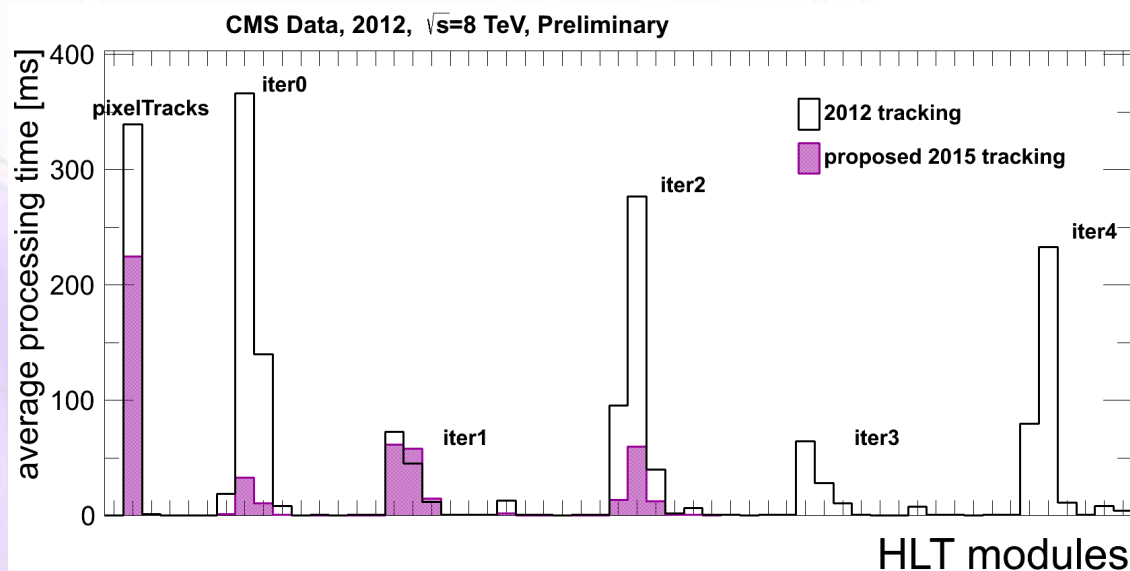
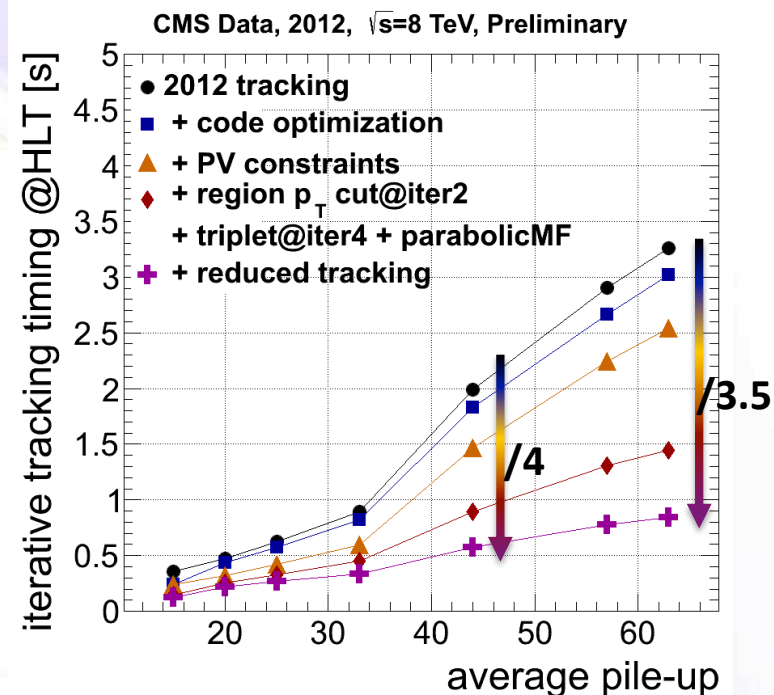
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 - **code optimization**
 - **PV constraint** : PV constraint also at iter0
 - **region p_T cuts@iter2** : tighter cut on region p_T at iter2
 - **triplet@iter4** : strip triplets instead of pairs
[mitigates the combinatorics and decrease the fake rate as well]
 - **parabolic MF** : magnetic field parameterized as a parabola
[use a parameterized magnetic field in both building and fitting step]



tracking timing improvements

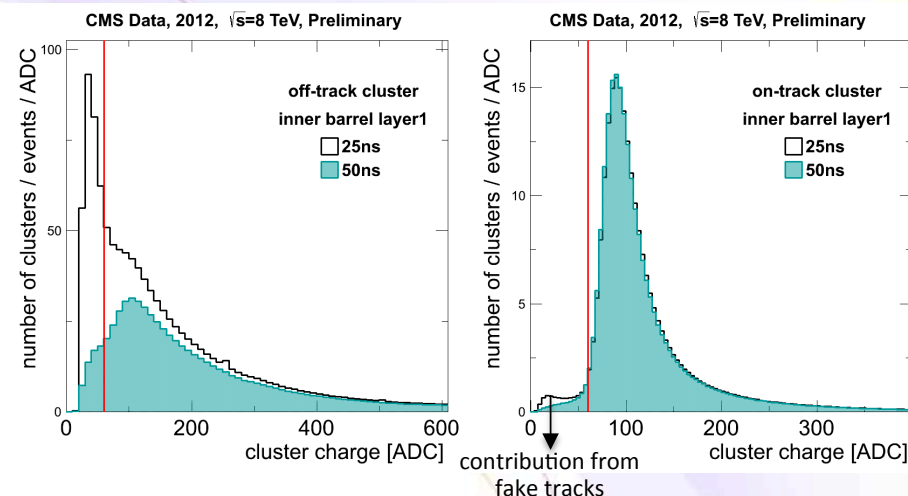
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 - **region p_T cuts@iter2** : tighter cut on region p_T at iter2
 - **triplet@iter4** : strip triplets instead of pairs
 - **parabolic MF** : magnetic field parameterized as a parabola
 - **reduced tracking** : only iter 0,1,2
- [not use iter3 and iter4 for standard track reconstruction]



what about 25ns and OOTPU ?

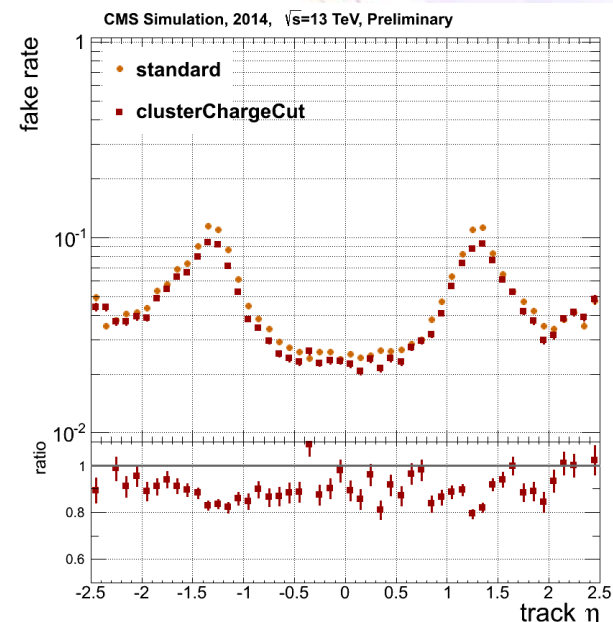
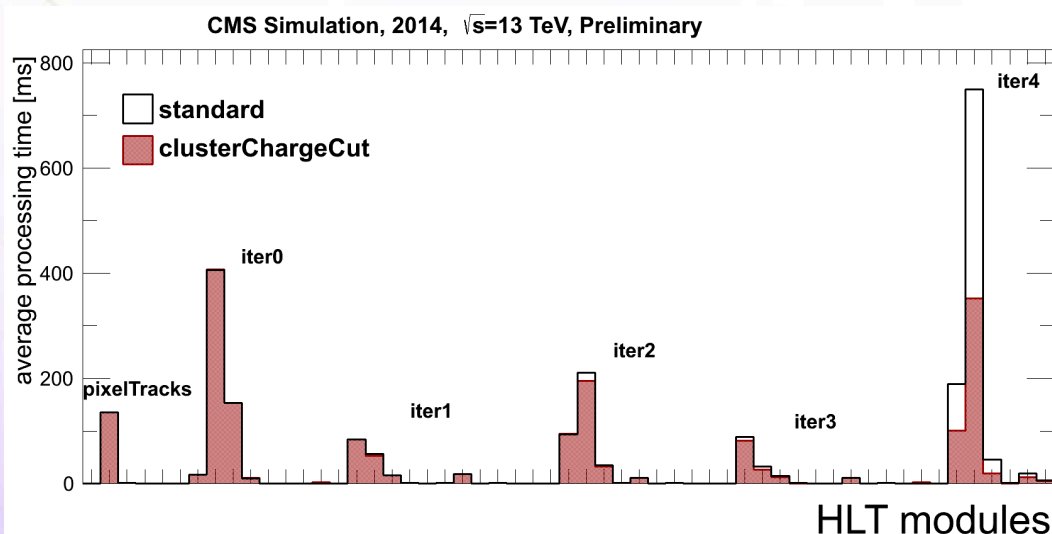
@25ns bunch spacing scheme, the **out-of-time pile-up** has a larger impact on track reconstruction

- larger cluster occupancy in the strip detector [+35%]
 ➤ w/o special tuning, tracking is longer !
- **strip cluster charge** distribution shows an excess @low value in 25ns



a **simple cut on the strip cluster charge** [red line : 60 ADC] reduces capability for fractional charged searches

- **mitigate the OOTPU effects on tracking timing and fake rate**



conclusion...

CMS plans to extend the usage of Particle Flow technique at **HLT** for Run2 and to use **tracking** also in lepton isolation and b-tagging

track and vertex reconstructions are very challenging at LHC [while guarantying the highest performance]

➤ dramatic combinatorics and timing increase at very high PU

⚠ offline reconstruction does not fit the online timing constraints

still **keeping the same algorithm as offline**

DONE drastically reduce iterative tracking timing by

- applying track reconstruction
 - at the end [after other requirements]
 - only in interesting regions
- specialized track and vertex reconstruction works very well

✓ **higher efficiency**
 ✓ **lower fake rate**
 ✓ **speed up**

tracking [3 main flavours]

1. Kalman Filter → muon

2. iterative tracking → jet, tau, MET, b-tagging, isolation

3. GSF tracking → electron

vertexing [2 main flavours]

1. pixel vertices w/ constraint [depending on the physics object]

2. vertices w/ full tracking → b-tagging

DONE tracking is widely used at HLT

- ✓ **improves physics objects performance**
 [b-tagging, lepton, tau and jet/MET]
- ✓ **gain in signal efficiency and background rejection**
 - **keep rate under control**
 - **keep interesting events for physics analyses**

this is not the end,
 further tuning and improvements will continue,
 but the main goal for trigger developments
 towards physics project goals of Run2
 has been addressed



BACKUP

GSF tracking

@CMS electrons frequently initiate an EM shower
in the tracking system ($= 0.5$ to $2 X_0$),

- ➡ complicating both clustering and tracking
- ➡ suffer large backgrounds from jet misid

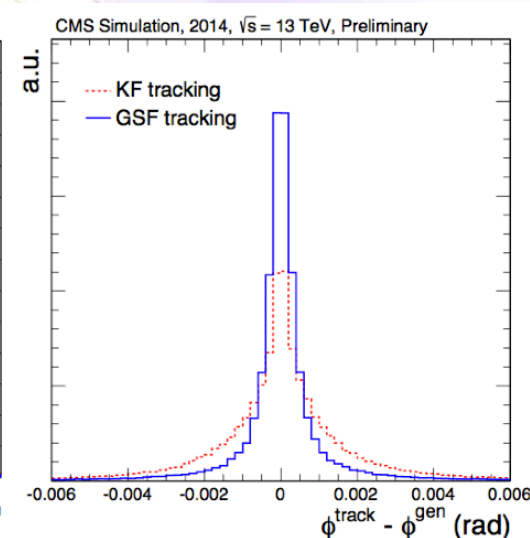
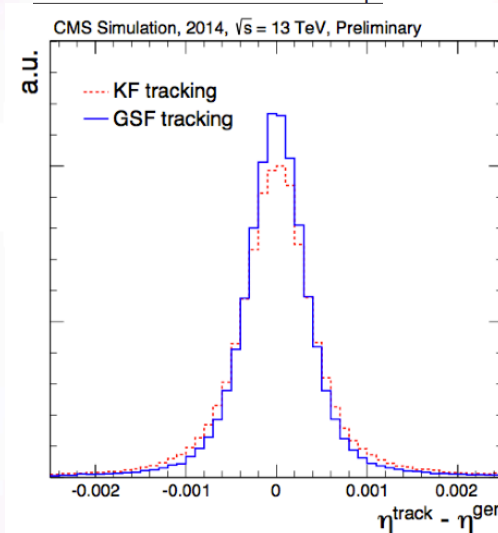
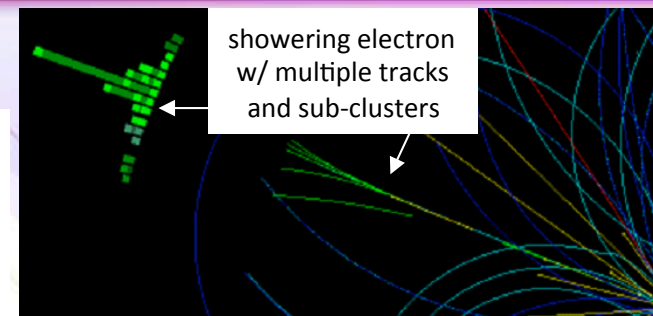
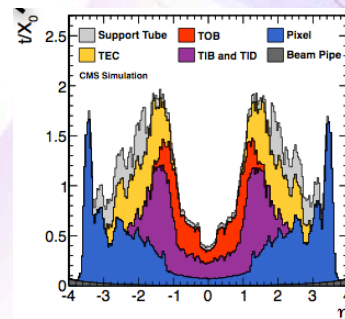
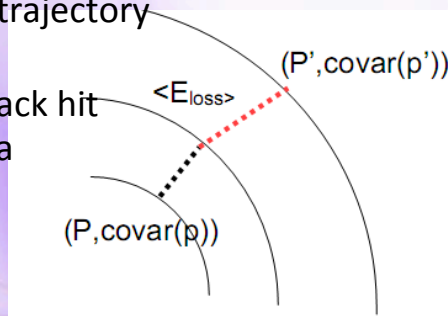
ELECTRON RECONSTRUCTION

1. find cluster-of-clusters = “Superclusters” [SC],
use primary vertex & SC centroid to define a search road
2. correct energy deposit by detector effects
[laser corrections, energy containment, ..]
3. **pixel seeding**: look for 2-3 compatible hits in the road,
build a candidate hit list from **inside to outside**
[2 charge hypotheses tested]
4. fit trajectories using GSF algorithm w/ hit lists,
keep the best one(s)
5. ~~correct electron energy for losses~~

Gaussian Sum Filter [GSF] :=

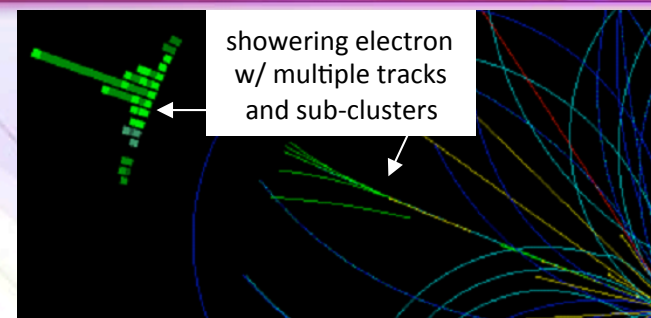
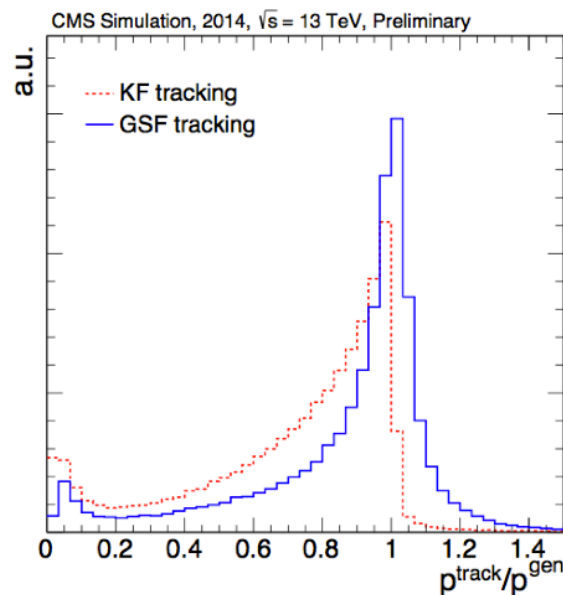
an **extended Kalman Filter [KF] tracking technique**,
which takes into account the effect of the interaction
of the tracker material w/ a particle on its trajectory
@each layer of material,
re-estimate window to look for the next track hit
based on Bethe-Heitler energy loss formula
(approximated by a **sum of gaussians**)

- ➡ resulting GSF fit on candidate hits
has **track parameters varying vs R**



in electron reconstruction
GSF tracking gives a 25% rate reduction
and ~0 efficiency loss w.r.t. KF tracking

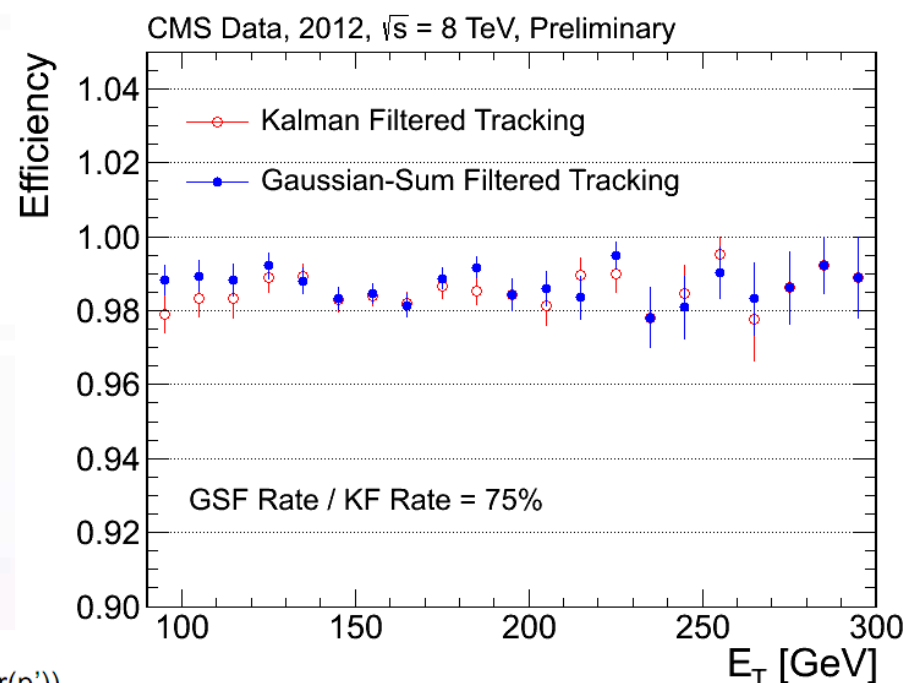
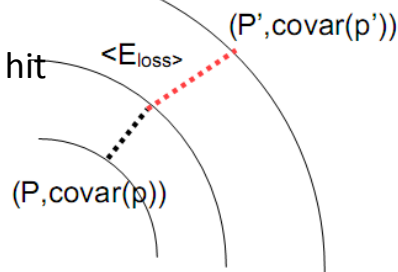
GSF tracking



Gaussian Sum Filter [GSF] :=

an **extended Kalman Filter [KF] tracking technique**, which takes into account the effect of the interaction of the tracker material w/ a particle on its trajectory @each layer of material, re-estimate window to look for the next track hit based on Bethe-Heitler energy loss formula (approximated by a **sum of gaussians**)

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in electron reconstruction
GSF tracking gives a 25% rate reduction and ~ 0 efficiency loss w.r.t. KF tracking