Study of a possible τ Trigger at Level 1 with Pixel Detector of CMS for Phase 2 Upgrade

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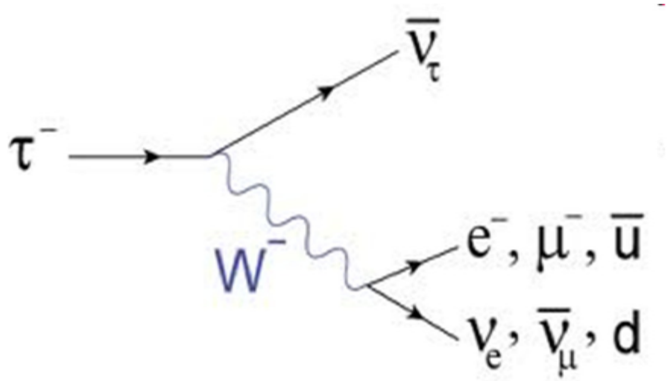
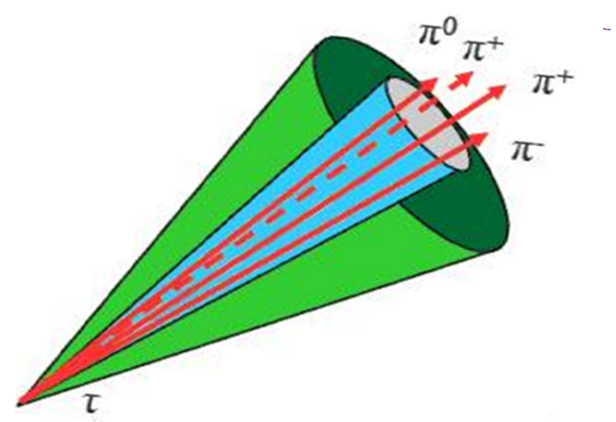
Physics motivations



Decay mode	Branching Fraction
$\tau^- \rightarrow l^- \nu_l \nu_\tau$	35.2%
$\tau^- \rightarrow$ 1 charged particle	47%
$\tau^- \rightarrow$ 3 charged particles	14.6%
Other decays	3.2%

- τ mass: 1.78 GeV/c^2
- Typical mean flight distance: few mm

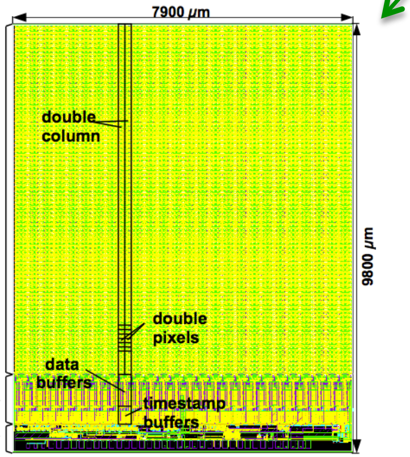


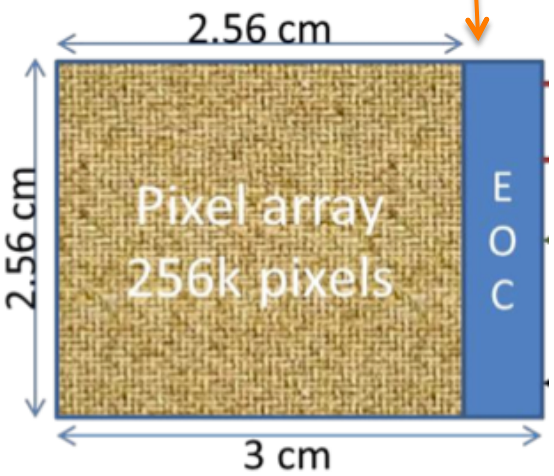
- The experimental signature of "hadronic-tau" (τ_{jet}) is a jet with a small opening cone (~ 2° for a τ with a momentum of 40 GeV/c), with one or three charged particles (prongs - π/K), one neutrino (ν_τ) and photons from π^0 .

These properties for a $\tau \rightarrow$ 3 prongs can be used to identify τ events using CMS Pixel Detector, which is not yet used for the on-line reconstruction.

New CMS Pixel Chip for Real time τ reconstruction

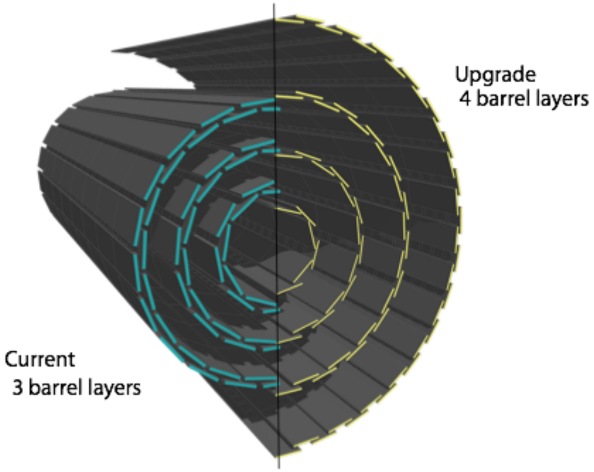
Characteristics	Current chip	New chip
Dimensions (cm x cm)	0.79 x 0.98	2.56 x 2.56
Pixel Pitch (μm x μm)	100 x 150	25 x 100





From J. Christiansen – Upgrade Week - October 2013 Trigger Performance and Strategy Working Group

CMS Pixel Barrel Detector



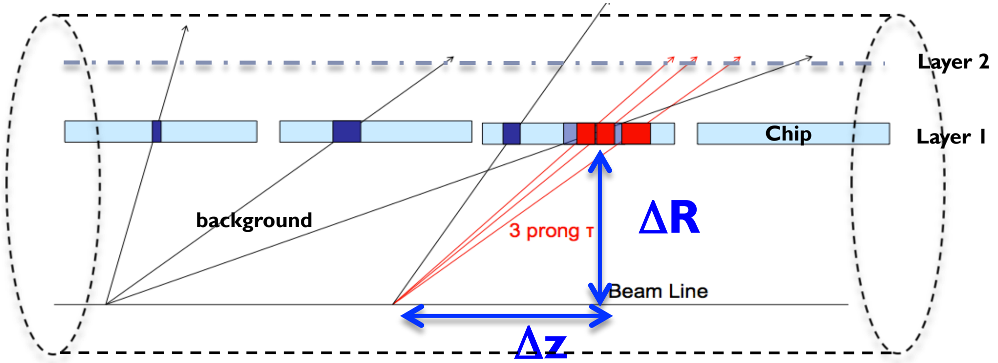
Layer	Old radius (cm)	New radius (cm)
BPIX1	4.4	3.0
BPIX2	7.3	6.8
BPIX3	10.2	10.2
BPIX4	-	16.0

- Possibility to implement a more sophisticated logic at chip level to reconstruct τ on-line
- Very stringent constraint is Readout rate: about 5 Gb/s per readout chip in total

Feasibility of a τ trigger at Level 1 using Pixel Detector

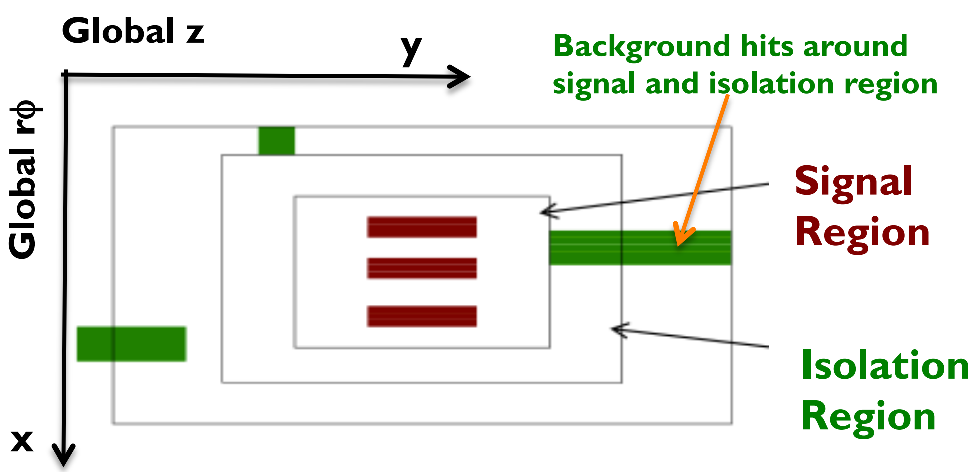
- Average decay angle of τ with transverse momentum (P_T) greater than 40 GeV/c is ~2°
  - It means that all three prongs can be found in a single chip, in fact, to keep most of τ is enough to have a signal region in the 1st Layer of diameter of 4 mm
- Expected similar cluster* size along the beam line for the prongs originated from the same vertex
- Expected 3 isolated clusters (triplet) above a given P_T threshold. Eventually merging for higher P_T.

Global Coordinate System



$$\Delta z = z_{cluster\_barycenter} - z_{\tau ProductionVertex}$$

Example picture of a τ → 3 prongs + PU events on a single chip



 * Isolated charge deposit made by one or more tracks

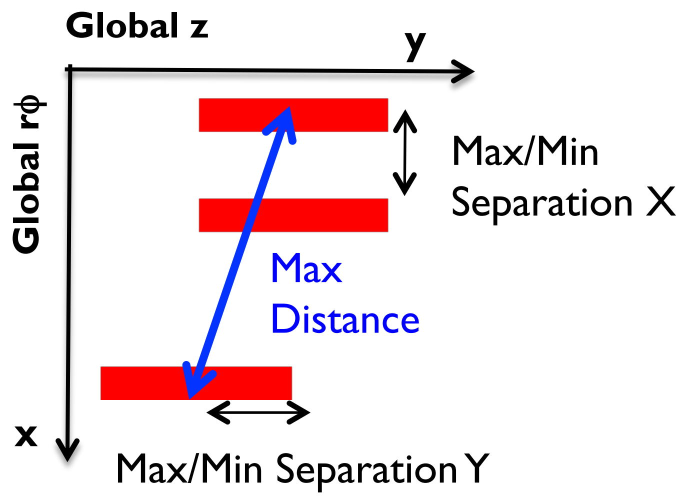
Characterization of τ trigger Algorithm

- Performance of the algorithm can be characterized by following parameters:
  - τ Detection Efficiency = ratio between # τ which are detected by the algorithm and total # τ
  - Algorithmic Efficiency = ratio between # τ decayed in a single chip, which are detected by algorithm, and total # τ decayed in single chip
  - Background rate [MHz] = 40 MHz (beam collision rate) × # of candidates accepted by the algorithm on background sample

- We optimized the algorithm to select a τ with observable P_T ($\Sigma P_T^{charged\ prong}$) ≥ 40 GeV/c, detectable in the first 3 layers in the Pixel Barrel Detector, and to maximize rejection of background .

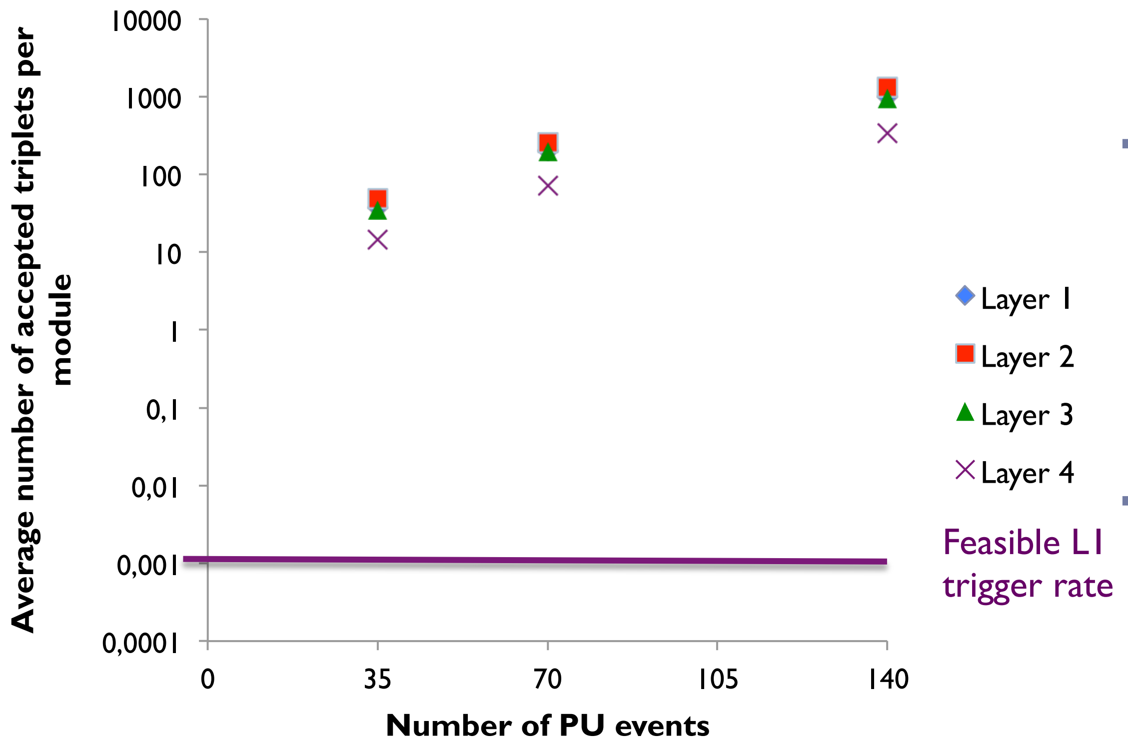
τ identification in a single chip

- The most sensitive variables to discriminate τ events from background in a single chip in a single layer are:
  - Max Cluster Size along local X and local Y (in pixel unit)
  - Min/max separation along X and Y
  - Max distance
  - Similarity on Size X and Size Y (max ΔSize ≤ 1 pixel)



- No Isolation requirements are applied due to the huge background occupancy (tracks from PU) in the Pixel Detector volume

Algorithm performance on Background events for different Pile-Up in a single chip



Algorithm applied on background samples (Minimum Bias) with 35, 70 and 140 Pile-Up

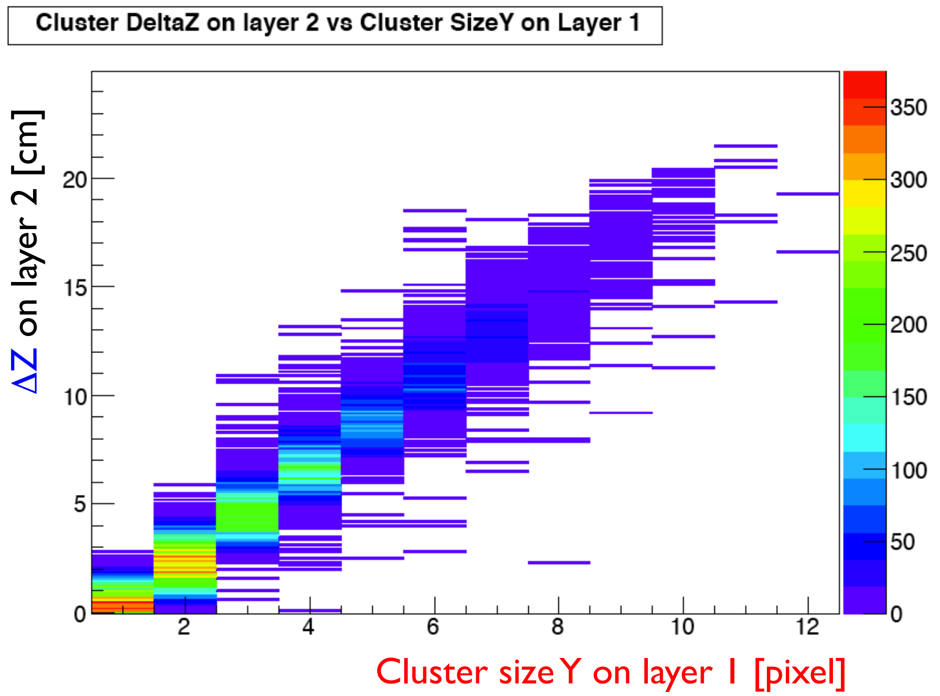
- The average number of accepted triplets increases exponentially with Pile-Up!
  - Study of background source shows that majority of fake triplets are produced by uncorrelated primary processes in high occupancy environment
- Information available in a single chip is not enough to reduce such background

Needed a combination of more layers!

τ identification combining three layers

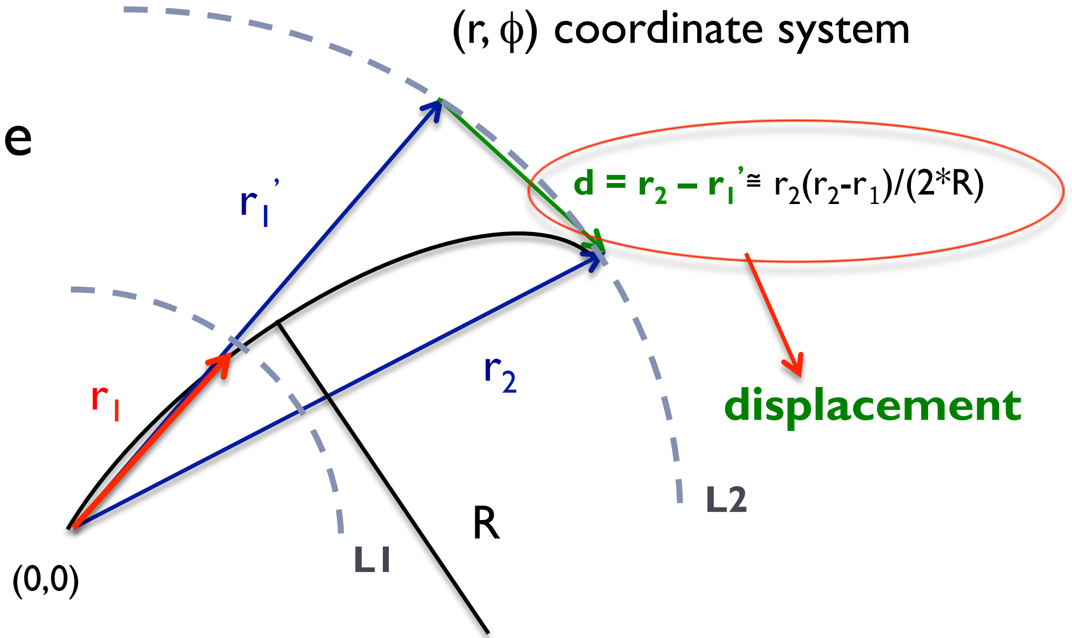
To combine the first three layers information, we started from the barycenter of a triplet selected in the 1st layer:

1. τ "pixel track" candidate is searched in a $(\Delta Z, \Delta\phi)$ region on the 2nd layer:
   - ΔZ, $\Delta\phi$ are determined:
     - ΔZ: using average cluster size along global z in the 1st layer
     - $\Delta\phi$: using triplet barycenter position, due to small track bending for high P_T τ
2. Required similar cluster size between the triplets in the 1st and 2nd layer



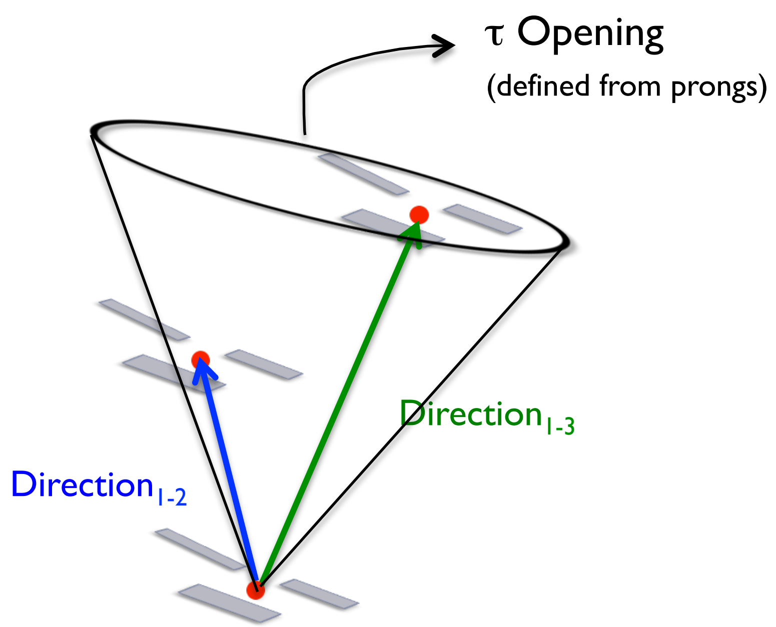
τ identification combining three layers

3. Required that all prong track candidates are independent and have small displacement on the 2nd layer
   - Assuming that τ vertex is near to the beam spot in the transverse plane, high P_T prongs should have small displacement
4. $|\tau$ charge$|$ = 1 or charge undetermined(for prongs with very small displacement)



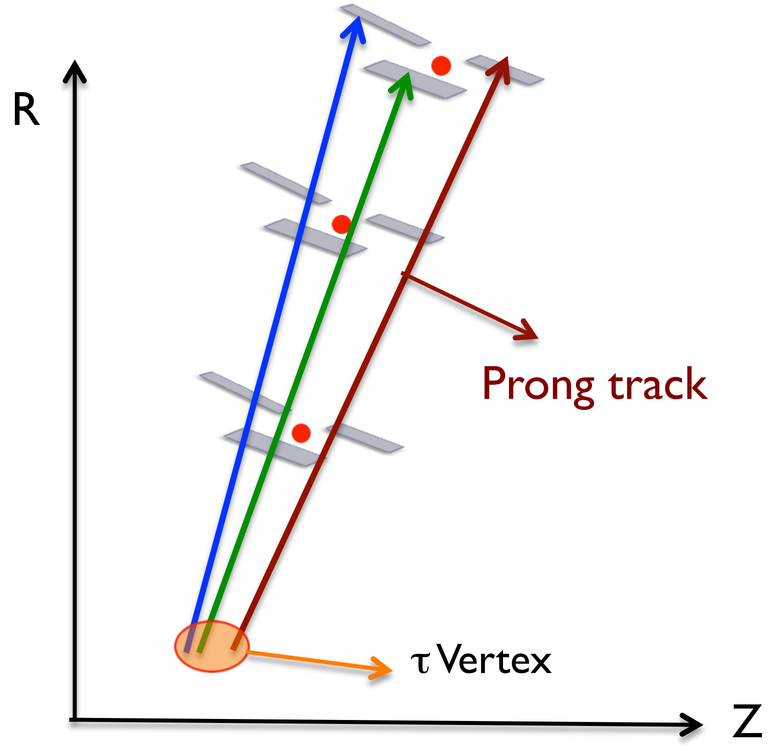
τ identification combining three layers

5. The algorithm looks for triplet in the 3rd layer requiring the cluster size similarity and that this triplet is inside a cone around τ direction
6. We applied a cut on Prong P_T, which is estimated from track curvature
   - Curvature is the inverse of the radius of circle reconstructed from 3 clusters barycenters in the 3 layers
7. τ charge requirement based on prong track curvature
8. Estimated τ Vertex position in the transverse plane, which is expected to be close to beam spot

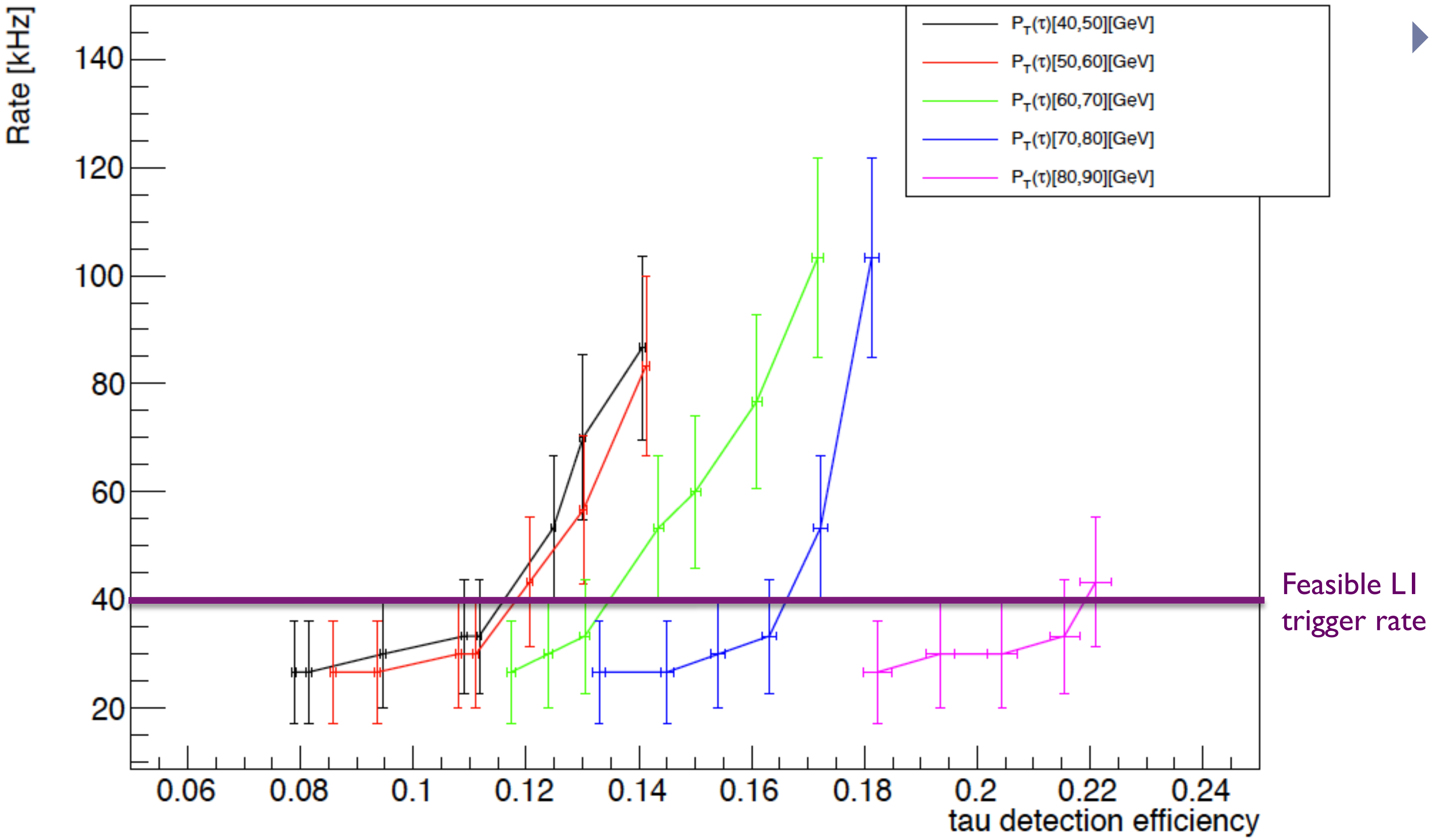


τ identification combining three layers

9. Fixed all other parameters, we selected four further variables, which are very effective to reject the background
   - Min prong P_T
   - Middle prong P_T
   - Leading prong P_T
   - $D^2 = \min(\Sigma d_i^2)$, where d_i is the distance between the prong track projection on RZ plane and the τ vertex
10. Scan of these variables to choose an optimal combination between Tau Detection Efficiency and Background Rejection

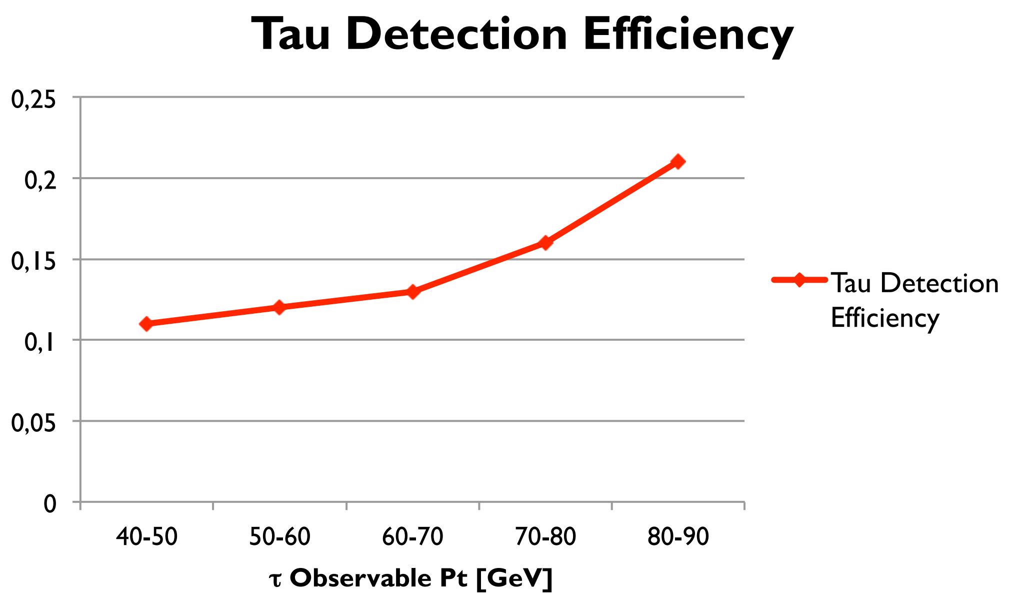


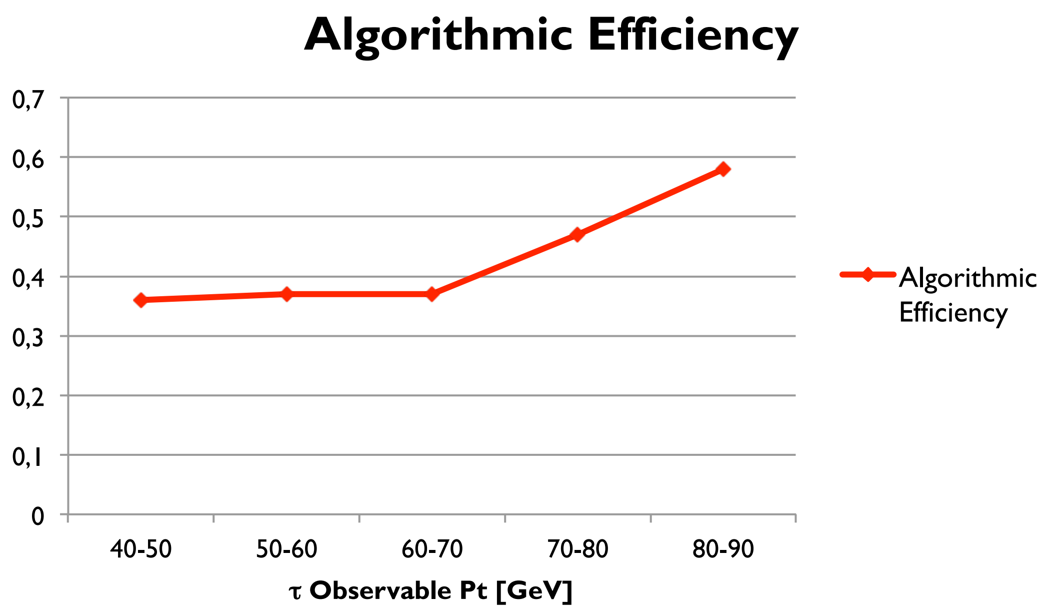
Trigger Rate vs. Tau Detection Efficiency



- Reasonable trigger rate of 40 KHz corresponds for each curve to a τ detection efficiency
  - For τ with observable P_T [40,50] GeV, τ detection efficiency= 11.2% , chosen as Reference Point (see next slide)

Efficiencies at the Reference Point





- For sustainable trigger rate of ~34 kHz, Tau Detection Efficiency* varies from 11% to 21% and Algorithmic Efficiency* from 36% to 58%, depending on τ observable P_T .

* See definitions in slide 7

Data rate estimation with acceptable max rate ~O(1Gb/s)

Layer	Average number of clusters per chip	Average number of triplets per chip
1	7	4
2	6	5
3	5	6

- Per triplet packing is not efficient, because amount of triplets is the same order of # clusters

Sending separate clusters or clusters packed per region

Layer	Average Rate per chip [Gigabit/s]	Max Rate per chip [Gigabit/s]
1 (separate clusters)	6.06	15.12
1 (regional packing)	5.60	13.72
2 (separate clusters)	5.36	12.60
2 (regional packing)	5.28	11.80
3 (separate clusters)	4.40	9.24
3 (regional packing)	4.72	9.24

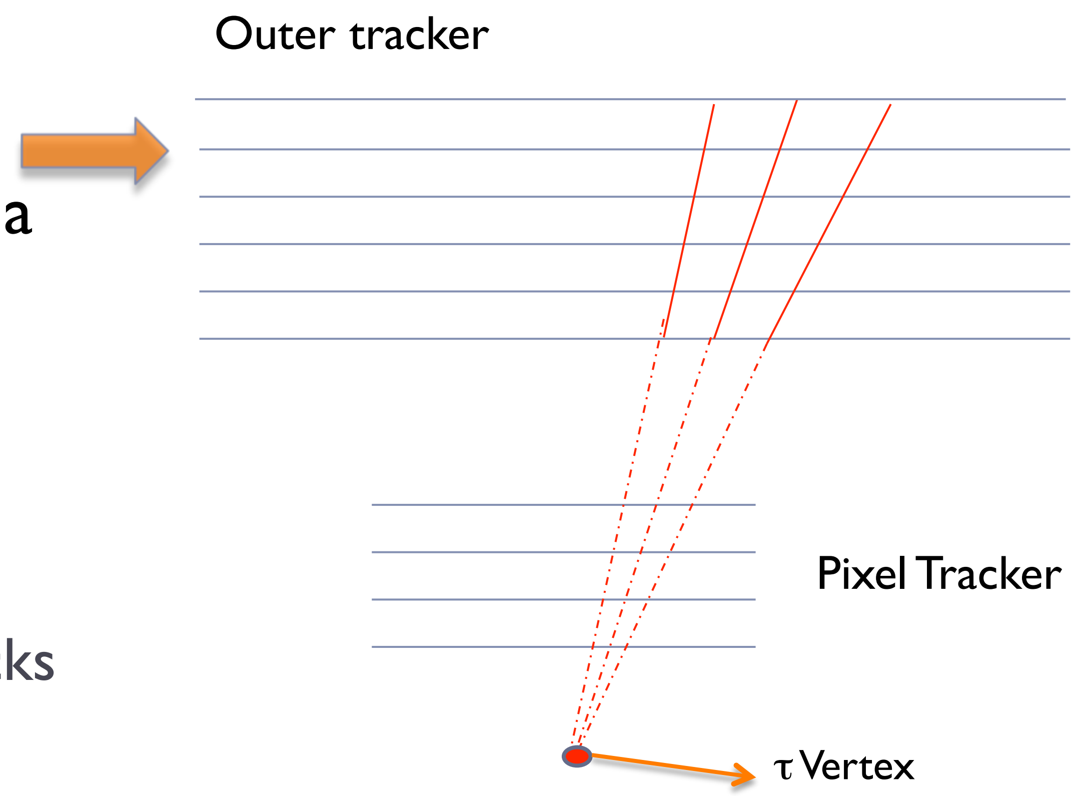
- Separate cluster representation requires 21 bits per cluster (16 bits per position + 5 bits per size)
- Regional packing representation requires: 11 bits per region header and 16 bits per cluster
- Data Rate produced by a Single Layer Algorithm is too high to be implemented at hardware level

Conclusion on Standalone τ Pixel Trigger at Level 1

- Performed physics feasibility studies of a τ trigger at Level 1 using Pixel Barrel Detector, using one or more layers information, exploiting New Pixel Chip characteristics
- Following Trigger performance can be achieved:
  - Rate on background events = 34 kHz
  - τ detection efficiency = 11.2% for τ observable P_T from 40 to 50 GeV/c
- However, estimated data rate for the Standalone τ Pixel Trigger at Level 1 is too high to be sustainable at the hardware level

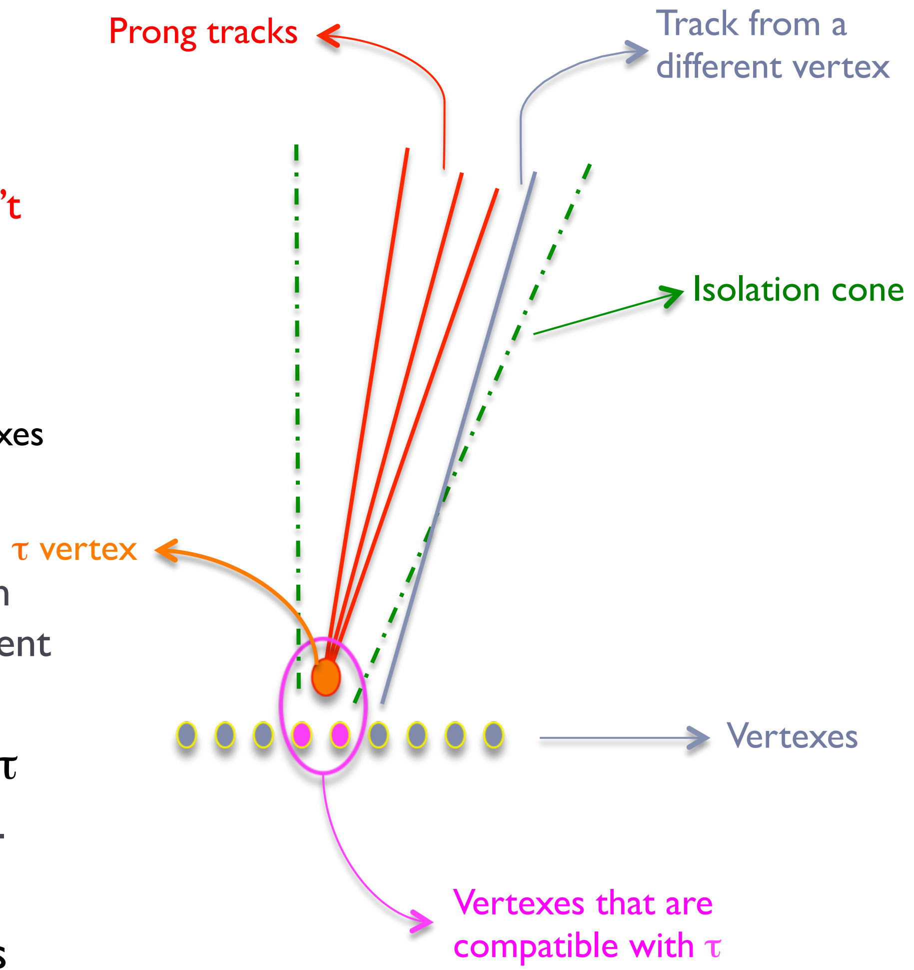
Future plans: τ Trigger using Outer Tracker and Pixel detector at L1

- Investigate the possibility to combine information from L1 τ tracks and Pixel Barrel Detector, in order to implement a τ trigger:
  - Add to the L1 tracks compatible hits from Pixel Barrel Detector
  - Reconstruct τ vertex
  - Reduce combinatoric and background in evaluation of the isolation for charged tracks
- An important check-point for these studies is the use of the same strategy at the HLT (see next slide)



Future plans: $\tau \rightarrow 3$ prongs trigger at HLT

- $\tau \rightarrow 1$ prong and $\tau \rightarrow 3$ prongs have significantly different signature.
- $\tau \rightarrow 3$ prongs characteristics are still not exploited at HLT:
  - HLT assumes as Primary Vertex (PV) the one with the highest sum P_T of charged tracks.
    τ production is assumed to be in this PV. With increasing PU this assumption can't be used.
  - We plan to use 2 or 3 reconstructed tracks, coming from an hadronic τ, to reconstruct the τ vertex
    - This may allow the use of the isolation requirements excluding tracks coming from vertexes that are not "compatible" with the τ vertex
  - We plan to study if it is possible to maintain sustainable trigger rates for $\tau \rightarrow 3$ prongs with high PU without increasing the P_T threshold and reducing τ detection efficiency with a separate path tuned for $\tau \rightarrow 3$ prong or adding filters to the current paths
- We (Siena, Pisa, Bari, Milano) plan to perform the analysis $X \rightarrow HH \rightarrow bb\,\tau\tau$
  - For this analysis, the use of a refined τ trigger may improve the fully hadronic sub-channel
- These studies for Run 2 will provide crucial check-point for Phase 2 studies



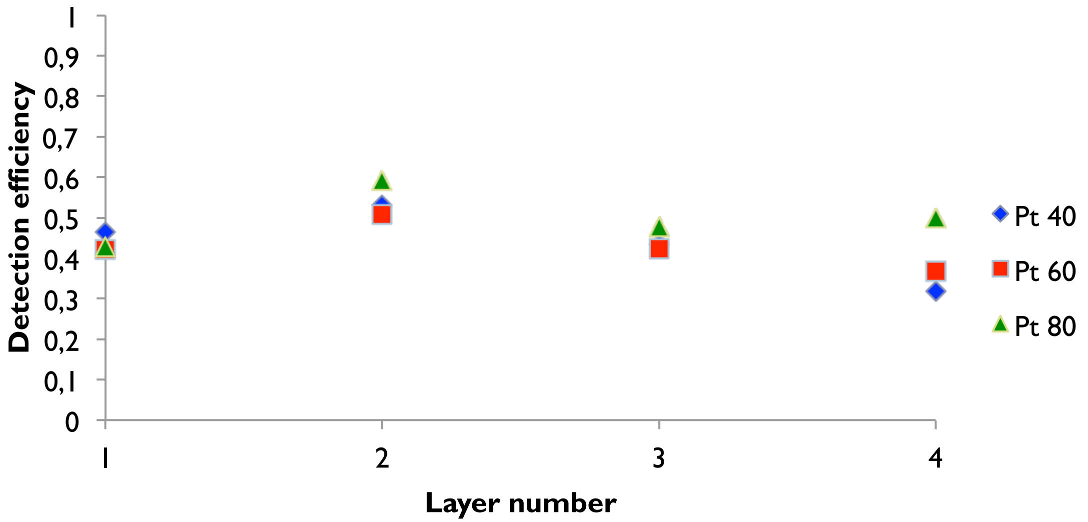
Backup

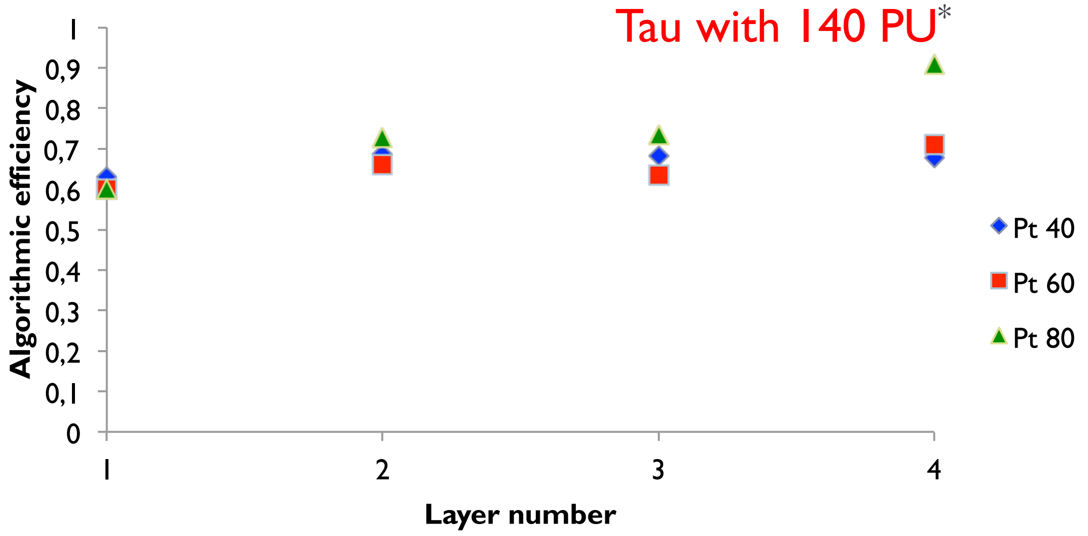
Tau Detection Efficiency and Algorithmic Efficiency for different Signal Phase Spaces

$$Tau\ Detection\ Efficiency = \frac{\text{N } \tau \rightarrow 3 \text{ prongs for which } \exists \text{ associated selected triplet in the given layer}}{\text{N of } \tau \rightarrow 3 \text{ prongs decayed within the layer acceptance}}$$

$$N\ Algorithmic\ visible\ \tau = \text{N of } \tau \rightarrow 3 \text{ prongs decayed in a single module in three different clusters within the layer acceptance}$$

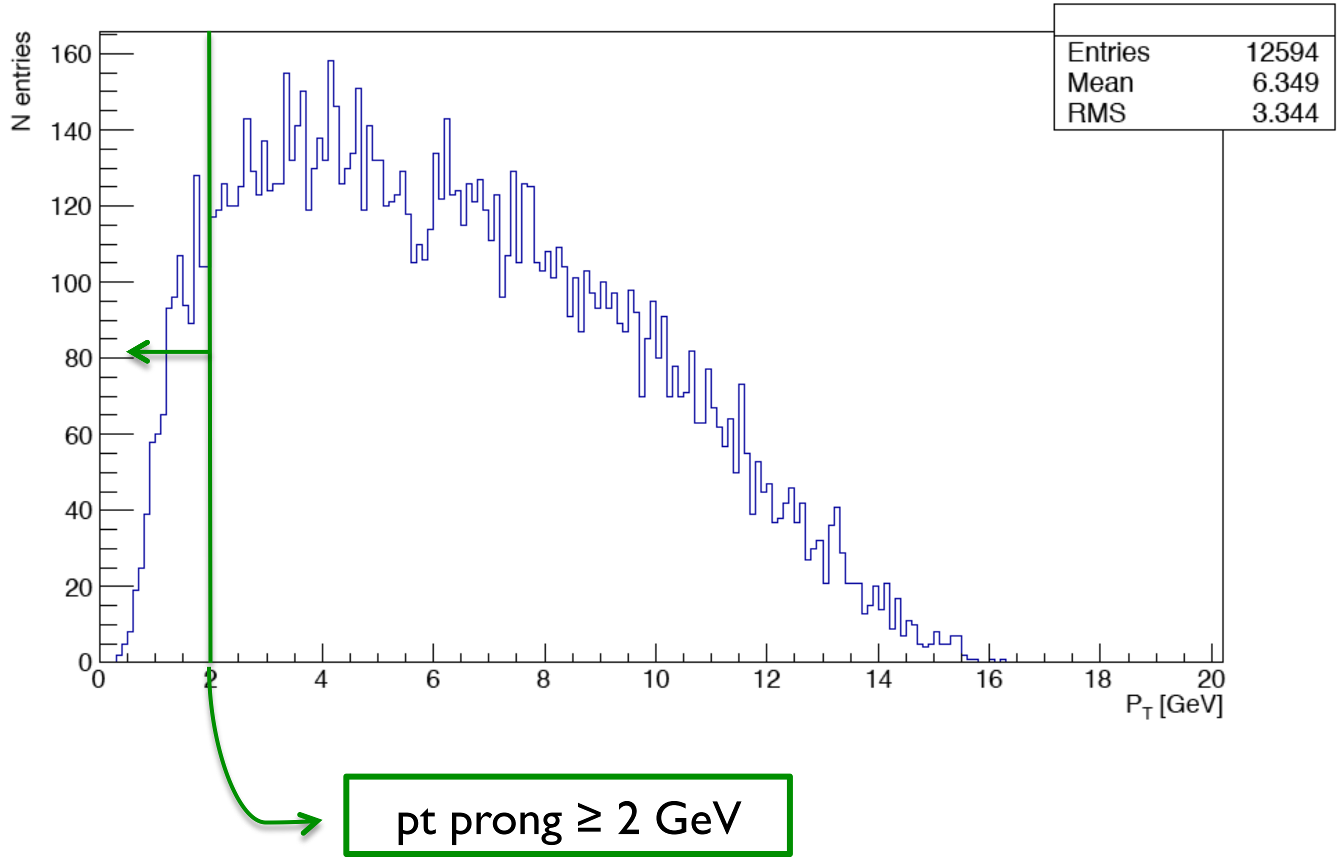
$$Algorithmic\ Efficiency = \frac{\text{N Algorithic visible } \tau \text{ for which } \exists \text{ associated selected triplet in the given layer}}{\text{N Algorithic visible } \tau}$$





* Required minimum P_T of the 3 Prongs > 2 GeV/c

Minimal P_T prong



- This distribution of minimal P_T prong is realized for τ with observable P_T between 40 and 50 GeV
- Requiring P_T of prong > 2 GeV allows us to remove fake tracks with big curvature.

Results for Single Layer Algorithm per chip

$$\textbf{\textit{Tau Detection Efficiency}} = \frac{\text{N } \tau \to 3 \text{ prongs for which } \exists \text{ associated selected triplet in the given layer}}{\text{N of } \tau \to 3 \text{ prongs decayed within the layer acceptance}}$$

$$\textbf{\textit{N Algorithmic visible }}\tau = \text{N of } \tau \to 3 \text{ prongs decayed in a single chip in three different clusters in all 3 layers}$$

$$\textbf{\textit{Algorithmic Efficiency}} = \frac{\text{N Algorithmic visible } \tau \text{ for which } \exists \text{ associated triplet in the given layer}}{\text{N Algorithic visible } \tau}$$

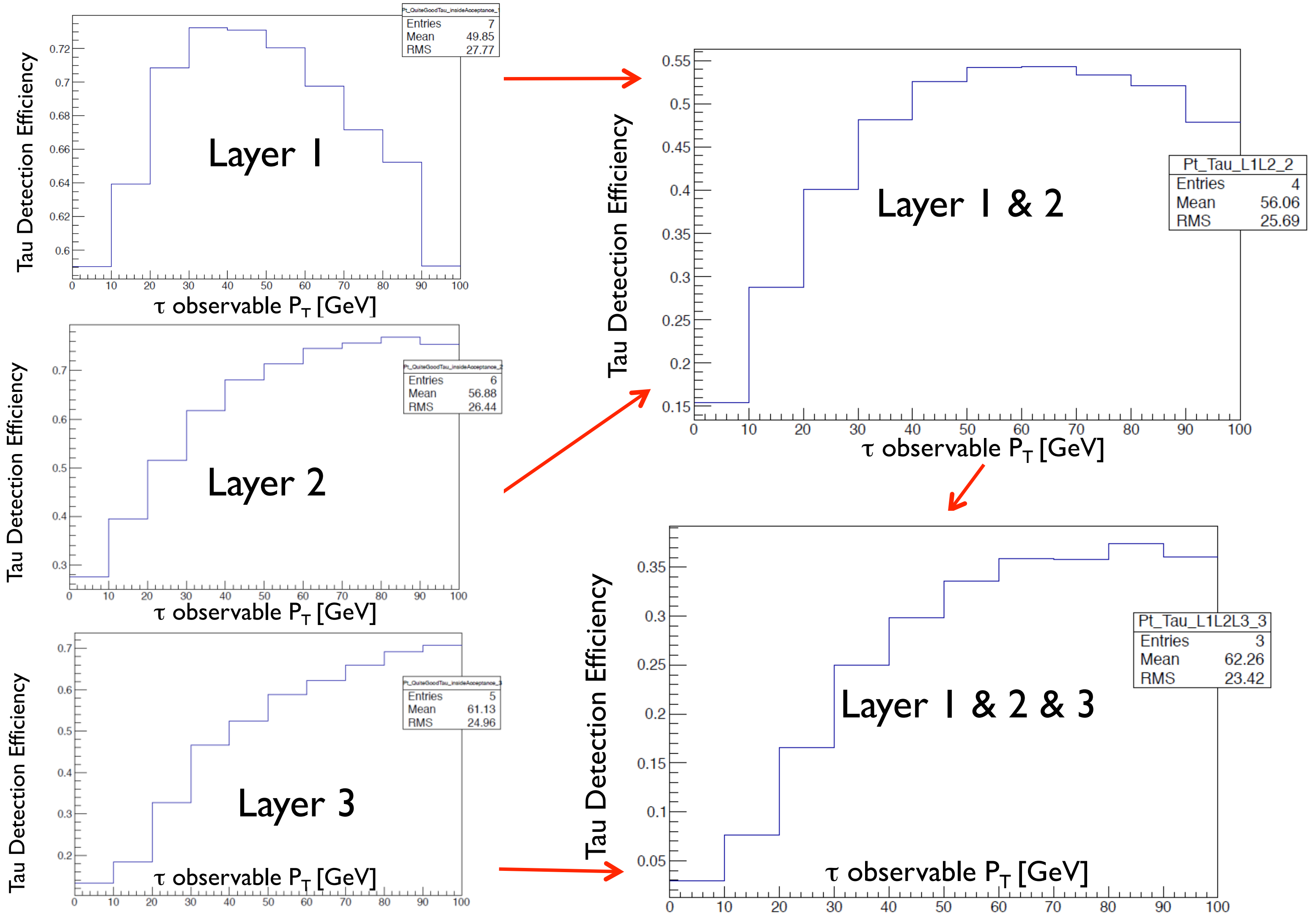
Efficiency– τ with 140 PU

	Layer 1	Layer 2	Layer 3
Detection efficiency	0.5067 ± 0.0004	0.5903 ± 0.0004	0.5000 ± 0.0004
Algorithmic efficiency	0.7324 ± 0.0008	0.8492 ± 0.0008	0.8656 ± 0.0008

Average number of accepted triplets in Minimum Bias event with 140 PU

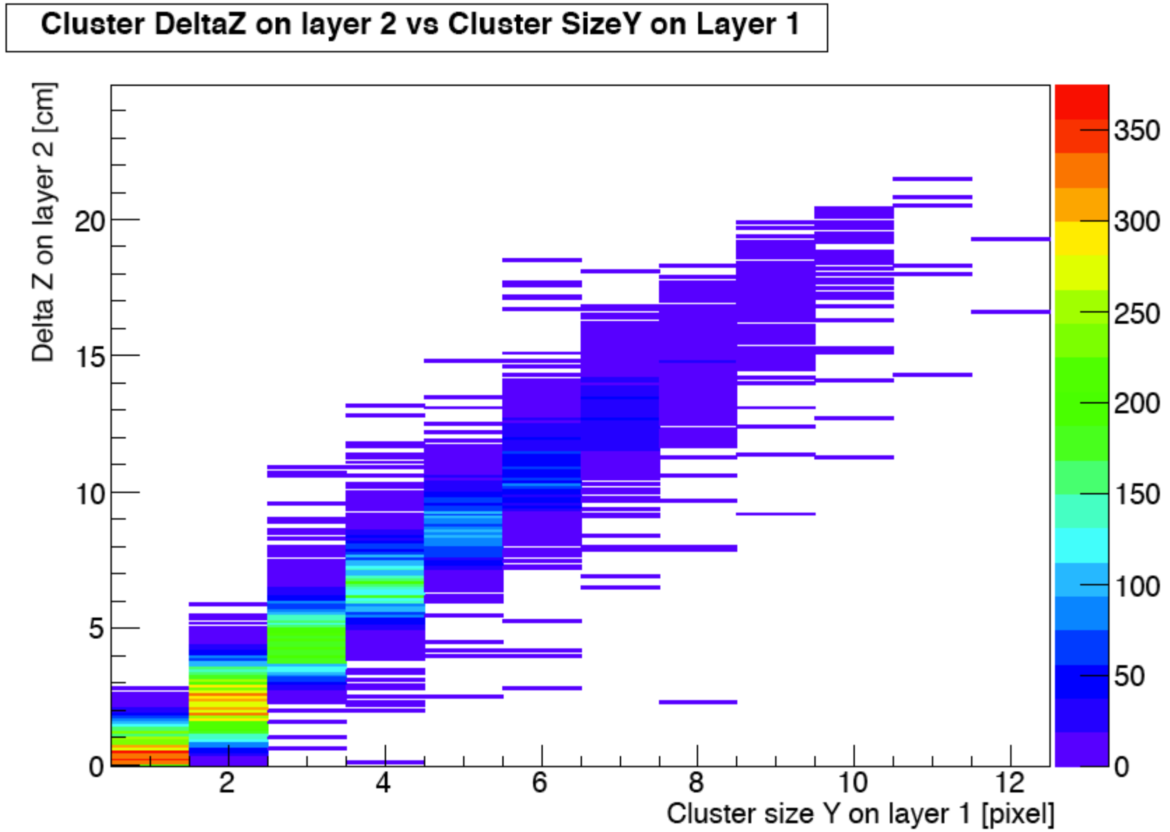
Layer 1	Layer 2	Layer 3
231 ± 1 (stat.) ± 89 (RMS)	1042 ± 4 (stat.) ± 391 (RMS)	1738 ± 6 (stat.) ± 640 (RMS)

Limitation of layer match algorithm

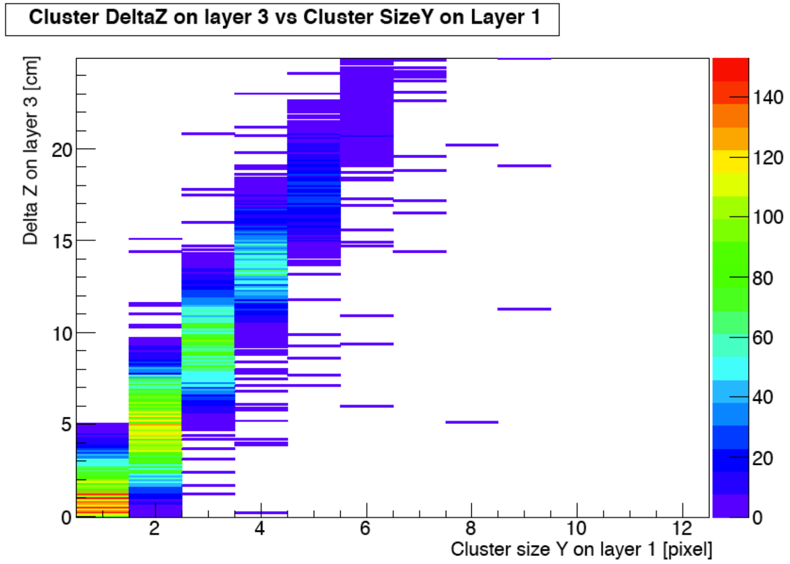


- Maximal achievable efficiency obtained using MC truth
- Efficiency is limited due to requirement of having cluster from all three prongs in a single chip
- Therefore, for τ with observable P_T [40,50] GeV/c, maximal achievable efficiency, using 3 layers, is ~ 30%

Prediction of τ_{Track} direction



- Based on linear dependency between cluster Size along beam and Δz, it is possible to estimate for each average cluster size on the 1st layer which is the region on the 2nd layer where to search possible candidates
- Prediction based on cluster Size Y on outer pixel layers is too wide, which leads to a huge amount of combinations
- Only option is to start from 1st layer



Results for 2 layers matching

$$\textit{Tau Detection Efficiency} = \frac{\text{N } \tau \rightarrow 3 \text{ prongs for which } \exists \text{ associated pixel tau track candidate}}{\text{N of } \tau \rightarrow 3 \text{ prongs decayed within the layers acceptance}}$$

$$\textit{Algorithmic Efficiency} = \frac{\text{N Algorithmic visible } \tau \text{ for which } \exists \text{ associated tau track candidate in the given layer}}{\text{N Algorithic visible } \tau}$$

Efficiency - τ with 140 PU

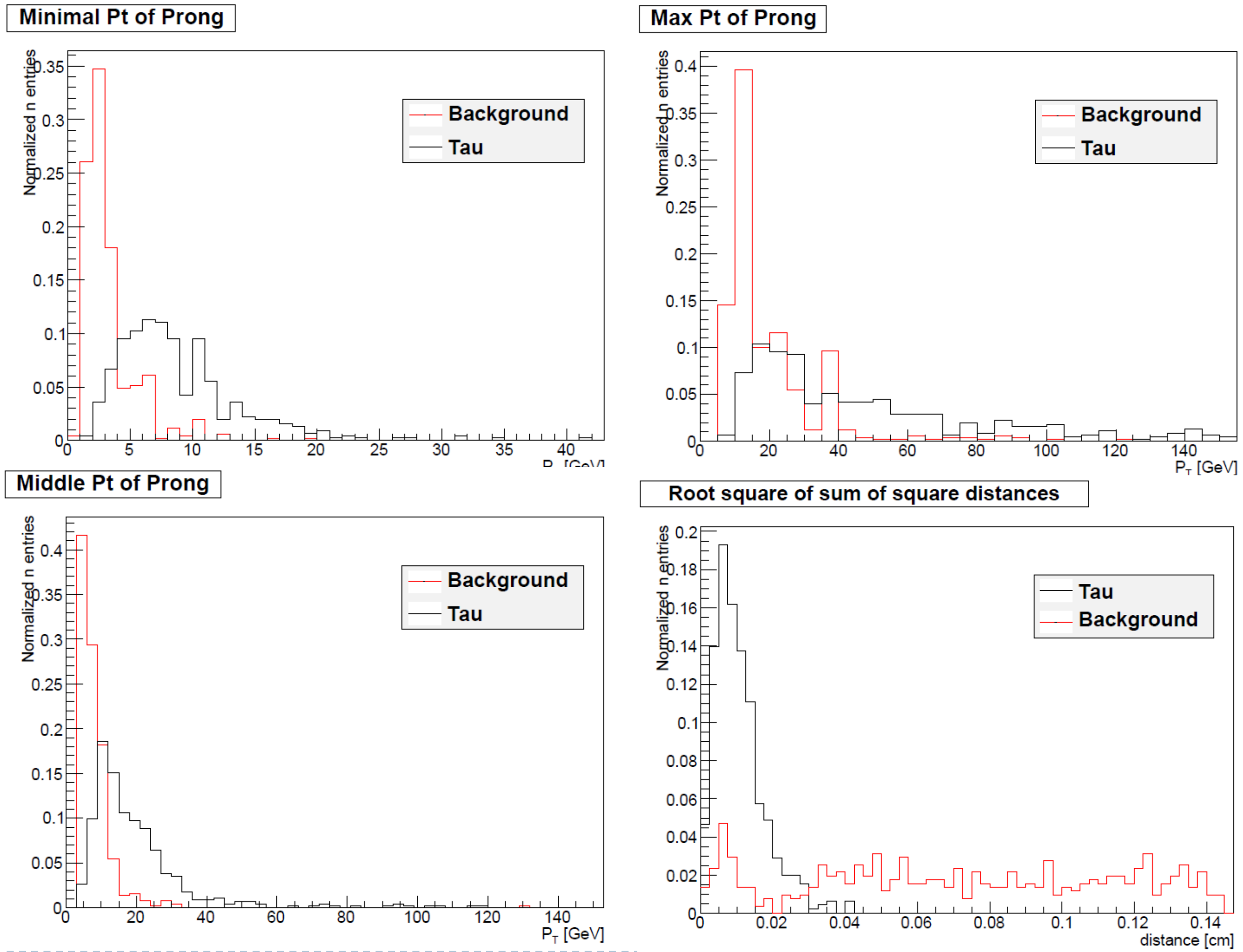
P_T parameter	Layer 1-2
Detection efficiency	0.3060 ± 0.0003
Algorithmic efficiency	0.5682 ± 0.0005

Average number of τ "pixel track" candidates in Minimum Bias event with 140 PU

Layer 1-2
18.8 ± 0.2 (stat.) ± 19.4 (RMS)

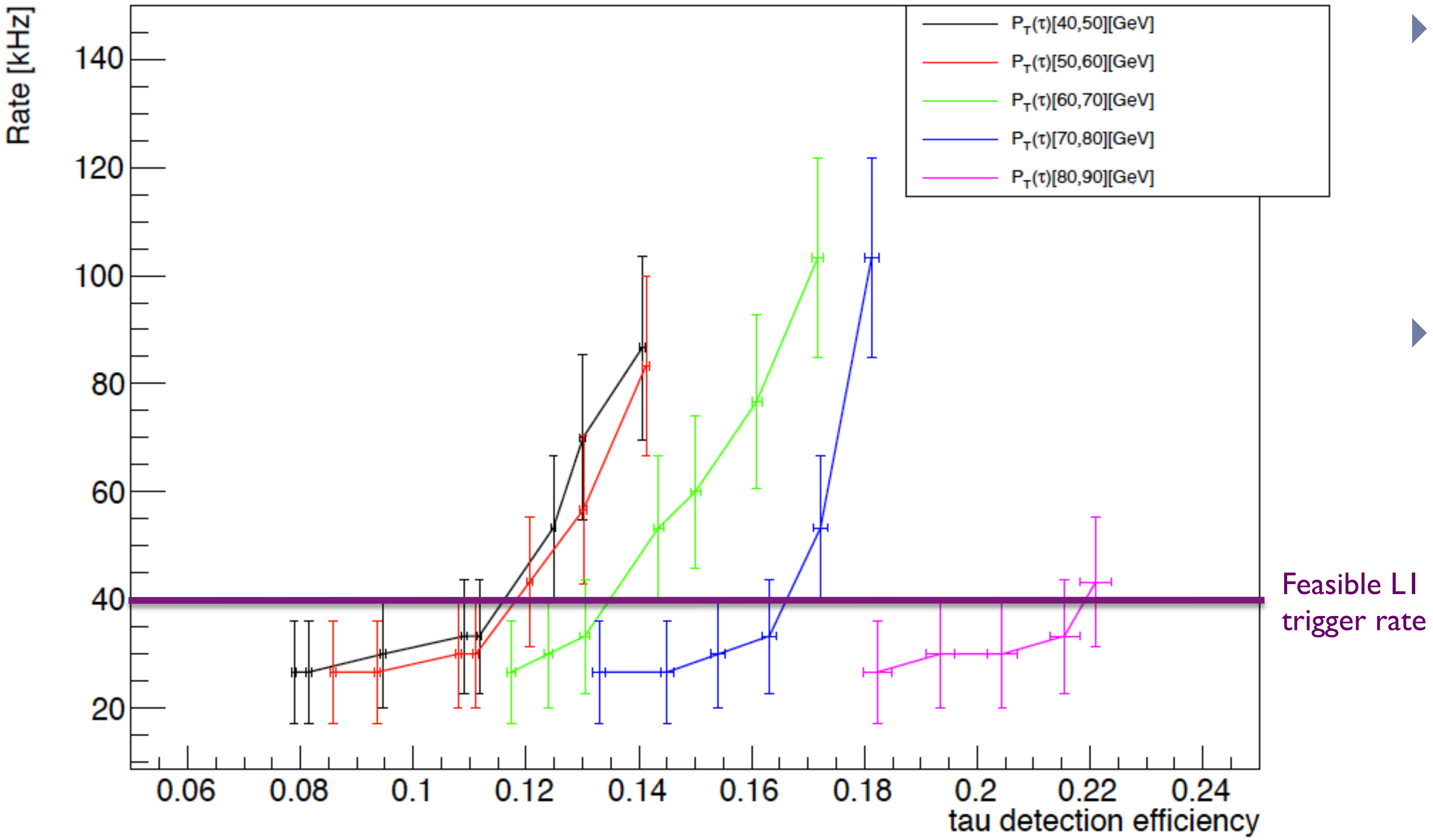
- *Reduction of fake τ candidates by a factor 7, comparing to Single Layer results.*

Scan for 3 layer match parameters



- These distributions are made fixing single and double layer phase space to the final values and after applying cut on "fixed parameters" for 3 layer matching.
- For the following parameters are used relaxed cuts :
  - Min P_T prong
  - Middle P_T prong
  - Max P_T prong
  - $\sqrt{(D^2)}$
- These distributions show an evident discrimination between signal and background
- The scan has been made using step 1 GeV for P_T parameters and 0.01 cm for $\sqrt{(D^2)}$

Trigger Rate vs. Tau Detection Efficiency



- Reasonable trigger rate of 40 KHz corresponds for each curve to a τ detection efficiency
- For τ with observable P_T [40,50] GeV, τ detection efficiency= 11.2% , chosen as Reference Point
  - Min P_T = 5 GeV
  - Middle P_T = 7 GeV
  - Leading P_T = 8 GeV
  - $\sqrt{(D^2)}$ = 0.04 cm