A Level 1 Tracking Trigger for the CMS Experiment at the LHC Phase 2 Luminosity Upgrade

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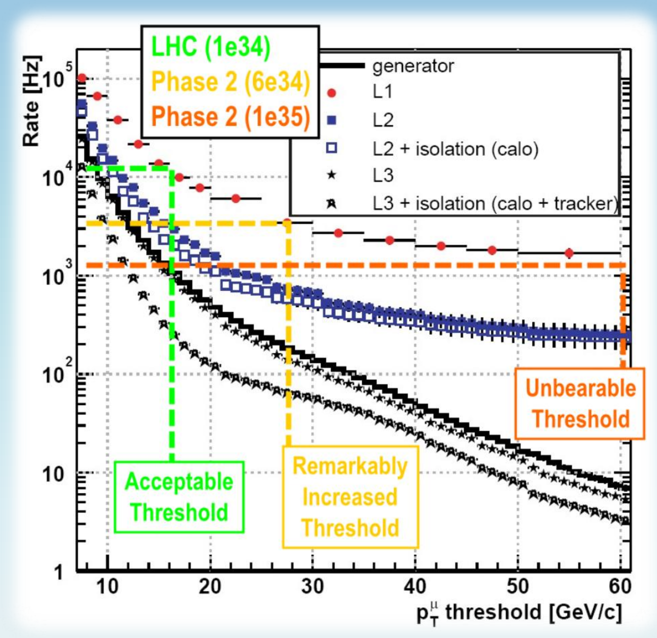
motivation

The second decade of LHC operations, from about 2020 onwards, envisages an **increase in collider luminosity of one order of magnitude** above the project one.

As a major challenge for the CMS experiment, the present tracker must be replaced with a system providing excellent tracking quality at higher luminosities, as well as **tracking trigger inputs to the first level of the CMS trigger** at the full 40 MHz bunch-crossing rate. The minimal requirements for a tracking trigger would be the capability to **confirm the presence of high-p_T tracks associated with calorimeter and/or muon Level 1 triggers**.

Tracker information is currently employed in the HLT, ensuring **precise momentum measurement in order to keep thresholds low**.

__RIGHT:__ example of the inclusion of tracking information in current muon trigger: Level 1 muon bandwidth is limited to 12.5 kHz; shifting the rate scale gives approximate estimate of trigger rate at higher luminosities.

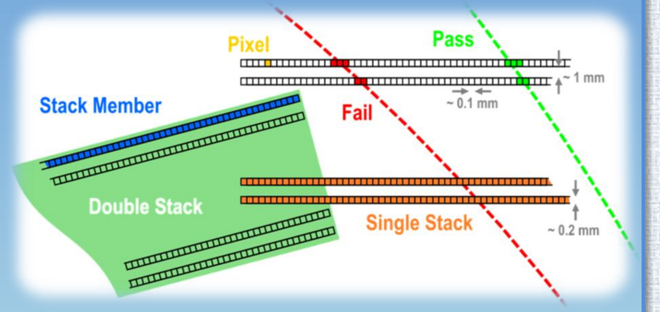


(adapted from the CMS Physics Technical Design Report Volume 1: Detector Performance and Software, CMS-TDR-008-1)

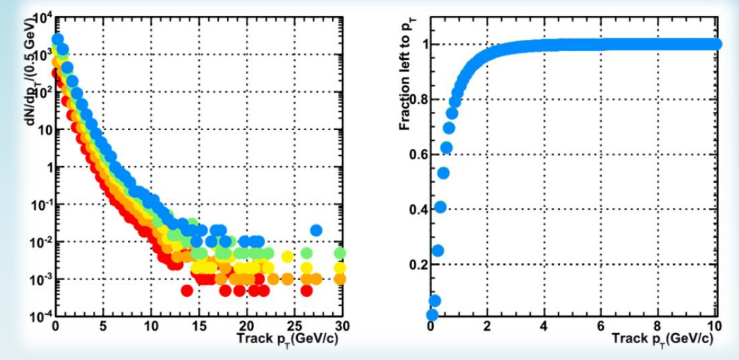
p_T module concept

Maintaining the data rates within a manageable bandwidth requires sensor modules able to locally sparsify the data. **Measuring at detector module level the track direction in the transverse plane, and hence deriving its transverse momentum, is the most promising solution.**

These so-called **p_T modules would only transmit to the Level 1 trigger track *stubs*, pairs of correlated hits in two closely separated sensors**, derived by tracks with p_T above a given threshold.



The p_T modules consist of **a pair of segmented silicon sensors**, featuring **pattern hit correlation across the module** and a single hit position resolution high enough to resolve track direction despite a **lever arm of about only 1 mm**.

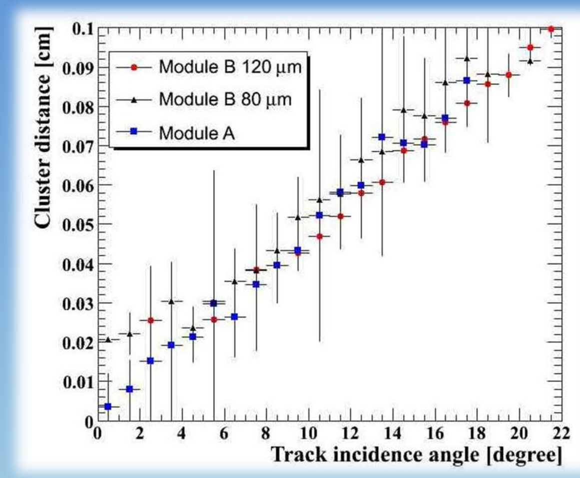


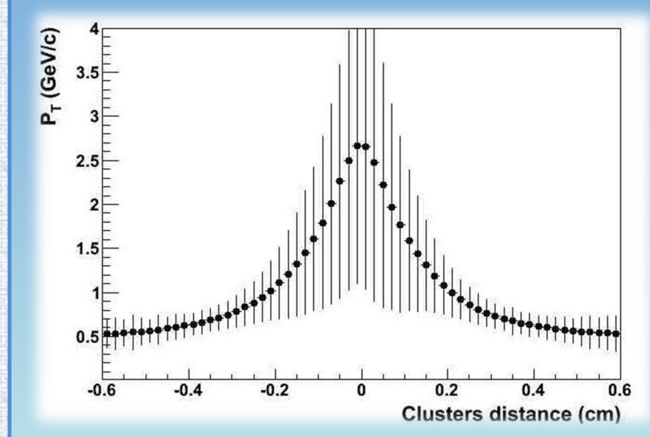
Simulations show that **a 2 GeV/c threshold would cut data rate of more than a factor 10 with a pitch of about 100 μm**.

__ABOVE:__ Spectrum of charged particles in minimum-bias events, ranging from 25 to 200 pile-up, leaving hits at 32 cm from the beamline [L], and fraction of tracks with p_T lower than a chosen value [R].

experimental proof of principle

Measurements with cosmic rays using custom prototypes built with spare strip modules of current CMS tracker show that distance between clusters, in sensors separated by about 2 mm, clearly depend on track incidence angle.

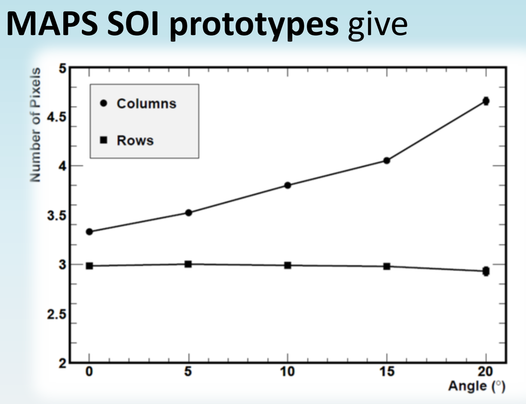




Offline analysis of collision data at √s = 7 TeV of hits in double-sided tracker outer barrel strip modules show that distance between hits decreases with increasing p_T.

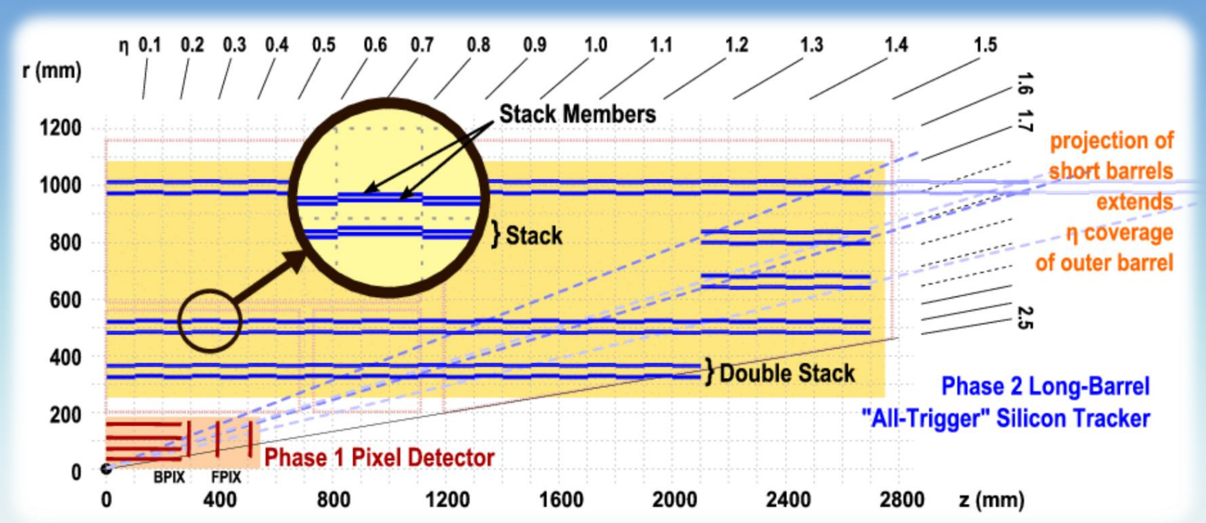
(both pictures above from J. Bernardini et al., JINST **5** *(2010) C11018)*

Measurements with 200 GeV pions at SPS on MAPS SOI prototypes give information on the track rejection using **cluster width instead of hit correlation**. Pixel pitch of 13.75 μm and depletion depth of 100 μm are optimal conditions to verify that a pitch-to-depth ratio of 1:10 is necessary, but **it would be unpractical and costly, with large material budget, using current MAPS or hybrid pixel technologies.**



(courtesy of M. Battaglia, UCSC and CERN)

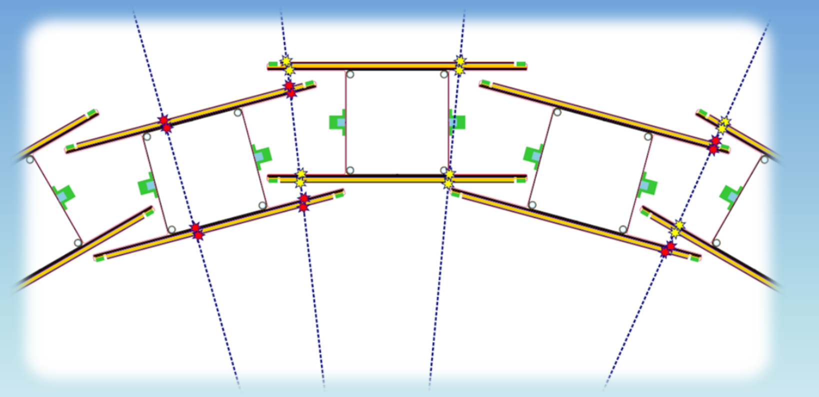
the Long-Barrel tracker concept



A tracker concept layout, the so-called Long-Barrel, consisting in an **outer tracker completely built out of p_T modules**, has been proposed. The Long-Barrel tracker is particularly flexible in simulation studies of Tracking Trigger as it allows for information from several layers of the tracker to be combined in a projective geometry. For this reason, it is meant as a testing ground to compare the performance of different designs and configurations.

The Long-Barrel layout also allows the generation of even more structured trigger objects such as *tracklets*, consisting of pairs of stubs in opportunely paired layers, which can in turn be used as seeds to generate *Level 1 tracks*, including even more stubs.

The described studies employed 100 μm × 1 mm pixels (in r-φ × z), 1 mm lever arm in stacks, and trigger layers arranged in double stacks with 4 cm separation.

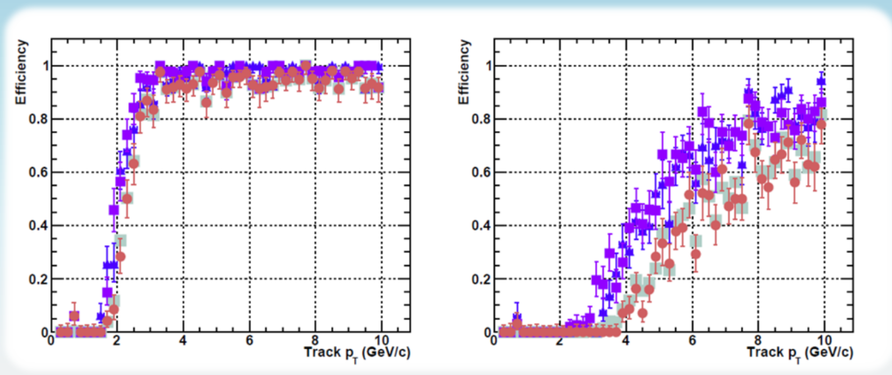


Hermetic coverage in φ allows the production of tracklets while keeping the data flow within each ladder.

track stubs

Track stubs are the **Level 1 tracking trigger primitives** built after pattern hit correlation within p_T-modules. Hits can be pixel clusters built with simple boolean logic. Pattern hit correlation is likely to be implemented in look-up tables, but other approaches based on geometry are under study. **The final fake rate may depend on the chosen algorithm and detector design.**

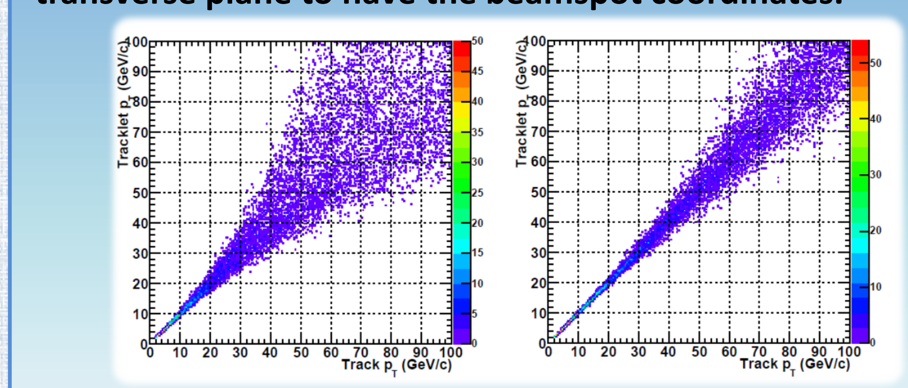
__BELOW:__ Pixel pitch allows sharp threshold at 2 GeV/c [L] in simulations (single muon) while a 5 GeV/c one [R] is smeared – stub production efficiency in stacks at 32 cm, 36 cm, and in both of them within same ladder (gray is product, red is measured).



tracklets

Stubs can be used like "hits from tracks with p_T above threshold", and they can be thus associated with each other in opportunely paired trigger layers to form tracklets. **Assuming the vertex in the transverse plane, the trajectory can be fully constrained with simple trigonometry to get p_T and φ.**

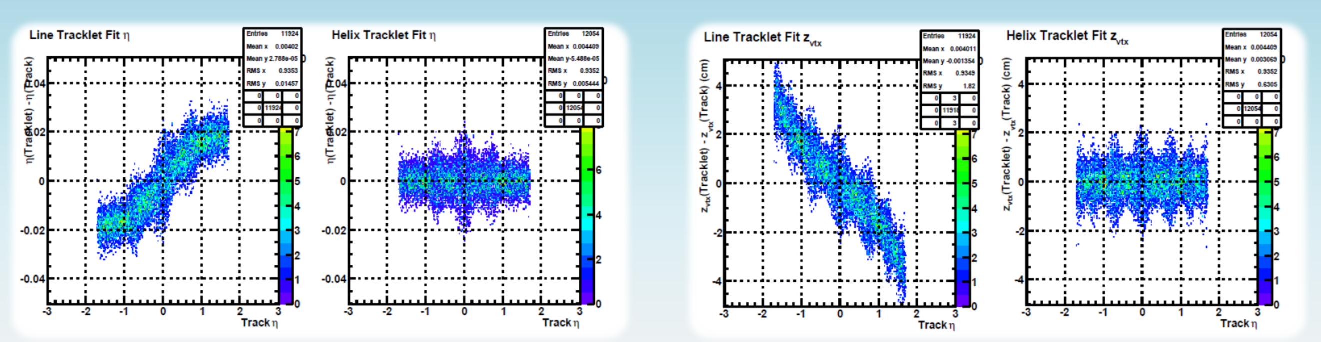
Tracklet p_T resolution is enhanced assuming the vertex in the transverse plane to have the beamspot coordinates.



__ABOVE:__ 32-36 cm trigger layers tracklet p_T vs. track p_T in single muon events with vertex displaced of few tenths of mm in x, assuming vertex in the transverse plane to be (0,0) [L] or beamspot coordinates [R].

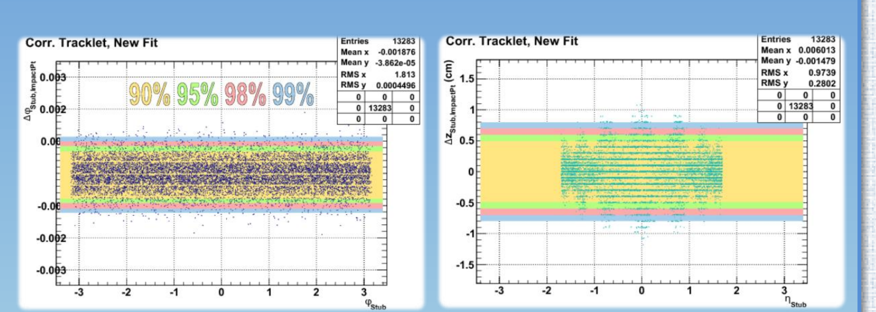
Large-p_T form of tracklet fit in z and η, with constant $\Delta z/\Delta r$, introduces systematic deviations, at low p_T and large radii, from the helix fit (constant $\Delta z/\Delta\varphi$,wrt trajectory axis).

__BELOW:__ 98.5-102.5 cm trigger layers tracklet fit residuals of η [L] and z_{VTX} [R] vs. track η in single muon events with fixed p_T = 3 GeV/c, obtained with simplified fit and helix fit. __NOTE:__ resonant behavior is due to pixel length of 1 mm, different lengths give different position and size.



tracks in Level 1 trigger

Tracklets can be used to seed Level 1 tracks composed of at least 3 stubs in 3 different trigger layers. **A simple propagator calculates the expected impact point after either forward or backward propagation** of a tracklet to other trigger layers. ***Δφ* and *Δz* between impact point and stub position are used to define search windows depending on seed layers, target layer and seed p_T.** These templates are pruned of symmetric left and right tails to define different window size and different matching probabilities.



__ABOVE:__ $\Delta\varphi$ vs. φ [L] and Δz vs. η [R] between stub and impact point for propagation of tracklets (beamspot and helix correction) in fixed p_T = 10 GeV/c single muon events, from 48-52 cm stacks to 98.5 cm one.

All major effects described for tracklets reflect into seed propagation and Level 1 track formation:

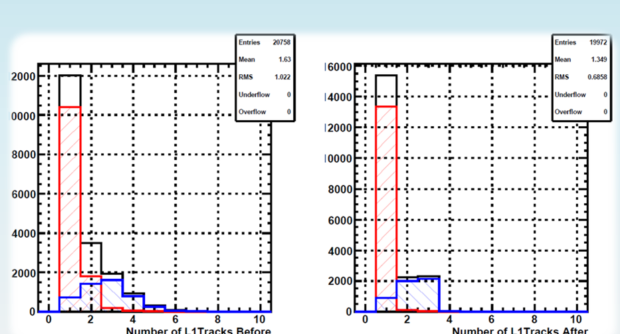
1. use of beamspot coordinates in tracklet fit
2. use of helix tracklet fit instead of large-p_T one
3. effect of pixel length in longitudinal tracklet fit and seed propagation.

Corrections are needed for a plain definiton of matching windows, flat in φ and η (1 and 2 already implemented).

Level 1 track production efficiency reaches 98% at p_T = 4 GeV/c and drops at pseudorapidities corresponding to pruned tails (using 99% windows and inclusive wrt number of stubs in the track). Fake rate estimate needs more reliability of simulation tools at very high luminosities.

Level 1 track vertex and momentum fit is based on the helix one for tracklets: each ordered triplet of stubs undergoes tracklet fit, results are averaged without weighting. **Inclusion of seed vertex in the fit gives benefits** in p_T estimate. Goodness-of-fit, at this stage, is given by sum of squares of residual in the transverse plane.

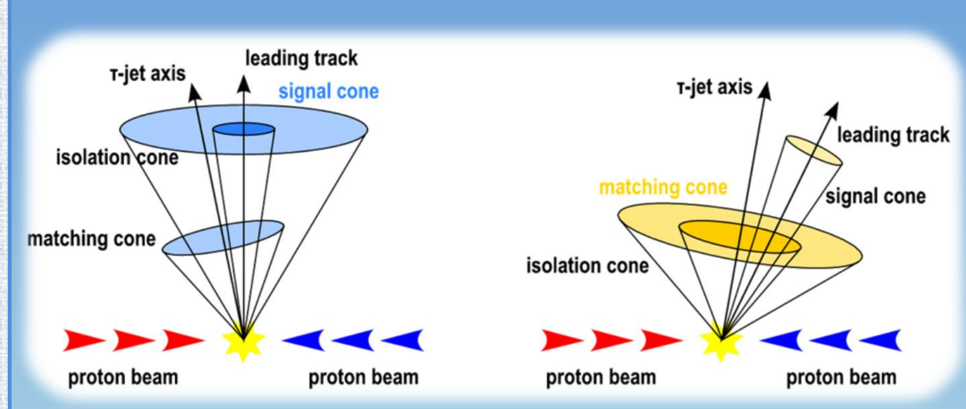
Duplicates arise from seed in different pairs of trigger layers and from overlap regions: when 2 stubs are shared, the Level 1 track with worse goodness-of-fit is removed.



__RIGHT:__ number of Level 1 tracks before [L] and after [R] removal of duplicates in $Z\rightarrow\tau\tau$ events at √s = 14 TeV; tracks are classified according to τ lepton decay (hadronic inclusive, 1-prong, and 3-prongs).

a Level 1 tracking trigger for τ leptons

A particular challenge for the trigger system is given by τ leptons produced in many rare processes searched at the LHC. The performance of a tracking trigger on final states with τ leptons will be crucial at very high luminosities.



Current τ trigger at CMS finds **Level 1 calorimeter candidates, which are matched to tracks in the HLT.** Calorimeter candidates are built with comparison of calorimeter towers with predefined patterns.

τ candidates require isolation in HLT, based on the amount of tracks within a signal cone and an isolation cone,opened around the calorimeter candidate (pixel only) or the leading matched track (full tracker).

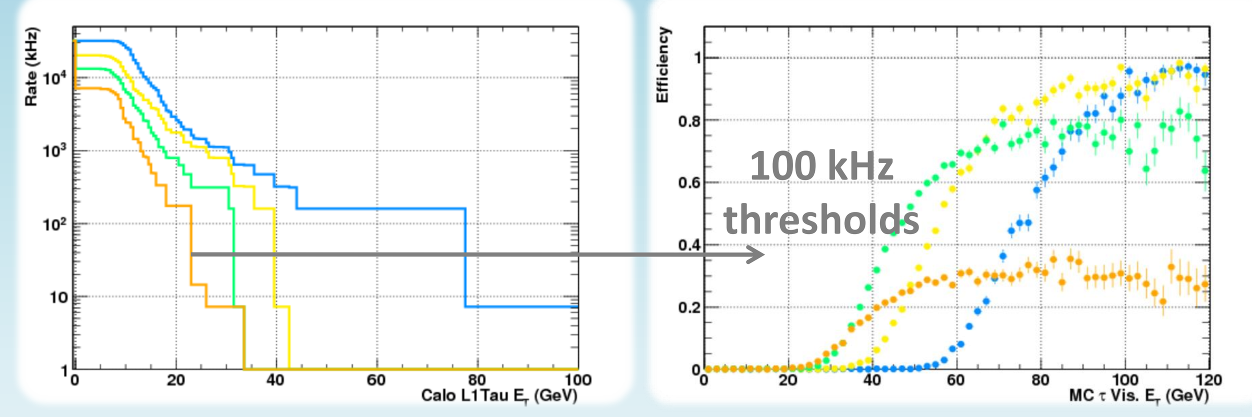
IDEA for Phase 2: exploit Level 1 tracking trigger to check isolation of calorimeter τ candidate.

Level 1 tracks (after duplicate removal) in τ decays are contained within narrow cones (R = 0.2) and share extrapolated z_{VTX} within 5 mm.

Different cone sizes were tried:

1. too high standalone calorimeter rate
2. tracker-confirmed calorimeter rate is slightly lower
3. **rate is strongly reduced with isolation:**
   - the total p_T in the isolation ring
   - the number of tracks in the isolation ring sharing vertex with the signal leading track

Best background suppression with R_{SIGNAL} = 0.16 and R_{ISO} = 0.40.



__ABOVE:__ background rate at luminosities of 10^{35} cm^{-2}s^{-1} at 40 MHz as a function of calorimeter candidate E_T [L] and efficiency on hadronic decays on τ leptons in SM Higgs boson production events, m_H = 120 GeV/c^2, with thresholds corresponding to 100 kHz rate for different calo/trk candidates [R].