SEMANTIC SEGMENTATION FOR CMS PIXEL CLUSTERING

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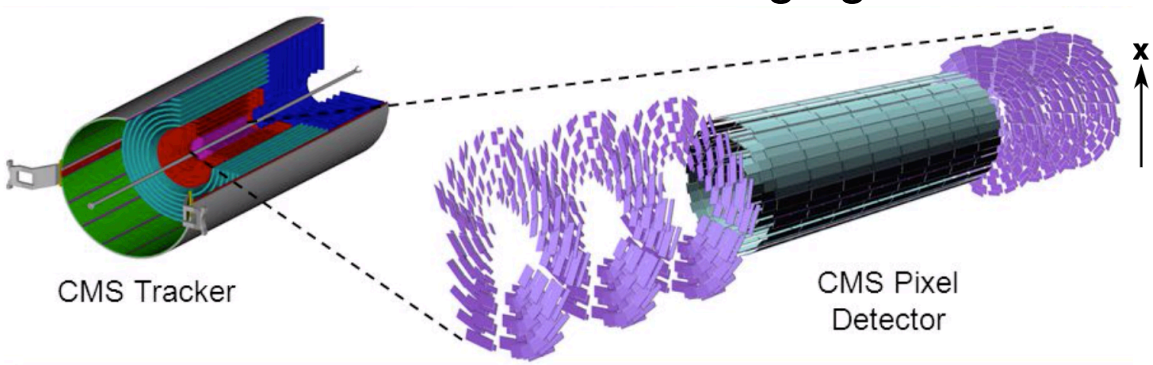
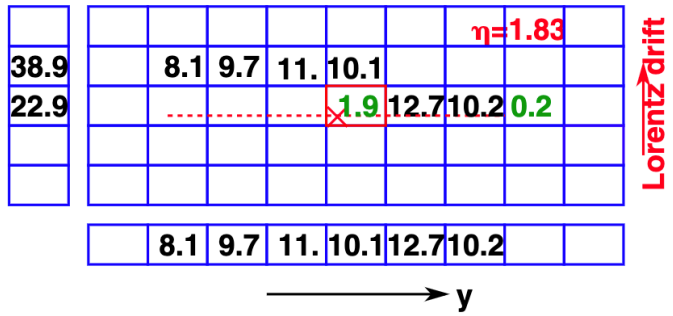
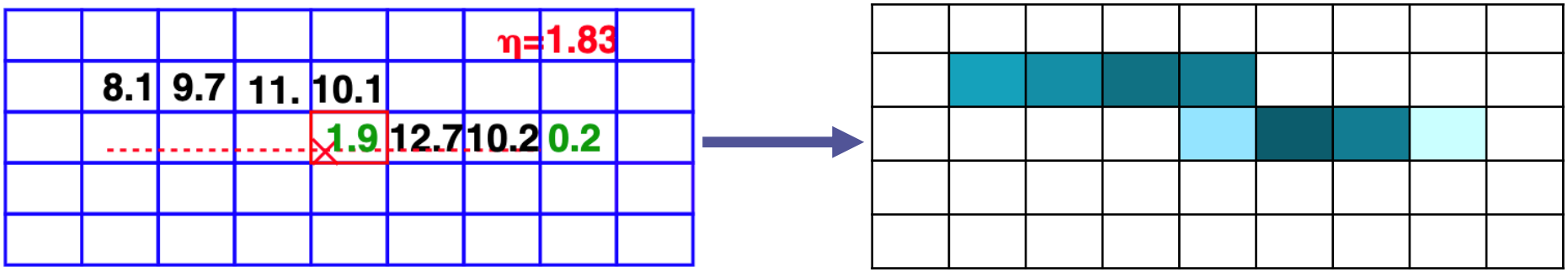
Pixel Clustering

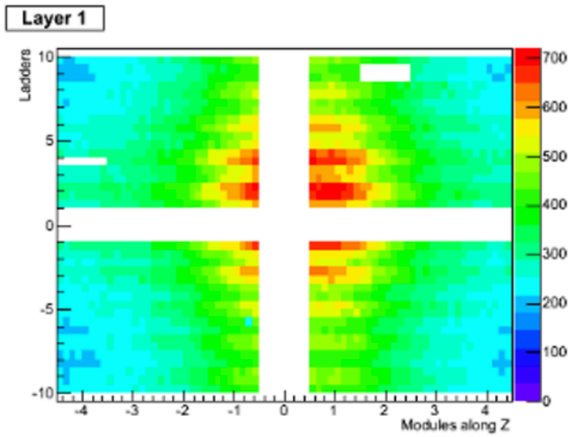
- Pixel detector is the inner-most layer of CMS
- Pixel clusters (hits) used for track-seeding and vertex finding
- Current clustering:
  - Clusters formed by considering adjacent pixels
  - Fast algorithm (track seeding): project clusters onto an axis, consider relative charge of edge pixels $u_{\text{hit}} = u_{\text{geom}} + \frac{Q^u_{\text{last}} - Q^u_{\text{first}}}{2(Q^u_{\text{last}} + Q^u_{\text{first}})} |W^u - W^u_{\text{inner}}| - \frac{L_u}{2},$
  - Precise algorithm (track fitting): compare clusters to simulated templates
- HL-LHC will have higher pile up and occupancy
  - More clusters per bunch-crossing
  - Increased risk of cluster merging

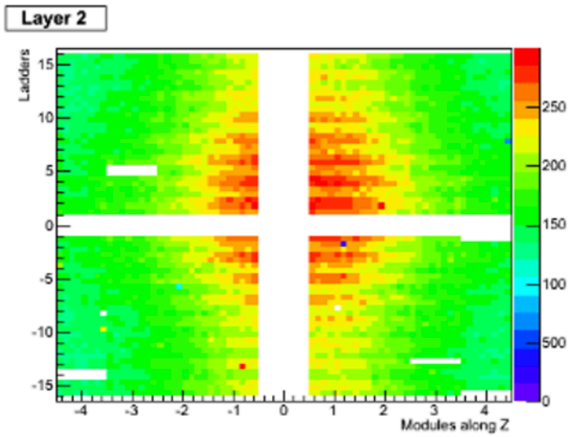




Pixel Images



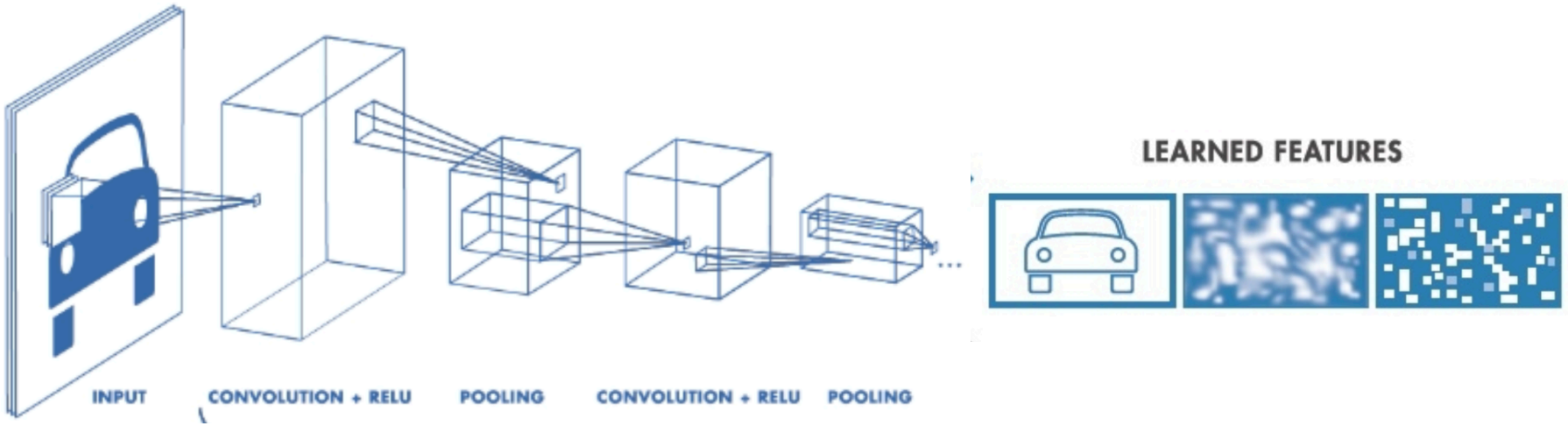




- Pixel tracker read-outs map easily to images
- Can we leverage image based machine learning to improve clustering?

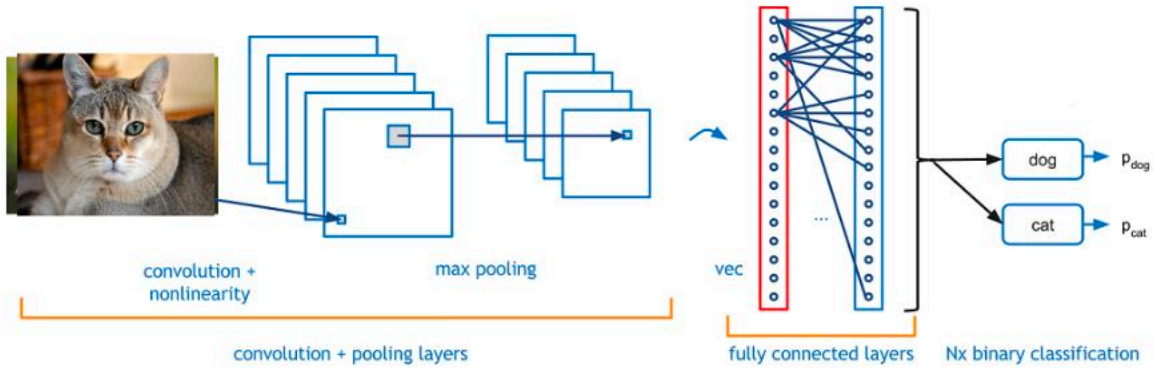
Convolutional Neural Networks

- CNNs are the standard ML technique for image processing:
  1. ‘Read in’ images as a matrix of pixels with numerical values
  2. Convolve the image with filters to create multiple, high-dimensional representations of the original image
  3. Use these new representations to better complete a task
- Different filters learn different features of the input image



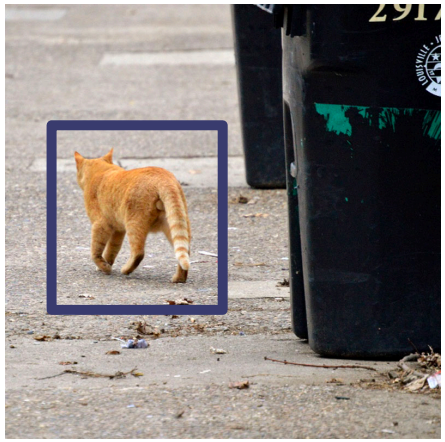
Computer Vision Tasks

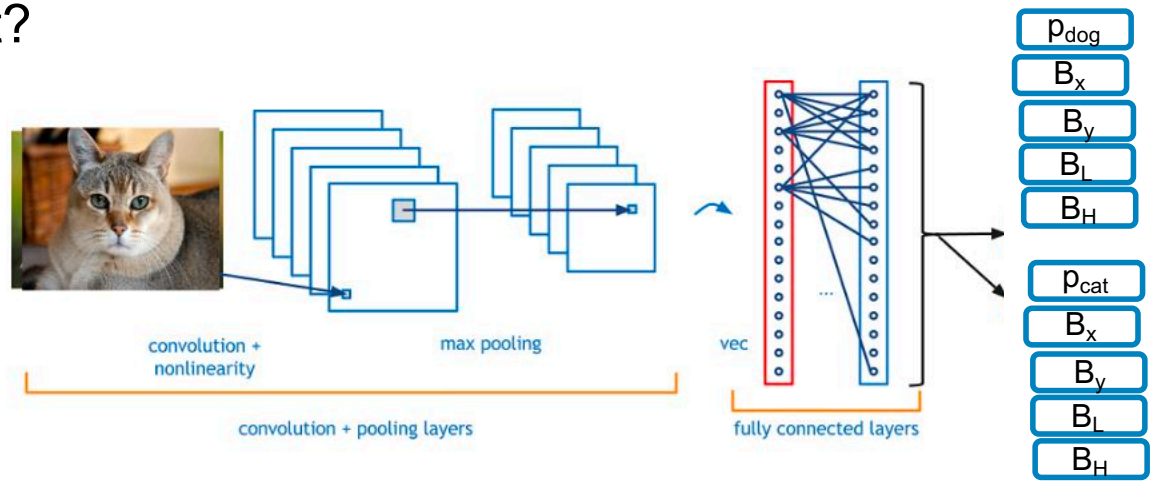
Classification: is it a cat?



Standard NN classifier

Localization: where is a cat?

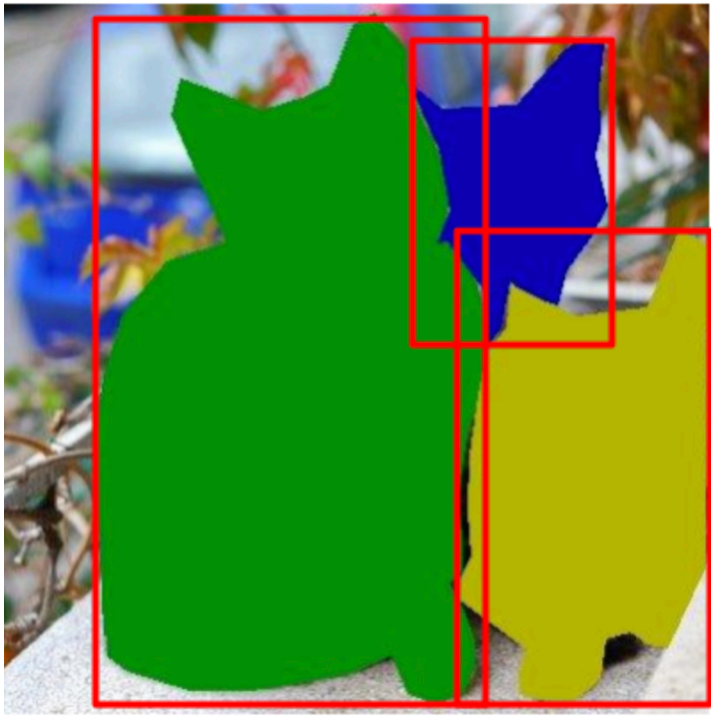




Classifier NN + boundary box

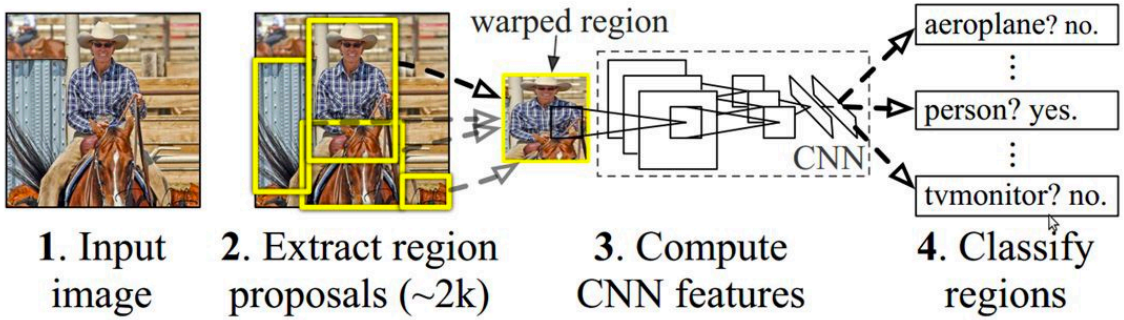
Our Problem

How many cats are there, where are they, which pixels belong to which cats?!



Semantic Segmentation

Region Based CNN

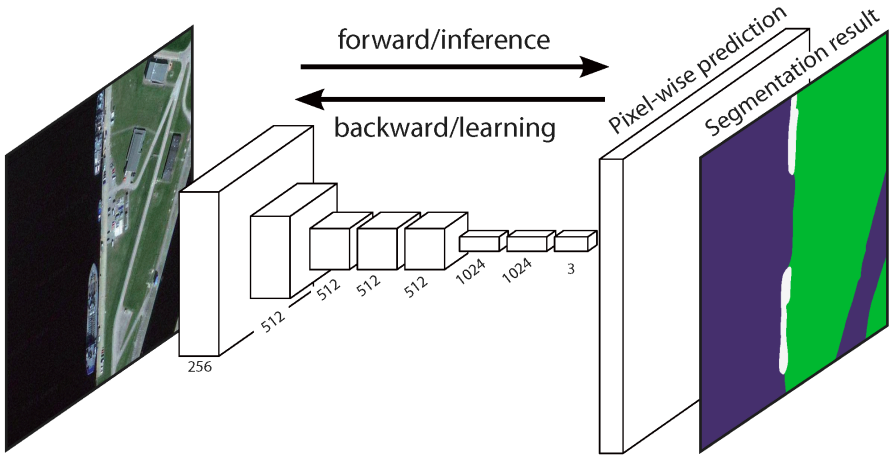


3 module pipeline:

1. Extract regions
2. Convolve all regions
3. Predict class for each region

- Modules generally trained separately
- Pixel classification done at prediction stage

Fully Convolutional NN

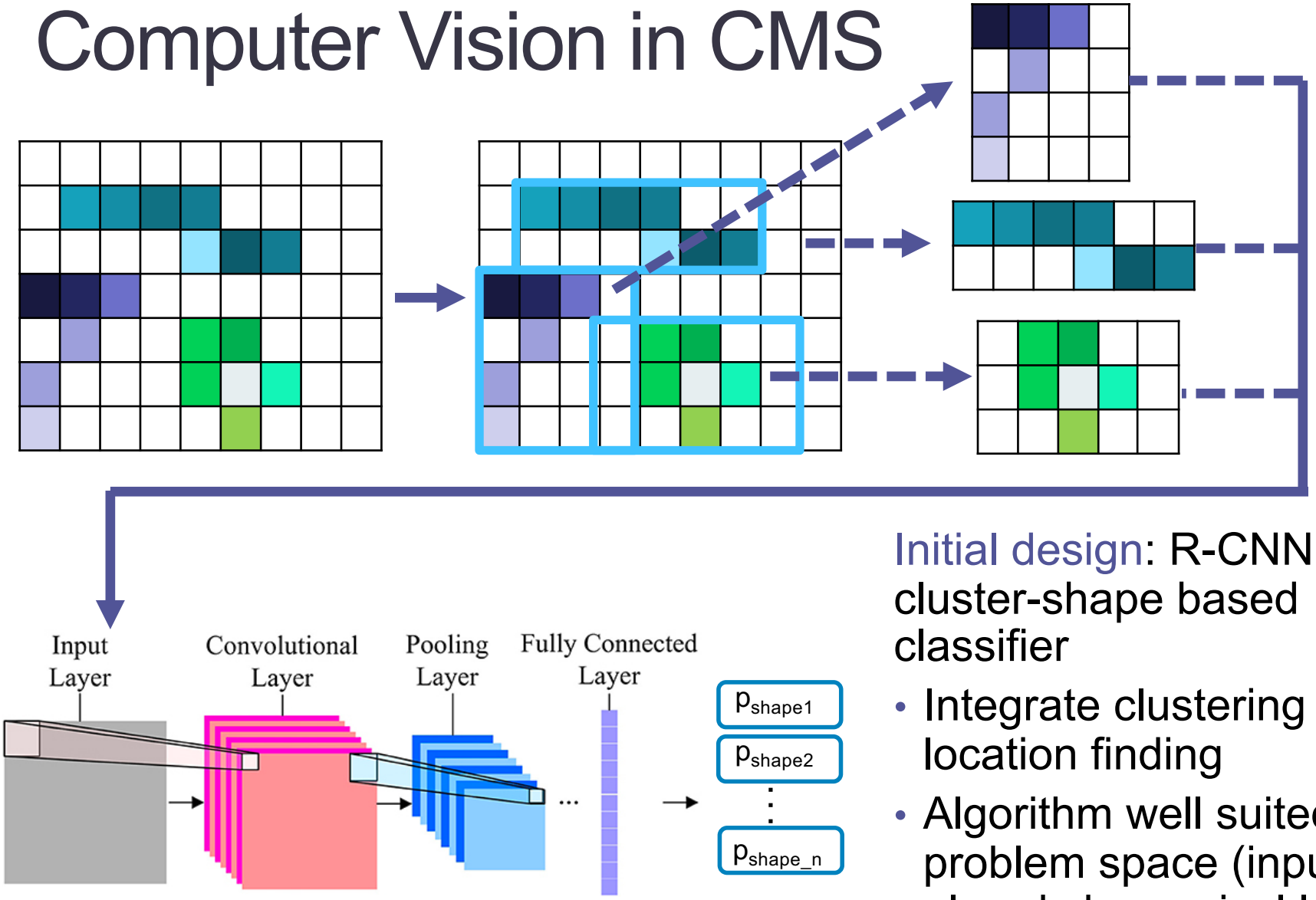


Pixel to pixel learning:

1. Convolve input image
2. Up-sample resulting representation
3. Predict labels for each pixel

- Essentially encoder/decoder pair

Computer Vision in CMS

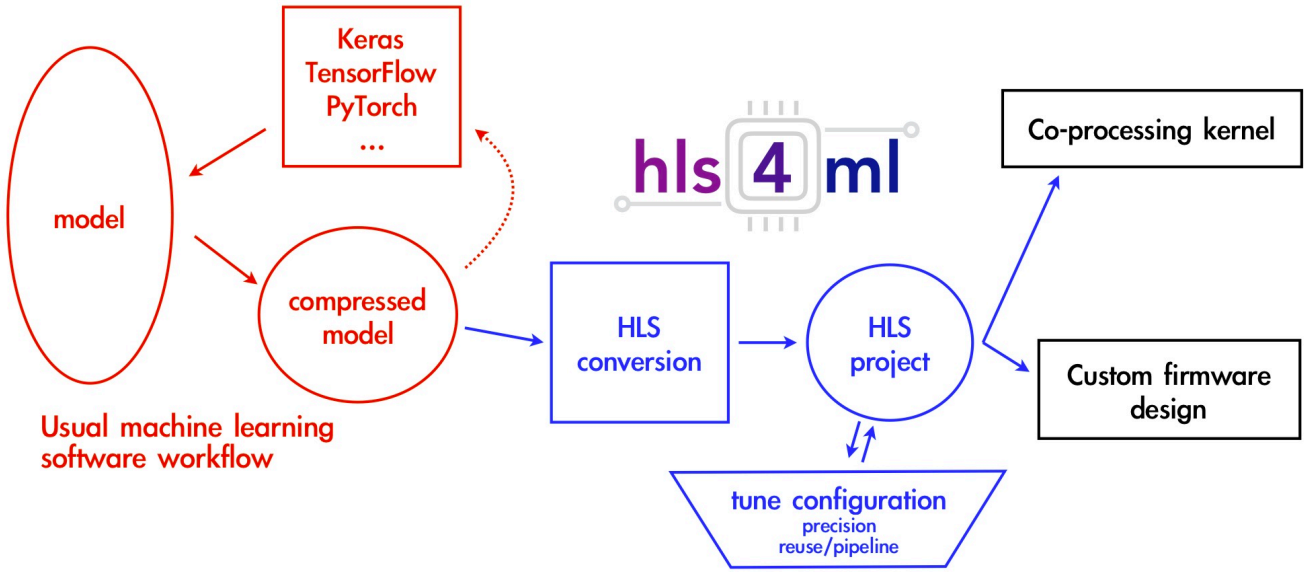


Initial design: R-CNN with cluster-shape based classifier

- Integrate clustering and location finding
- Algorithm well suited to problem space (inputs already have pixel labels)

Clustering at the HLT

- Once trained, full semantic segmentation pipeline can be implemented in firmware for use at the HLT
- Can leverage hardware acceleration methods
- Opensource HLS package hls4ml developed specifically for HEP applications on FPGAs
  - Fully-connected NNs already implemented, CNNs in beta testing



Conclusions

- Industry standard computer vision techniques can be leveraged for clustering in the CMS pixel detector
- Several opportunities for processing acceleration:
  - Critical for HL-LHC
  - Combine clustering and centroid resolution stages
  - Can accelerate inference with FPGAs
  - Could eliminate the need for separate fast and precise clustering algorithms
- Current status: developing selective search network for R-CNN pipeline based on YOLO methods
  - Can consider F-CNN architecture in parallel