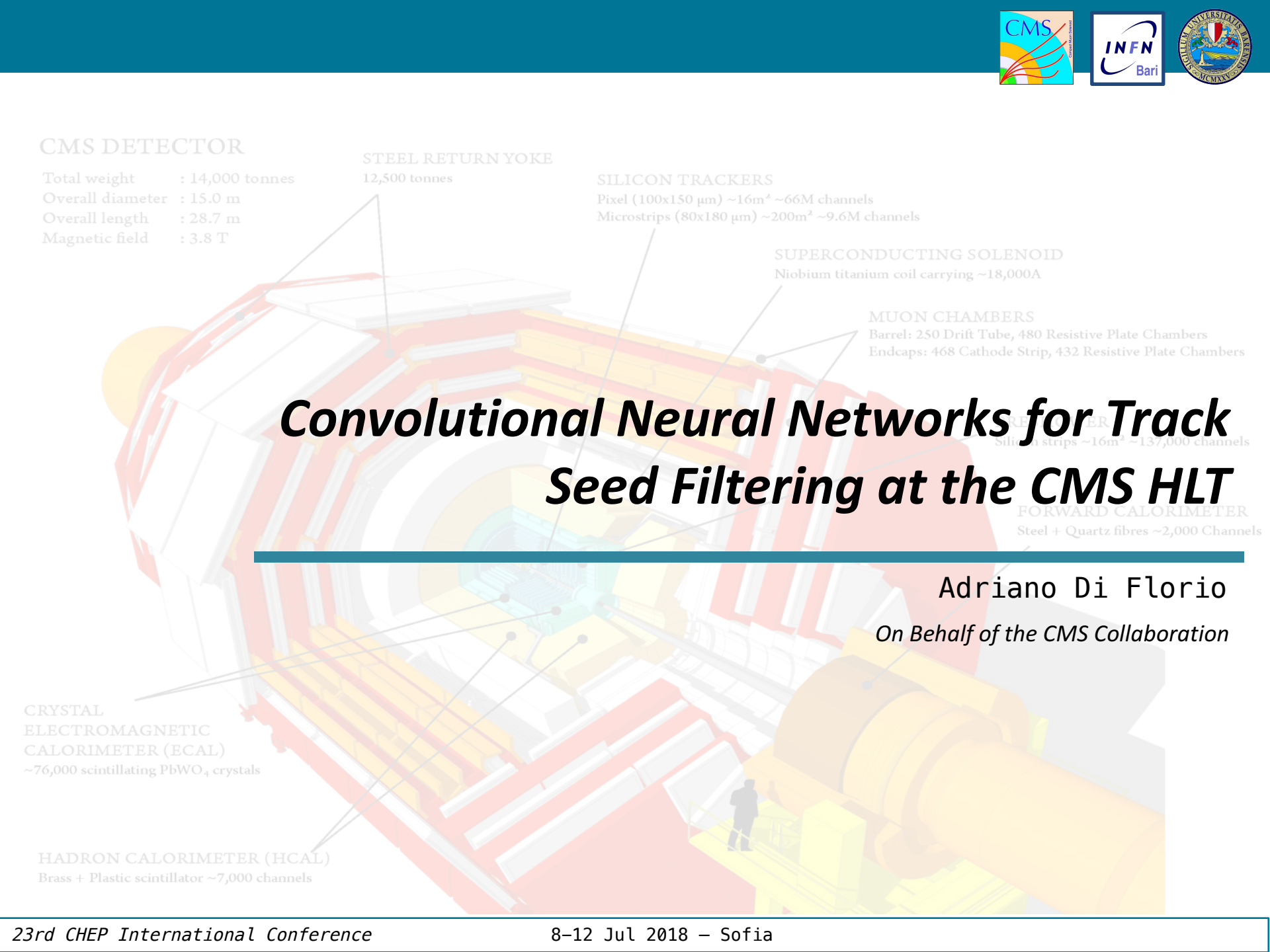


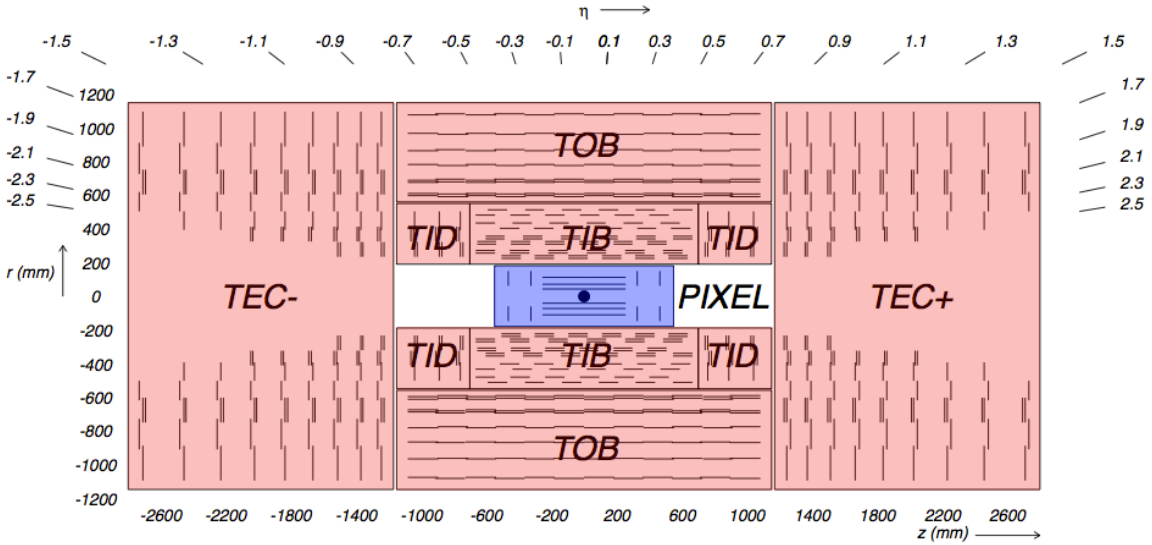
Convolutional Neural Networks for Track Seed Filtering at the CMS HLT

Adriano Di Florio

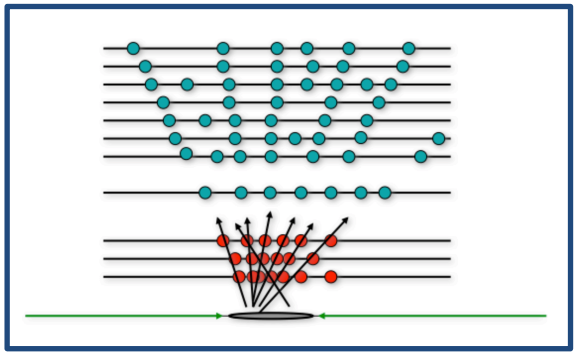
On Behalf of the CMS Collaboration

Track reconstruction @ CMS

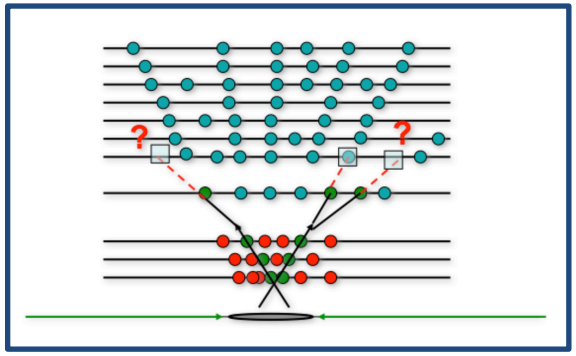
In **CMS** the tracking algorithm consists of an **iterative procedure**, in which tracks are reconstructed according to progressively looser quality criteria starting from hits on the **silicon tracker detector.**



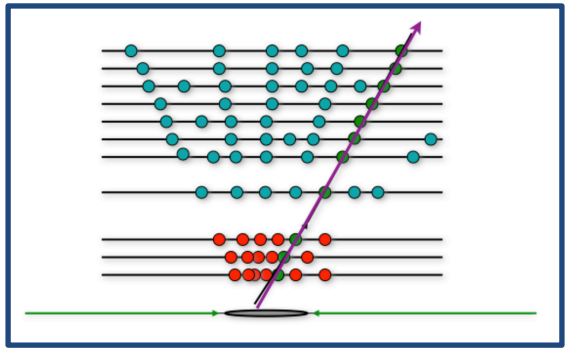
TRACKS RECONSTRUCTION @ CMS



Seeding



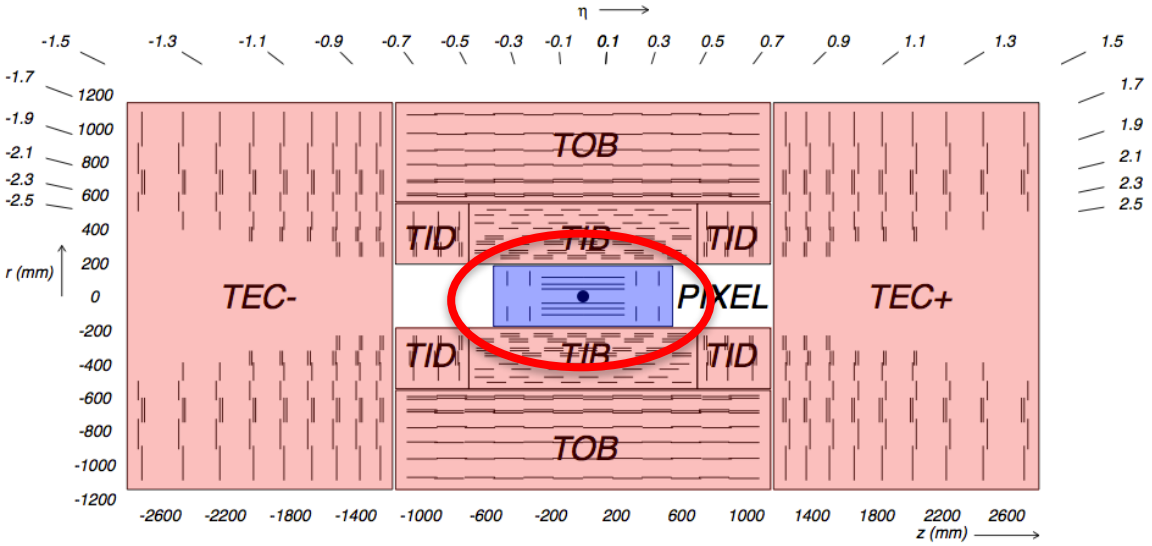
Tracks Building



Track fitting

Track reconstruction @ CMS HLT

In **CMS** the tracking algorithm consists of an **iterative procedure**, in which tracks are reconstructed according to progressively looser quality criteria starting from hits on the **silicon tracker detector.**



HIGH LEVEL TRIGGER (HLT)

- **100 KHz in / 1 KHz out**
- ~ 500 KB / event
- Processing time: ~30 ms
- Simplified global reconstruction
- Software implemented on CPUs

ONLY ABOUT **1000 EVENTS/SEC** [@ ~ 1 MB/EVENT] CAN BE RECORDED ON DISK

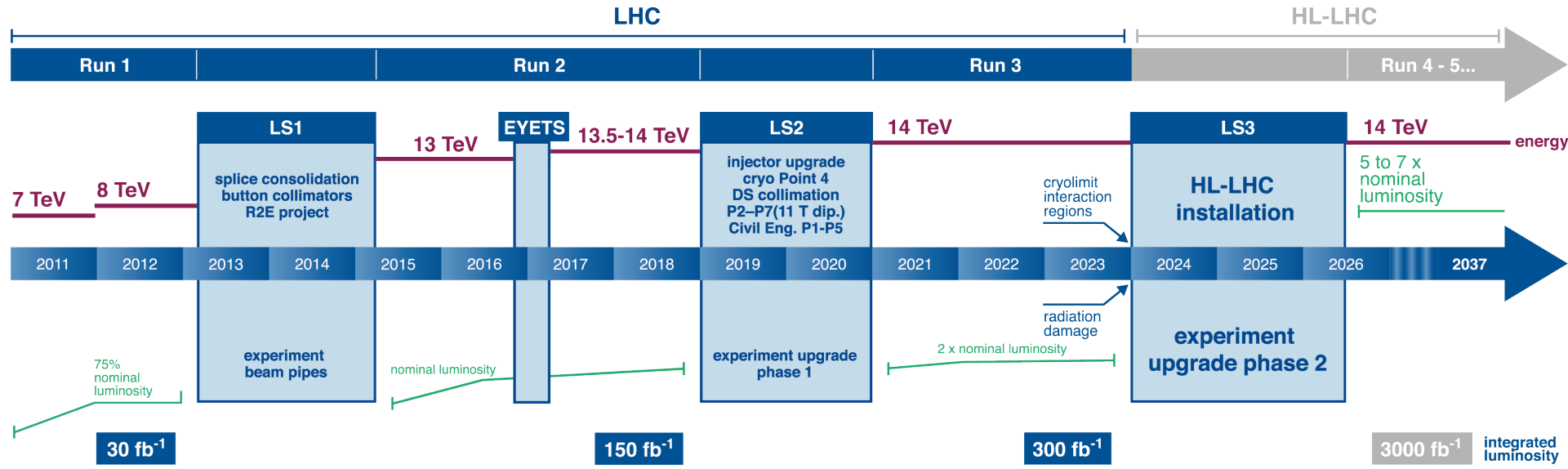
ONLINE RECONSTRUCTION (HLT)

Practically the same reconstruction procedure as the one run offline. It has to undergo stringent time limits : O(100) ms. It is based on **pixel-only reconstruction.**

Pixel Hits → **Doublets Seeds** → **Cellular Automaton** → **Tracks Fitting** → **Tracks Selection**

What's next?

LHC / HL-LHC Plan

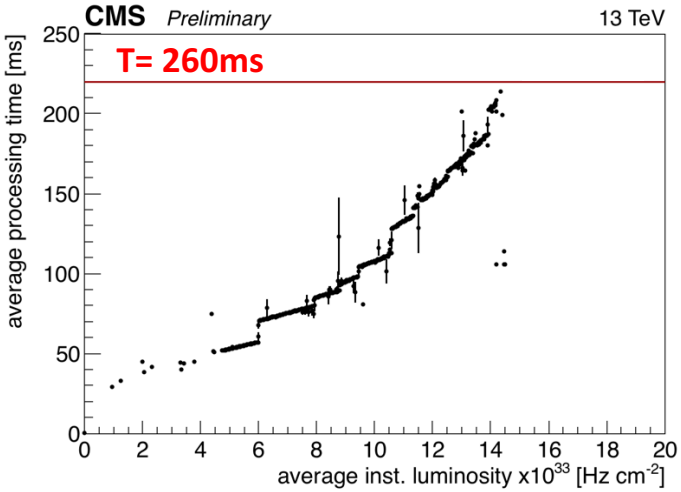


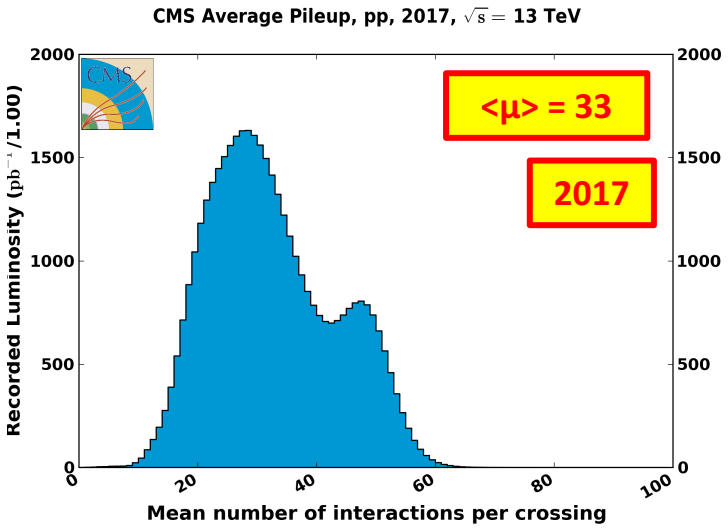
What's next?

INSTANTANEOUS LUMINOSITY & SIMULTANEOUS COLLISIONS (PILE-UP) INCREASE

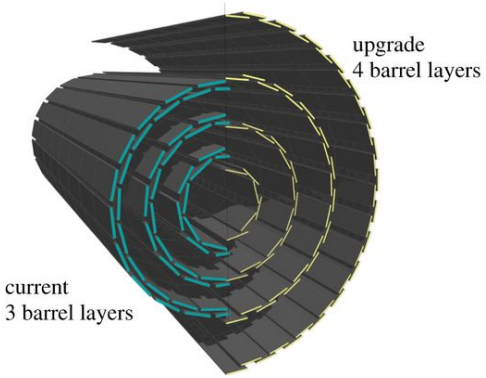
$\mathcal{L} = 5 \cdot 10^{34} cm^2 s^{-1}$

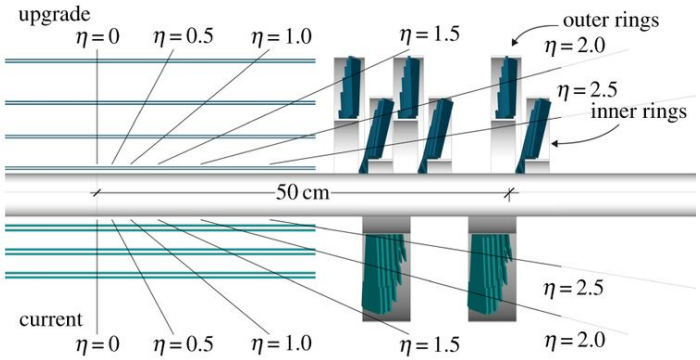
$< PU > \sim 200$





INCREASED DETECTOR COMPLEXITY (SINCE MARCH 2017)



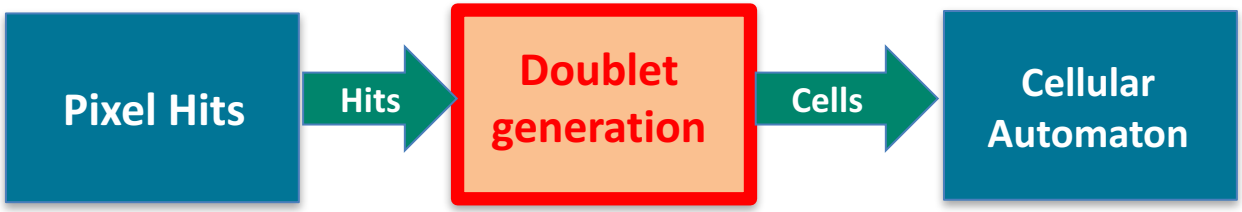


The already complex online and offline track reconstruction has to deal not only with a much more crowded environment but also with data coming from a more complex detector.

10 layers (6 endcap + 4 barrel)

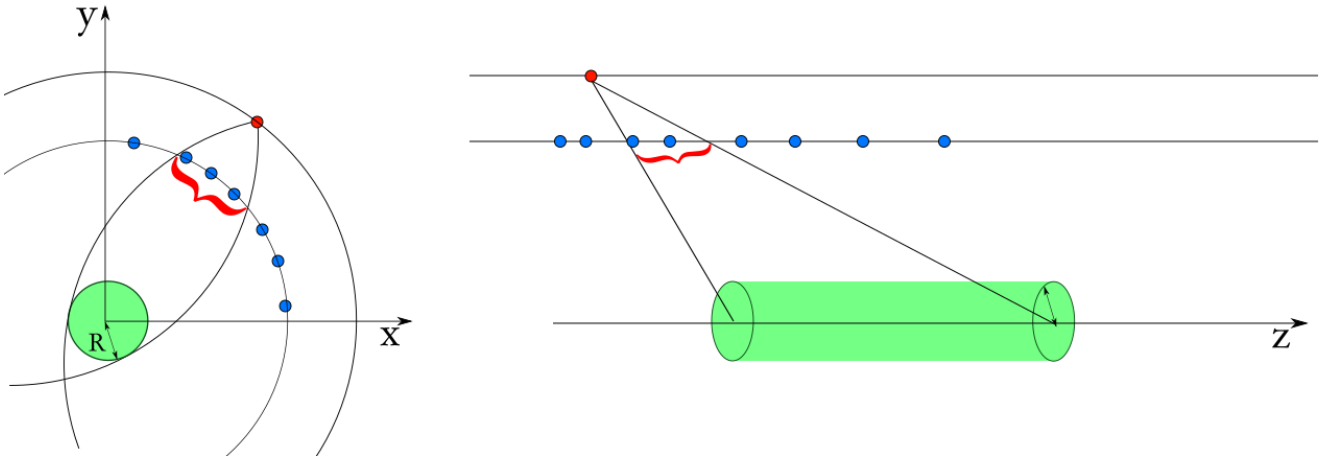
Doublets Generation

- **Doublet seeds generation:** bottleneck due to huge combinatorial background.

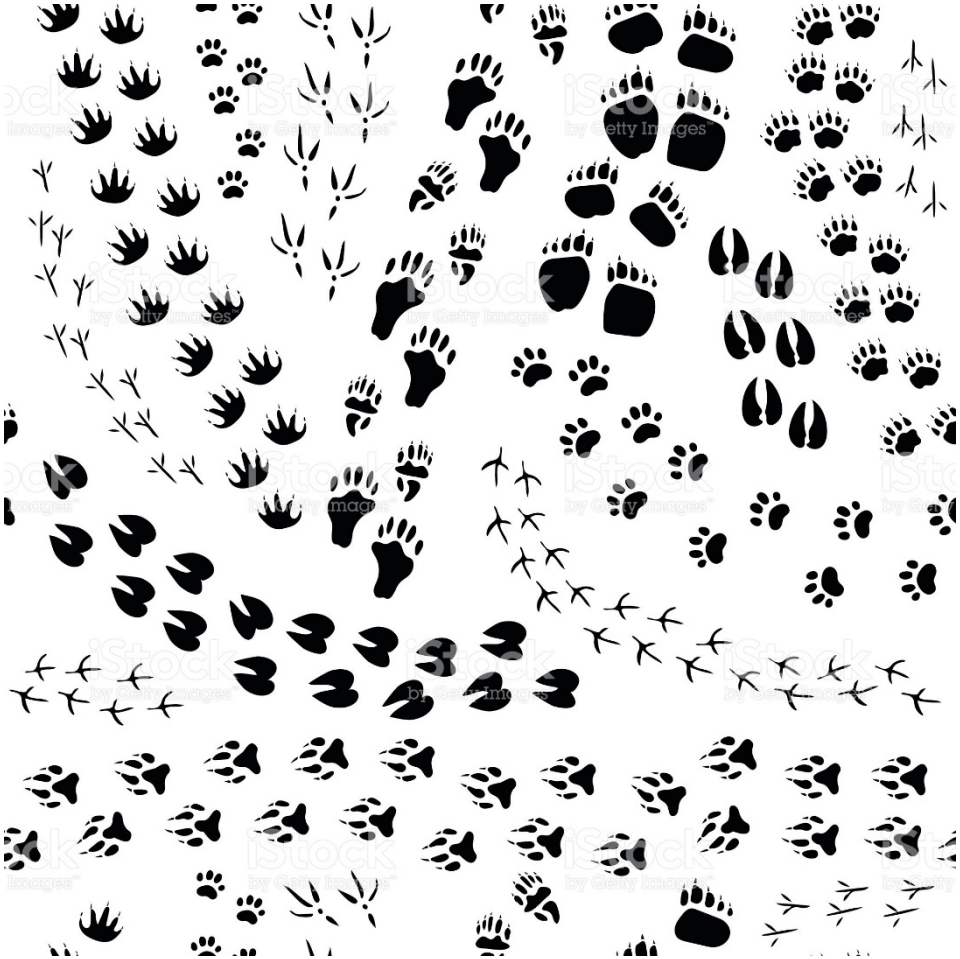


- For a single $t\bar{t}$ at $\sqrt{s} = 13\text{TeV}$ with $< PU > = 35$ simulated event: $O(10^5)$doublets produced with fake ratio $\sim O(100)$ corresponding to $O(1000)$ true doublets.

- But doublet selection is based **only on geometrical compatibilty checks.**

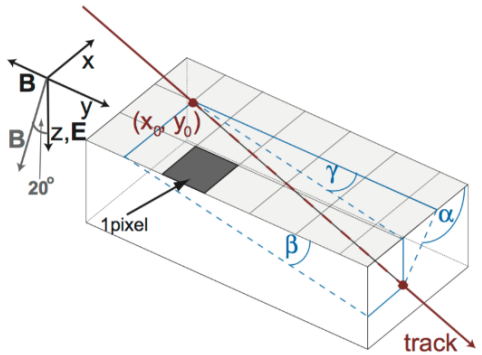


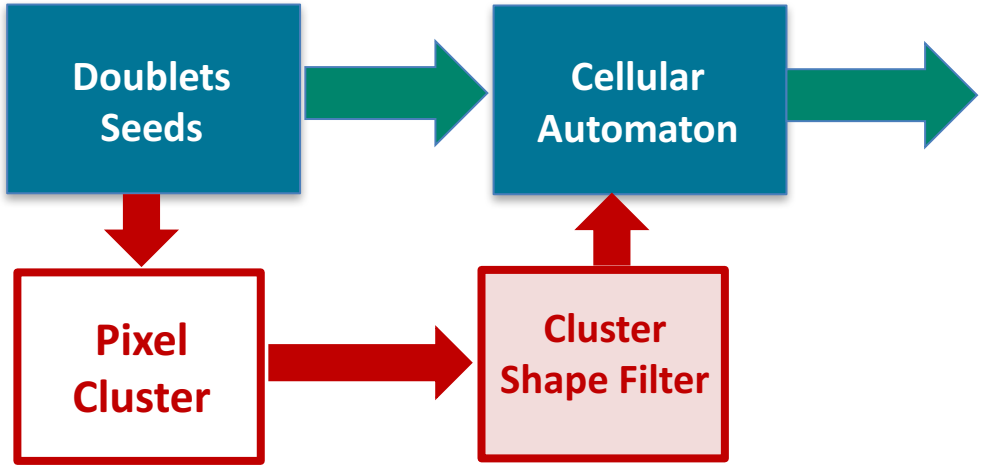
There is some more information…



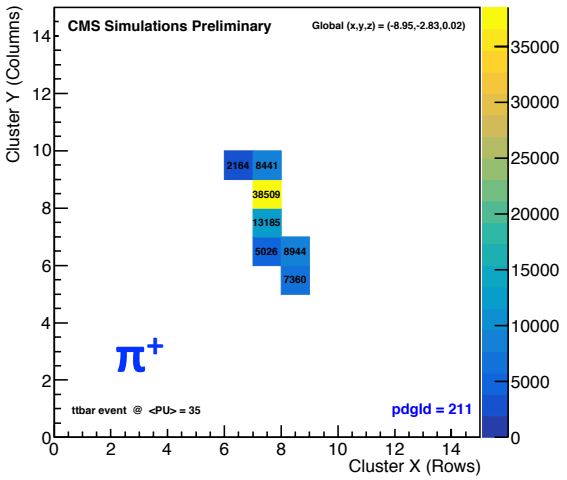
Pixel Clusters

- Each doublet is built from a couple of hits on the **silicon pixel tracker detector**. Each hit is not simply a point on the detector but it is a collection of **pixels (in** 2D) **on or off.** Each pixel is associated with an **ADC** level (16 bit) proportional to the **charge** deposited by a particle.

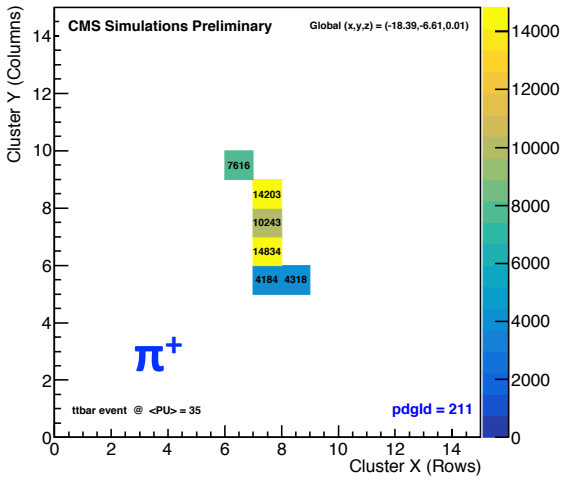




BPix1 - Inner Hit



BPix2 - Outer Hit

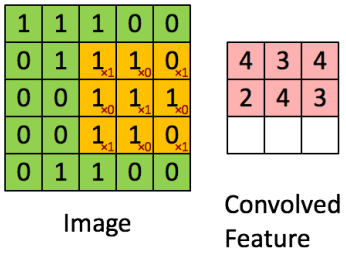


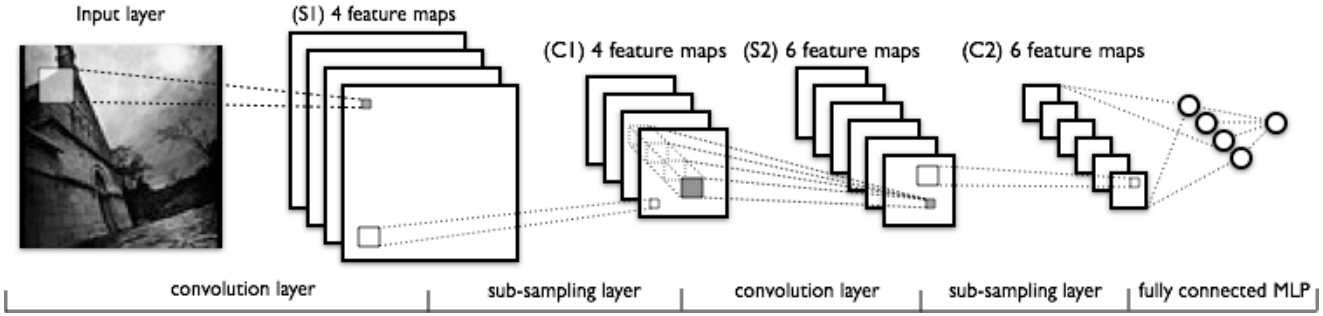
- Each hit is then a 2D pixel image centred on the centre of charge. (15x15)

Typical pattern recognition problem (true/fake classification): suitable for a Convolutional Neural Network approach

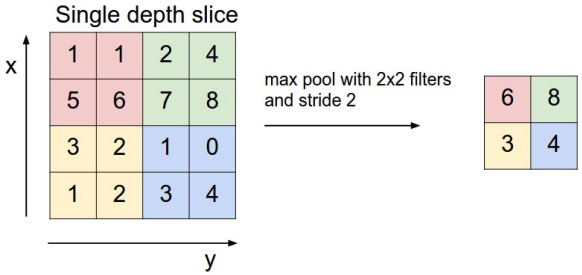
Convolutiona Neural Networks

- Convolutional Neural Networks are a specialized kind of neural networks for processing data that has a grid-like structure, such as 2D images. The building block of a CNNs is a layer that uses discrete convolution in place of general matrix multiplication.

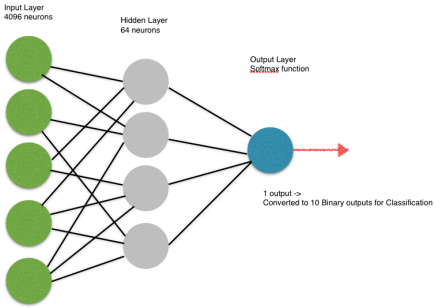




- **Pooling:** its function is to progressively reduce the spatial size of the representation.



- **Fully connected:** Neurons in a fully connected layer have full connections to all activations in the previous layer, as seen in regular Neural Networks. Reduce input to a unique score: ***softmax***.



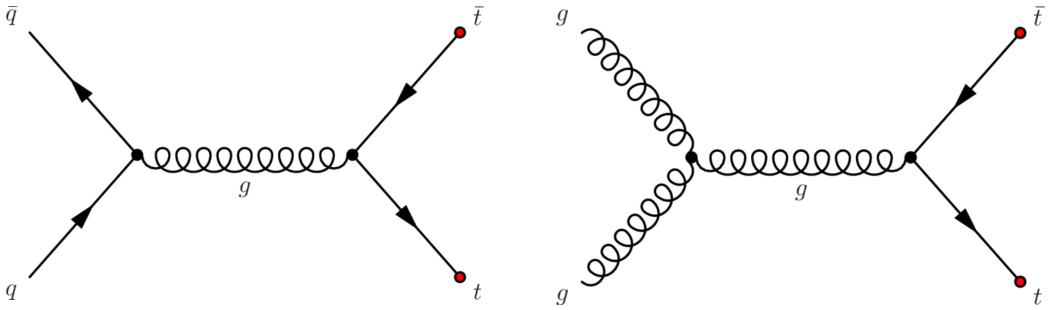
$$\sigma(\mathbf{z})_j = \frac{e^{z_j}}{\sum_{k=1}^{K} e^{z_k}}$$

per $j = 1, \ldots, K.$

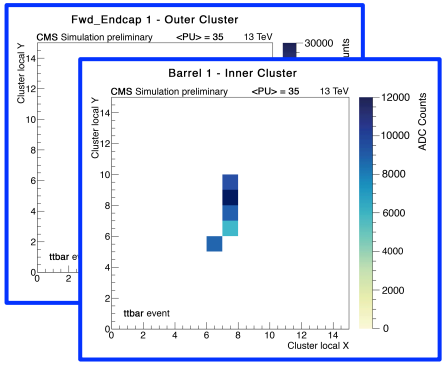
In our usecase the CNN acts as a **binary classifier (signal or background)** and reduce the whole picture to a single score correspodent to $\mathbf{p_{true}(x)}$.

Ttbar dataset

- Generation of $t\bar{t}$ at $\sqrt{s} = 13\text{TeV}$ with $< PU > = 35$ simulated events (via PYTHIA integrated in CMS reconstruction software, CMSSW): $O(10^5)$ doublets produced with *fake ratio* $\sim O(100)$ equals to a $O(1000)$ **true doublets**.



- Association **RECO - MC**
  1. **all matched tracking particles** track hits
  2. **all doublets** produced
  3. true doublets = doublets formed by hits from the same tracking particle



To each doublet are associated:

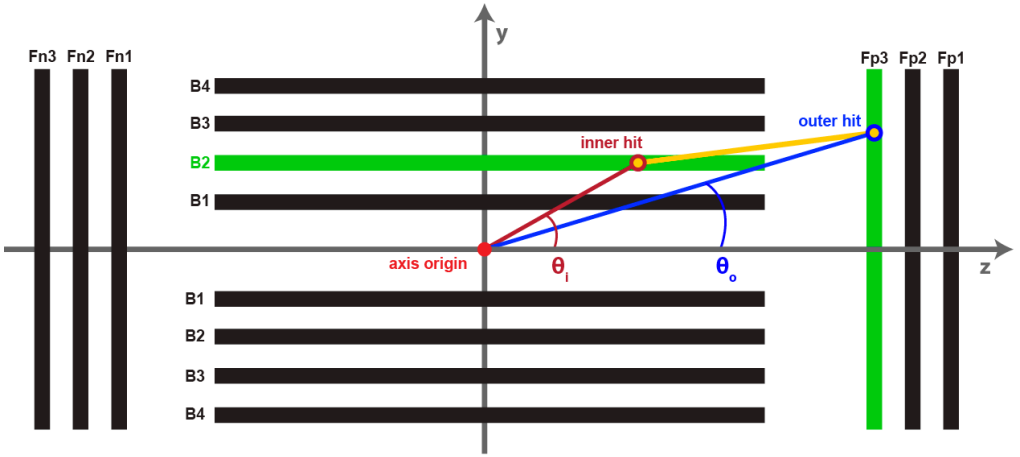
- two 15x15 images (one for inner and one for outer hit)
- set of local informations (x,y,z, charge,, …)

- **2.5 millions doublets generated (about 1000 events)**

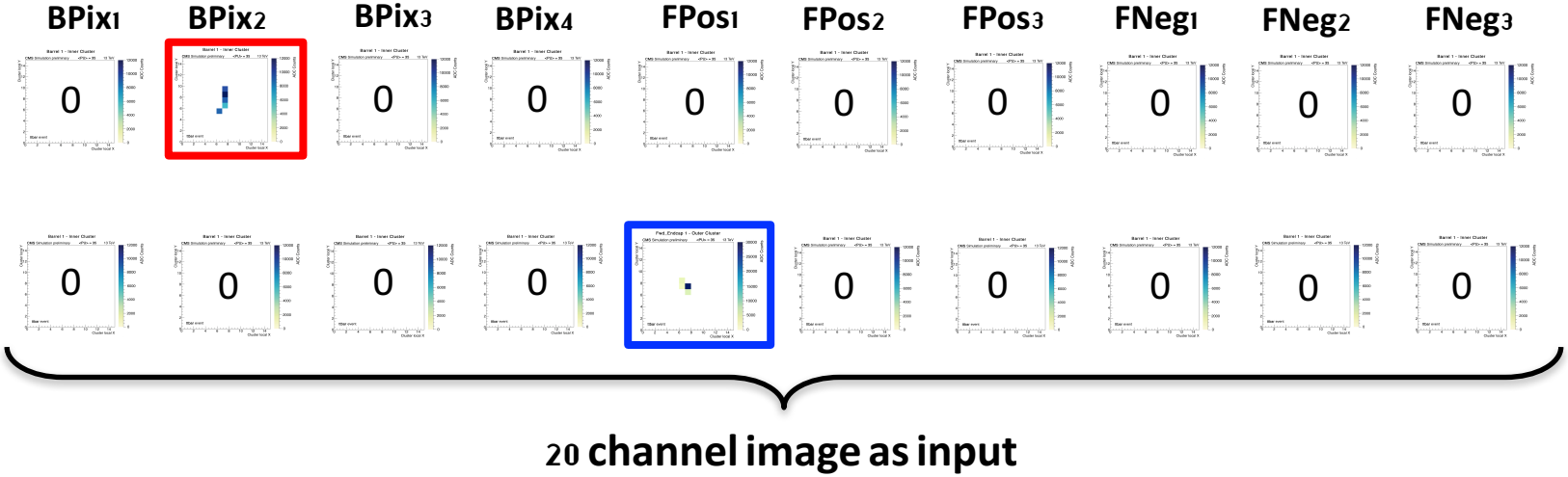
Data prepocessing

- Make of use of the layer structure of the detector to extend each single doublet from two pictures to 20 channels, one per each layer (6 barrel + 4 endcap)

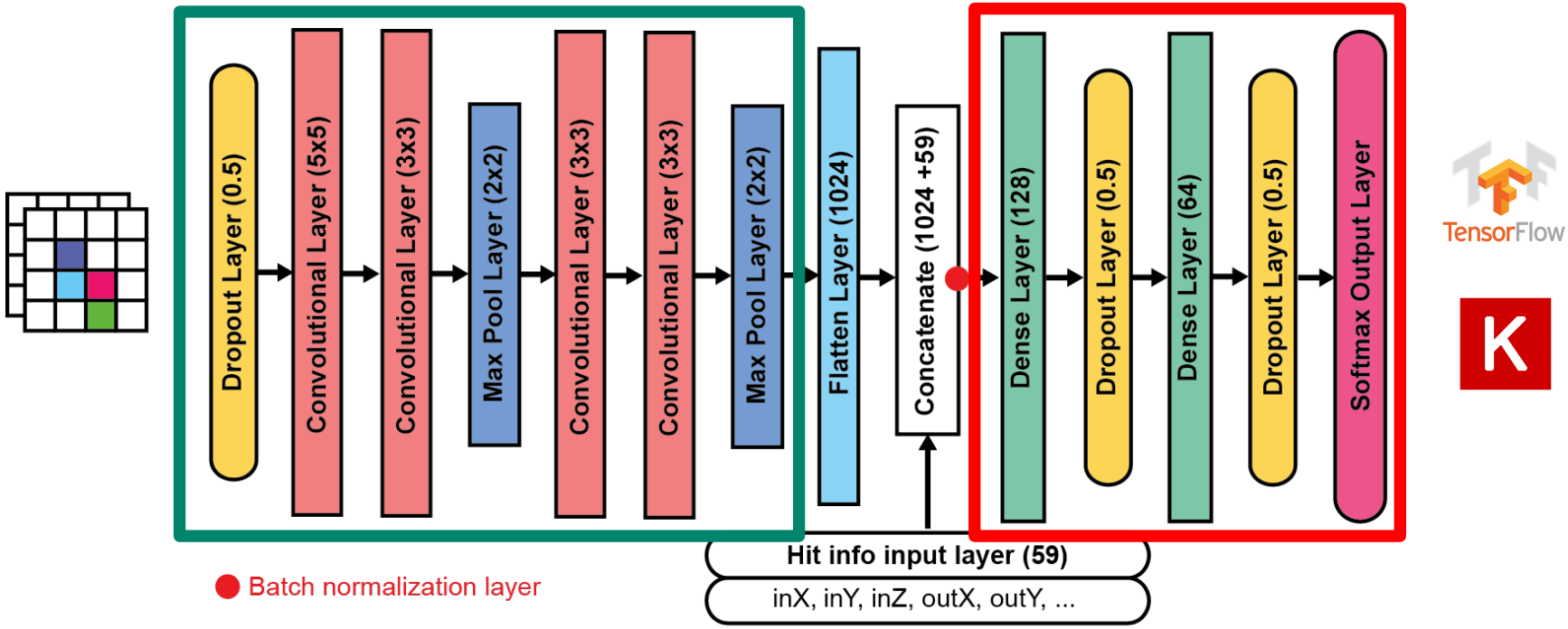
- **Channels:** a common picture is usually a superimposition of different color levels. **E.g. RGB levels.**



- **E.g.** A doublet on *barrel2* and *forward endcap3*



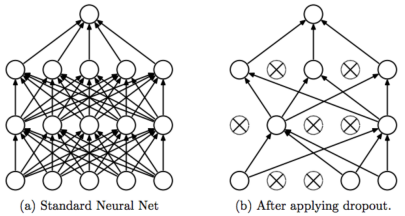
The model



- A single doublet is a **20 levels** image. The model *concatenates:*
  - *CNN architecture* stack of convolutional layers (4) and max pooling (2)
  - *"DENSE" architecture* dense layers (2) fed with the 1-dim reduced images + **doublets infos** (inX,inY,inZ)

- **Dropouts & early stopping** to prevent overfitting

- **Train & val** datasets balanced (0.5)


(a) Standard Neural Net (b) After applying dropout.

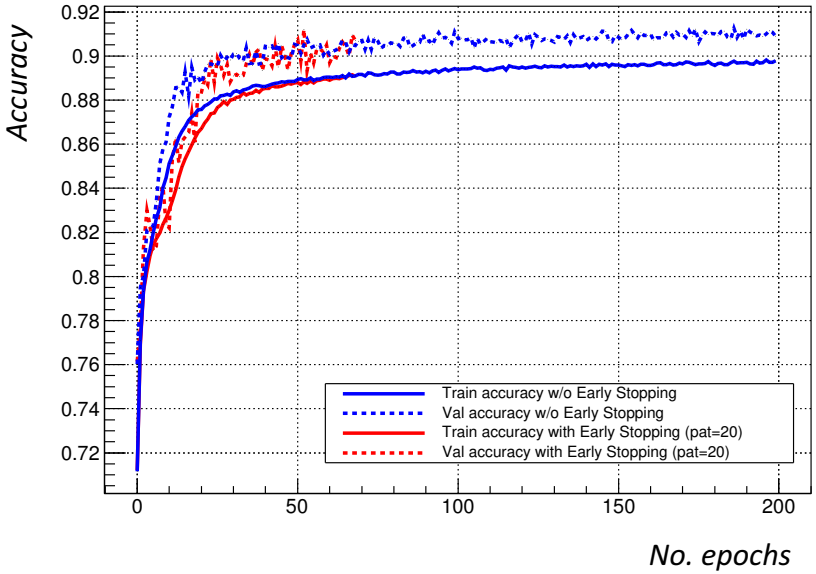
Results - I

- Results on 2.5 millions **doublets training**

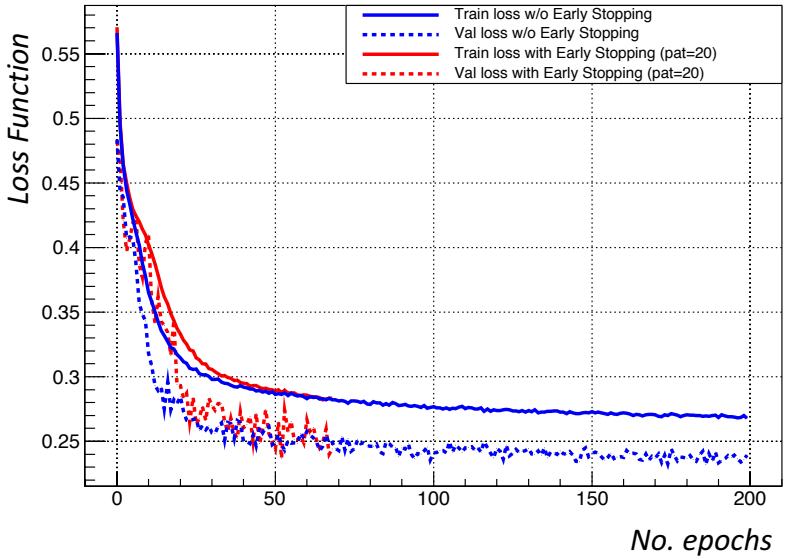
$$ACC = \frac{VP + VN}{P + N} > 0.90$$

$$H(p,q) = -\sum_{x} p(x)\,\log q(x).$$

Accuracy (training on 250k dataset)



Cross Entropy (training on 250k dataset)



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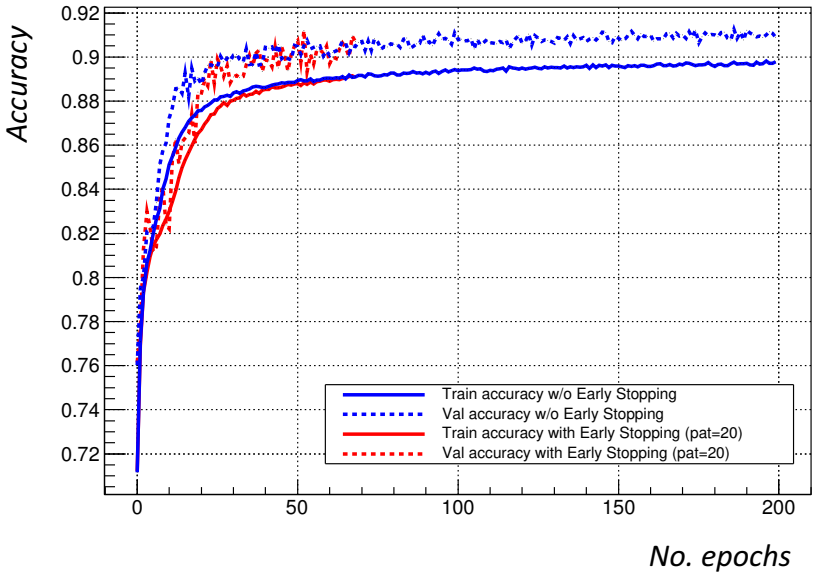

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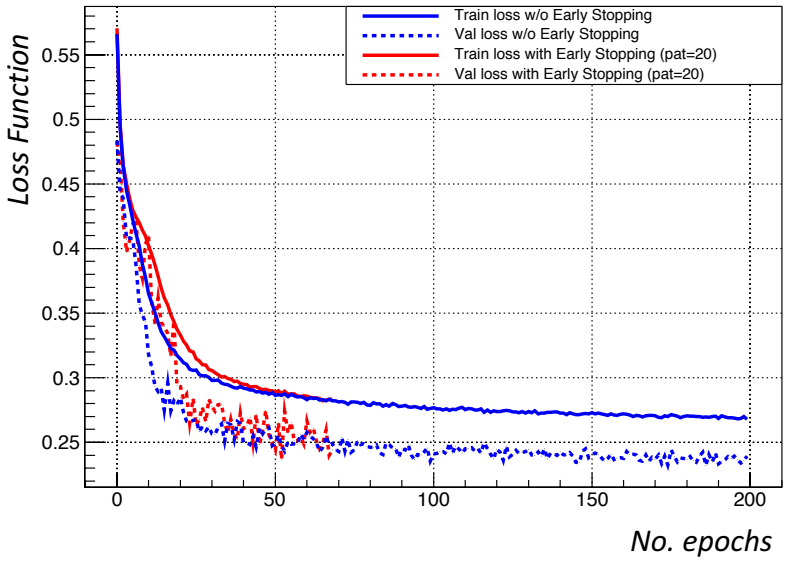


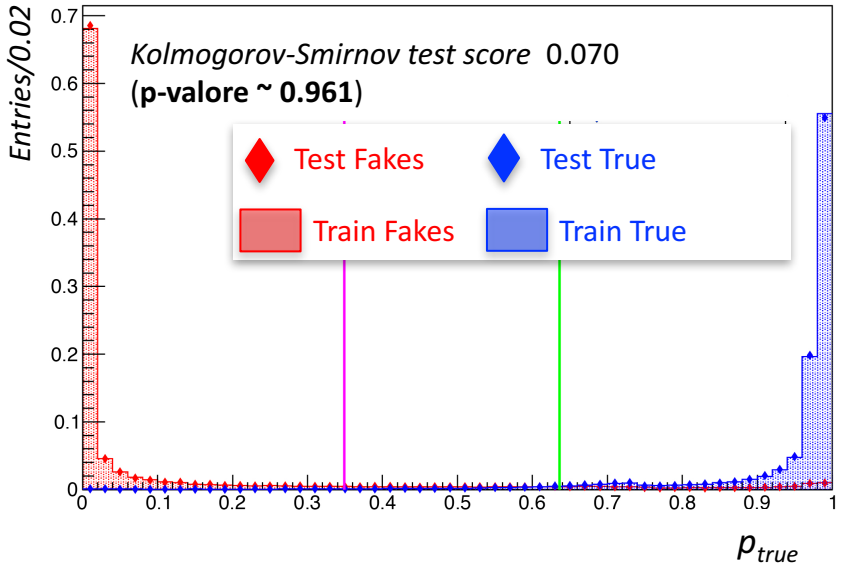
Whole Dataset Training	@ Max Acc				Rej @ Eff		Eff @ Rej	
	AUC	ACC	Efficiency	Rejection	0.99	0.999	0.99	0.5
Test	0.921	0.90	0.96	0.91	0.81	0.65	0.54	0.99
Val	0.919	0.90	0.95	0.91	0.81	0.66	0.54	0.99
Train	**0.920**	**0.91**	**0.96**	**0.91**	**0.81**	**0.65**	**0.55**	**0.99**

Results - II

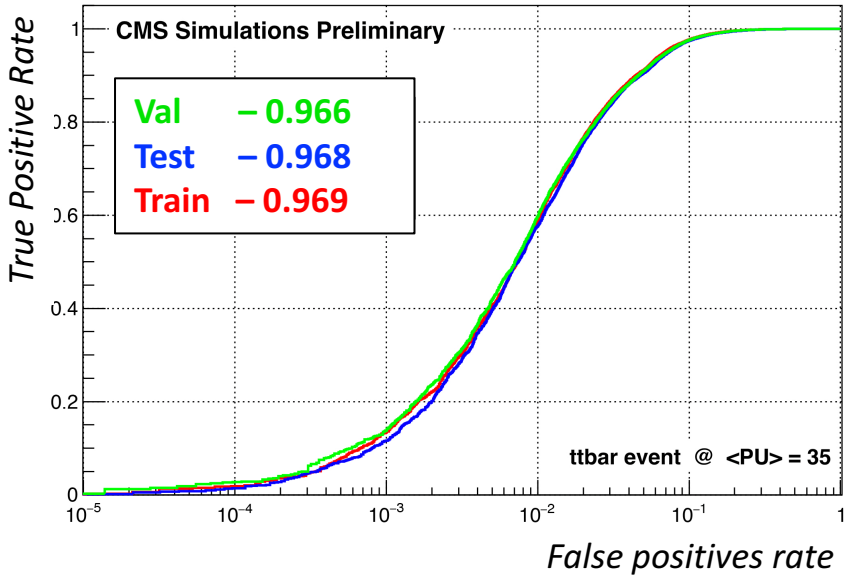
- Results on 2.5 millions **doublets training**

$$FVP = \frac{VP}{P} \quad \textit{Sensitivity} \qquad FFP = \frac{FP}{P} \quad \textit{1-Specificity}$$

Classifier output score (training on whole dataset)



ROC Curve (training on whole dataset)



Whole Dataset Training	@ Max Acc				Rej @ Eff		Eff @ Rej	
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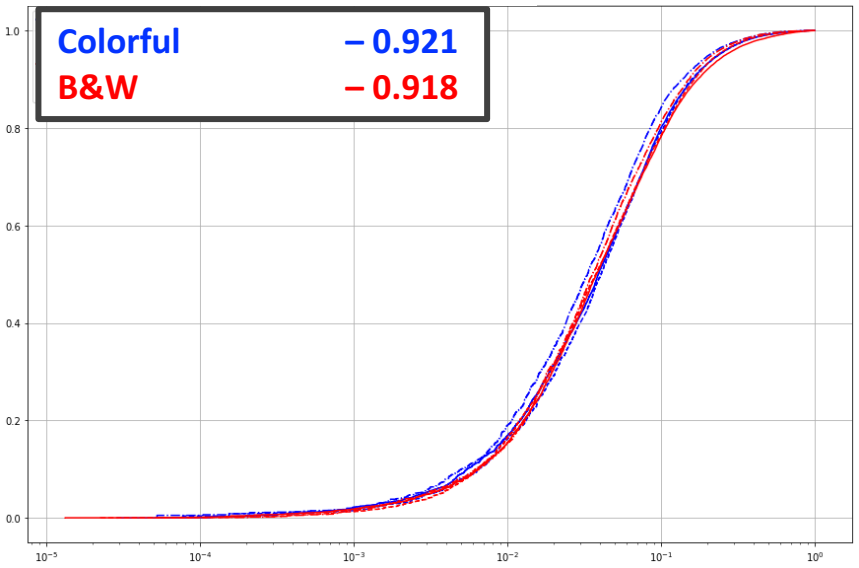
Train	**0.920**	**0.91**	**0.96**	**0.91**	**0.81**	**0.65**	**0.55**	**0.99**

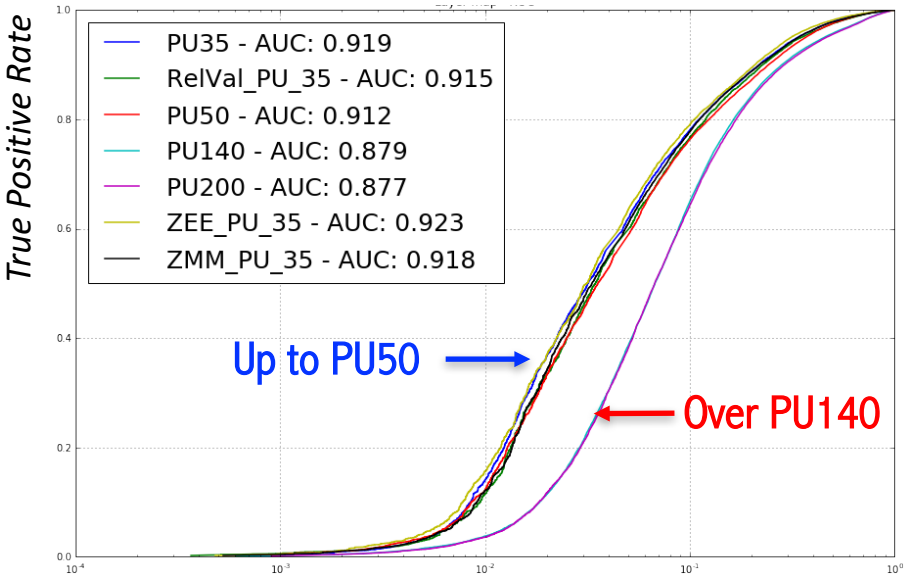
Results - III

- Further crosschecks

ROC Curve (training on 250k sample)



ROC Curve (full TTbar PU35 dataset training)

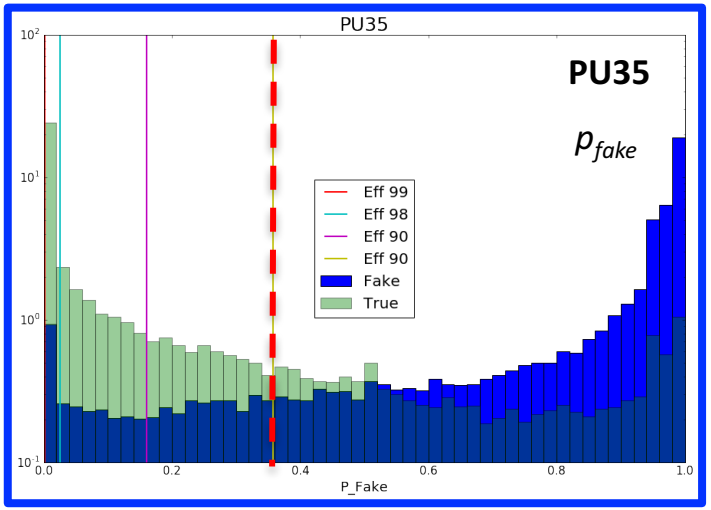


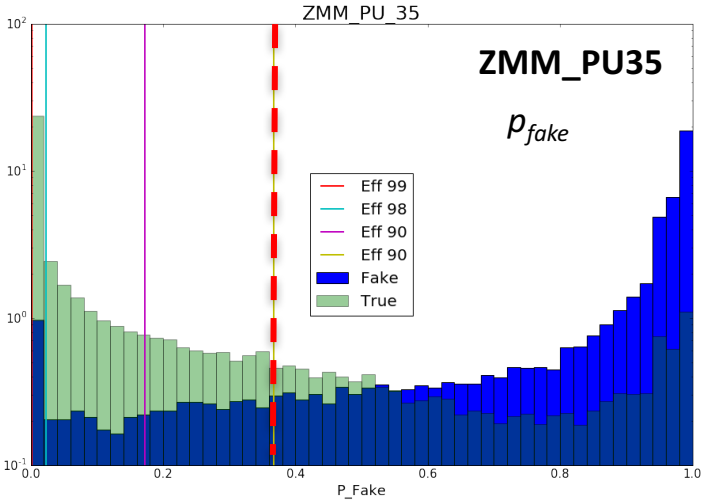
- Setting ADC levels to **0** or **1** only for turned **off** and **on pixels.** Black and white model.
- Comparing with the colorful model with ADC levels
- Testing with other **MC PYTHIA** recipes (see backup)
- Testing with **higher pile up** conditions

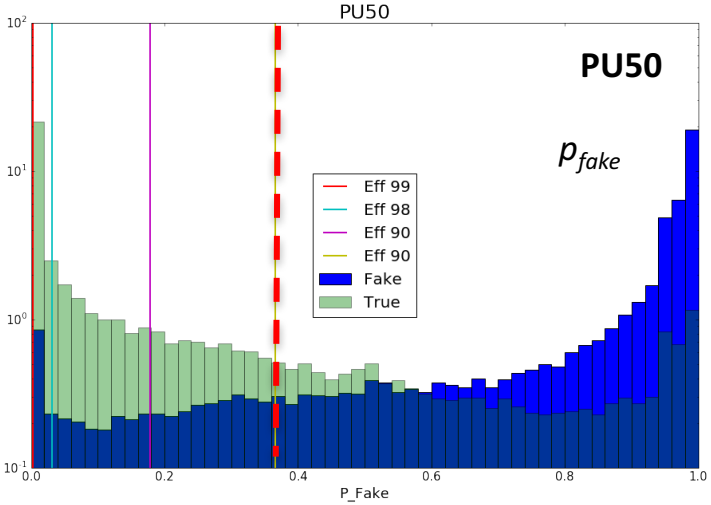
Results - IV

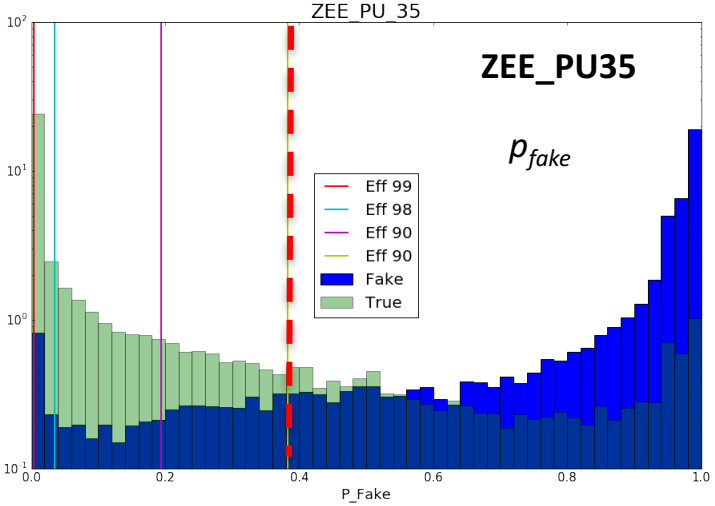
- Output scores with thresholds **99% efficiency threshold**

Training environment









Conclusions and perspectives

- CNN techniques for mitigating combinatorial explosion look very promising
- Ongoing work and next steps
  - **Integration** in the CMS reconstruction framework
  - Verification of the **effect** on the downstream track reconstruction
  - Exploration of different hardware architecture for **fast inference**
  - Input variables **ranking**
  - Possible extension to **PID** @ silicon pixel detector

THANK YOU

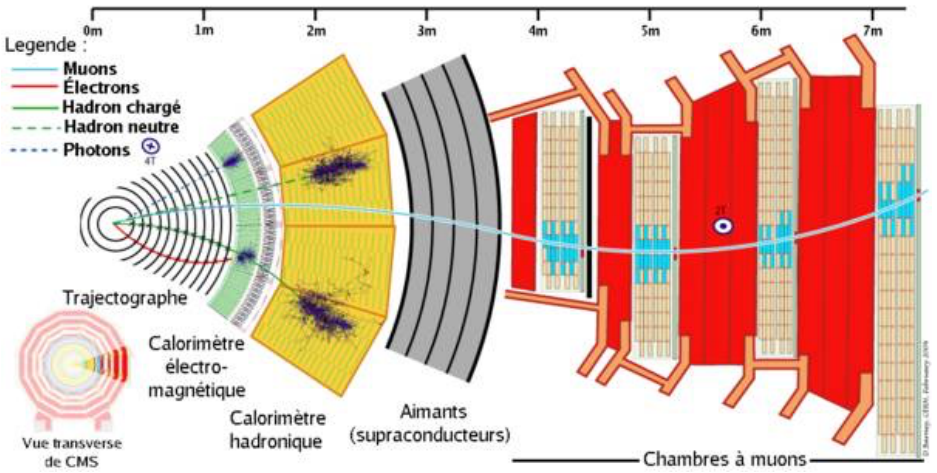
"I am putting myself to the fullest possible use, which is all I think that any conscious entity can ever hope to do"

HAL9000

BACKUP

Two level event selection @ CMS

The Compact Muon Solenoid (CMS) is a general purpose detector designed for the precision measurement of leptons, photons, and jets, among other physics objects, in proton–proton as well as heavy ion collisions at the CERN LHC



ONLY ABOUT **1000 EVENTS/SEC** [@ ~ 1 MB/EVENT] CAN BE RECORDED ON DISK

L1 TRIGGER

- 40 MHz in / 100 KHz out
- ~ 500 KB / event
- Processing time: ~10 µs
- Based on coarse local reconstructions
- FPGAs / Hardware implemented

HIGH LEVEL TRIGGER (HLT)

- 100 KHz in / 1 KHz out
- ~ 500 KB / event
- Processing time: ~30 ms
- **Based on simplified global reconstructions**
- Software implemented on CPUs

The doublet features

450 ADC pixels [2x15x15 pads]

inPixLab = ["inPix1","inPix2", . . . , "inPix224","inPix225"]

outPixLab = ["outPix1","outPix2", . . . ,"outPix224","outPix225"]

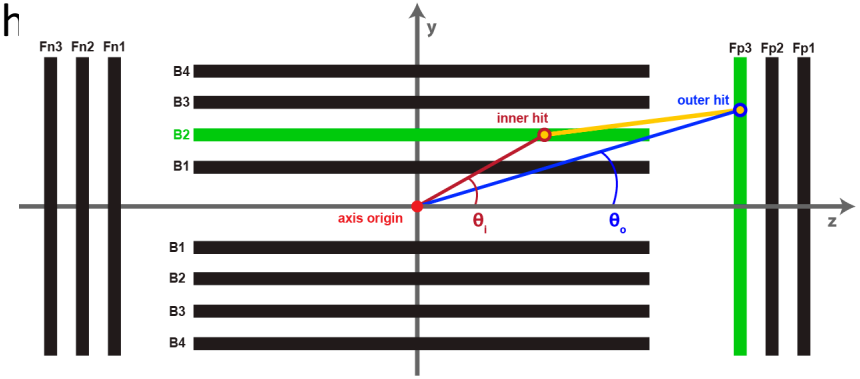
63 features defined for each doublet [*true* or *fake*] **that <u>may</u> be used as additional features** to the pixel pad

headLab = ["run","evt","detSeqIn","detSeqOut","inX","inY","inZ","outX","outY","outZ", "inPhi","inR", "outPhi", "outR", "detCounterIn", "detCounterOut", "isBarrelIn", "isBarrelOut", "layerIn", "ladderIn", "moduleIn", "sideIn","diskIn", "panelIn","bladeIn","" layerOut","ladderOut","moduleOut","sideOut","diskOut","panelOut","bladeOut","isBigIn","isEdgIn","isBadIn","isBigOut", "isEdgOut","isBadOut", "isFlippedIn","isFlippedOut", "iCSize","pixInX","pixInY", "inClusterADC", "iZeroADC","iCSize", "iCSizeX","iCSizeY", "iOverFlowX", "iOverFlowY","oCSize","pixOutX", "pixOutY","outClusterADC", "oZeroADC","oCSize","oCSizeX","oCSizeY"","oOverFlowX","oOverFlowY","diffADC"]

24 labels defined only for MC matched doublets

tailLab = ["idTrack","px","py","pz","pt","mT","eT","mSqr","rapidity","etaTrack", "phi", "pdgId", "charge", "noTrackerHits", "noTrackerLayers","dZ","dXY","Xvertex","Yvertex", "Zvertex", "bunCross", "isCosmic", "chargeMatch", "sigMatch

Normalization with incident angle



QCD processes recipe

```
*-------  PYTHIA Process Initialization  ------------------------*
|                                                                |
| We collide p+ with p+ at a CM energy of 1.300e+04 GeV          |
|                                                                |
|----------------------------------------------------------------|
|                                                |               |
| Subprocess                                 Code |   Estimated   |
|                                                |    max (mb)   |
|                                                |               |
|----------------------------------------------------------------|
|                                                |               |
| g g -> g g                                  111 |   2.865e-07   |
| g g -> q qbar (uds)                         112 |   7.083e-09   |
| q g -> q g                                  113 |   1.019e-06   |
| q q(bar)' -> q q(bar)'                      114 |   3.727e-07   |
| q qbar -> g g                               115 |   3.415e-09   |
| q qbar -> q' qbar' (uds)                    116 |   2.381e-09   |
| g g -> c cbar                               121 |   2.361e-09   |
| q qbar -> c cbar                            122 |   7.937e-10   |
| g g -> b bbar                               123 |   2.361e-09   |
| q qbar -> b bbar                            124 |   7.936e-10   |
|                                                |               |
*-------  End PYTHIA Process Initialization ----------------------*
```

```
--------  PYTHIA Event Listing  (hard process)  -----------------------------------------------------------------------------

   no        id   name            status     mothers    daughters     colours      p_x        p_y        p_z        e          m
    0        90   (system)          -11      0     0     0     0     0     0       0.000      0.000      0.000  13000.000  13000.000
    1      2212   (p+)              -12      0     0     3     0     0     0       0.000      0.000   6500.000   6500.000      0.938
    2      2212   (p+)              -12      0     0     4     0     0     0       0.000      0.000  -6500.000   6500.000      0.938
    3        21   (g)               -21      1     0     5     6   101   102       0.000      0.000   1011.756   1011.756      0.000
    4        21   (g)               -21      2     0     5     6   103   101       0.000      0.000   -125.216    125.216      0.000
    5         6   (t)               -22      3     4     7     8   103     0     -89.550    -23.812    -28.501    200.827    175.878
    6        -6   (tbar)            -22      3     4     9    10     0   102      89.550     23.812    915.041    936.145    174.589
    7        24   (W+)              -22      5     0    11    12     0     0       3.932     30.665    -30.680     92.502     81.606
    8         5   b                  23      5     0     0     0   103     0     -93.481    -54.477      2.179    108.325      4.800
    9       -24   (W-)              -22      6     0    13    14     0     0     125.765     29.471    595.533    614.505     79.196
   10        -5   bbar               23      6     0     0     0     0   102     -36.215     -5.659    319.508    321.640      4.800
   11        -1   dbar               23      7     0     0     0     0   104      11.092     45.836     10.255     48.262      0.330
   12         2   u                  23      7     0     0     0   104     0      -7.160    -15.171    -40.934     44.240      0.330
   13         3   s                  23      9     0     0     0   105     0      27.651    -20.416     75.613     83.061      0.500
   14        -4   cbar               23      9     0     0     0     0   105      98.114     49.887    519.919    531.444      1.500
                                Charge sum:  0.000           Momentum sum:       0.000      0.000    886.540   1136.972    711.865

--------  End PYTHIA Event Listing  -----------------------------------------------------------------------------------------
```

TTbar processes recipe

```
*-------  PYTHIA Process Initialization  ------------------------*
|                                                                |
| We collide p+ with p+ at a CM energy of 1.300e+04 GeV          |
|                                                                |
|----------------------------------------------------------------|
|                                                  |             |
| Subprocess                                  Code |   Estimated |
|                                                  |    max (mb) |
|                                                  |             |
|----------------------------------------------------------------|
|                                                  |             |
| g g -> t tbar                                601 |   7.216e-06 |
| q qbar -> t tbar                             602 |   9.331e-07 |
|                                                                |
*-------  End PYTHIA Process Initialization ---------------------*
```

```
--------  PYTHIA Event Listing  (hard process)  -----------------------------------------------------------------------------------

   no        id   name            status     mothers   daughters     colours      p_x        p_y        p_z        e          m
    0        90   (system)          -11      0     0     0     0     0     0       0.000      0.000      0.000  13000.000  13000.000
    1      2212   (p+)              -12      0     0     3     0     0     0       0.000      0.000   6500.000   6500.000      0.938
    2      2212   (p+)              -12      0     0     4     0     0     0       0.000      0.000  -6500.000   6500.000      0.938
    3        21   (g)               -21      1     0     5     6   101   102       0.000      0.000   1636.544   1636.544      0.000
    4        21   (g)               -21      2     0     5     6   103   104       0.000      0.000   -538.232    538.232      0.000
    5        21   g                  23      3     4     0     0   101   104     187.257    693.162   1249.420   1441.037      0.000
    6        21   g                  23      3     4     0     0   103   102    -187.257   -693.162   -151.107    733.739      0.000
                                 Charge sum:  0.000           Momentum sum:       0.000      0.000   1098.312   2174.776   1877.062

--------  End PYTHIA Event Listing  -----------------------------------------------------------------------------------------------
```

ZEE processes recipe

```
*-------  PYTHIA Process Initialization  --------------------------*
|                                                                   |
| We collide p+ with p+ at a CM energy of 1.300e+04 GeV             |
|                                                                   |
|-------------------------------------------------------------------|
|                                                |                  |
| Subprocess                                Code |    Estimated     |
|                                                |     max (mb)     |
|                                                |                  |
|-------------------------------------------------------------------|
|                                                |                  |
| f fbar -> gamma*/Z0                        221 |    3.845e-06     |
|                                                |                  |
*-------  End PYTHIA Process Initialization ----------------------*
```

```
--------  PYTHIA Event Listing  (hard process)  -----------------------------------------------------------------------------

    no        id  name            status     mothers   daughters     colours      p_x        p_y        p_z        e          m
     0        90  (system)          -11      0     0     0     0     0     0      0.000      0.000      0.000  13000.000  13000.000
     1      2212  (p+)              -12      0     0     3     0     0     0      0.000      0.000   6500.000   6500.000      0.938
     2      2212  (p+)              -12      0     0     4     0     0     0      0.000      0.000  -6500.000   6500.000      0.938
     3        -2  (ubar)            -21      1     0     5     0     0   101      0.000      0.000      1.842      1.842      0.000
     4         2  (u)               -21      2     0     5     0   101     0      0.000      0.000  -1105.446   1105.446      0.000
     5        23  (Z0)              -22      3     4     6     7     0     0      0.000      0.000  -1103.604   1107.288     90.241
     6        11  e-                 23      5     0     0     0     0     0    -10.016      3.637    -13.819     17.450      0.001
     7       -11  e+                 23      5     0     0     0     0     0     10.016     -3.637  -1089.785   1089.837      0.001
                                Charge sum:  0.000          Momentum sum:      0.000      0.000  -1103.604   1107.288     90.241

--------  End PYTHIA Event Listing  -----------------------------------------------------------------------------------------
```