Convolutional Neural Network for Track Seed Filtering at the CMS HLT

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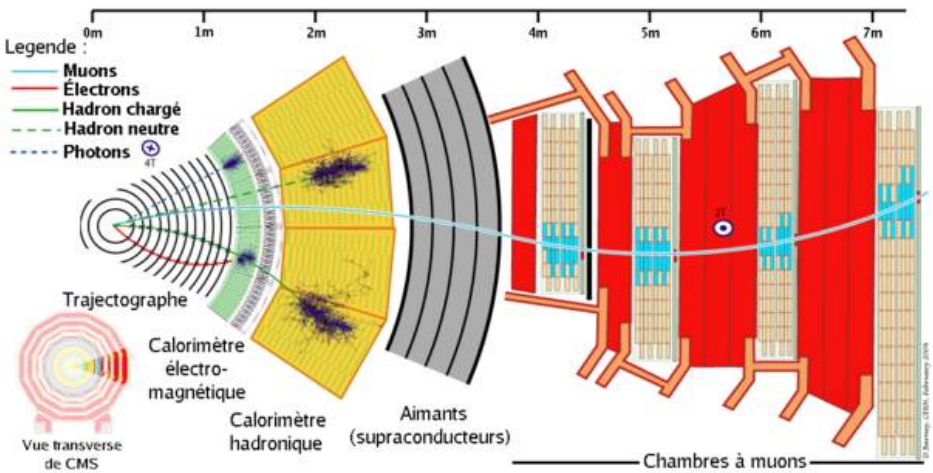
On Behalf of the CMS Collaboration

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

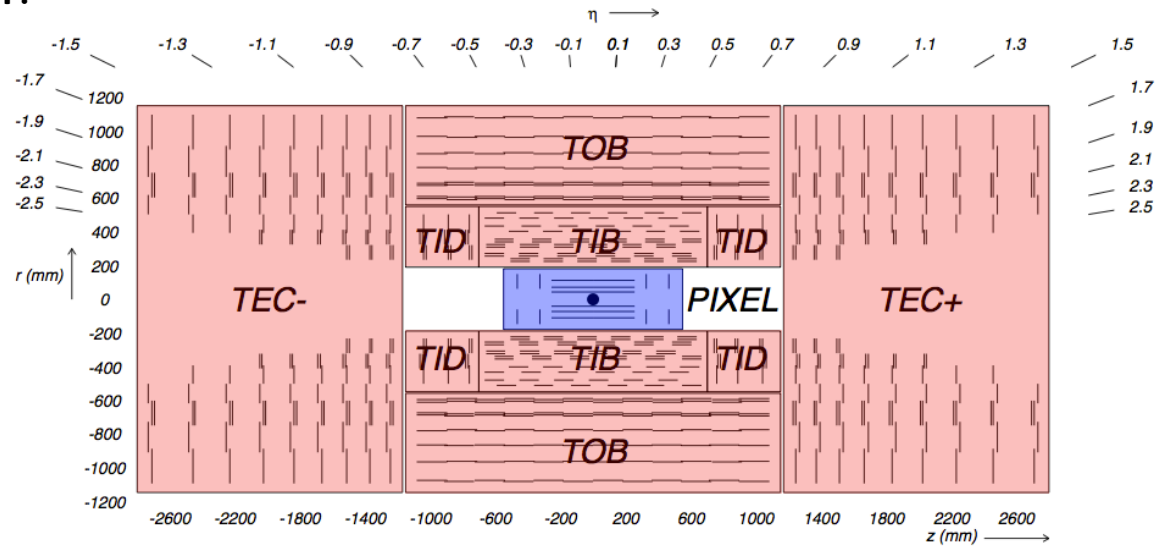
- 40 MHz in / 100 KHz out
- ~ 500 KB / event
- Processing time: ~10 µs
- Based on coarse local reconstructions
- FPGAs / Hardware implemented

HIGH LEVEL TRIGGER (HLT)

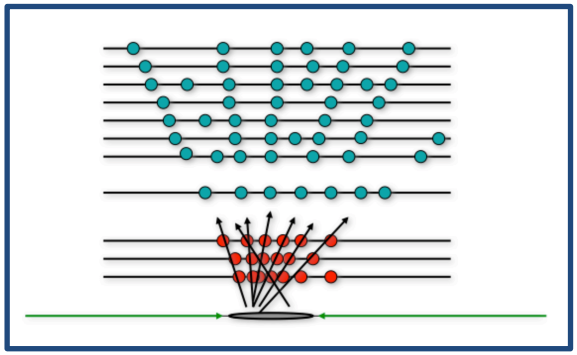
- 100 KHz in / 1 KHz out
- ~ 500 KB / event
- Processing time: ~30 ms
- **Based on simplified global reconstructions**
- Software implemented on CPUs

Track reconstruction @ CMS

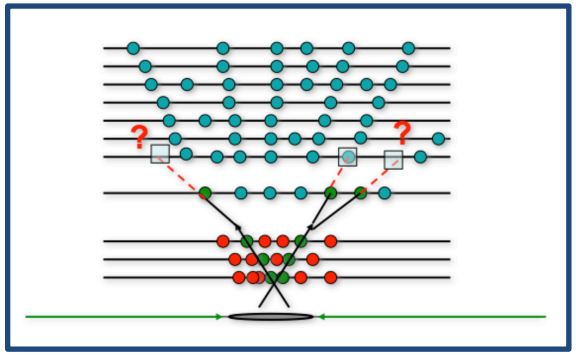
- In CMS, the tracking algorithm consists of an iterative procedure, in which tracks are reconstructed according to progressively looser quality criteria starting from hits on the **silicon tracker detector**.



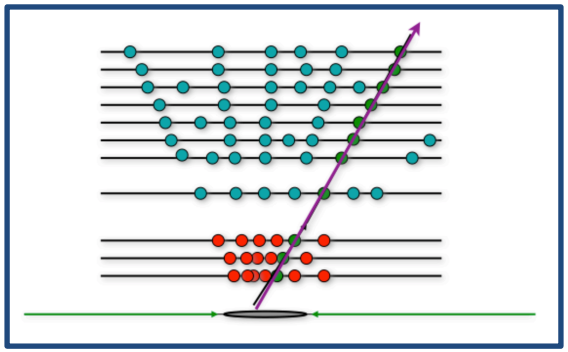
TRACKS RECONSTRUCTION @ CMS



Seeding



Tracks Building



Track fitting

Track reconstruction @ CMS HLT

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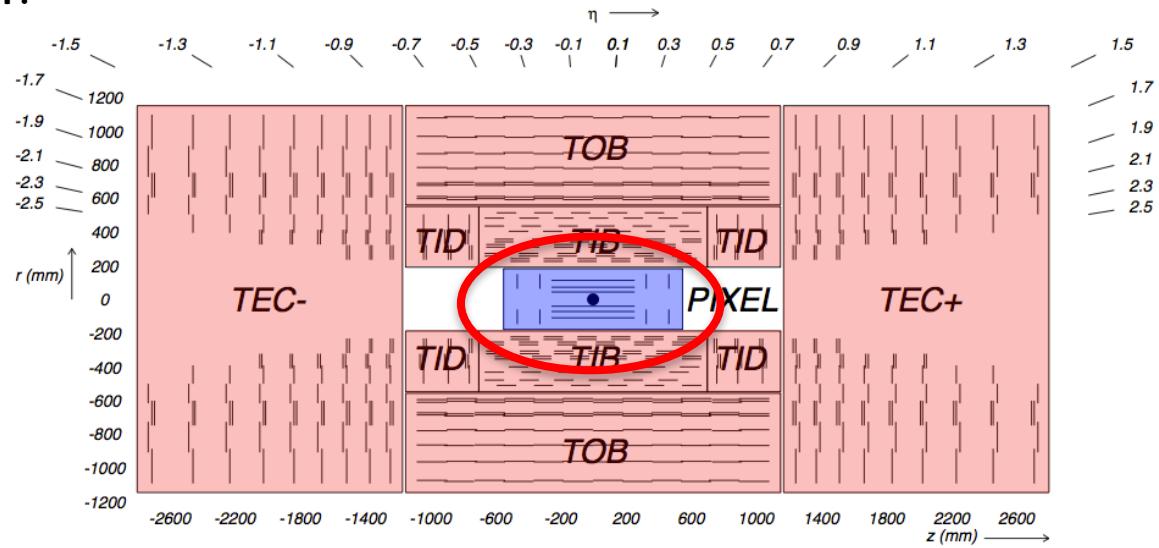


ONLINE RECONSTRUCTION (HLT)

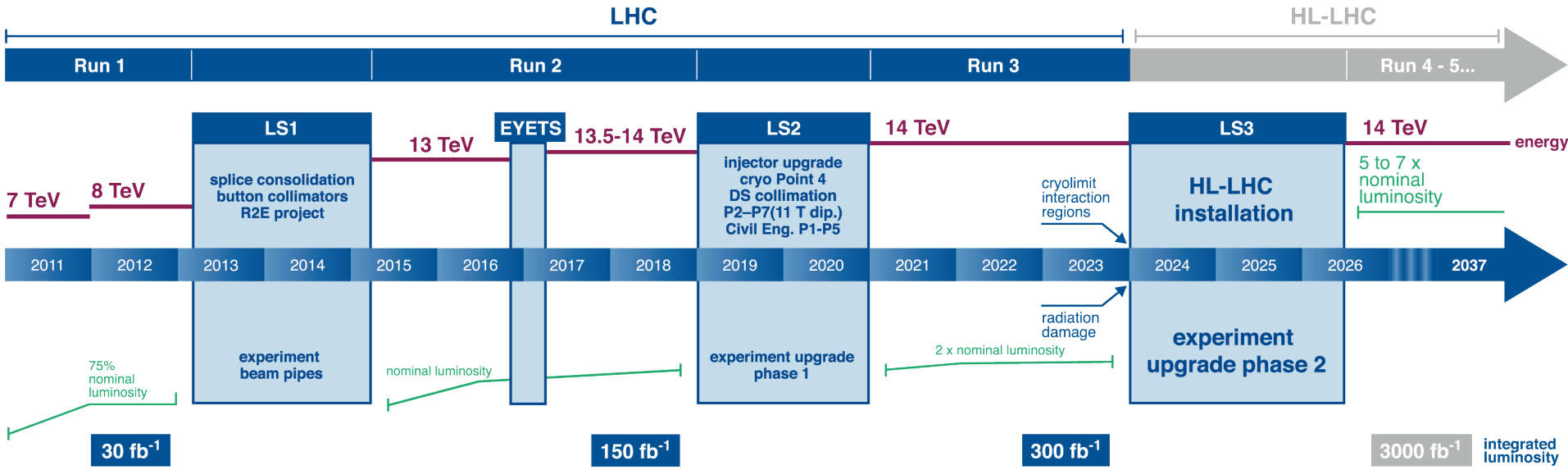
Practically the same reconstruction procedure as the one run offiline. It has to undergo stringent time limits : O(100) ms. It is based on **pixel-only reconstruction**.

Pixel Hits

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

What's next?

LHC / HL-LHC Plan



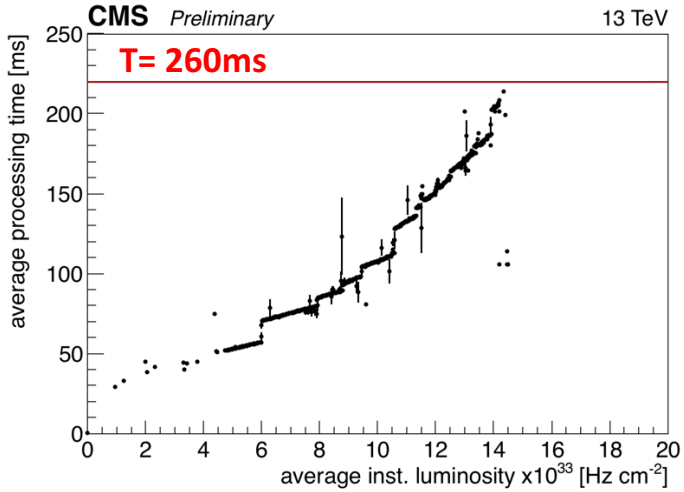
What's next?

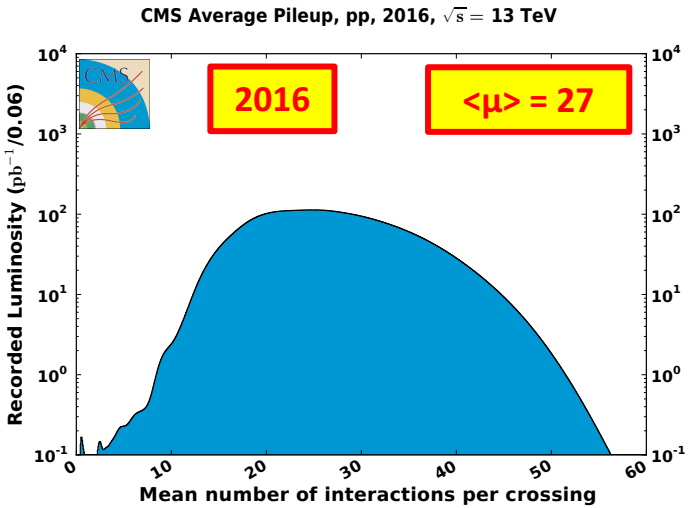
INSTANTANEOUS LUMINOSITY & SIMULTANEOUS COLLISIONS (PILE-UP) INCREASE

Ultimate goals

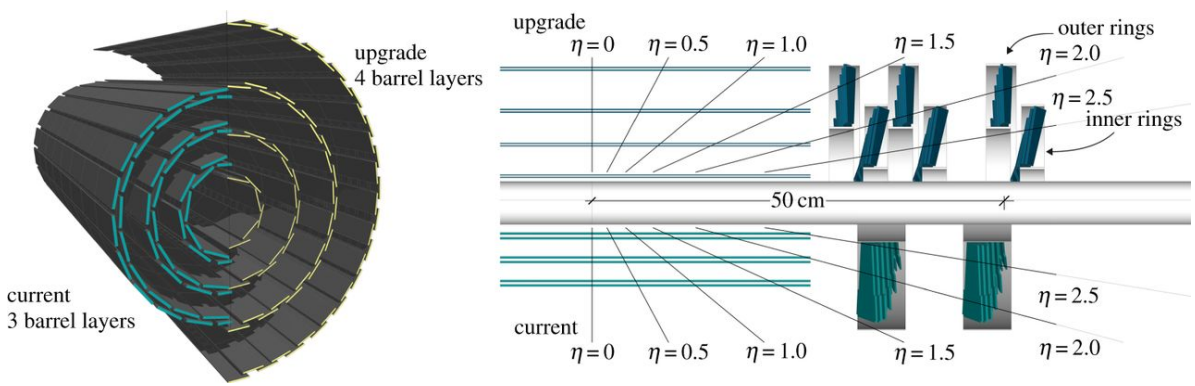
$\mathcal{L} = 5 \cdot 10^{34} cm^2 s^{-1}$

$< PU > \sim 200$





INCREASED DETECTOR COMPLEXITY (SINCE MARCH 2017)

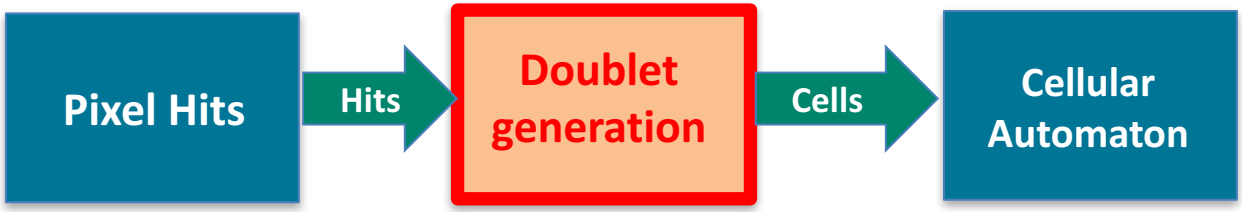


The already complex online and offline track reconstruction has to deal not only with a much more crowded environment but also with data coming from a more complex detector.

10 layers (6 endcap + 4 barrel)

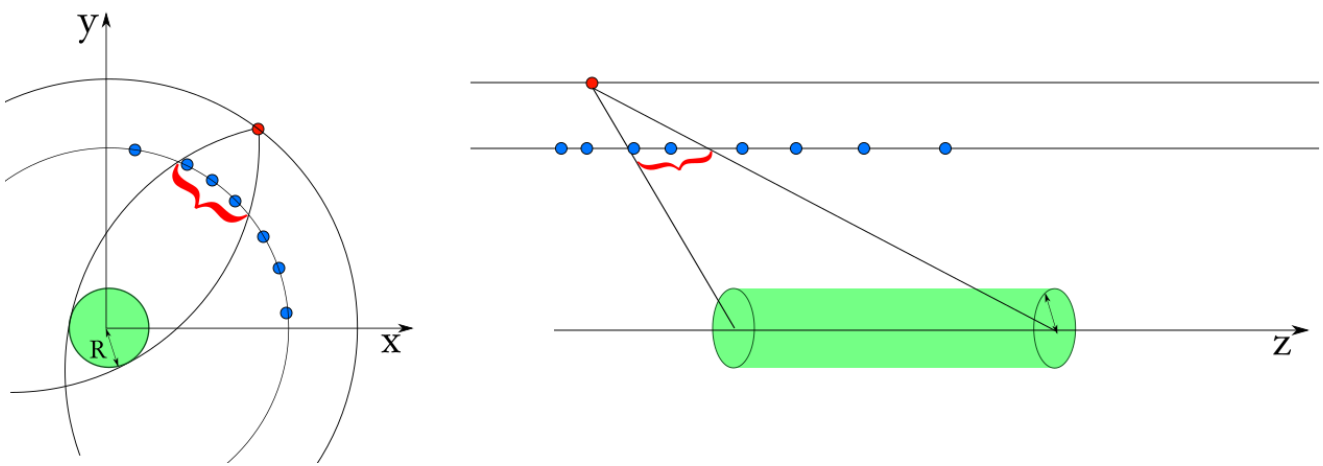
Doublets Generation

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

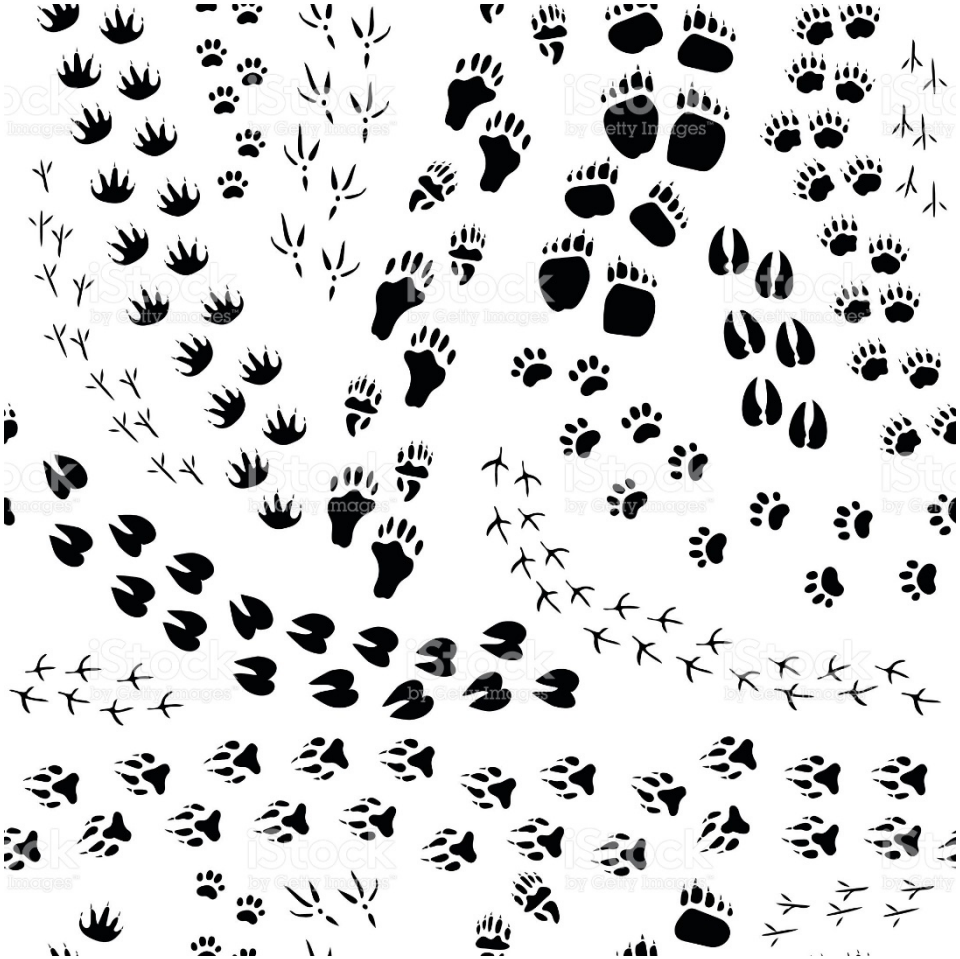


» For a single $t\bar{t}$ at $\sqrt{s} = 13\text{TeV}$ with $< PU > = 35$ simulated event: $O(10^5)$**doublets** produced with ***fake ratio*** $\sim O(100)$ corresponding to $O(1000)$ **true doublets**.

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

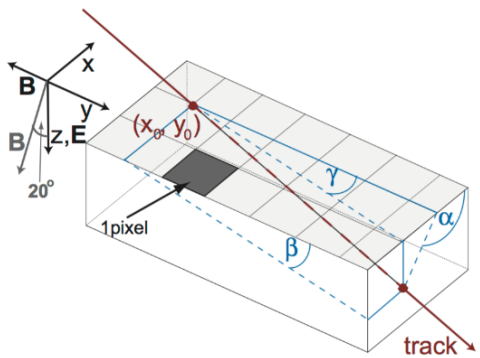


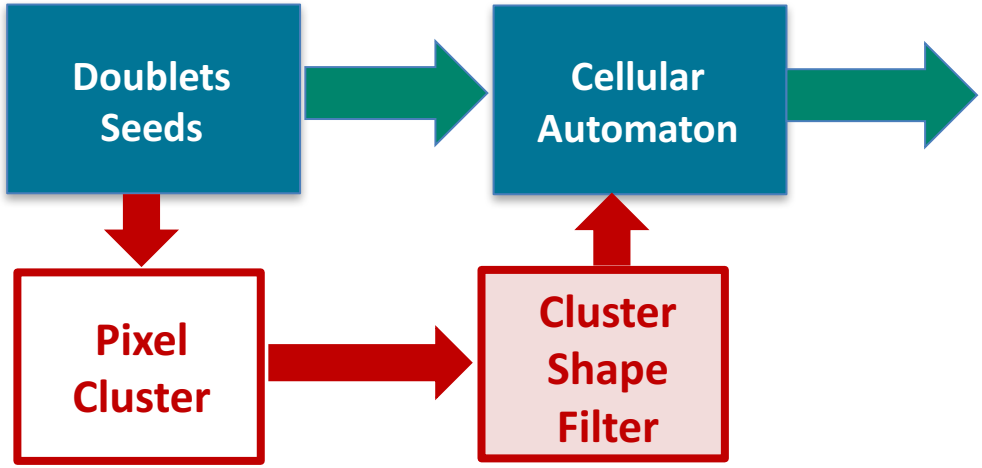
There is some more information…



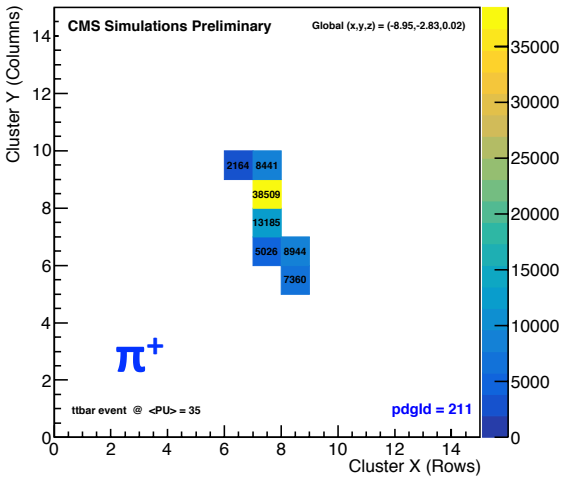
Pixel Clusters

- Each doublet is build 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 o **pixlels** (2D) **on or off**. Each pixel is associated with an **ADC** (16 bit levels) level proportional to the charge deposited by a particle.

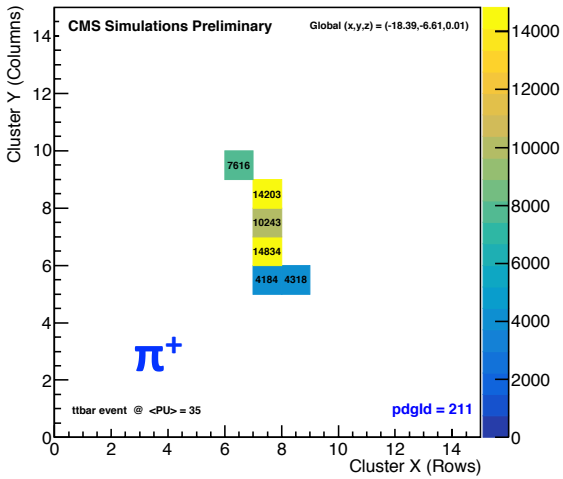




BPix1 - Inner Hit



BPix2 - Outer Hit

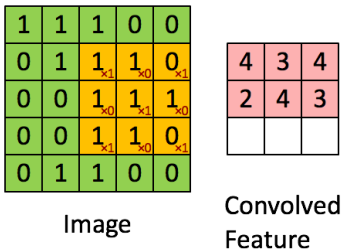


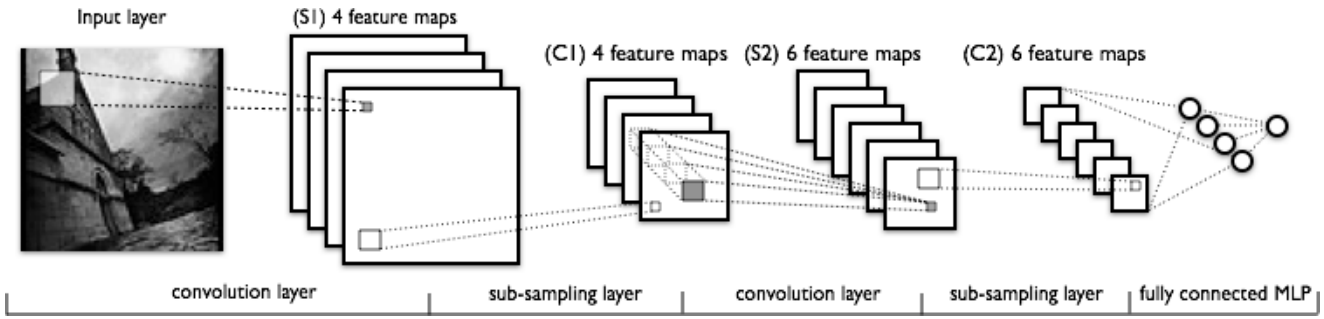
- Each hit is then a 2D pixel image centered on the center of charge. (**15x15**)

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

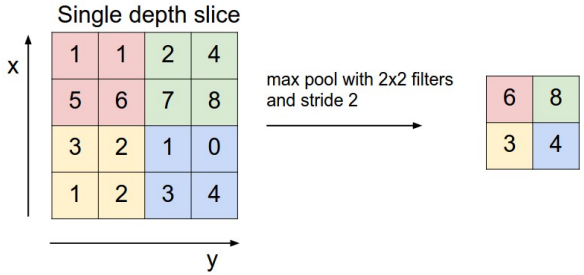
Convolutiona Neural Networks

- Convolutional Neural Networks are a specialized kind of neural network 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.

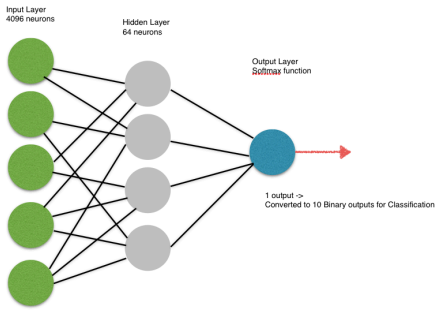




- **Pooling:** its function is to progressively reduce the spatial size of the representation.



- **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***.



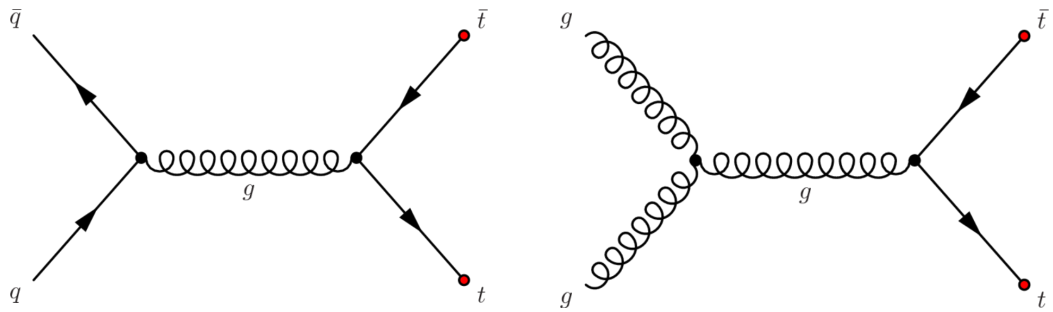
$$\sigma(\mathbf{z})_j = \frac{e^{z_j}}{\sum_{k=1}^{K} e^{z_k}}$$

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

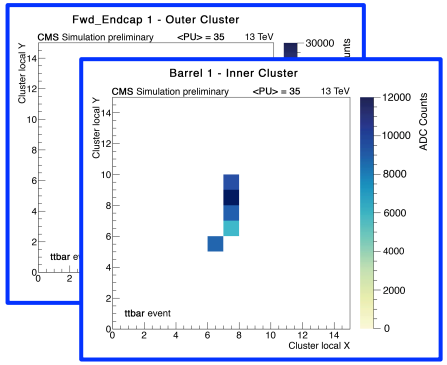
In our usecase the CNN acts as a **binary classifier** (**signal or background**) and reduce the whole picture to a single score correspodent to $\mathbf{p_{true}}(\mathbf{x})$.

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. get list of all **matched reconstructed tracks** track hits
  2. get list of **all doublets** produced
  3. **true doublets** = doublets formed by hits from the same sim matched track



To each doublet we the associate

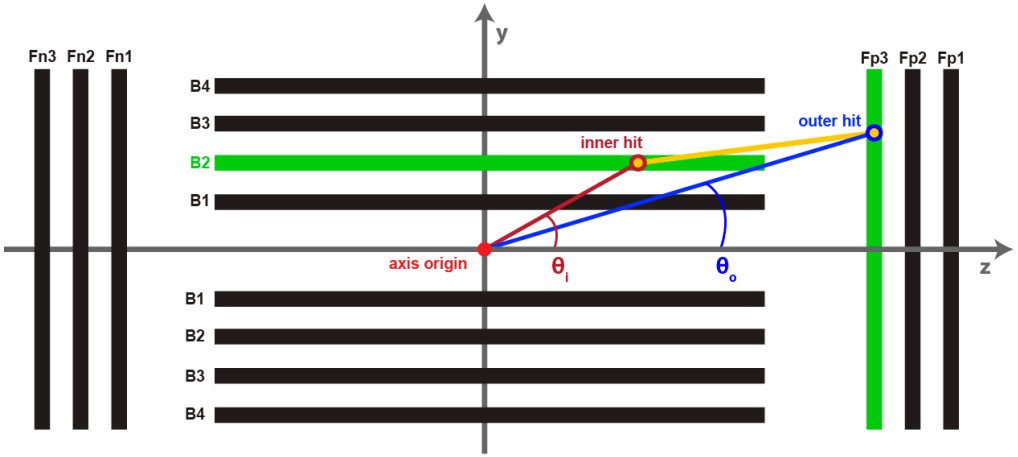
- ***two*** **15x15 images** (one for inner and one for outer hit)
- set of **local informations**(x,y,z, charge,, …)

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

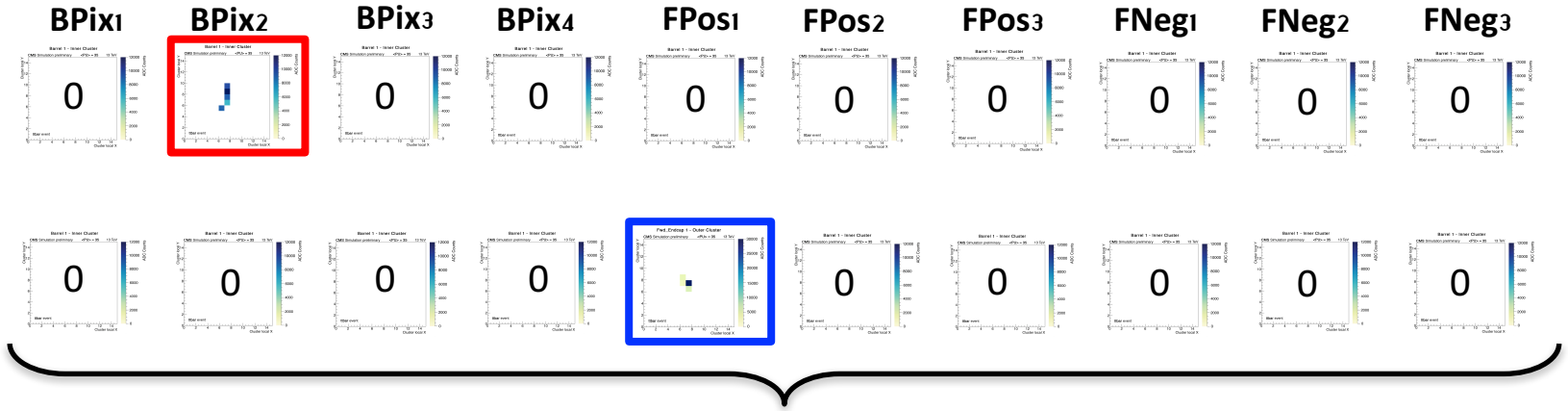
Data prepocessing

- 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.

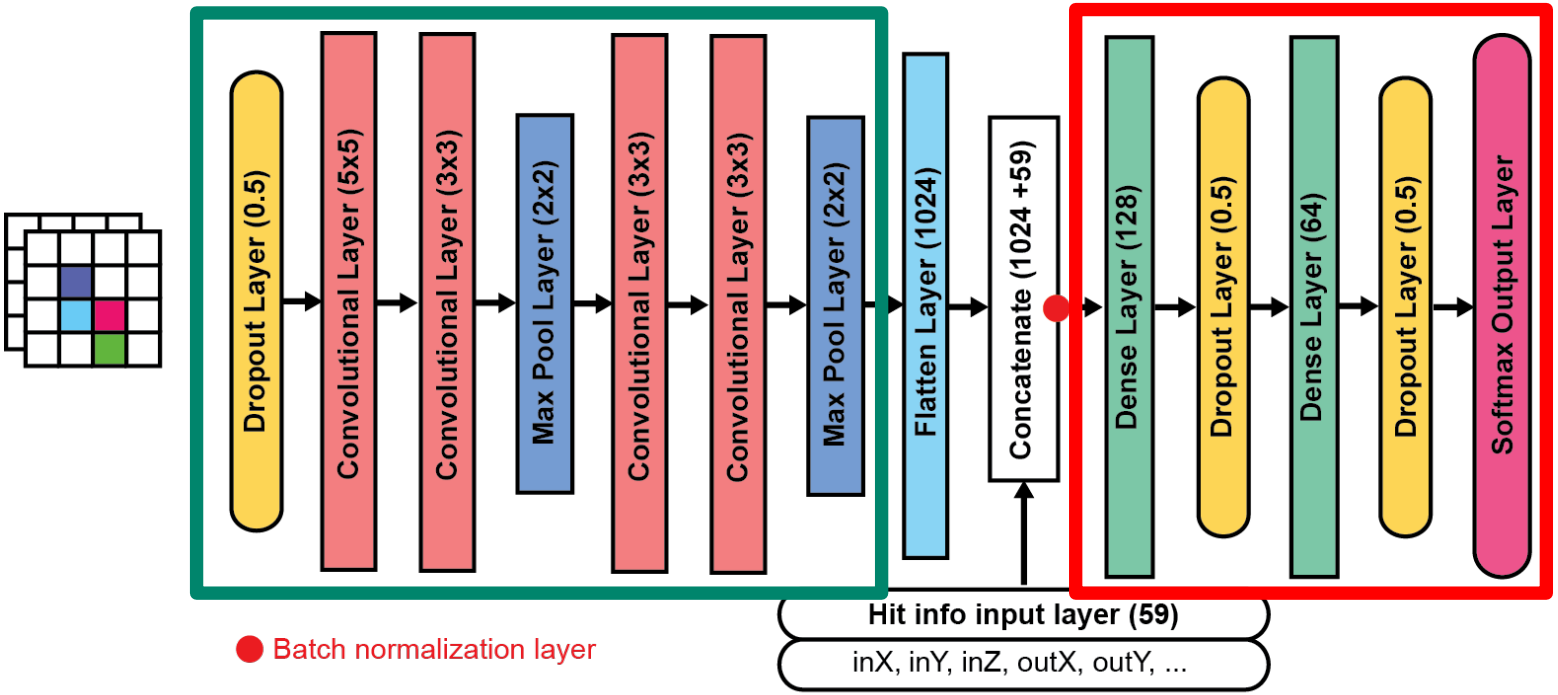


- E.g. A doublet on *barrel2* and *forward endcap3*

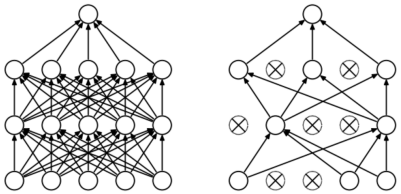


20 channel image as input

The model



- A single doublet is a **20 levels** image. *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)*



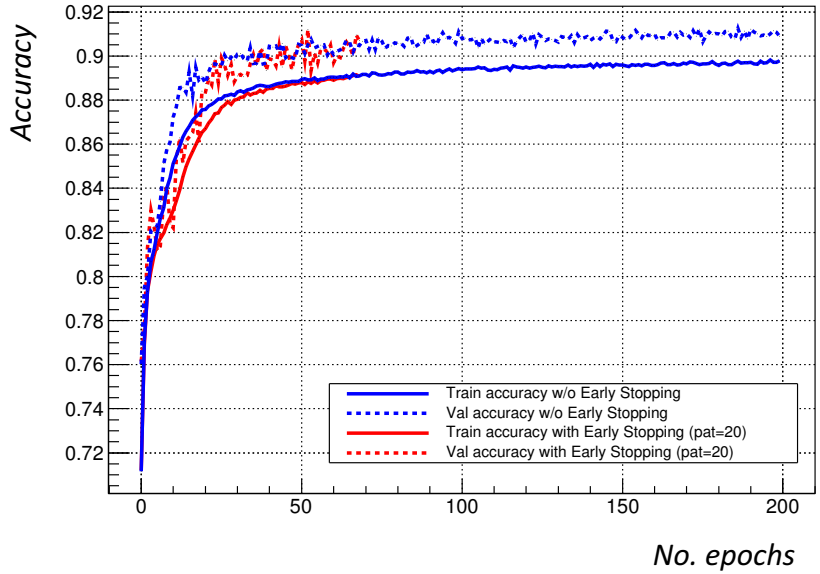
Results - I

- Results on 2.5 millions **doublets training**

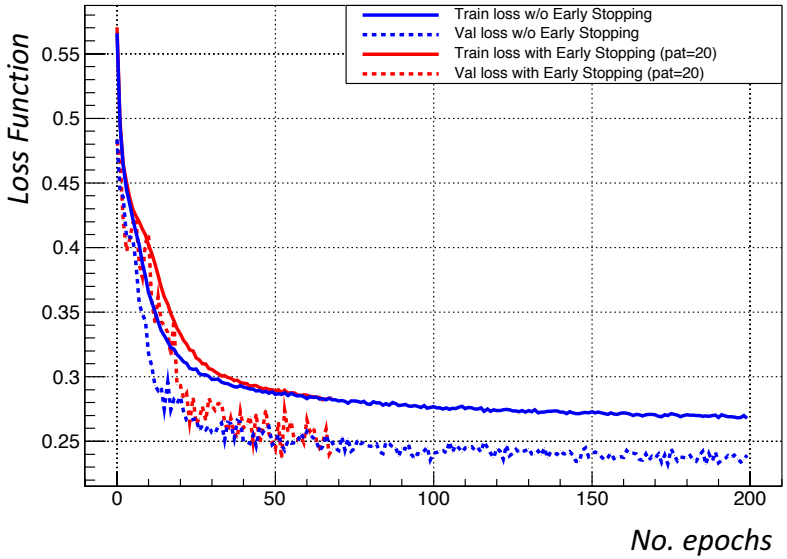
$$ACC = \frac{VP + VN}{P + N} > 0.90$$

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

Accuracy (training on 250k dataset)



Cross Entropy (training on 250k dataset)



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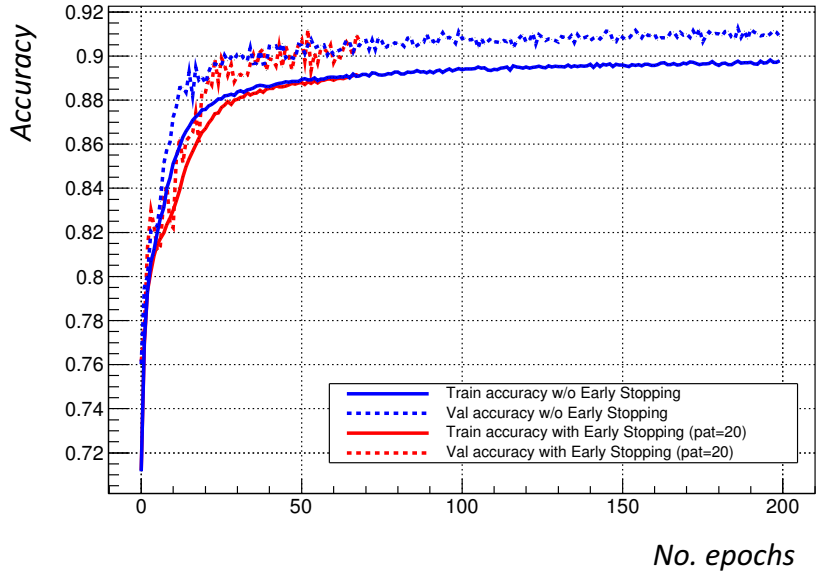

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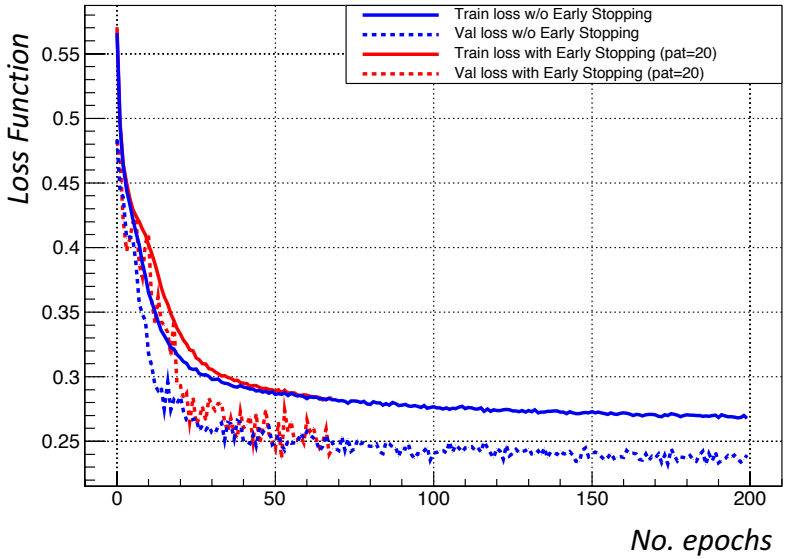

Whole Dataset Training			@ Max Acc		Rej @ Eff		Eff @ Rej	
	AUC	ACC	Efficiency	Rejection	0.99	0.999	0.99	0.5
Test	0.968	0.90	0.96	0.91	0.81	0.65	0.54	0.99
Val	0.966	0.90	0.95	0.91	0.81	0.66	0.54	0.99
Train	0.969	0.91	0.96	0.91	0.81	0.65	0.55	0.99

Results - I

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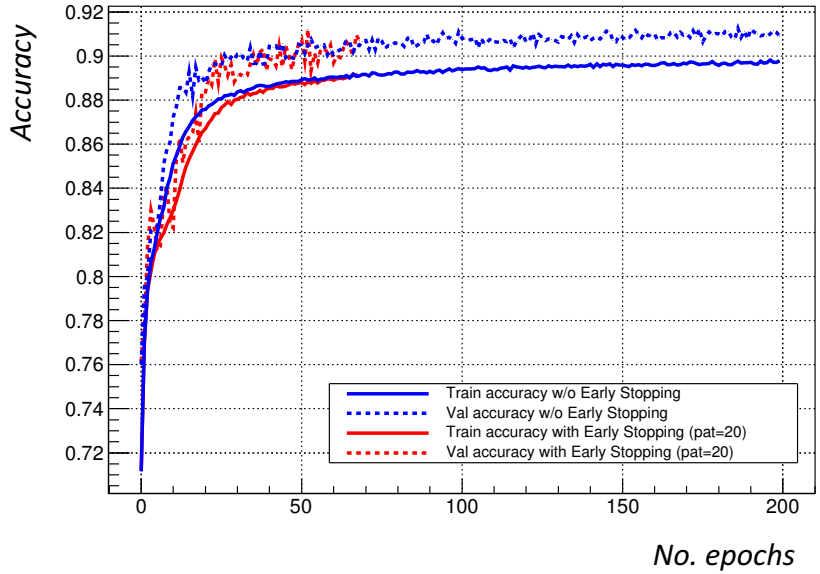

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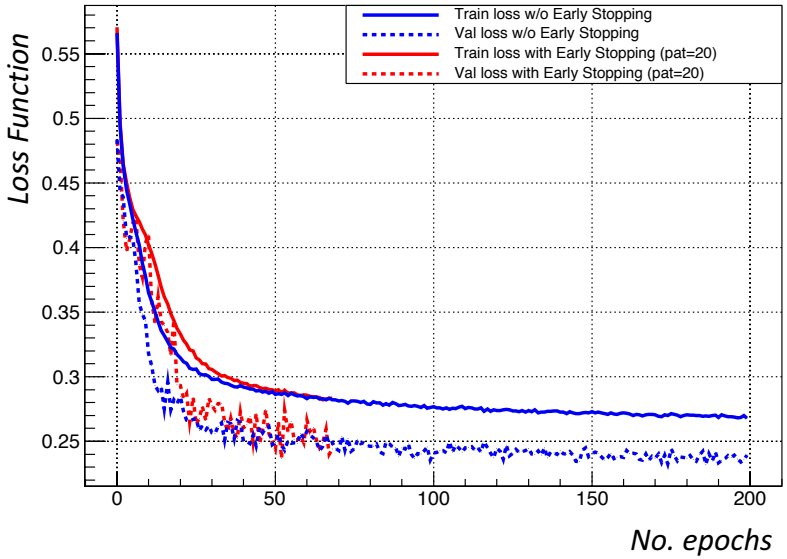

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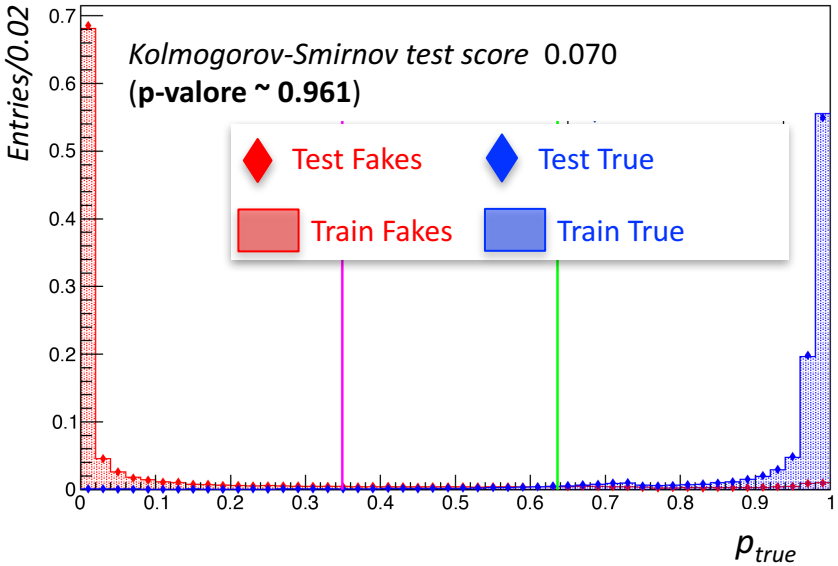
Train	0.969	0.91	0.96	0.91	0.81	0.65	0.55	0.99

Results - II

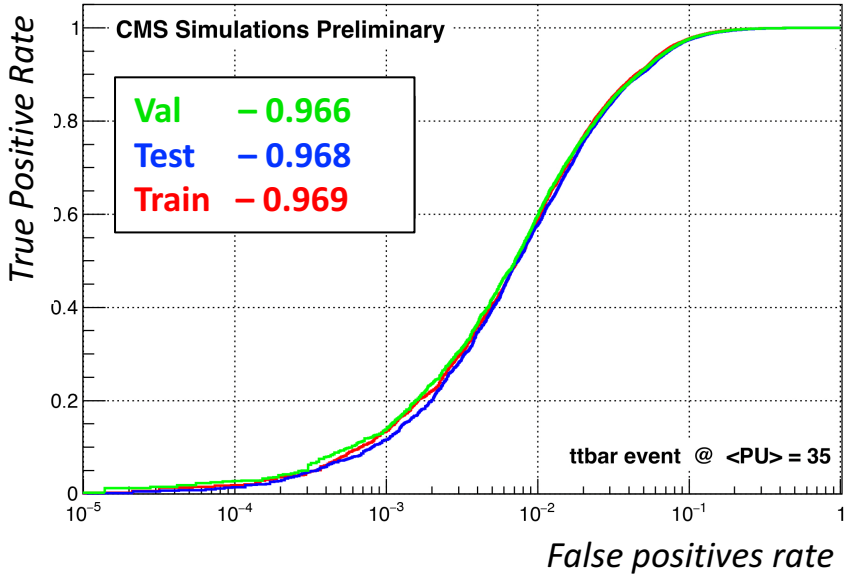
- Results on 2.5 millions **doublets training**

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

Classifier output score (training on whole dataset)



ROC Curve (training on whole dataset)

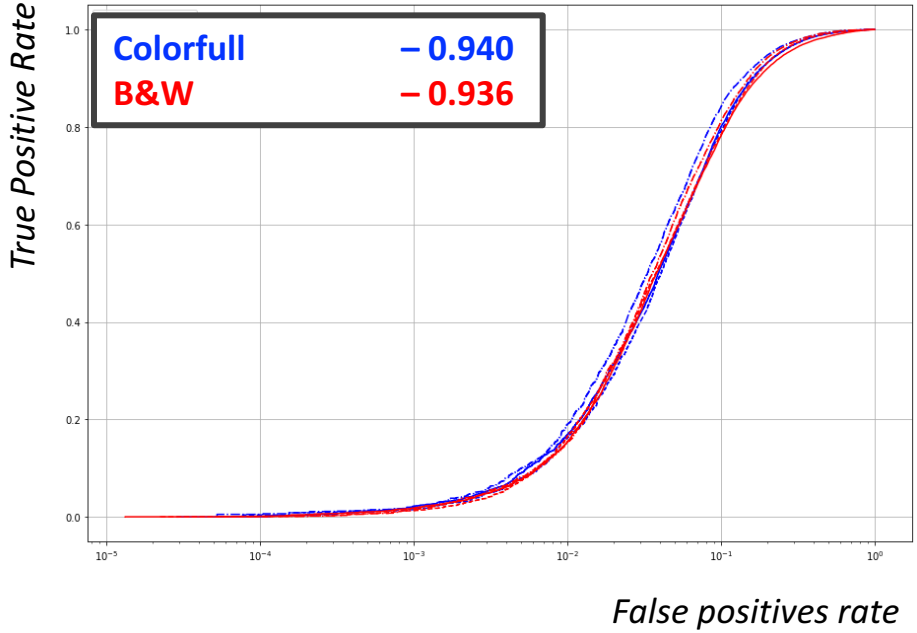


Whole Dataset Training			@ Max Acc		Rej@ Eff		Eff @ Rej	
	AUC	ACC	Efficiency	Rejection	0.99	0.999	0.99	0.5
Test	0.968	0.90	0.96	0.91	0.81	0.65	0.54	0.99
Val	0.966	0.90	0.95	0.91	0.81	0.66	0.54	0.99
Train	0.969	0.91	0.96	0.91	0.81	0.65	0.55	0.99

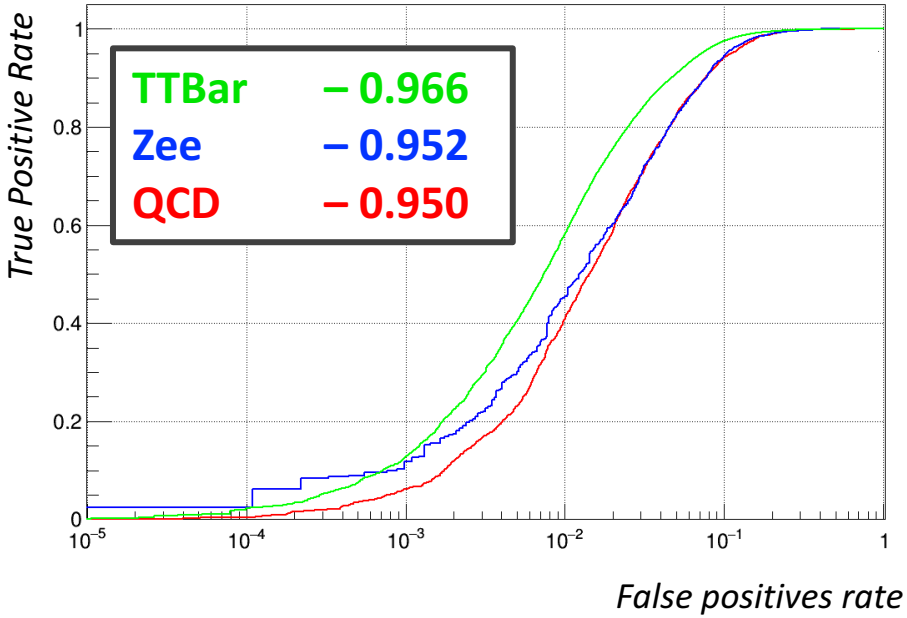
Results - III

- Further crosschecks

ROC Curve (training on 250k sample)



ROC Curve (training on whole dataset)



- Setting ADC levels to **0** or **1** only for turned **off** and **on pixels.** **Black and white model.**
- Comparing with the **colorfull model** with ADC levels
- Testing with other **montecarlo PYTHIA** recipies

Conclusions and perpectives

- CNN techniques for mitigating combinatorial explosion look very promising
- "Small" use case that shows how CNNs (or DNNs) cam help handling tracking @ HEP
  - Exploring the integration in the CMS reconstruction Framework
  - Verification of the effect on the downstream track reconstruction ongoing
  - Exploration of different hardware architecture for fast inference ongoing
  - 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

The doublet features

450 ADC pixels [2x15x15 pads]

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

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

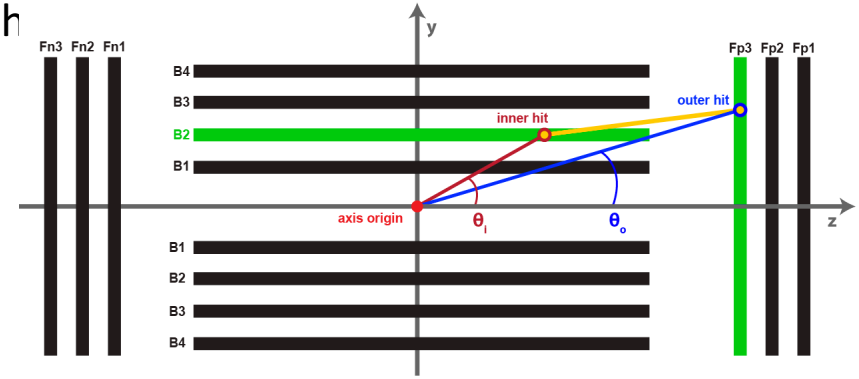
63 features defined for each doublet [*true* or *fake*] **that <u>may</u> be used as additional features** to the pixel pad

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  ------------------------------------------------------------------------------------------------------
```

MC Recipes - II

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 -----------------------*
```

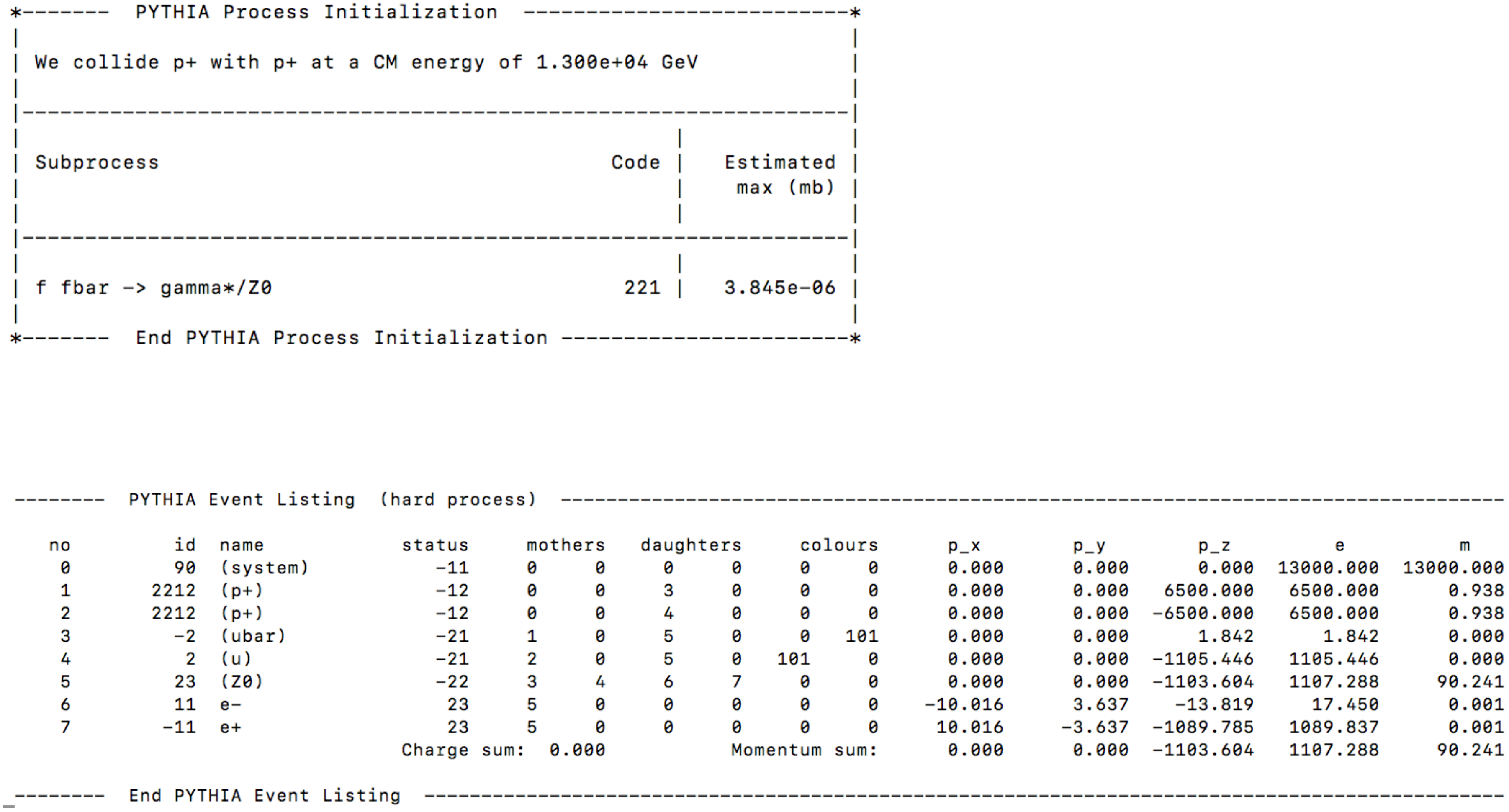
```
--------  PYTHIA Event Listing  (hard process)  ------------------------------------------------------------------------------------------------------------------------------------------------------------------
```

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  ------------------------------------------------------------------------------------------------------------------------------------------------------------------
```

MC Recipes - III

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  -----------------------------------------------------------------------------------
_
```