

# Deep Learning Strange Jets

**Yuichiro Nakai (Rutgers)**

**Based on YN, D. Shih and S. Thomas, in preparation.**

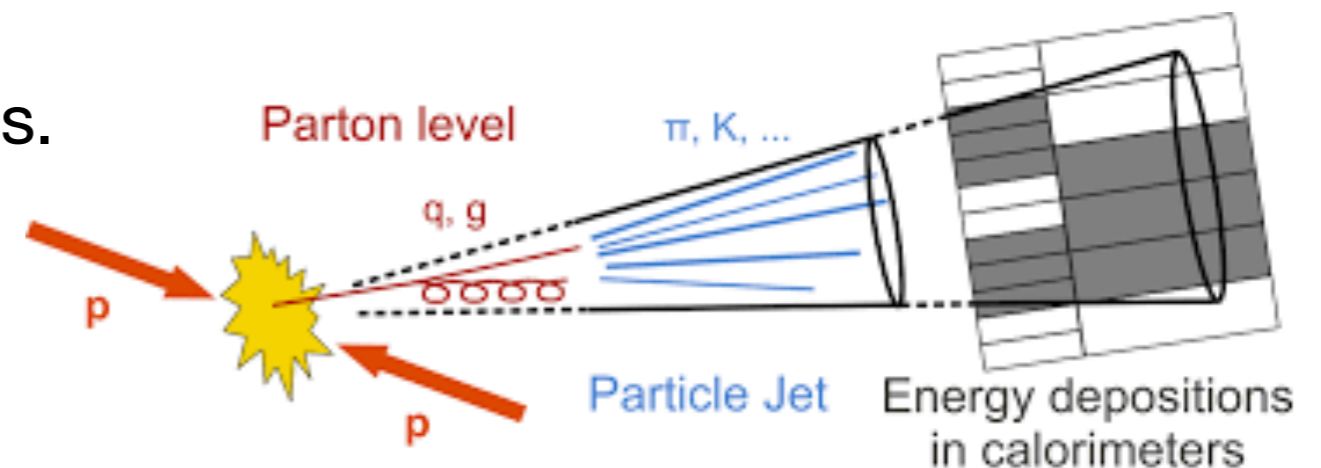
# Jets at the LHC

**Jet** : collimated bunch of hadrons as the signatures of quarks and gluons produced in high-energy collisions

✓ QCD partons are never observed isolated due to confinement.

✓ They give cascades of radiation (parton shower) by QCD processes.

✓ Hadrons are formed at  $\sim \Lambda_{\text{QCD}}$



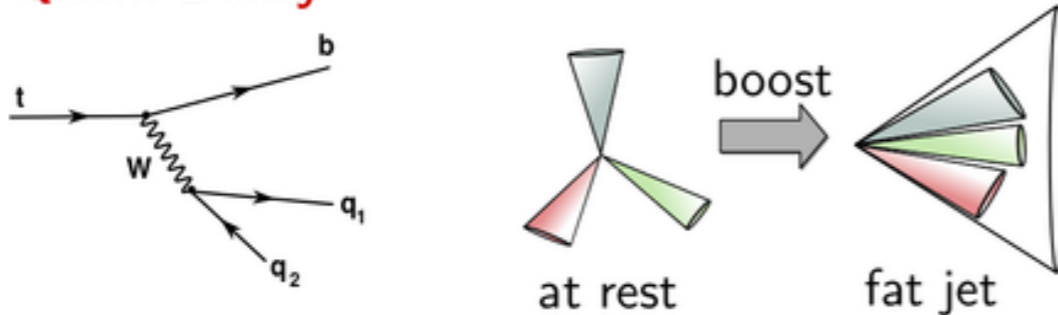
Understanding jets is a key ingredient of physics measurements and new physics searches at the LHC.

**What initial parton produces a jet ?**

# Quark and Gluon Tagging

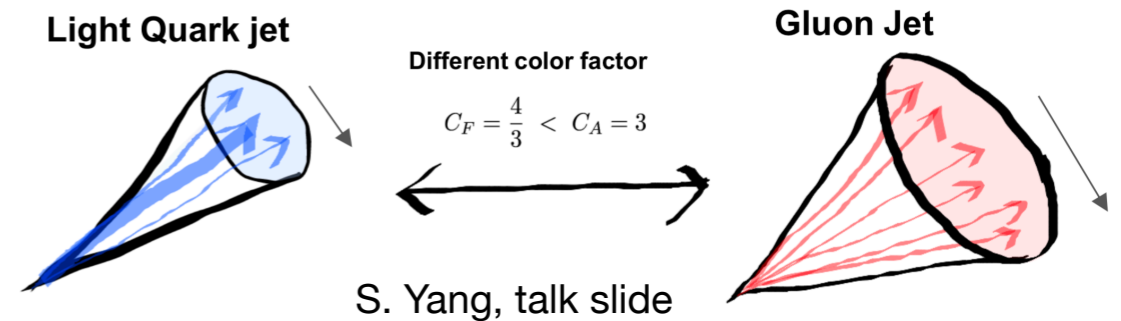
## ☑ Top quark

### Top Quark Decay



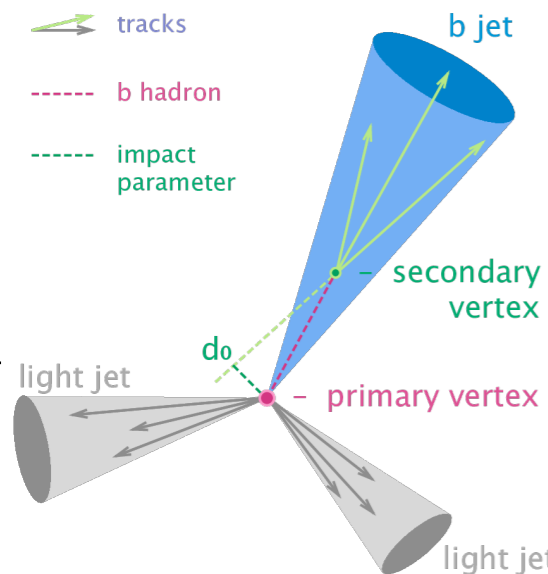
Jet mass, N-subjettiness, ...

## ☑ Gluon



More constituents with more uniform energy fragmentation and wider.

## ☑ Bottom/Charm



Look for a displaced (secondary) vertex.

Wikipedia

## ☑ Up-type vs Down-type

$p_T$ -weighted jet charge

$$Q_{\kappa}^i = \frac{1}{(p_T^{\text{jet}})^{\kappa}} \sum_{j \in \text{jet}} Q_j (p_T^j)^{\kappa}$$

The last missing piece :

# Strange quark tagging?

# Applications of Strange Tagging

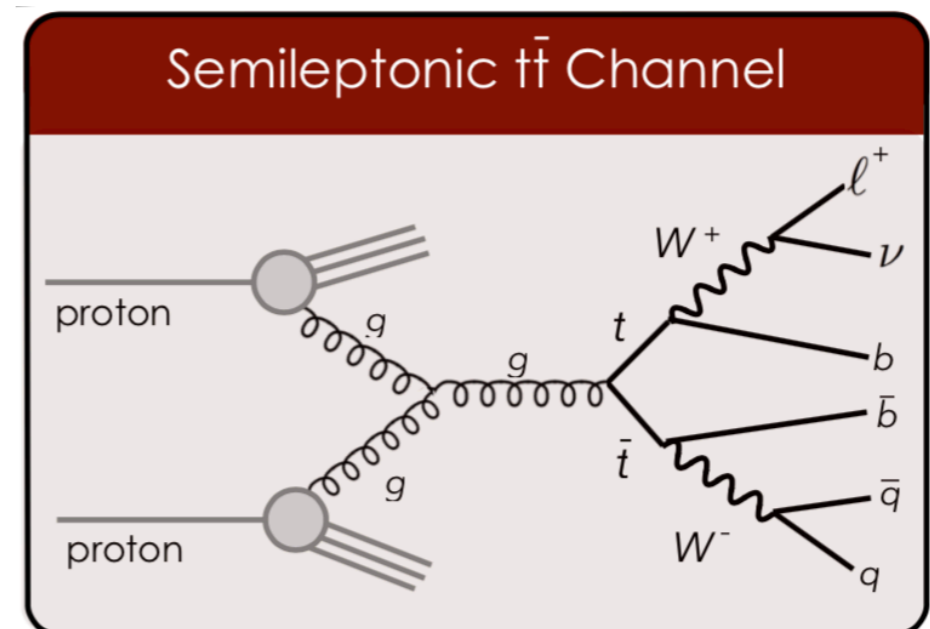
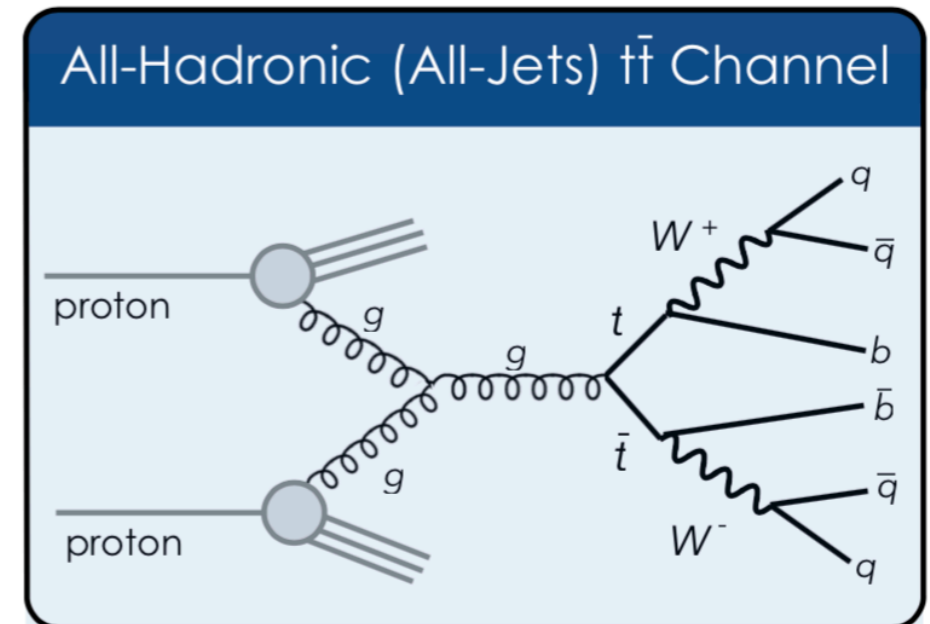
## • Top quark reconstruction

### ✓ All-hadronic channel

- 😊 Full event reconstruction is possible.
- 😱 Jet combinatorics and large multi-jet background are problematic.

### ✓ Semileptonic channel

- 😊 Leptonic top identifies event and hadronic top can be reconstructed.
- 😞 Jet combinatorics and multi-jet background are still issues.



**Which jets are  $W \rightarrow cs, us, cd, ud$  decay products?**

T. McCarthy, talk slide

Identification of strange jet may give some help.

# Applications of Strange Tagging

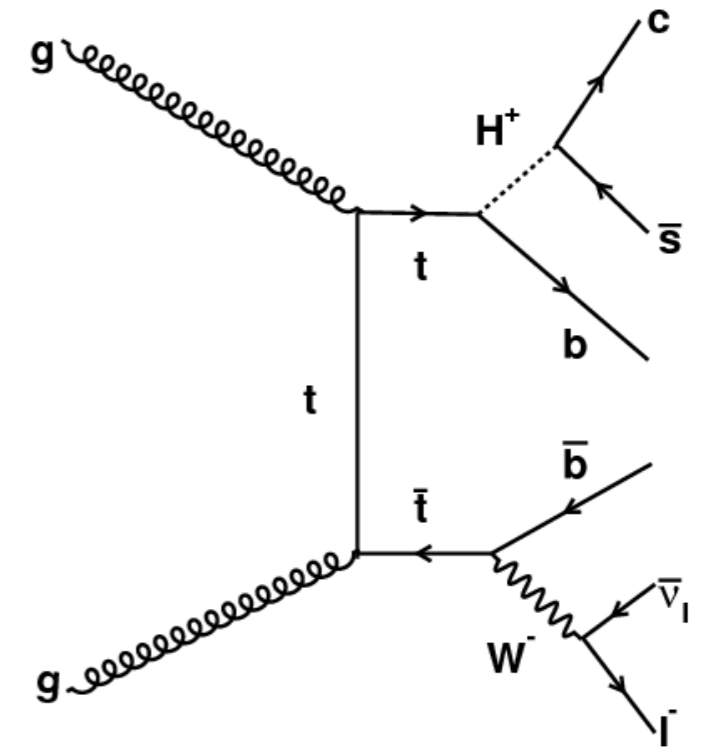
## • Light charged Higgs search

Production :  $t\bar{t} \rightarrow W^\pm b H^\mp \bar{b}$

Decay :  $H^+ \rightarrow c\bar{s}$

😓 The same issue as top quark reconstruction is applied.

😱 We do not know the charged Higgs mass!



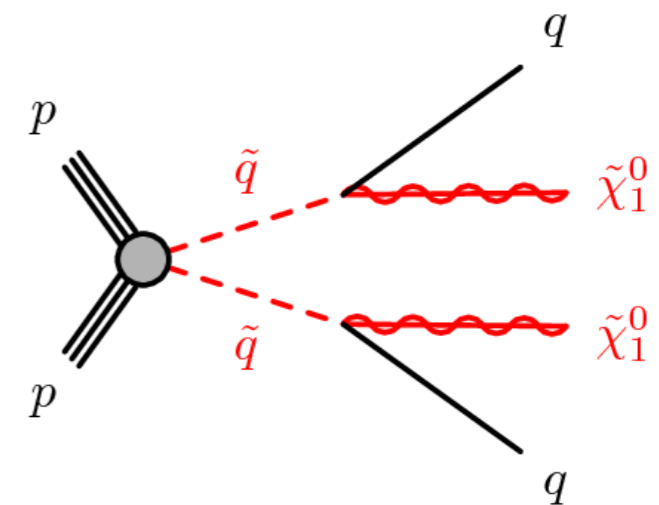
CMS

## • Squark search

Identification of strange jet can ...

✓ reduce the background  $Z(\rightarrow \nu\nu) + \text{jets}$

✓ identify squark flavor after the discovery



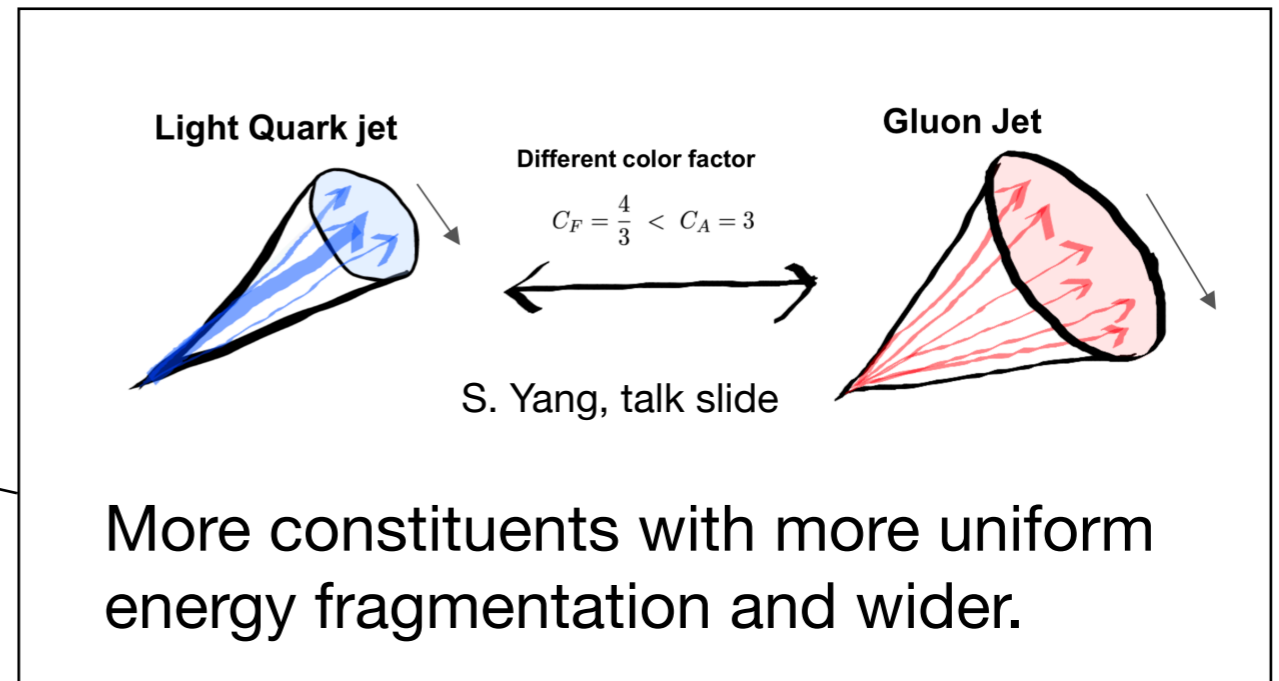
CMS

Strange tagging may be important !

# Tagging Strategy

- **Strange vs Gluon**

We can expect the same thing as quark/gluon discrimination.



- **Strange vs Up**

We can expect the same thing as up/down discrimination.

$p_T$ -weighted jet charge

$$Q_{\kappa}^i = \frac{1}{(p_T^{\text{jet}})^{\kappa}} \sum_{j \in \text{jet}} Q_j (p_T^j)^{\kappa}$$

- **Strange vs Down**

**Possible ??**

Both are quarks with the same charge.

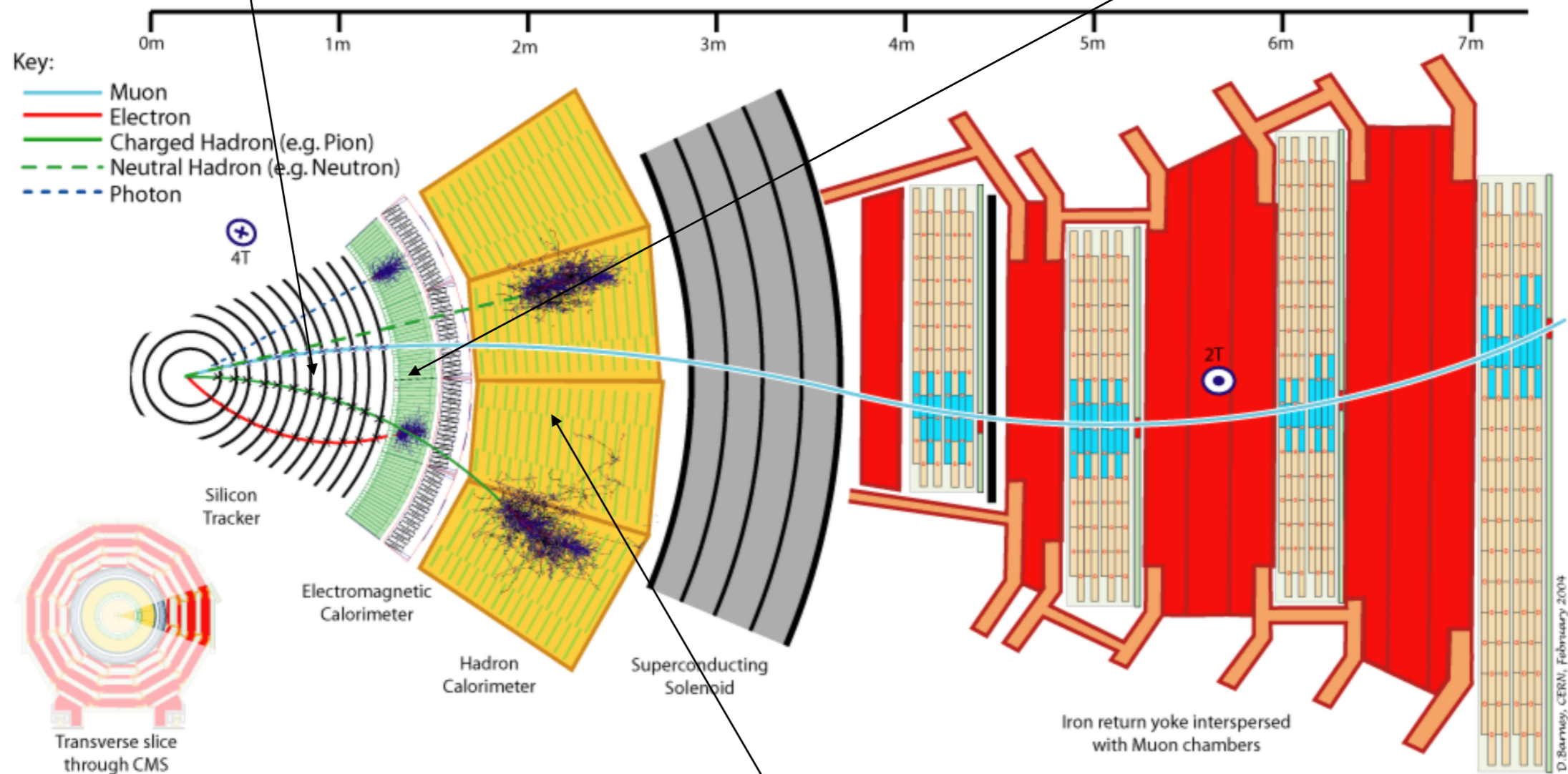
Main theme of this talk

# Tagging Strategy

## CMS experiment at the LHC

**Tracker** : trajectories of charged particles

**ECAL** : energy of electrons and photons



**HCAL** : energy deposits of hadrons

# Tagging Strategy

After hadronization, strange quarks form Kaons :

$$K^- = s\bar{u}, \quad K^+ = \bar{s}u, \quad K_L \approx \frac{s\bar{d} - d\bar{s}}{\sqrt{2}}, \quad K_S \approx \frac{s\bar{d} + d\bar{s}}{\sqrt{2}}$$

$$\boxed{K_L, K^\pm} \quad \gamma c\tau \sim 3 \text{ m}$$

No decay inside the detectors

$$\boxed{K_S} \quad \gamma c\tau \sim 3 \text{ cm}$$

Decay inside the detectors

$$K_S \rightarrow \pi^+\pi^- (\sim 70\%), \quad \pi^0\pi^0 (\sim 30\%)$$

Detector responses to hadrons :

	$K_L$	$K_S$	$K^\pm$	$\pi^0$	$\pi^\pm$
HN	○	△			
ECAL		△		○	
Tracker		△	○		○

No difference

Down jets

Strange jets

Hadronic Neutral (HN) = HCAL - Tracker

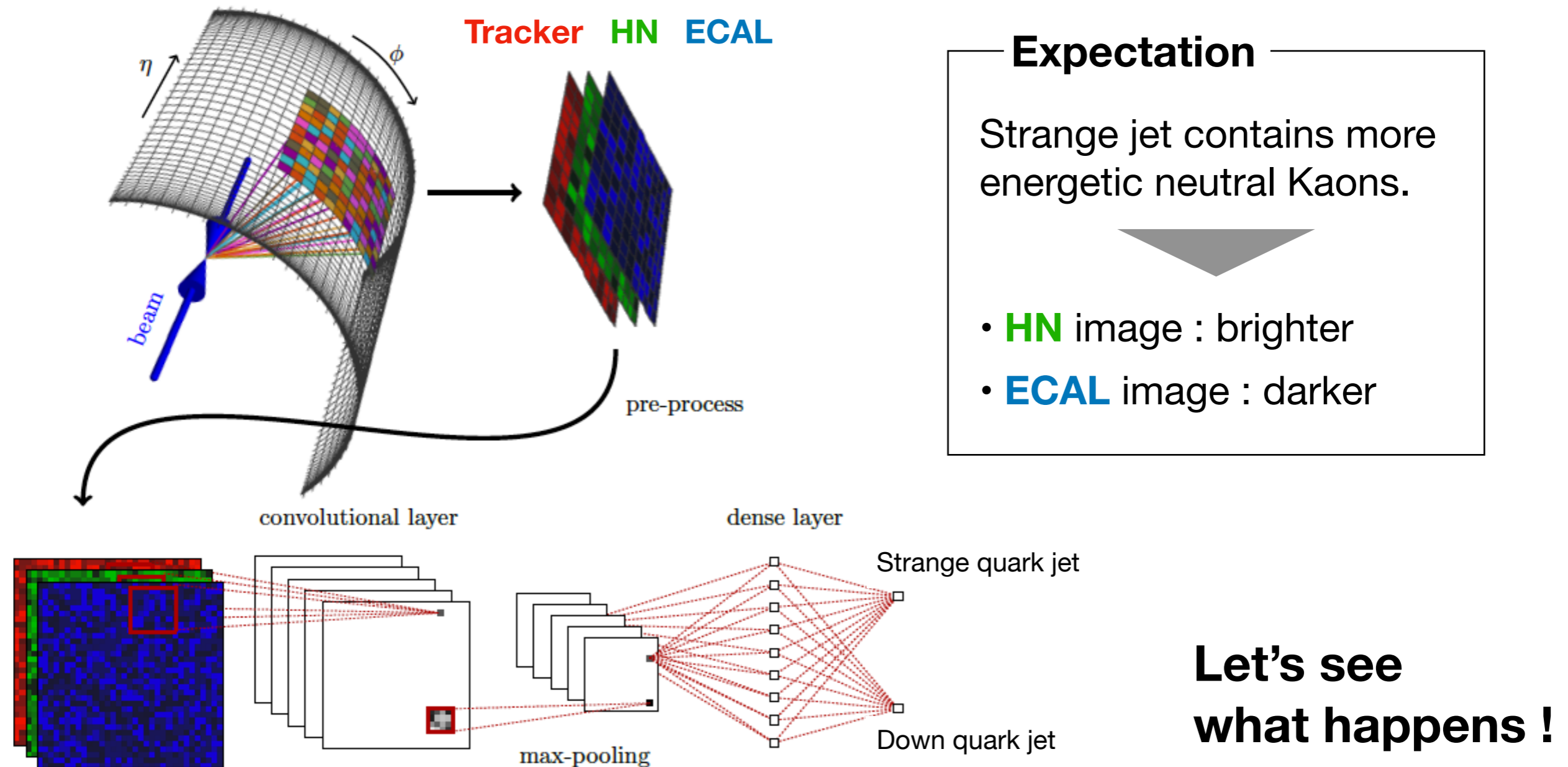
**K-long (and K-short) can be used for tagging !**



# Jet Images and CNN

Classification problem : **Strange jet** vs **Down jet**

Create jet images with colors (Tracker, HN, ECAL) and feed them into CNN.



**Let's see  
what happens !**

# Jet Samples

Generate strange/down jet samples by using MadGraph, PYTHIA and Delphes.

100000 events for each case of :

$$Z \rightarrow s\bar{s} \quad (p_T > 20 \text{ GeV})$$

$$Z \rightarrow d\bar{d} \quad (p_T > 20 \text{ GeV})$$

$$s\bar{s} \quad (p_T > 200 \text{ GeV})$$

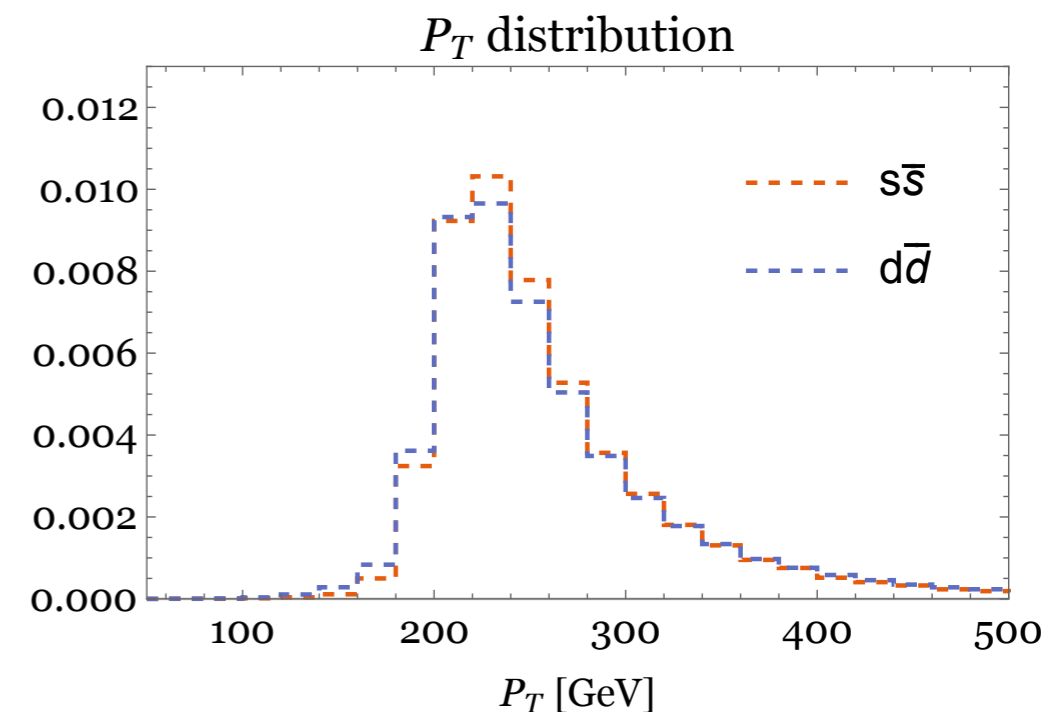
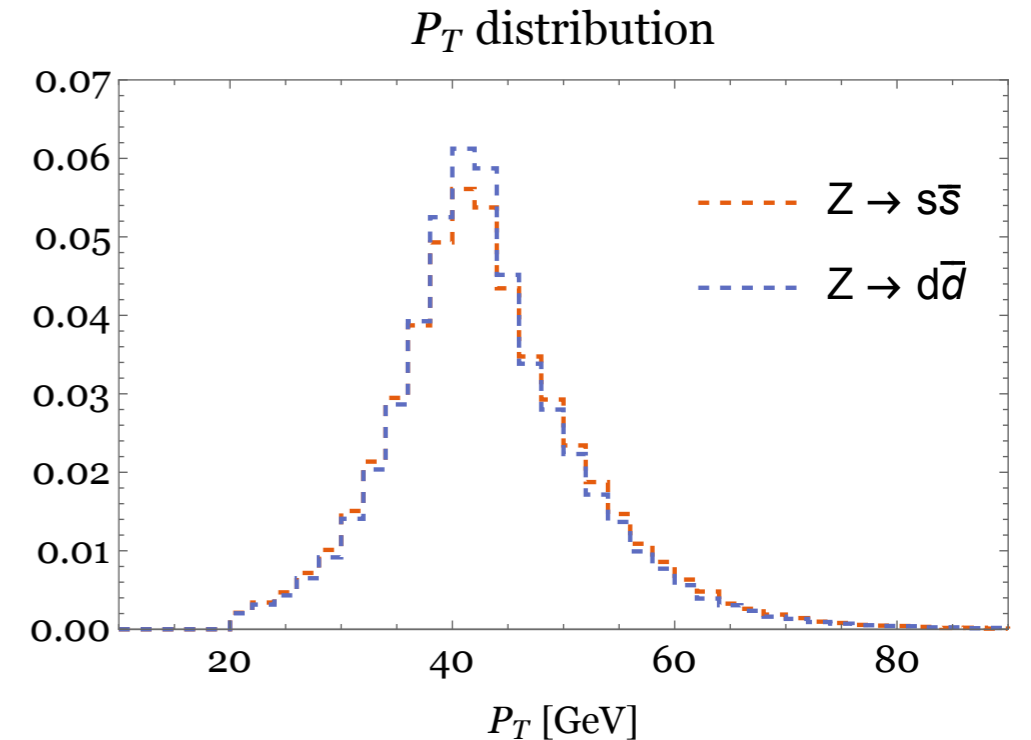
$$d\bar{d} \quad (p_T > 200 \text{ GeV})$$

$$(|\eta| < 0.05)$$

Initial parton is required to

be inside the leading jet :  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$

Herwig gives the similar results.

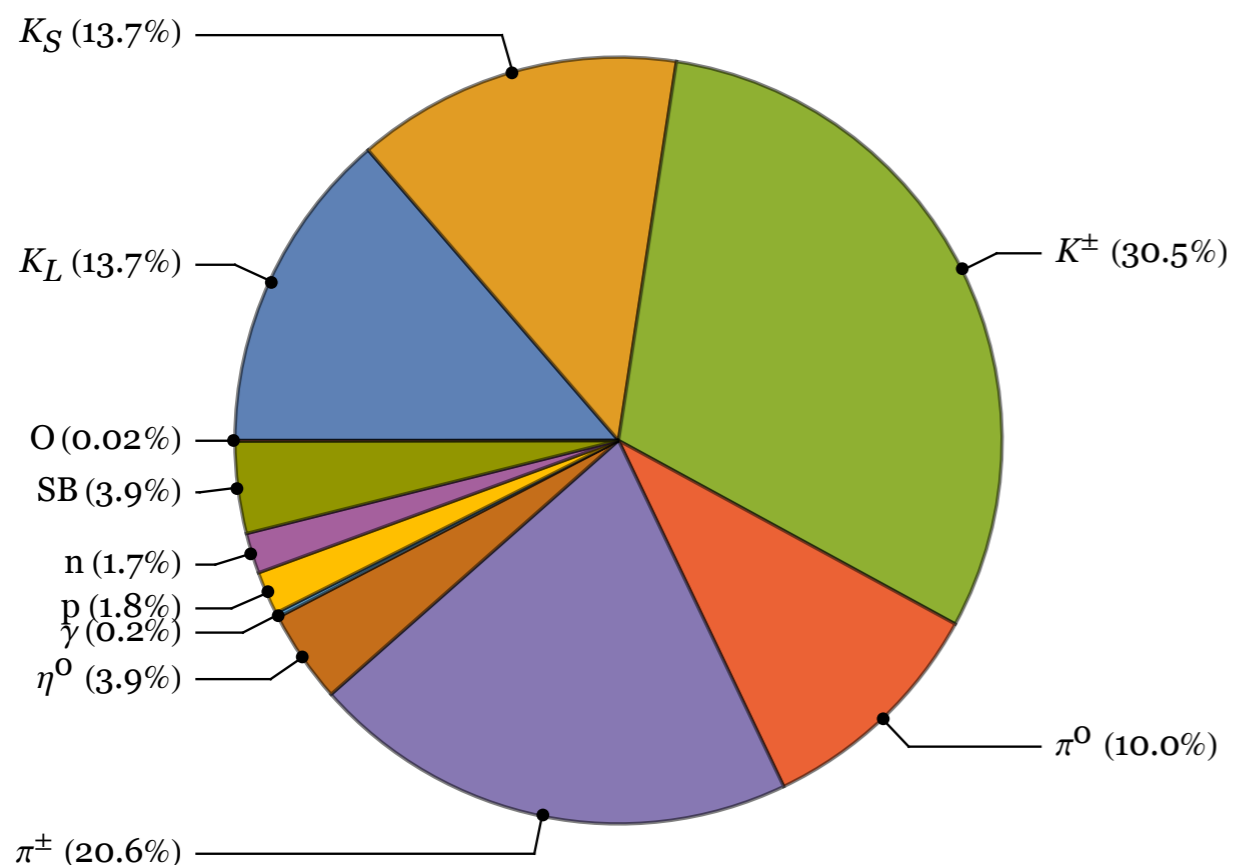


# Jet Classification

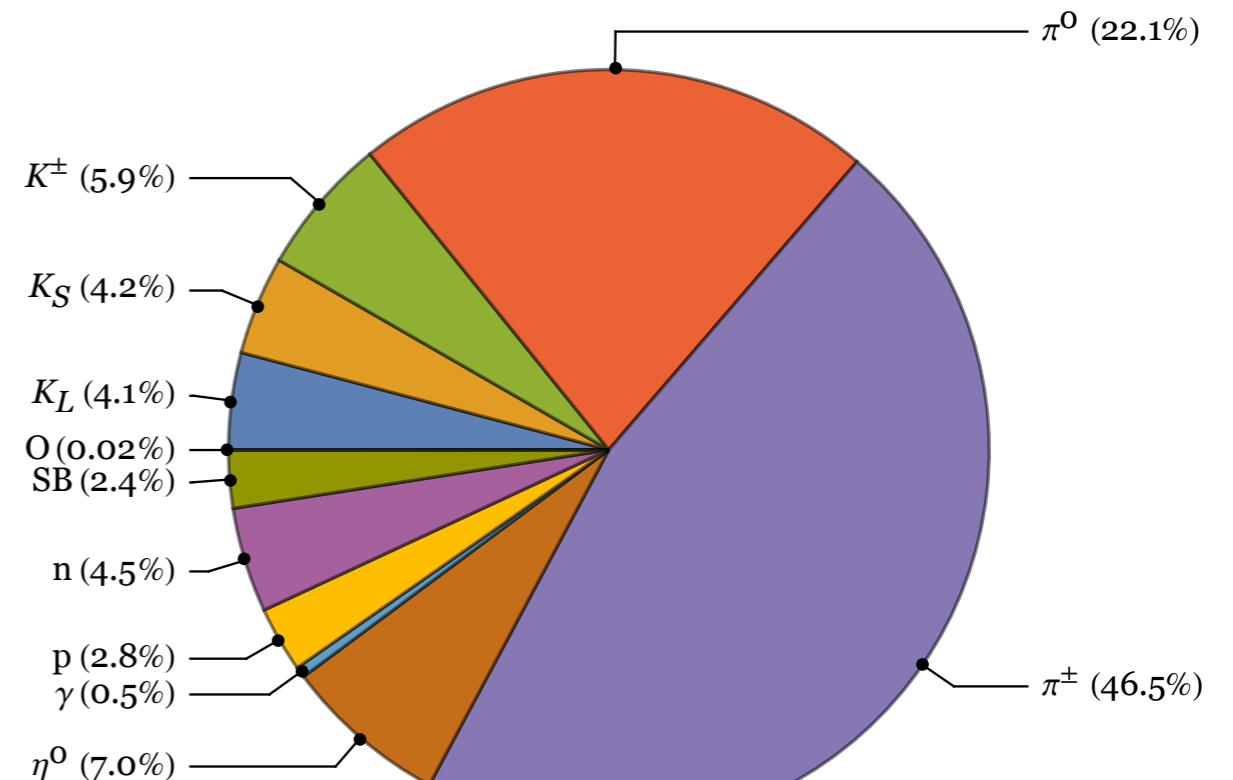
**Strange jets contain more energetic Kaons than down jets.**

Classification of jet samples in terms of hadron with the highest PT inside the leading jet.

$Z \rightarrow s\bar{s}$  ( $p_T > 20$  GeV)



$Z \rightarrow d\bar{d}$  ( $p_T > 20$  GeV)



SB: strange baryons, O: others

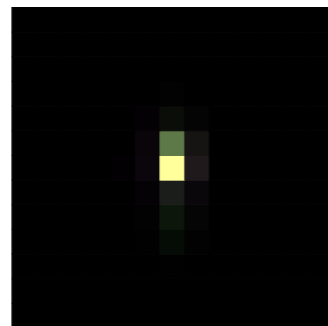
# Jet Images

Create jet images with colors (**Tracker**, **HN = HCAL - Tracker**, **ECAL**).

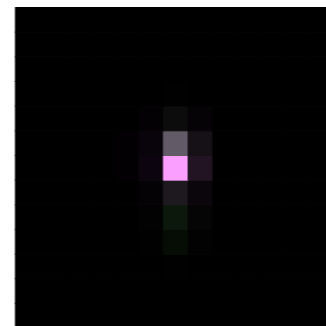
## Image pre-processing

1. Shift an image so that the centroid is at the origin
2. Rotate the image so that the major principal axis is vertical
3. Flip the image so that the maximum intensity is in the upper right region
4. Normalize the image to unit total intensity :  $\sum_{jet} (\hat{p}_T^{track} + \hat{E}_{had} + \hat{E}_{em}) = 1$
5. Pixelate the image :  $\Delta\eta = \Delta\phi = 1.2$  13 x 13 pixels

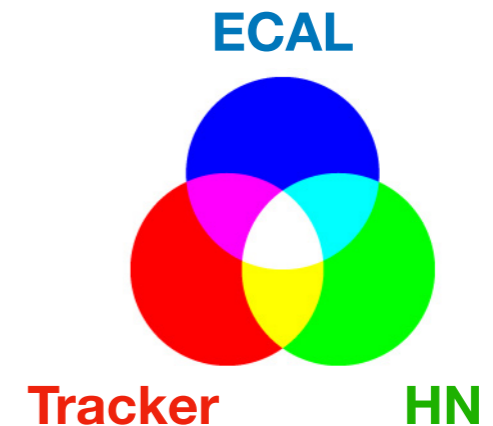
Average images :



$Z \rightarrow s\bar{s}$  ( $p_T > 20$  GeV)

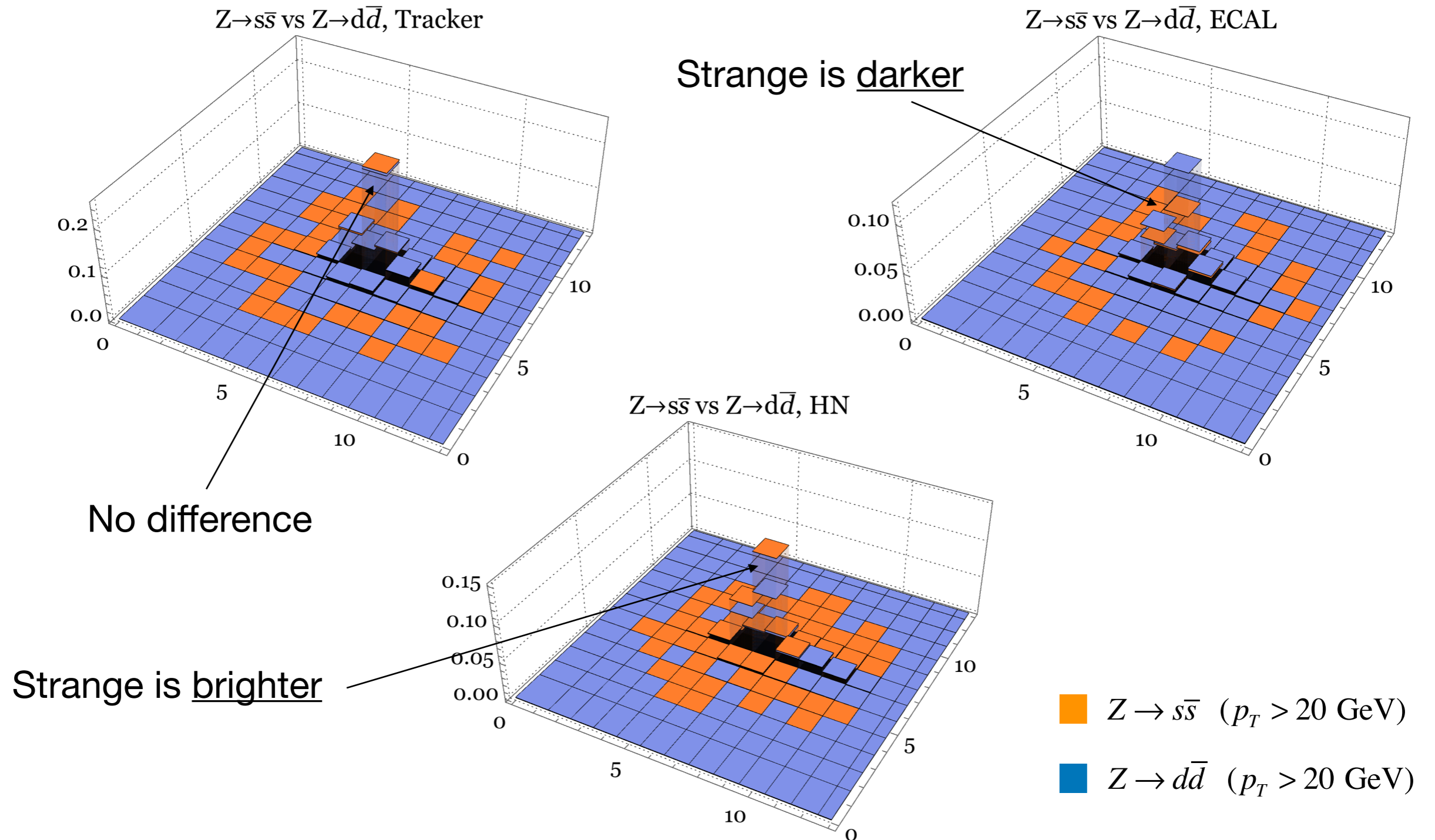


$Z \rightarrow d\bar{d}$  ( $p_T > 20$  GeV)



# Average Images

**Strange jet (average) image is brighter in HN and darker in ECAL.**

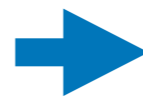


# Cut-Based Tagging

Classify each image into strange jet (signal) or down jet (background).

Put a cut in distribution of some combination of HN, ECAL and Tracker.

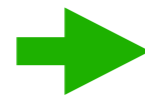
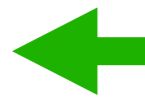
Measures to estimate efficiency and accuracy of taggers



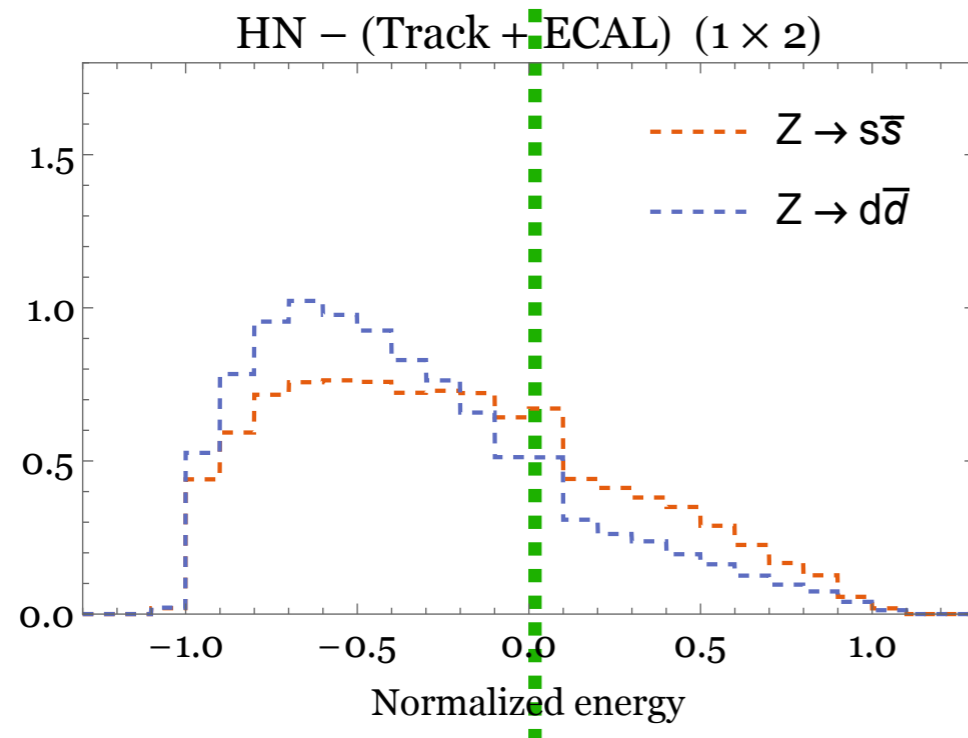
$$\varepsilon_S = \frac{\text{(Correctly classified into signals)}}{\text{(Total number of signal jets)}}$$

$$\varepsilon_B = \frac{\text{(Misclassified into signals)}}{\text{(Total number of backgrounds)}}$$

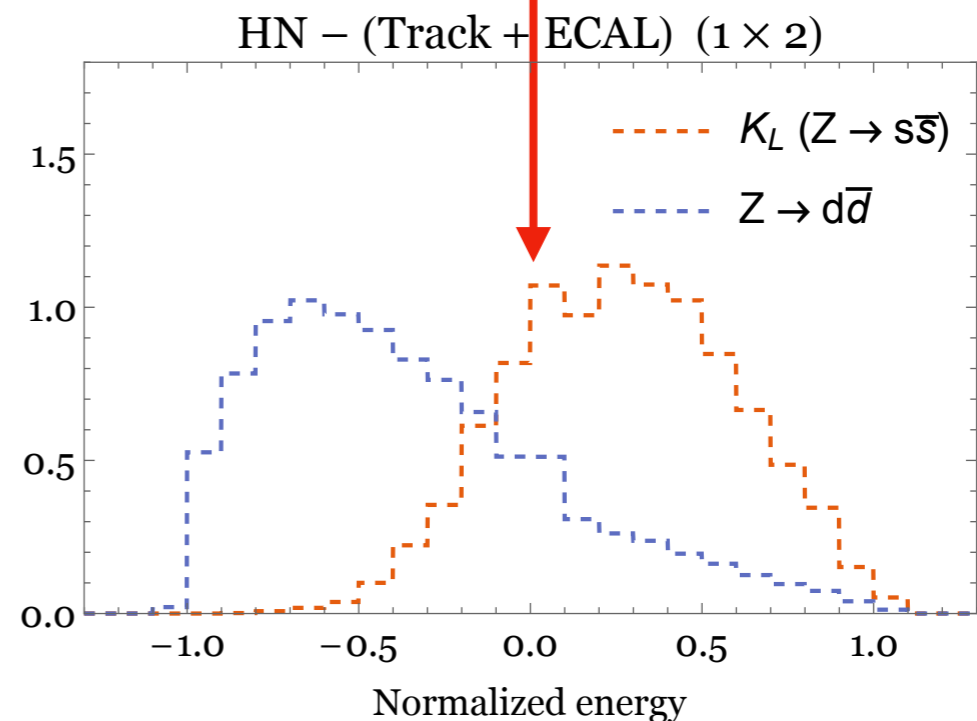
Larger  $\varepsilon_S$   
Larger  $\varepsilon_B$



Smaller  $\varepsilon_S$   
Smaller  $\varepsilon_B$

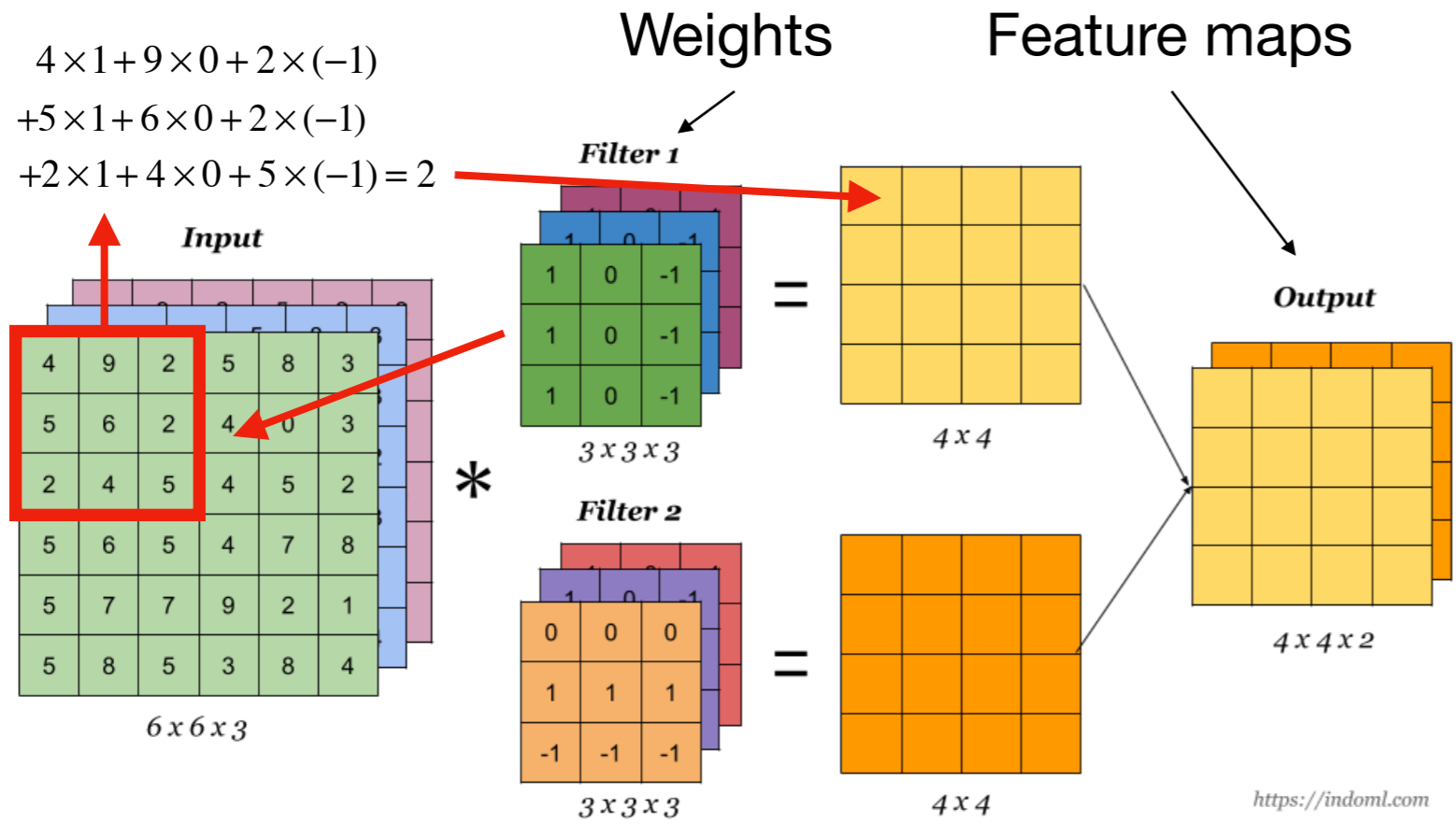


**Extract K-long samples**



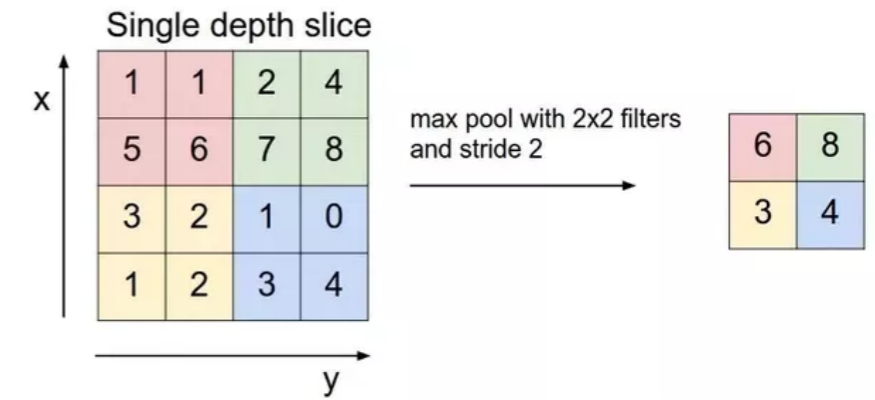
# Network Architecture

## Convolutional layer

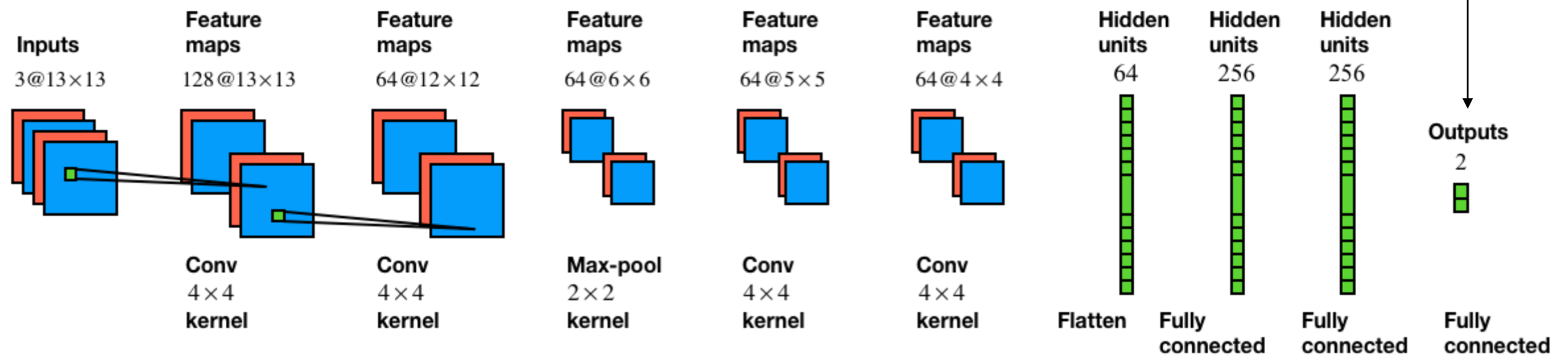


## Max pooling

Reduce the image size



Probabilities of signal and background



# Training

The goal of training is to minimize loss function :

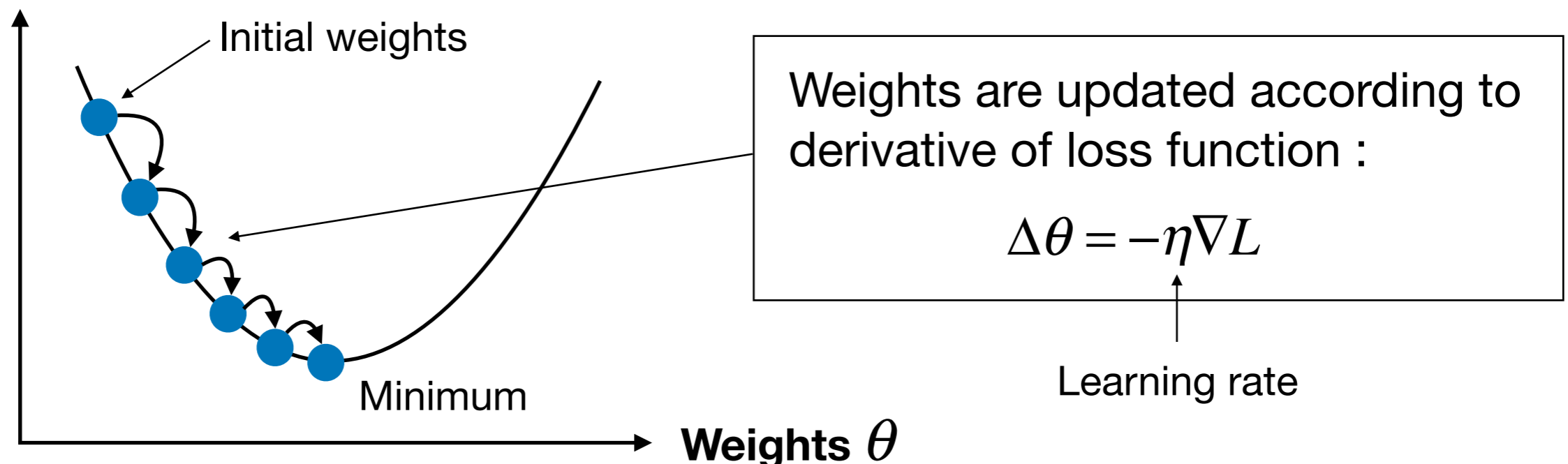
**Network prediction**

$$L = \sum_i f(p(\theta, x_i), y_i) \quad p(\theta, x_i) : \text{Signal probability} \quad \theta : \text{Weights}$$

$$x_i : \text{Input} \quad y_i : \text{Truth label of example } i \quad \left( \begin{array}{l} y_i = 0 : \text{Signal} \\ y_i = 1 : \text{Background} \end{array} \right)$$

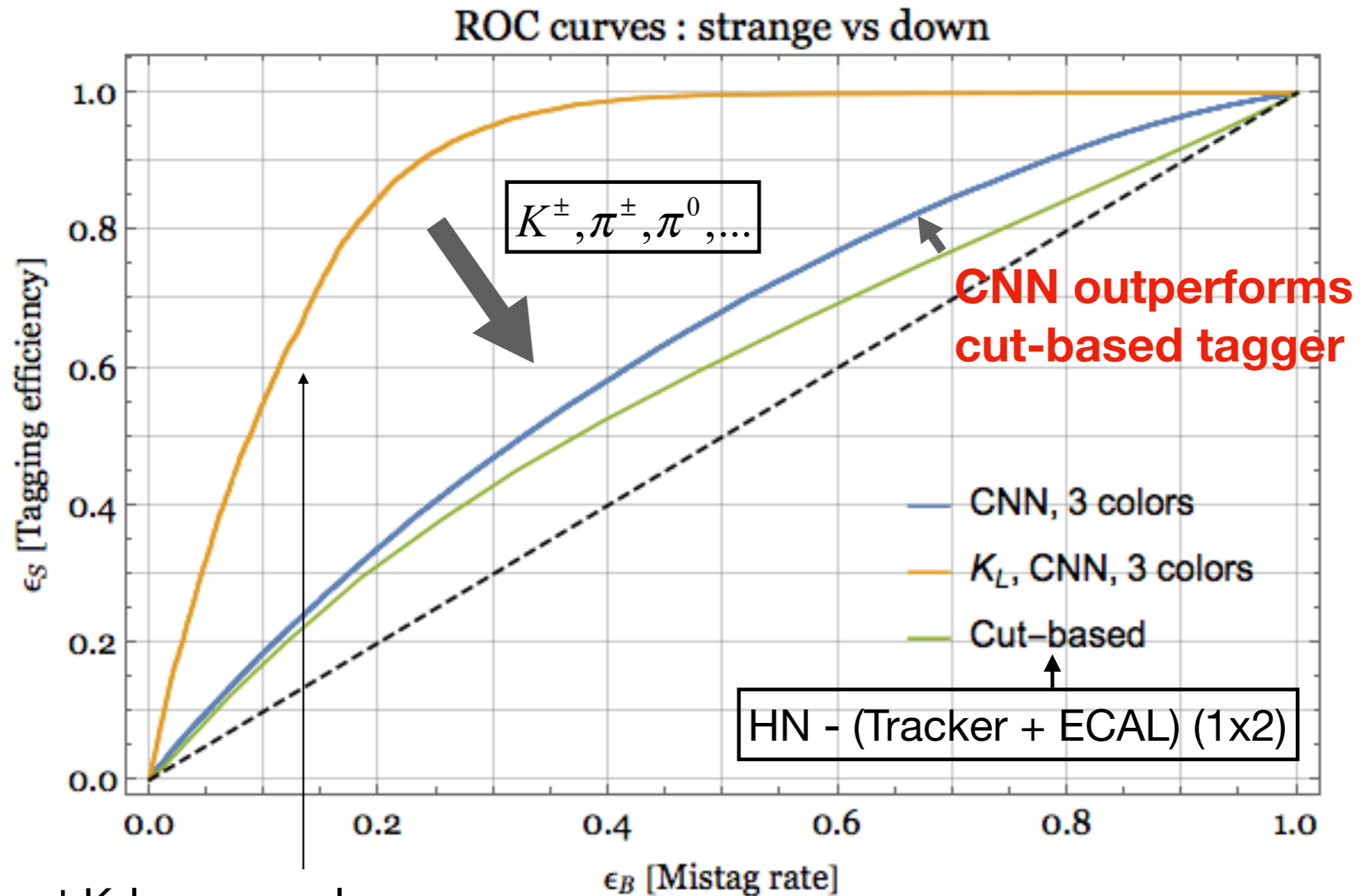
We use cross entropy :  $f(p, y) = -(y \log(1 - p) + (1 - y) \log p)$

**Loss function  $L$**





# Results



**K-long ROC curve is very good and contamination with other hadrons lowers the performance.**

# Summary

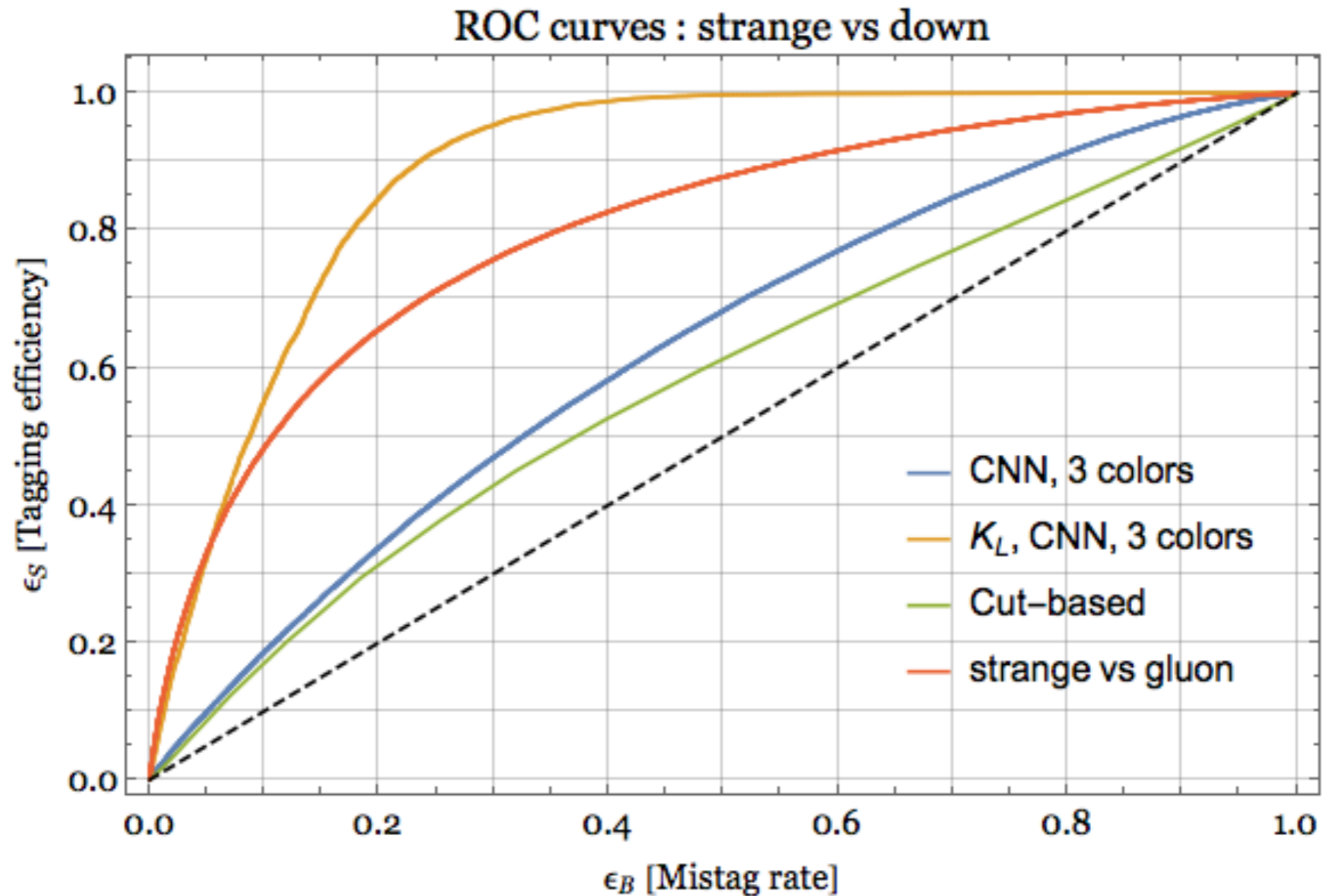
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- ✓ Strange tagging is the last missing piece of quark/gluon tagging.
- ✓ Identification of strange jet may be important for top quark reconstruction, ...
- ✓ Neutral Kaons can be used for strange tagging.
- ✓ We create jet images with colors (**Tracker**, **Hadronic Neutral**, **ECAL**).  
(= **HCAL - Tracker**)
- ✓ Average images of strange jets can be distinguished from down images.
- ✓ Convolutional Neural Network outperforms cut-based tagger.

*Thank you.*

# **Backup Material**

# Results



Quark and gluon jets are more different than strange and down jets and quark/gluon tagger has higher performance than strange/down tagger.