Intro to LHC jet tagging task

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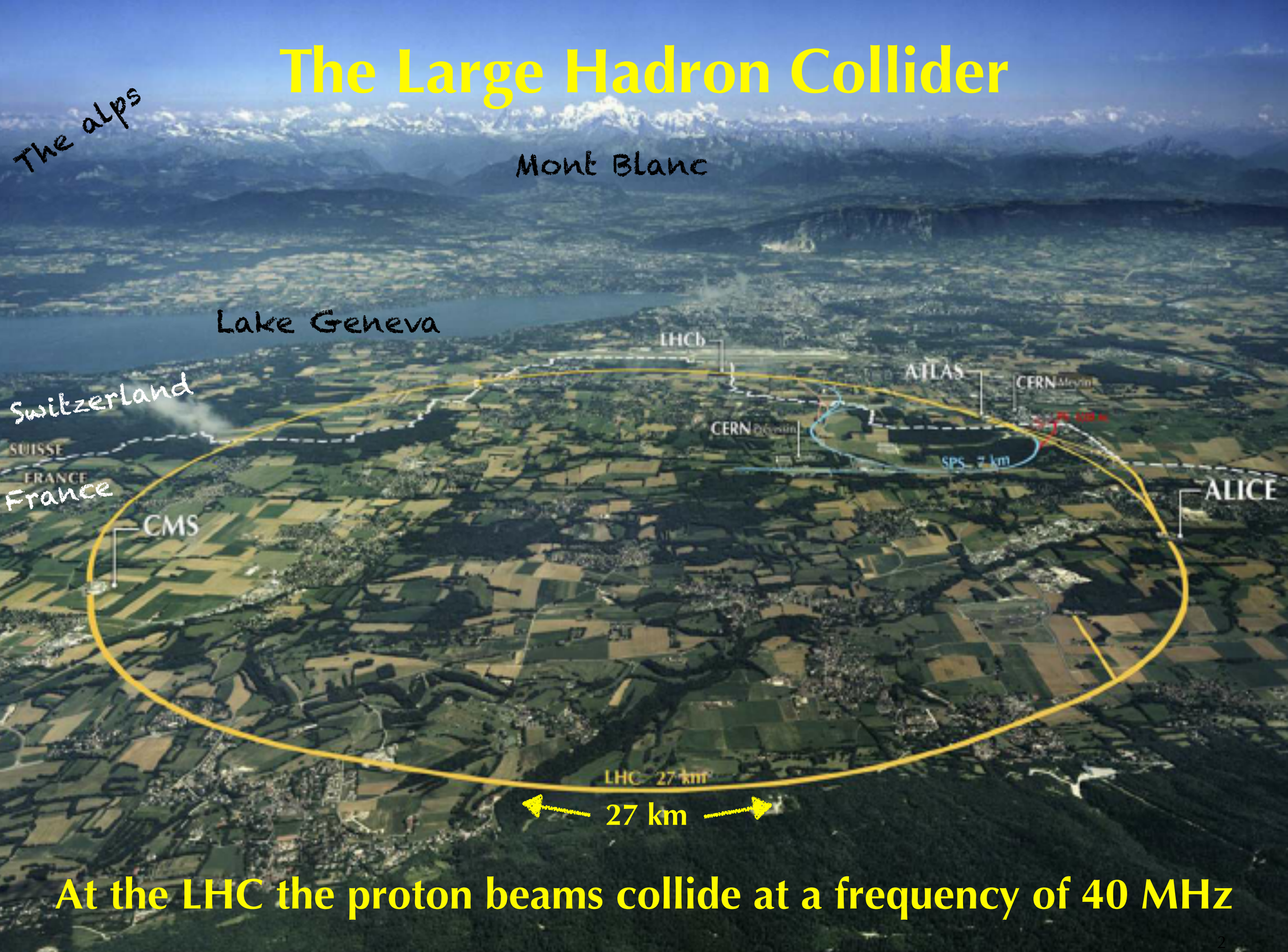
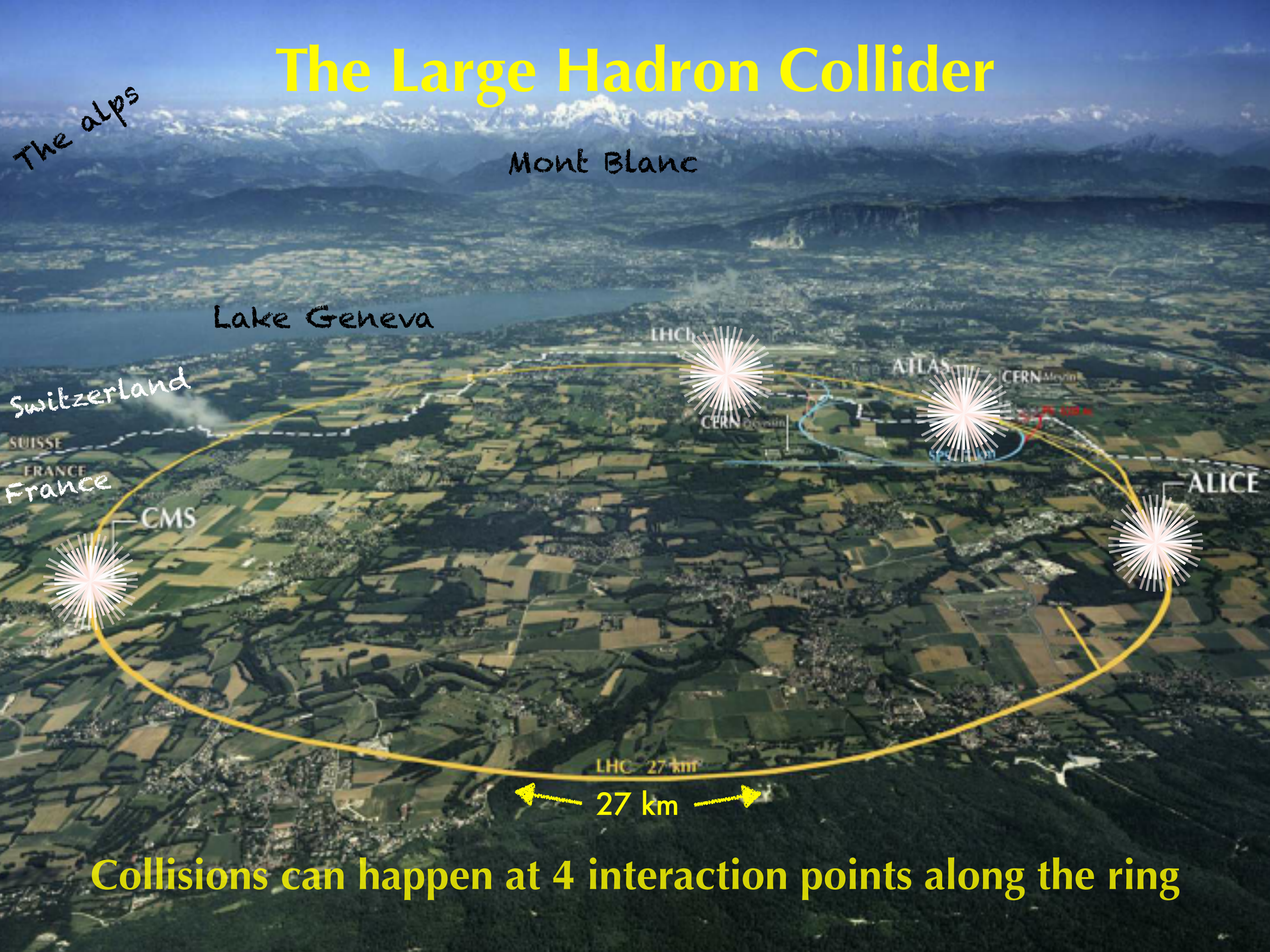
The Large Hadron Collider



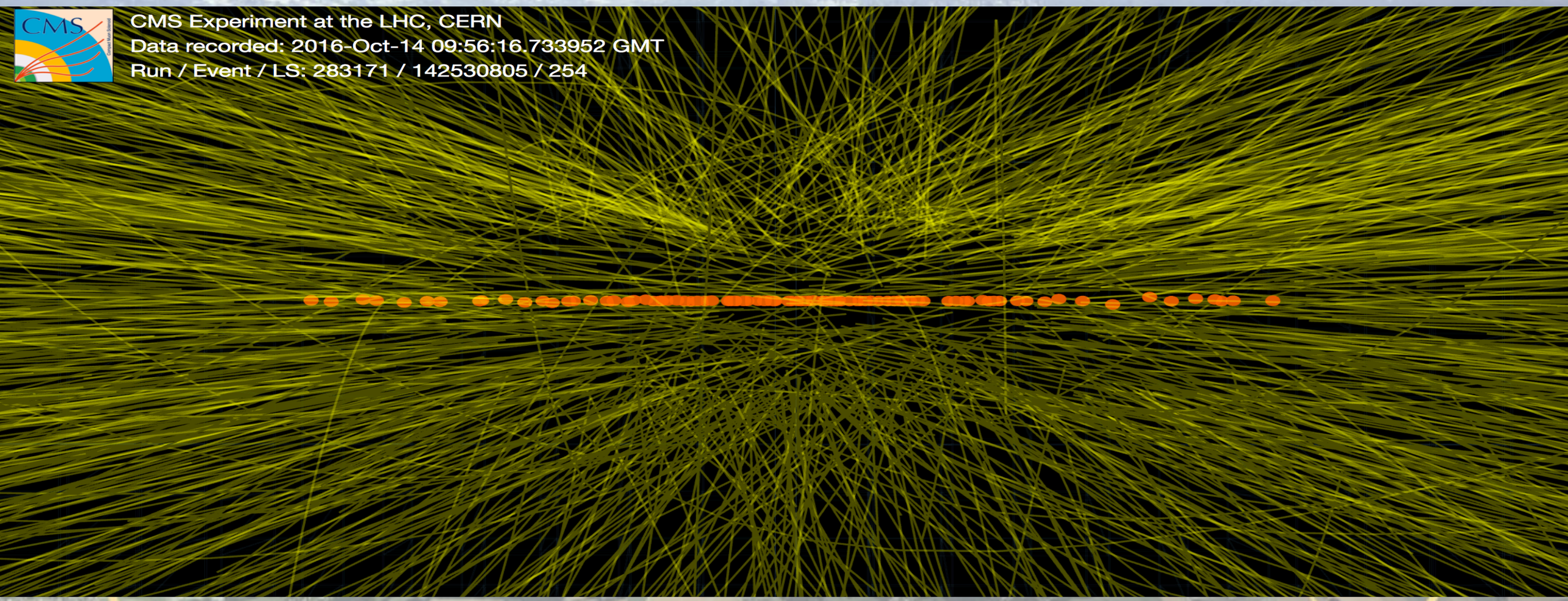
At the LHC the proton beams collide at a frequency of 40 MHz

The Large Hadron Collider



Collisions can happen at 4 interaction points along the ring

The Large Hadron Collider



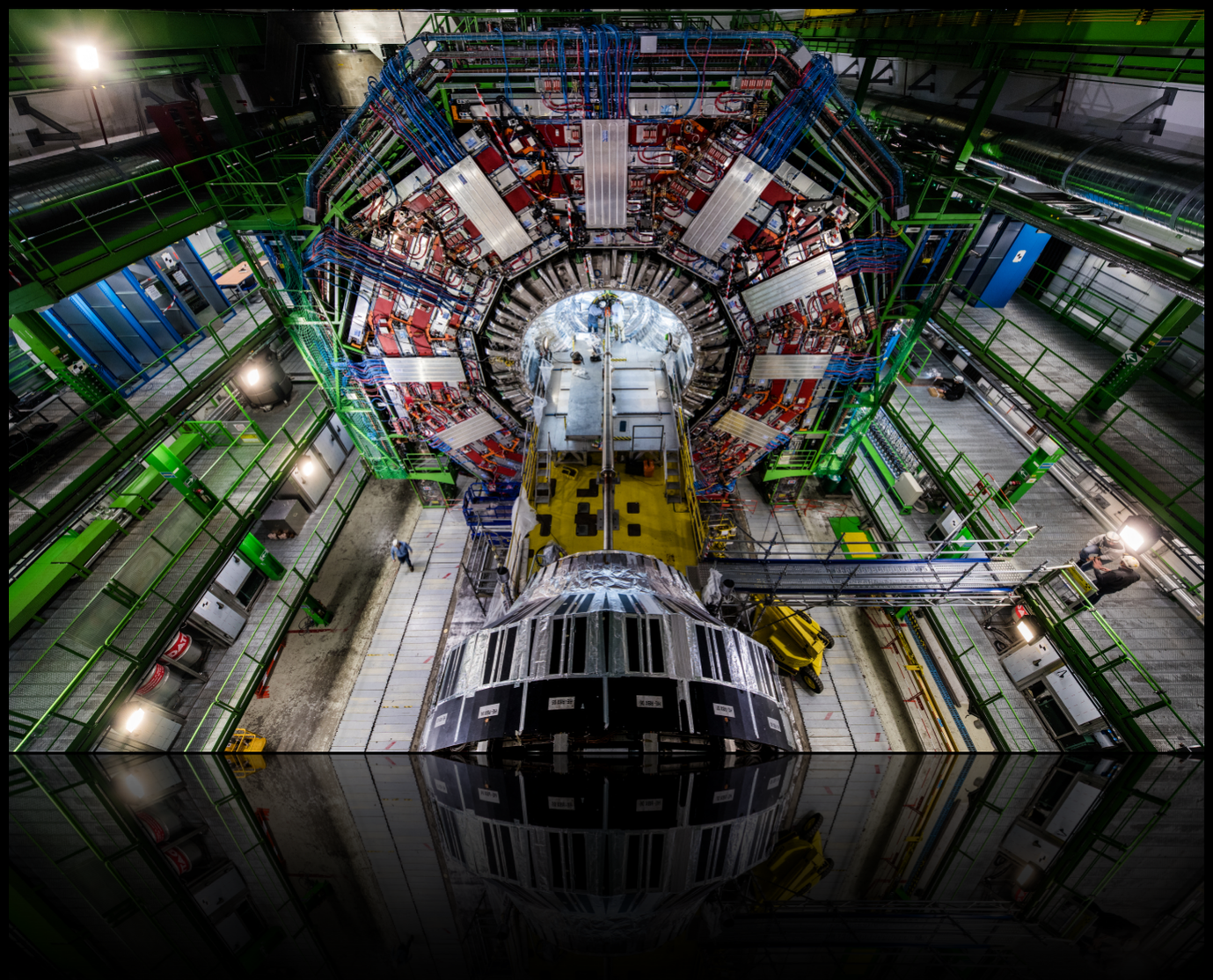
Each collision produces O(10^3) particles!

The Large Hadron Collider

ex, the Compact Muon Solenoid

The detectors have O(10^8) sensors used to detect these particles

The CMS detector



A giant, high-speed and high-resolution camera, taking 3D “photographs” of particle collisions.

With 100 million pixels can take 40 million pictures per second.

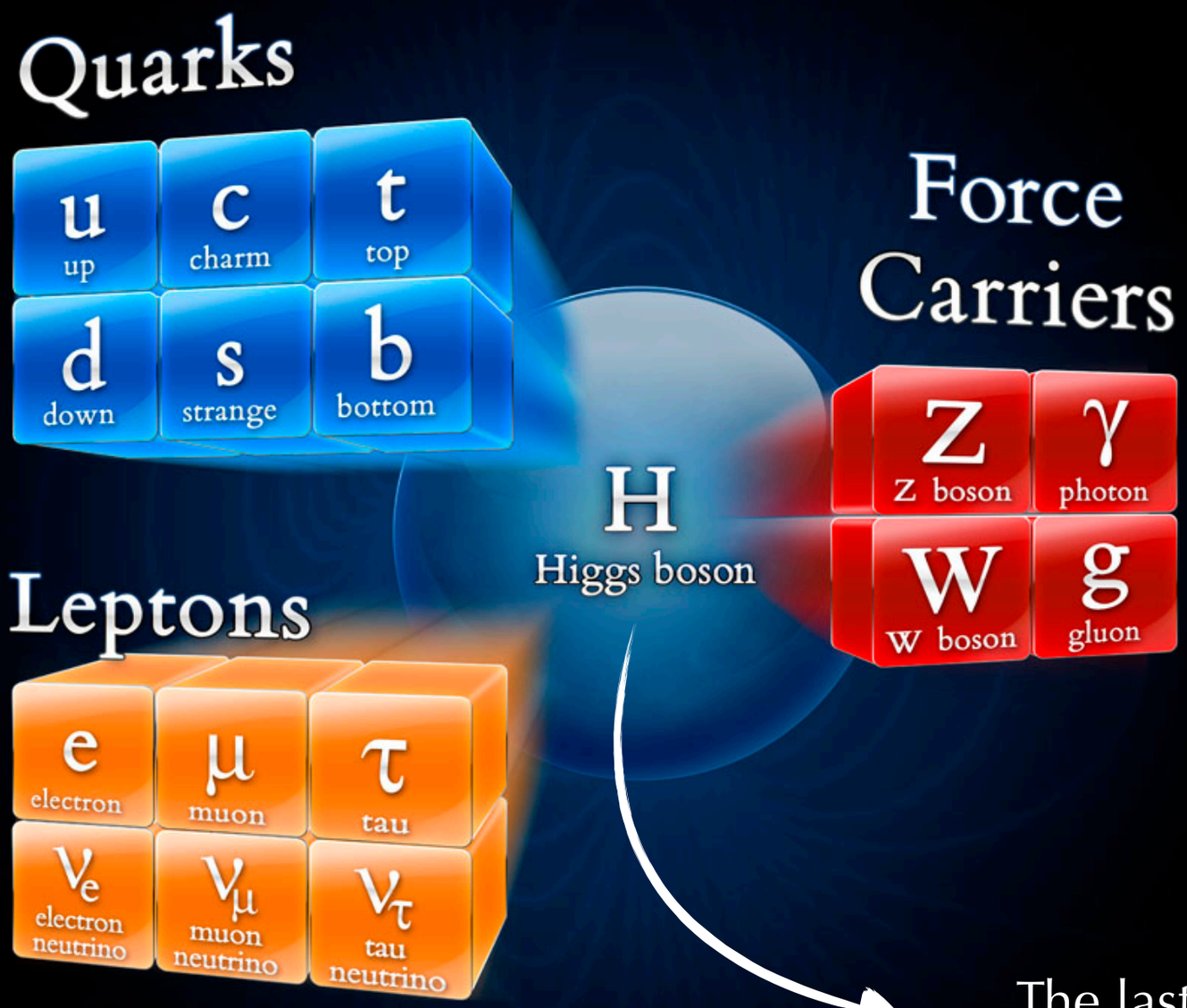
Big data @ LHC

Collision frequency: 40 MHz
Particles per collision: O(10^3)
Detector resolution: O(10^8) channels
Number of collaborators: O(10^3)
Cost: O(10) B euros

Extreme data rates of O(100) Tb/s!

What do we know?

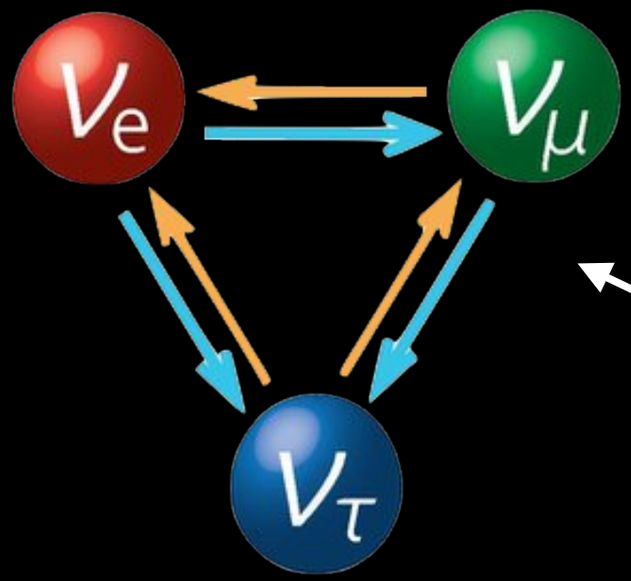
The Standard Model of particle physics



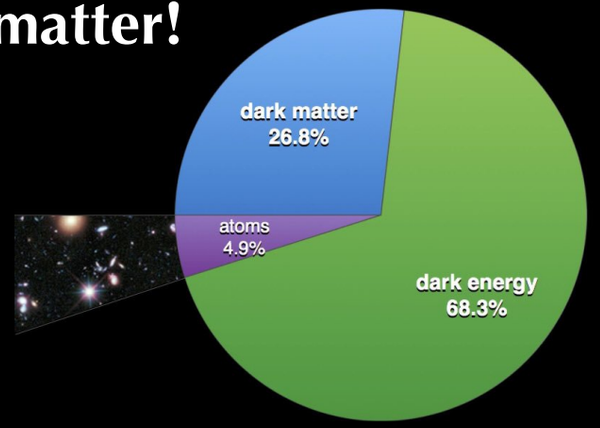
The last missing piece,
discovered in 2012 at the LHC!

What we DON'T know?

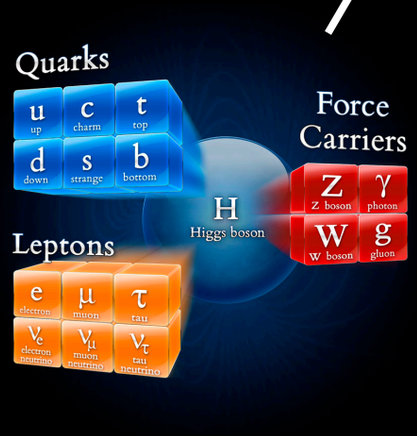
Neutrino masses?



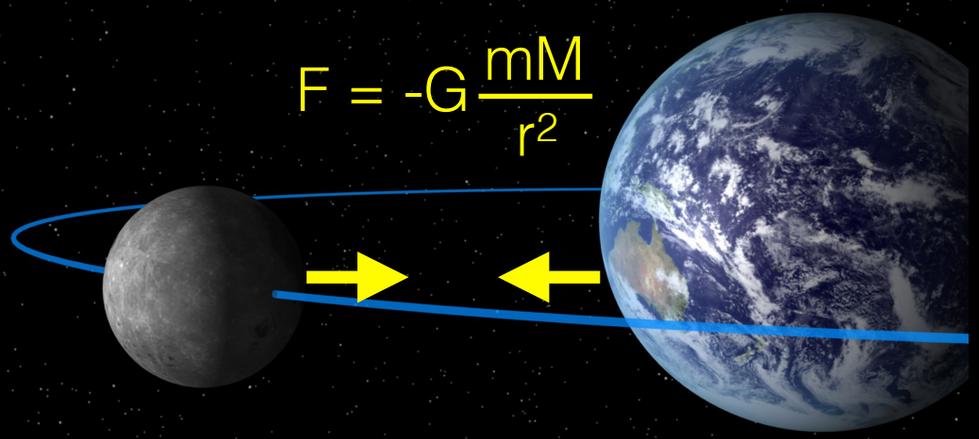
Explains only 5% of the universe. No SM candidate for dark matter!



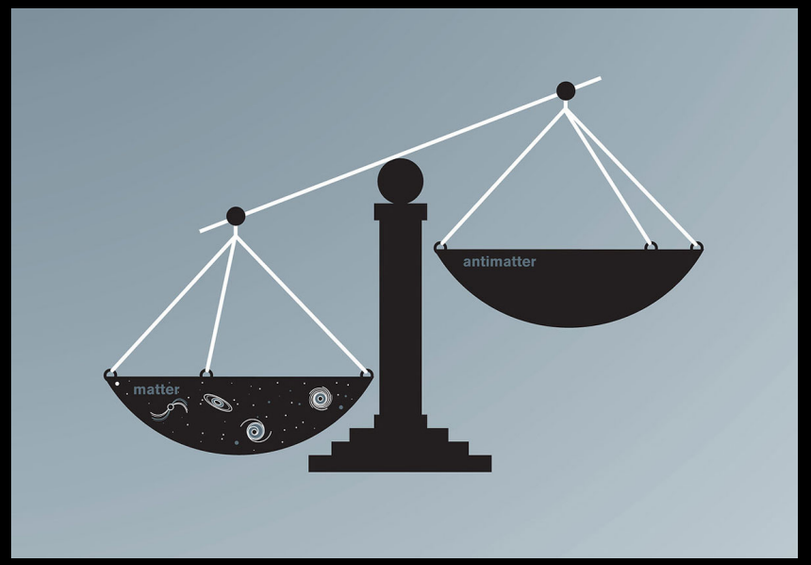
@AstroKatie/Planck13



Gravity not included in the theory

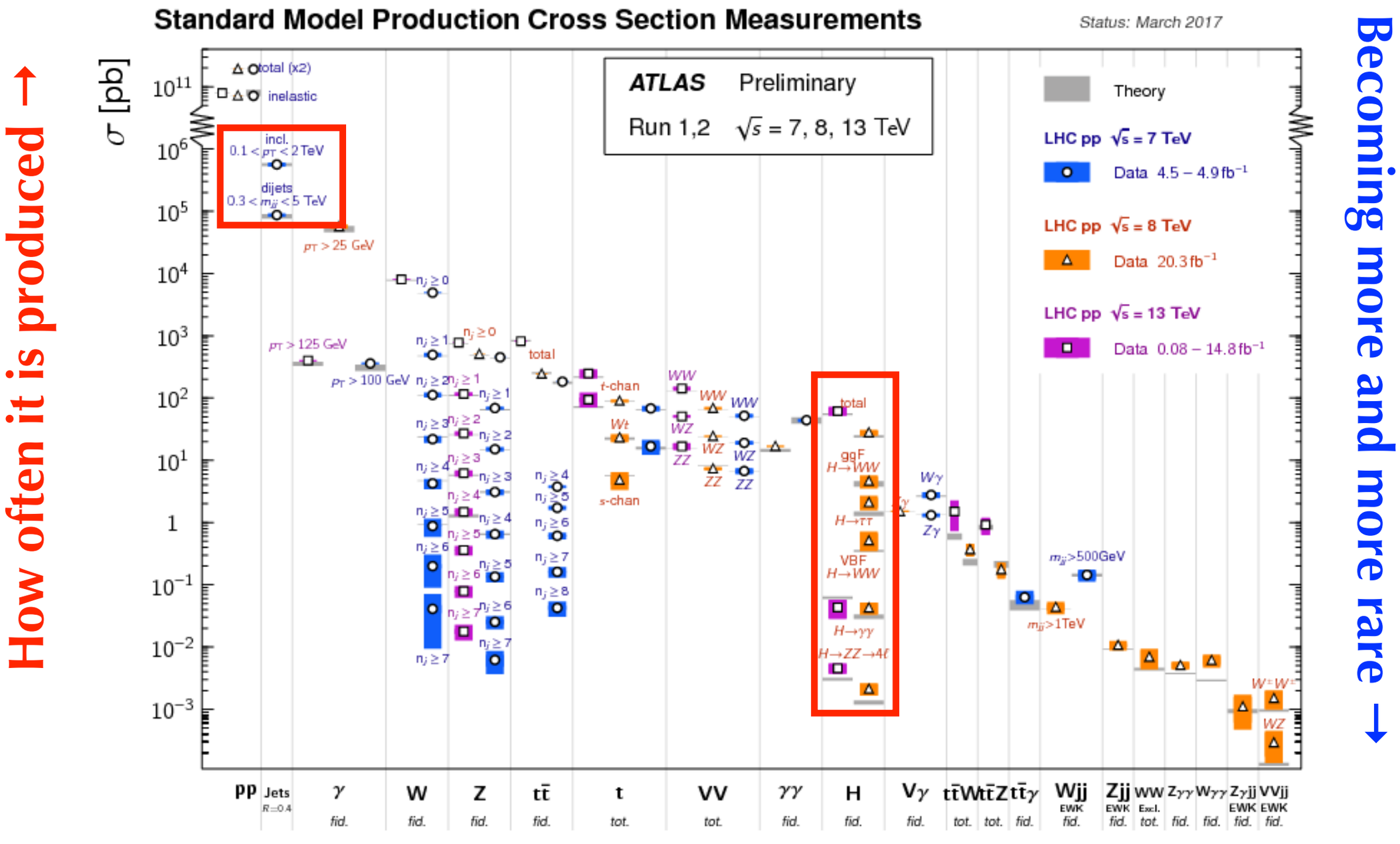


Matter-antimatter asymmetry?



Collisions which produce interesting products (ex: Higgs boson) are typically very rare

The probability of producing a Higgs boson is 5-9 orders of magnitude smaller than producing only jets



Heavy jet tagging

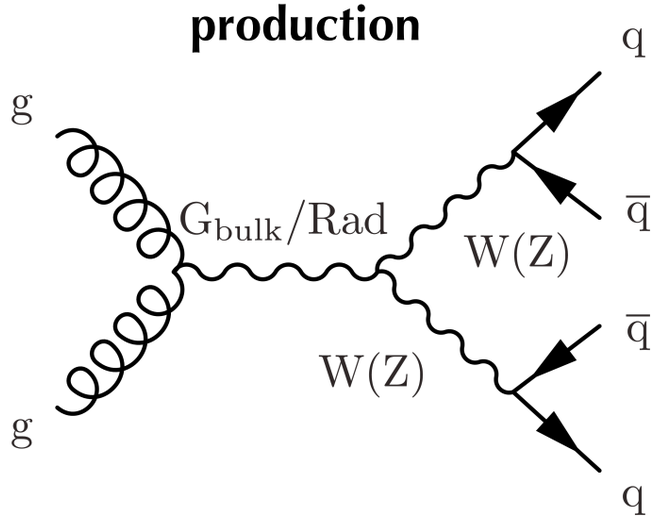
- **Identification of jets arising from hadronization of boosted W/Z/H/top is a key task in LHC physics:**

  - new physics searches, standard model measurements, higgs sector

  - **unique signature** from hadrons merging in single jet with substructure

  - exploit to suppress **overwhelming background from multijet** processes in most sensitive all-hadronic and semi-leptonic channels

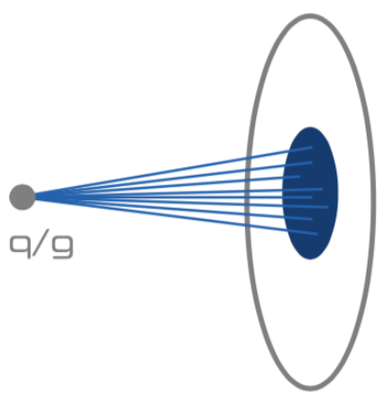
ex: Graviton or Radion production



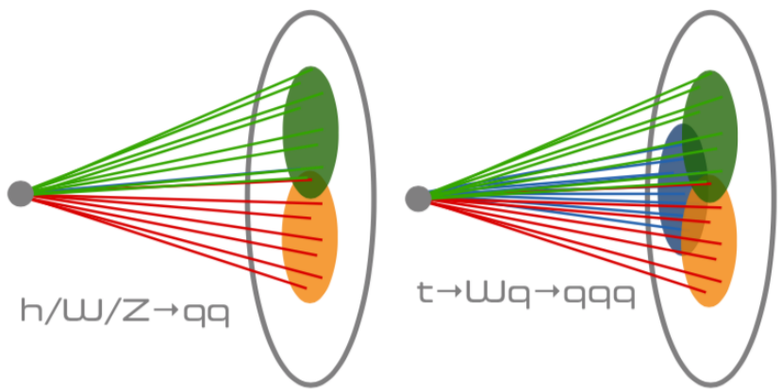
- A topic of interest in both theory and experiment communities since ~ 30 years

- Recent years advancement in ML enabled more powerful algorithms

BACKGROUND JET (single q/g)

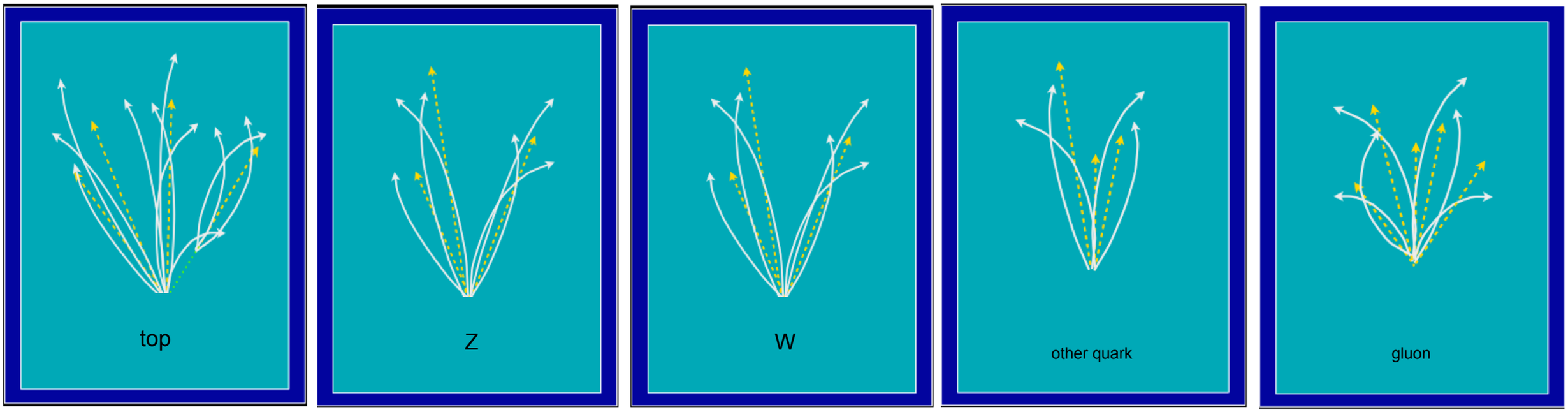


SIGNAL JETS



Physics case: jet tagging

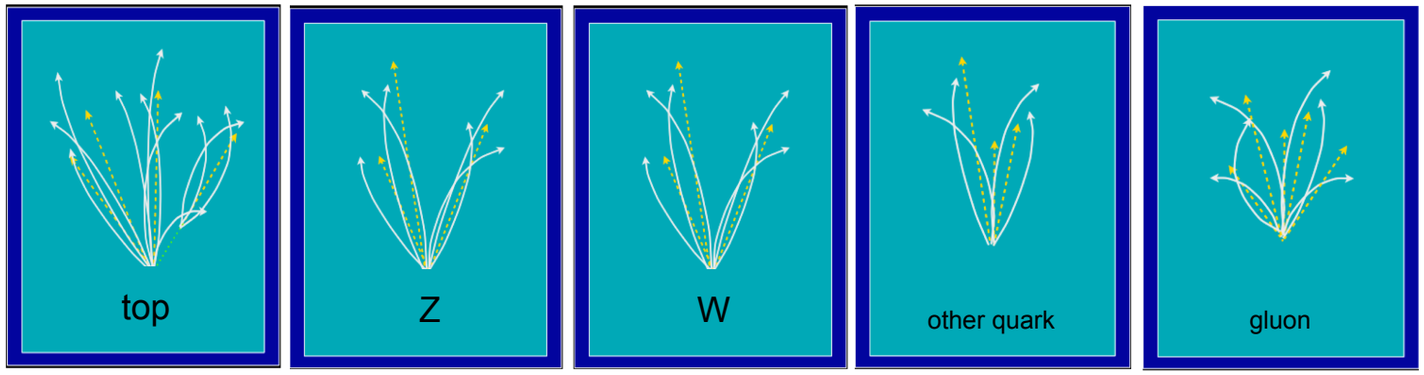
Study a **multi-classification task to be implemented on FPGA:** discrimination between highly energetic (boosted) ***q, g, W, Z, t*** initiated *jets*

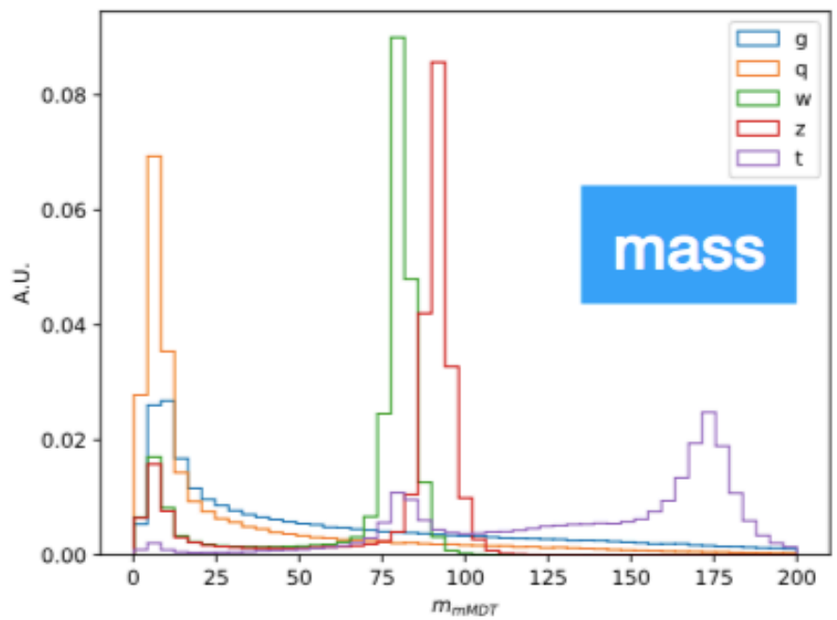


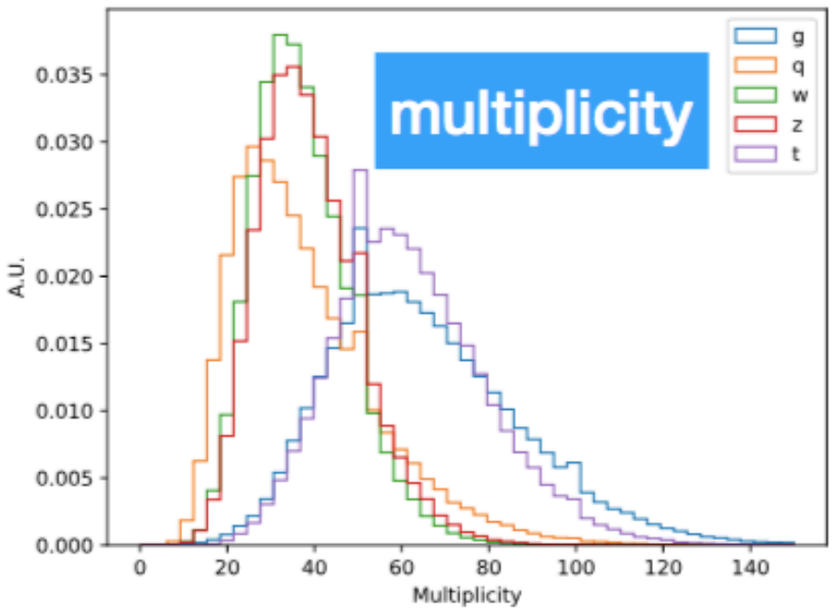
t→bW→bqq	**Z→qq**	**W→qq**	**q/g background**
3-prong jet	2-prong jet	2-prong jet	no substructure and/or mass ~ 0

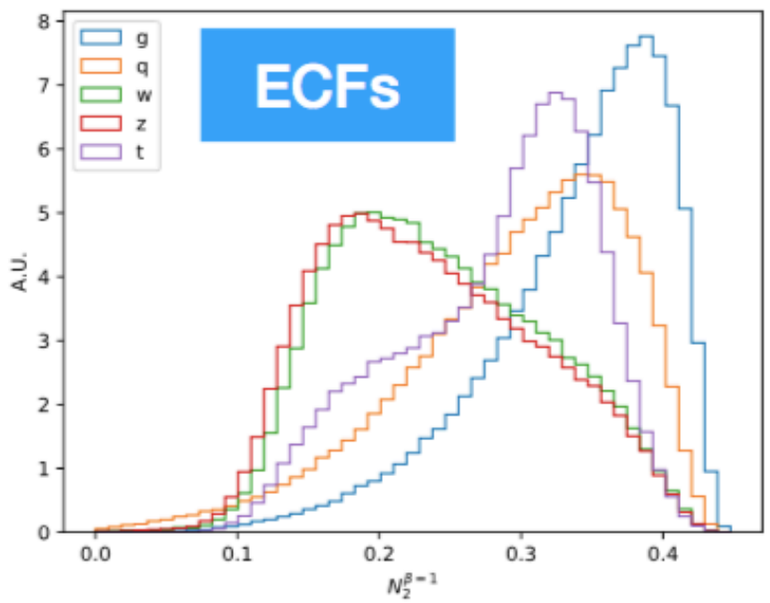
Reconstructed as one massive jet with substructure

High-Level Features









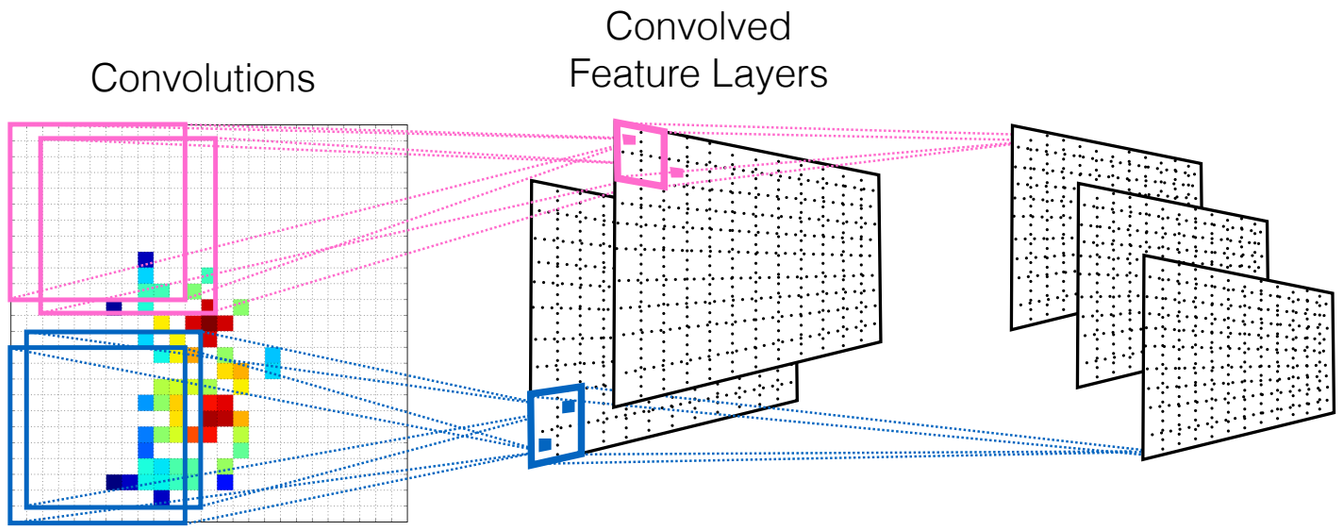
Input variables: several observables known to have high discrimination power from offline data analyses and published studies [*]

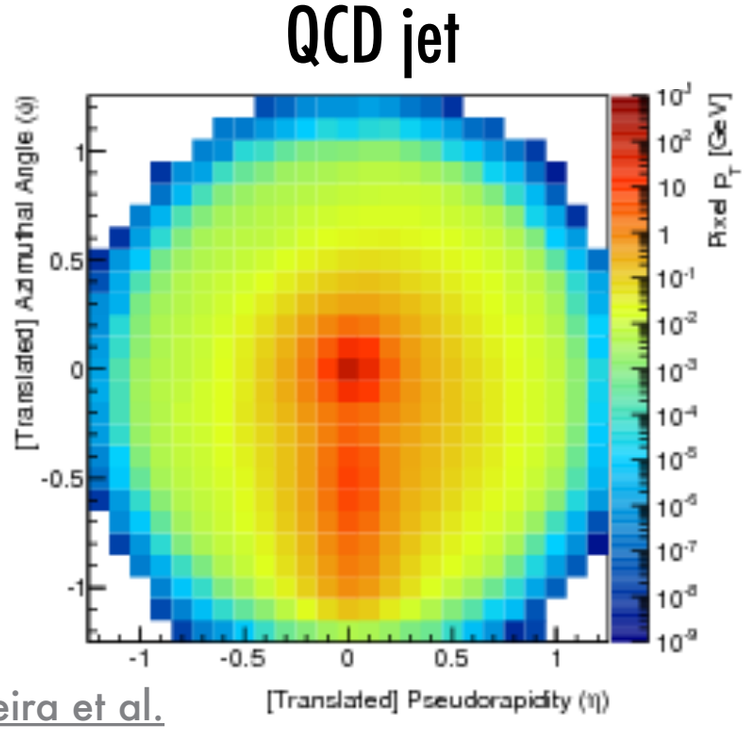
m_{mMDT}
$N_2^{\beta=1,2}$
$M_2^{\beta=1,2}$
$C_1^{\beta=0,1,2}$
$C_2^{\beta=1,2}$
$D_2^{\beta=1,2}$
$D_2^{(\alpha,\beta)=(1,1),(1,2)}$
$\sum z \log z$
Multiplicity

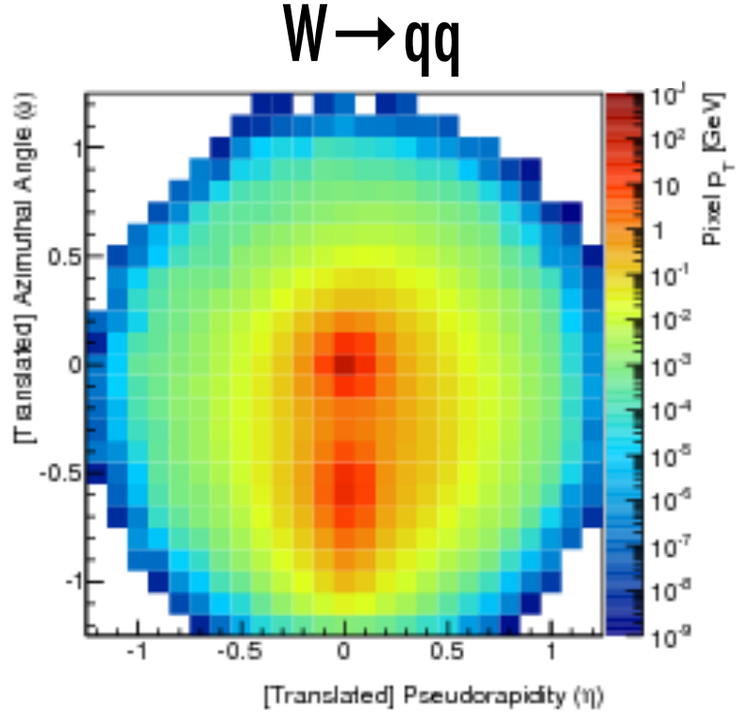
[*] D. Guest at al. PhysRevD.94.112002, G. Kasieczka et al. JHEP05(2017)006, J. M. Butterworth et al. PhysRevLett.100.242001, etc..

Jets as images

- Pixelate the surface covered by the jet and fill each pixel summing up the momenta of the jet constituents pointing to it
- Pixel size determined by calorimeter resolution
- Process the images through **state-of-the-art industry computer vision methods**
- Innovation: ***convolutional NN***
  - apply same matrix of weights to consecutive subsets of the image
  - reduced # parameters
  - able to learn features like edges, corners, etc… from raw data



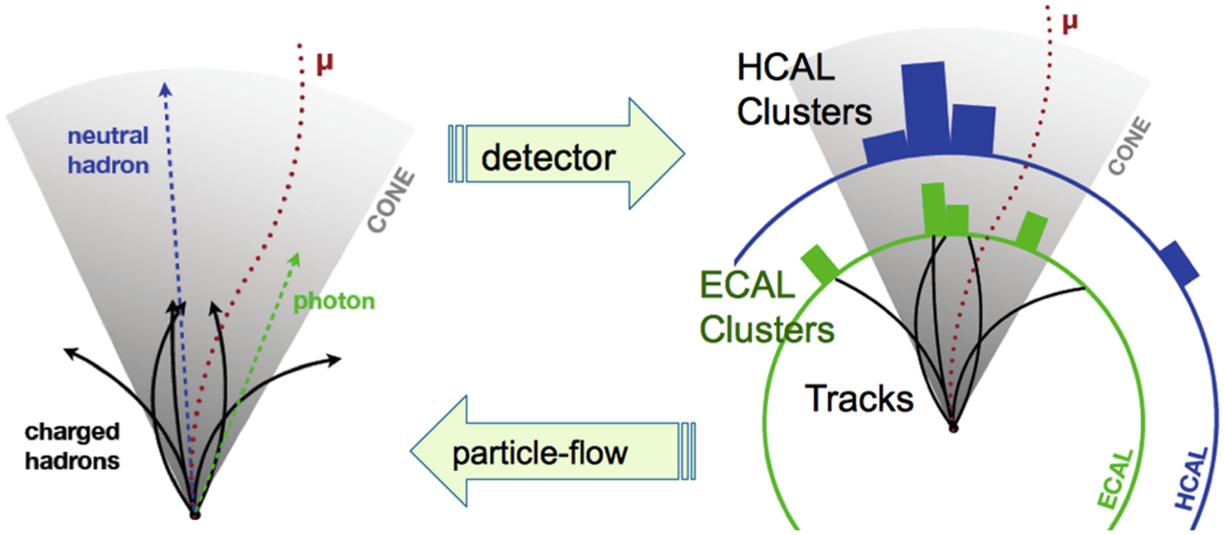


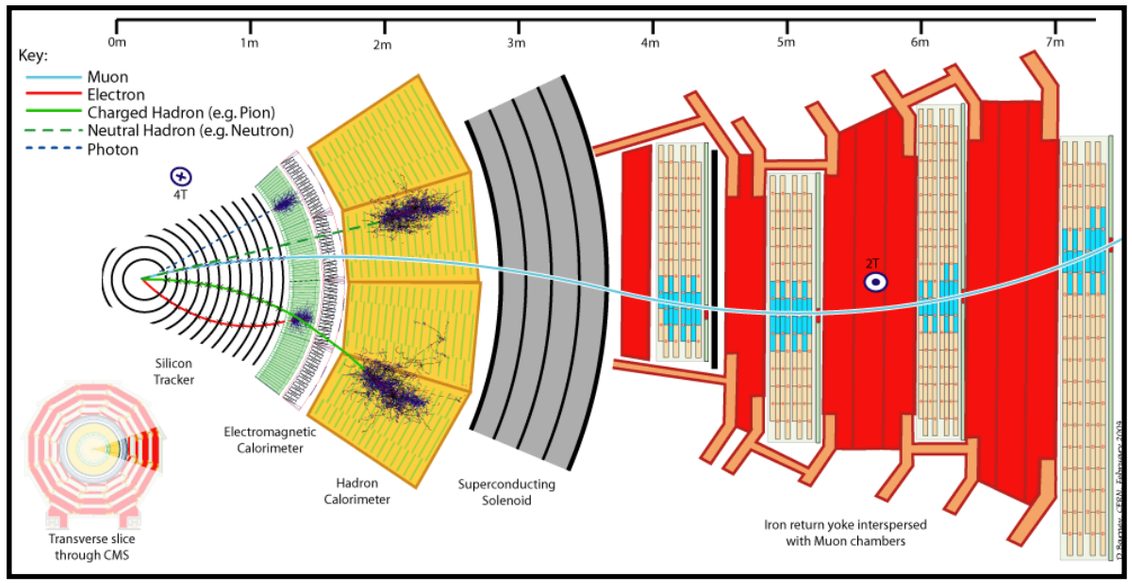


L. de Oliveira et al. JHEP 07 (2016) 069

Is it a good representation?

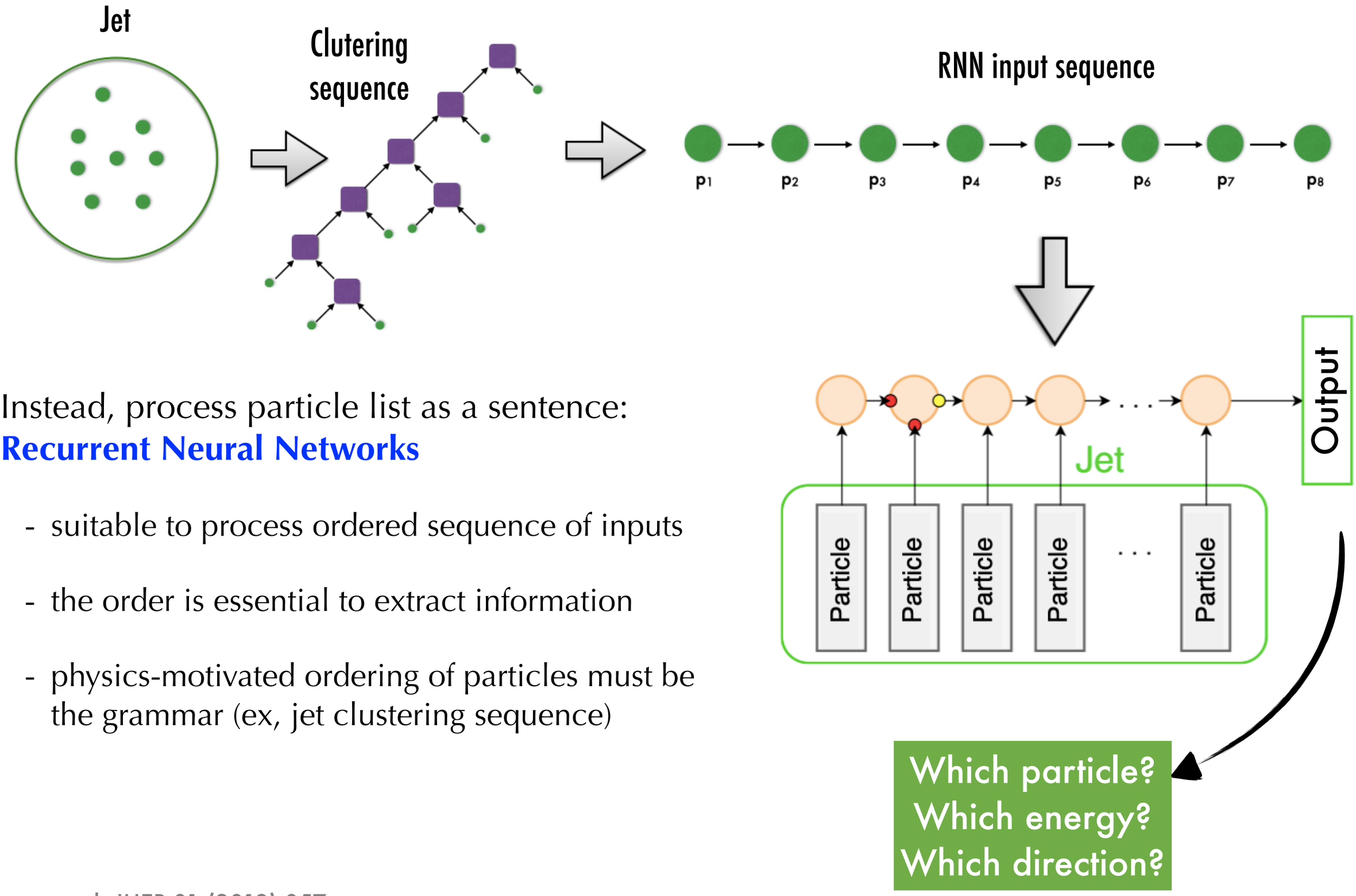
- Using images works good IF individual particles forming the jet were measured in the calorimeter only
- This is not always the case: the particle flow reconstruction makes **extensive use of track information** that cannot be captured by the image → **loss in information and resolution**





Detector	p_T-resolution	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (barrel)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (barrel)

Jets as sentences



- Instead, process particle list as a sentence:
  Recurrent Neural Networks
  - suitable to process ordered sequence of inputs
  - the order is essential to extract information
  - physics-motivated ordering of particles must be the grammar (ex, jet clustering sequence)

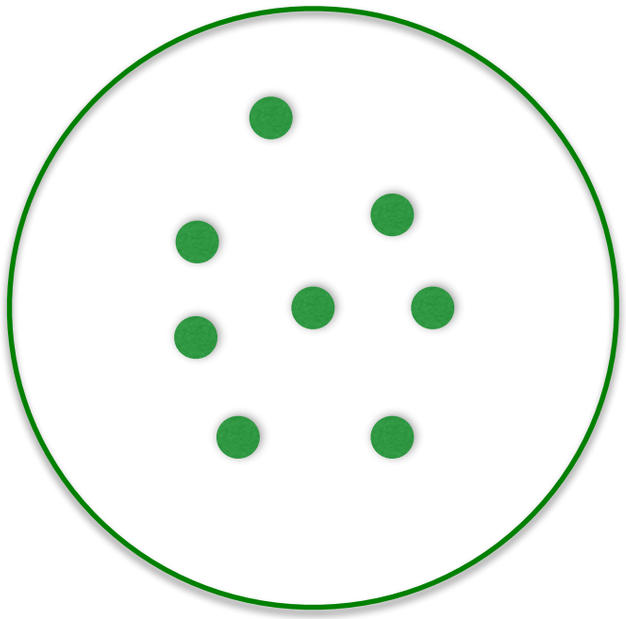
G. Louppe et al: JHEP 01 (2019) 057

Jets as graphs

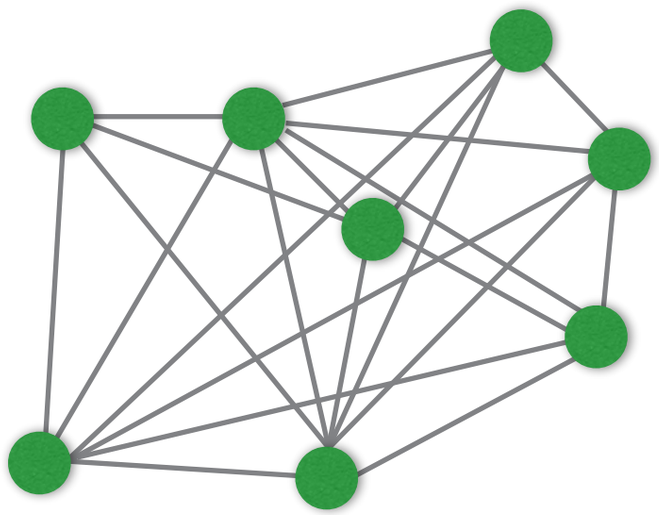
- What if the assumed clustering sequence is not the best ordering?
  → impose **less constraints** and let the NN learn the jet structure

- Represent particles in the jet by **a set of points in space**, where the points themselves are also **sparse and unordered** → graphs as a more natural representation (rather than forcing data into a CNN or RNN)

A Jet



A Graph

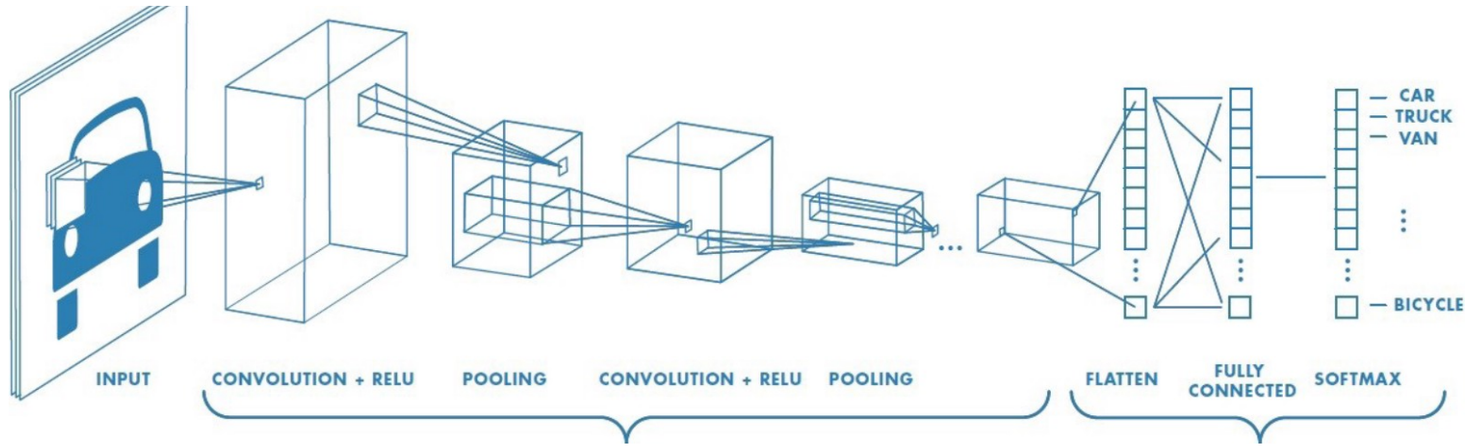


I. Henrion et al. NeurIPS ‘17
E. Moreno et al.: arxiv.1909.12285
E. Moreno et al.: Eur. Phys. J. C 80, 58 (2020)
H. Qu et al.: Phys. Rev. D 101, 056019 (2020)

One problem, many solutions

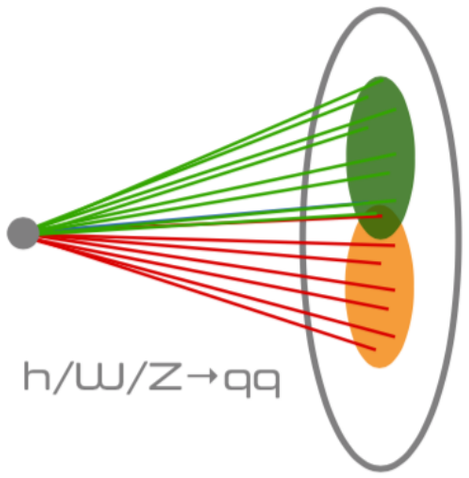
- **Jets as images:**

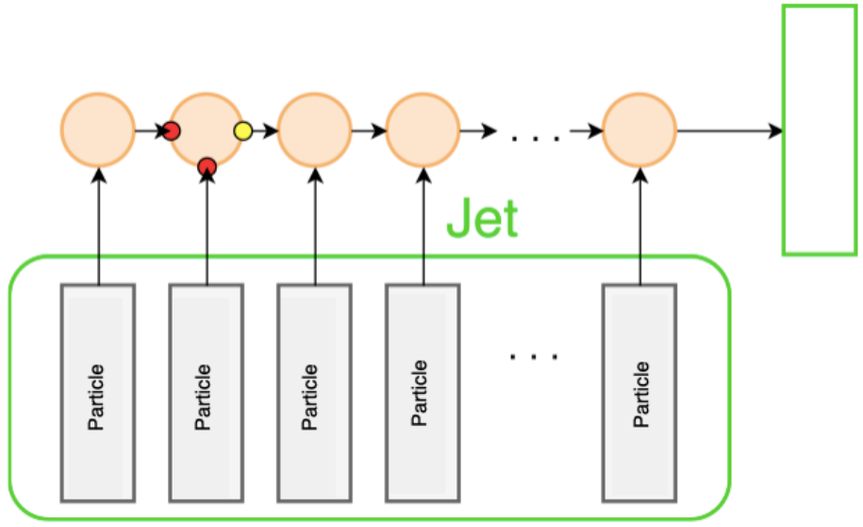
  - can use computer vision techniques



- **Jets as sentences:**

  - can use natural language processing techniques





- **Jets as graphs:**

  - can use graph networks as in social media analyses