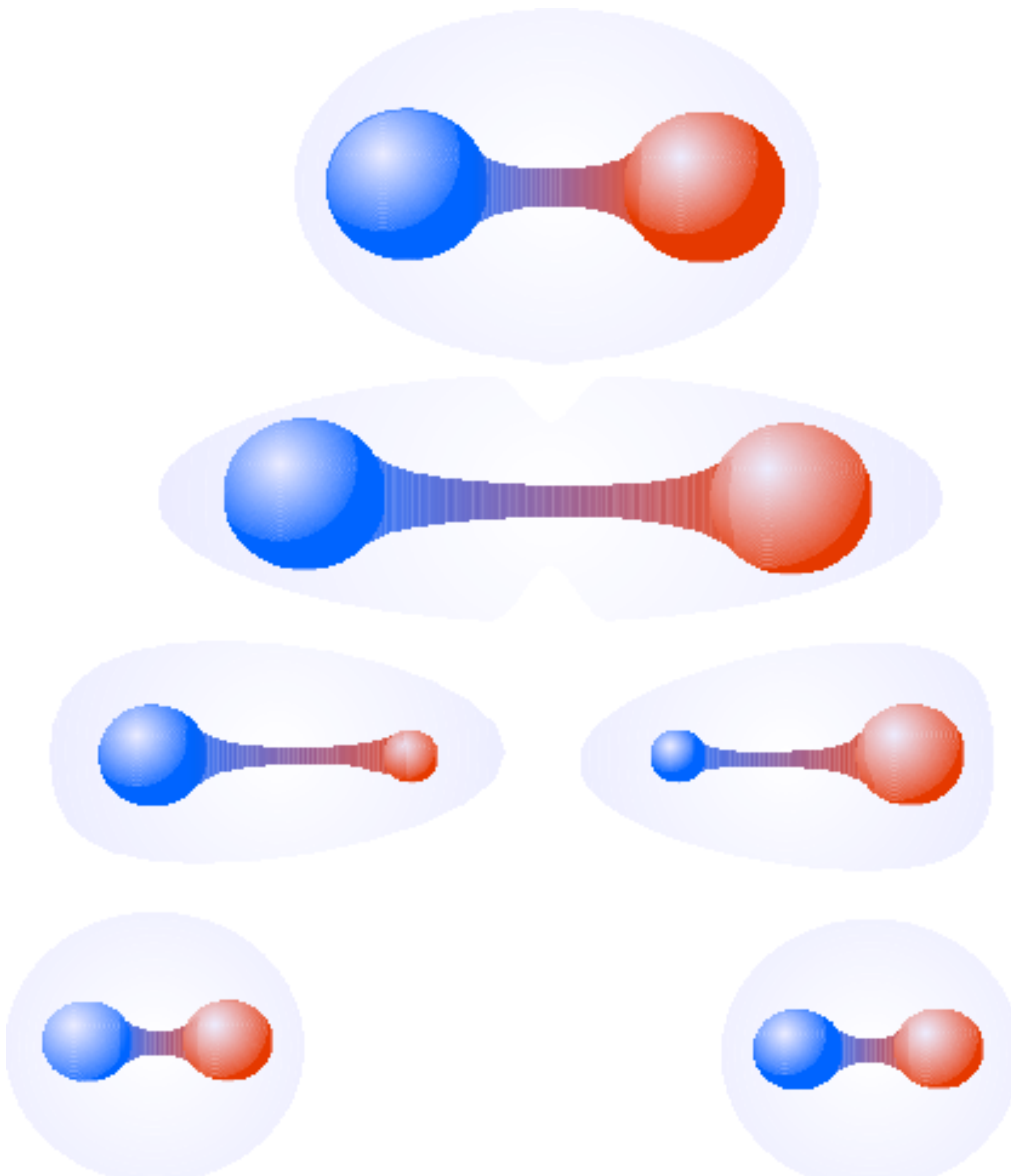
QCD

- So what happens if you try to, say, pull apart a pion?



As you try to break the quarks apart, a quantum pair of quarks is pulled from the vacuum, and you get two hadrons instead of one!

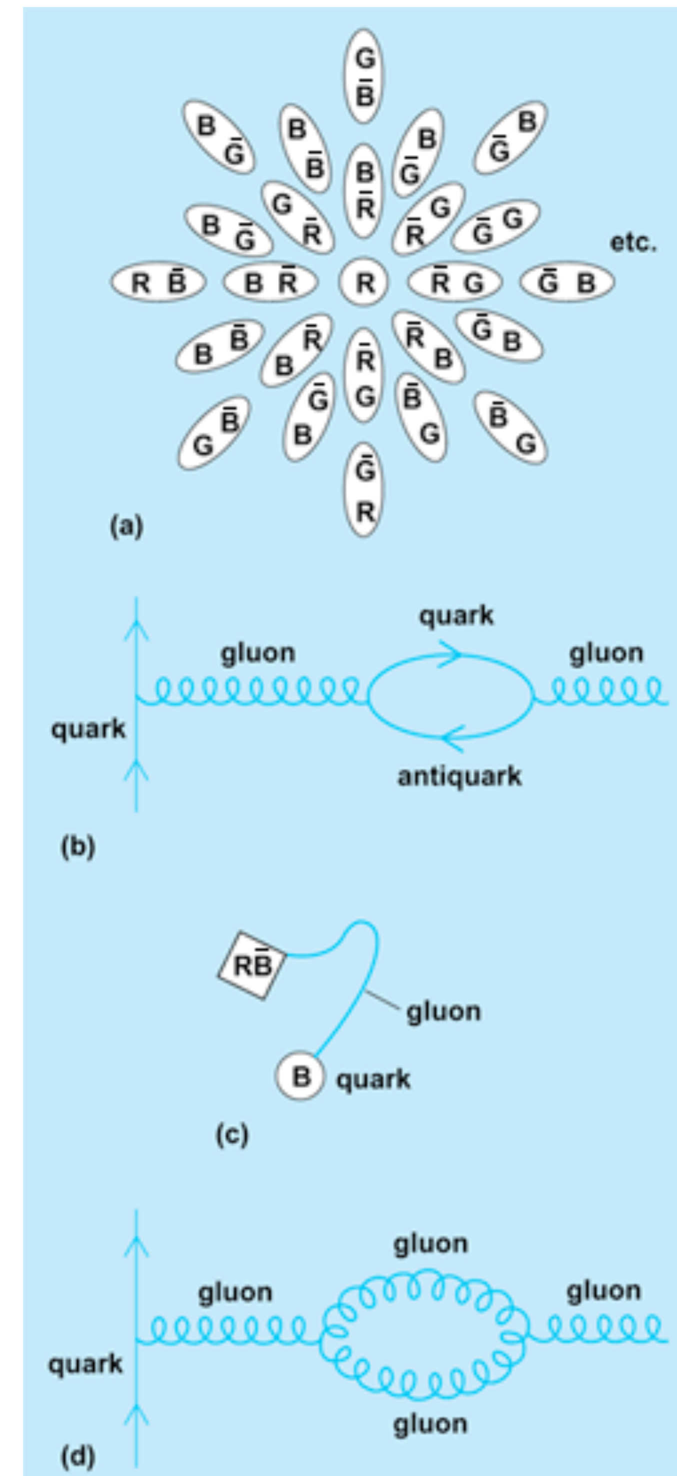
Quarks are confined!

http://zam581.zam.kfa-juelich.de/nic/Publikationen/Broschuere/elementarteilchenphysik-e.html

QCD

- In terms of the running coupling constants, the quarks and gluons see MORE charge at low energy

QCD

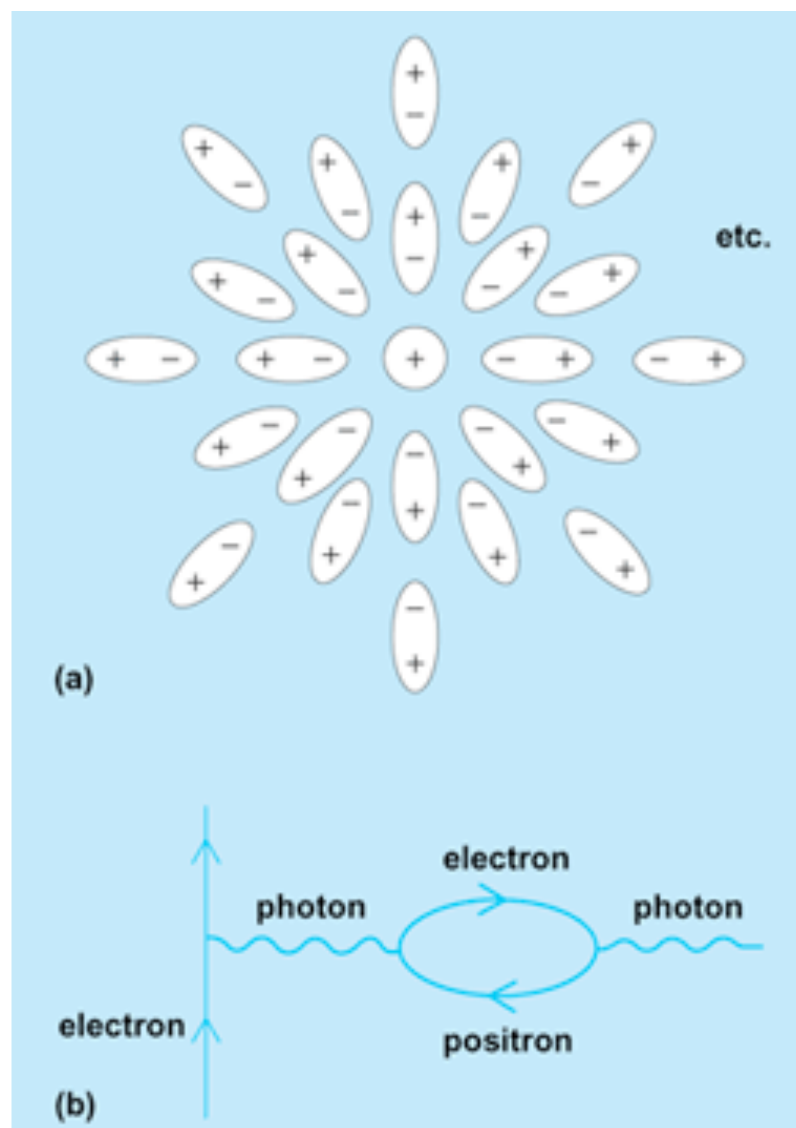


- This is “antiscreening”

http://www.accessscience.com/overflow.aspx?SearchInputText=Quantum+chromodynamics&ContentTypeSelect=10&term=Quantum+chromodynamics&rootID=796322

- This is different from QED, which sees LESS charge at low energy

QED



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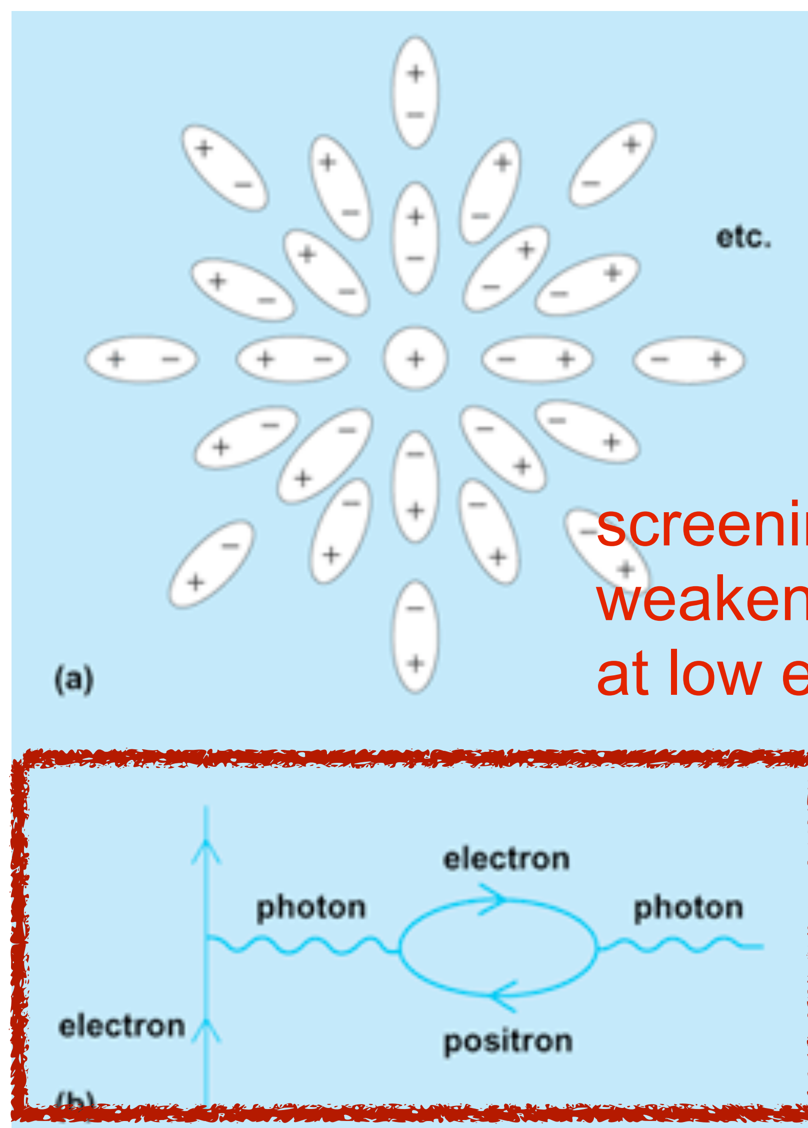
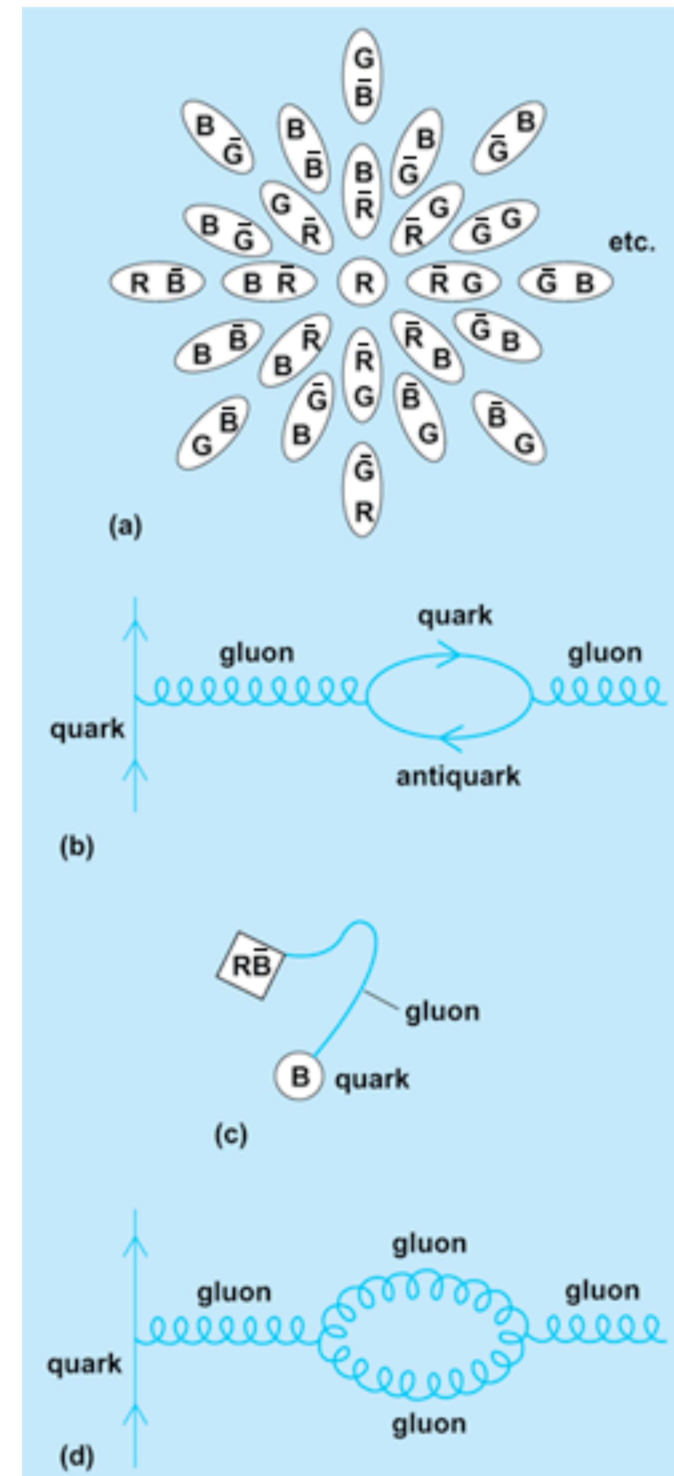
QED



screening : weakens force at low energy

QCD



QCD

- In terms of the running coupling constants, the quarks and gluons see MORE charge at low energy
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QCD

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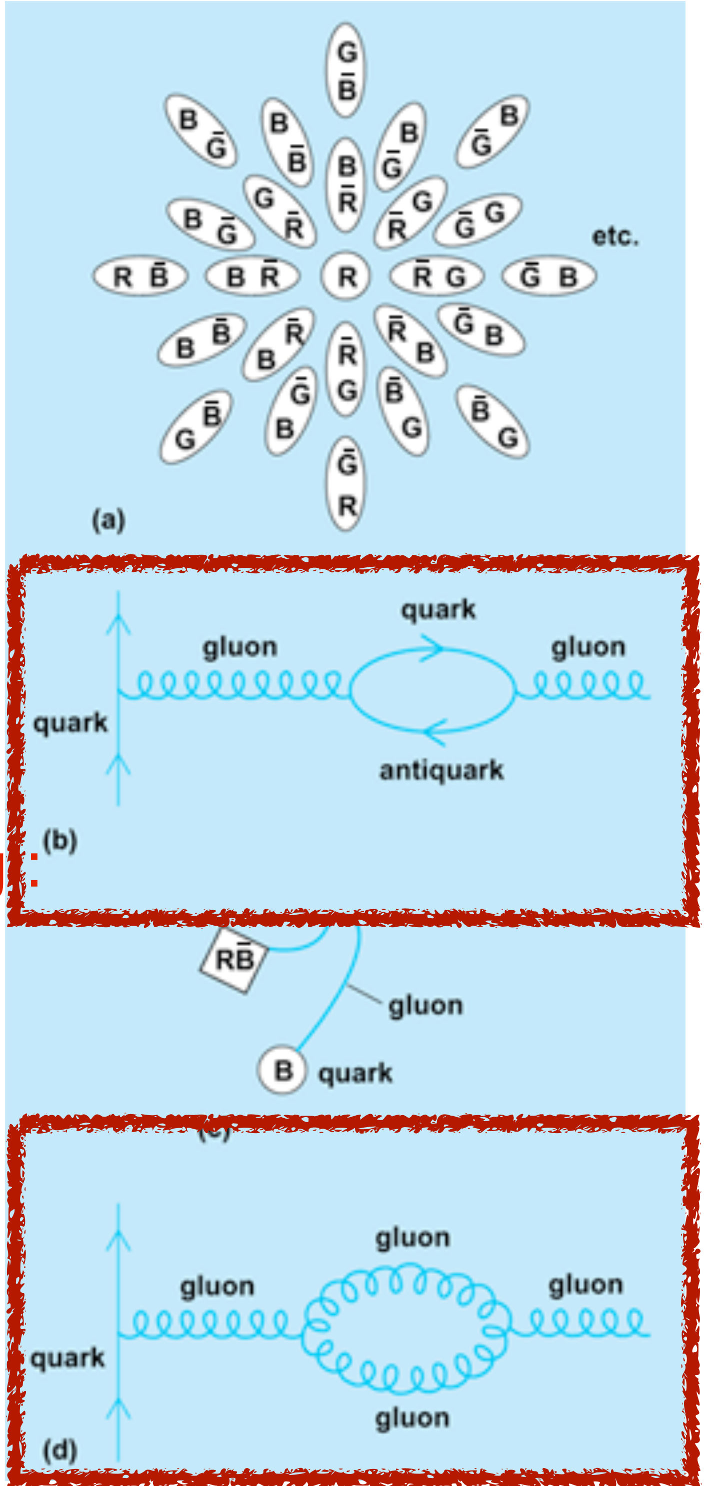
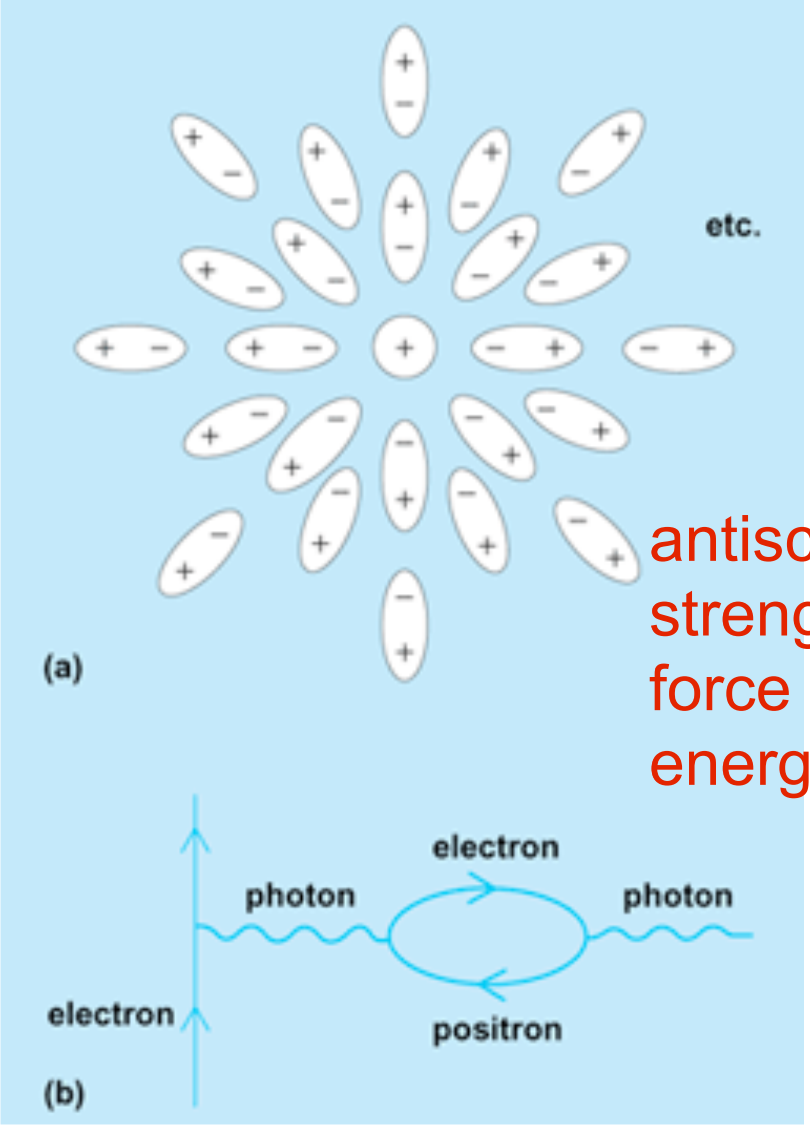


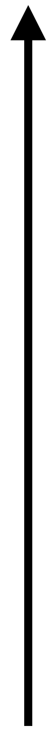
QED



antiscreening: strengthens force at low energy

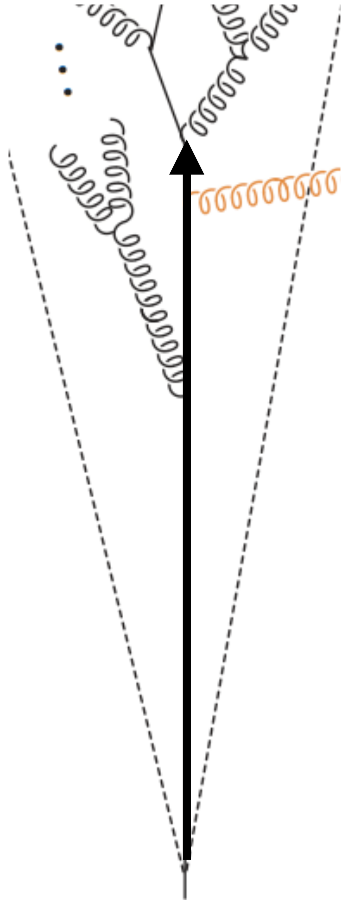
Jets

- “Free” quark produced at the LHC…



Jets

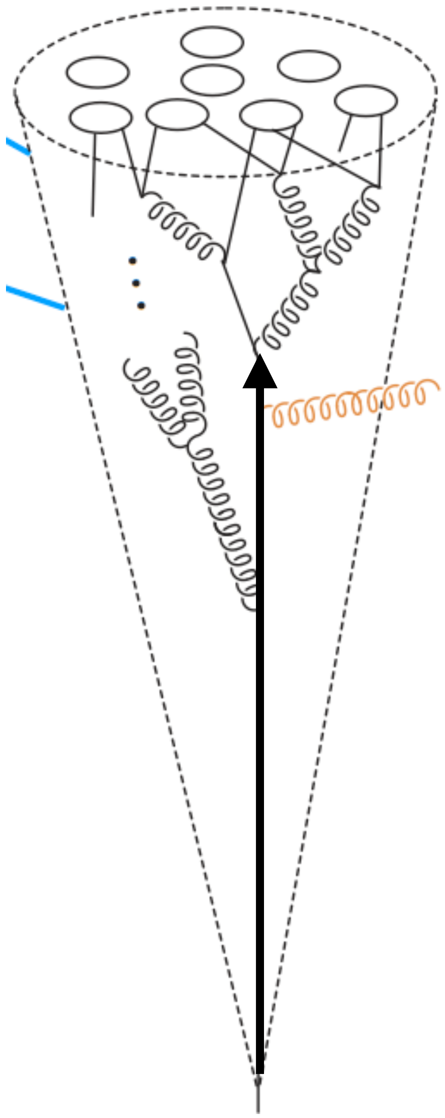
- “Free” quark produced at the LHC… asymptotic freedom makes it radiate collinearly



Jets

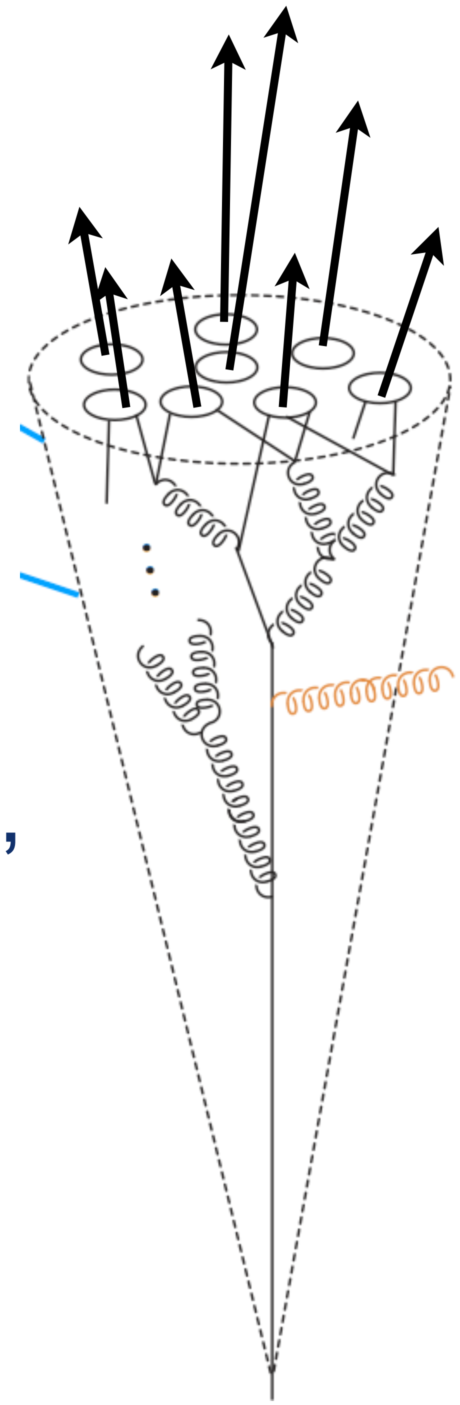
- "Free" quark produced at the LHC… asymptotic freedom makes it radiate collinearly

- Quarks combine with other quarks from the quantum vacuum



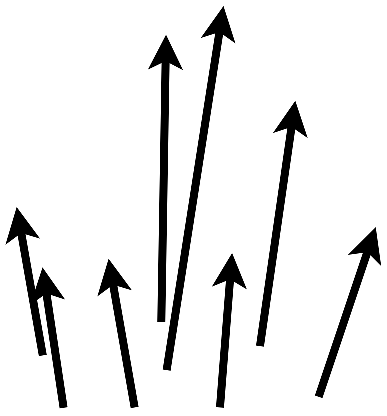
Jets

- "Free" quark produced at the LHC… asymptotic freedom makes it radiate collinearly
- Quarks combine with other quarks from the quantum vacuum
- These fragment into observable particles like pions, kaons, protons, etc



Jets

- "Free" quark produced at the LHC… asymptotic freedom makes it radiate collinearly



- Quarks combine with other quarks from the quantum vacuum

- These fragment into observable particles like pions, kaons, protons, etc

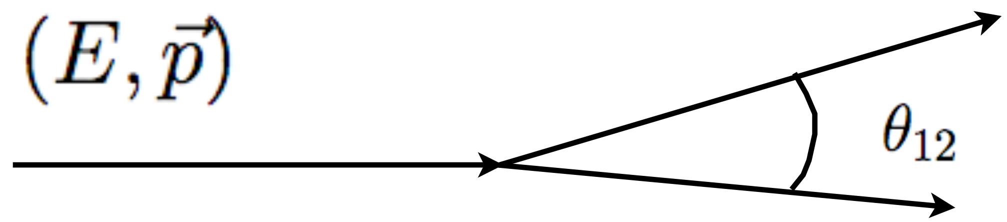
Use "data science" algorithms to back these out!

(PS HEP has been doing data science since WAAYY before it was cool)

- We actually detect those remnants, not the original quark

Boosted Particles

$$p^\mu = (E, \vec{p})$$



$$p_1^\mu = (E_1, \vec{p_1})$$

$$p_2^\mu = (E_2, \vec{p_2})$$

$$\begin{aligned} p^\mu p_\mu &= (p_1 + p_2)^\mu (p_1 + p_2)_\mu \\ m^2 &= (E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2}) \cdot (\vec{p_1} + \vec{p_2}) \\ m^2 &\approx 2E_1 E_2 (1 - \cos(\theta_{12})) \end{aligned}$$

Assume E1=E2 = E/2

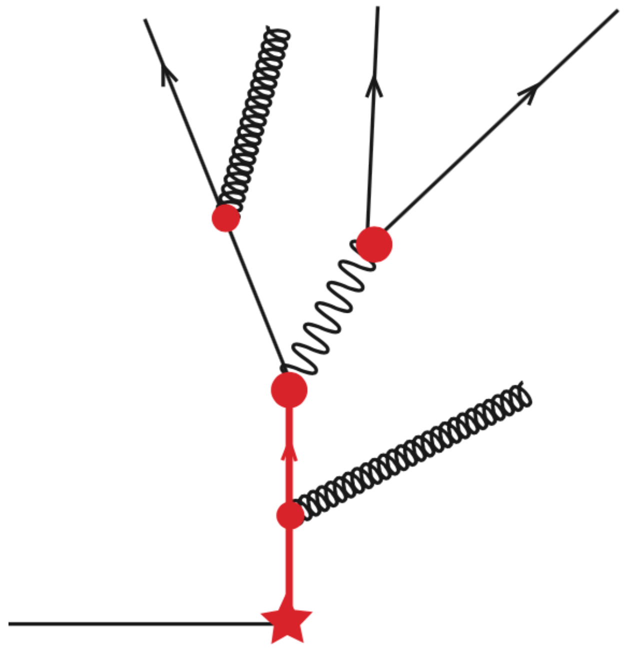
$$\begin{aligned} m^2 &\approx E^2 (1 - \cos(\theta_{12})) \\ \cos(\theta_{12}) &\approx 1 - \frac{m^2}{E^2} \approx 1 - \frac{1}{\gamma^2} \end{aligned}$$

$$\boxed{\theta_{12} \approx \frac{2m}{E} = \frac{2}{\gamma}}$$

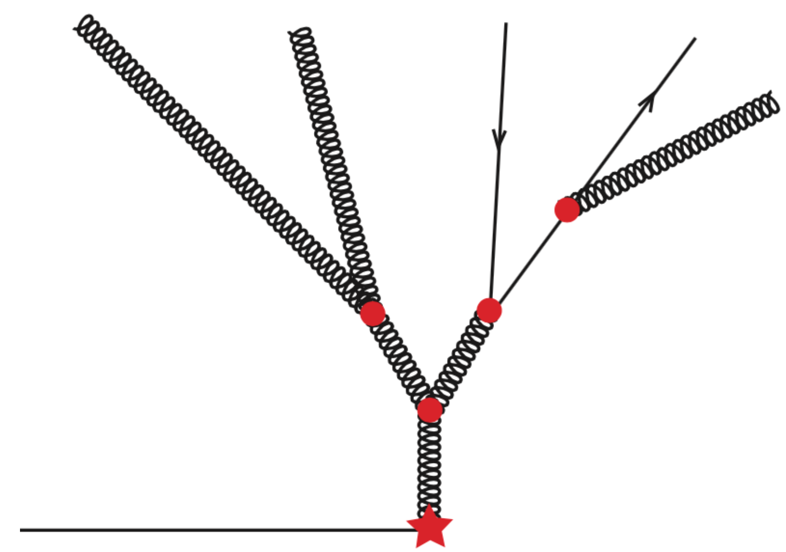
Both Jets and Boosted SM particles result in collimated sprays of particles, need to classify! (More later)

Undergrad Physics —> Groundbreaking Research

- Goal: Classify sprays of strongly interacting particles ("jets") :



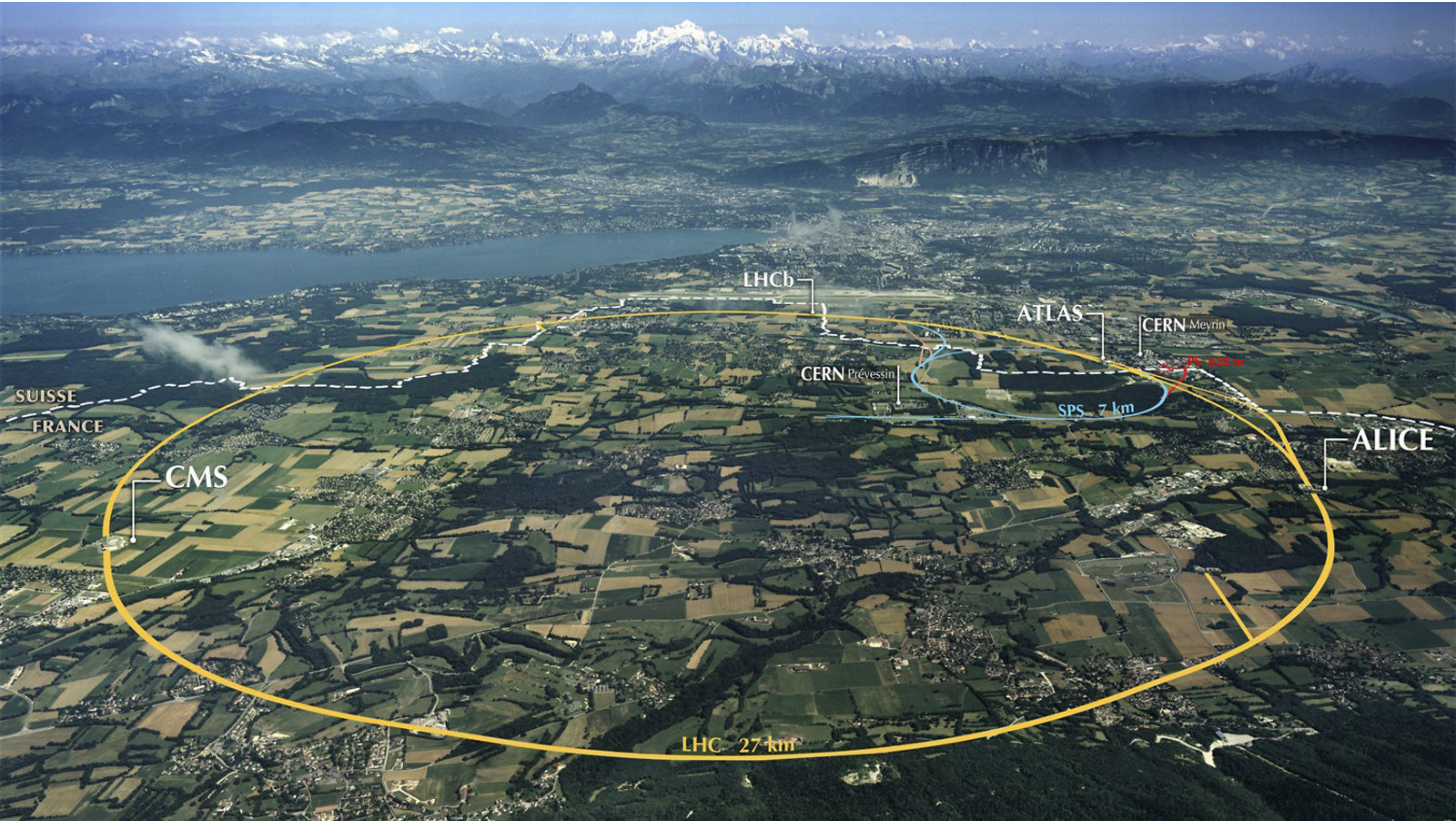
Category A:
Heavy particles decaying into jets



Category B:
Light particles decaying into jets

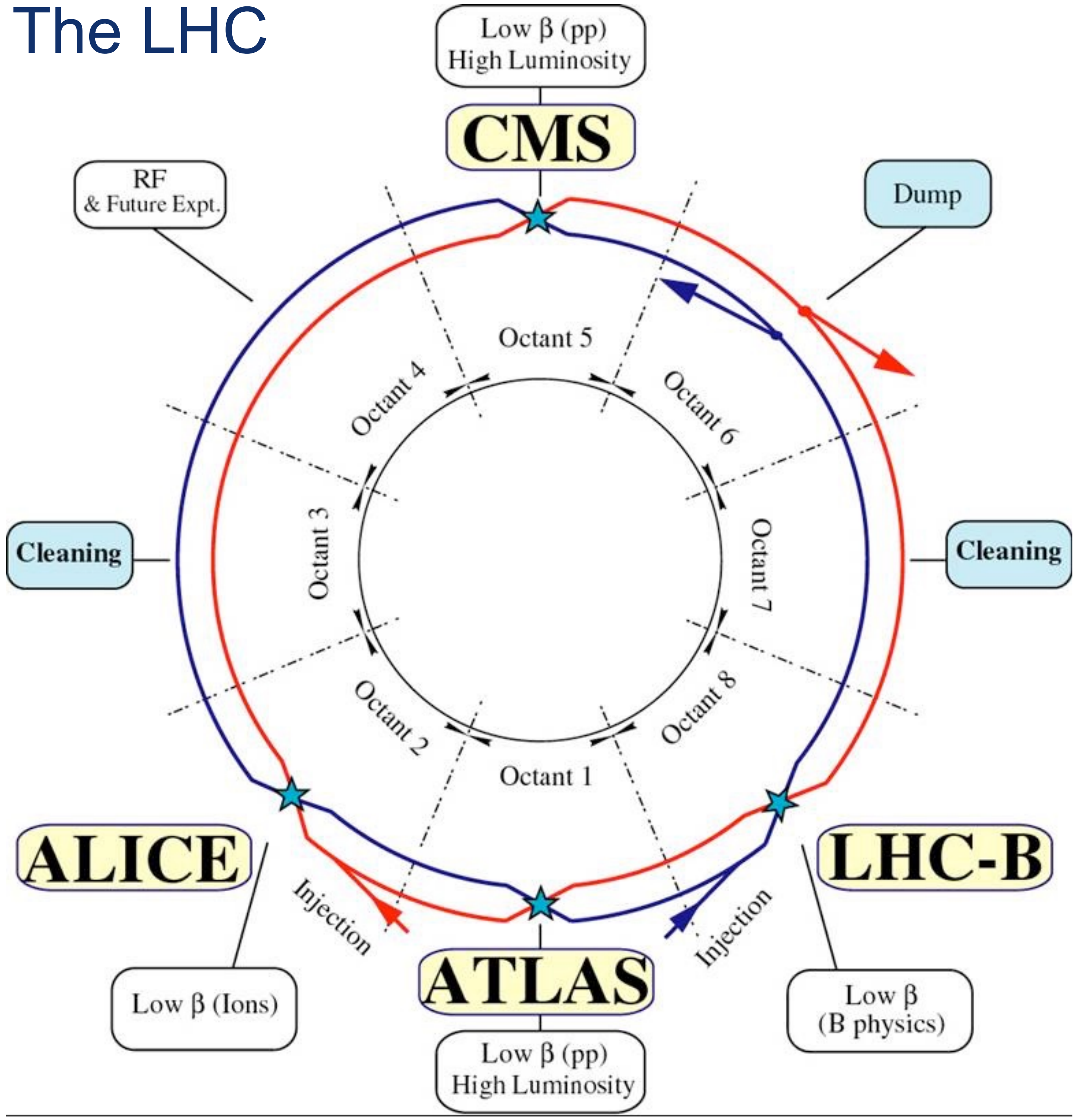
How do we get there?

The Large Hadron Collider



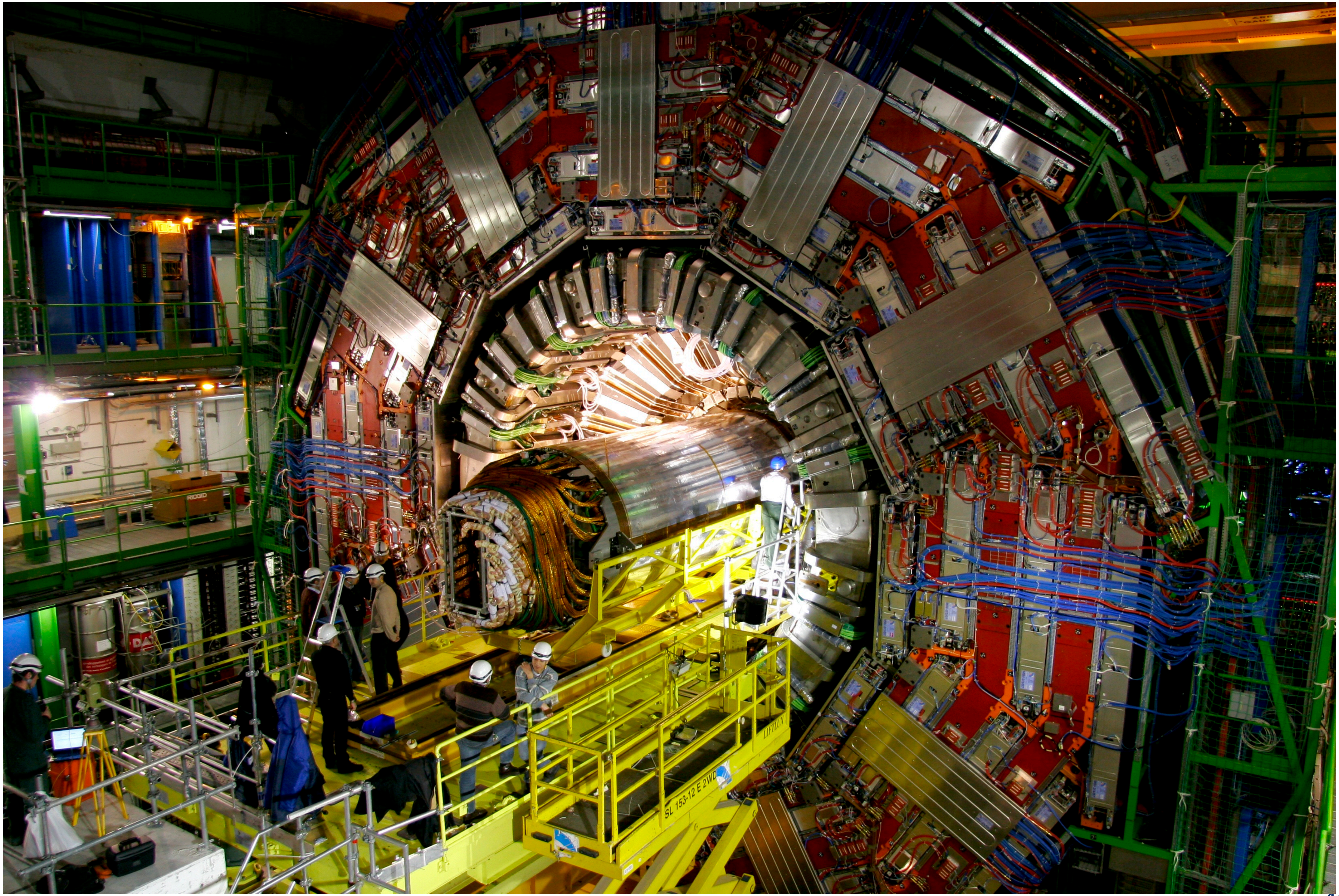
The Large Hadron Collider

The LHC

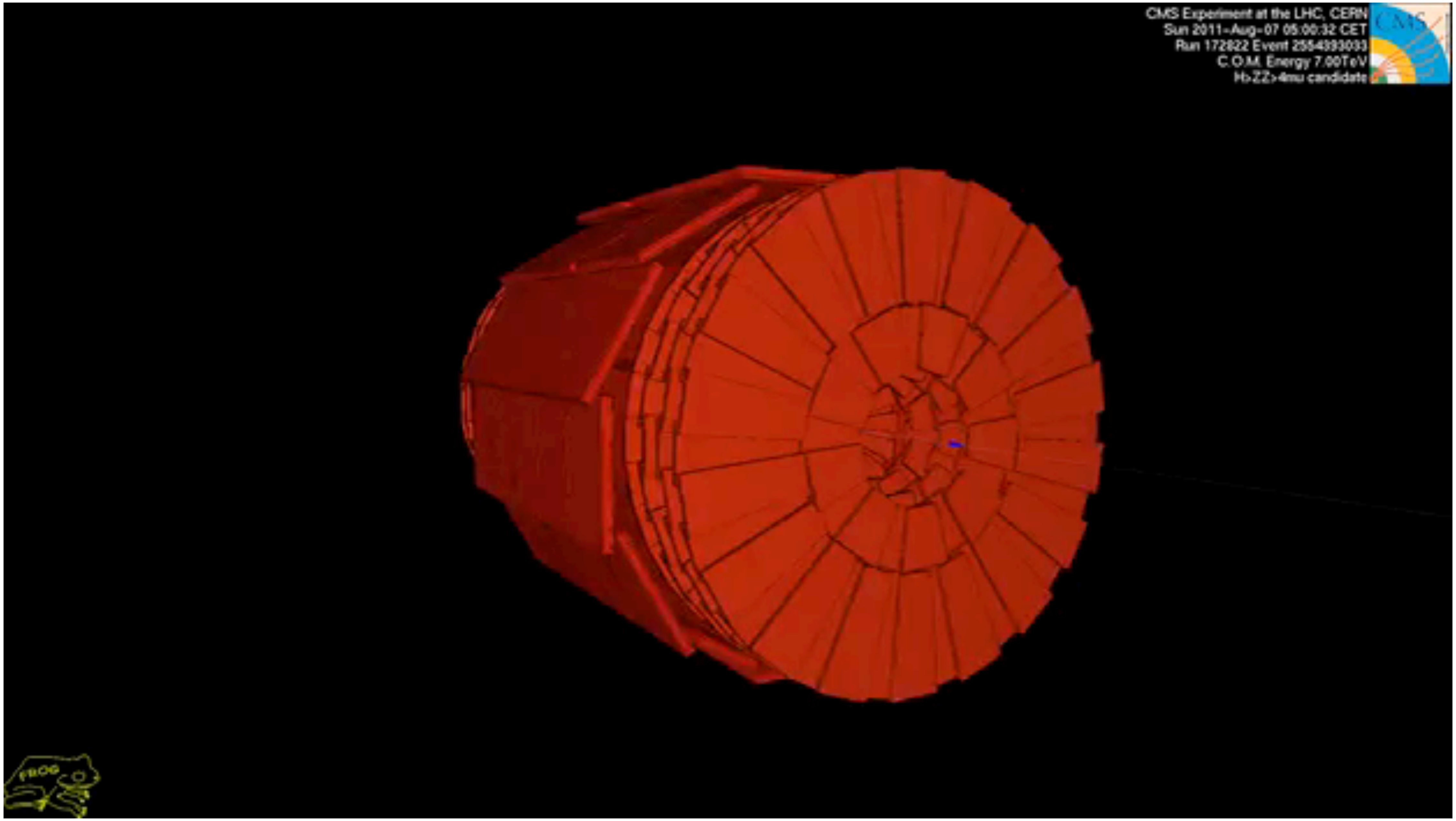


- Geneva, Switzerland and surrounding areas in France
- 27 kilometer circumference
- 50-175 meters underground
- Proton-on-proton collisions
  - 7 TeV : 2010-2011
  - 8 TeV : 2012
  - 13 TeV : 2015-2018
  - >13 TeV: 2021+

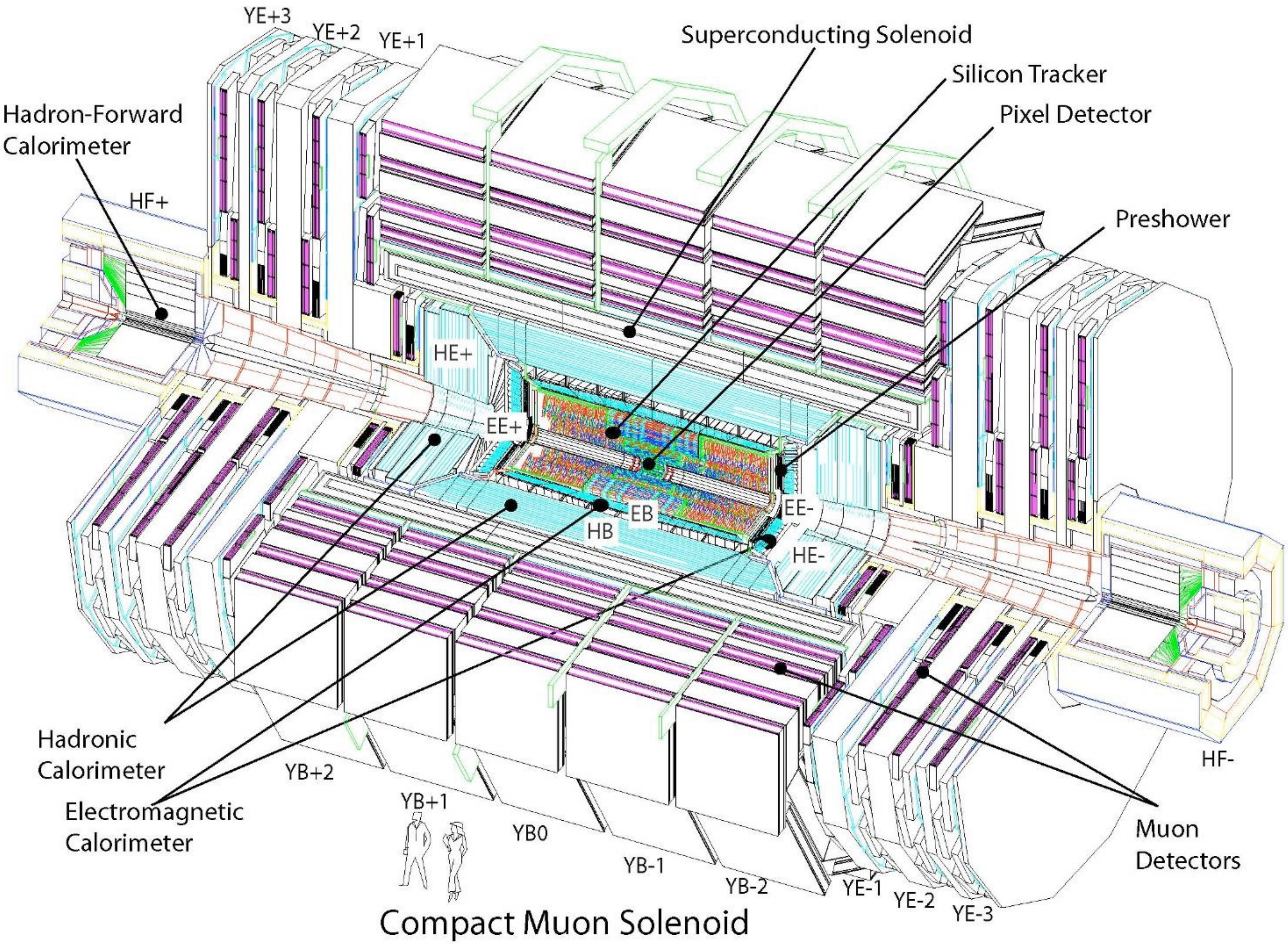
The Compact Muon Solenoid



The Compact Muon Solenoid



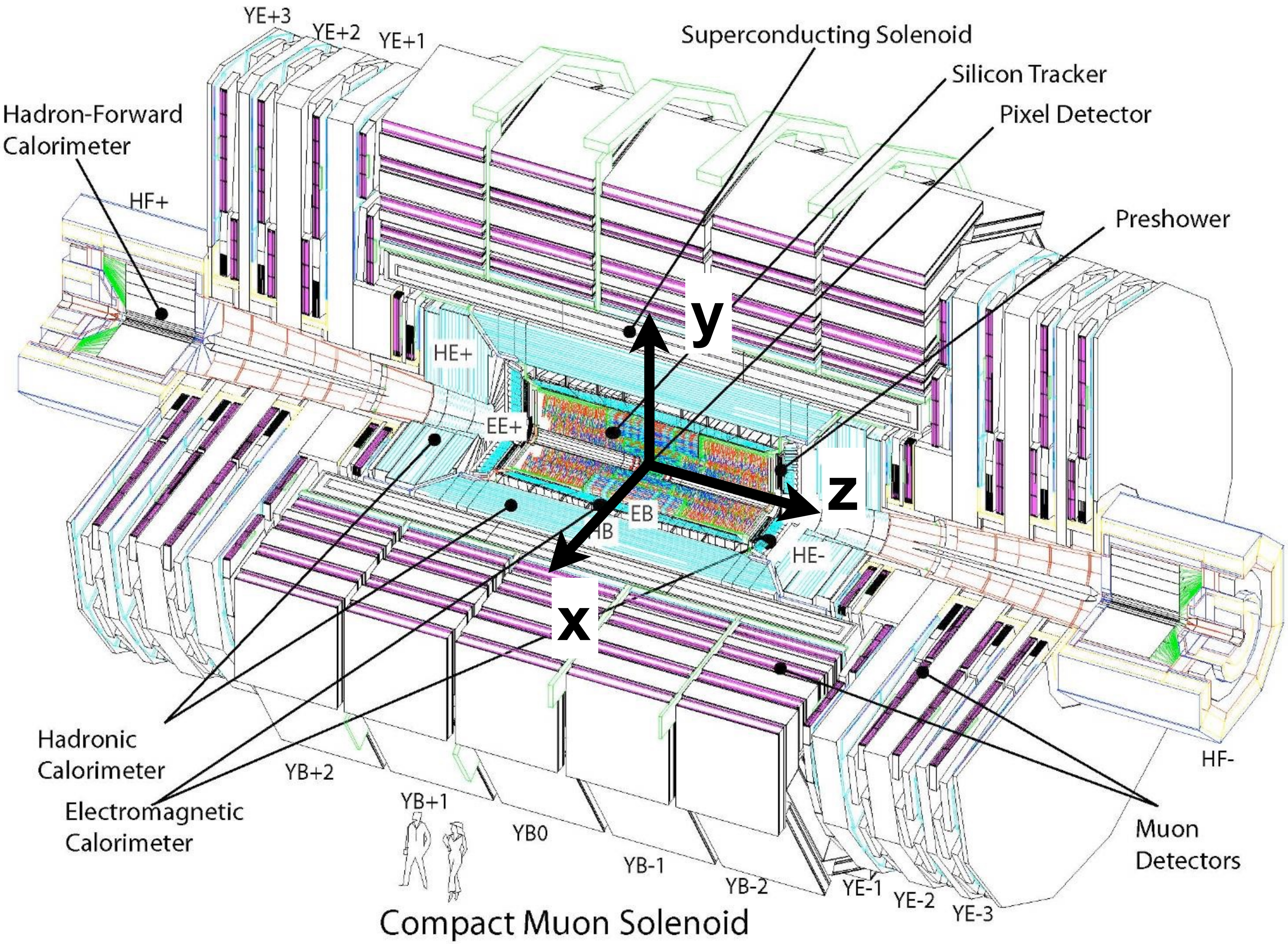
The Compact Muon Solenoid



φ : Azimuthal angle around z-axis

θ : polar angle from z-axis

The Compact Muon Solenoid



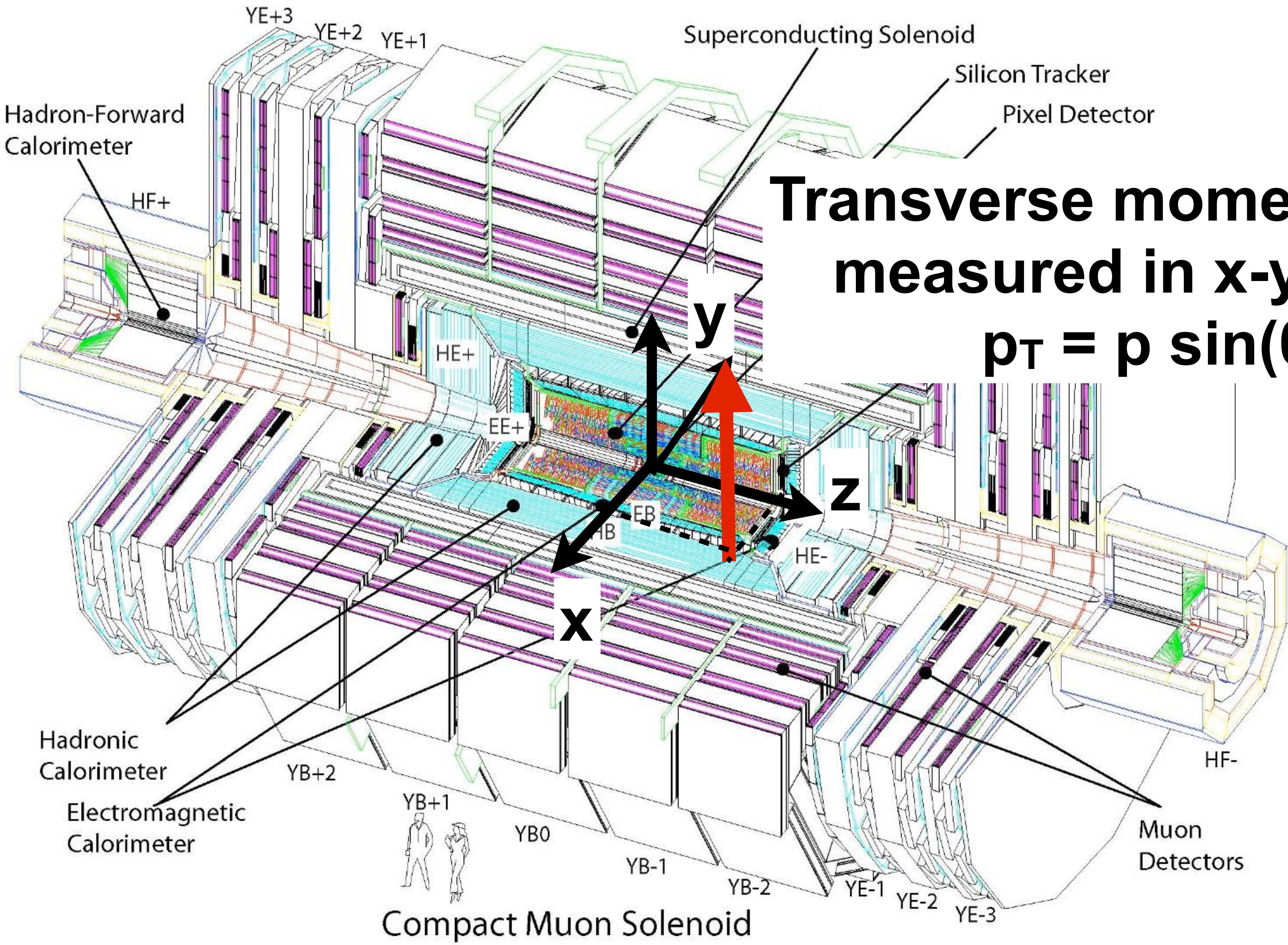
φ : Azimuthal angle around z-axis

θ : polar angle from z-axis

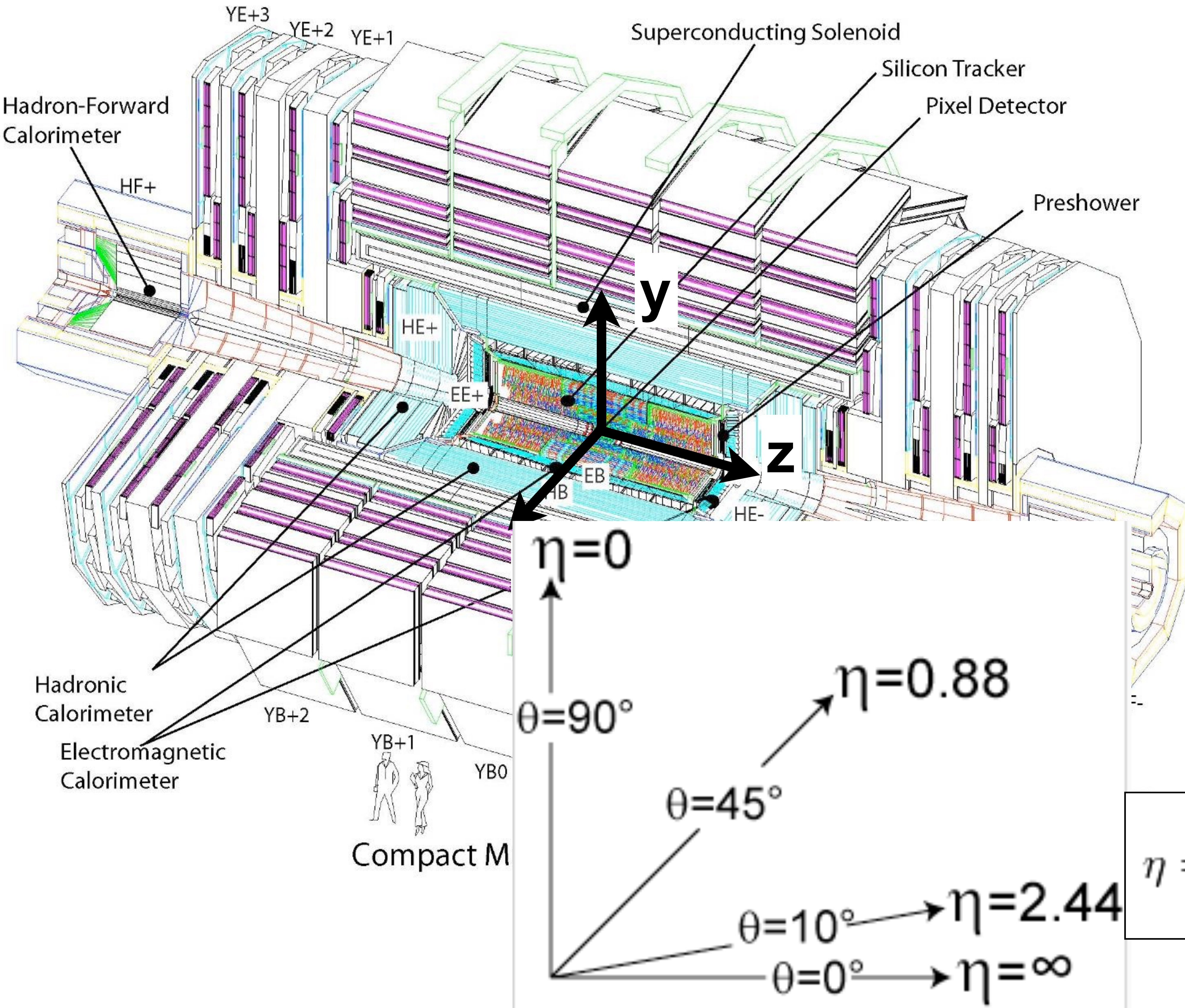
The Compact Muon Solenoid

Transverse momentum: p_T measured in x-y plane

$p_T = p \sin(\theta)$



The Compact Muon Solenoid



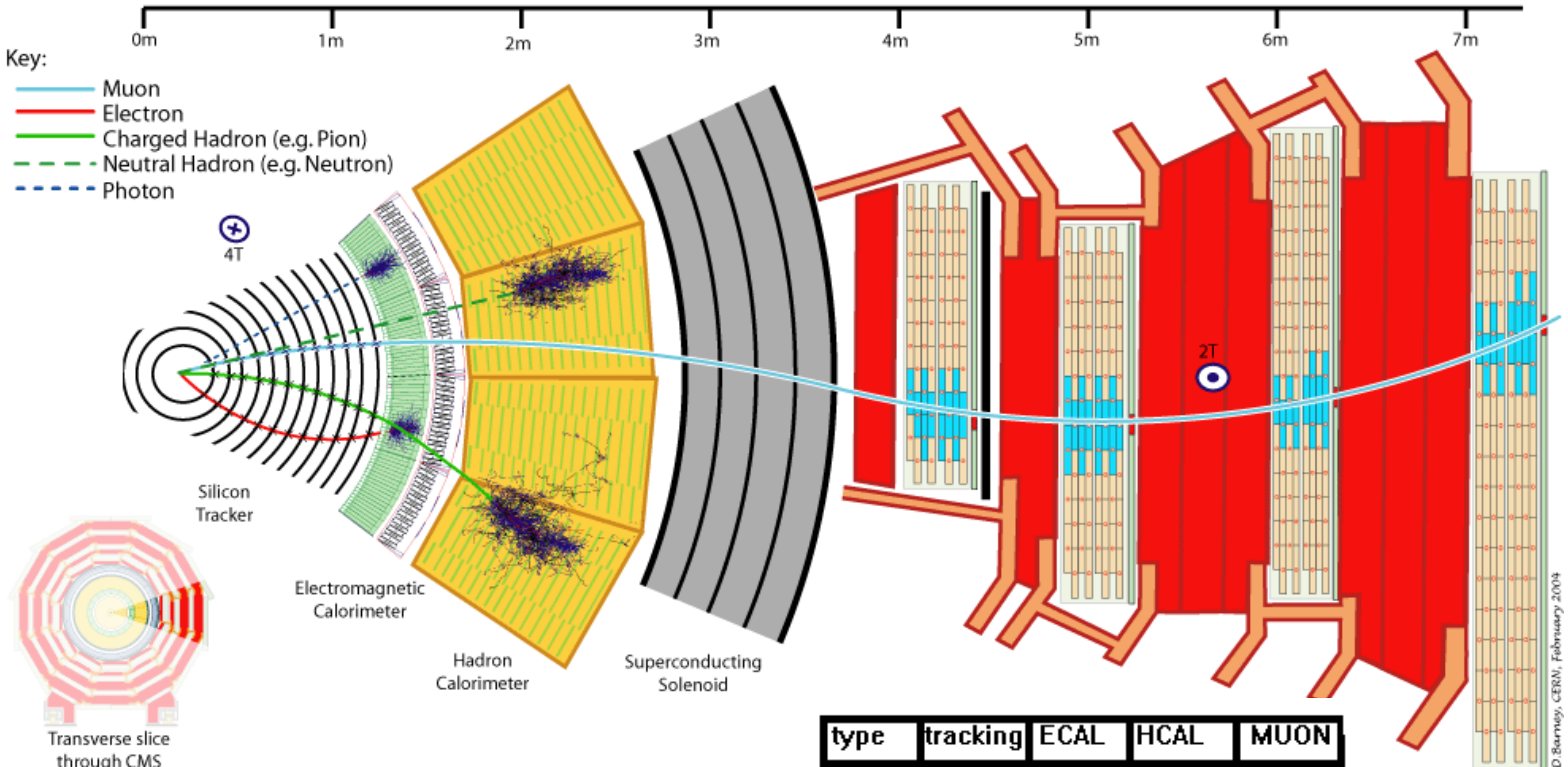
φ : Azimuthal angle around z-axis

θ : polar angle from z-axis

η : pseudo-rapidity, invariant under Lorentz boosts

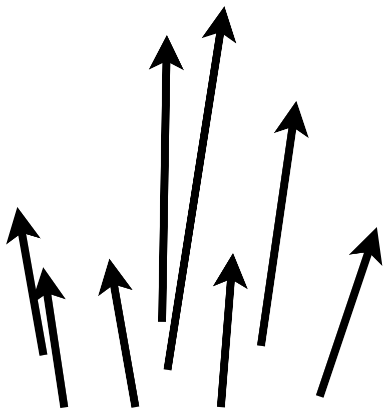
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

The Compact Muon Solenoid



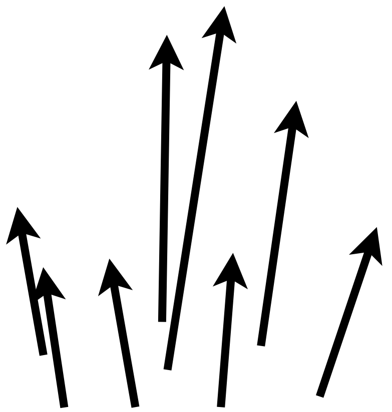
type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				

Clustering



- Clustering: grouping N particles into k jets
  - Hey! Sounds like a data science algorithm!

Clustering

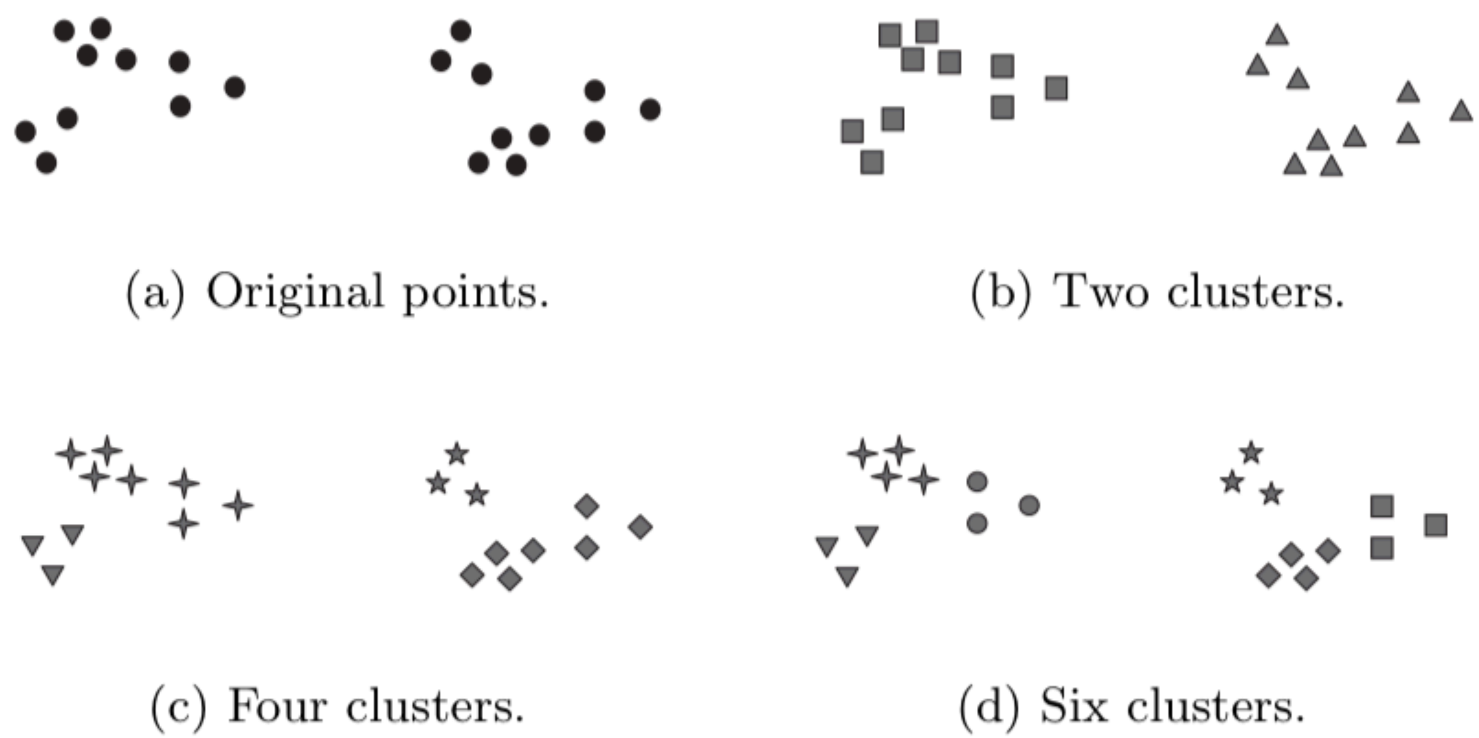


- Clustering: grouping N ~~particles~~ into k ~~jets~~

points in space partitions

Clustering

- Goal: Given N points in space, associate to k partitions
- Many applications:
  - Data classification
  - Galaxy clustering
  - Jet clustering
  - Sociology
  - Social networks



(a) Original points. (b) Two clusters.

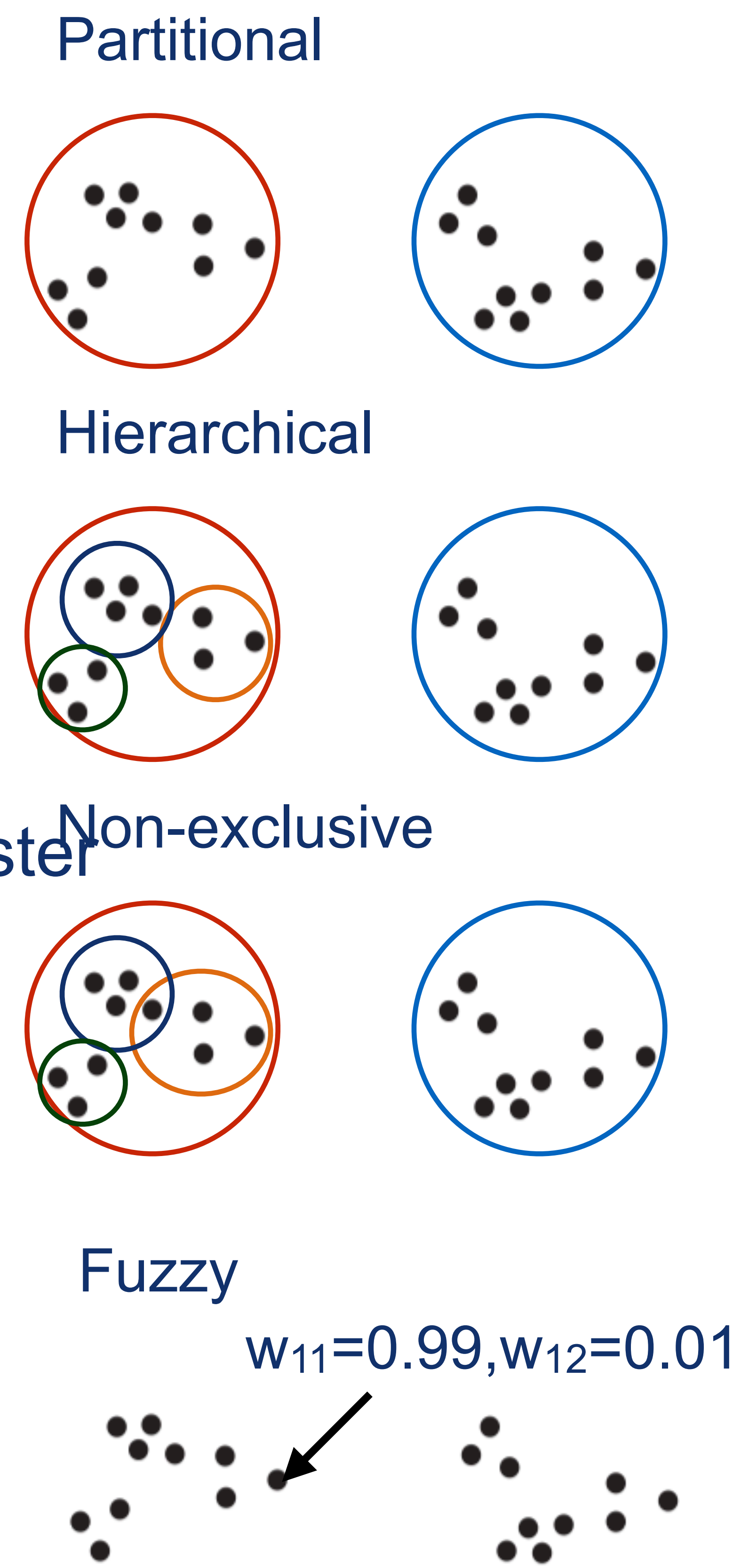
(c) Four clusters. (d) Six clusters.

https://www-users.cs.umn.edu/~kumar001/dmbook/ch8.pdf

https://en.wikipedia.org/wiki/Cluster_analysis

Clustering

- Uses:
  - Summarize / compress “spatial” informatior
  - Find nearest neighbors
- Types of clustering algorithms:
  - Exclusive:
    - Partitional: divide into k exclusive catego
    - Hierarchical: can have sub-clusters
  - Non-exclusive:
    - Add same element to more than one cluster
  - Fuzzy:
    - Weight elements according to cluster
- Each can be either complete or partial



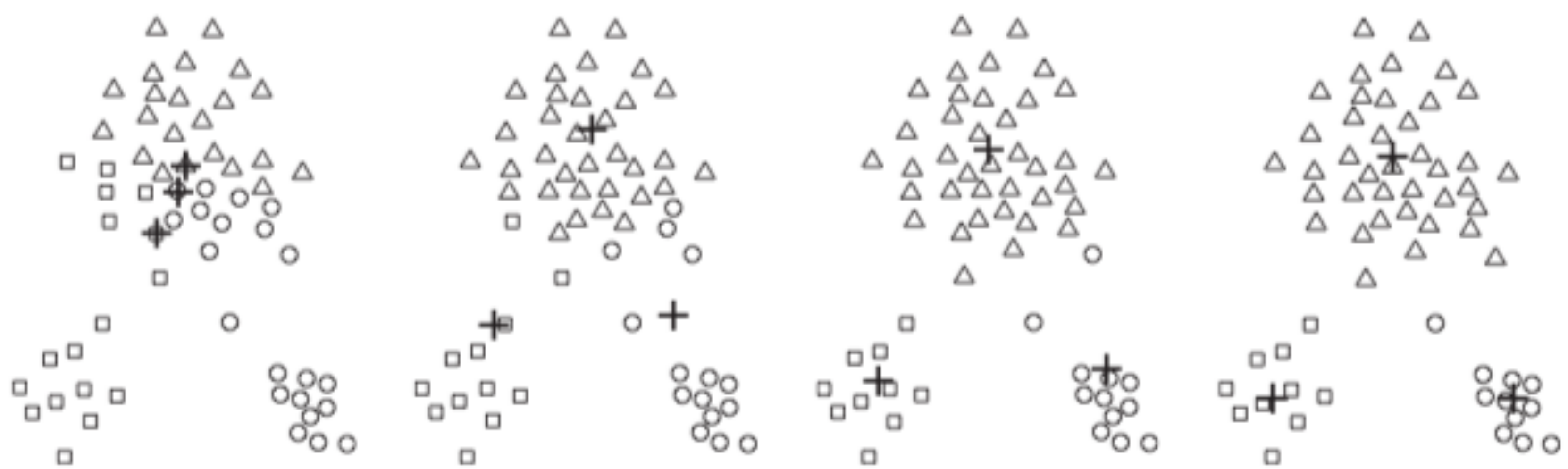
Clustering

- Popular categories :
  - K-means
    - Partition into k clusters using mean central values (usually exclusively)
  - Agglomerative hierarchical clustering
    - Pair individual elements into clusters given some distance metric
  - Density based scan
    - Considers low-density regions to be noise, not exclusive clustering

- K-means algorithm:

Algorithm 8.1 Basic K-means algorithm.

Select K points as initial centroids.
repeat
    Form K clusters by assigning each point to its closest centroid.
    Recompute the centroid of each cluster.
until Centroids do not change.



(a) Iteration 1. (b) Iteration 2. (c) Iteration 3. (d) Iteration 4.

Clustering

- Computational complexity is ~linear in product of:
  - Number of points
  - Number of “dimensions” (or attributes)
  - Number of clusters
  - Number of iterations to converge

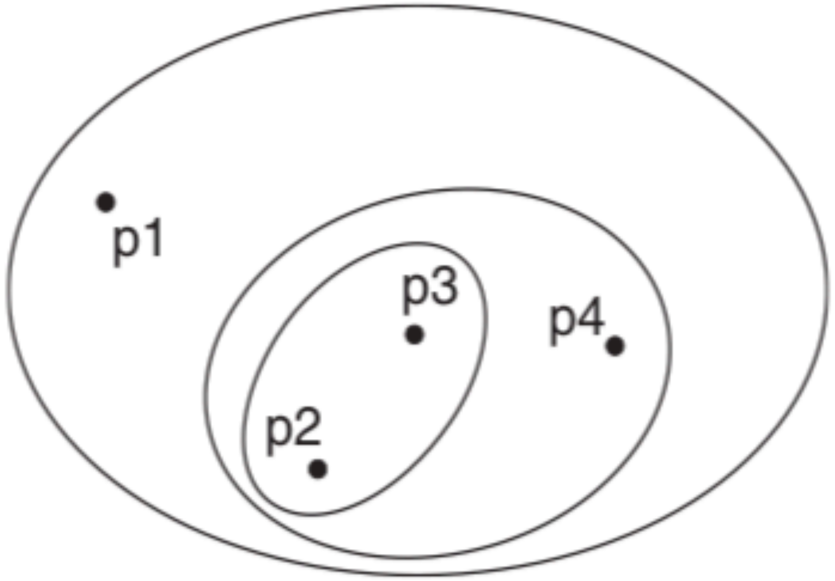
- Shortcomings of k-means:
  - As in all minimization routines, danger of local minima
    - Need heuristic methods to avoid them
  - Can result in empty clusters if initialized poorly
  - Outliers have disproportionate impact
- Can try to split and merge centroids to mitigate these!

Clustering

- Hierarchical clustering:
  - Agglomerative ("bottom up"):
    - Start with individual constituents, merge until criteria met
  - Divisive ("top down"):
    - Start with conglomerate, split until criteria met (or you get to individual constituents)
  - Represent by a tree ("dendrogram") or Venn diagram ("nested cluster diagram"):

Basically the same, but in reverse

(a) Dendrogram.



(b) Nested cluster diagram.

Clustering

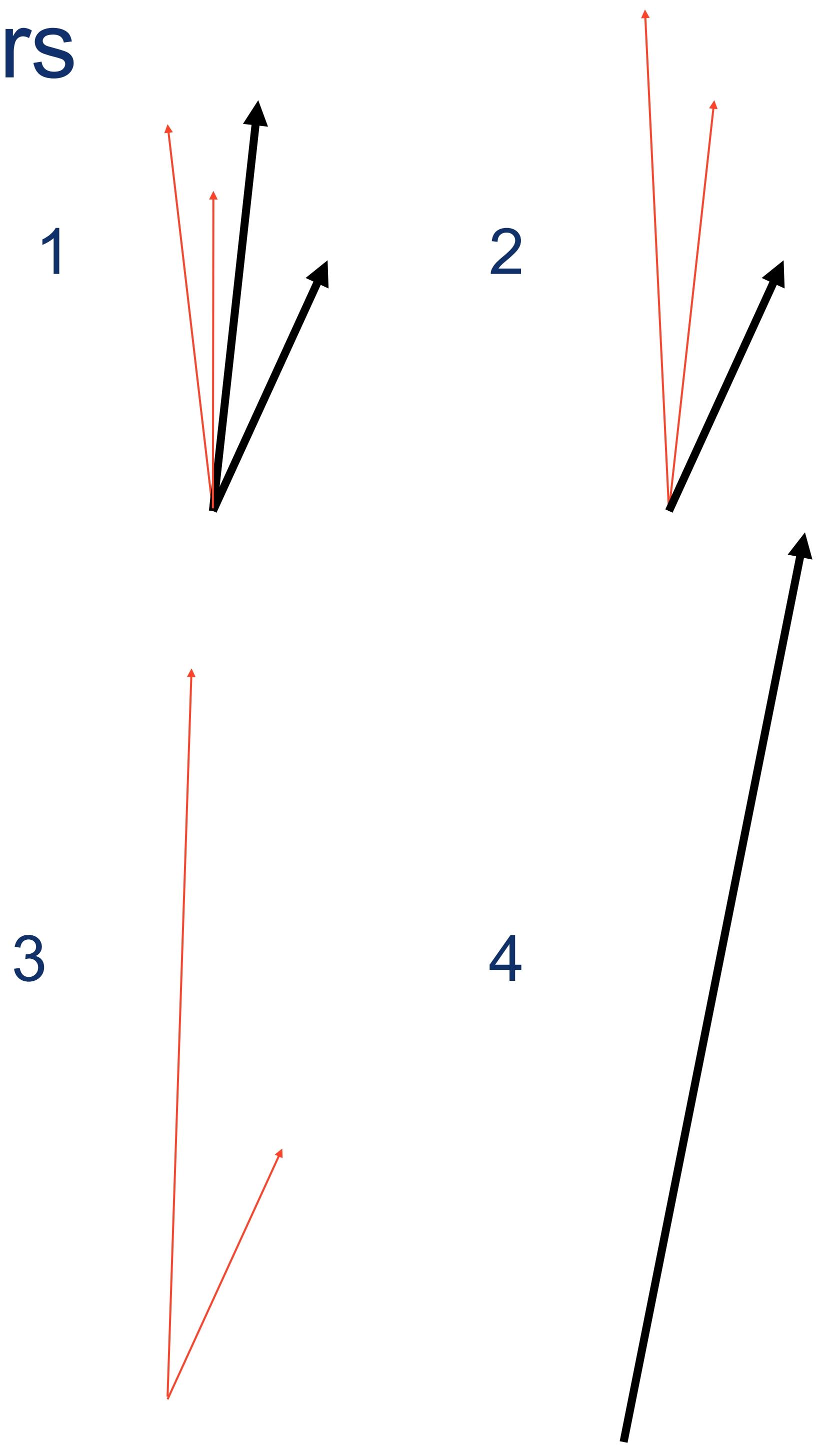
- Pairwise examination of input 4-vectors
- Calculate d_{ij}

$$d_{ij} = min(k_{ti}^{n}, k_{tj}^{n})\Delta R_{ij}^{2}/R^{2}$$

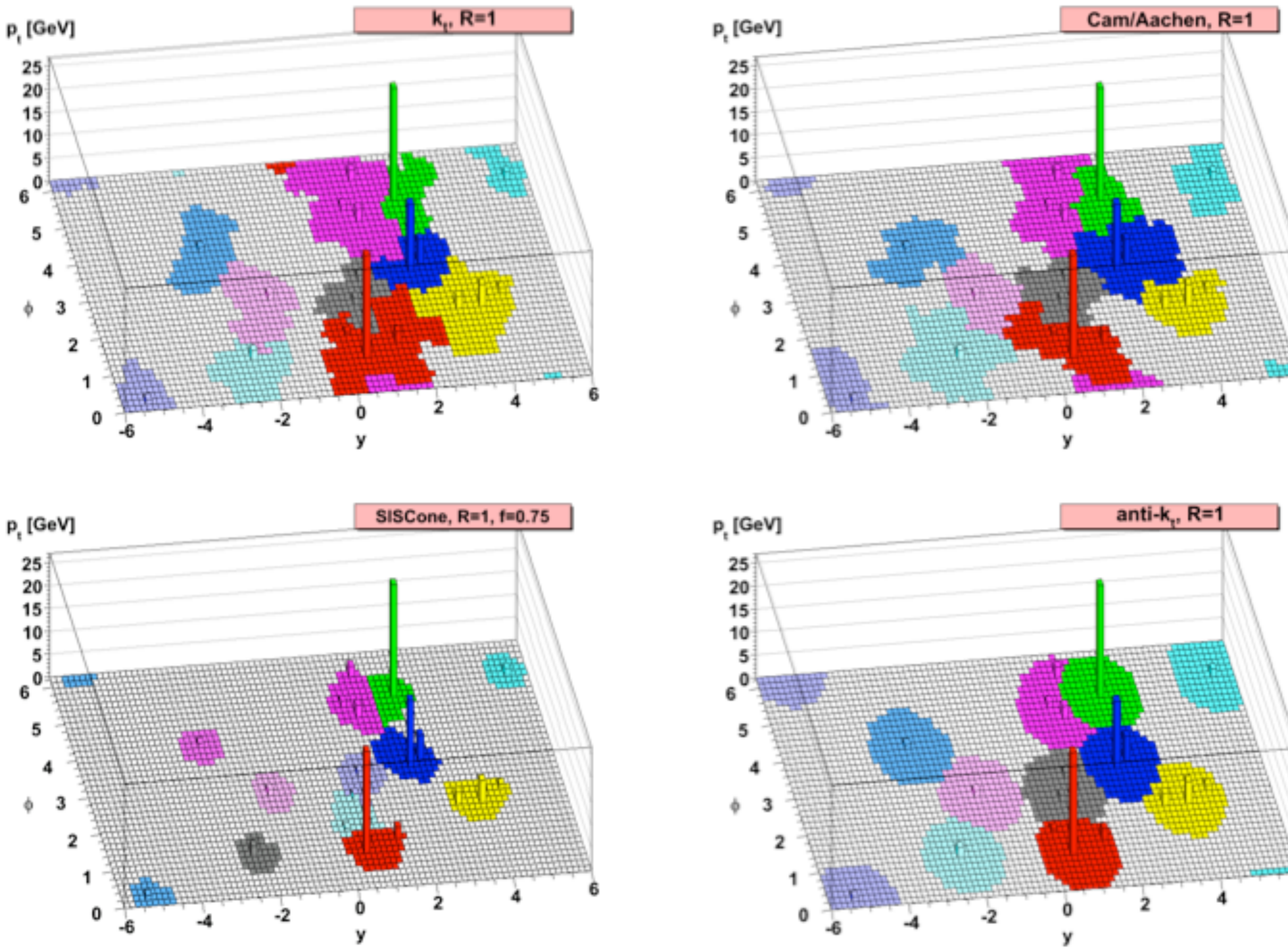
- Also find the "beam distance"

$$d_{iB} = k_{T,i}^{n}$$

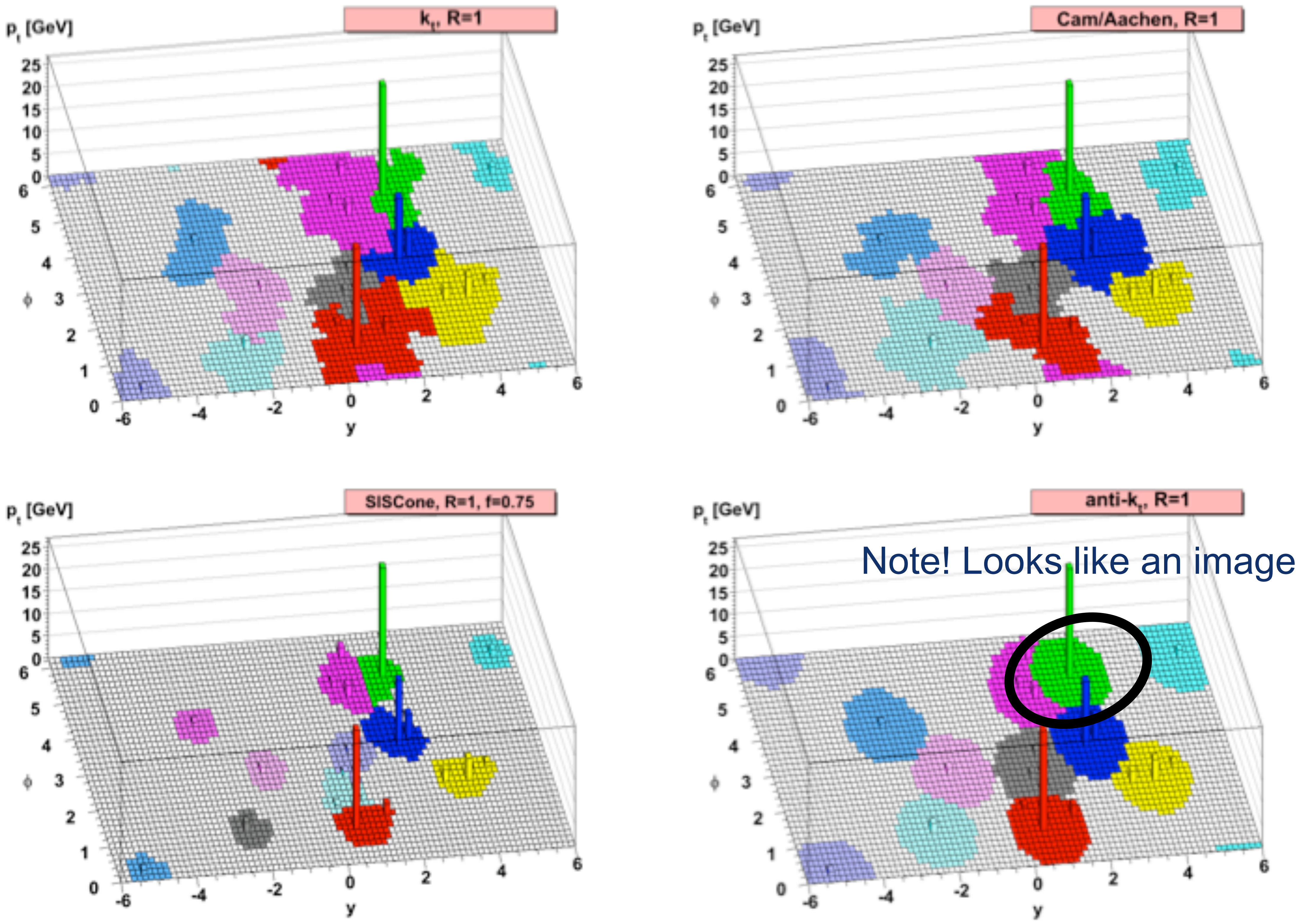
- Find min of all d_{ij} and d_{iB}
  - If min is a dij, merge and iterate
  - If min is a d_{iB}, classify as a final jet
- Continue until list is exhausted



Clustering



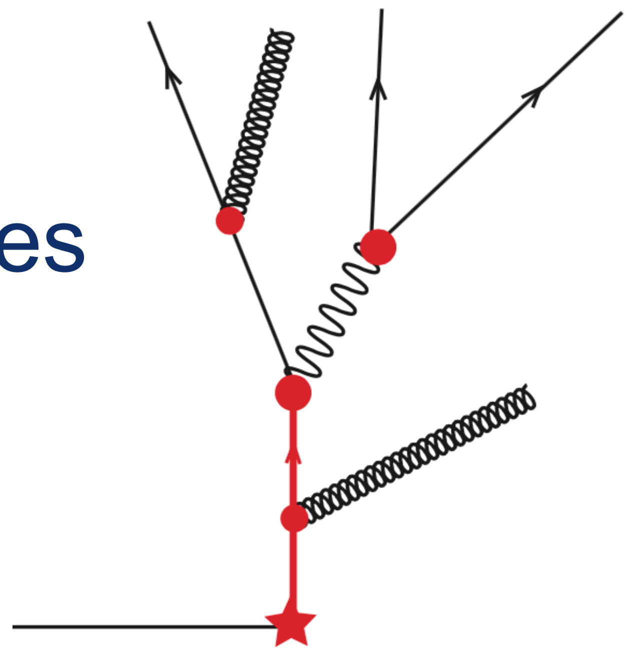
Clustering



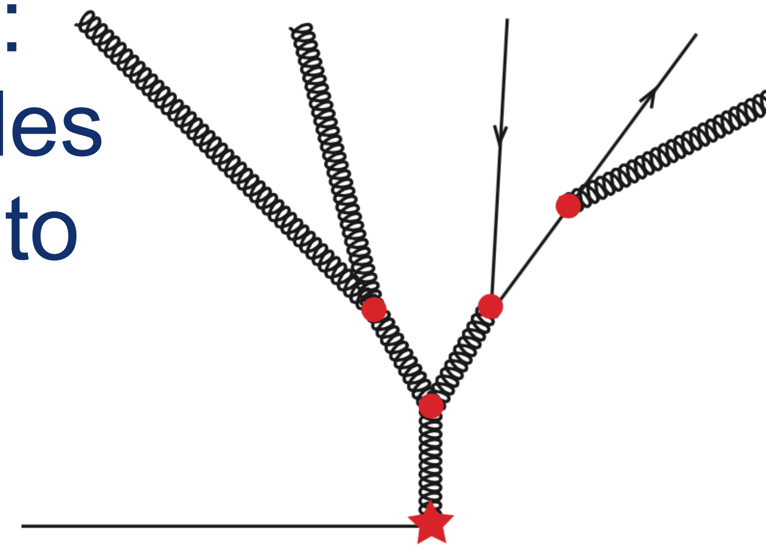
k_t, R=1
Cam/Aachen, R=1
SISCone, R=1, f=0.75
anti-k_t, R=1
p_t [GeV]
ϕ
y
Note! Looks like an image!

Classification : “High Level” / “Expert” Information

Category A:
Heavy particles decaying into jets



Category B:
Light particles decaying into jets



	Category A	Category B
Mass	Driven by particle mass (W: 80 GeV, Z: 90 GeV, H: 125 GeV, t: 173 GeV)	Driven by QCD radiation
Particle content	Often decay to b quarks	Sometimes decay to b quarks
Shape	Normally 2- or 3-pronged	Normally 1-pronged

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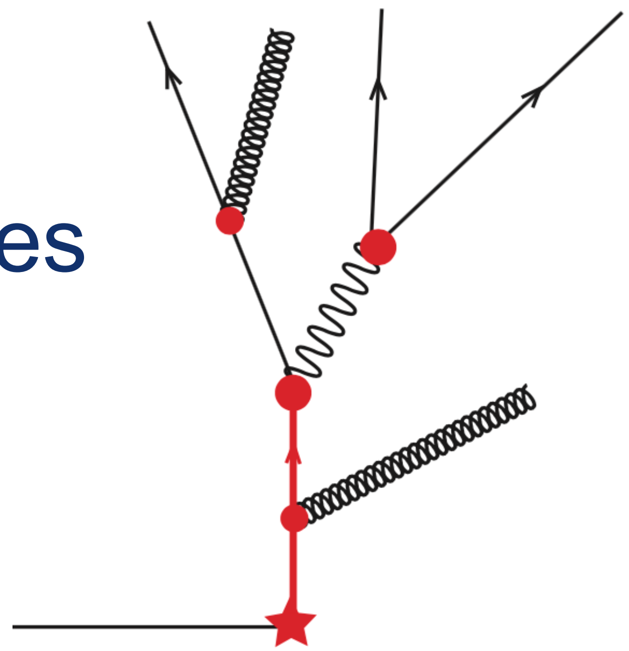
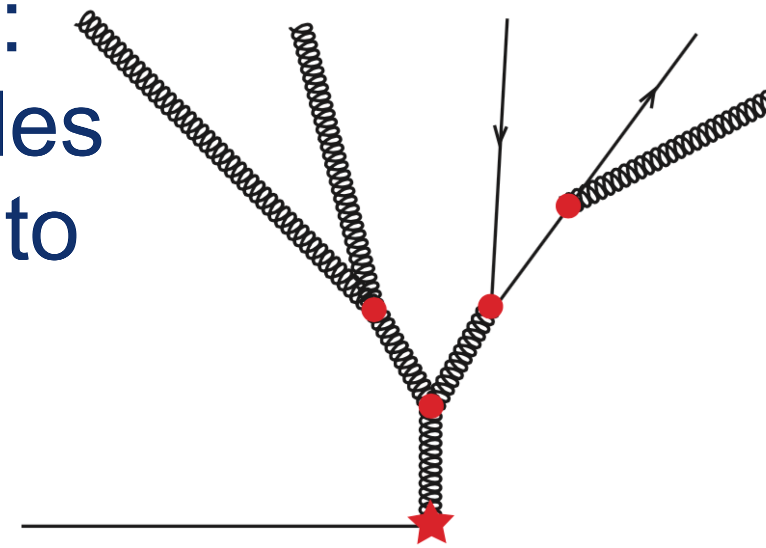


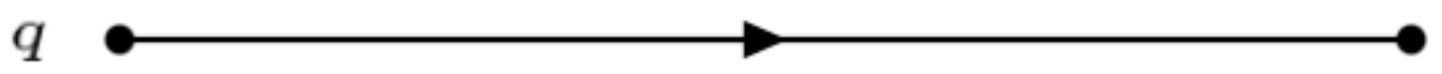
Category B:
Light particles decaying into jets



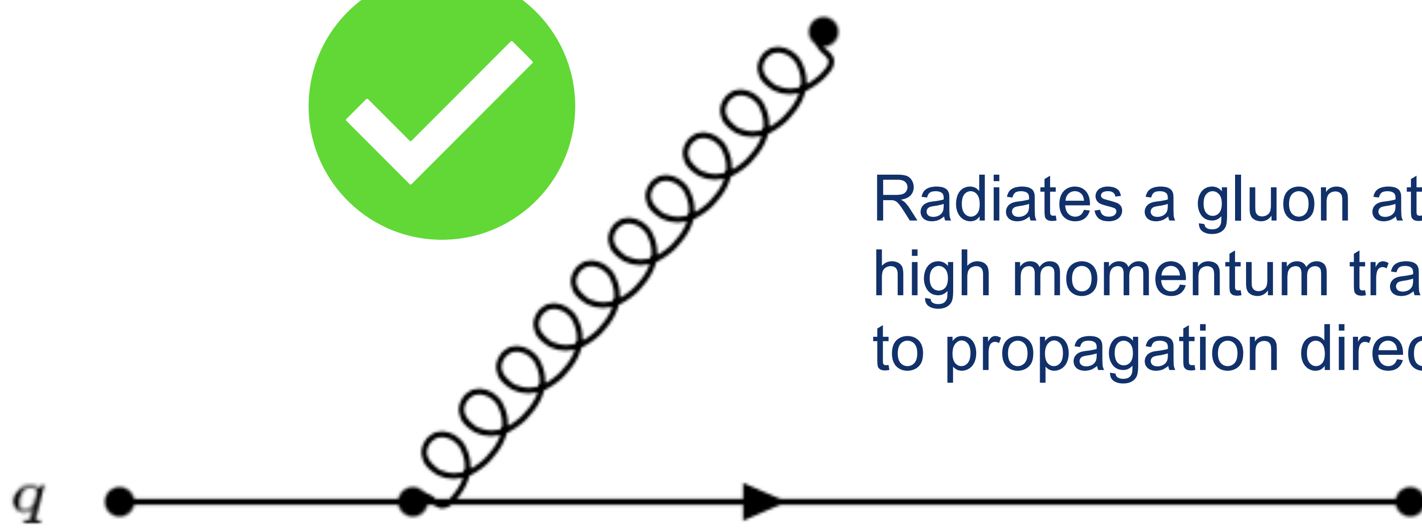
Mass	Driven by particle mass (W: 80 GeV, Z: 90 GeV, H: 125 GeV, t: 173 GeV)	Classify by “grooming” soft radiation	Driven by QCD radiation
Particle content	Often decay to b quarks	Classify by displaced particles	Sometimes decay to b quarks
Shape	Normally 2- or 3-pronged	Classify by shape	Normally 1-pronged

Grooming soft radiation

Propagating quark through space



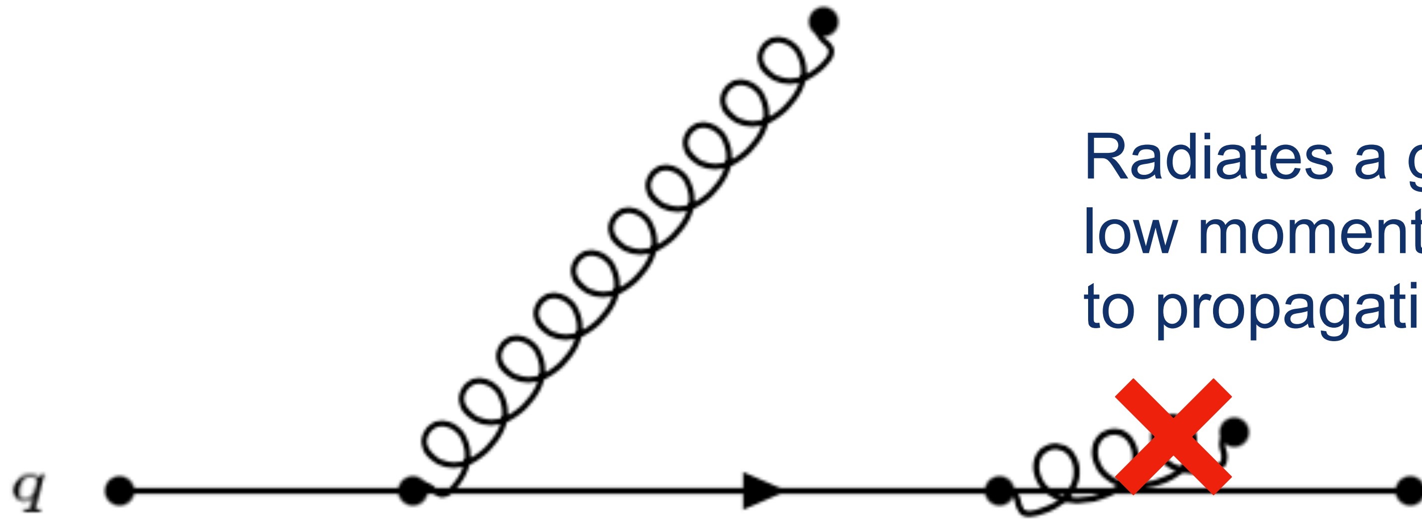
Grooming soft radiation



Radiates a gluon at wide angle,
high momentum transverse
to propagation direction?

OK

Grooming soft radiation



Radiates a gluon at low angle,
low momentum transverse
to propagation direction?

Reject

Grooming soft radiation