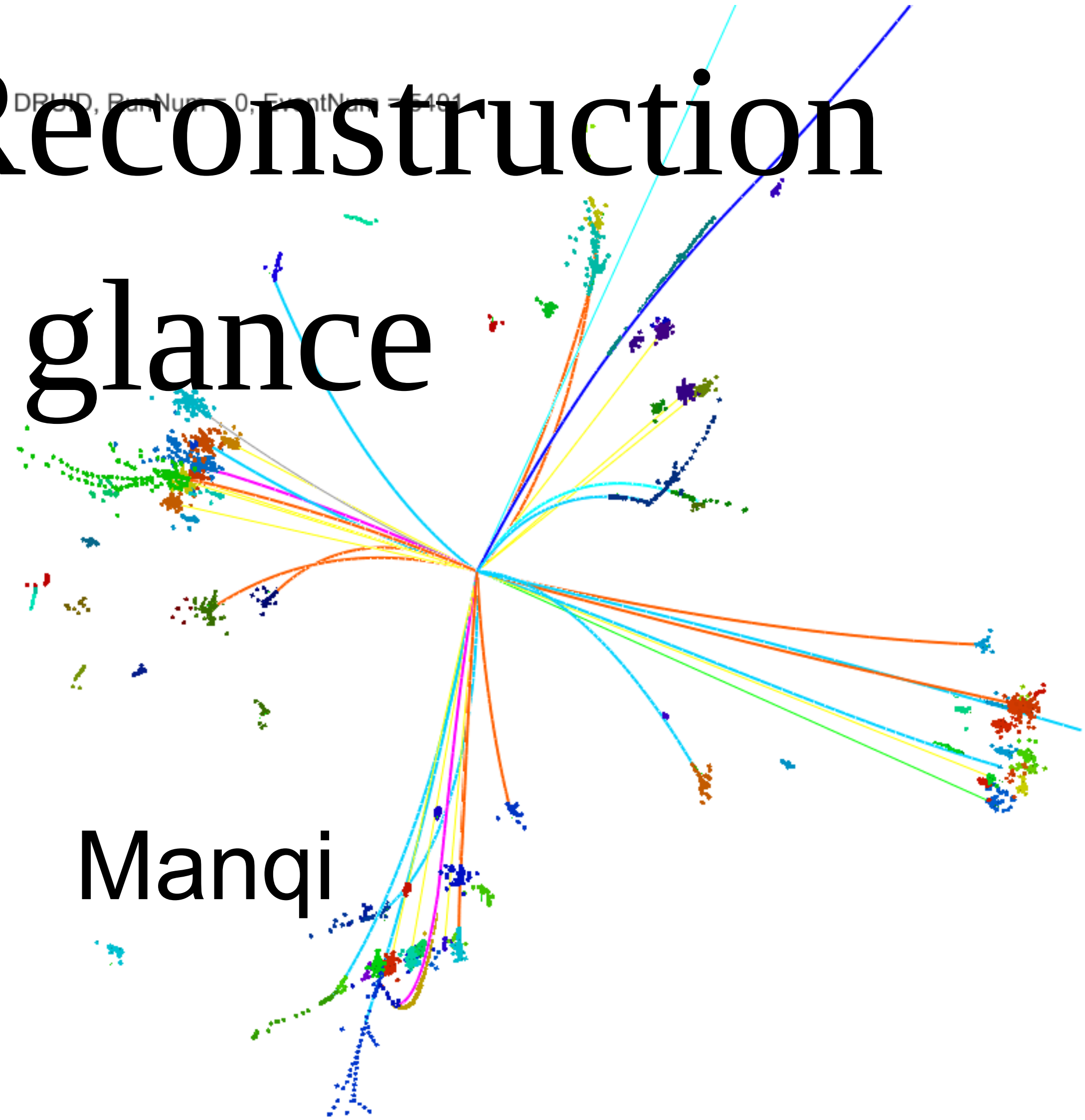
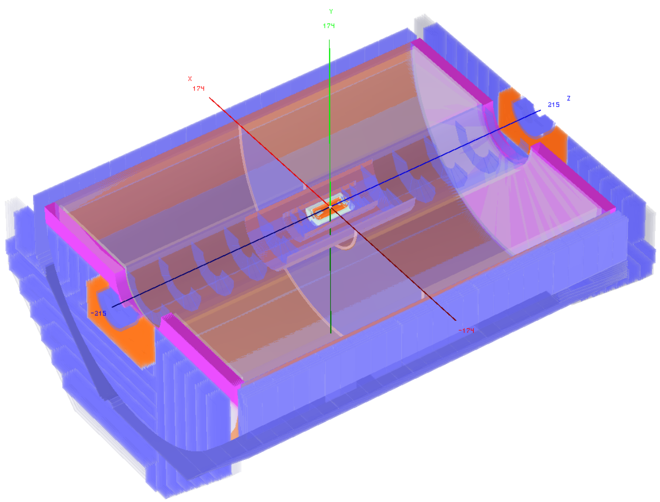
Detector & Reconstruction
A first glance



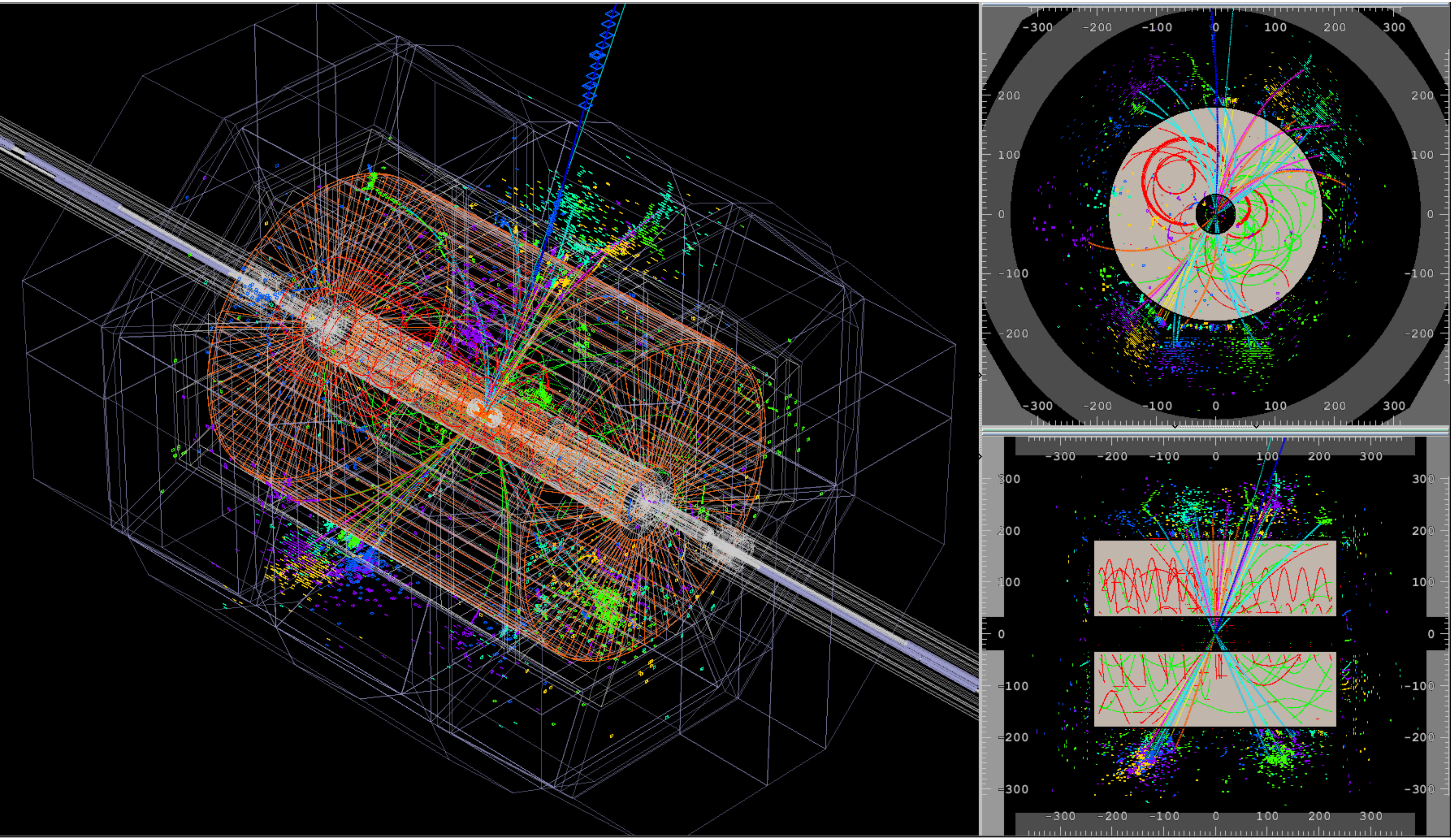


Manqi

Outline

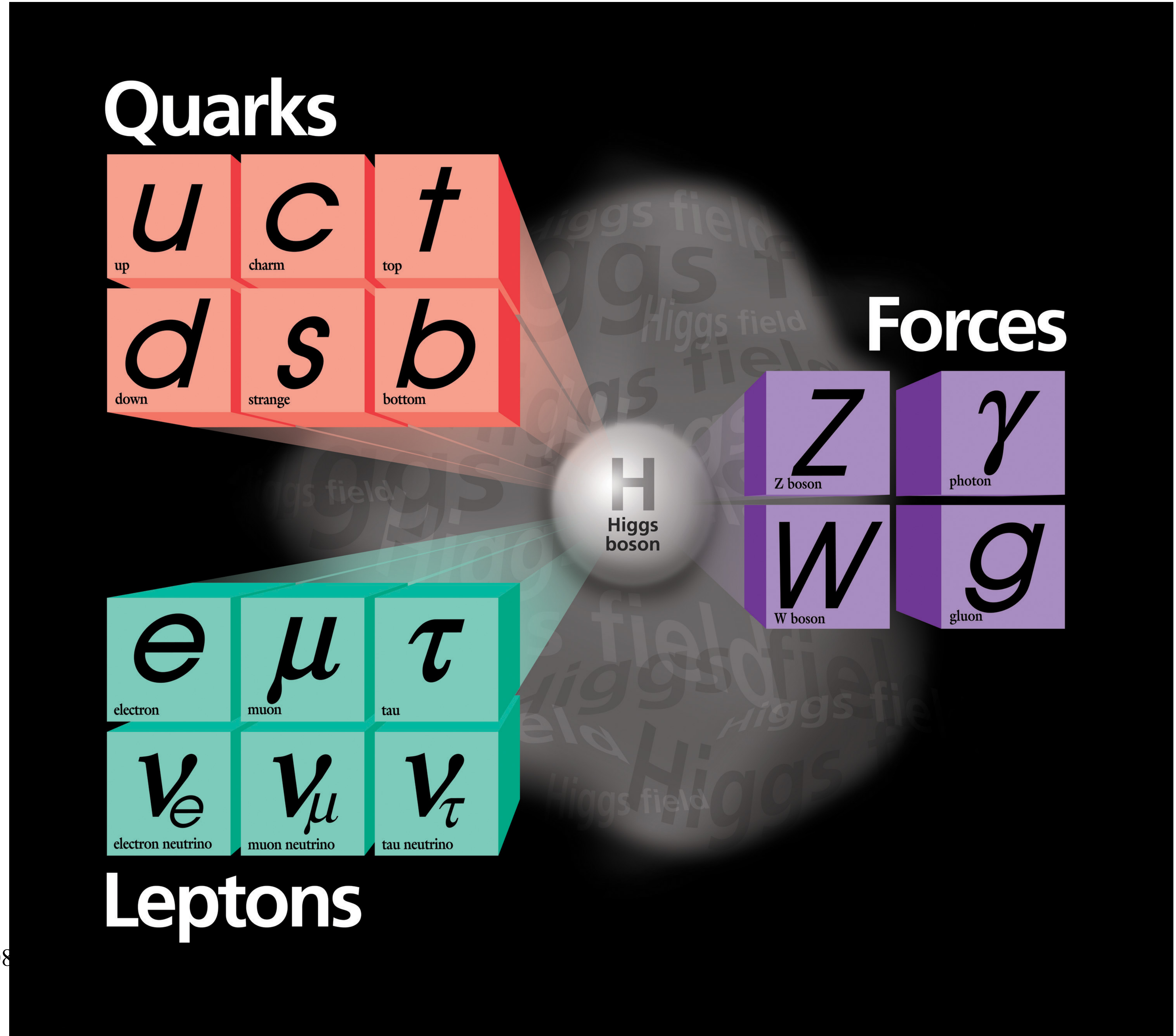
- Introduction
- “Stable” particles at detector scale
- Particle detections
- PFA: Tracking, Clustering, etc
- Key problems for the future
- Summary

A physics event at e^+e^- collider



Detector: take a snapshot & understand the snapshot

- Detector: sensor, structure/support, absorbers & DAQs...
- Direct probe: from final state particles
  - Self: Particle lives/travels longer enough to hit the sensitive volume;
  - Daughter: Particle decayed, but its daughters reaches sensitive volume;
- Indirect: from kinematic constrains
  - i.e: recoil mass method, measurement of missing energy/momentum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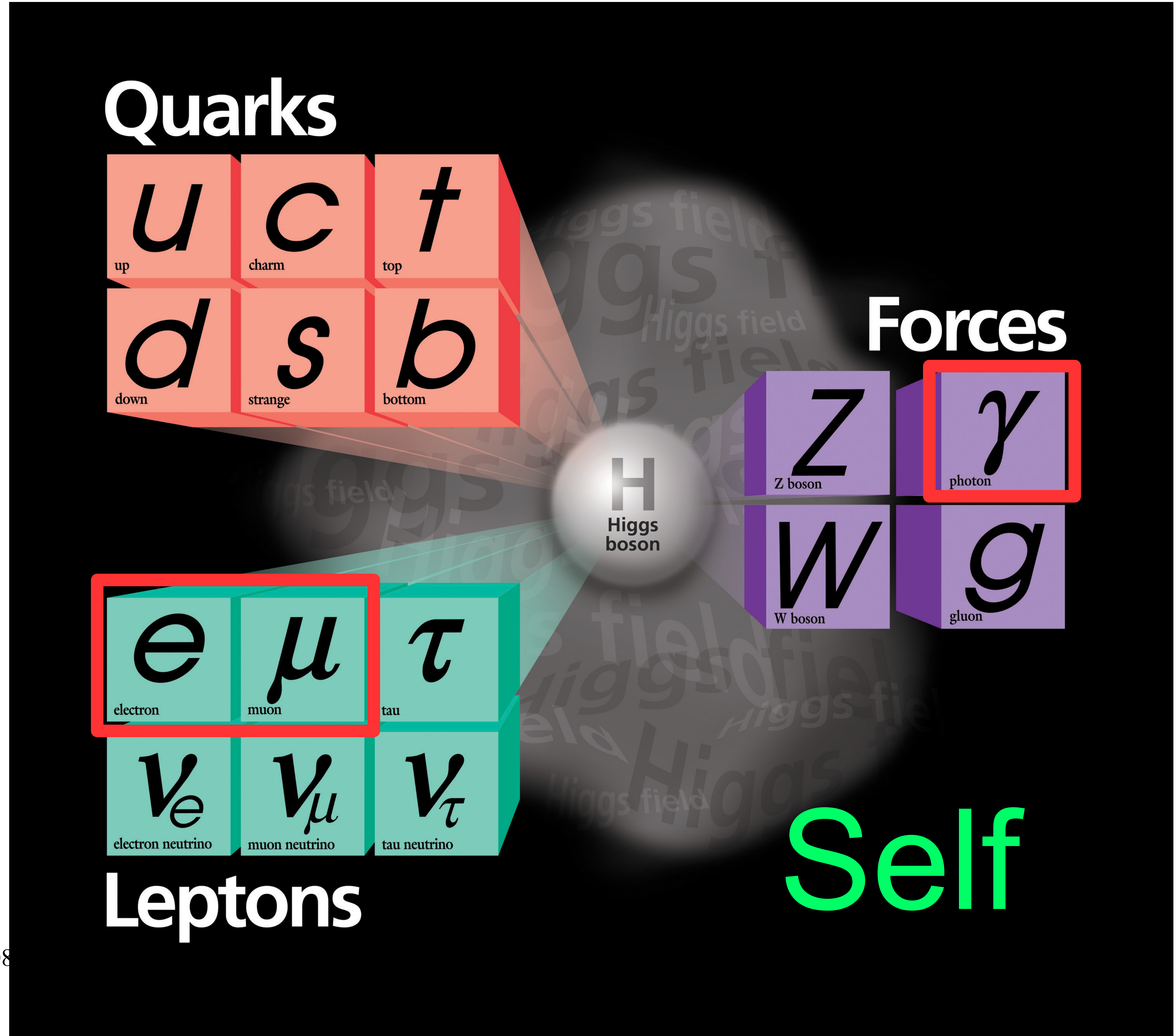
Leptons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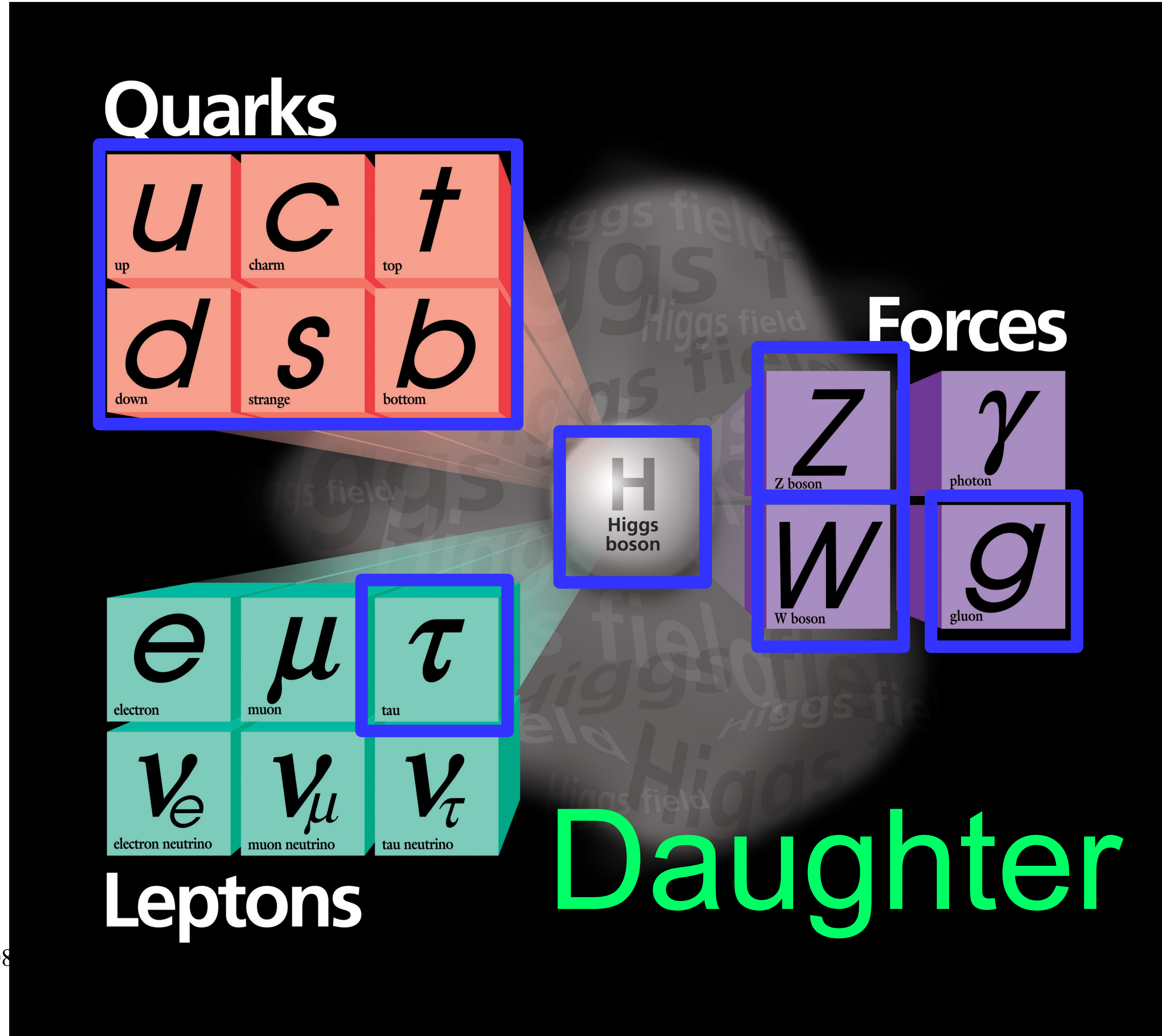
Leptons
Self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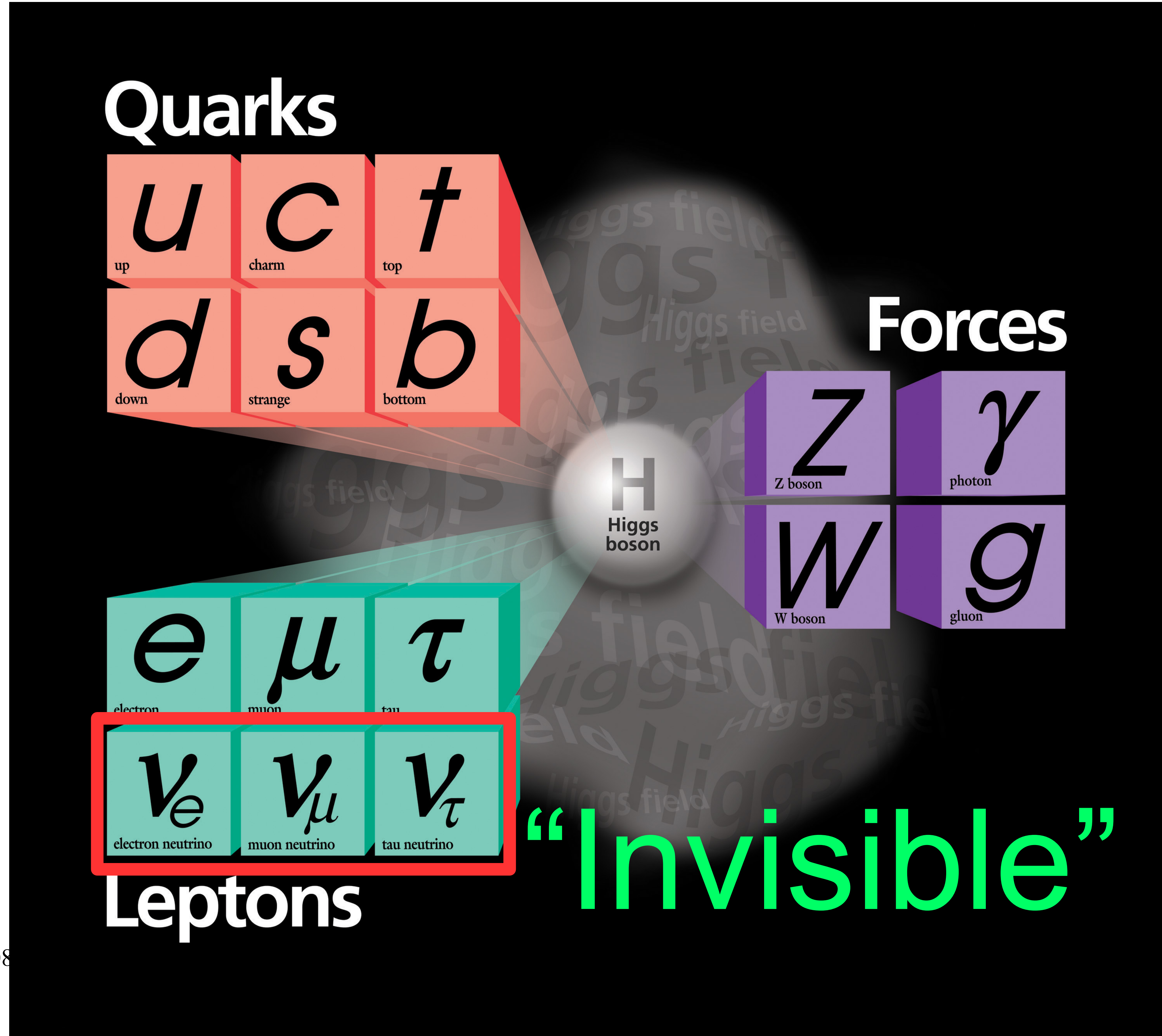
Leptons
Daughter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Leptons
"Invisible"

Stable particles: composited

- Nucleon:
  - Proton & Neutron
- Mesons:
  - Charged Pion, Kaon, etc
- Hadrons:
  - Lambda, Delta, etc
- Nuclei: D, He, etc

http://pdg.lbl.gov/2013/tables/contents_tables.html

$\pi^{\pm}$ $\quad I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

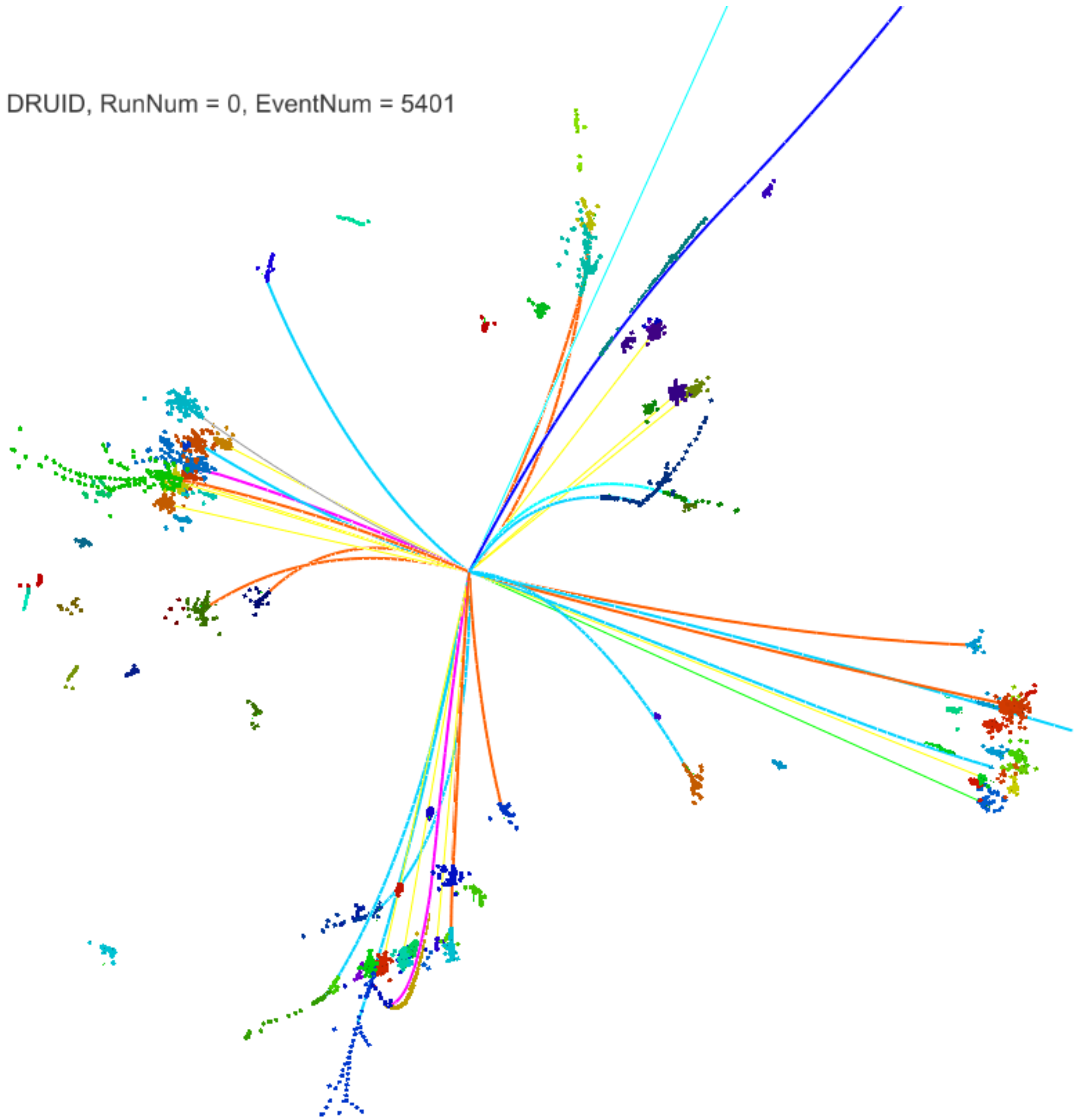
$\pi^{\pm} \to \ell^{\pm}\nu\gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

Traveling length = $\gamma\beta\tau \sim \gamma c\tau$

- *Homework: tag the "stable" particles in the PDG...*
  - *1^{st} : $c\tau > 1$ cm*
  - *2^{nd} : $1\text{cm} > c\tau > 1\ \mu\text{m}$*
  - *If composited, understand its composition*

Color confinement: quark/gluon jet



A typical light jet (u, d, s g):

~60% energy in Charged Hadron
(Mainly pion, kaon)

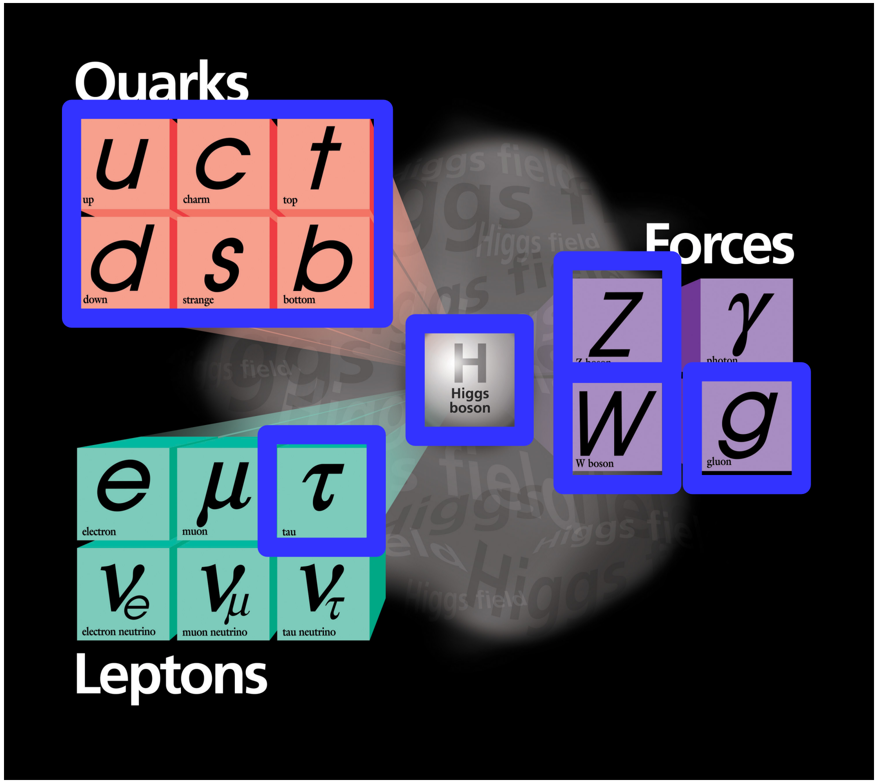
~30% energy in Photons
(from pion0)

~10% in neutral hadrons

Possible to generate neutrinos
& leptons...

SM particles that can be reconstructed from its daughter

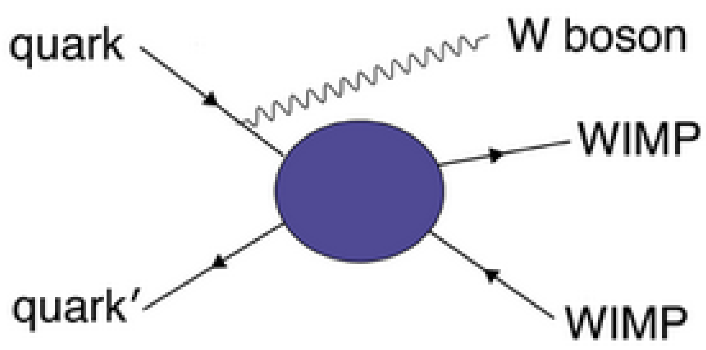
- Quarks (except top) & Gluons: Jets
- Top quark
  - W & b, then cascade
- W & Z
  - 30% leptonic decay
  - 70% decay to quarks: jets
- Tau
  - 35% leptonic decay
  - 50% 1-prong hadron
  - 15% 3-prong, else
- Higgs

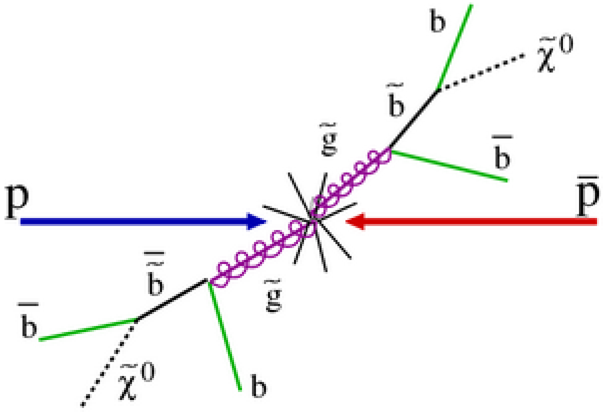


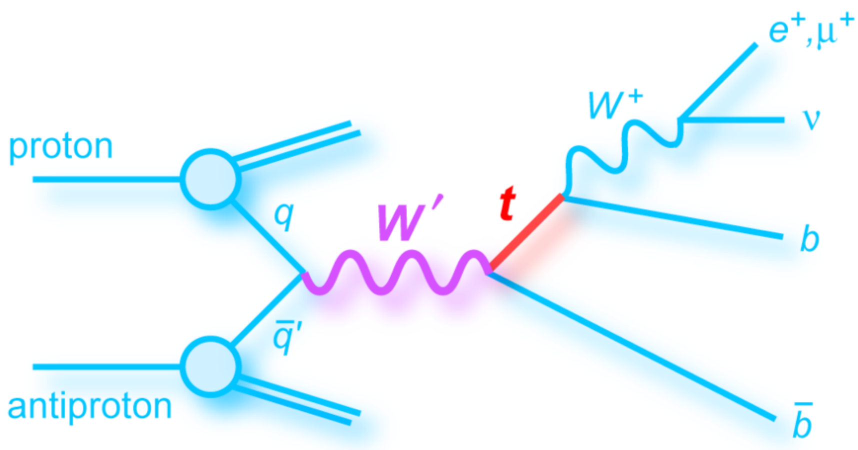
Mode	$b\bar{b}$	$c\bar{c}$	gg	WW^*	$\mu^+\mu^-$	$\tau^+\tau^-$	ZZ^*	$\gamma\gamma$	$Z\gamma$
BR (%)	57.8	2.7	8.6	21.6	0.02	6.4	2.7	0.23	0.16

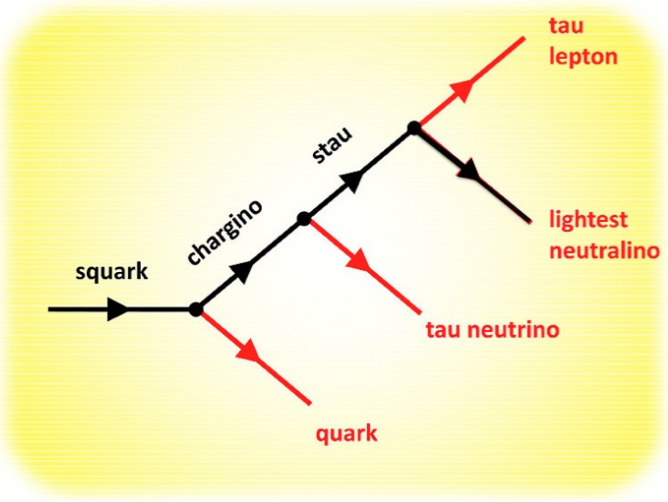
New Physics Particles

- Decay into SM particles and/or invisible particles



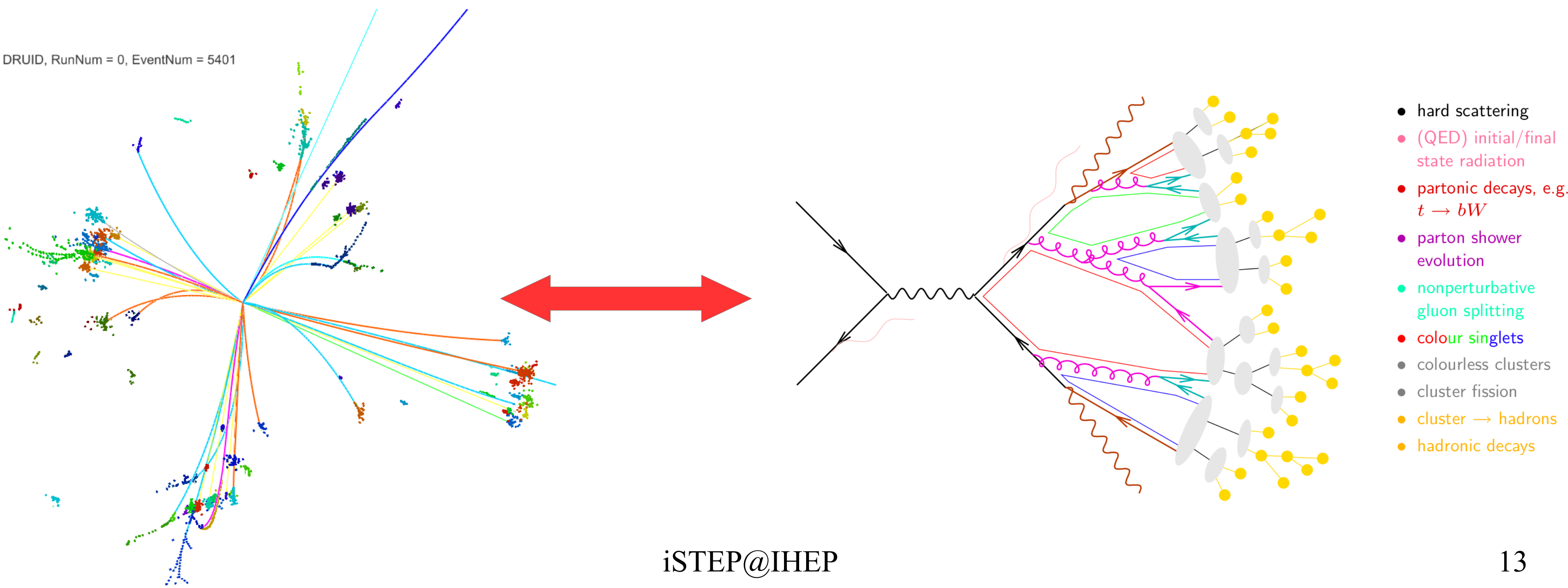






A detector/camera that can reproduce the Feynman diagram at the IP

- Tag final state particles and precisely measure their 4 – momentum
  - Hadrons (pion, kaon, ...), leptons(e, muon) and photons
- Distinguish different, unstable SM particles: tau, W, Z, Higgs, top; different flavor(s) of jets (uds, g, c, b)
- Precisely measure the total 4 momentum ~ missing energy/momentum



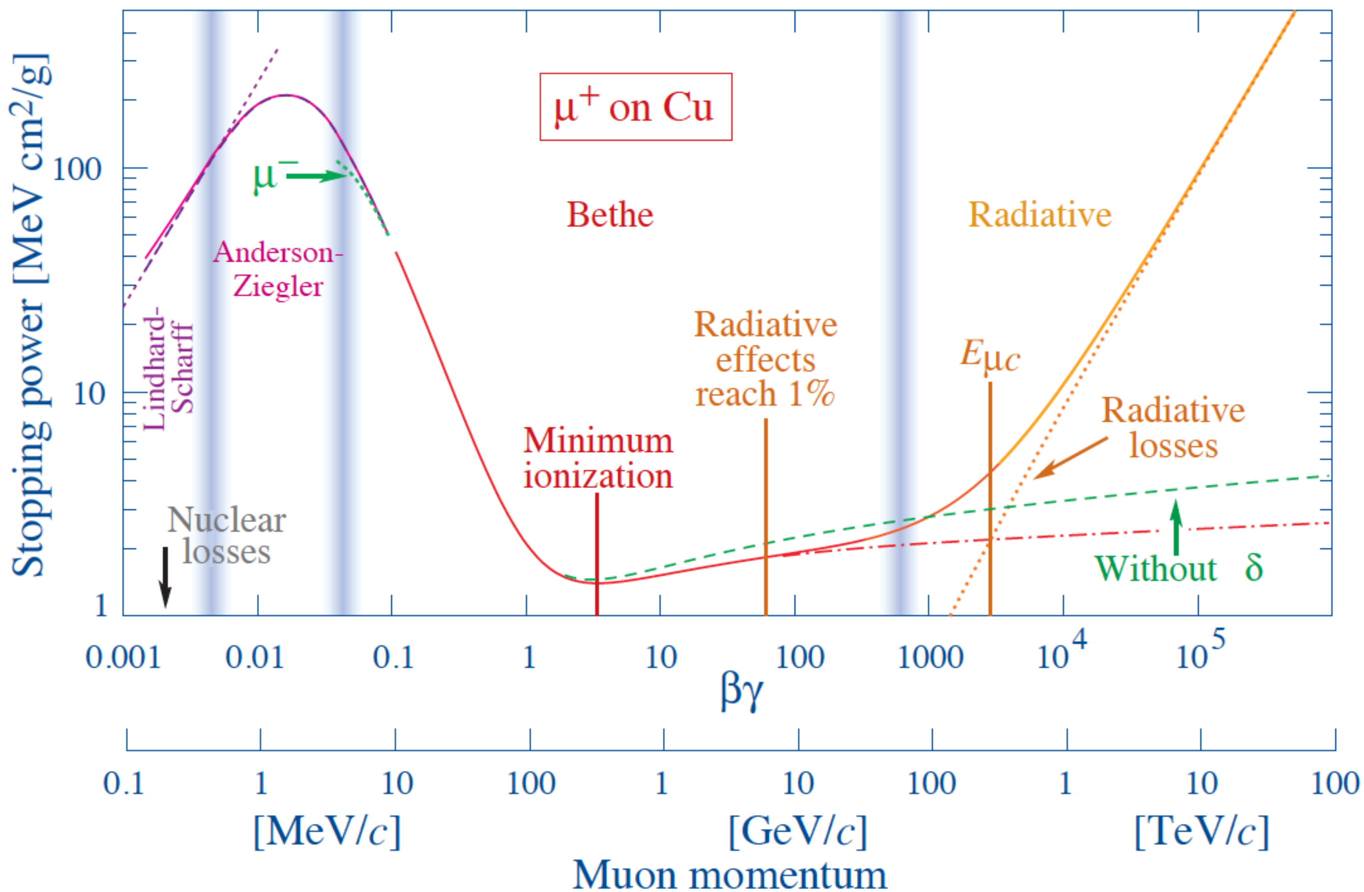
Particle Detection

Particle detection: though Particle-Matter interaction

- Charged Particle: ionization
  - Tracking at Tracker
- Neutral Particle: Energy deposition/absorption at Calorimeter
  - Electromagnetic interaction: Ecal
  - Hadronic interaction: Hcal
  - *Ionization is also one of the important ways that shower deposit energy in Calorimeter*
- Advanced: Jet Tagging & Identification: Jet Clustering and Flavor tagging
  - Combination of Track informations...

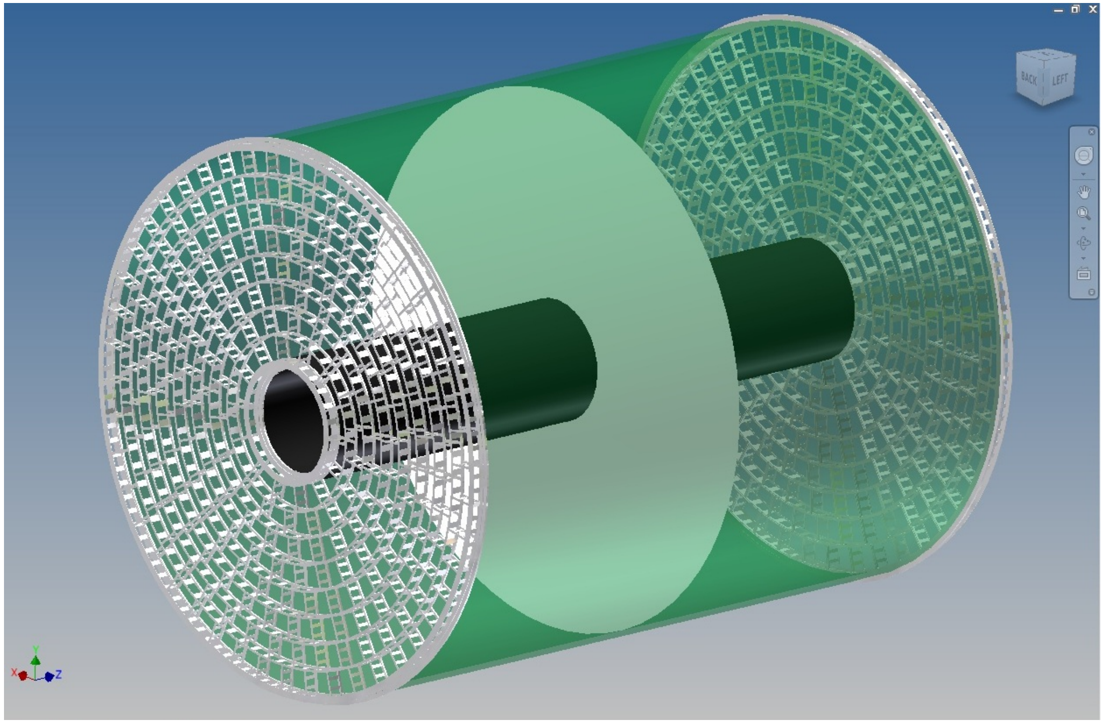
Ionization

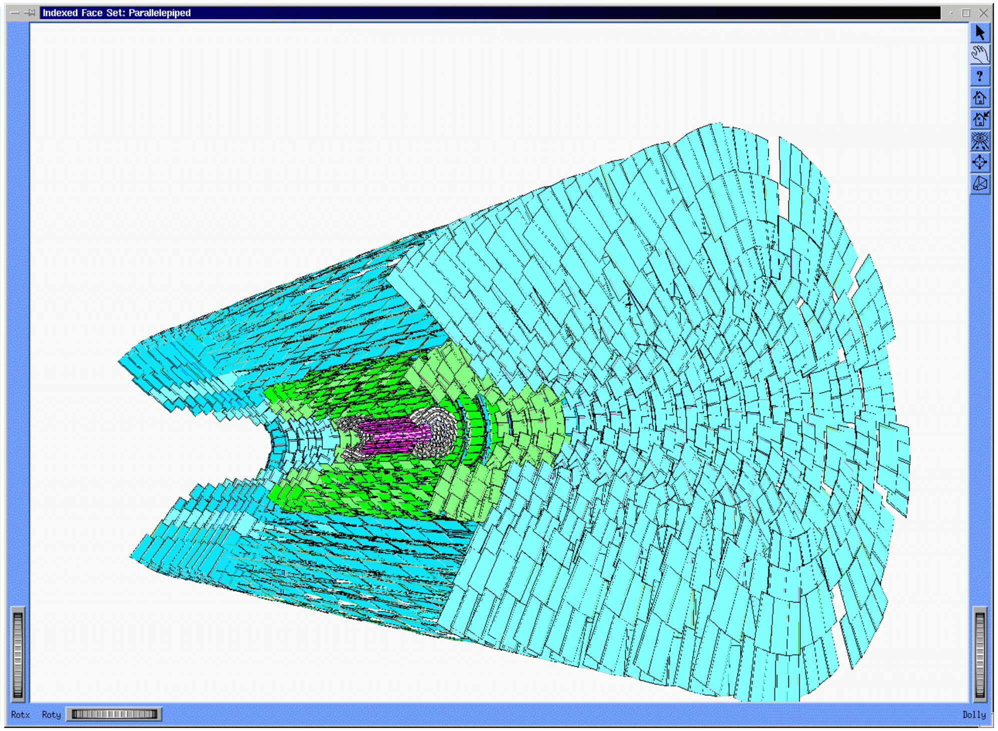
- Characteristic: dE/dx - number of ionizations per unit length
- MIPs: Minimal Ionization Particle, basic unit to record the energy deposition in a sensitive volume



At Fe: 1.6 GeV/m

Tracker

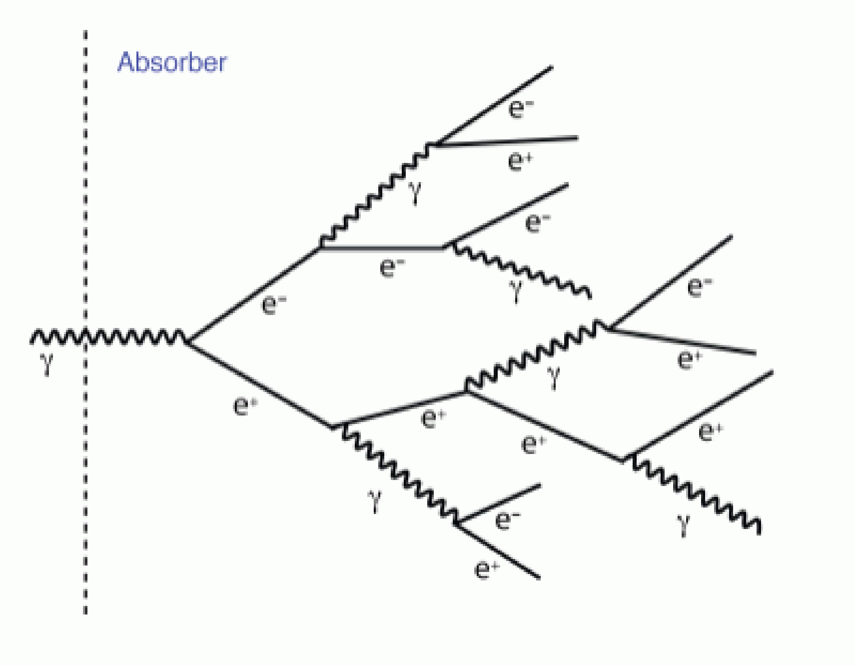


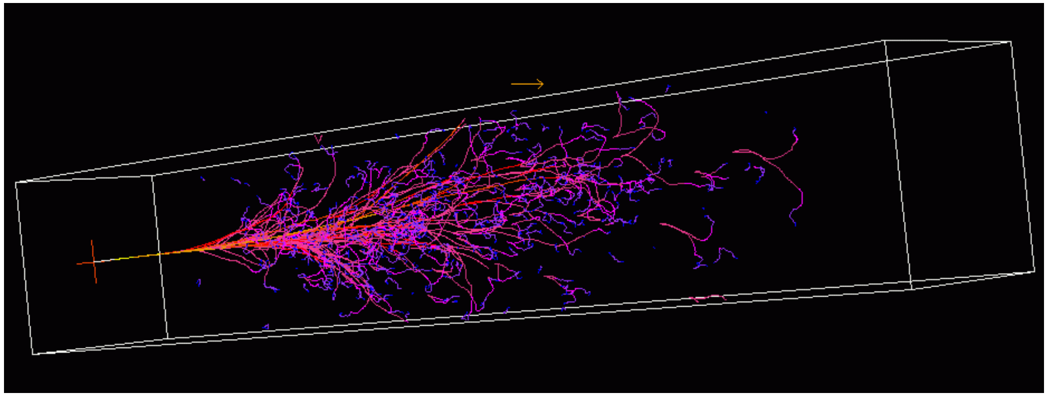


- Charged particles create tracker hits from ionization;
- Tracker hits are recorded, and fitted into tracks;
- The Pt information is represented by the curvature of the track;
- The impact parameters can also be reconstructed
- Less material, high precision & high readout speed

ElectroMagnetic interaction

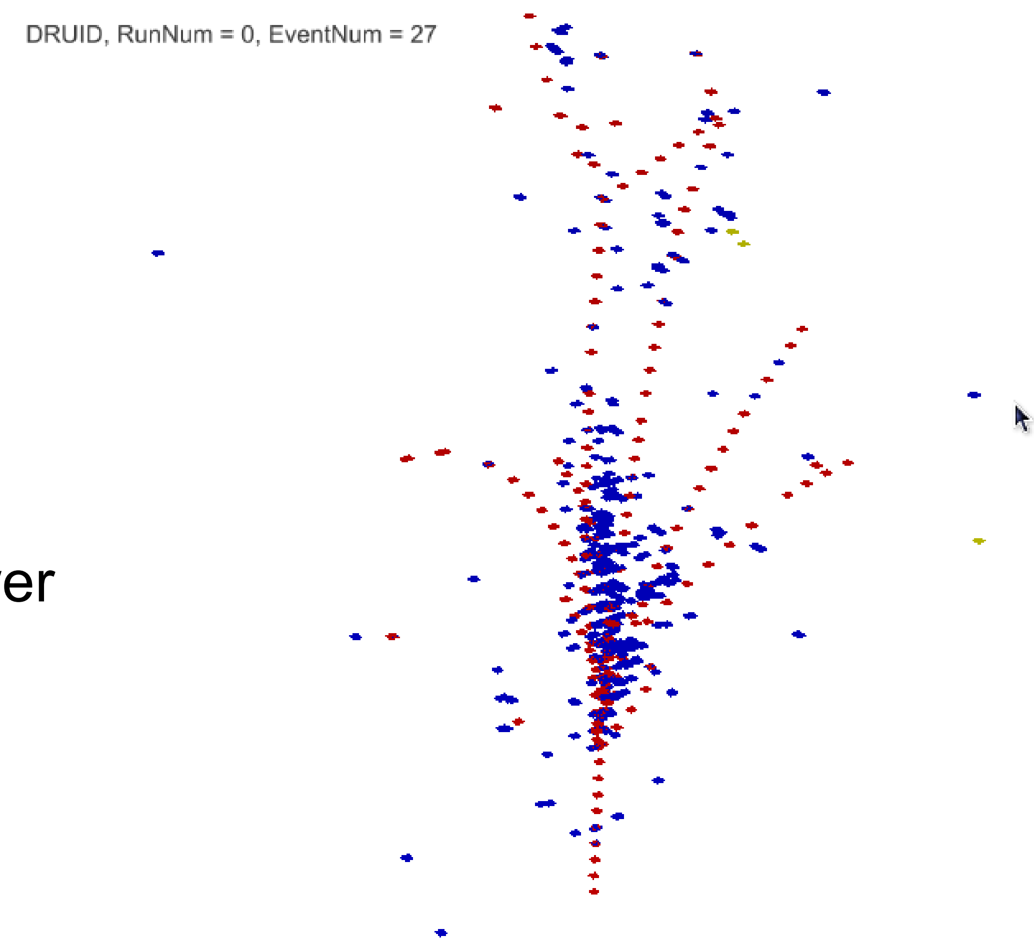
- Particles: electron, positron and photon (thus pi0)
- Physics processes:
  - Pair production
  - Bremsstrahlung
- Characteristic:
  - Radiation length (X0)
  - Moliere radius





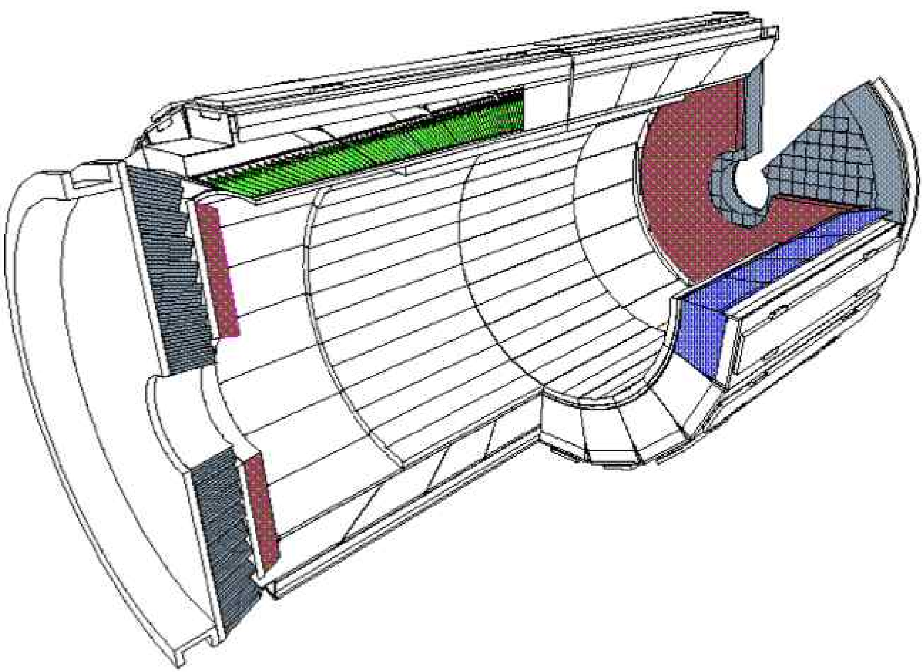
Hadronic interaction

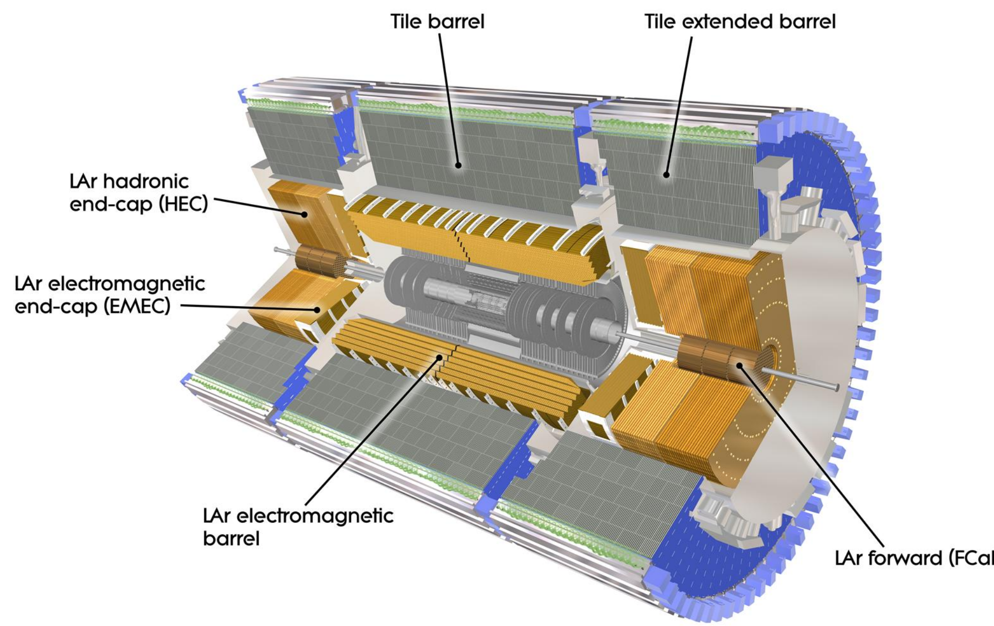
- Hadrons & Mesons
- Nuclear interactions:
  - nuclear breakups,
  - bremsstrahlung with pion
  - Isospin exchange...
- Much complicated than EM shower: in fact, hadronic shower can contain EM sub-showers
- Characteristic:
  - Interaction length (~ 20 cm for iron)



Calorimeter

- Particles should exhaust its energy in Calorimeter system + detector price ~ size;
- Compact, Dense Calorimeter System;
- Separate different particles – high granularity;
- Precisely reconstruct particle energy: sampling or crystal;



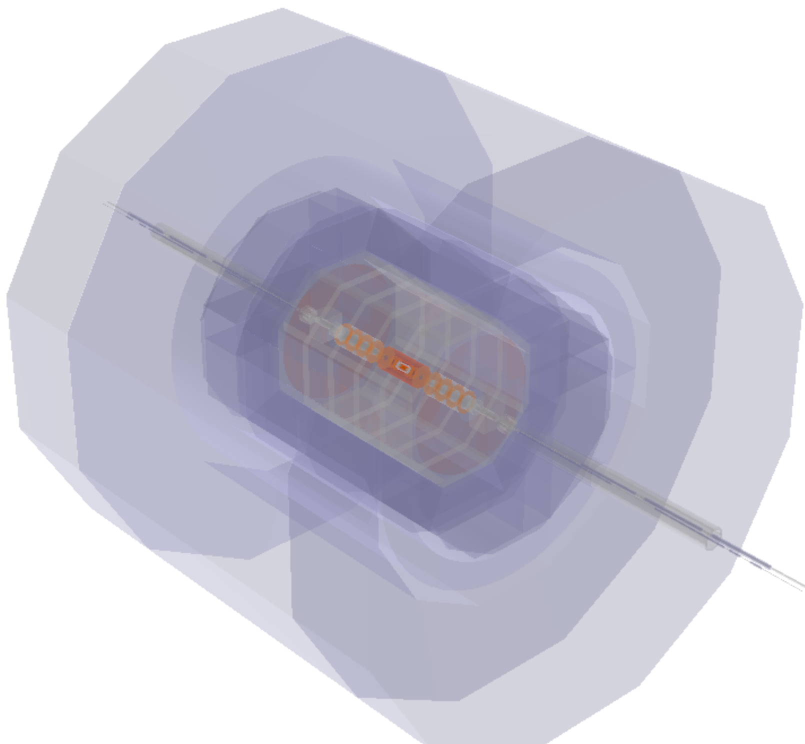


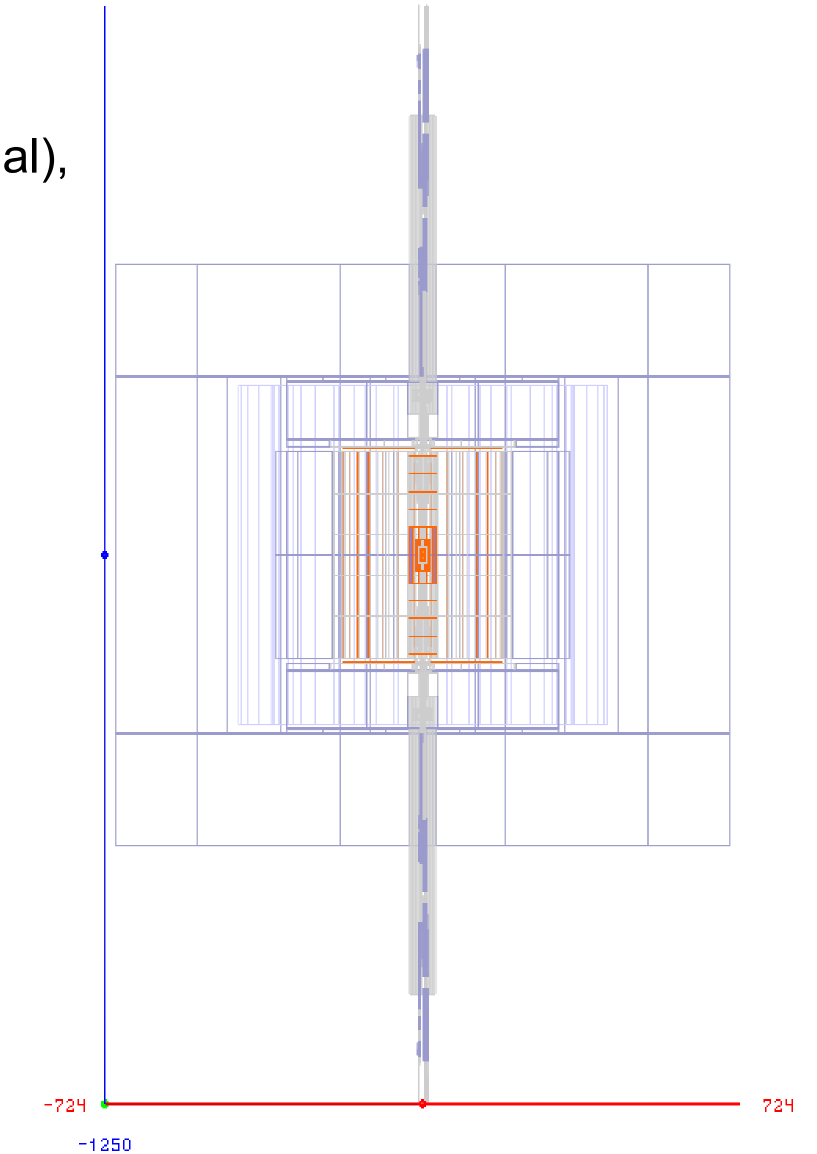
A closer look at the detector

Reference detector for CEPC: ILD

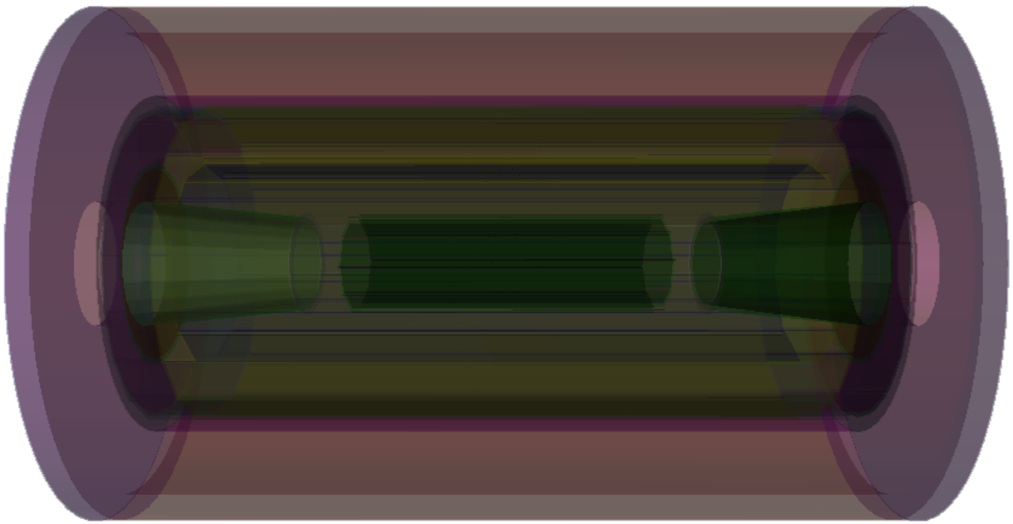
Scale: half_Z: 12.5/6.62 meter, radius 7.24 meter

Sub detectors: VTX, SIT, FTD, TPC, SET/ETD(optional),
Ecal, Hcal, Coil, Muon

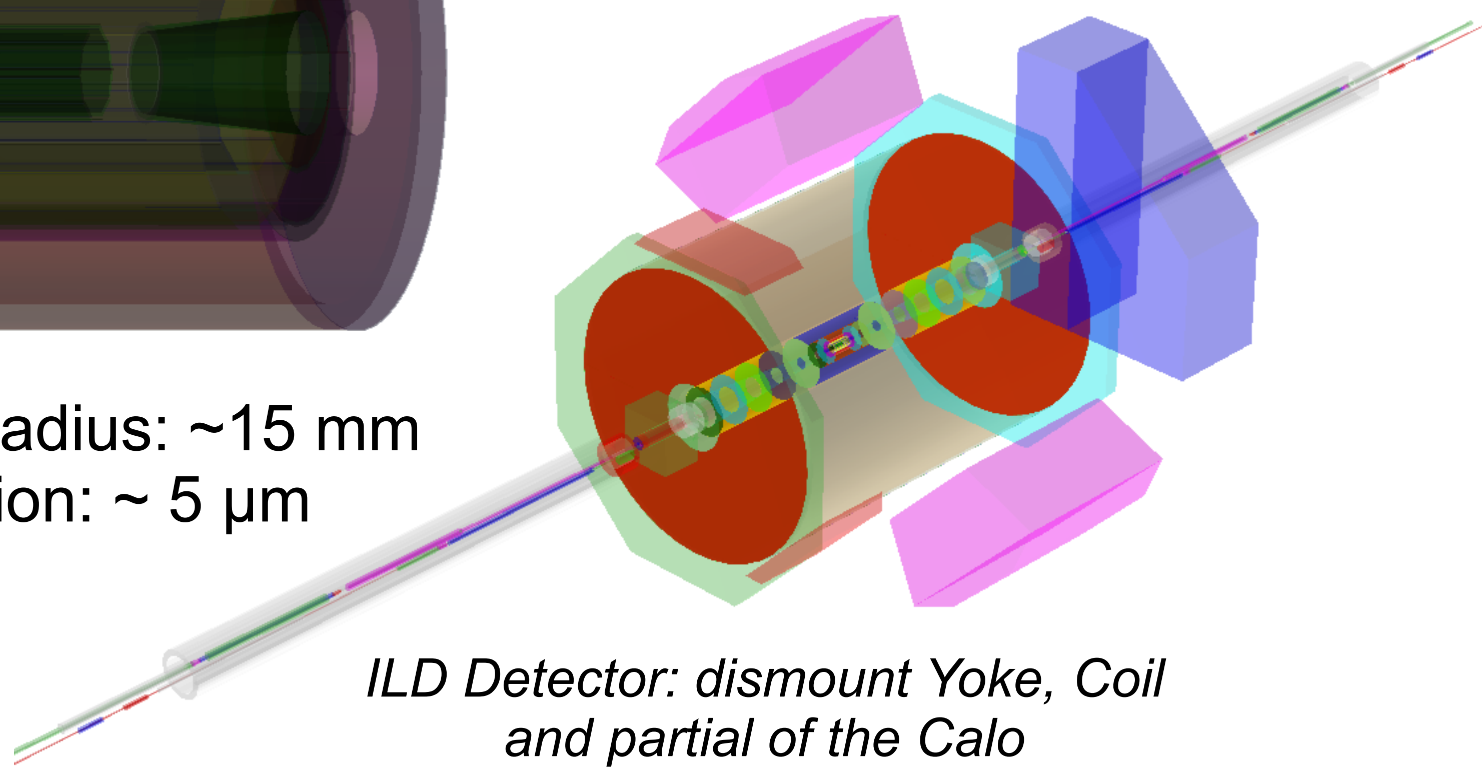




Vertex detector

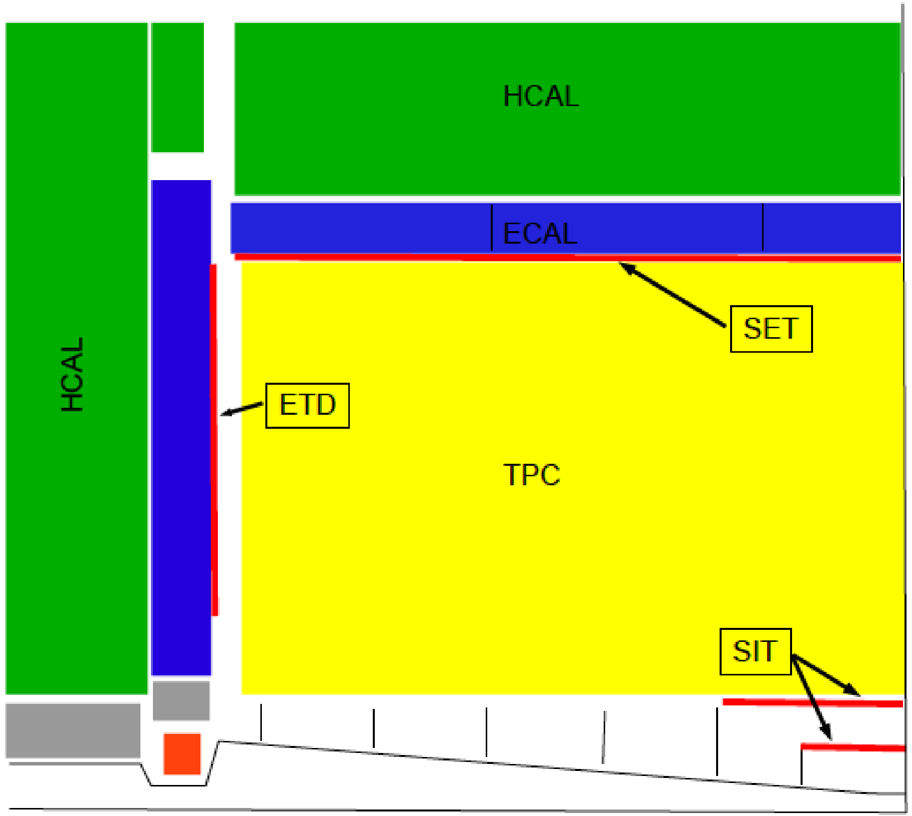


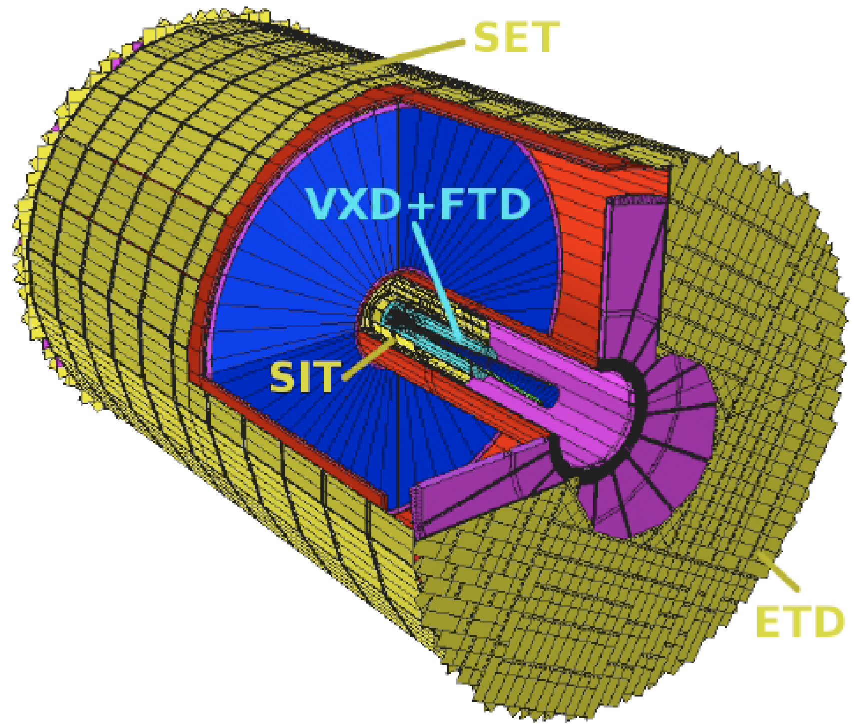
Inner most layer Radius: ~15 mm
Spatial resolution: ~ 5 μm



ILD Detector: dismount Yoke, Coil and partial of the Calo

Silicon Tracking at ILD





- Massive usage of silicon pixel/strips in the tracking system & VTX: ensures good accuracy in Impact parameter & momentum measurement

ILD Main Tracker: TPC

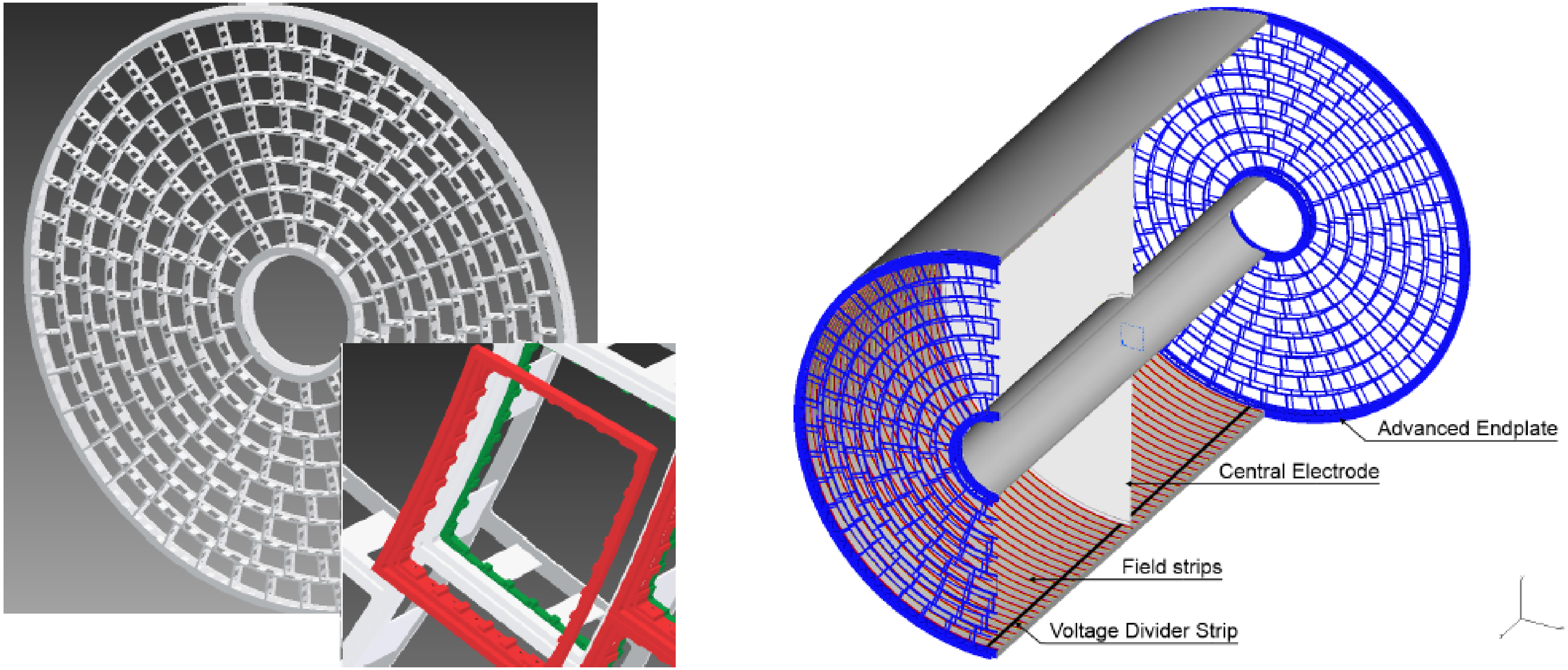
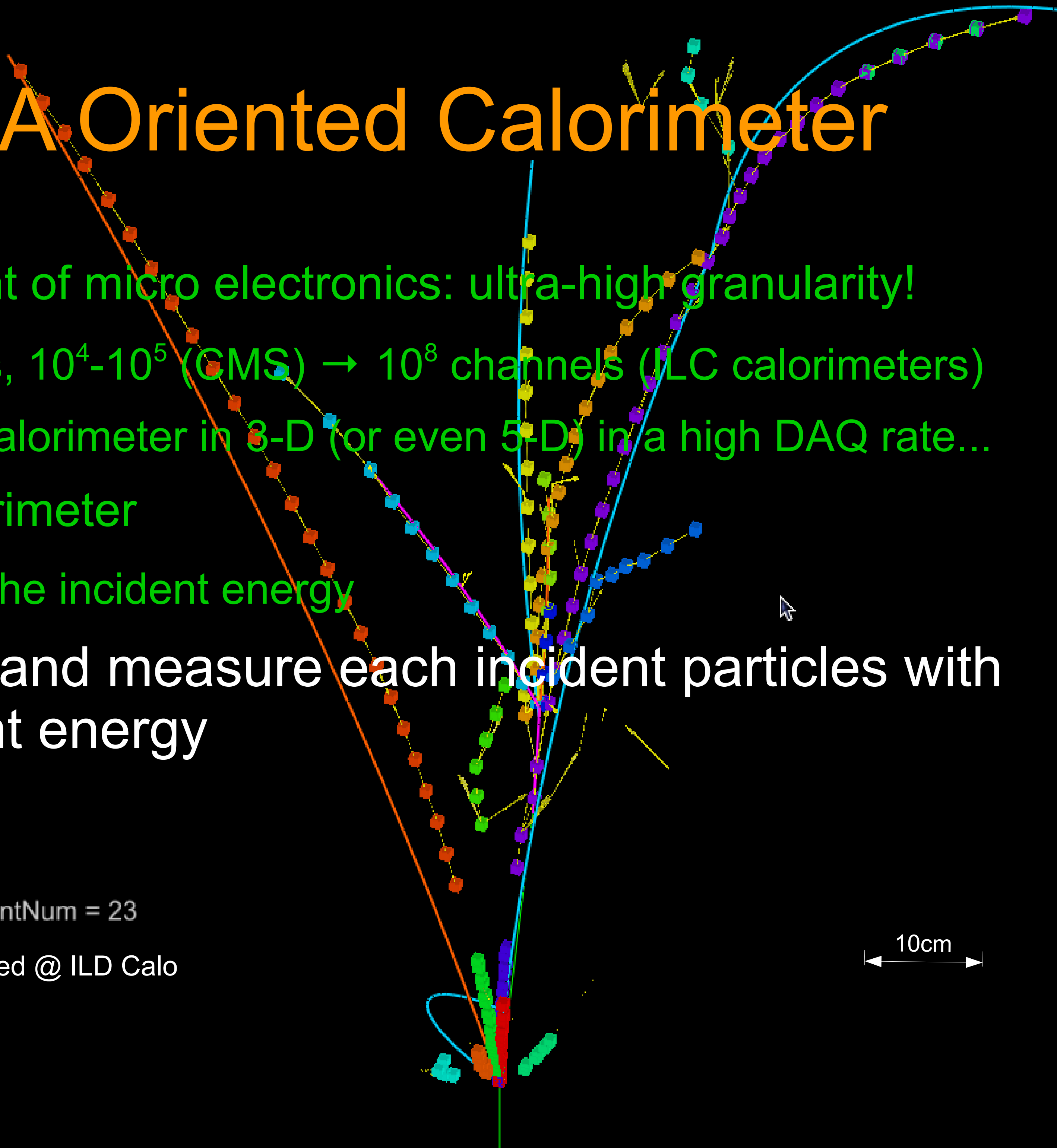


Figure III-2.11. Left: Drawing of the proposed end-plate for the TPC. In the insert a backframe which is supporting the actual readout module, is shown. Right: Conceptual sketch of the TPC system showing the main parts of the TPC (not to scale).

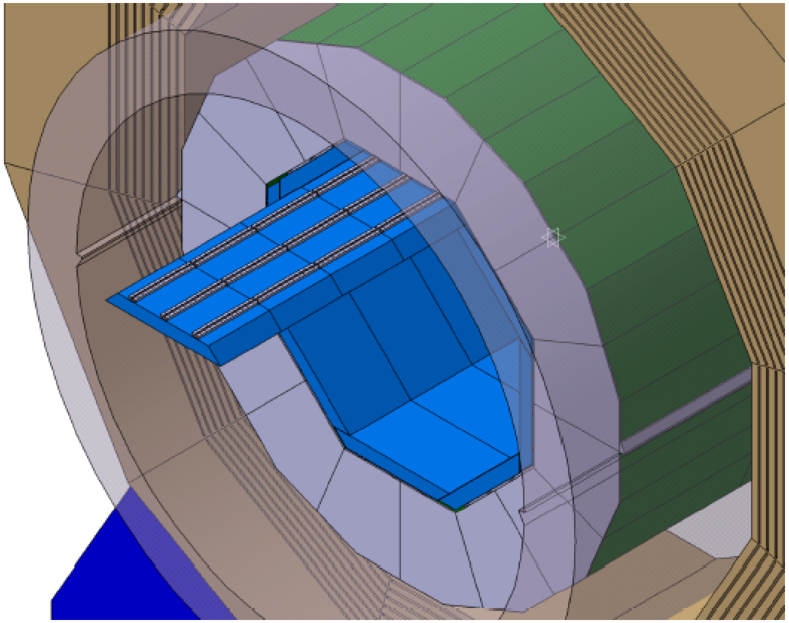
PFA Oriented Calorimeter

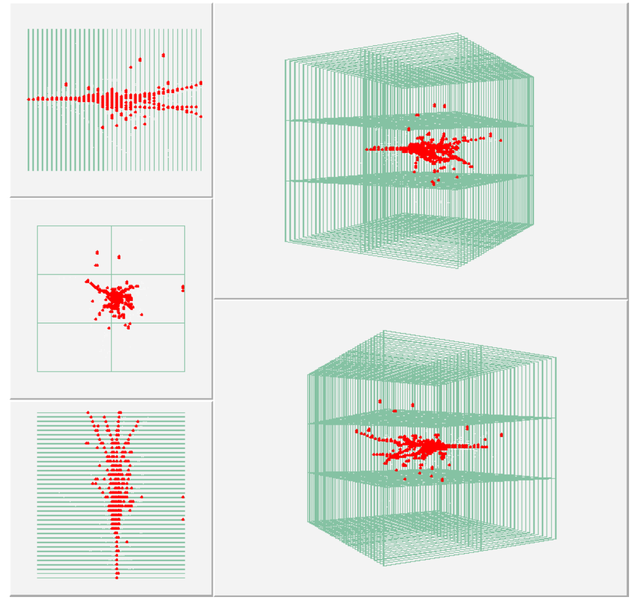
- Development of micro electronics: ultra-high granularity!
  - #channels, 10^4-10^5 (CMS) → 10^8 channels (ILC calorimeters)
  - Imaging calorimeter in 3-D (or even 5-D) in a high DAQ rate...
- Role of calorimeter
  - Measure the incident energy
  - Identify and measure each incident particles with sufficient energy

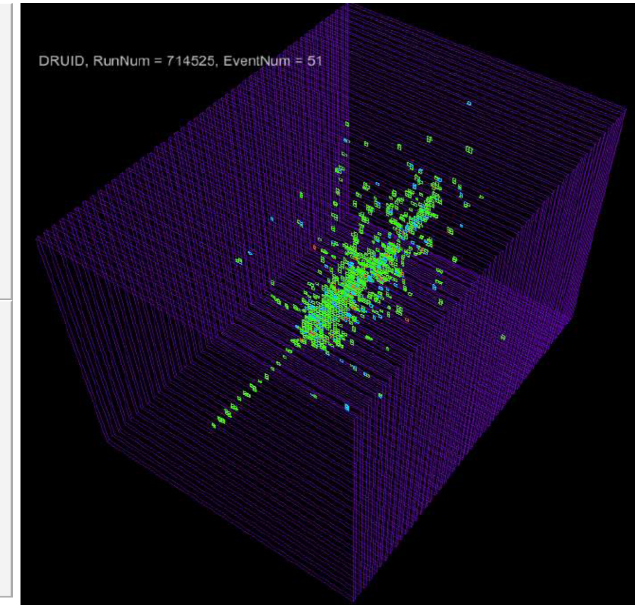


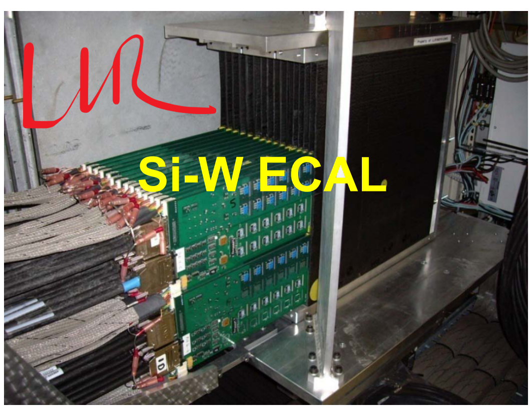
20 GeV Klong reconstructed @ ILD Calo

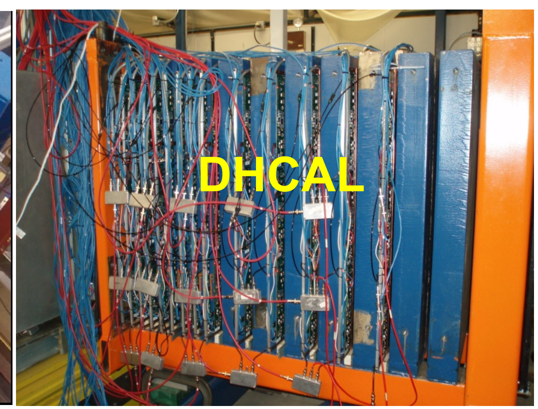
Calorimeter R&D for ILD



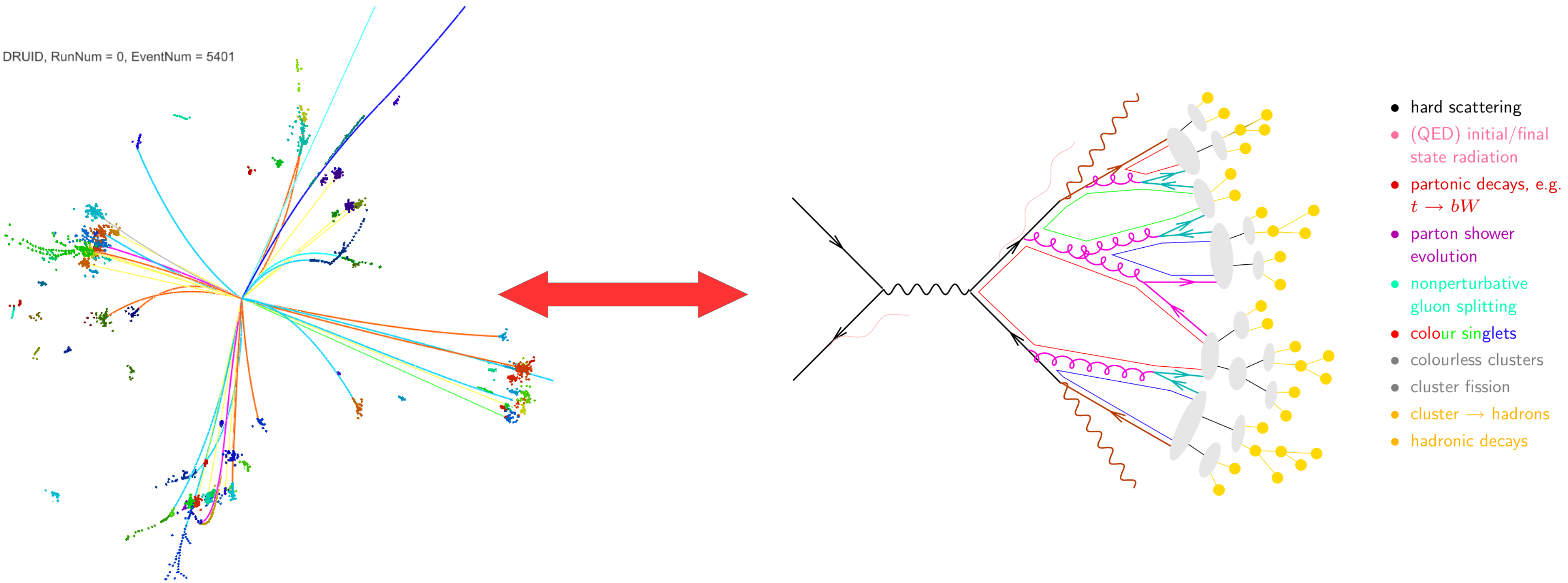








Ultra high granularity ~ 1 channel cm^{-3}. 3d, 4d or 5d image...

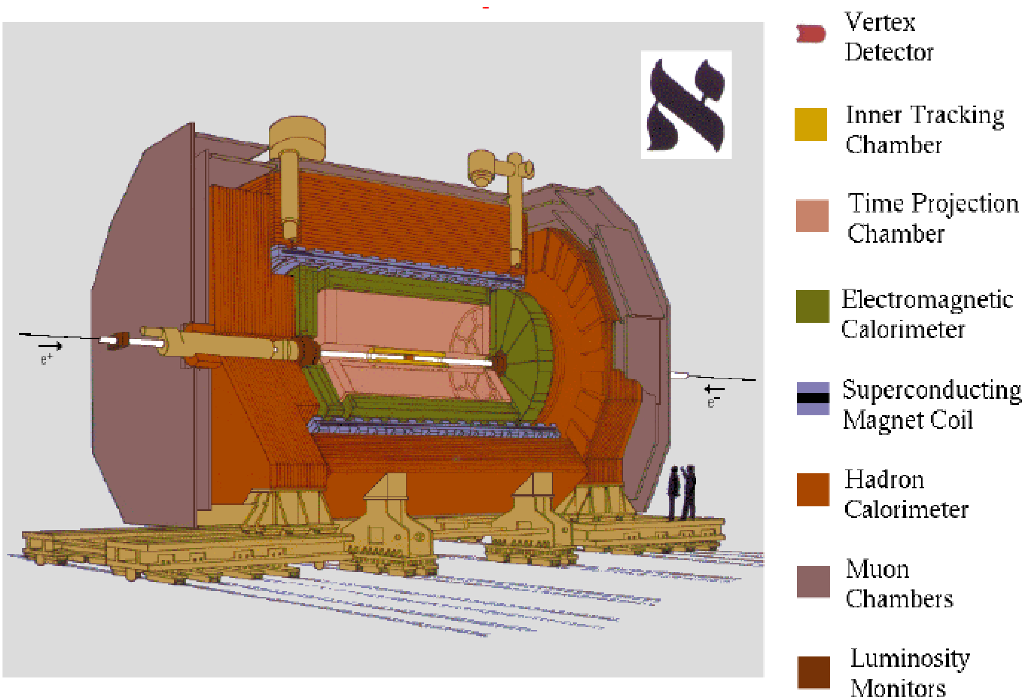


Our goal:
A detector/camera that can reproduce the Feynman diagram at the IP

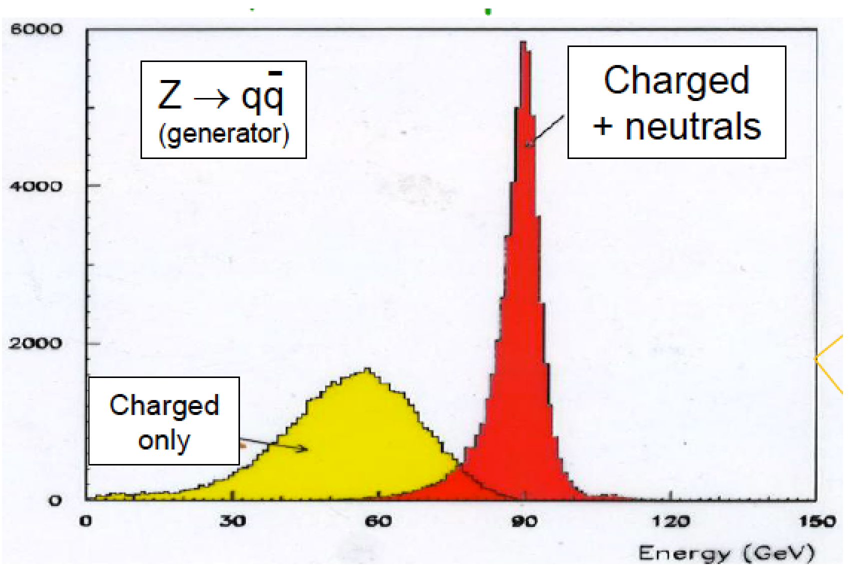
Therefore

- The ultimate goal for detector is
  - Tag Every final state particles, identify them and precisely measure their energy momentum and positions
  - A.K.A, Particle Flow Algorithm (Principle)
- With the development of Electronics: PFA serves as the compass for detector design/reconstruction algorithm development
- A PFA oriented detector:
  - Separate the energy deposition of each final state particle
  - Follow each one of them, and reconstruct them in the most suited sub-detectors
    - i.e, charged particle at tracker;
    - Photons at ECAL
    - Neutral hadrons at HCAL

PFA @ ALEPH



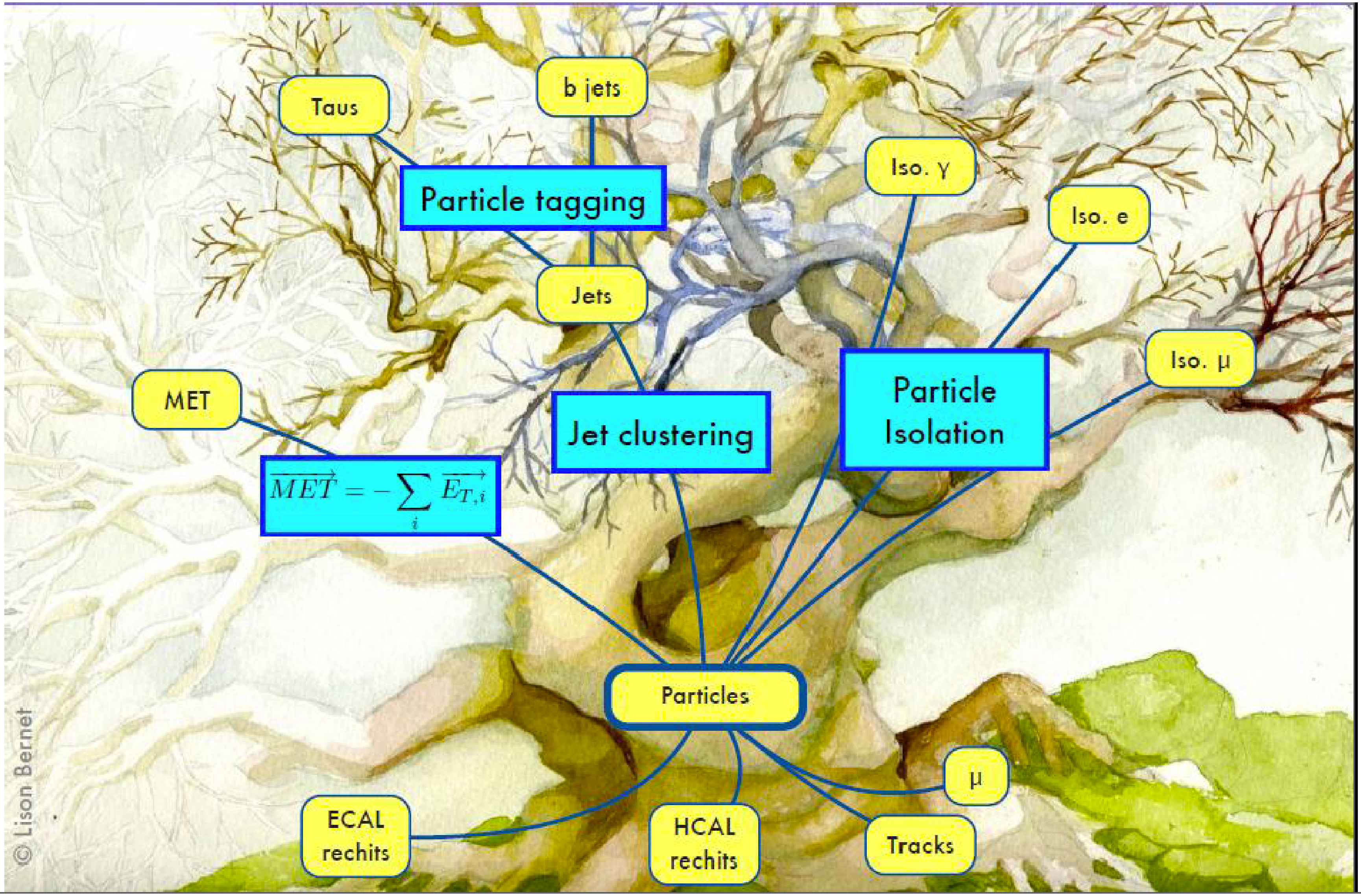
The ALEPH Detector



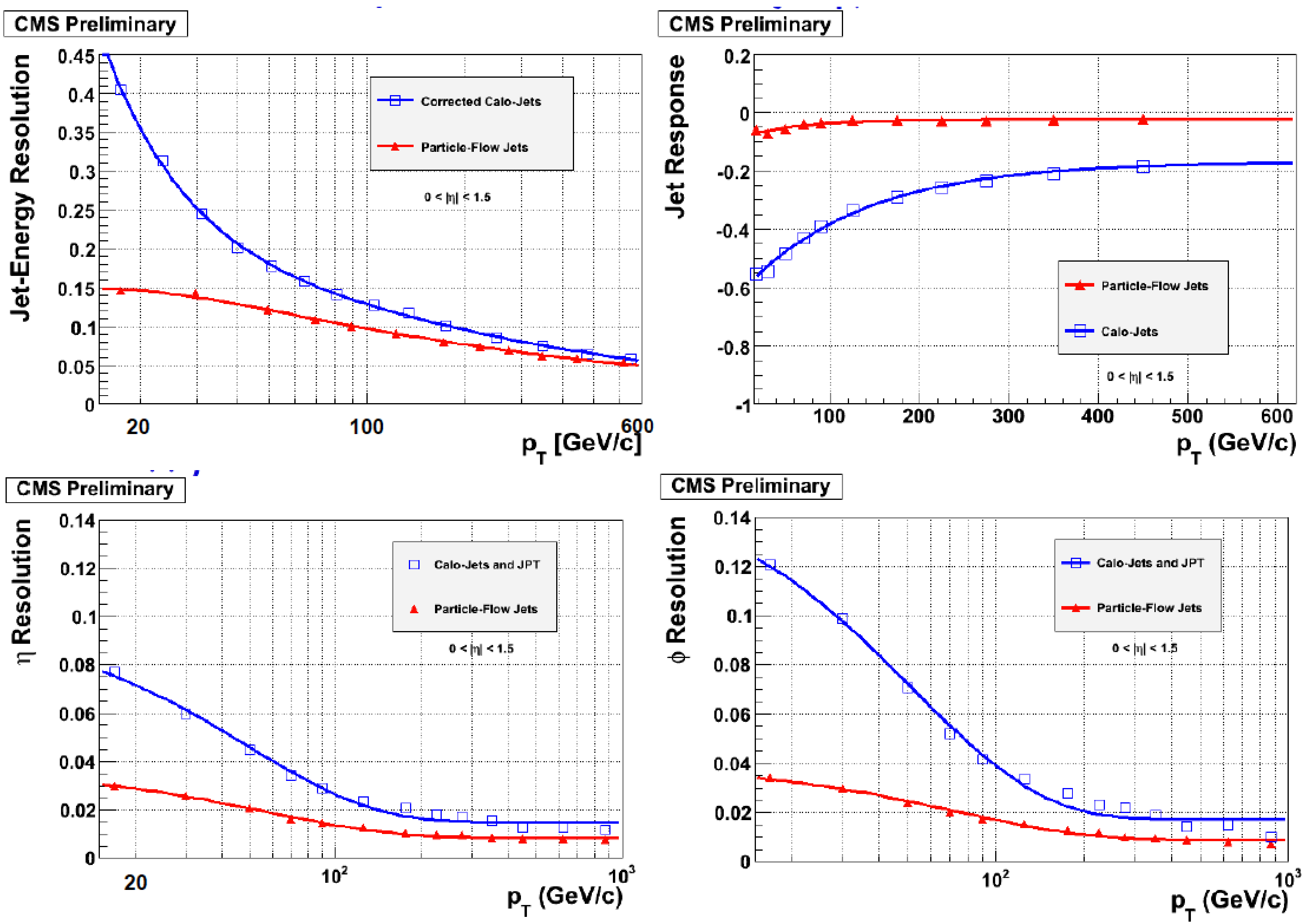
- Measured resolution twice as large:
  - $E_{tot} = 90.5 \pm 6.2$ GeV
- But remember with calorimeters only:
  - $E_{tot} = 72 \pm 13$ GeV

Particle-Flow performance in CMS (4)

- Physics objects from the global event description with particles

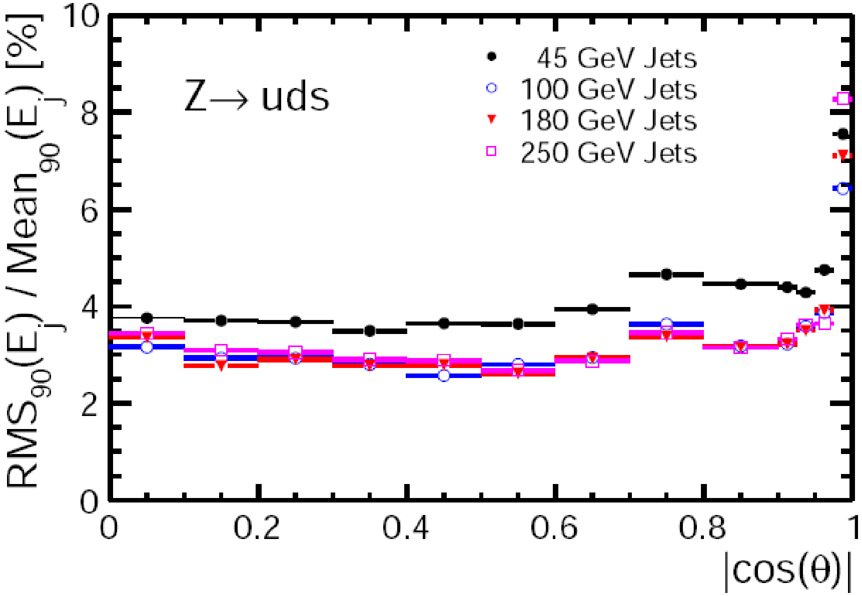


PFA Performance at CMS



PFA @ ILC

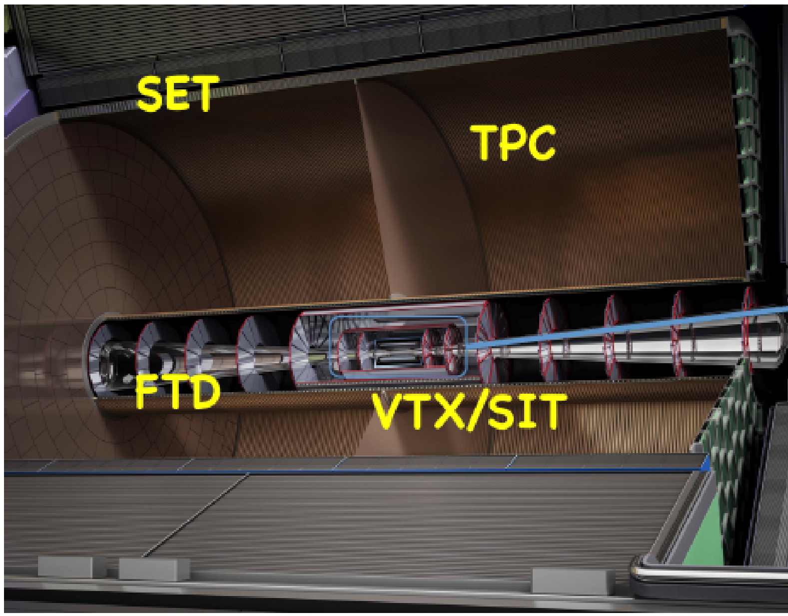
Multi bosons	Multifermions + Boson(s)
ZH	e^+e^- H , e+e- Z
WW	νν H , νν Z
ZZ	ttH
ZHH	e ν W
ZZZ	νν WW, νν ZZ
ZWW	ttbar

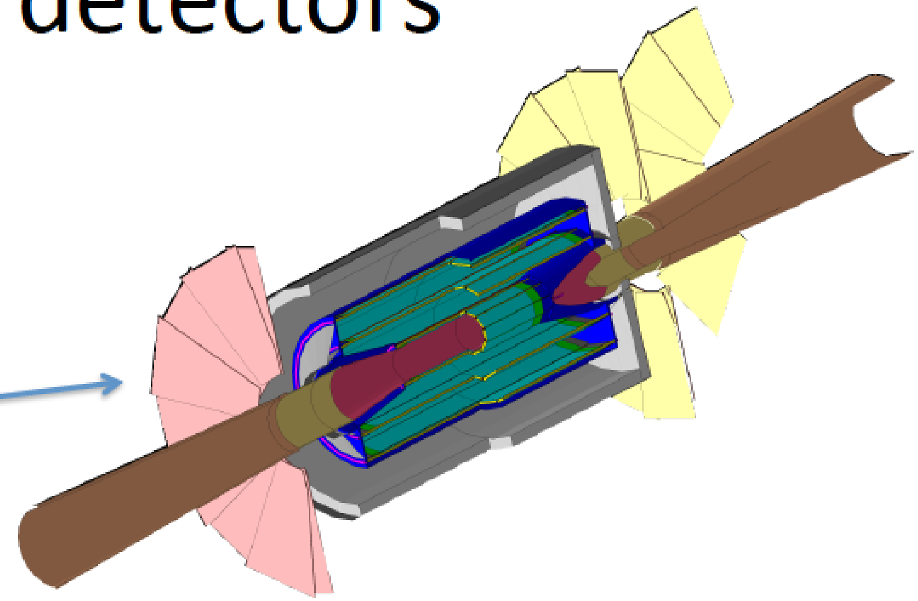


- LC detector: precisely identify and measure final state particles (*visible*)
  - Calorimeter: jet energy, PID
- Available:
  - *Pflow, SiD-IowaPFA, Trackwise Clustering...*
  - **PandoraPFA**: achieves the Benchmark requirement: δE/E ~ 3%
  - Arbor

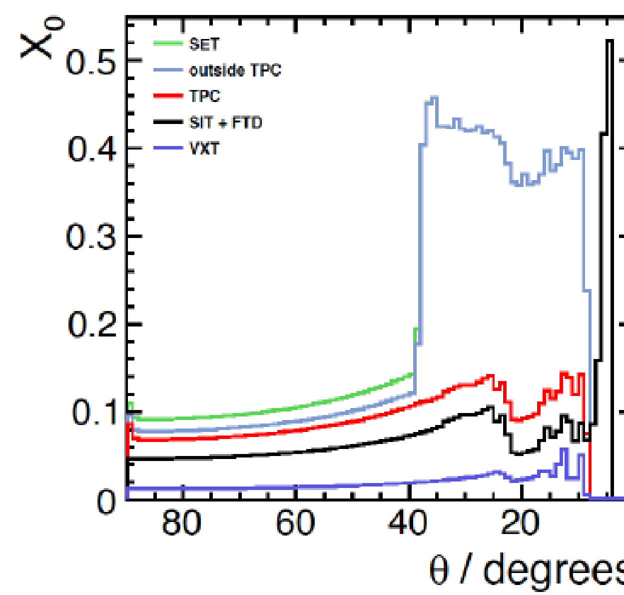
Tracking:
tracker hits → tracks

Tracking detectors



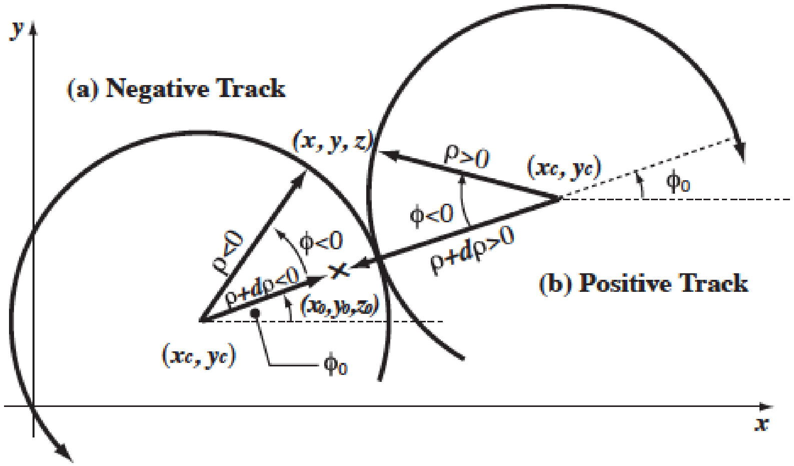


Detector	Point Resolution		
VTX	$\sigma_{r\phi,z}$	=	2.8μm (layer 1)
	$\sigma_{r\phi,z}$	=	6.0μm (layer 2)
	$\sigma_{r\phi,z}$	=	4.0μm (layers 3-6)
SIT	σ_{α_z}	=	7.0μm
	α_z	=	$\pm 7.0°$ (angle with z-axis)
SET	σ_{α_z}	=	7.0μm
	α_z	=	$\pm 7.0°$ (angle with z-axis)
FTD *Pixel*	σ_r	=	3.0μm
	$\sigma_{r_\perp}$	=	3.0μm
FTD *Strip*	σ_{α_r}	=	7.0μm
	α_r	=	$\pm 5.0°$ (angle with radial direction)
TPC	$\sigma^2_{r\phi}$	=	$(50^2 + 900^2 \sin^2\phi + ((25^2/22) \times (4T/B)^2 \sin\theta)\ (z/\text{cm}))\ \mu\text{m}^2$
	σ^2_z	=	$(400^2 + 80^2 \times (z/\text{cm}))\ \mu\text{m}^2$
	where ϕ and θ are the azimuthal and polar angle of the track direction		

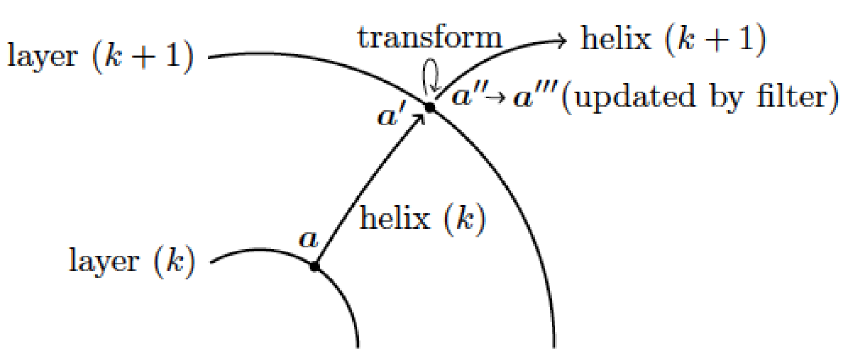


KalTest

- Helical track model:



- Recently development: non-uniform B field



- Track equation:

$$\begin{cases} x = x_0 + d_\rho \cos\phi_0 + \frac{\alpha}{\kappa}(\cos\phi_0 - \cos(\phi_0+\phi)) \\ y = y_0 + d_\rho \sin\phi_0 + \frac{\alpha}{\kappa}(\sin\phi_0 - \sin(\phi_0+\phi)) \\ z = z_0 + d_z - \frac{\alpha}{\kappa}\tan\lambda\cdot\phi \end{cases},$$

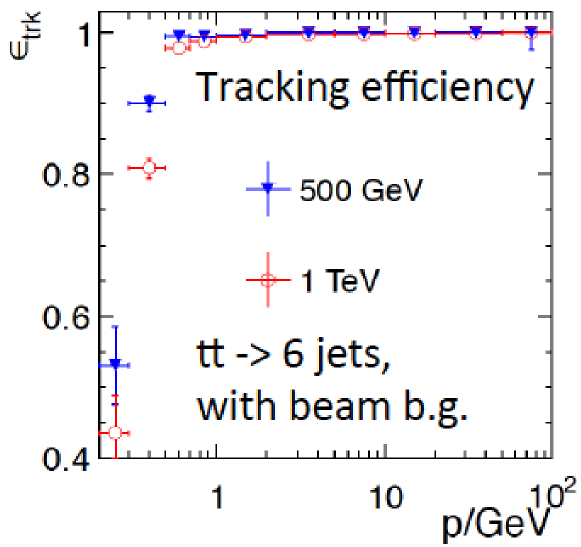
- State vector:

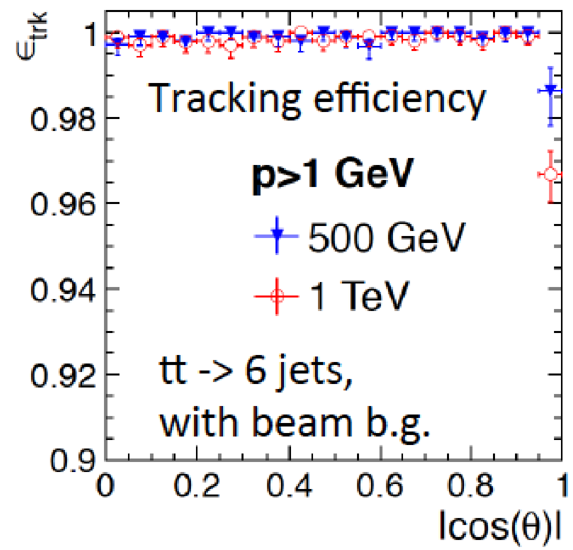
$$\boldsymbol{a}_k = \left(\ d_\rho, \phi_0, \kappa, d_z, \tan\lambda \ \right)^{\mathrm{T}}.$$

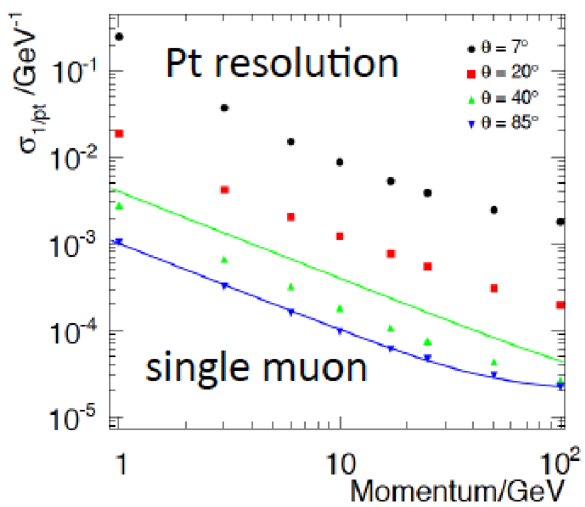
- Kalman filter: prediction + filtering

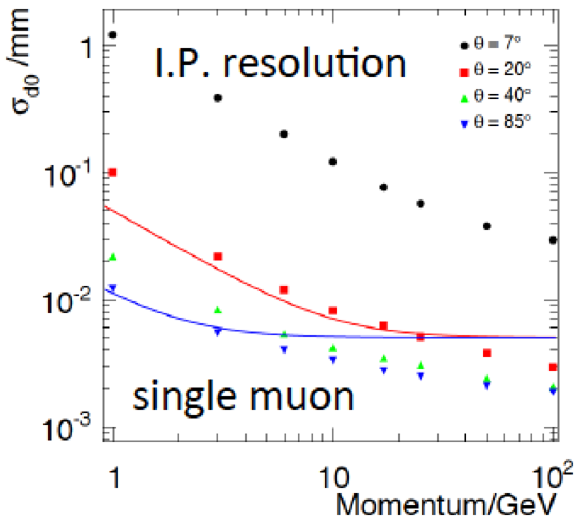
  - KalTest was put into ILCSoft svn repository in 2010, since then this package was used in both physics simulation (MarinReco) and large prototype TPC study (MarlinTPC).

Tracking performance





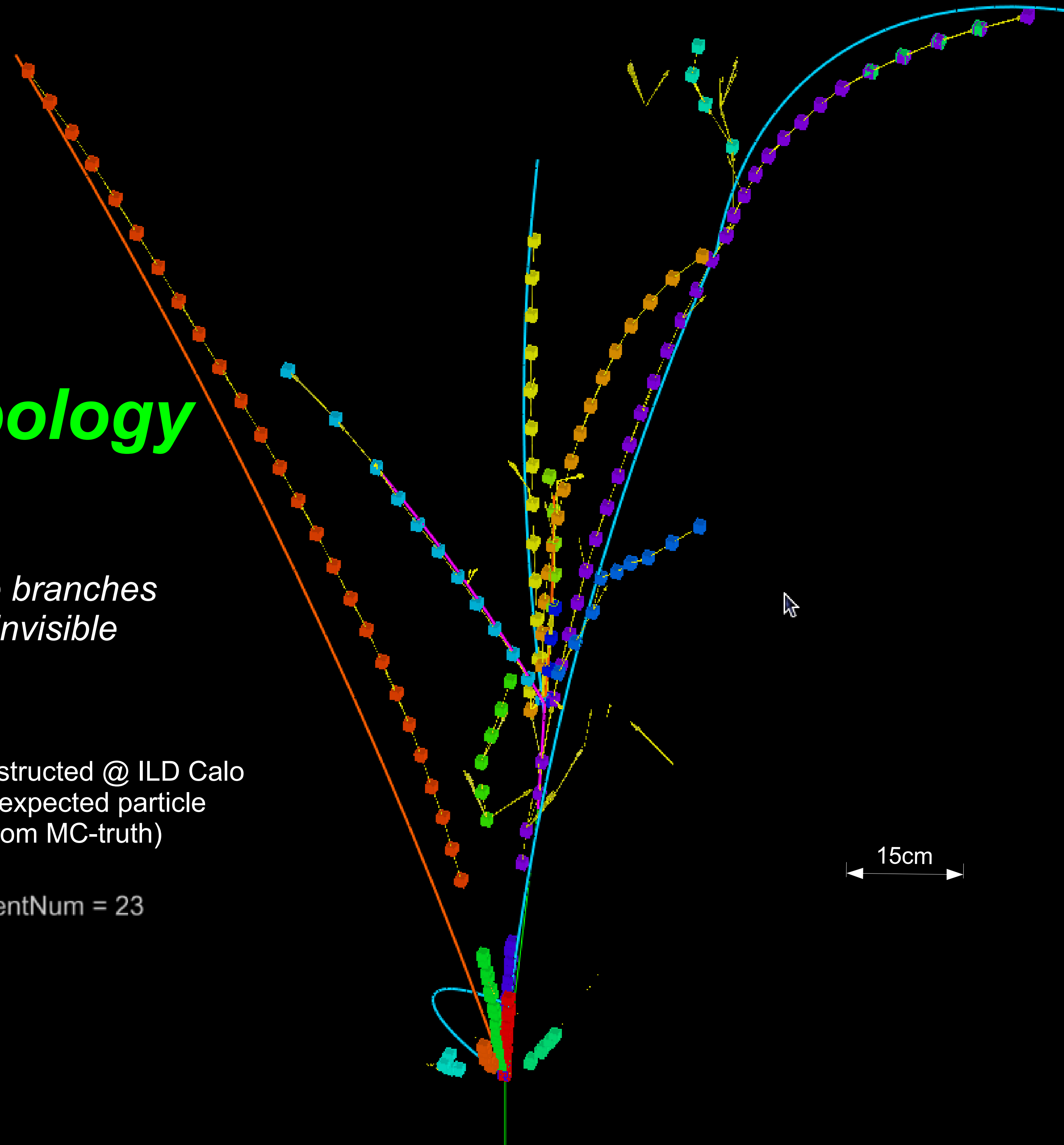




Clustering
Calorimeter hits → clusters

Tree Topology

Except some branches might be invisible

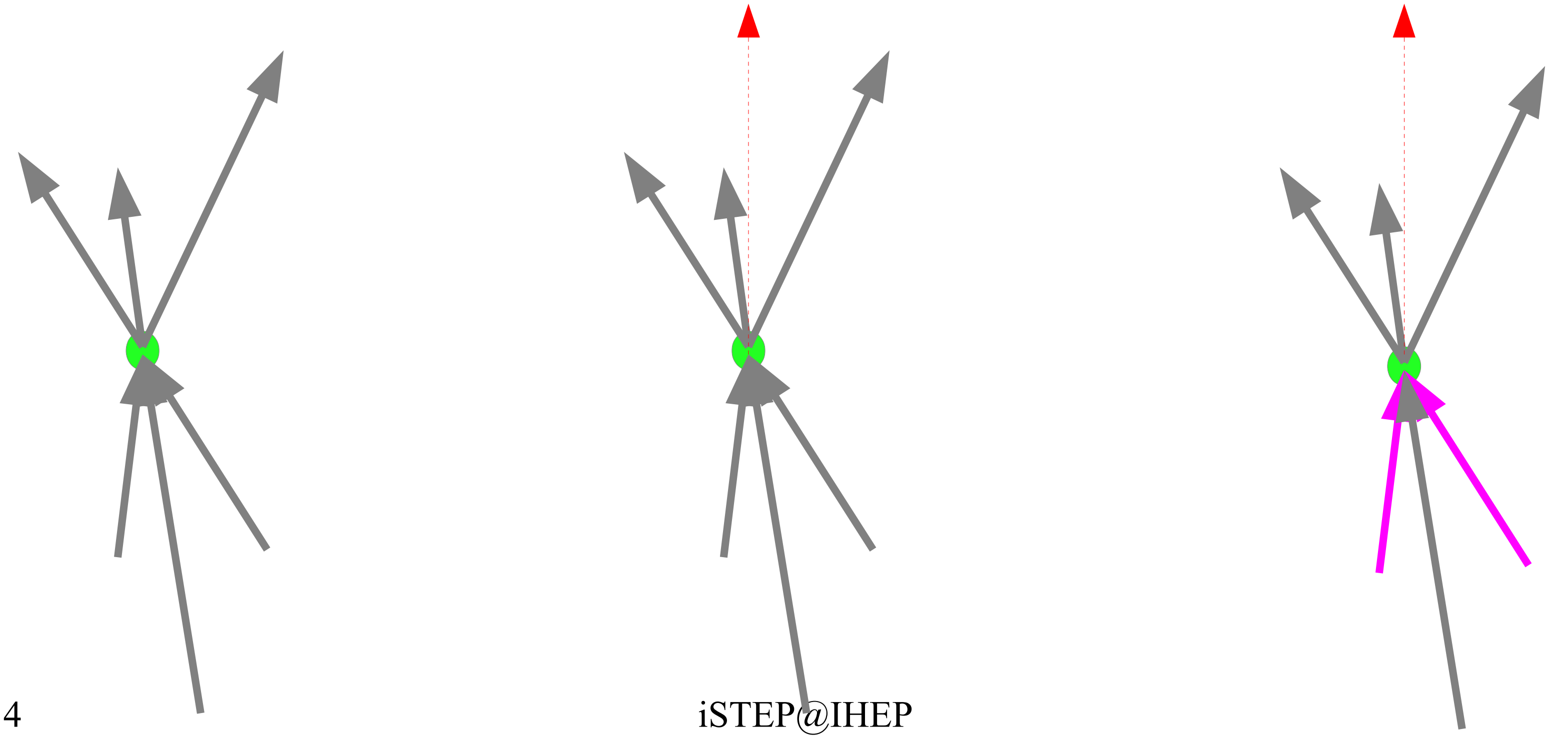


20 GeV Klong reconstructed @ ILD Calo
Curves indicating expected particle trajectories (from MC-truth)

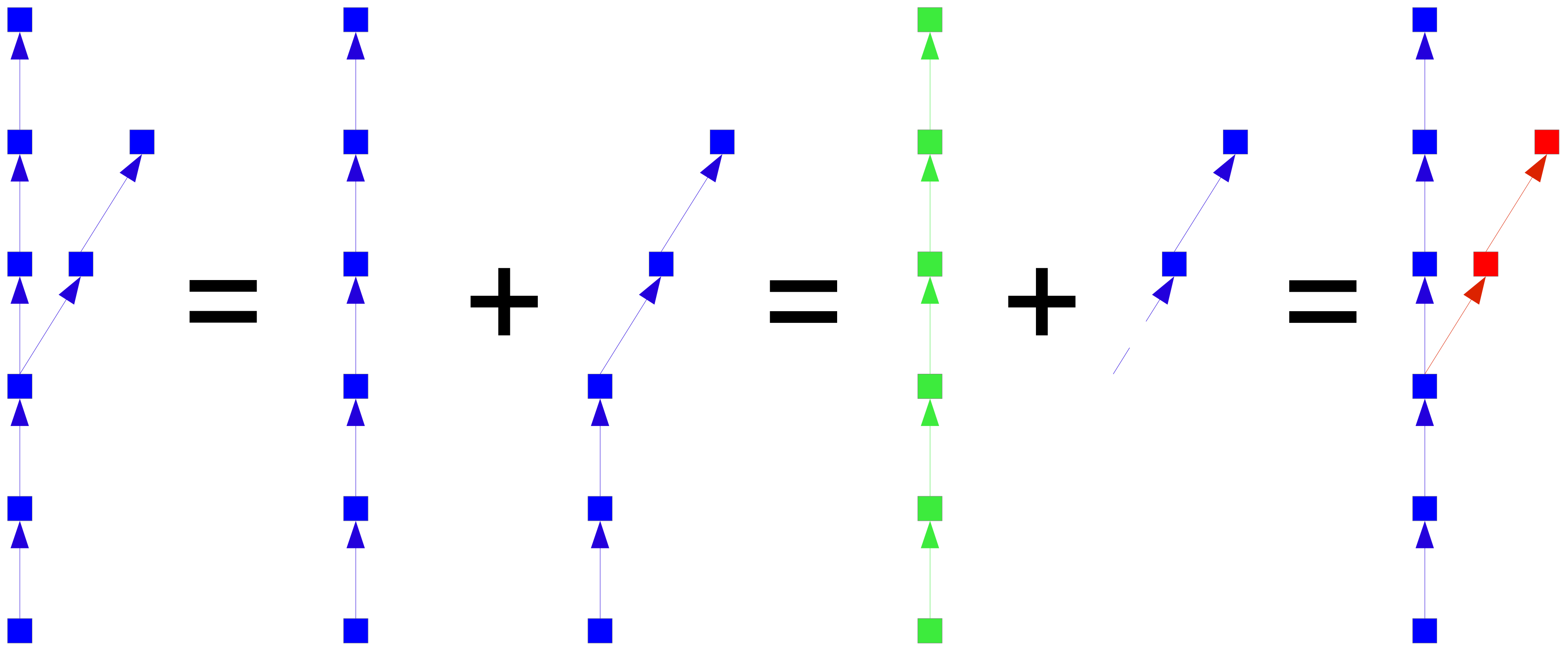
DRUID, RunNum = 0, EventNum = 23

Algorithm: hits→connector set

- Preparation: hits cleaning, pre-clustering, etc
- Create connector set between hits
  - Create all possible connectors (according to geometry constrains)
  - Clean: keep at most one connector end at a given hit
  - Iterate: change geometry constrain, add new connectors, and clean

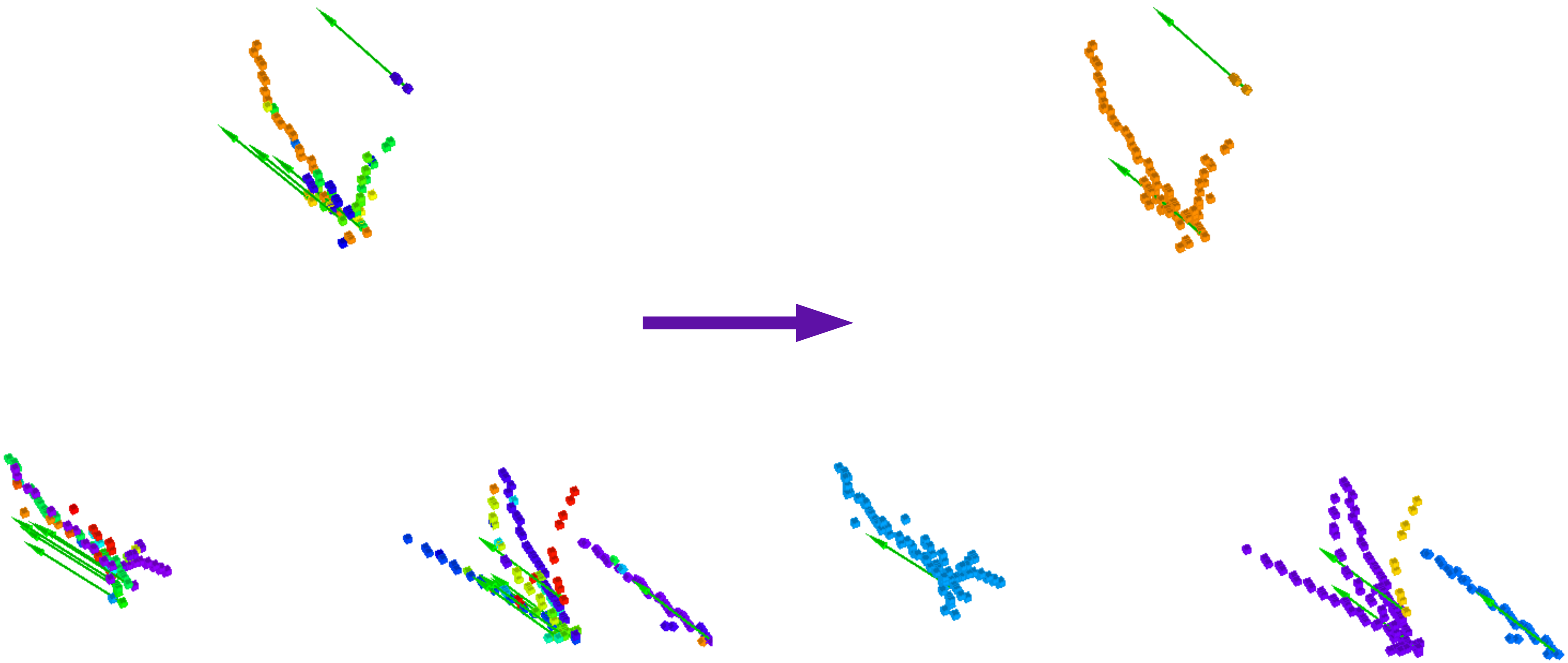


Algorithm: connector → branch

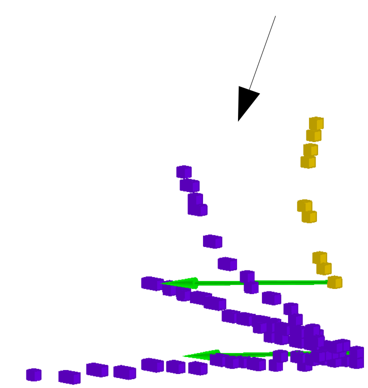


- Tag the unique branch set from connectors
  - Create all the possible branches (*from leaves to seed*)
  - Loop the branches with length order, flag hit, end the branch at the flagged hits

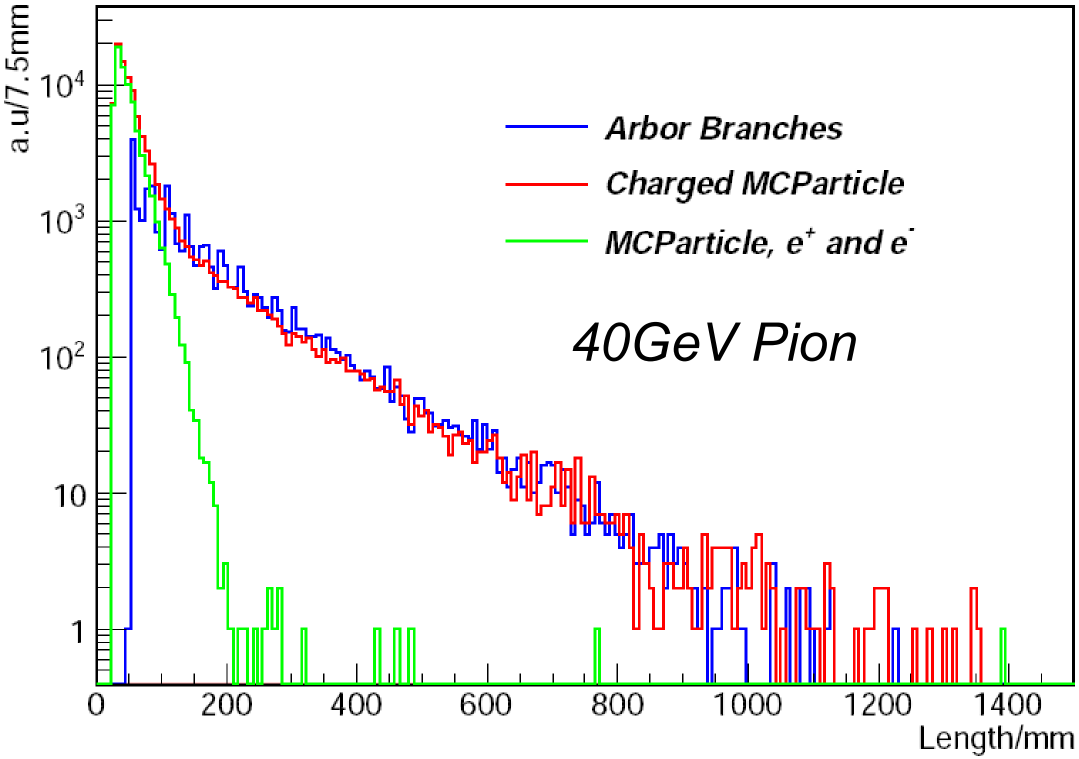
Algorithm: branch→tree

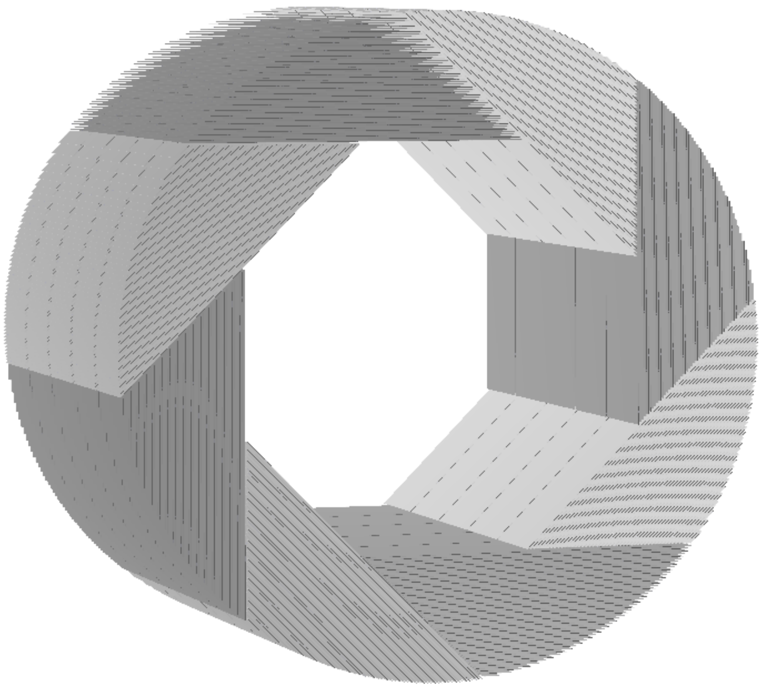


- Link branches to trees according to spatial distances
  - *Point distance, curve distance, projective distances...*



Validation: Arbor Branch Length (ABL) Vs MC Truth

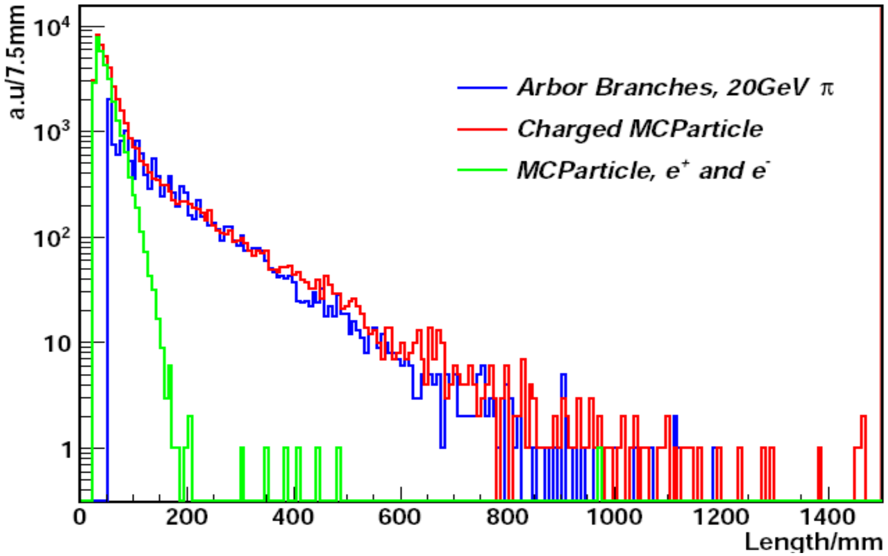




Arbor: successfully tag sub-shower structure

Samples: Particle gun event at ILD HCAL (readout granularity 1cm² & layer thickness 2.65cm)
Length:
Charged MCParticle: spatial distance between generation/end points
Arbor branch: sum of distance between neighbouring cells

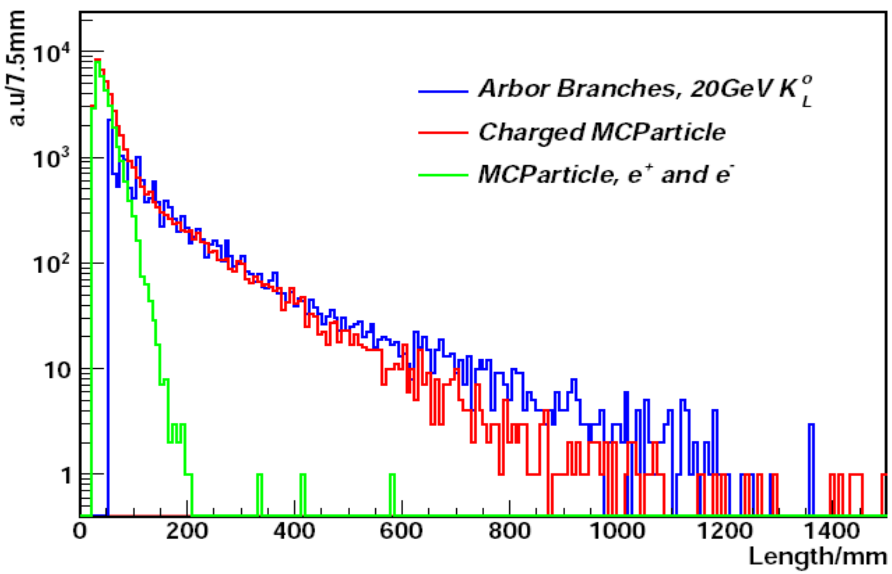
ABL @ different energy

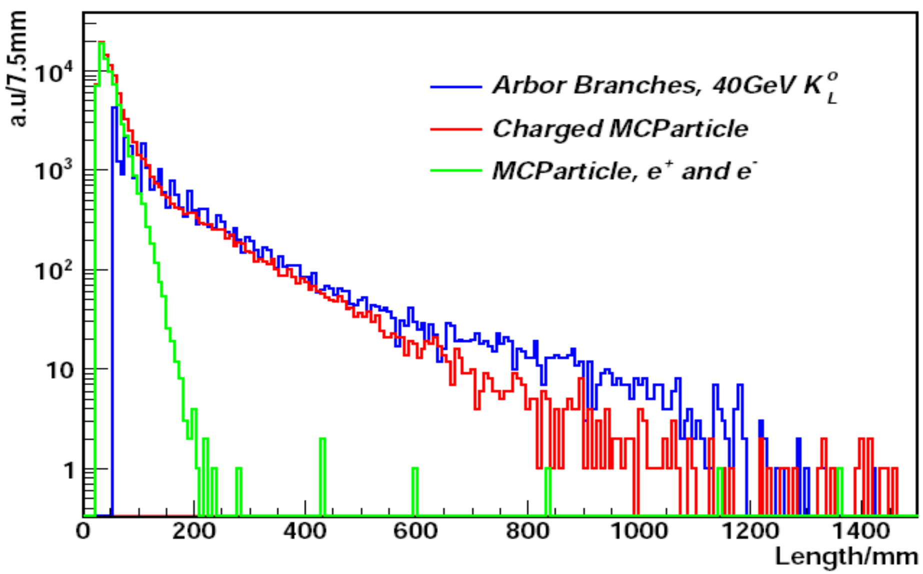


Arbor leading branches (geometrically allowed longest branch):

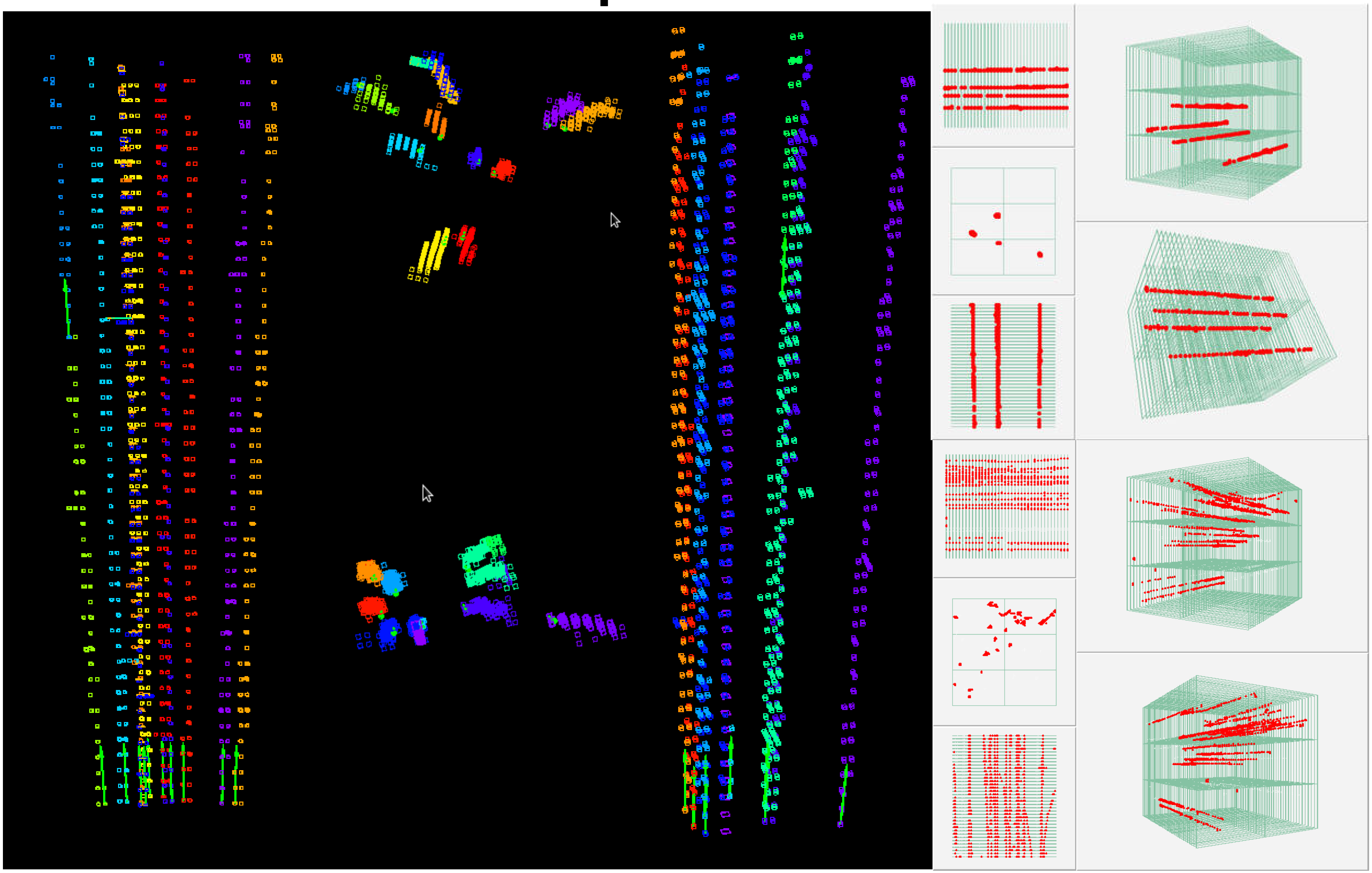
vetoed for pion shower (identified as the branch start at first layer)

cause bump at large length for klong shower

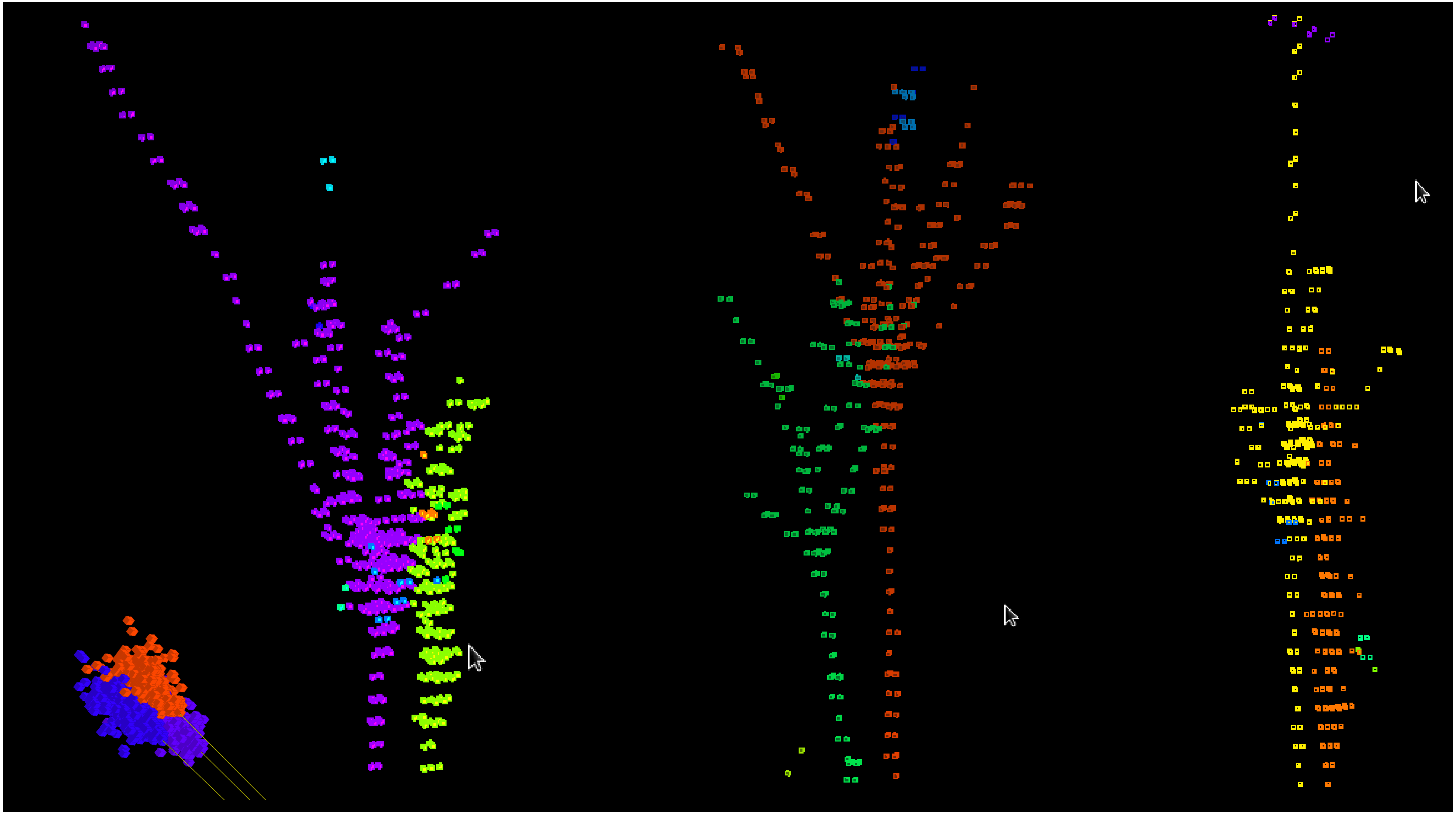




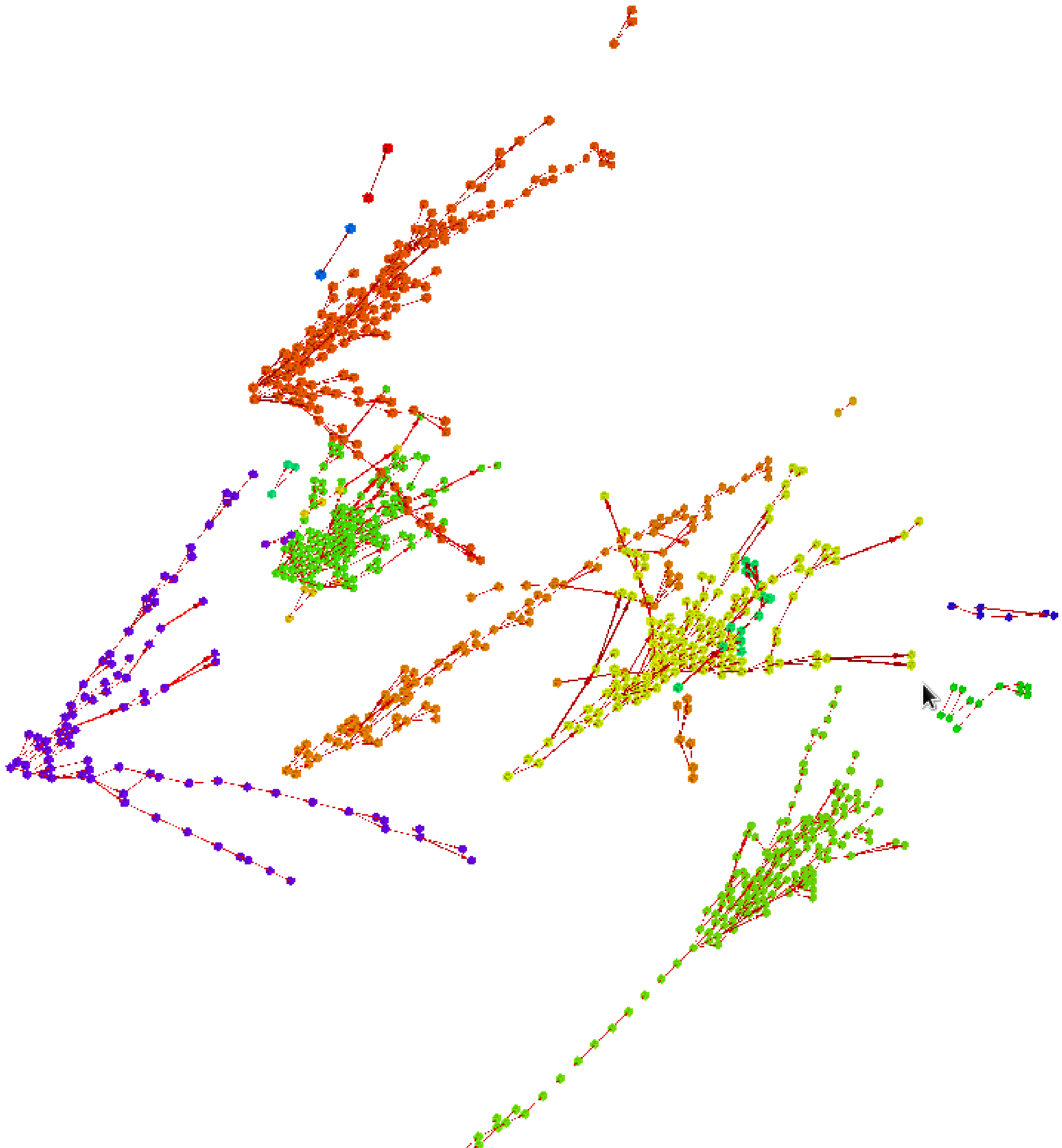
Separation: multiple muon

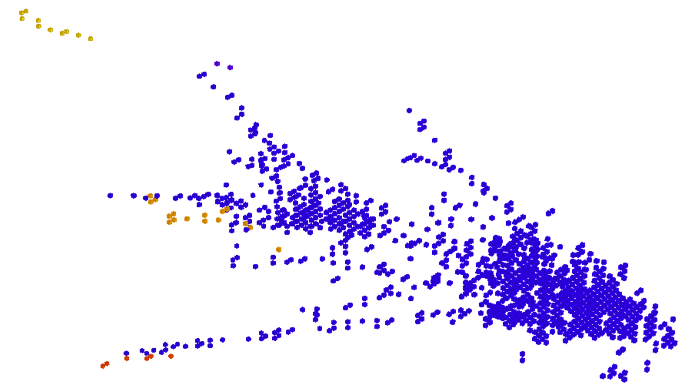


Separation: overlay showers

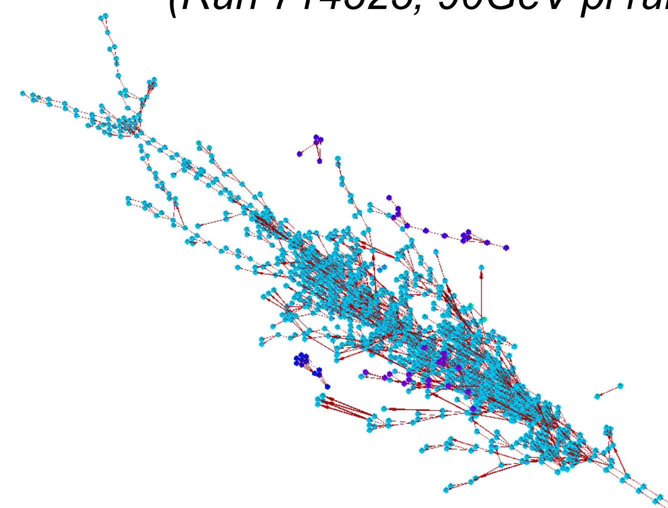


Test beam data



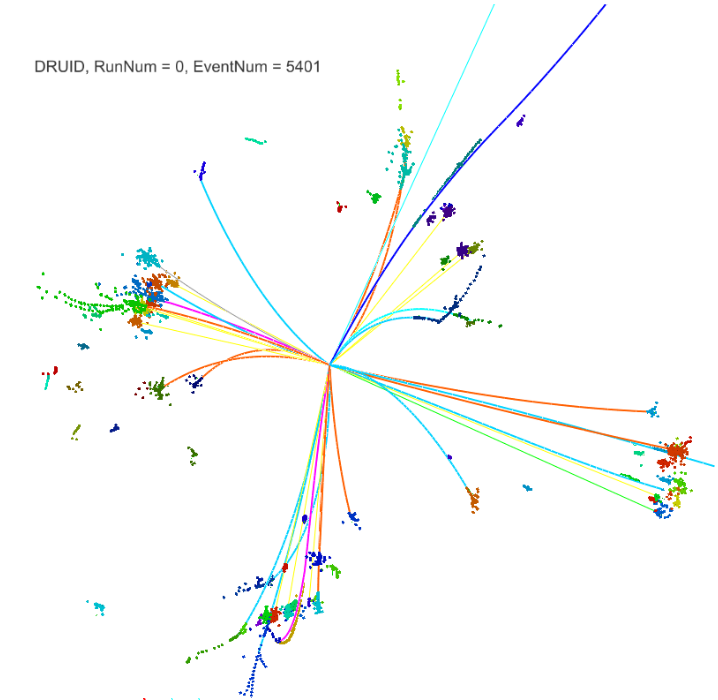


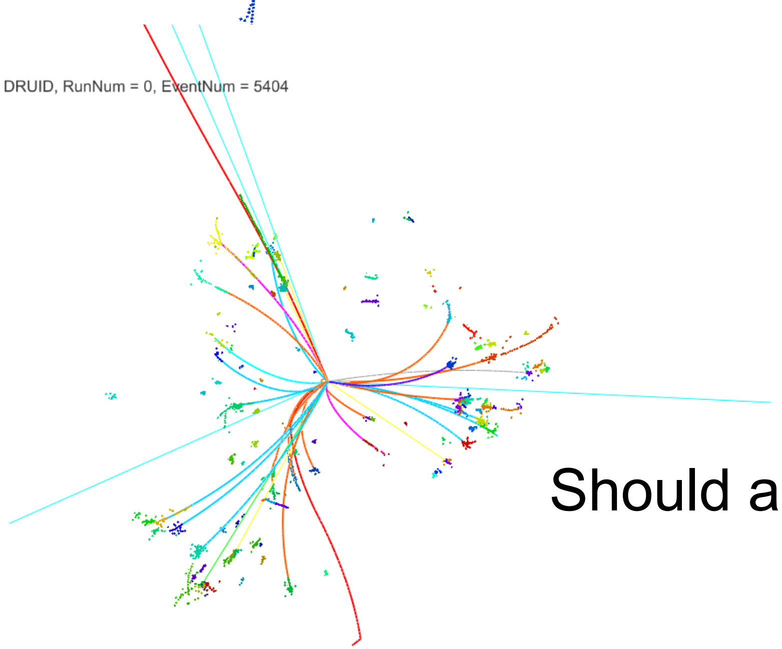
Connected tree +
small isolated bushes
(Run 714525, 90GeV pi run)

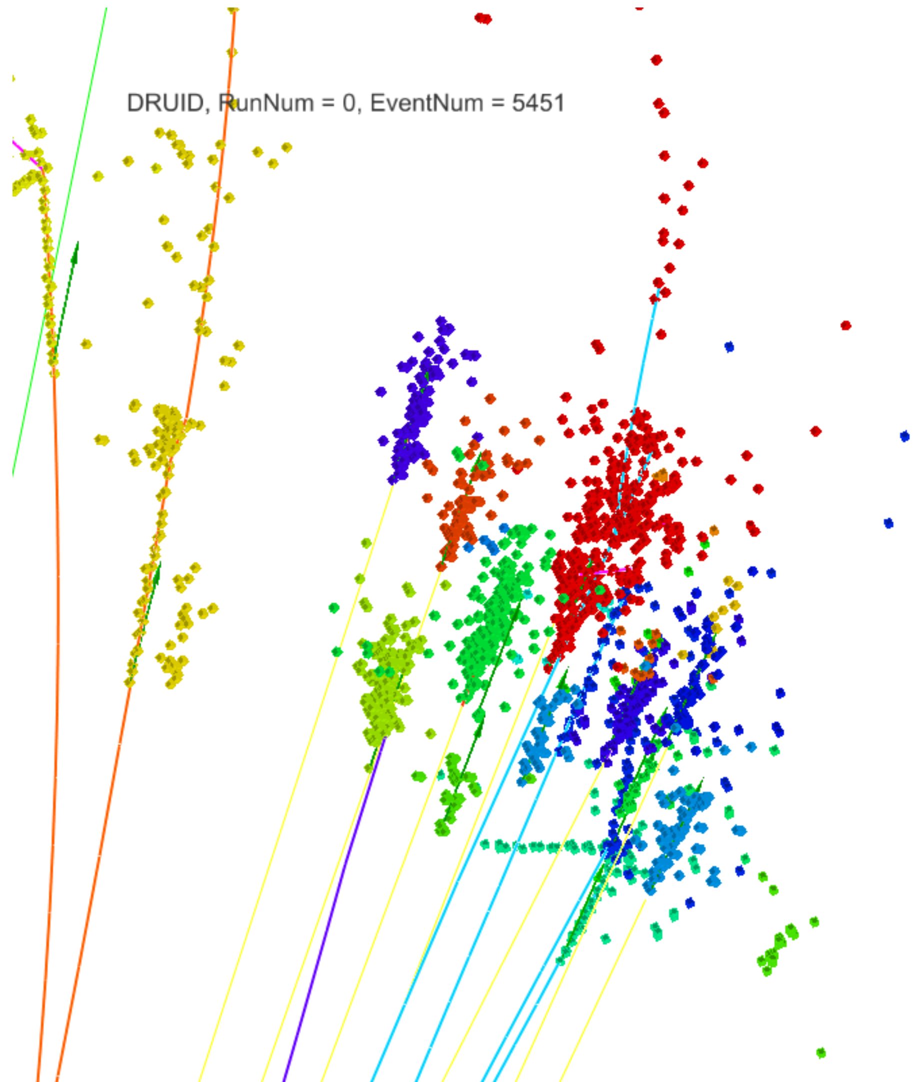


Matching:
tracks + clusters → reco-particles

Reconstruction with Arbor

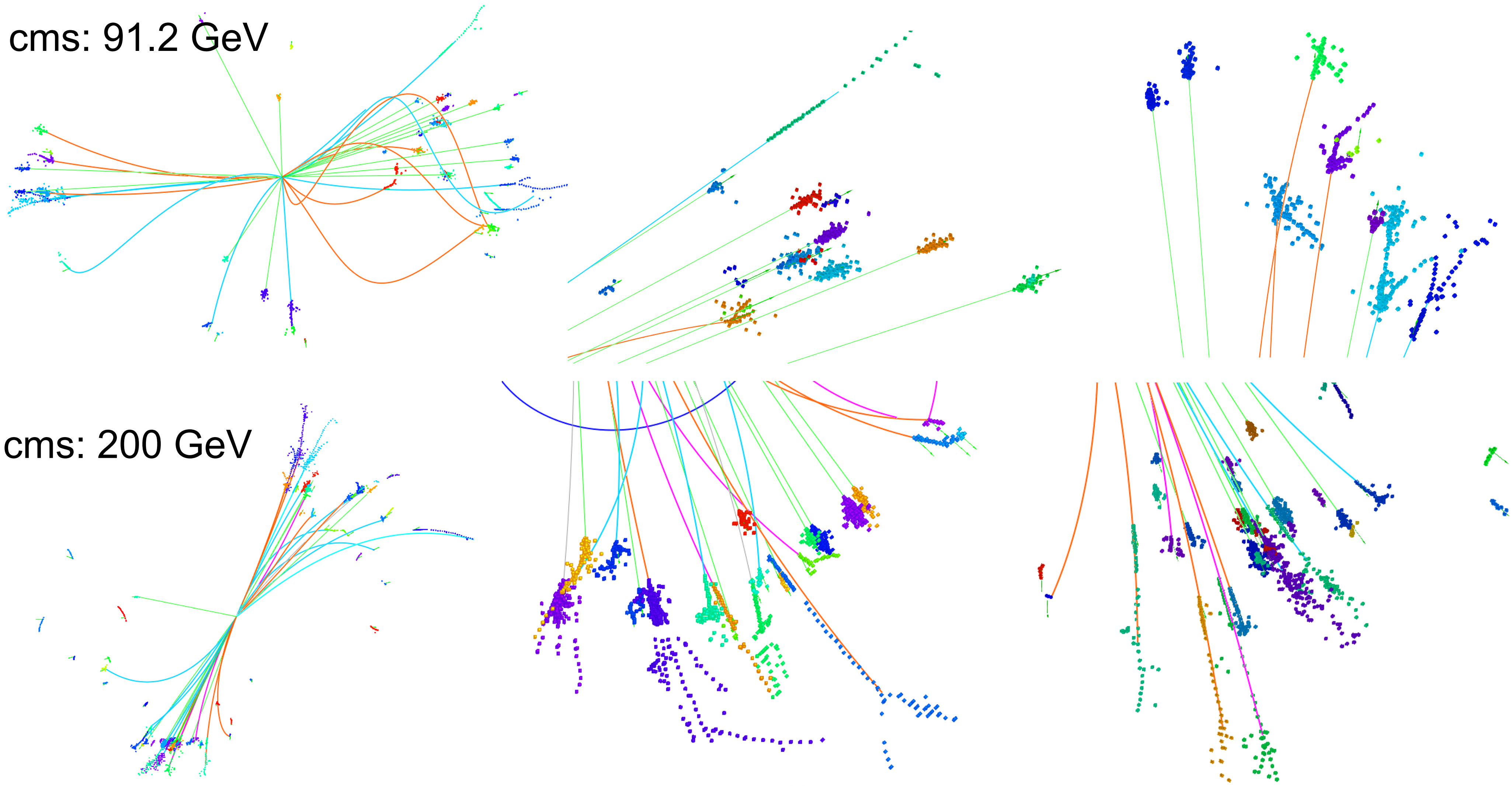






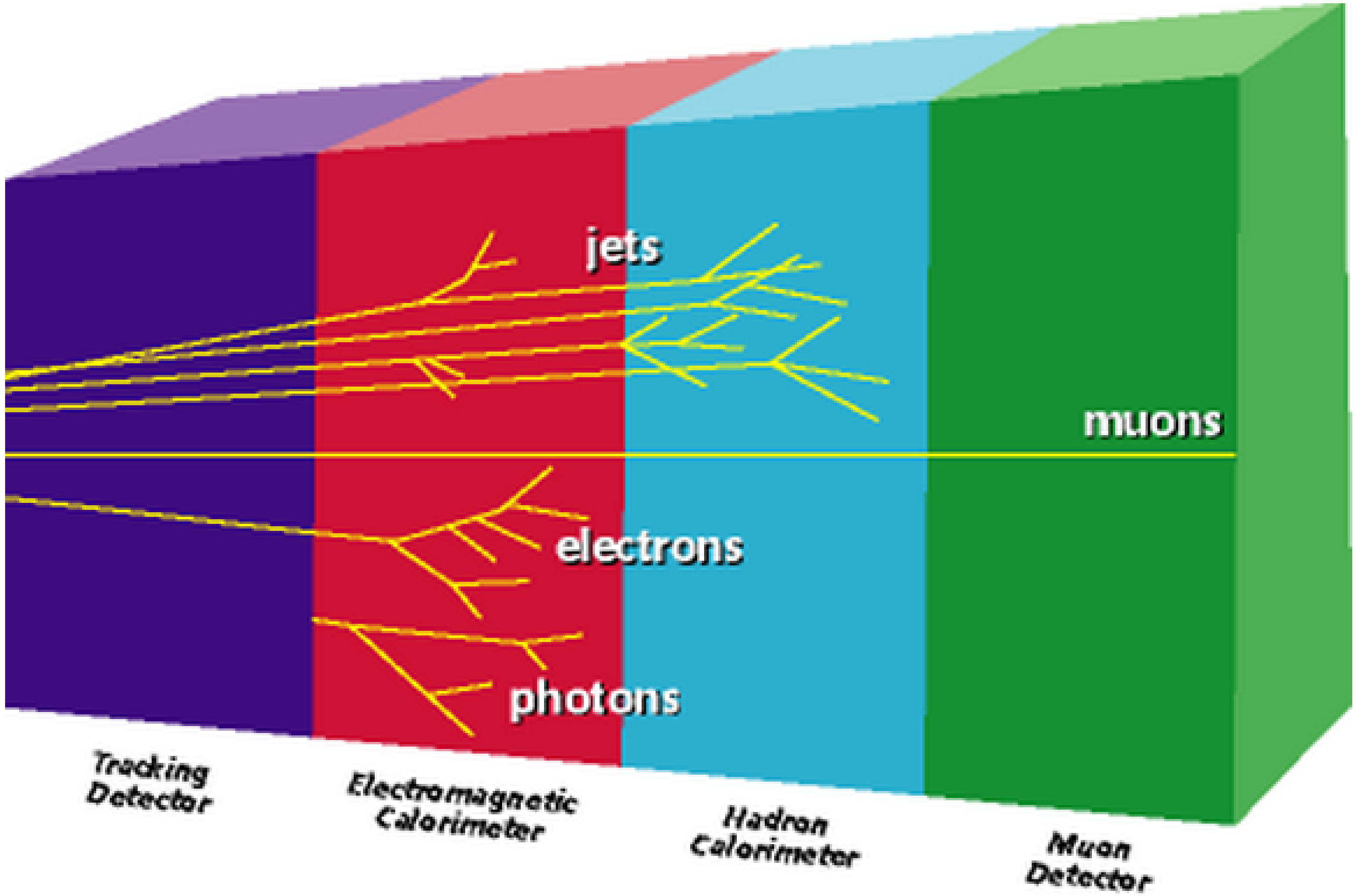
Should a track be linked with a/some cluster(s)?

Jet: qq event



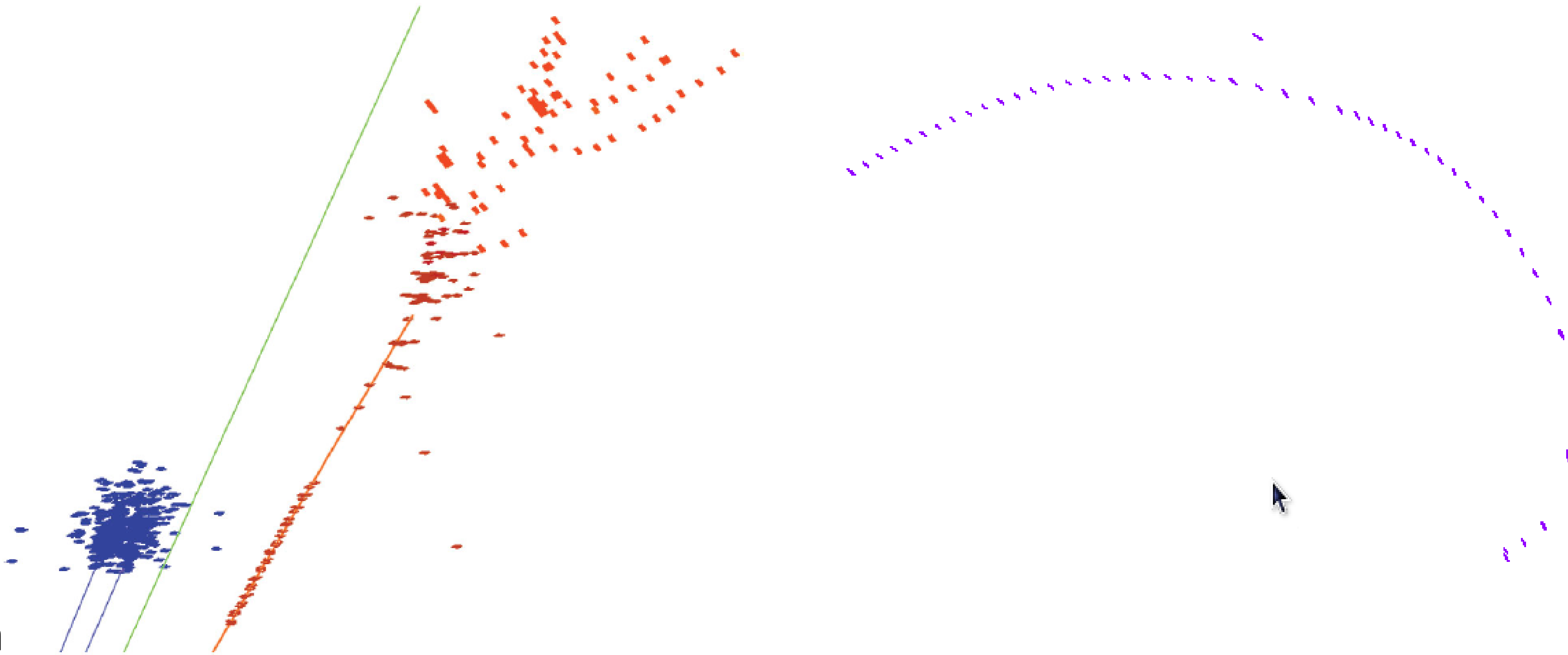
Identification & Measurement

Different particles act differently...



As shown above

Clue for particle identification

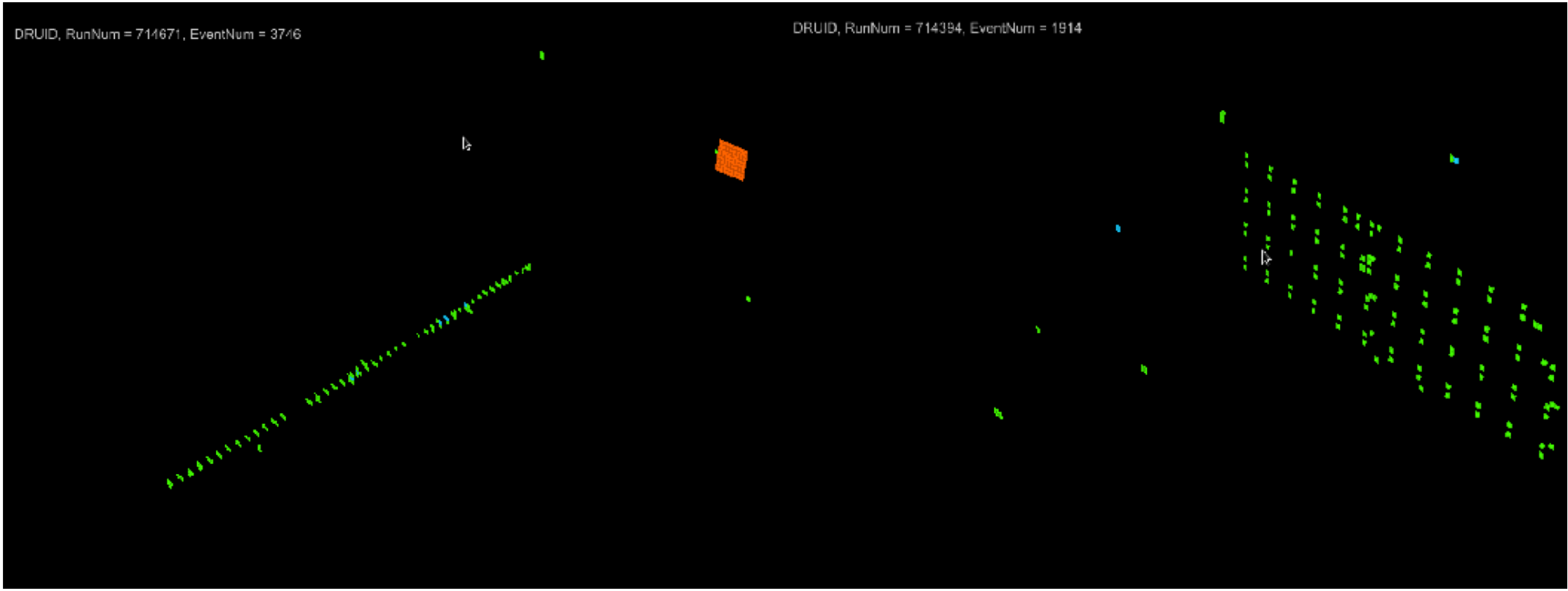


Tracker Information

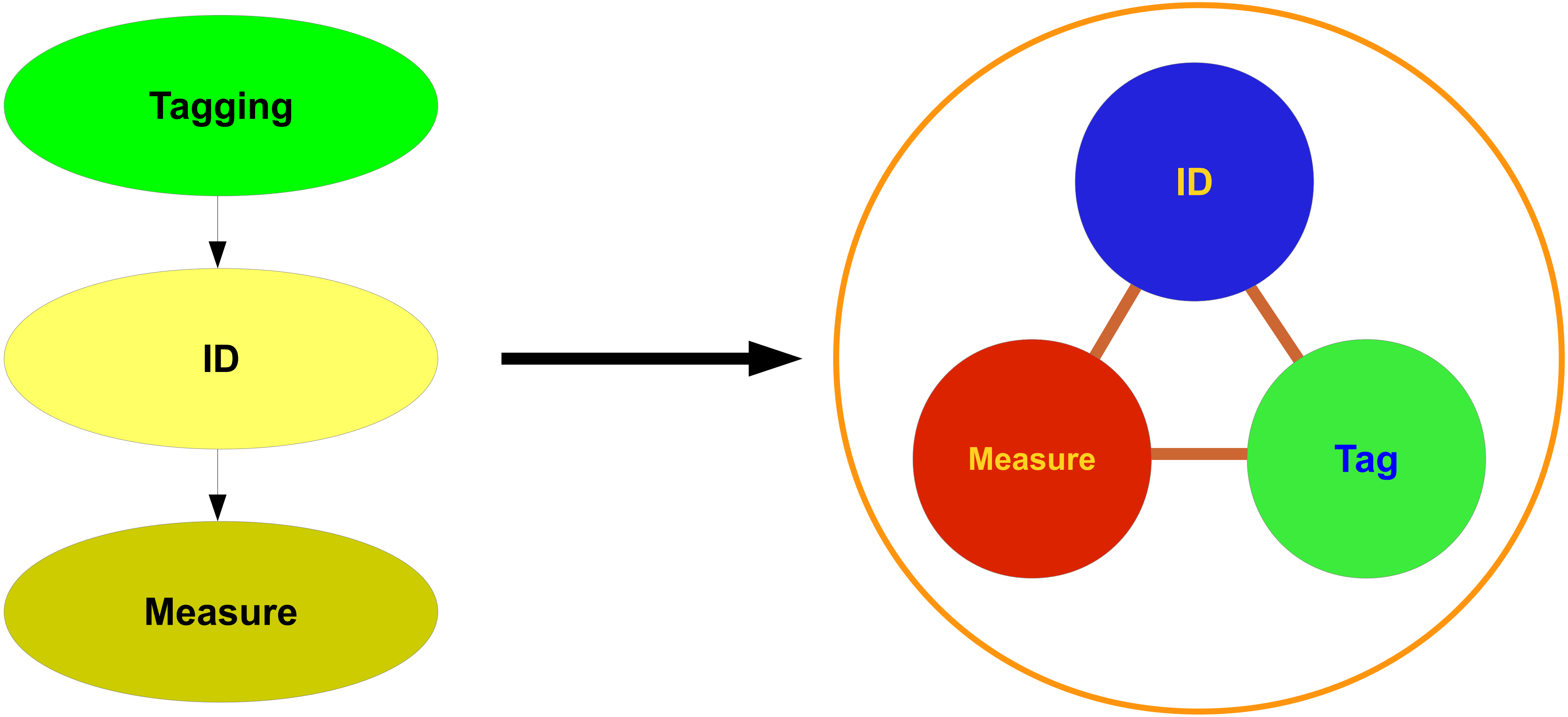
	EM	Had	MIP	Fragments	Noise
Charged	Electron & Positron	Pion, kaon, etc	Muons, etc		
Neutral	Photon	Neutron, Neutral Kaon, etc	Highly un-likely		

Calorimeter Information

In Real data: Noise & Fragments...

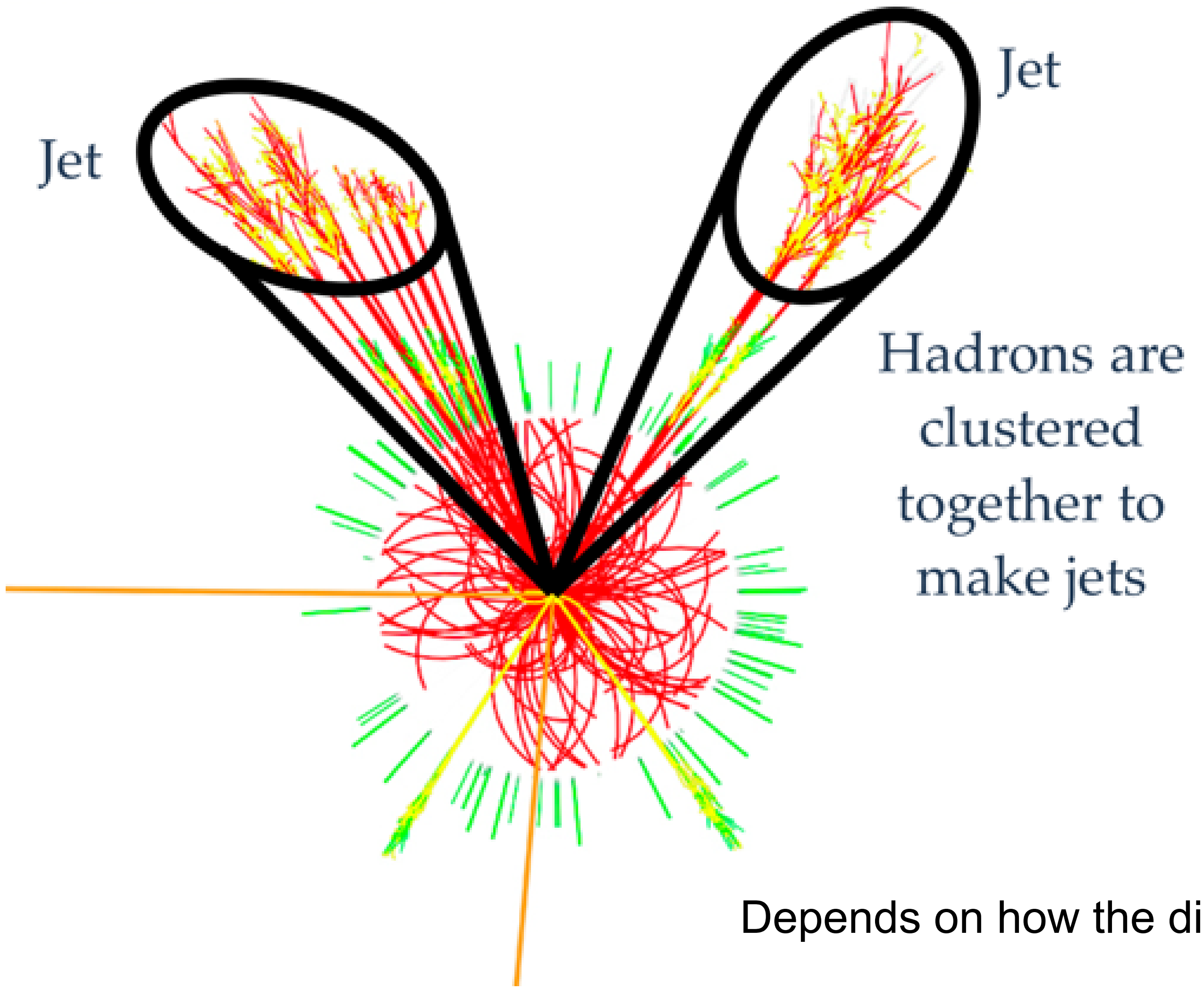


Iterations



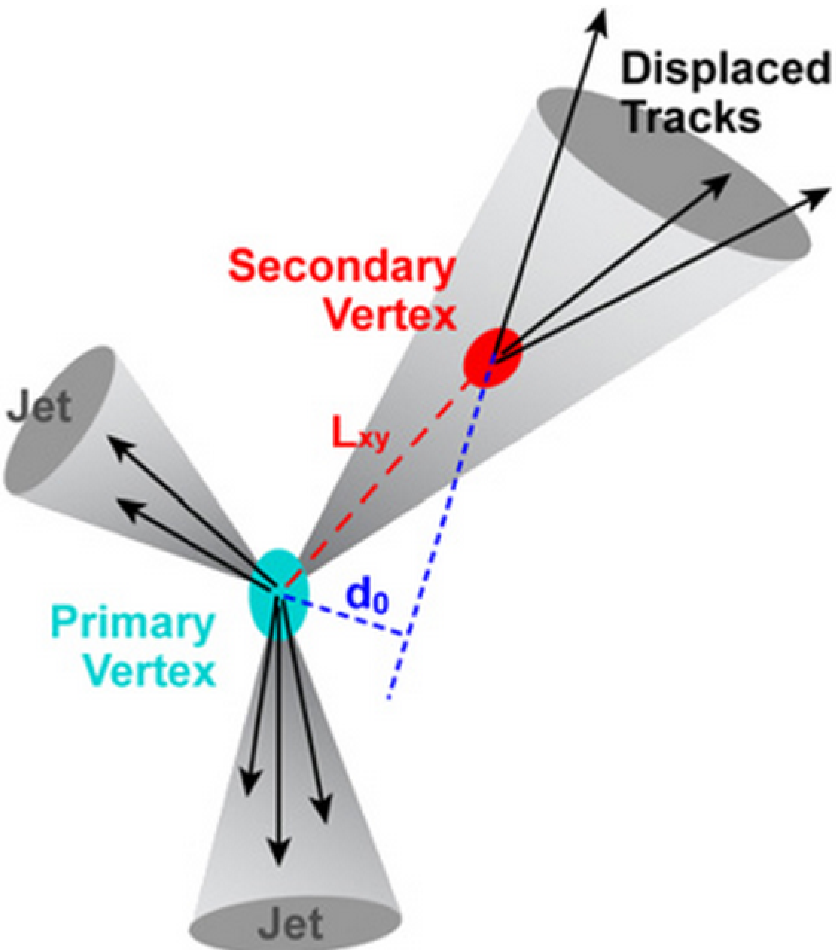
Jet Clustering & Flavor tagging: final state particles → jets with tagged flavor

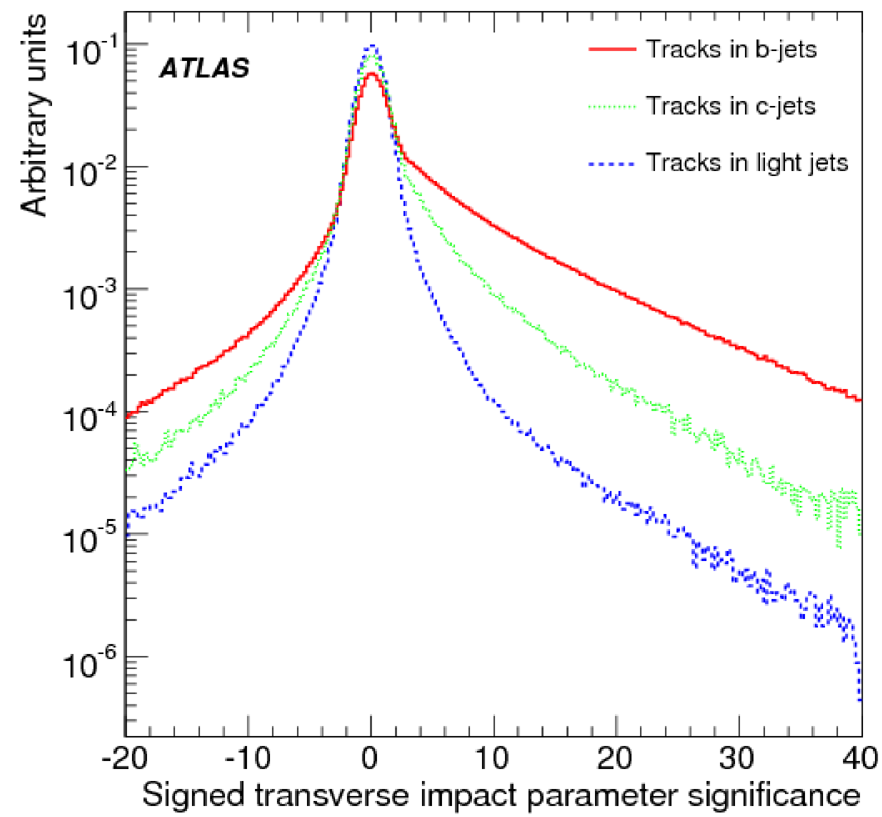
Grouping final state particles into Jets



Depends on how the distance is defined

Flavor tagging



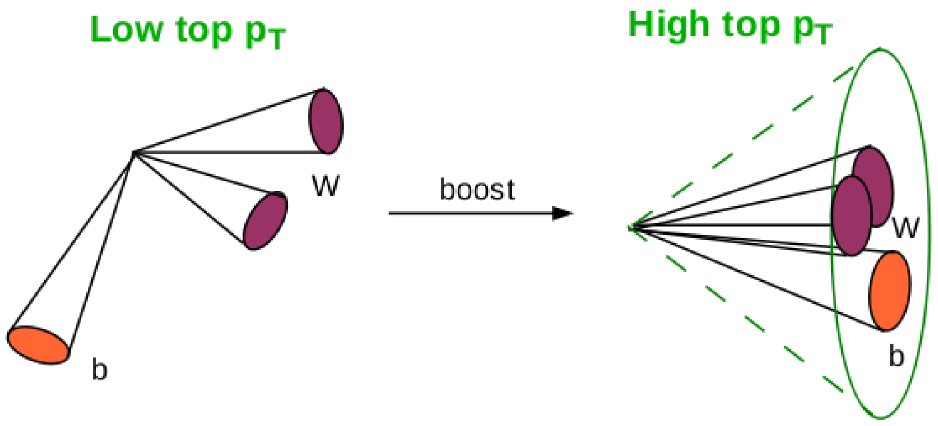


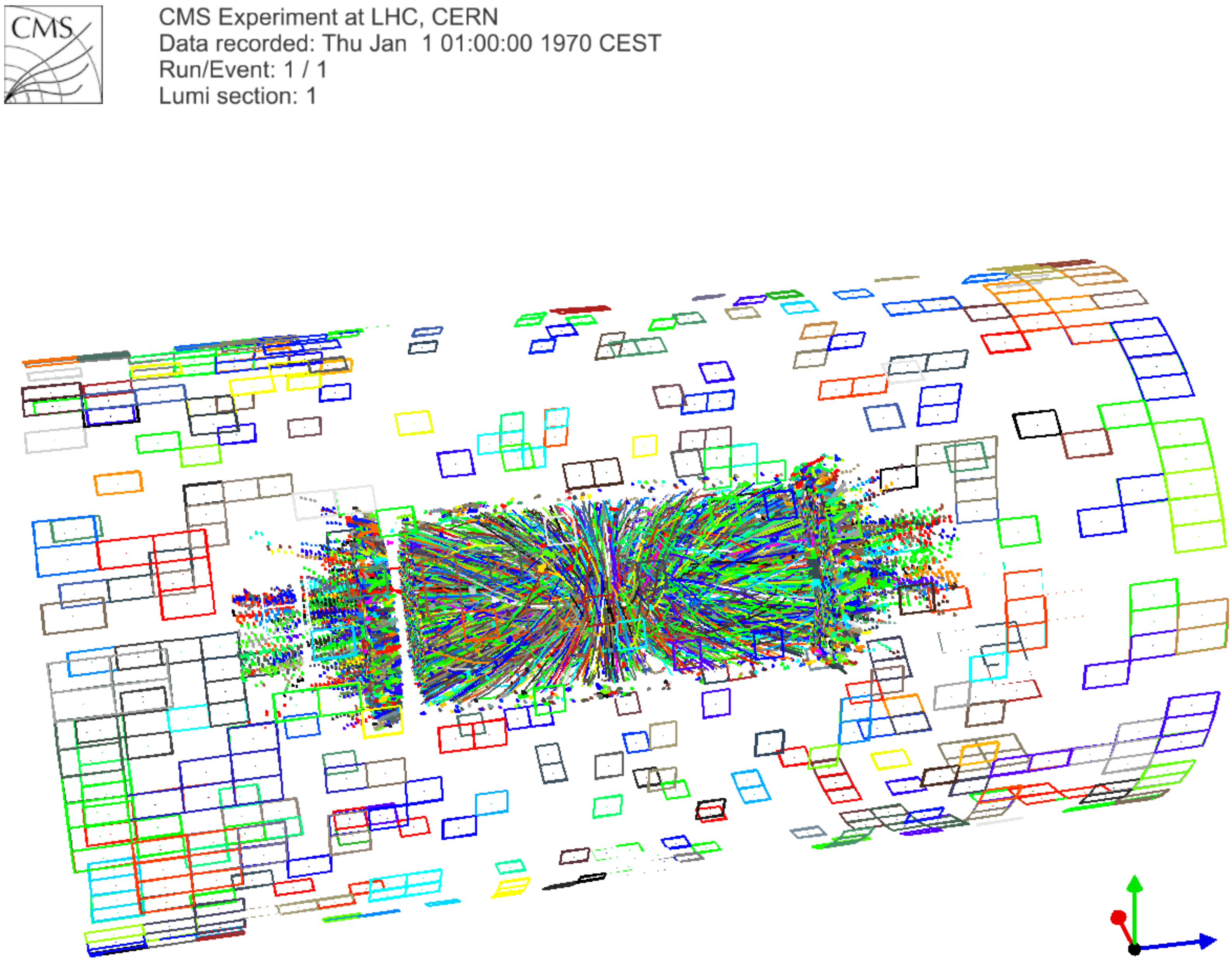
b, c quarks have non-vanishing cτ;
Many other information might be used

Once Reconstructed: Portal to the analysis...

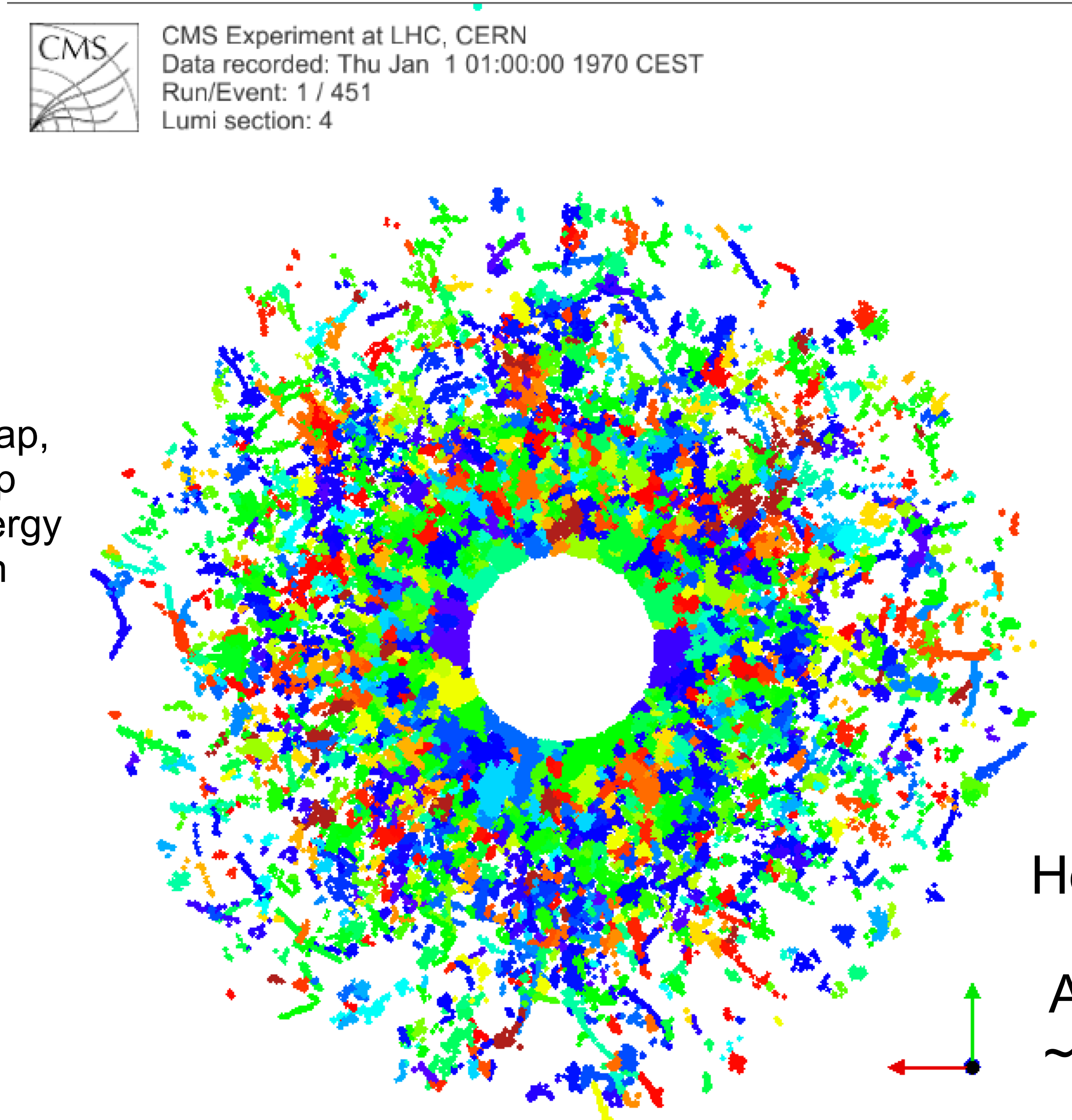
Some challenges for the future

- For electron positron machine:
  - Balance between different performance requirements & cost
  - Tuning & optimization
- For proton-proton machine:
  - Feasibility at
    - high pile-up
    - high occupancy
    - extremely noisy environments
  - Tagging & Identification of highly-boosted objects
  - ...
- Iteration with detector design & optimization




CMS
CMS Experiment at LHC, CERN
Data recorded: Thu Jan 1 01:00:00 1970 CEST
Run/Event: 1 / 1
Lumi section: 1

14 TeV
CMS End Cap,
140 Pile up
~ 70 TeV energy
deposition



How would it be,

At 100 TeV with
~ o(100 - 1000)
Pile Ups?

Summary

- Reconstruction: indispensable bridge between Detector signal & Physics analysis
- Detector design/Reconstruction algorithm development are based on basic particle-matter interactions, including ionization, electromagnetic shower & hadronic shower
- Particle Flow Principle: pointing to the ultimate goal of reconstruction: measure each final state particle to the best precision
  - Emphasize on the separation, tagging, identification
  - Eventually leads to much better measuremnts
- Future: Lots of challenges, and fun

Pillars of reconstruction

- Tracks: made from tracker hits, though tracking
- Clusters: made from calorimeter hits, though clustering
- PFA: Taking Tracks & Clusters as input, match clusters and tracks, identify the nature of those signals by pattern recognition, and output the reconstructed particles