Reconstruction

>> Event reconstruction <<

The process of interpreting the electronic signals produced in a high-energy physics (HEP) experiment's detector to determine what original particles passed through the detector and their characteristics.

>> Event reconstruction <<

- Tracking and Vertexing
  - Hit Point
  - Track Finding
  - Track Fitting
  - Vertex Fitting
- Particle ID
  - Electron and Photon
  - Muon
- Jet Identification
  - Identification of b-jets

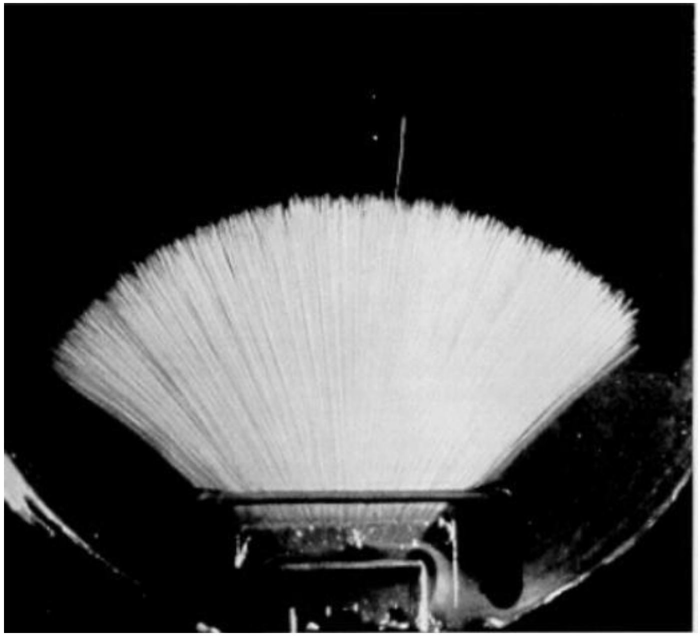
Track Reconstruction

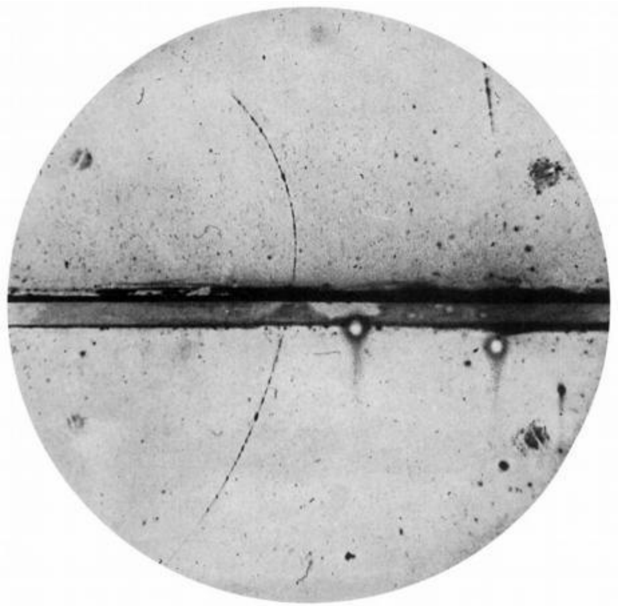
(Slides are reused from https://indico.tlabs.ac.za/event/112/contributions/3196/attachments/1062/1453/MM_Tracking_TIPP_2023.pdf)

Tracking Systems in 'Old Days'

At the beginning of particle physics, the techniques for observing particles were developed together with the physical ideas about them.
Most techniques were based on optically observing their paths and recording them by photographs.

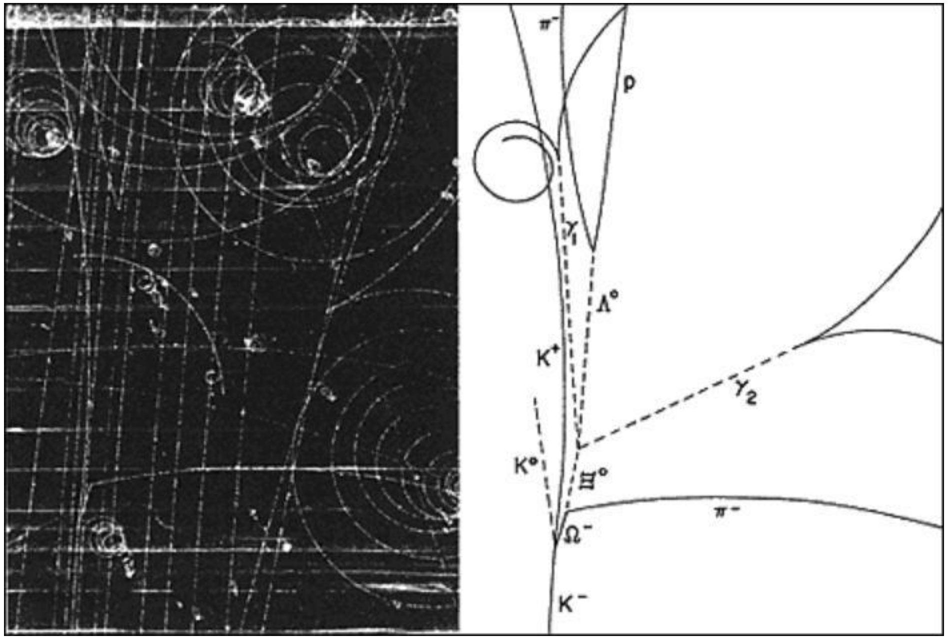
A first tracking detector was the cloud chamber invented by Wilson in 1910: Particles traverse supersaturated water/alcohol vapor. The e^-/ion pairs in the track act as condensation nuclei.



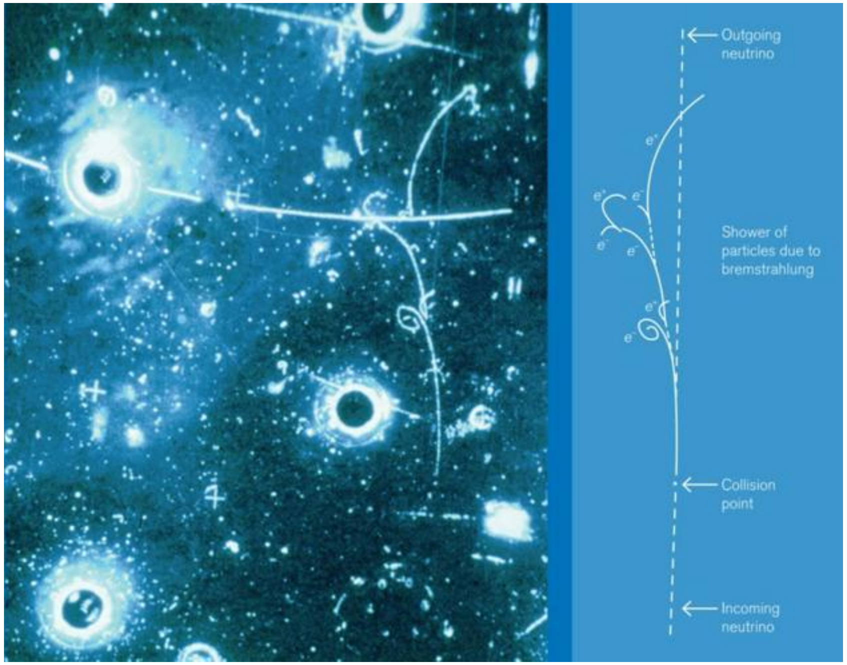


Bubble Chambers

The bubble chamber was invented by D. Glaser in 1952 (NP 1960). Particles traverse a superheated liquid and the deposited energy creates bubbles → Photos are made.



Discovery of the Ω^- in 1964



Discovery of Neutral Currents

General Requirements for a Tracking System

Some general statements can be made on general requirements of a tracking system:

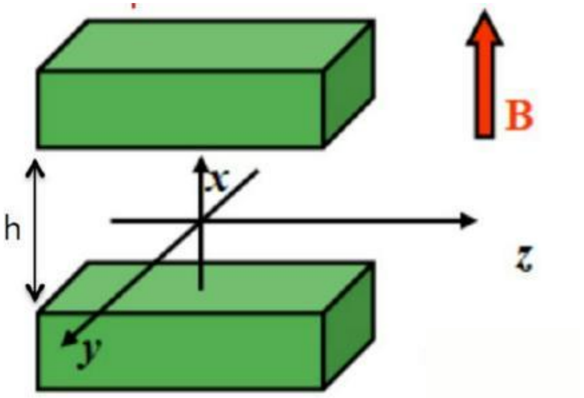
- Detect charged particles with high efficiency
- Precise measurement of particle track (direction, origin, etc)
- Momentum measurement
- Determining the sign of the charge, possibly also the charge itself
- Particle identification for example by dE/dx
- Study impact parameter, that is the distance of the track to the expected point of collision
- Robust measurements in environments with many tracks
- Operation for a long time, in particular also able to stand a lot of radiation without aging
- Cheap

Experiment specific requirements will often surpass these.

Magnet Field Configurations

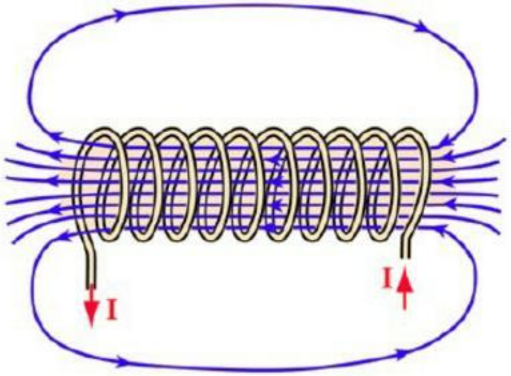
In HEP experiments three field configurations are used:

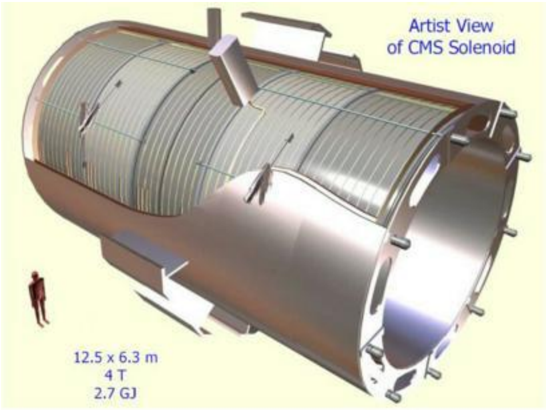
1) Dipole fields
(for fixed target
experiments)



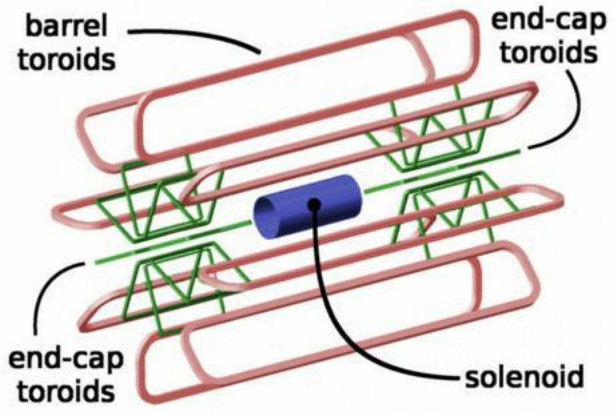

BGO in Bonn

2) Solenoidal fields
(for collider experiments)





3) Toroidal fields
(for muon system of
collider experiment)



Track Parameters in B-fields (I)

In magnetic fields, the particle path can be derived starting from the Lorentz force:

$$\vec{F}_{Lorentz} = m\dot{\vec{v}} = q\left(\vec{v} \times \vec{B}\right)$$

Assuming a homogenous B field, which can be directed along the z axis allows to solve for v:

$$\vec{v}(t) = \begin{pmatrix} v_T \cos\left(\eta\omega_B t + \psi_0\right) \\ -v_T \sin\left(\eta\omega_B t + \psi_0\right) \\ v_z \end{pmatrix}$$

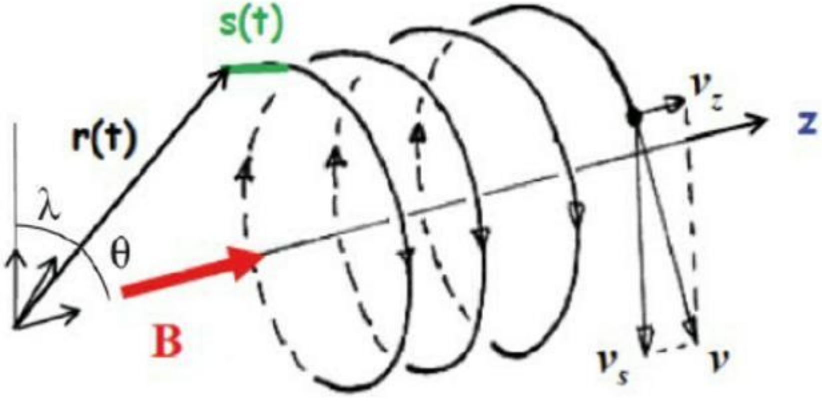
with $\omega_B = |q|B/\gamma\, m$, $\eta = q/|q|$, and $v_T = \sqrt{v_x^2 + v_y^2}$

Integration gives

$$\vec{x}(t) = \begin{pmatrix} x_0 + \frac{v_T}{\eta\omega_B} \sin\left(\eta\omega_B t + \psi_0\right) \\ y_0 + \frac{v_T}{\eta\omega_B} \cos\left(\eta\omega_B t + \psi_0\right) \\ z_0 + v_z t \end{pmatrix}$$

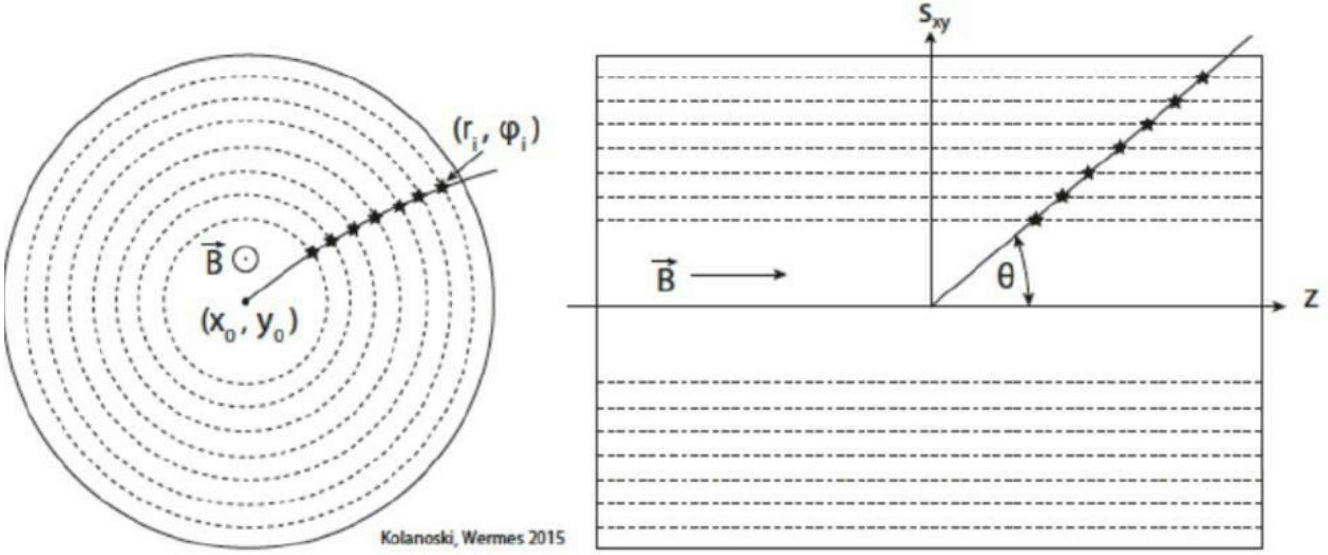
=> Helix trajectory

with 6 parameters x_0, y_0, v_T, η, ω_B, ψ_0



Solenoidal Setup

The calculation for *dp/p* is completely analog to the sagitta method



Kolanoski, Wermes 2015

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{det} = \frac{p_T}{0.3|z|}\frac{\sigma(x)}{BR^2}\sqrt{\frac{720}{N+4}}$$

1) Momentum resolution improves quadratically with radius
2) Momentum resolution improves linearly with the B-field
3) Detectors with better spatial resolution helps
4) Number of track points also improves the result
5) $\sigma(p)/p$ increases with p → more difficult to measure high energetic tracks

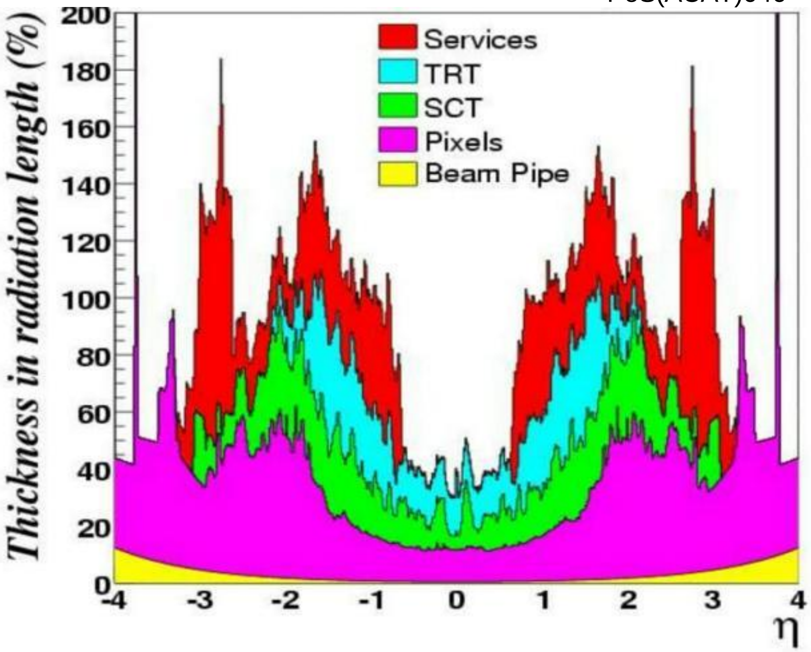
Example ATLAS TrackingPerformance

The estimate of $\left.\frac{\sigma_{p_T}}{p_T}\right|^{det} = 0.0004 \cdot p_T$ fits well with the official detector

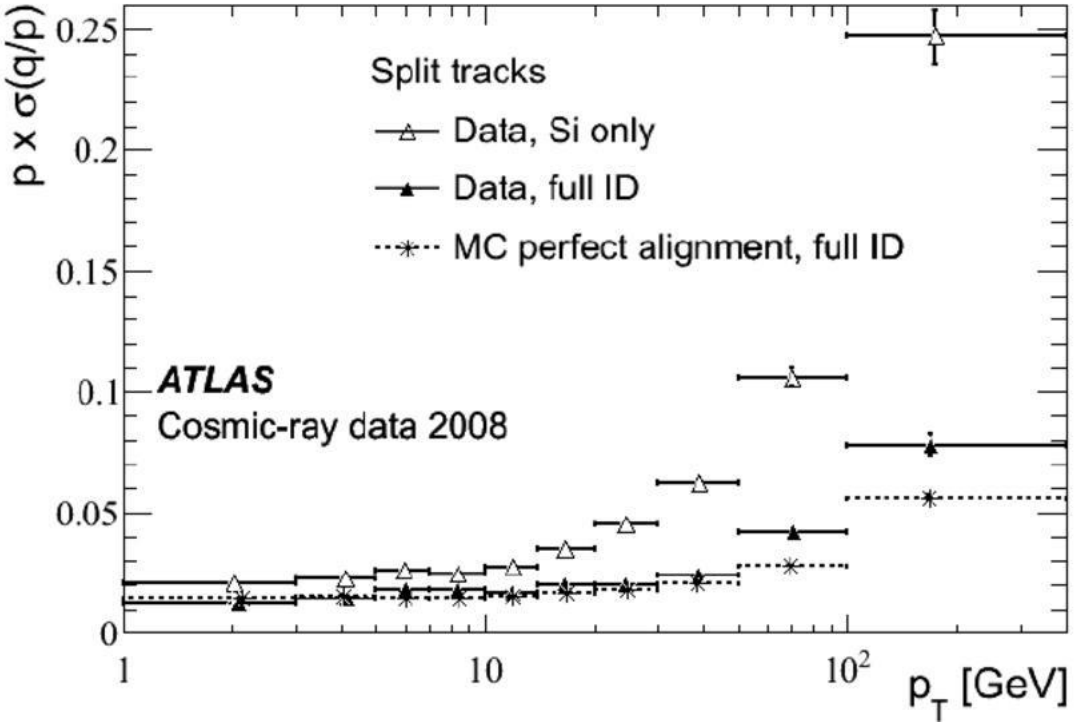
requirement of $\sigma_{pT} / p_T = 0.05\%\ p_T\ (\mathrm{GeV/c}) + 1\%$

The additional 1% is given because of the material budget of the inner detectors:

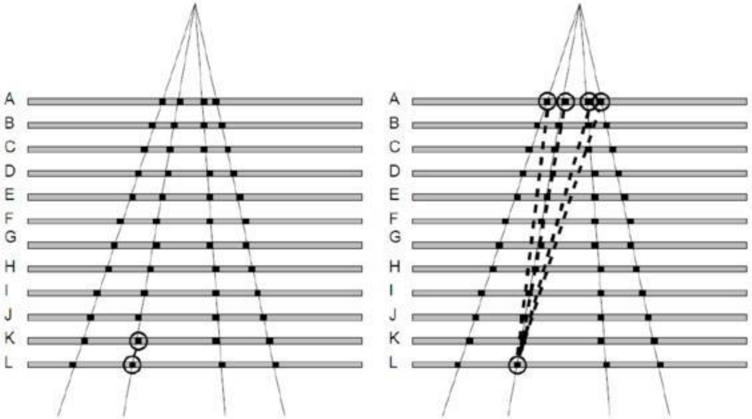
PoS(ACAT)046



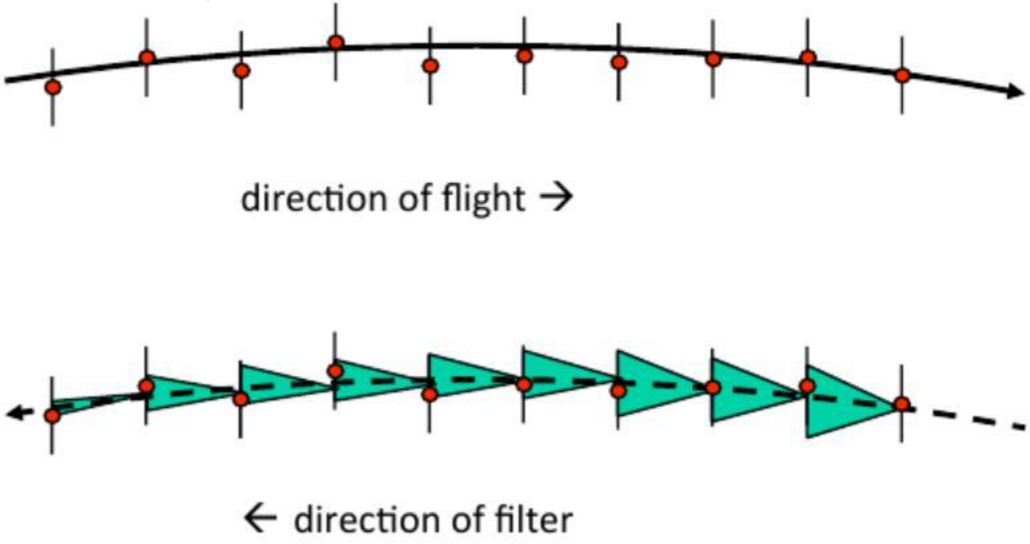
arXiv:1004.5293v2



KF for Track Finding



1) **Find a seed track**: This is often a combinatorial approach using the 2-3 outermost layers and an inner layers of measurement. The outside is chosen, because tracks are separated and possible combinations are reduced.
2) **Make a track estimate:** Based on the currently available track points and their errors, a prediction is made for hits in the next detector layer.
3) **Looking for hit:** If hit is found, add it to track and update the track prediction for the next layer.

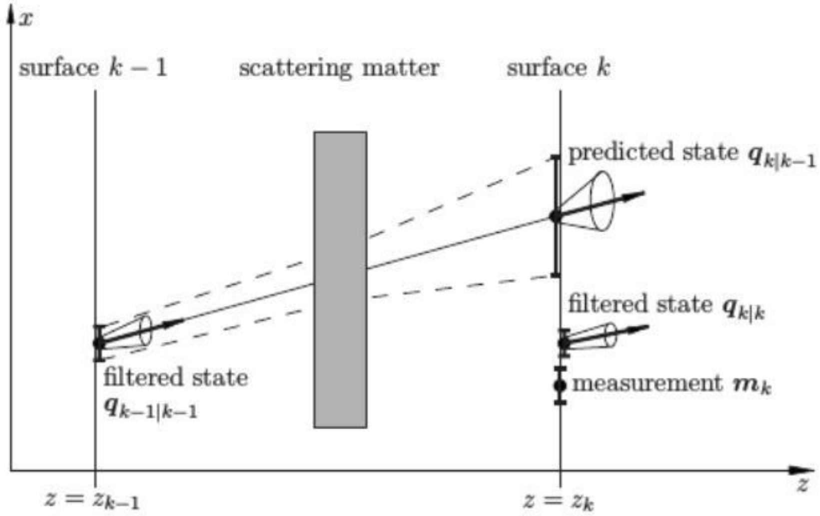


Advantages of the KF

It is easy to take detector effects into account

- Energy loss
- Multiple Scattering
- Bremsstrahlung

can be accommodated by recognizing the effect and correcting for it in the next step.



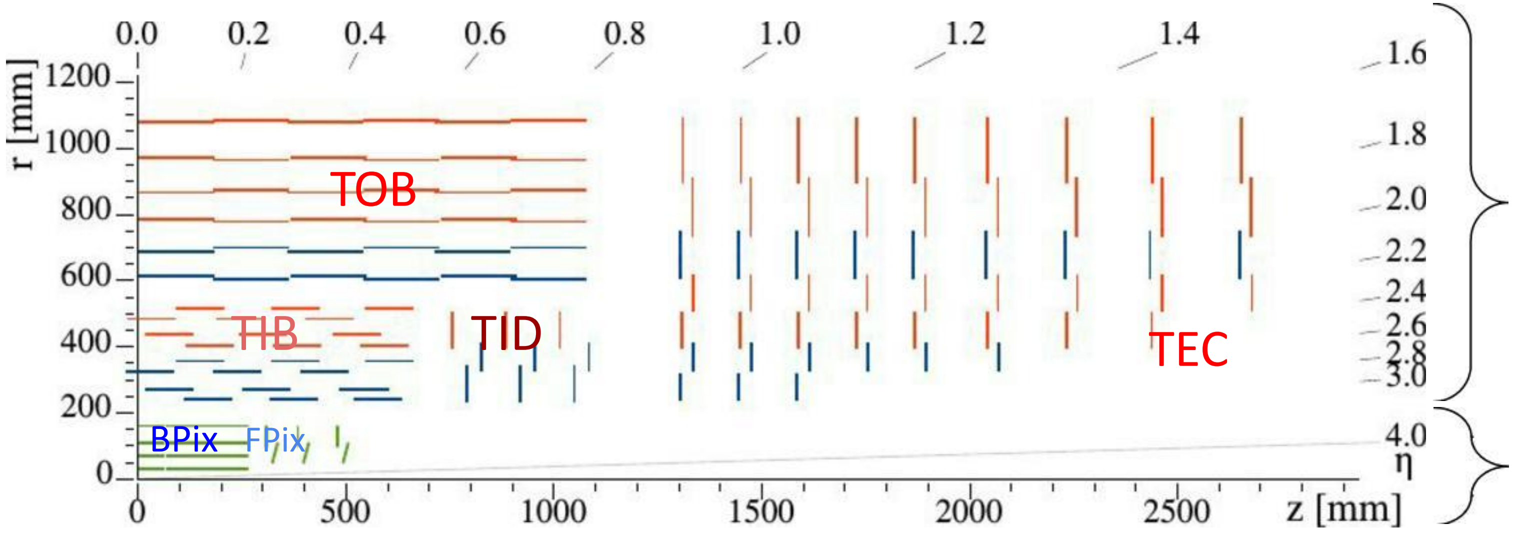
REVI. MOD. PHY., 82, 2010, 1419

A filter can be built, that stores the intermediate results of the filter
→ outliers such as noise or hits from close tracks can be identified and removed afterward.
The best parameter estimate can be given at any point.

Because of the flexibility, the algorithm is widely used for tracking objects in real time:
Radar tracking, sonar ranging, satellite orbit computation, automated driving

CMS Silicon Tracker

- All-silicon design:
  - Allows for high-precision charged particle tracking up to |η|<3;
  - Essential in particle identification, heavy-flavour tagging, trigger decisions, vertex reconstruction;
  - Largest Si tracker in the world: ~200 m^2 area, ~135M electronic channels
- Comprised of the Pixel (innermost parts)
  - 4 layers in the barrel (BPix) and 3 disk (FPix) in the forward regions:
    - 1,856 Pixel modules.
- and the Strips sub-detectors (outer parts)
  - 10 layers in the barrel (TIB, TOB) and 12 forward disks (TID, TEC):
    - 15,148 Strips modules.

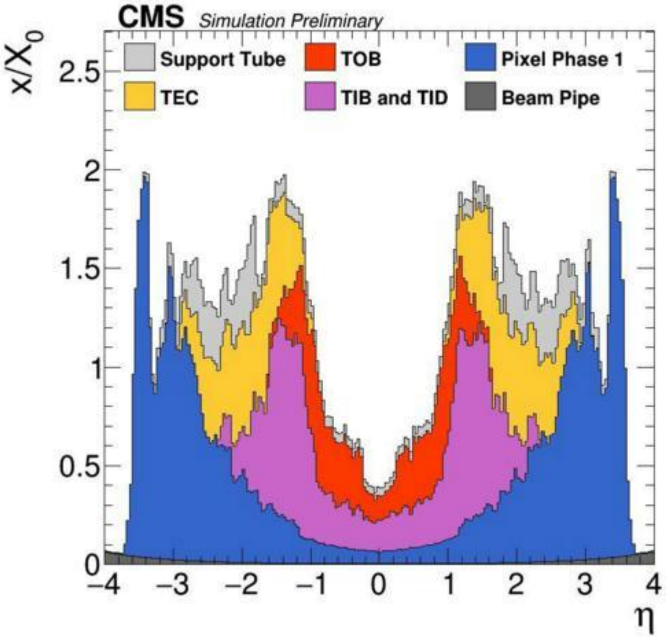


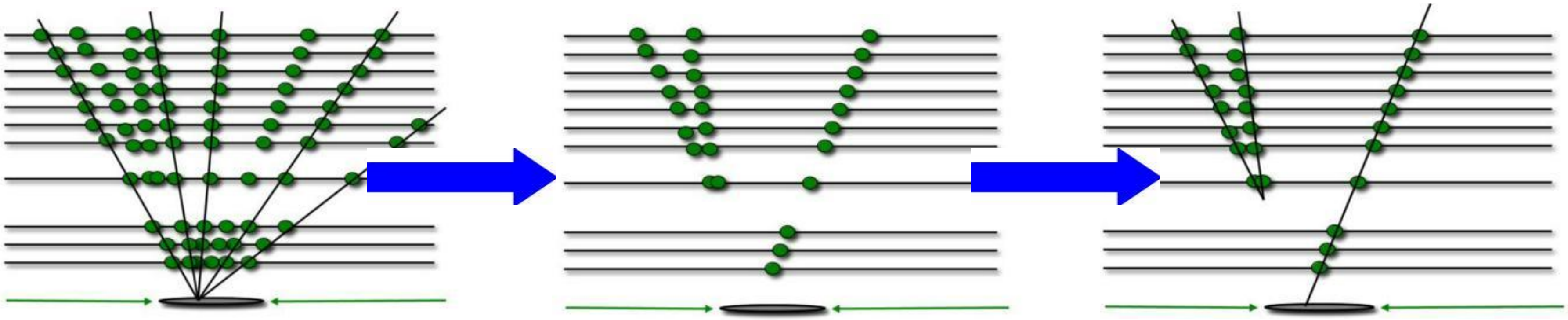
- Micro-strip sensors
- Stereo modules (two components with a 100 mrad stereo angle)
- Analog readout

- pixel sensors
- ~124M channels
- digital readout

Track reconstruction in CMS

- Few, but precise measurements;
- Dead material inside the tracker volume
- Main tracking algorithm: Combinatorial Track Finder used in iterative steps:
  - limits the number of combinatorics in pattern recognition
  - tracking reach guaranteed, w/o degrading computing performance





Track reconstruction in CMS

In each iteration, tracks are reconstructed in four steps:

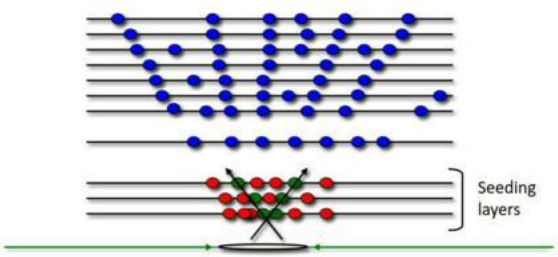
1. Seeding:
  - provides track candidates, with an initial estimate of the trajectory parameters and their uncertainties (use combination of pixel, strip or mixed hits);

2. Pattern recognition:
  - hits compatible with the predicted track position are added (Kalman update) to the trajectory and track parameters are updated;

3. Final fit:
  - taking into account the B-field non uniformity and a detailed description of the material budget;
  - provides the best estimate of the parameters of each smooth trajectory after combining all associated hits (outlier hits are rejected);

4. Selection:
  - sets quality flags based on a ML-based MVA with more than 20 inputs;
  - aims to reject fake tracks; tracks sharing too many hits are also cleaned as duplicates;

1



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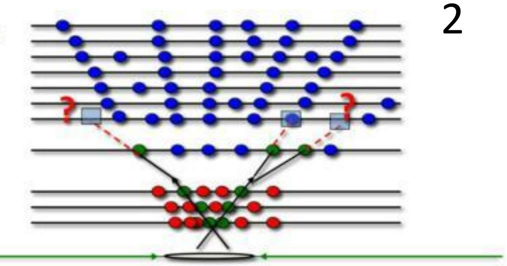

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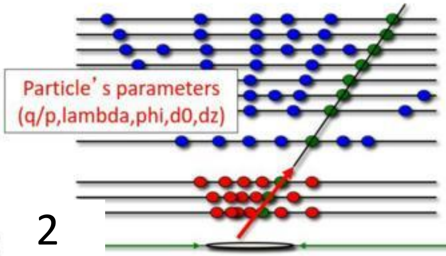

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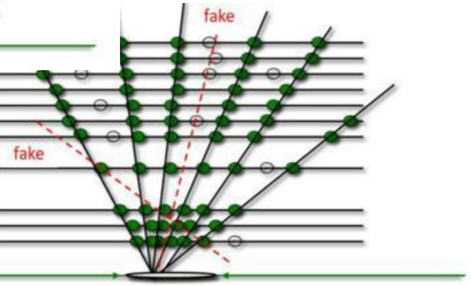
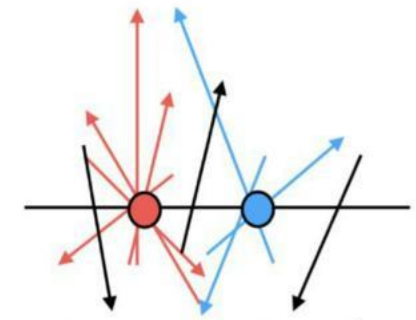
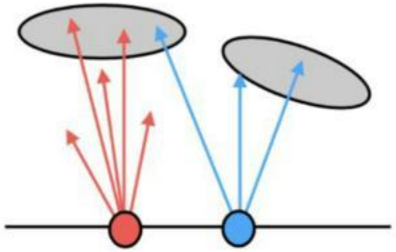
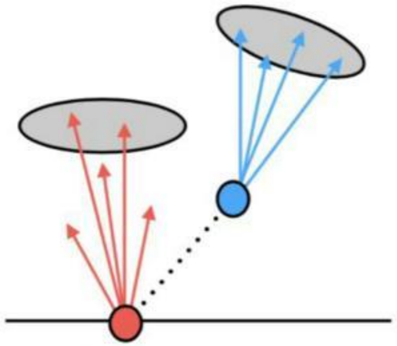


The tracking challenge at LHC

- The tracking challenge at the LHC:
  - typically 30 charged particles within the tracking volume acceptance per proton-proton collision
  - and 50-60 collisions per event: O(1500) charged particles per event;
- These need to be reconstructed:
  - with very high efficiency (>90% for ~GeV pions)
  - precise track parameters
  - very low fake rate: O(~ few %)
  - quickly (stringent CPU limits)
- Very strong requirements on track reconstruction algorithms
- Track reconstruction is not just about reconstructing charged particles:
  - used in almost every element of reconstruction


vertex reconstruction


pile up removal


jet flavour tagging

Summary for Tracking

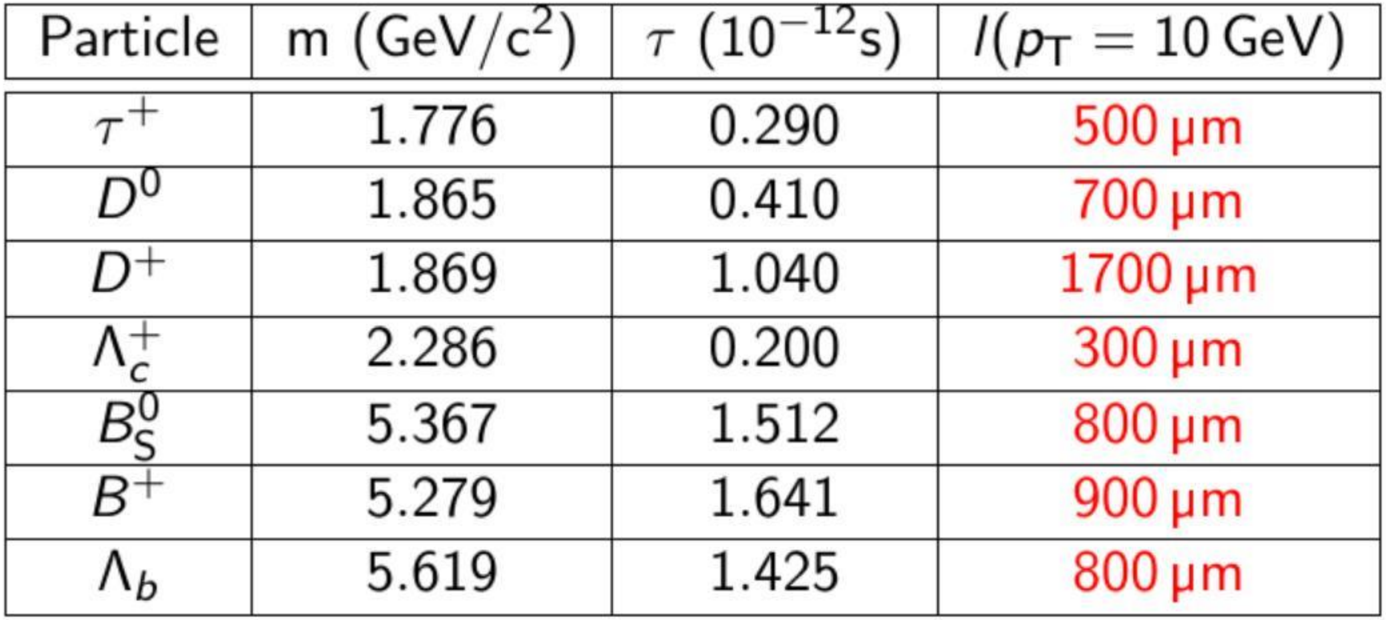
- Tracking algorithms need to provide high-quality tracks efficiently andwith an efficient usage of resources:
  - high tracking and vertexing performance is a must (despite challenging conditions at the LHC);
- To provide more precise and accurate track reconstruction sophisticated algorithms, techniques and calibrations have been developed.

Vertex Reconstruction

Vertex Reconstruction

Particles produced in the collision decay fast, but they can fly a certain distance before decaying:

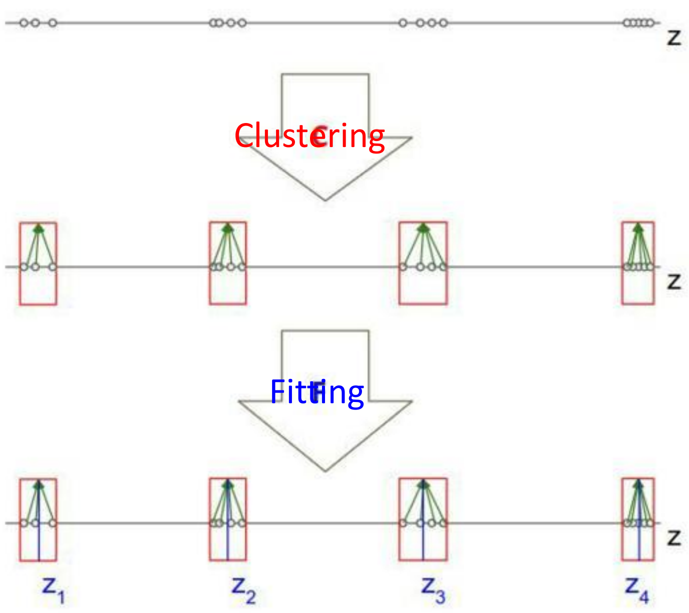
$$l = \beta\gamma\, c\, \tau$$



Particle	m (GeV/c^2)	τ $(10^{-12}\mathrm{s})$	$l(p_T = 10\,\mathrm{GeV})$
τ^+	1.776	0.290	500 μm
D^0	1.865	0.410	700 μm
D^+	1.869	1.040	1700 μm
Λ_c^+	2.286	0.200	300 μm
B_S^0	5.367	1.512	800 μm
B^+	5.279	1.641	900 μm
Λ_b	5.619	1.425	800 μm

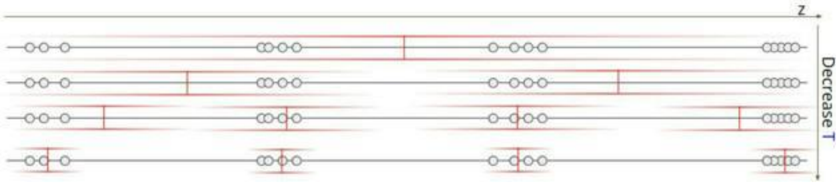
Vertexing

- Vertexing starts from a set of tracks.
- Then proceeds into two steps:
    - Clustering: group together close-by tracks in cluster candidates. The algorithm used is deterministic annealing;
    - Fitting: fit vertex properties of those clusters from those of the tracks. The algorithm used is Adaptive vertex fitting algorithm;

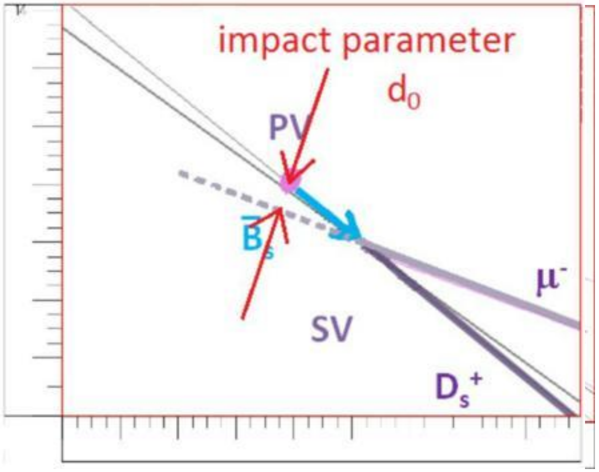


- Vertexing is based on optimizing an energy (assignment) function with a penalization entropy term:
    - Starting at very high temperature (T) all tracks are assigned to one single cluster;
    - As we lower T, splitting the cluster into several becomes beneficial;
    - Iteratively update assignment probabilities P_{ik} while lowering T provides a final robust estimation of the clusters.

$$E - TS = \sum_{i=1}^{I}\sum_{k=1}^{K} P_{ik}\frac{(z_i - z_k)^2}{\sigma_i^2} + T\sum_{i=1}^{I}\sum_{k=1}^{K} P_{ik}\log(P_{ik})$$



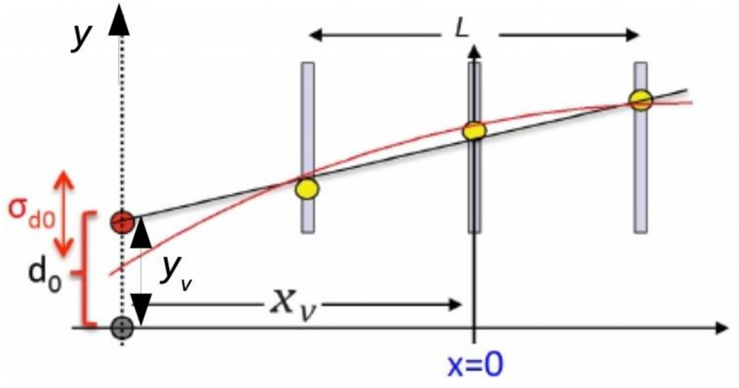
Impact Parameter



Impact parameter d_0 quantifies the mismatch to the primary vertex (PV)
The impact parameter significance $S_{d0} = d_0/\sigma_{d0}$ serves as selection criterion to distinguish tracks from primary or secondary vertices.

The track as measured by the tracking detectors has to be extrapolated to the vertices. This can be done with

- Linear extrapolation $y = a + bx$ (no magnetic field)
- Quadratic extrapolation $y = a + bx + cx^2$ (good approximation for helix in B)



Errors on the vertex position y_v is given for linear approx. by

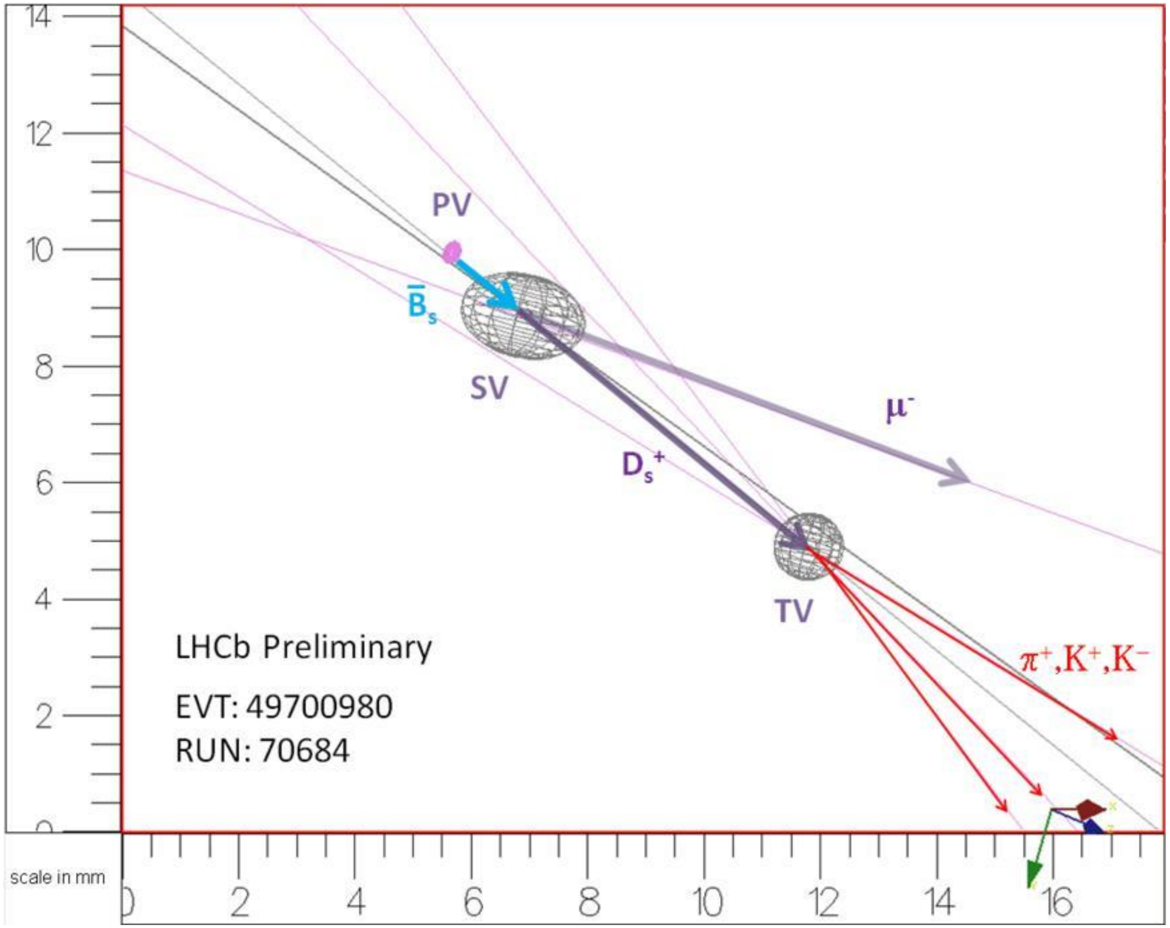
$$\sigma_{d_0} = \sigma_y = \sqrt{\sigma_a^2 + x_v^2 \sigma_c^2}$$

or for quadratic approx. by

$$\sigma_{d_0} = \sigma_y = \sqrt{\sigma_a^2 + x_v^2 \sigma_c^2 + \frac{1}{4} x_V^4 \sigma_c^2 + x_v^2 \sigma_{ac}}$$

Example of Decay Chain

Identifying the primary vertex (PV), secondary vertex (SV) and tertiary vertex (TV) is important to understand the decay chain of the particle and to reconstruct its mass and life time completely.



Muon Reconstruction

(Slides are reused from https://indico.cern.ch/event/242419/contributions/520665/attachments/412163/572720/LHCFrance_MuonReco_NVranjes.pdf)

Muon detectors

DT

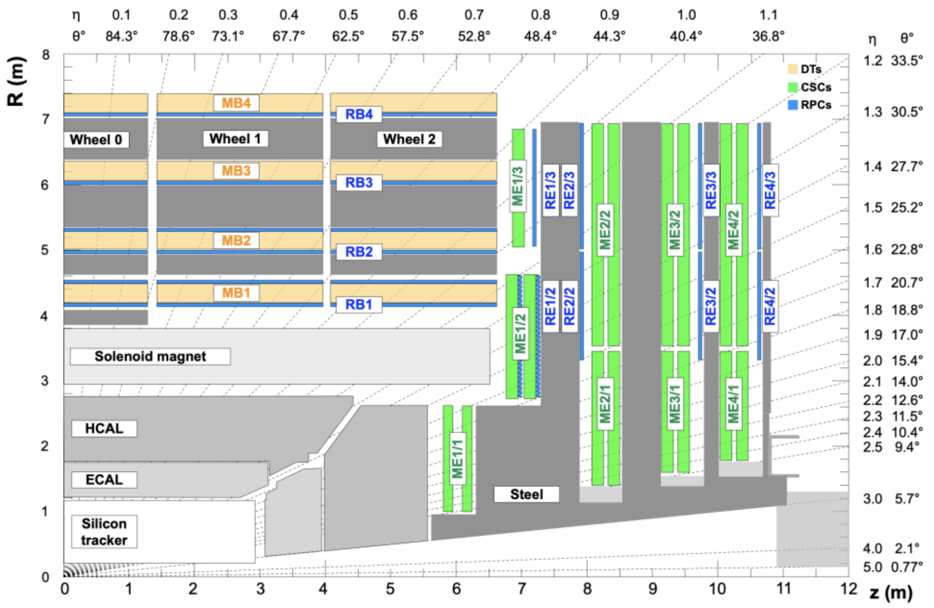
(Drift Tubes)

long drift time (380ns) – low rate reg.,
wire pitch 4.2cm
resolution (per chmber) rϕ:100 µm, rθ:150 µm
8ϕ+4θ layers in station (only ϕ in MB4)

RPC

(Resistive Plate Chambers)

Fast gaseous det. (~2ns), dedicated for L1
Efficiency >95% @ 1KHz
Low noise (<5Hz/cm2),
meas. Φ (strip Pitch 0.5-4cm)



CSC

(Cathode Strip Chambers)

fast response,
high rate
close wire spacing (res. R75-150 µm)
strips 6.7-16mm (res. Φ 150 µm)

Algorithms in Muon Detectors

Local Reconstruction: Find Track Segments which held information about position and direction of muon crossing one chamber. Track Segments are formed by straight line fit using multi-hit measurements in stations.

DT: hit position w.r.t. wire computed from drift time; r-ϕ (8meas.) and r-θ (4meas.); direction reconstructed independently and combined into segment

CSC: 2D points from wire and strips measurements in plane. Build segment using hits from up to 6 planes

RPC: secondary importance in track reconstruction (measure 3d hit only)

Stand-Alone Muon Reconstruction

Based on the Kalman Filter Technique
Propagation with energy losses, in non-constant magnetic field.

Seeding – definition of initial trajectory state.

Online: input (position, momentum) from L1 trigger
Offline: global analysis of segments. Seed kinematics is estimated by simple parametrisation of bending in/between segments.

Forward Pattern Recognition (pre-filtering) goes from most inner to outer muon station. Segments compatible with trajectory (χ^2 based) are collected constraining trajectory state.

Backward Pattern Recognition: Trajectory Fitting: propagating outside-in update trajectory with individual hits from segments (χ^2 based). Optionally update fit with vertex constraint

Algorithms in Tracker

Global Muon:

Define Region of Interest (ROI) which describes supposed track parameters at vertex (based on Stand-Alone Muon reconstruciton and assumed tolerances).

Offline: reuse tracks from standard tracker reconstruction
Combinatorial Track Finder (CTF) - Kalman Filter based algorithm consisting of global hit based seeding, inside-out pattern recognition, final cleaning, fitting and smoothing (backward fitting).) Select tracks compatible with ROI.

Online: run regional tracker track reconstruction in ROI (find pixel hit pairs or triplets which are compatible with ROI). Standard tracker CTF, customized cleaning.

Match tracker tracks to Stand-Alone Muon (check trajectory compatibility on intermediate surface).
Refit track using hits from Tracker Track and Stand-Alone Muon.

Tracker Muon

(offline only, alternative to start with Stand-Alone Muon)

Reuse tracks from standard tracker reconstruction
For each track combine muon signatures (energy in calorimeters, segment crossed by extrapolation, discance from chamber edges)

Flag track as Tracker Muon if track has MIP signal in calorimeter or at least one matched muon segment

Alignment

The structure of the CMS detector is not rigid:

- 1-3 cm deformation due to magnetic field
- 5-15 mm due to gravity (weight)
- 500 µm due to changes in temperature and humidity

Reconstruction requires a precise knowledge of the location of the detector components

(ex. In order not to degrade momentum measurements in muon system: 200 µm in the r-ϕ).

Alignment scenarios:

- Ideal: assumes a perfectly placed detector
- Startup: our best estimate of alignment at day one
- Long-term: our expectation of improved knowledge with data

CMS strategy for alignment is based on:

- Optical system
- Tracking (from collisions, cosmics, halo)

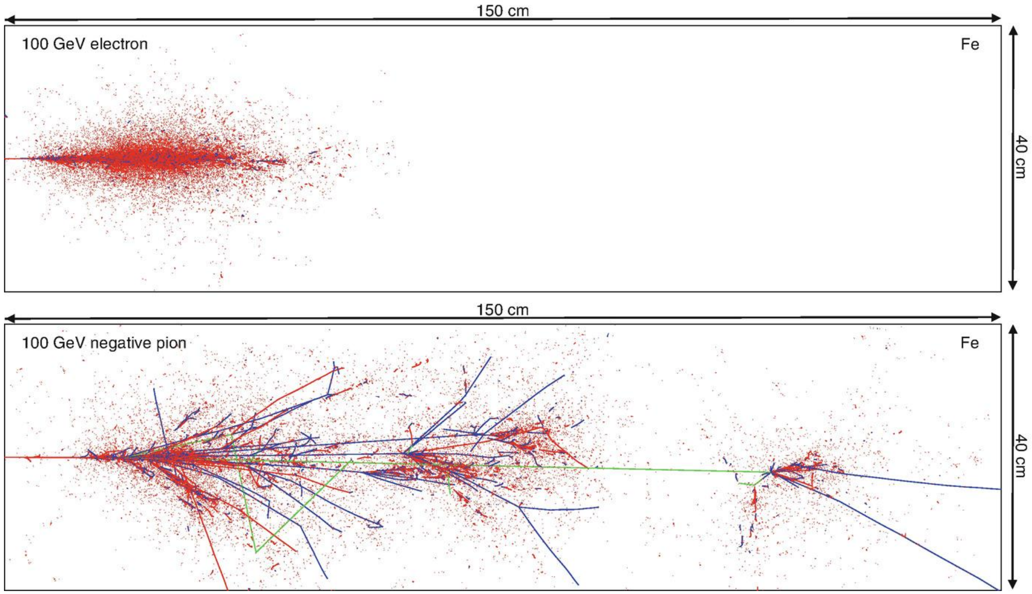
Electron & Photon Reconstruction

(Slides are reused from L. Finco, LPC Physics Forum 2021)

Definition of Calorimeter

- In particle physics a **calorimeter** is a **detector measuring** the **energy** carried by an incoming particle
  - **Instrumented blocks of matter** in which the particle interacts and **deposits all its energy** in the form of a cascade of particles

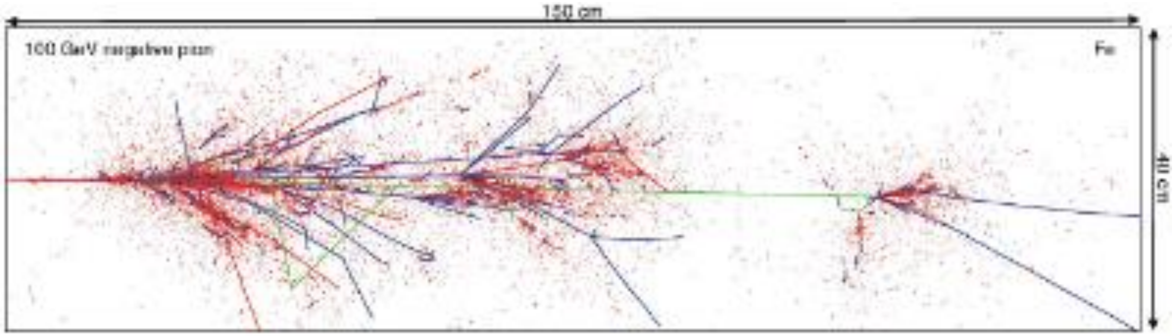
- The **particle energy** is **measured** in **eV** (MeV-GeV-TeV 10^6, $10^{9,}$ 10^{12} eV)
  - **1 eV** = energy acquired by one **electron** accelerated by **1 V**
  - The **temperature effect** of a 100 GeV particle in 1 litre of water (at 20 °C) is $\Delta T = 3.8 \times 10^{-12}$ K



https://doi.org/10.1007/978-3-319-47999-6_53-1

General Features of Caloremeters

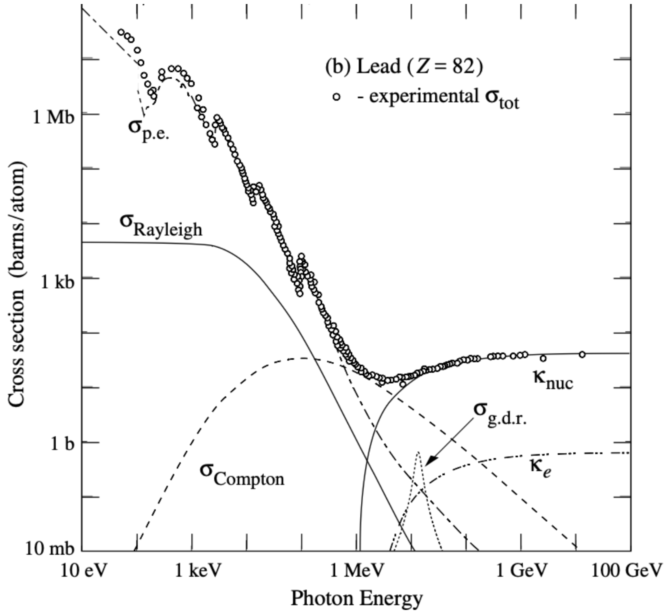
- Calorimetry is a “**destructive**” **method**
  - The energy is measured by **total absorption** of the particle
- A calorimeter **converts** the **energy** of an incident particle to a **detectable signal**, proportional to the incoming energy
- Calorimeters can measure the energy of **electromagnetic radiation** (electrons, photons) or **hadronic particles** (charged pions, protons, neutrons)
- The **charged component** of the **particles' cascade** deposits energy in the active part of the calorimeter and it is **detected** in the form of **charge or light**
- This talk is mainly focused on **electromagnetic calorimeters**

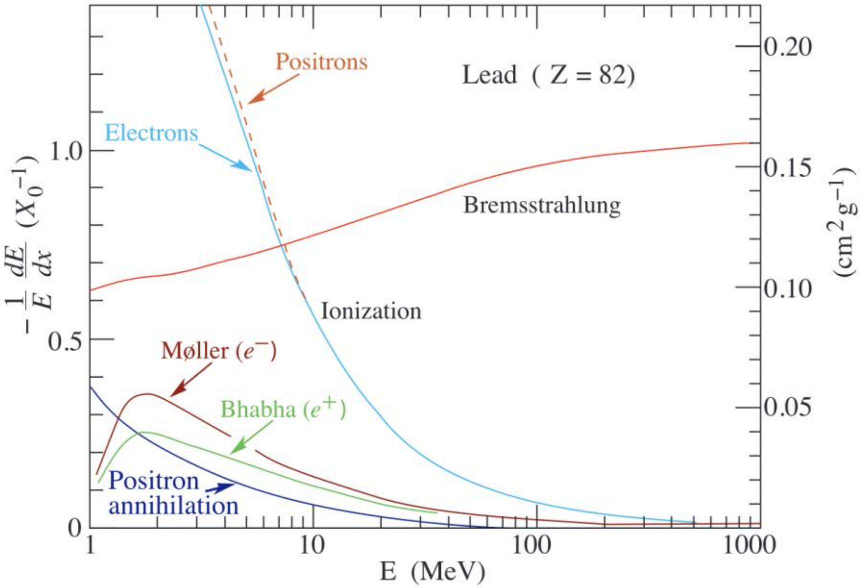


https://doi.org/10.1007/978-3-319-47999-6_53-1

Particle-Matter Interactions

- In matter **electrons** and **photons** loose energy **interacting** with nuclei and atomic electrons
- **Main photon interactions** with matter:
    - Photoelectric effect
    - Compton scattering
    - Pair production
- **Main electron interactions** with matter:
    - Ionization
    - Bremsstrahlung
    - Čerenkov radiation
    - Multiple scattering

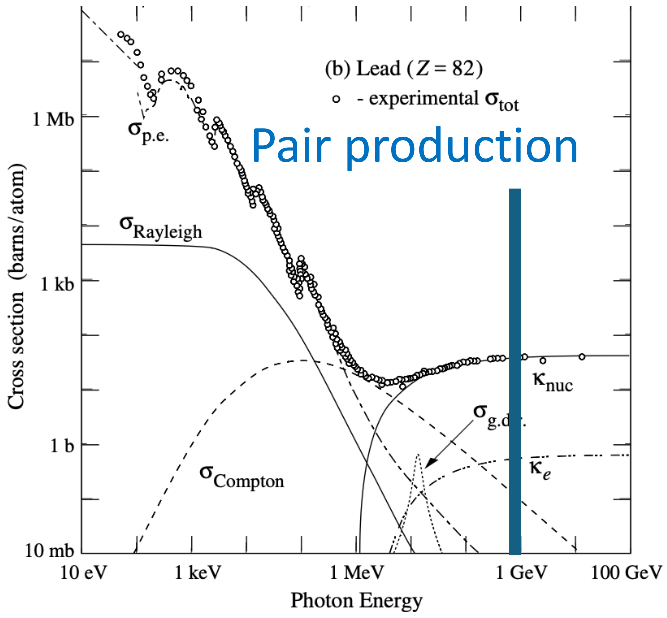


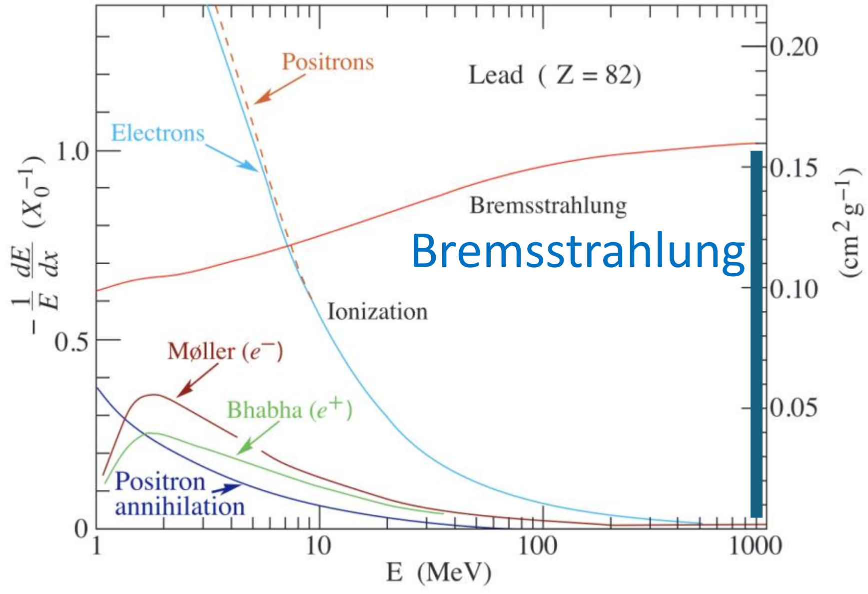


Particle-Matter Interactions

- In matter **electrons** and **photons** loose energy **interacting** with nuclei and atomic electrons
- **Main photon interactions** with matter:
  - Photoelectric effect
  - Compton scattering
  - Pair production
- **Main electron interactions** with matter:
  - Ionization
  - Bremsstrahlung
  - Čerenkov radiation
  - Multiple scattering

At colliders interesting electrons and photons have usually **E > 1 GeV**





Particle-Matter Interactions

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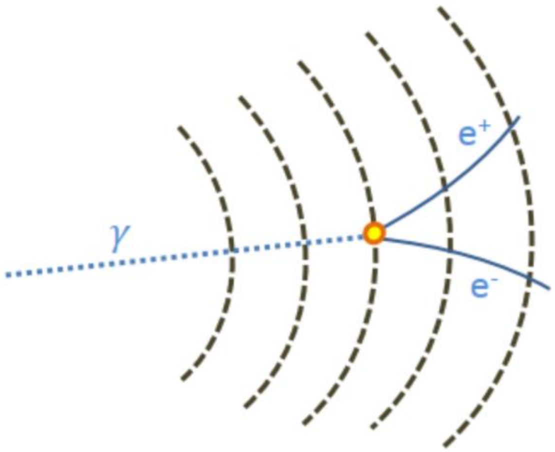
  - Čerenkov radiation
  - Multiple scattering

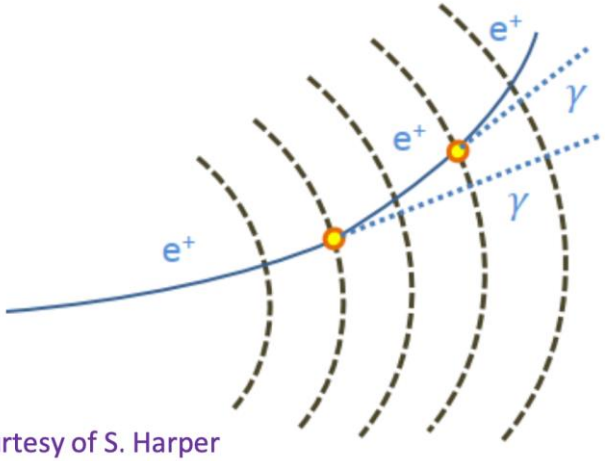
These **processes** are the **basis** of the **electromagnetic shower**

Pair production



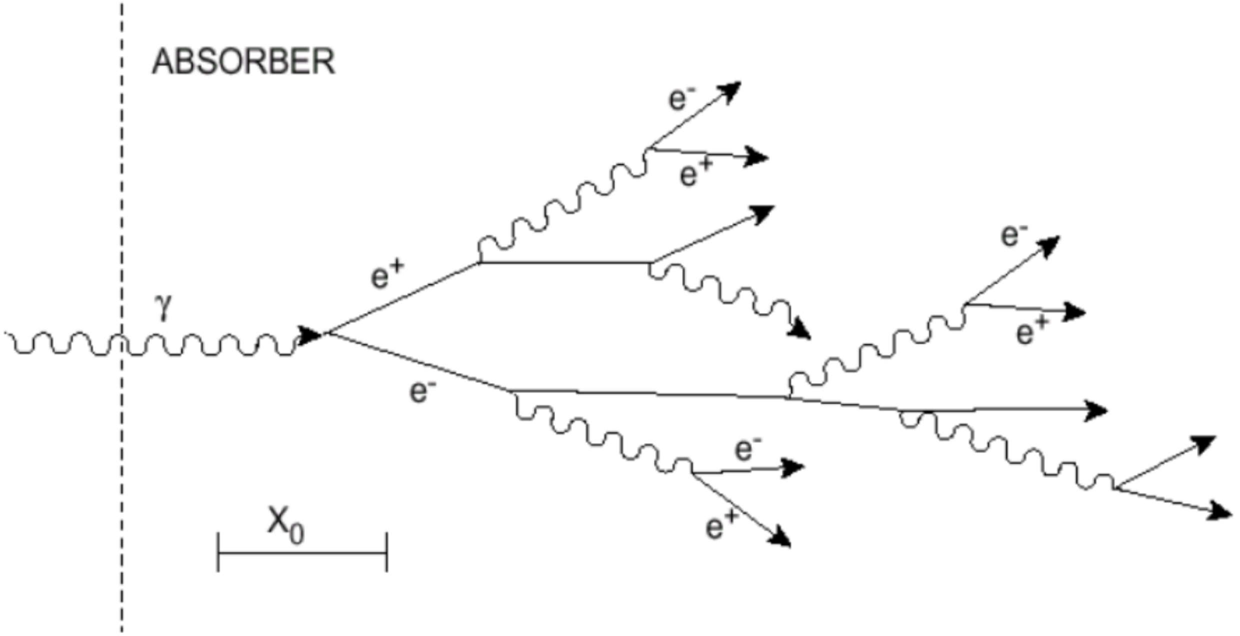
Courtesy of S. Harper

Bremsstrahlung



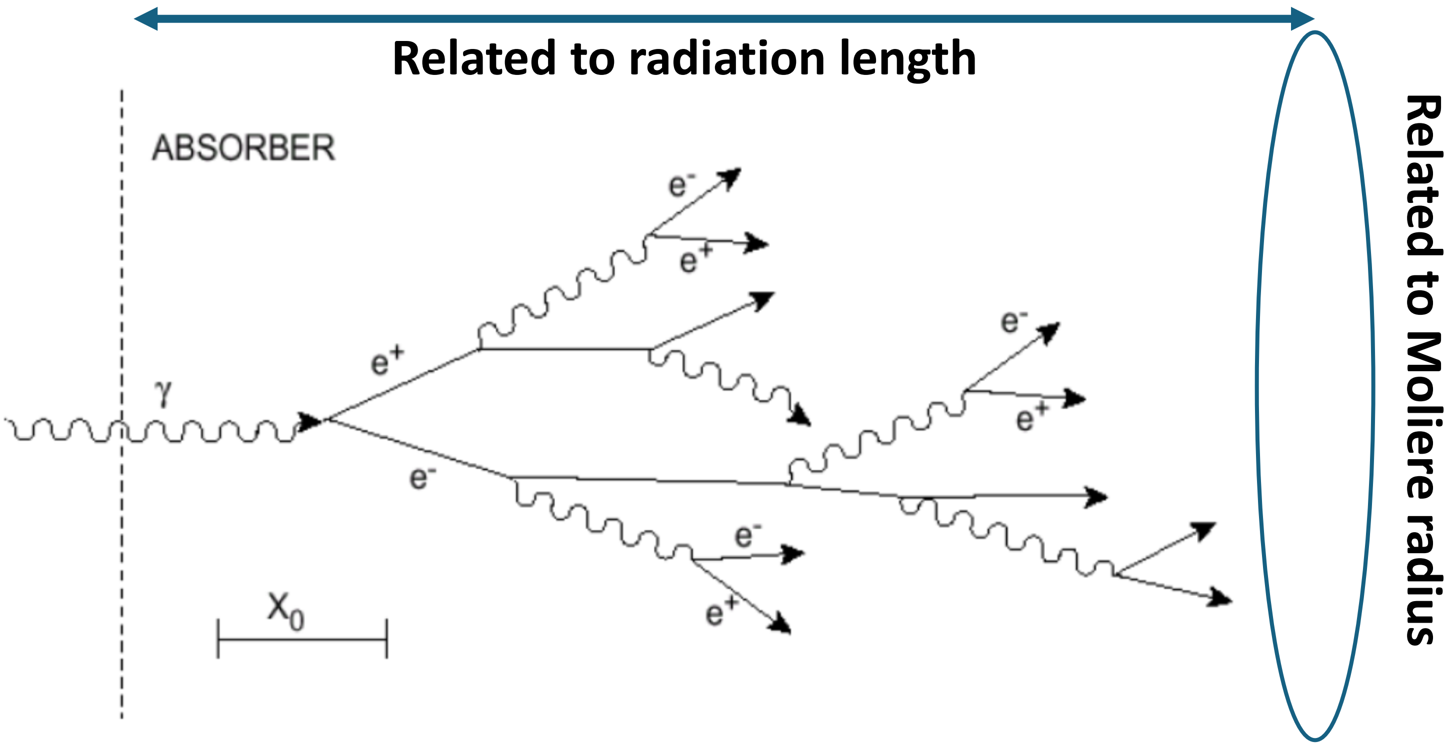
Courtesy of S. Harper

Electromagnetic Shower



- Electrons and photons create a **cascade** (shower) **of particles**
- **Number** of particles N
  - Is **proportional** to the **energy** of the incoming particle
  - **Increases until** the energy of the electron component falls below $\mathbf{E_c}$ (critical energy ~ 5-10 MeV)
- With $E < E_c$ a **slow decrease** in number of particles occurs as **electrons** are **stopped** and **photons absorbed**
- **Longitudinal extension** of the shower is **proportional** to $\mathbf{ln(E/ E_c)}$

Electromagnetic Shower



Related to radiation length

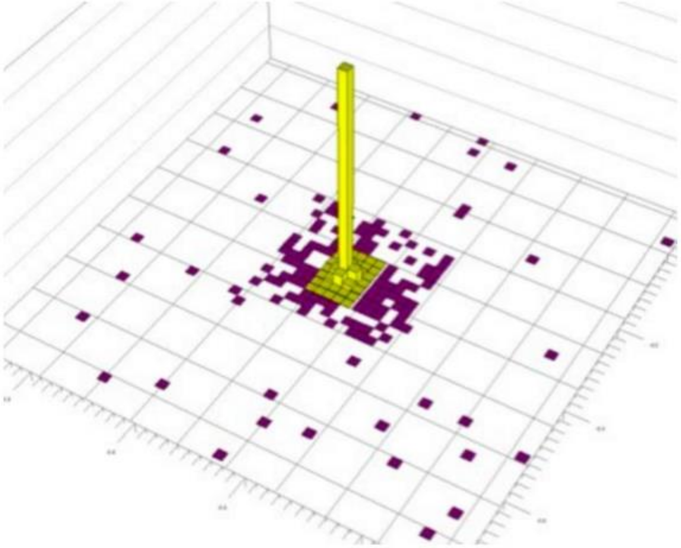
Related to Moliere radius

The evolution of an electromagnetic shower through a material is dictated by:

- **Radiation length** (X_0) :
  - Mean distance in which an electron will lose all but 1/e of its energy
  - 0.78 of mean free path of a photon (photon showers will start later)
- **Moliere radius** (M_R):
  - 90% of shower's energy is contained within a cylinder of radius = 1 MR
  - 2 M_R contain 95% of its energy

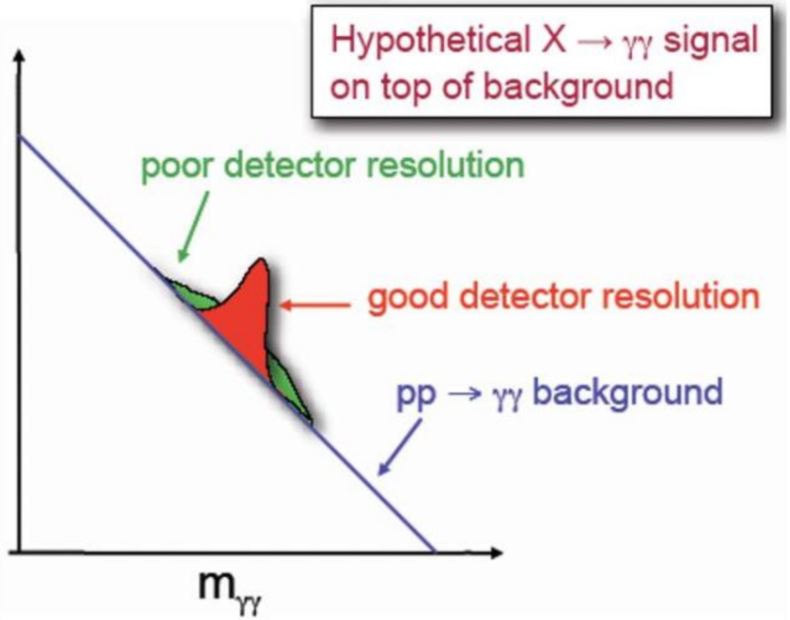
Calorimeter's Design Characteristics

- **Size of the detector**: the longitudinal depth of the detector is dictated by X_0 and is driven by the required resolution
  - **Small X_0** allows to reduce calorimeter size (compactness)
- **Cell size**: typically chosen such that 70-80% of energy of a centrally incoming particle is deposited in the cell, while having energy in the neighbouring cells large enough to measure the centre of gravity coordinates
  - Related to **M_R**
- **Granularity**: size of detector elements in the transverse and longitudinal direction, which determines the ability to resolve two showers induced by nearby particles as distinct. It depends on the shower size, distance from the interaction point and transverse size of detector elements/cells



LHC Requirements for Calorimeters

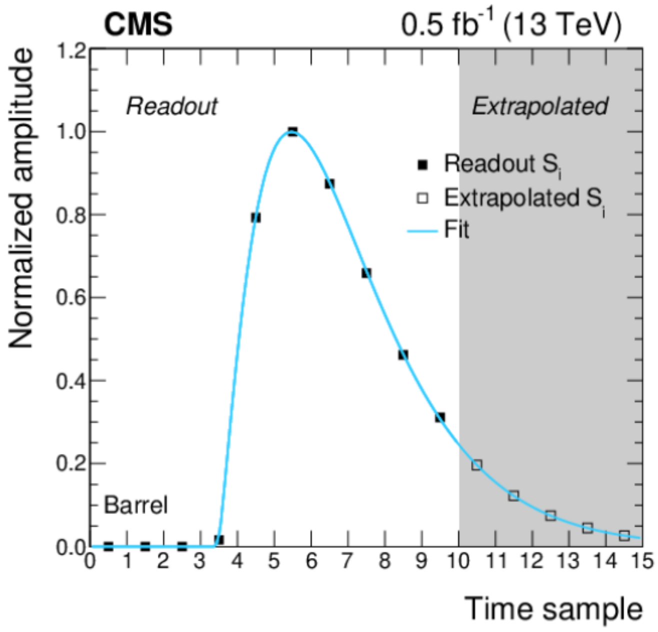
- **Fast response** (25 ns or faster) and **high granularity**, to reduce pile-up induced noise
- **Radiation-hard** detectors and electronics
- **Hermetic** and **cover** the full azimuthal angle and rapidity range, to tag very forward jets and well measure the missing energy
- **Excellent** electromagnetic **energy resolution**
    - To detect the two photon decay of an intermediate mass Higgs (golden channel together with H→ZZ →4l)



Courtesy of C. Mariotti

ECAL Energy Reconstruction

- Energy in the ECAL observed as a **pulse** as the photons from the shower arrive over time
    - This **pulse shape** is **converted** to an **energy** (E ∝ A, signal channel amplitude)
- In case of **out-of-time** pile-up **events**, **multiple pulses** from different bunch crossings are generated
    - They lead to an **apparent increased** amplitude measurement
- The **amplitudes** of different pulses are **resolved** by **fitting** the **multiple pulse shapes** simultaneously



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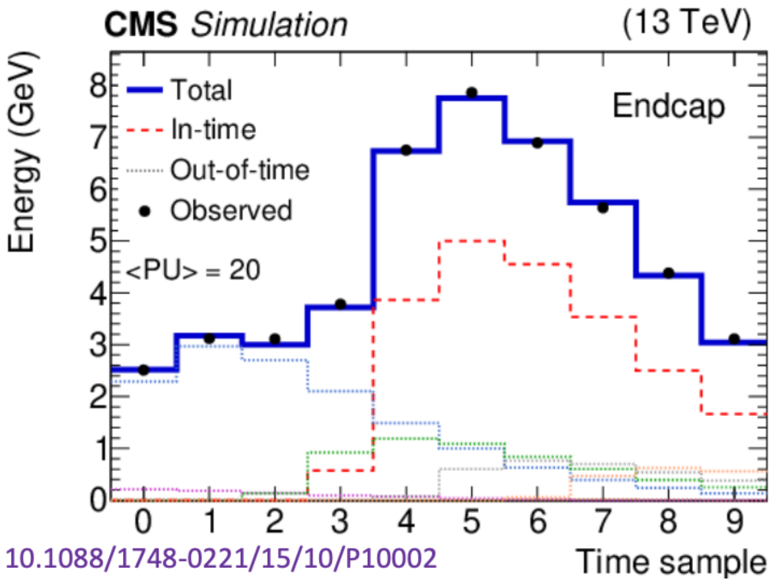

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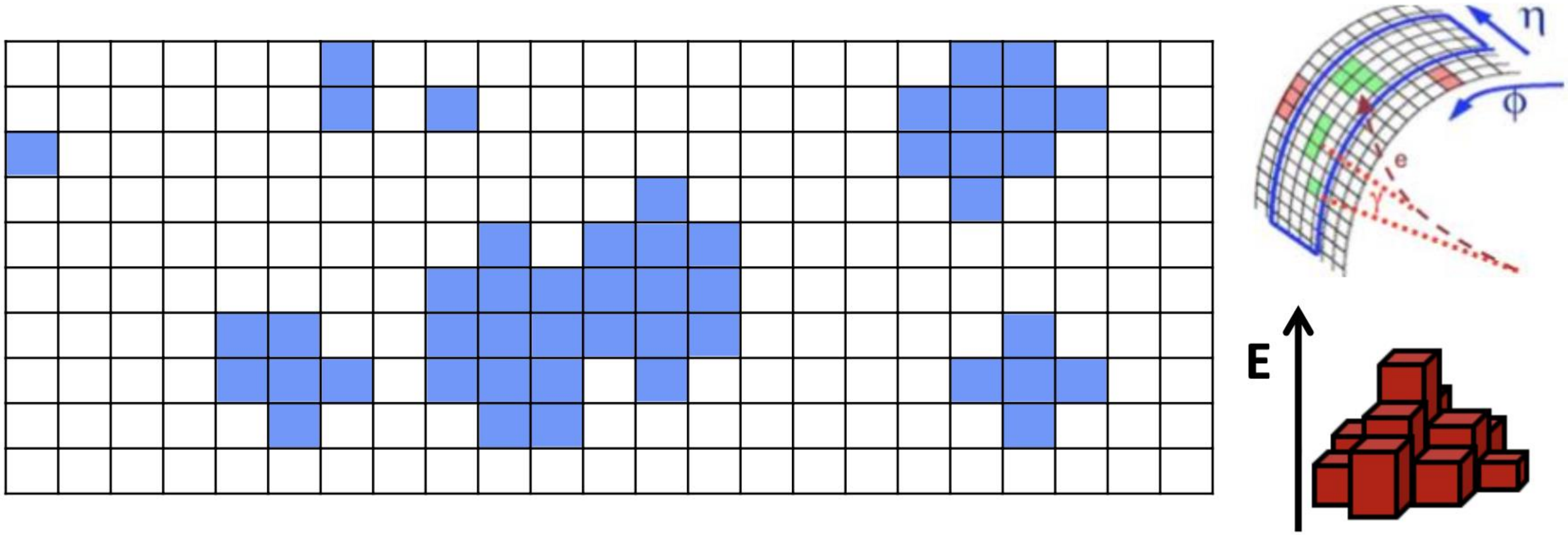
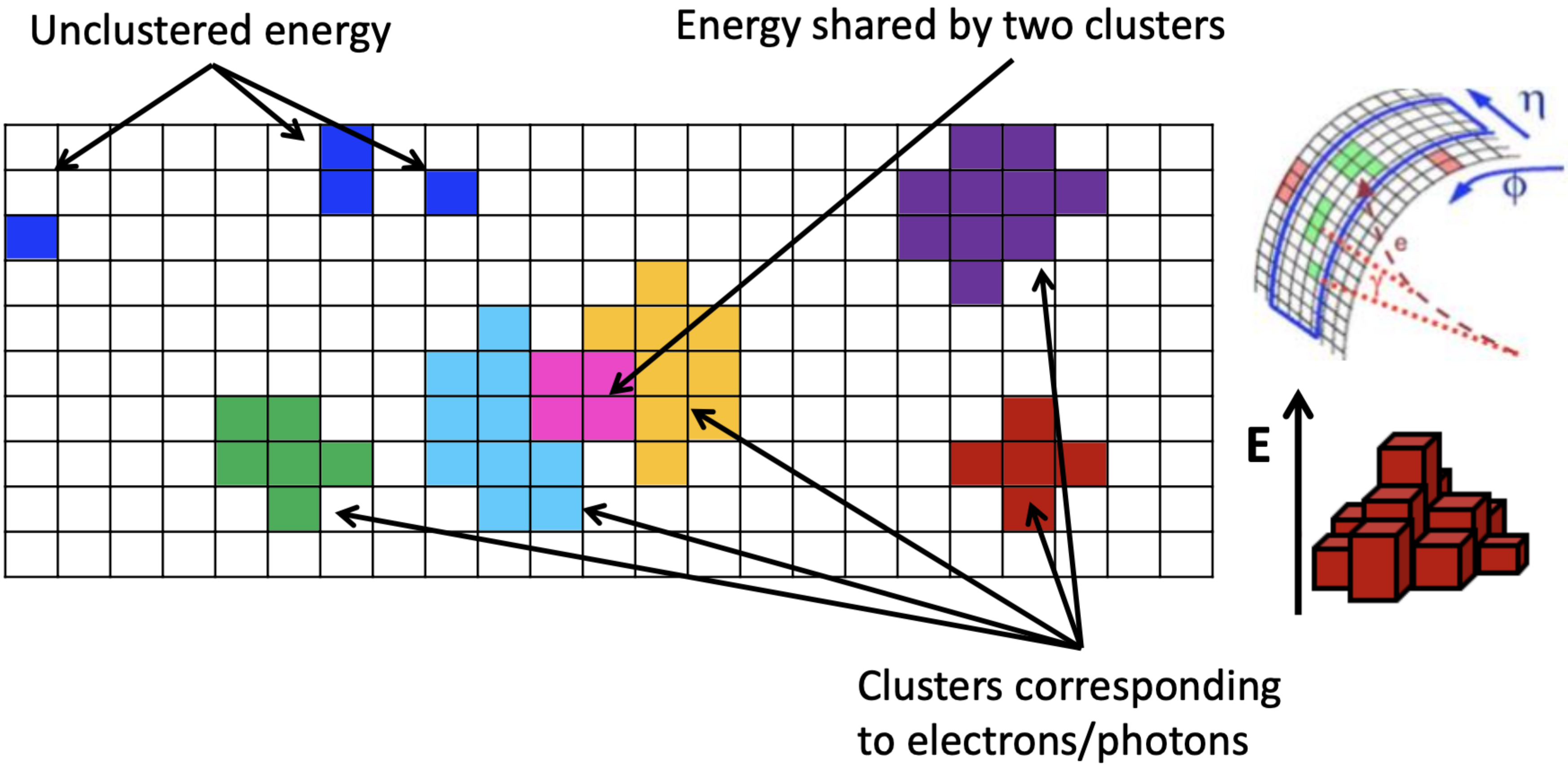
Electron and Photon Reconstruction



- First step is **to construct individual particles** from the reconstructed energy deposits (clustering)
- The **clustering procedure** looks for **local maxima** above a given threshold (1 GeV)
    - **Energies** between **overlapping** adjacent **clusters** are **shared**

Clustering of Crystals Energy



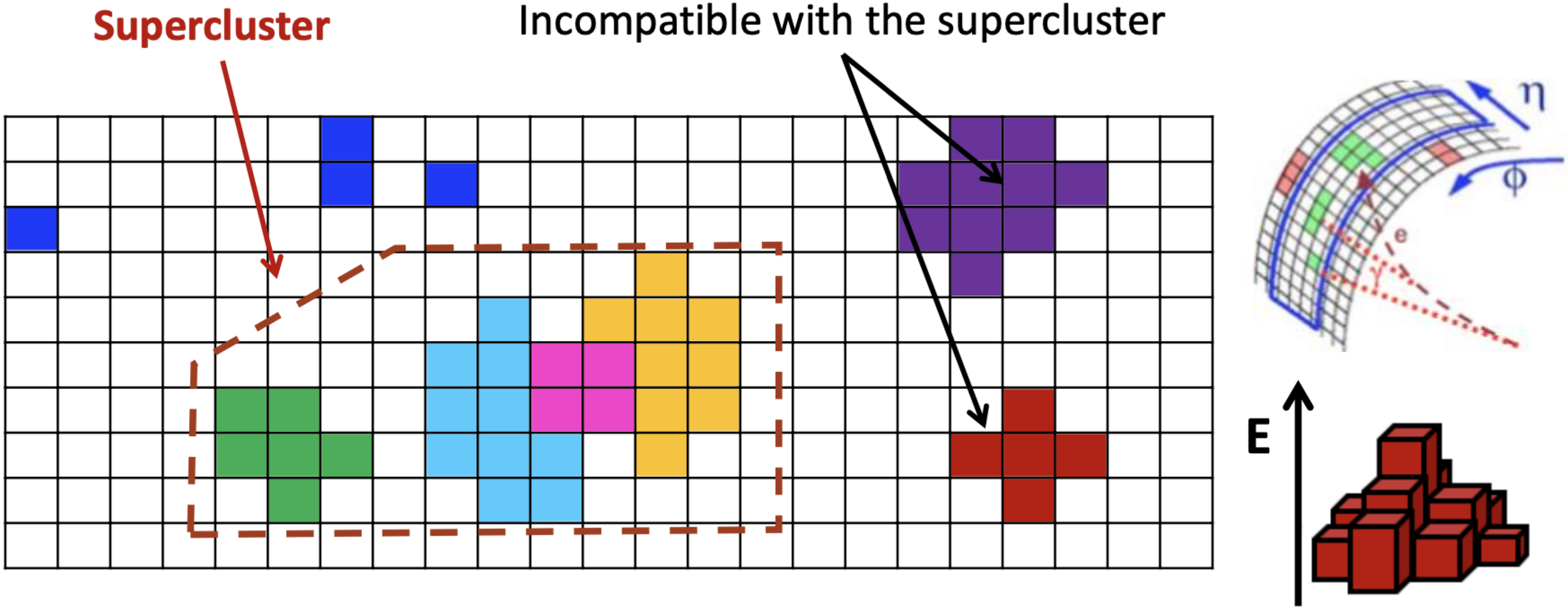
Unclustered energy

Energy shared by two clusters

Clusters corresponding to electrons/photons

- Found **5 clusters** in this region of the ECAL
- Each one represents the **energy deposits** of a **particle** (electron/photon)
- In practice **not** this **clean**: often clusters have a very large number of crystals with small energy fraction

Superclusters



Supercluster

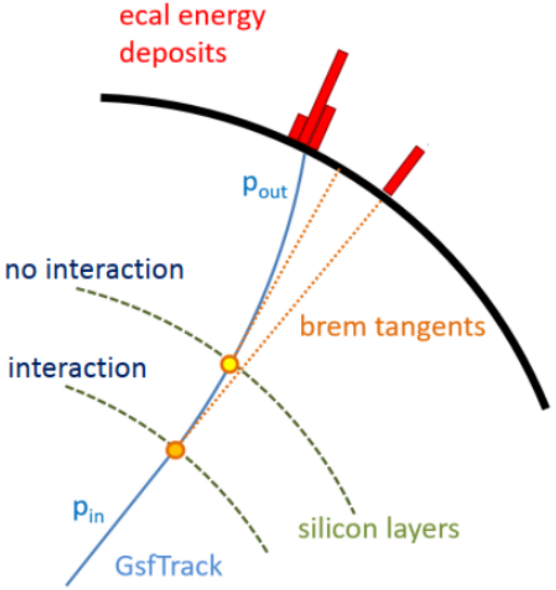
Incompatible with the supercluster

- **An electron** or **photon** when it arrives to ECAL, may be **accompanied** by **multiple secondary particles** created through interactions with matter on the way to ECAL
- **Superclustering** (clustering on clusters) aims to **combine** the individual electrons and photons **into a single object**, corresponding to the original electron/photon
- It starts by taking the **highest energy cluster** (in this case the light blue one) and **looks for compatible clusters**

Electron Track Reconstruction

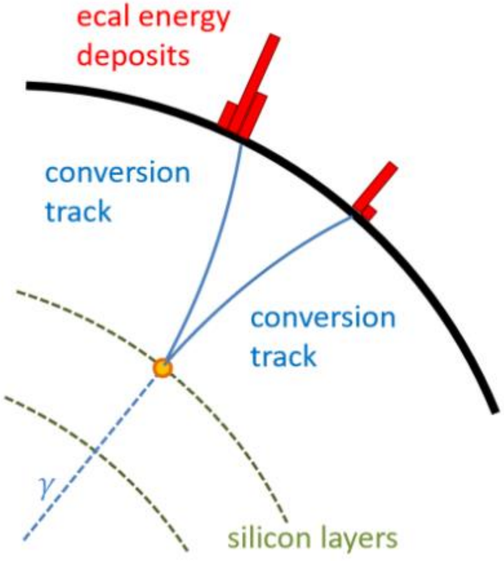
- **Electrons** leave a signal in both **tracker** and **calorimeter**
- Electron tracks have **changing curvature** because of **radiative energy loss** due to bremsstrahlung
- A **dedicated tracking algorithm** known as GSF tracking is used to take into account these changes in the curvature
- Used to **associate additional bremsstrahlung** radiation and photon **conversion tracks** to the **supercluster**

Bremsstrahlung



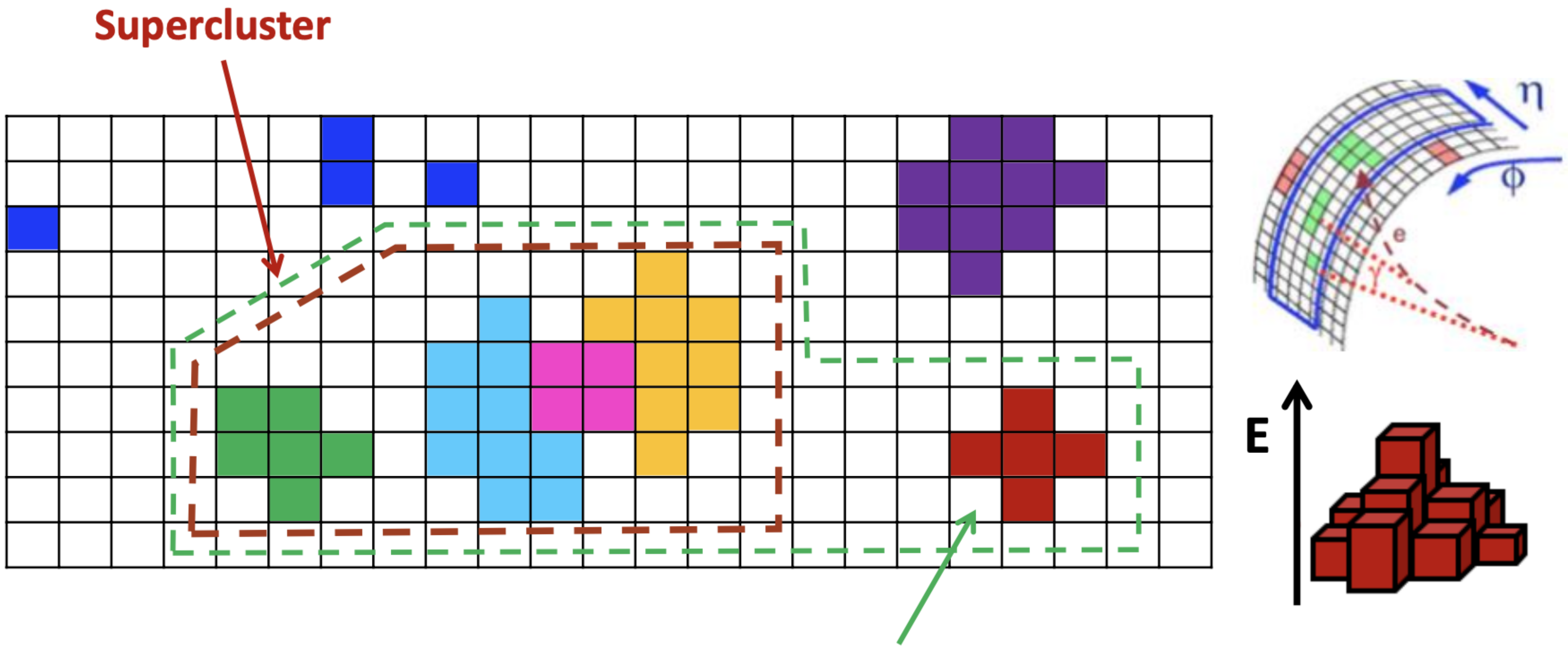
Courtesy of S. Harper

Pair production



Courtesy of S. Harper

Refined Superclusters



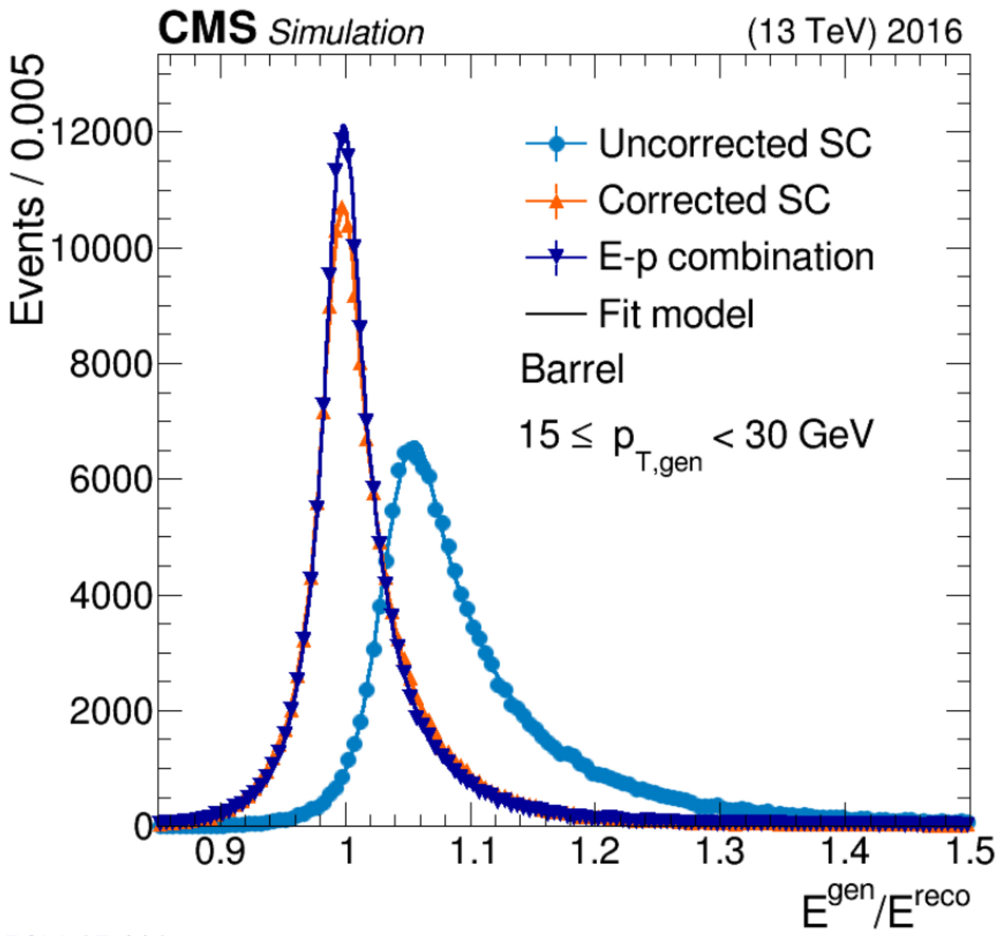
Recover of a very soft bremsstrahlung photon into the **refined supercluster**

- **Refined superclusters** use the information from the **tracker**, to be able to link bremsstrahlung emissions to missed ECAL deposits and reject some clusters which are highly incompatible with its matched tracks

Energy Corrections

- **Energy** deposited by electrons and photons in the ECAL and collected in superclusters is **subject to losses**
  - Energy lost in **gaps**
  - Large amount of **material upstream** of the calorimeter
  - Calorimeter measurements more sensitive to **pileup** than **tracking**.

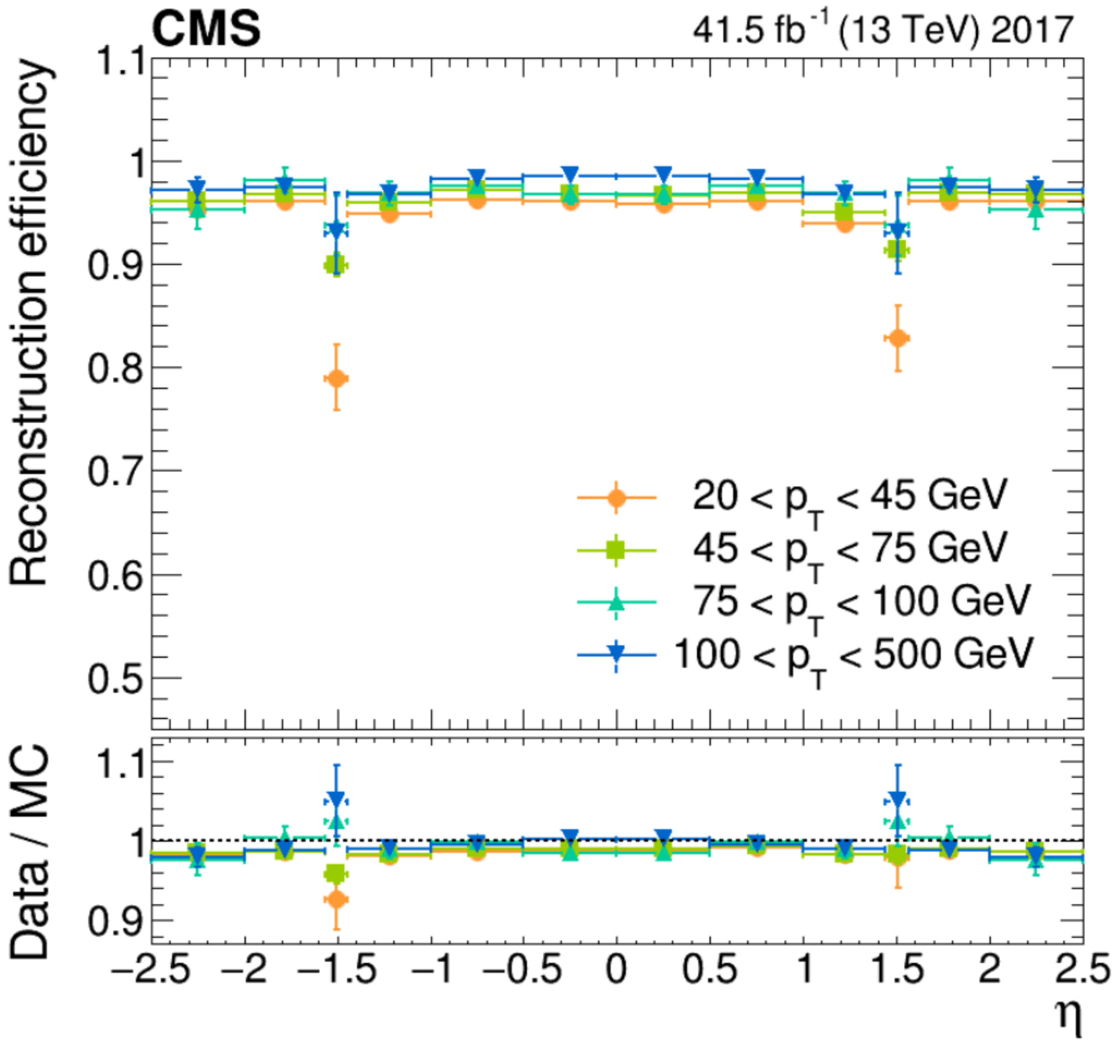
- To calibrate the reconstructed energy back to **generated energy** a **correction procedure** is needed
  - Based on simulation
  - Uses machine learning techniques
  - Applied on data and MC



EGM-17-001

Reconstruction Performance

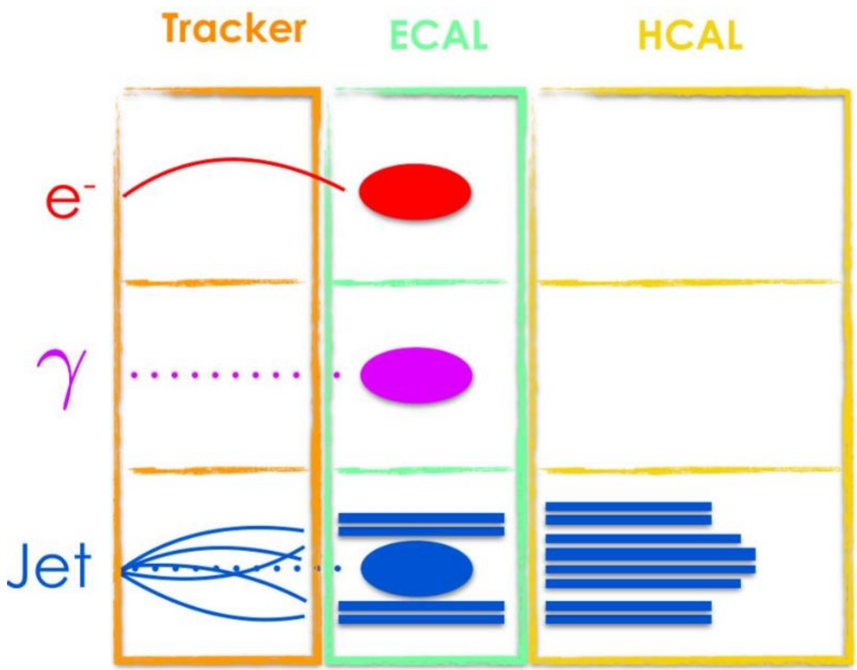
Electron reconstruction efficiency is higher than **95%** for E_T> 20 GeV and is **compatible** between **data and simulation** within 2%



EGM-17-001

Electron and Photon Identification

- Several **variables** are developed to **separate electrons/photons from background** (jets, photon conversions, particles from secondary vertices)
- They exploit that electrons/photons are **single objects** which are almost fully **contained** in the **ECAL**
- **Many** different **types**:
  - **Shower-shape variables**
  - **Track matching variables**
  - **Conversion ID variables**
  - **Isolation variables**



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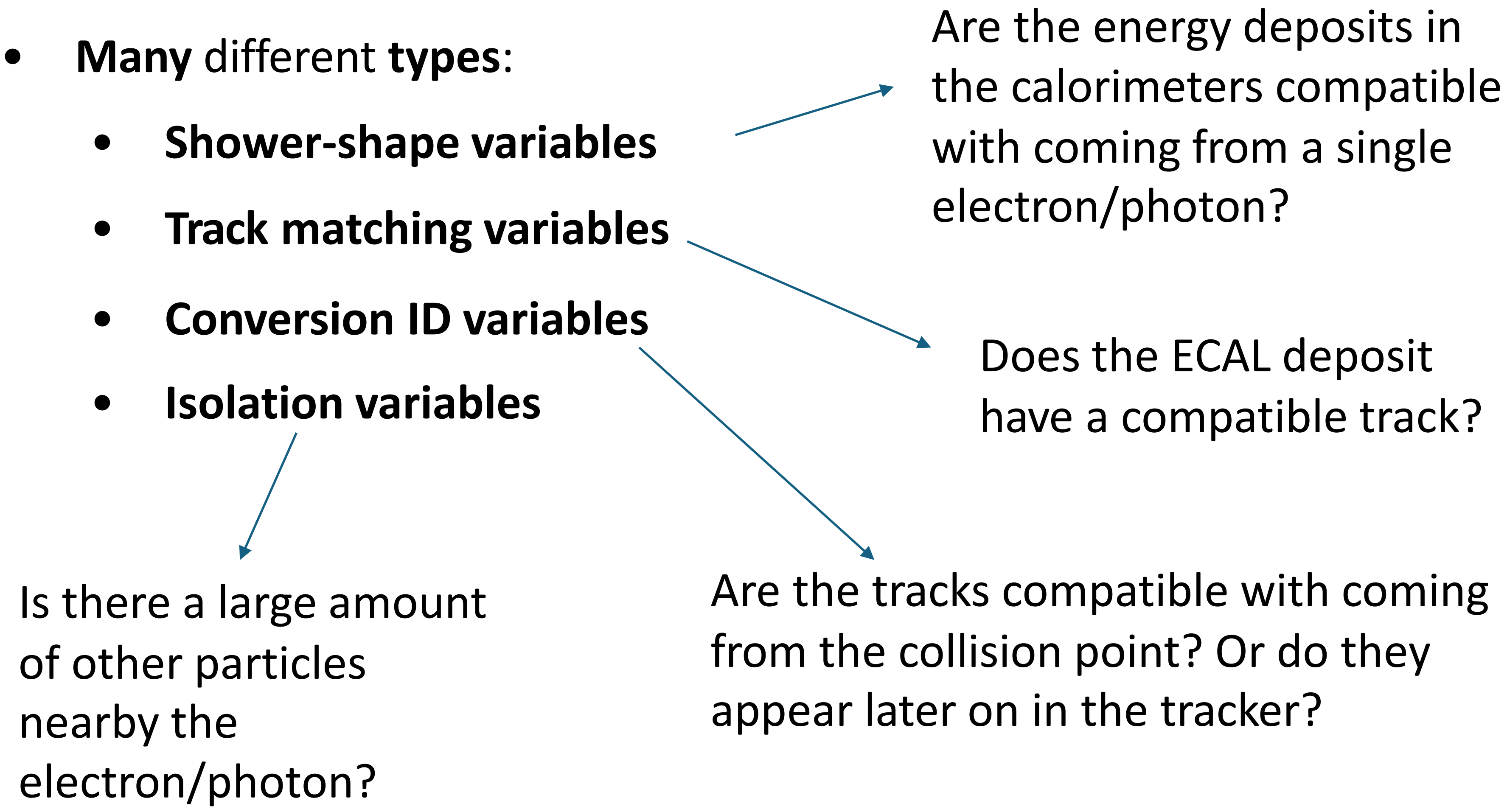


  - **Shower-shape variables**
  - **Track matching variables**
  - **Conversion ID variables**
  - **Isolation variables**

Are the energy deposits in the calorimeters compatible with coming from a single electron/photon?

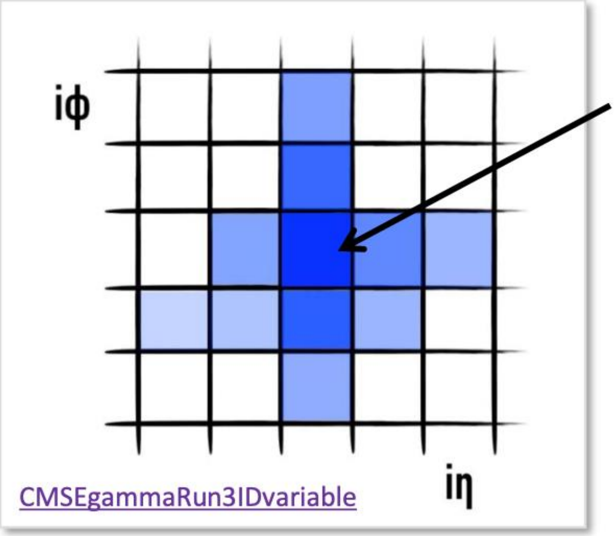
Does the ECAL deposit have a compatible track?

Is there a large amount of other particles nearby the electron/photon?

Are the tracks compatible with coming from the collision point? Or do they appear later on in the tracker?

Shower Shape Variables: $\sigma_{i\eta i\eta}$

- **$\sigma_{i\eta i\eta}$** is one of the **most important** electron/photon **ID variables** in CMS
- It measures the **spread** of an electromagnetic shower **along ieta** direction
- A **5x5 array of crystals** is the area where an electron/photon is almost **fully contained**

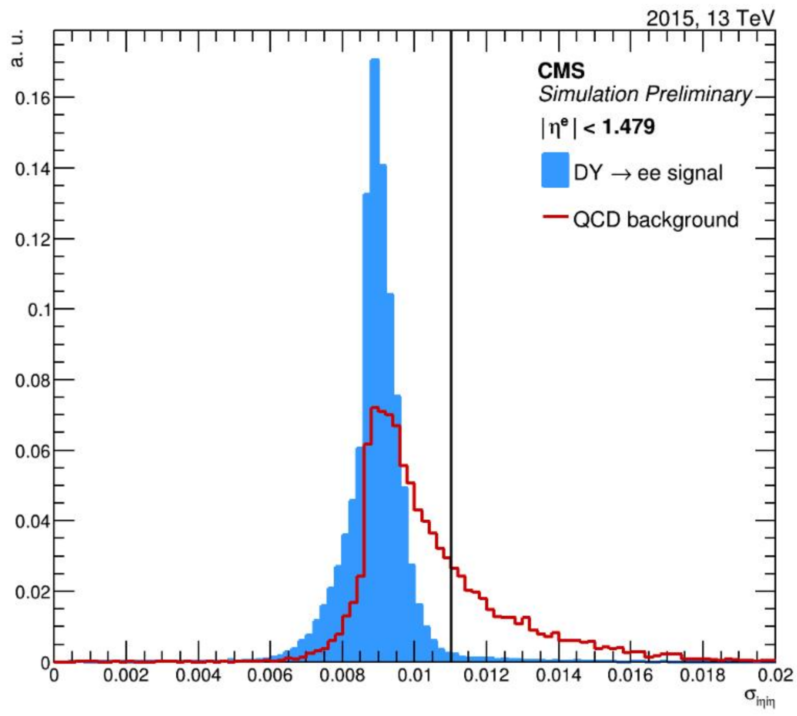


CMSEgammaRun3IDvariable

Most energetic crystal of 5x5 array

$$\sigma_{i\eta i\eta} = \sqrt{\left(\frac{\Sigma_i^{5\times5} w_i(\eta_i - \bar{\eta}_{5\times5})^2}{\Sigma_i^{5\times5} w_i}\right)}$$

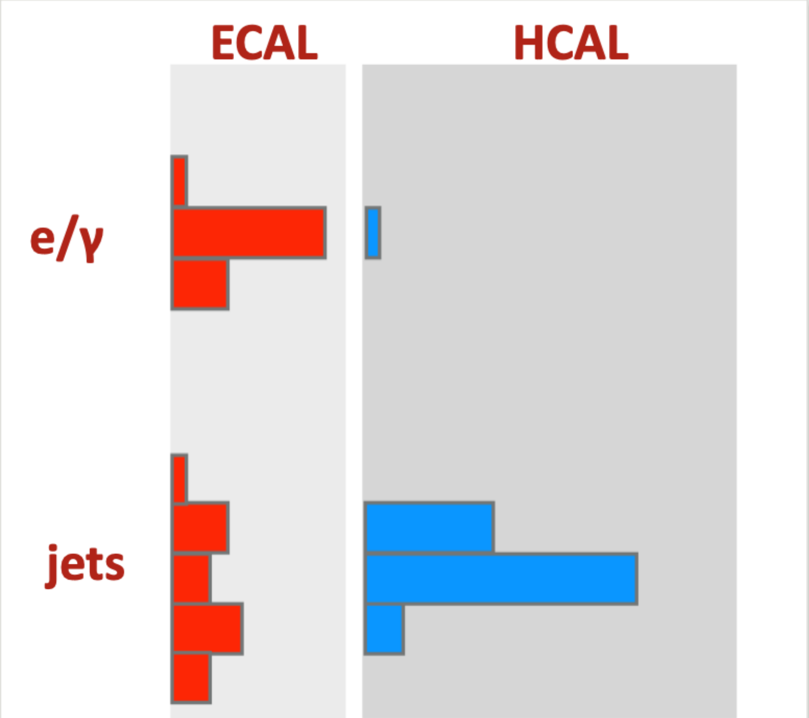
w_i non zero if $E_i > 0.9\%$ of E_{5x5}



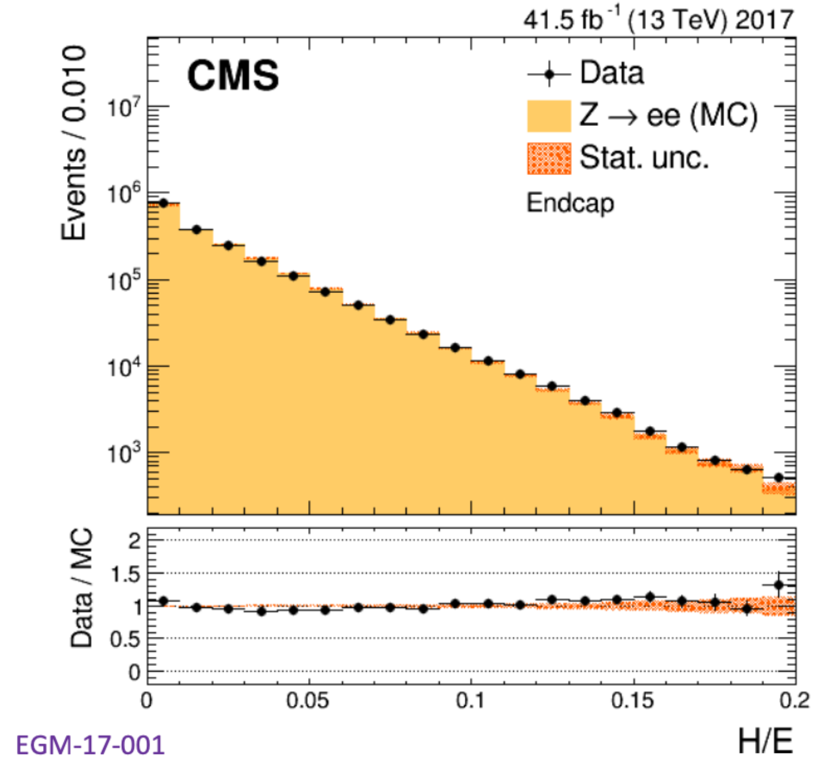
CHEP2015: Electron ID at the HLT

Shower Shape Variables: H/E

- **H/E** is the ratio of the **hadronic energy** to the **electromagnetic energy**
- **Excellent** ID **variable** used in electron and photon identification
- Very **well modelled** in simulation



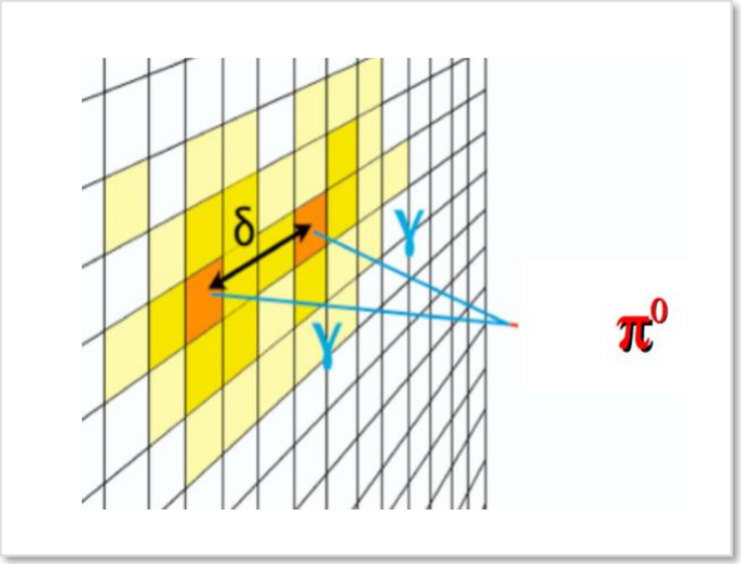
Courtesy of S. Mukherjee

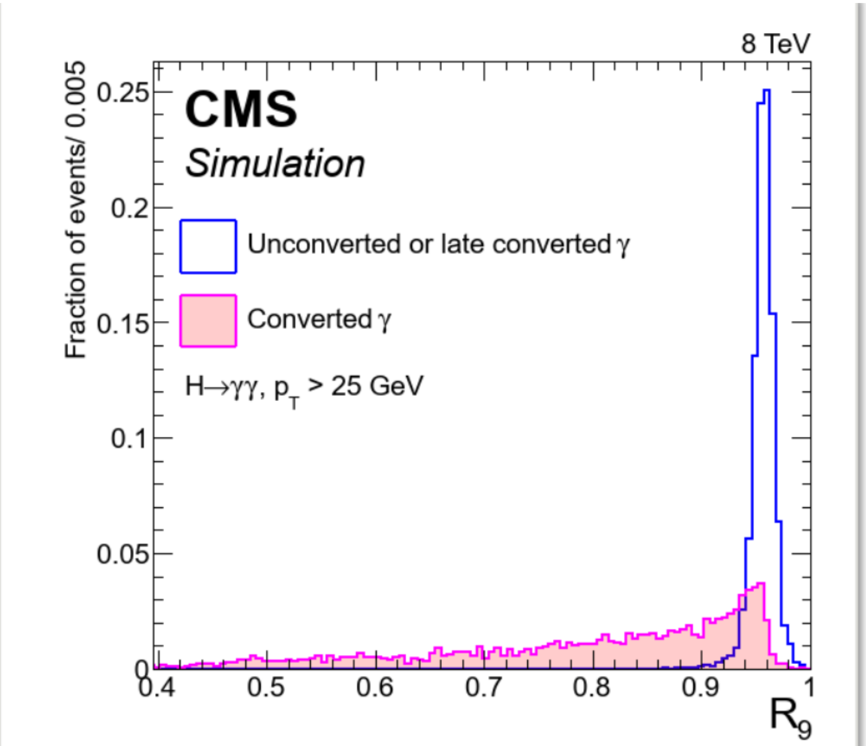


EGM-17-001

Conversion ID Variables: R_9

- **5x5 matrix** contains 96.5% (97.5%) of **unconverted photon energy** in EB (EE)
- **R_9** is the **energy sum** of the **3×3 crystals** centred on the most energetic crystal in the supercluster divided by the **energy** of the **supercluster**
- R_9 helps in **conversions identification** and to distinguish real photons from π_0





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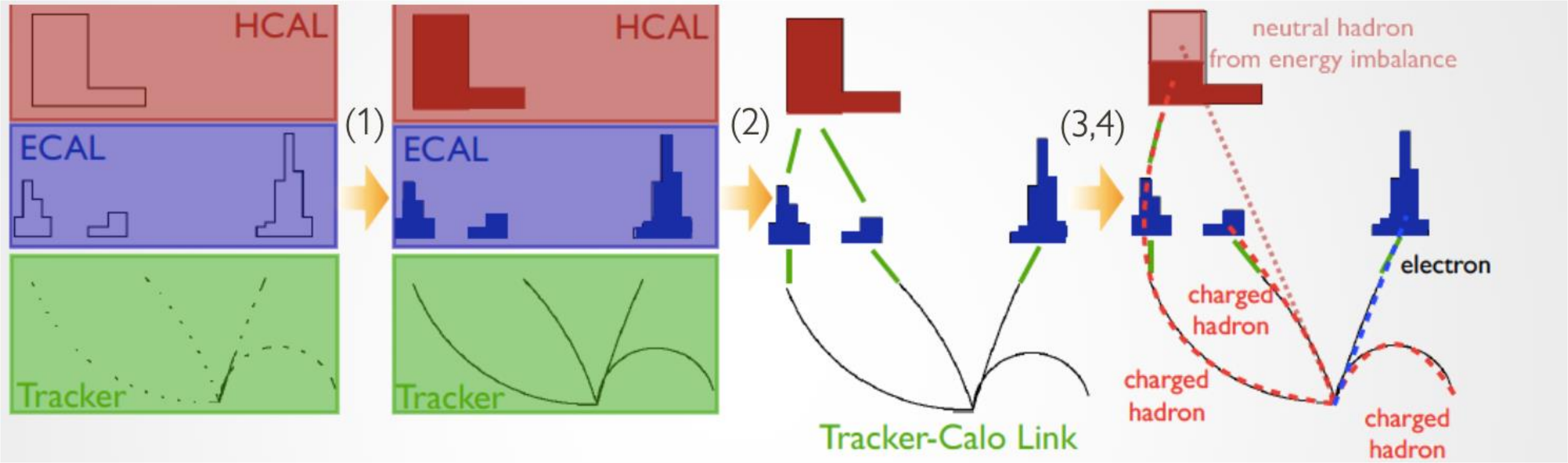
Jet Reconstruction

(Slides are resused from https://indico.cern.ch/event/975141/)

Event Reconstruction



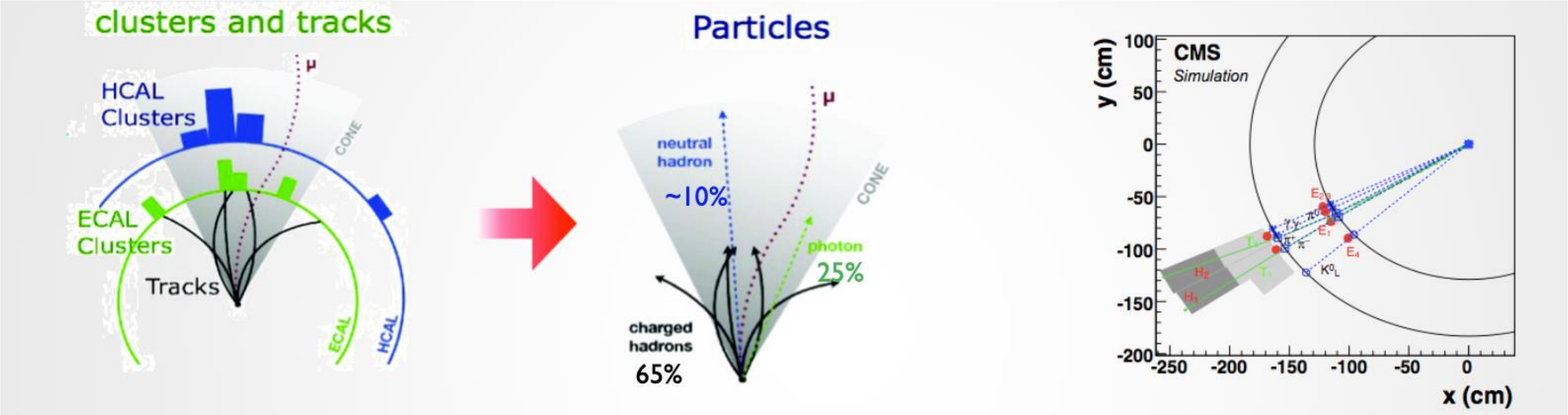
1. Build muon candidates (not shown), tracks, and calorimetry clusters

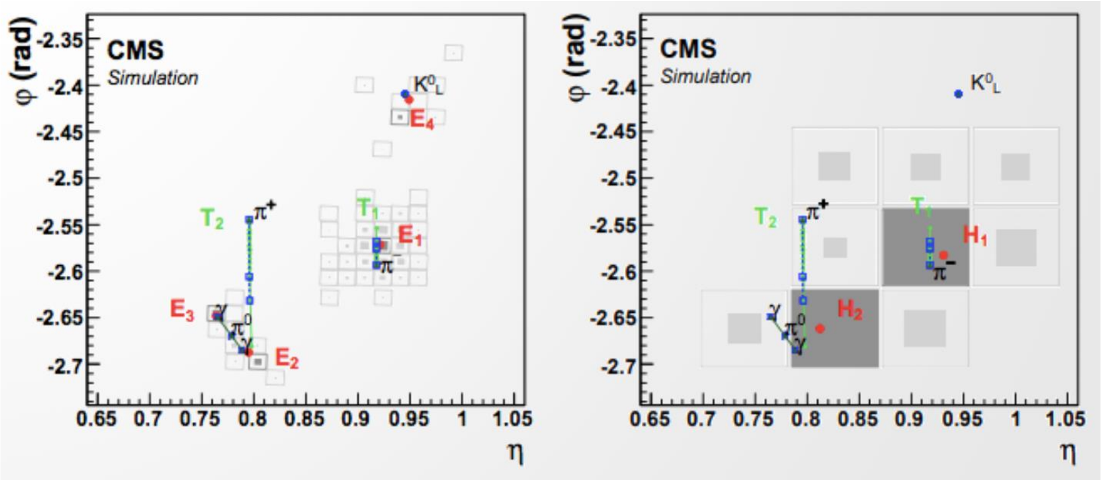
2. Link tracks and the calorimetry clusters based on spatial proximity

3. Identify 'charged hadron candidates' among the links by associating calorimetric energy to track momenta, when tracks are close

4. 'photon' and 'neutral hadron' candidates from excess energy

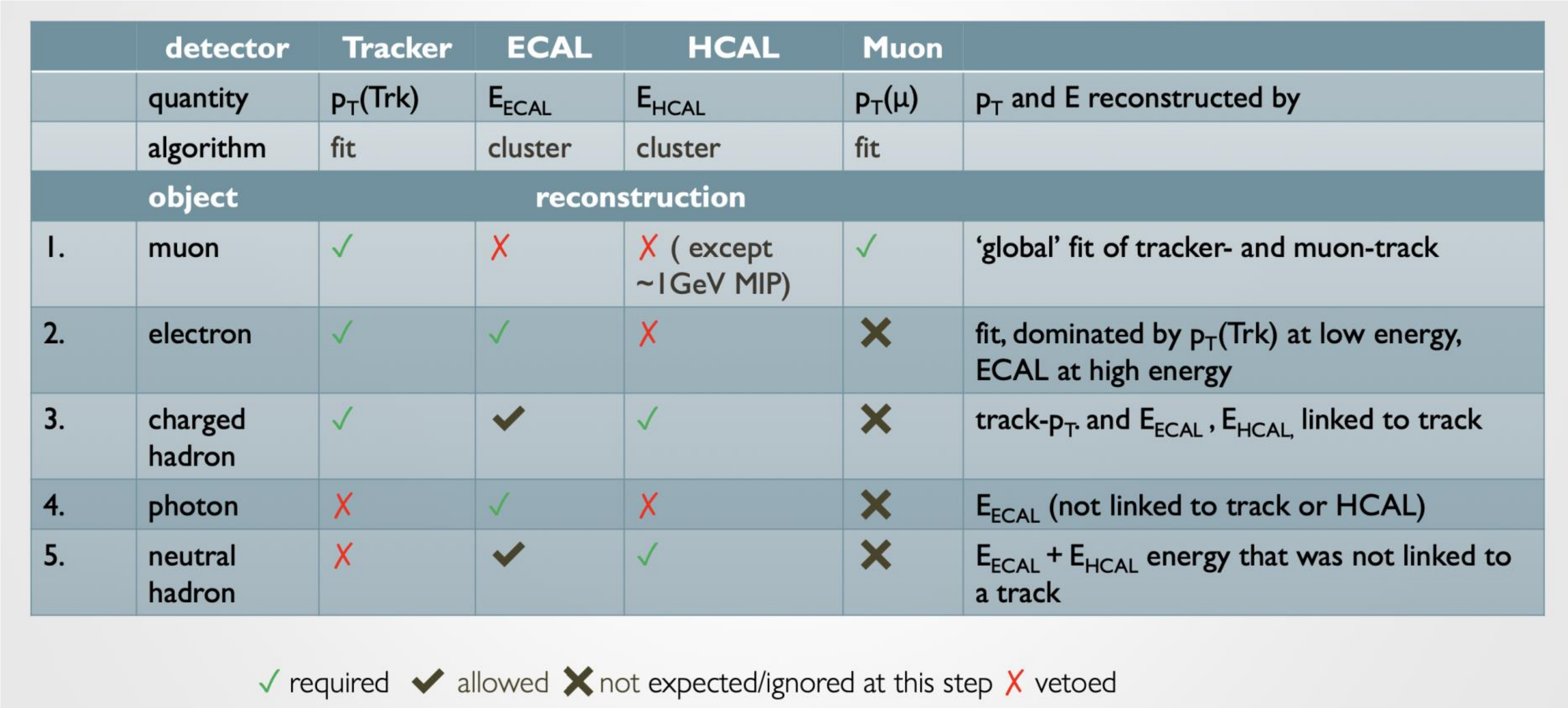
Particle Flow Event Reconstruction





- Reconstruct charged/neutral hadrons, $\gamma, e^{\pm}, \mu^{\pm}$
- fully exploit tracking resolution and fine ECAL granularity
- optimal combination of track and calorimetry resolution

Particle Flow Event Reconstruction



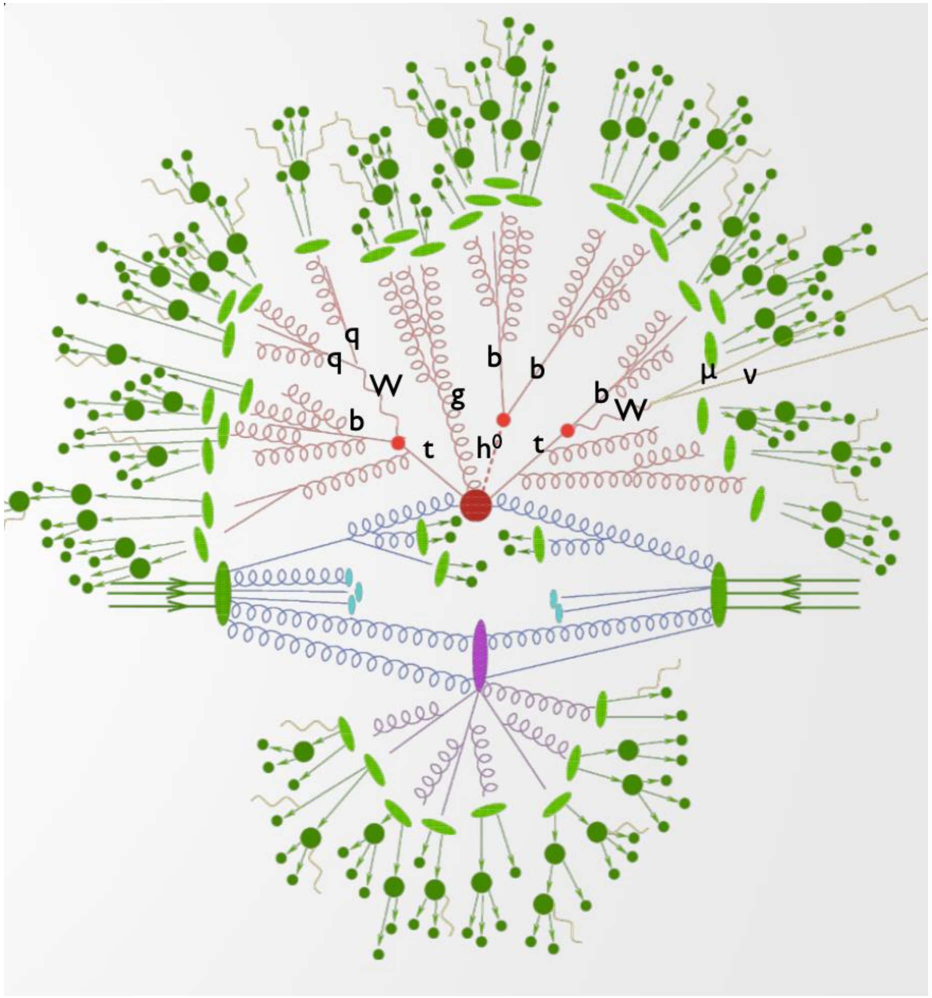
	detector	Tracker	ECAL	HCAL	Muon	
	quantity	p_T(Trk)	E_{ECAL}	E_{HCAL}	$p_T(\mu)$	p_T and E reconstructed by
	algorithm	fit	cluster	cluster	fit	
	object		**reconstruction**			
1.	muon	✓	✗	✗ (except ~1GeV MIP)	✓	'global' fit of tracker- and muon-track
2.	electron	✓	✓	✗	✖	fit, dominated by p_T(Trk) at low energy, ECAL at high energy
3.	charged hadron	✓	✔	✓	✖	track-p_T and E_{ECAL} , $E_{HCAL,}$ linked to track
4.	photon	✗	✓	✗	✖	E_{ECAL} (not linked to track or HCAL)
5.	neutral hadron	✗	✔	✓	✖	E_{ECAL} + E_{HCAL} energy that was not linked to a track

✓ required ✔ allowed ✖ not expected/ignored at this step ✗ vetoed

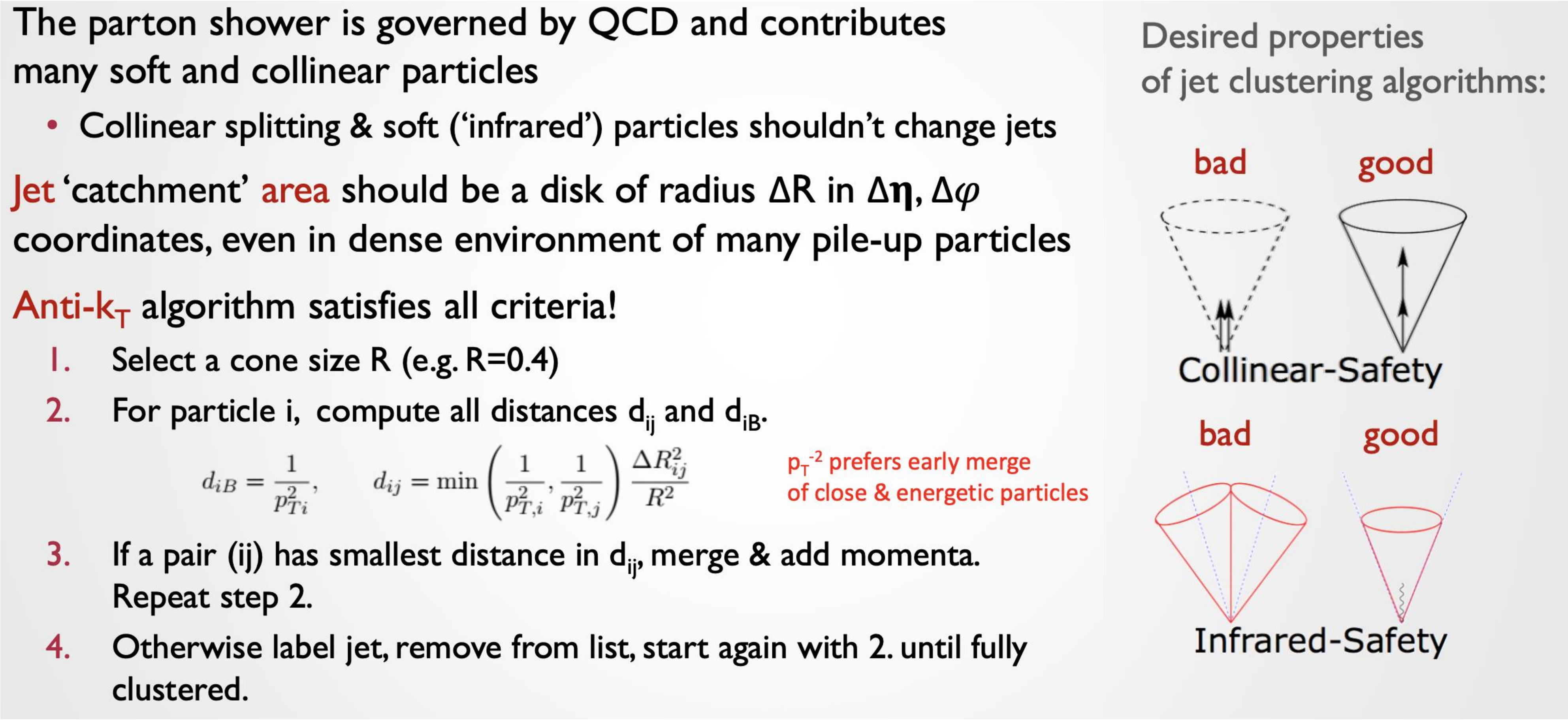
Jet Clustering

Event reconstruction provides list of particle candidates

- Need to correlate 'sprays' of particles from hadronization (jets) with the initial partons of the hard scatter event
- This is done by "sequential" jet clustering algorithms:
  - Identify seeds and devise a recursive procedure to associate other particles until the whole event is clustered
  - Controlled by an angular distance measure e.g. AR=0.4 ('slim' jets) or 0.8/1.0/1.2 ('fat' jets) that defines the angular size of the jets



Jet Clustering



The parton shower is governed by QCD and contributes many soft and collinear particles

- Collinear splitting & soft ('infrared') particles shouldn't change jets

Jet 'catchment' area should be a disk of radius ΔR in $\Delta\eta$, $\Delta\varphi$ coordinates, even in dense environment of many pile-up particles

Anti-k_T algorithm satisfies all criteria!

1. Select a cone size R (e.g. R=0.4)
2. For particle i, compute all distances d_{ij} and d_{iB}.

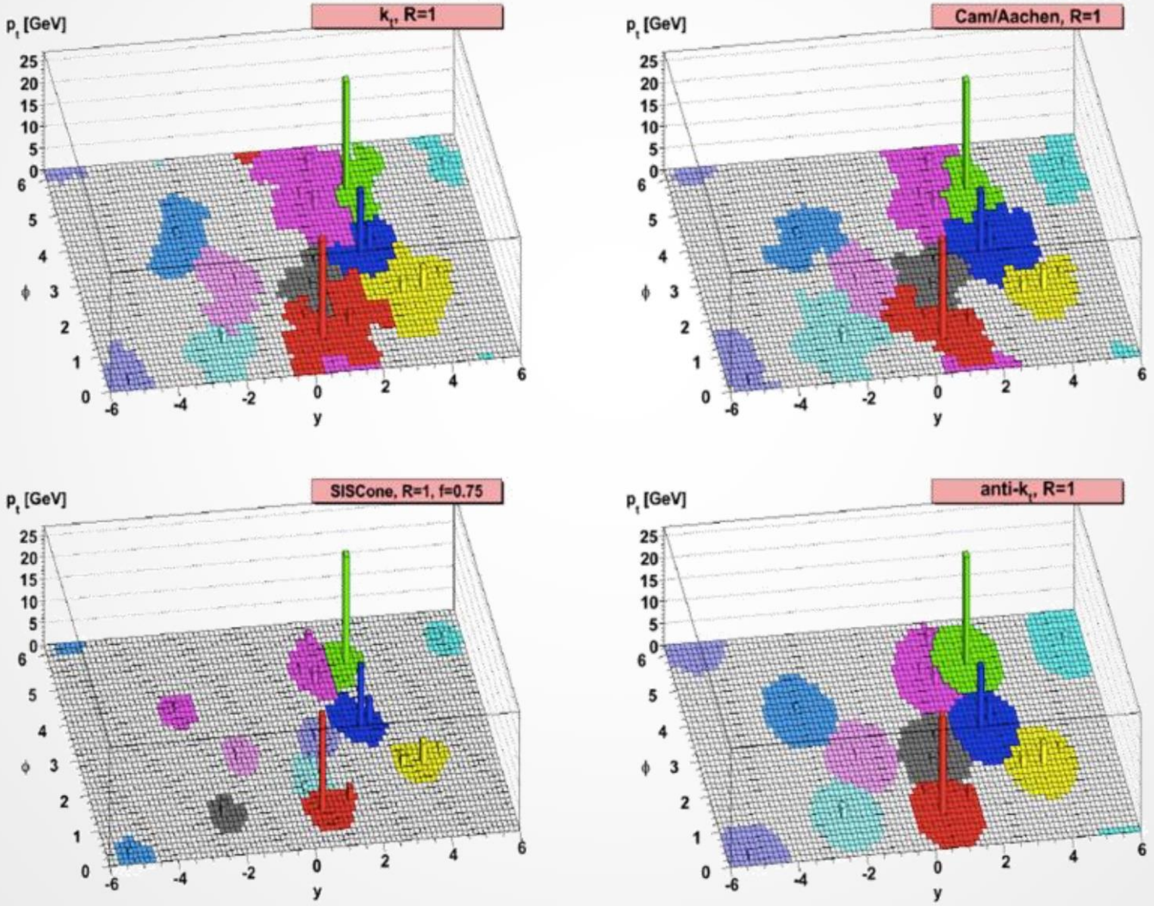
$$d_{iB} = \frac{1}{p_{Ti}^2}, \qquad d_{ij} = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

p_T^{-2} prefers early merge of close & energetic particles

3. If a pair (ij) has smallest distance in d_{ij}, merge & add momenta. Repeat step 2.
4. Otherwise label jet, remove from list, start again with 2. until fully clustered.

Desired properties of jet clustering algorithms:

Jet Algorithms



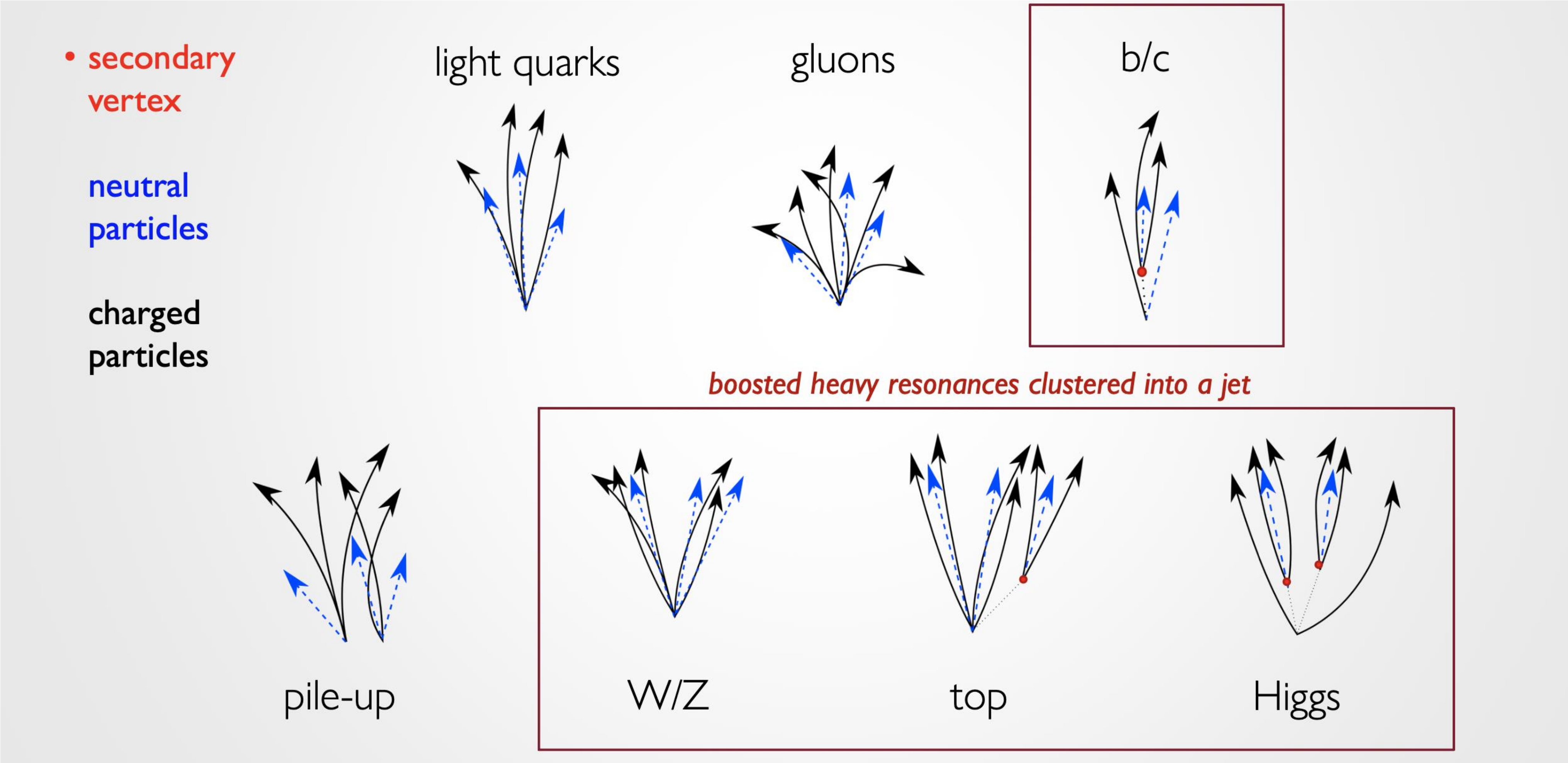
k_T algorithm
use p_T^2 instead of p_T^{-2}
late merge of high p_T objects (interesting for jet substructure information)

Cambridge-Aachen (CA)
Same as kT but only using ΔR

SisCone algorithm
Tries to find 'stable cones' when iterating an association procedure

Anti-k_T
Standard algorithm

Jet Substructure



- secondary vertex

neutral particles

charged particles

light quarks

gluons

b/c

boosted heavy resonances clustered into a jet

pile-up

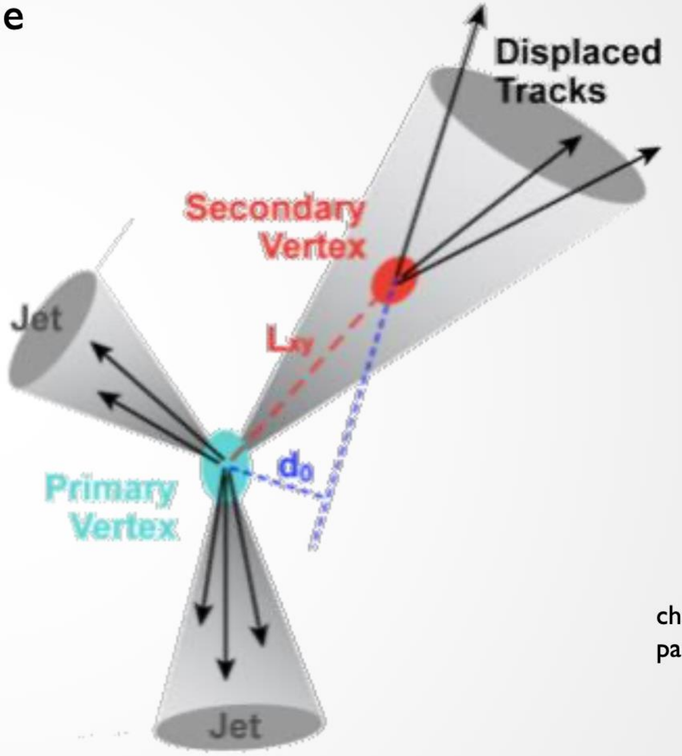
W/Z

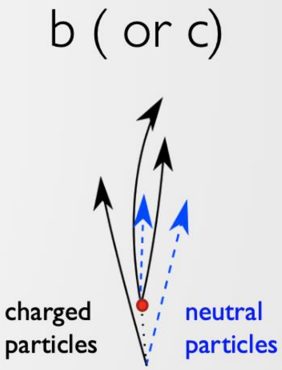
top

Higgs

Tagged Jets

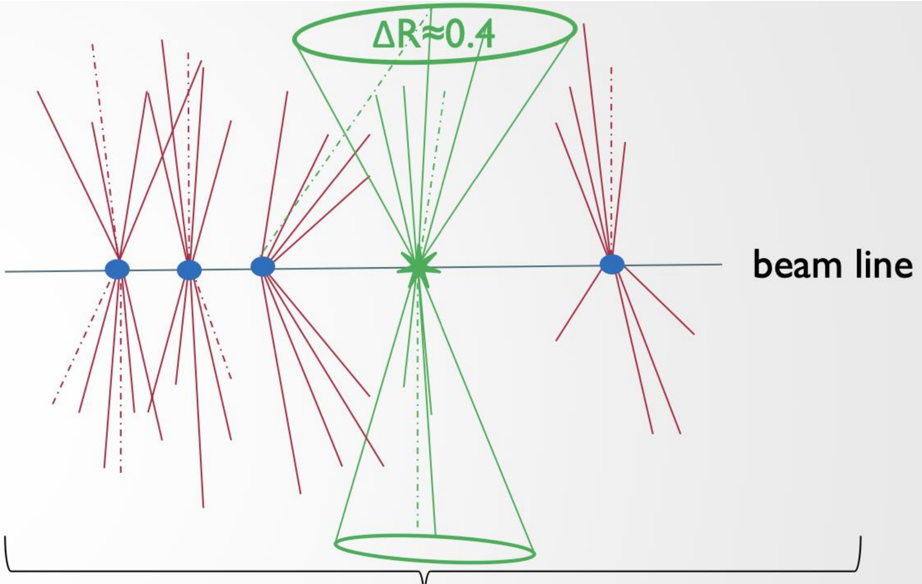
- in many physical processes, b-quarks play a crucial role
  - e.g. $t \longrightarrow bW$ with BR≈100%
- b-quarks hadronize into B-hadrons
- B-hadrons have a finite life time
  - displaced particles are clustered in jet
- Identify b-jets by the properties of the decay products
  - B-hadron with ~5 GeV mass
  - large life-time $c\tau \approx 450\mu$m, at E=70 GeV: $\beta\gamma c\tau \approx$ 5mm
    - displaced vertex identified by finding tracks that cross at large impact parameter L_{xy}, d_0
  - ~3 tracks at the displaced vertex
  - potentially a lepton at the displaced vertex
  - potentially tertiary vertex (B-meson decay to charmed hadron $c\tau \approx$ 120-310μm)
- all information is used in MVA classifier: typically find 60% at 1% mistag





Pile-Up Cleanup

- There are 10-40 pile-up (PU) collisions at each bunch crossing
  - Need to remove particles from PU collisions
- Vertices with charged particles are identified, and the most energetic one (leading vertex) is associated with a 'hard scatter'
- Remove all charged particles without association to the leading vertex
  - 'Charged hadron subtraction'
  - Neutral particles have no vertex association).
- Now proceed with jetclustering
  - neutral hadrons and photons from pile-up are a problem. How can it be tackled?



<pile-up>=25 collisions on a stretch of ~20cm
Minimum separation between vertices ~0.1mm

— charged hadron/e/μ from hard scatter
— charged hadron/e/μ from pile-up
-·-·- neutral hadron or photon
— particle in a jet
● pile-up collision
✳ hard scatter

Summary

Event reconstruction is a very rich topic. It combines particle interactions, detector knowledge, computing, algorithms, machine learning etc.

Event reconstruction is based on identification and reconstruction of individual objects such as tracks, vertices, electrons, photons, jets.

Data analysis is possible thanks to these objects.