Introduction to particle physics: experimental part

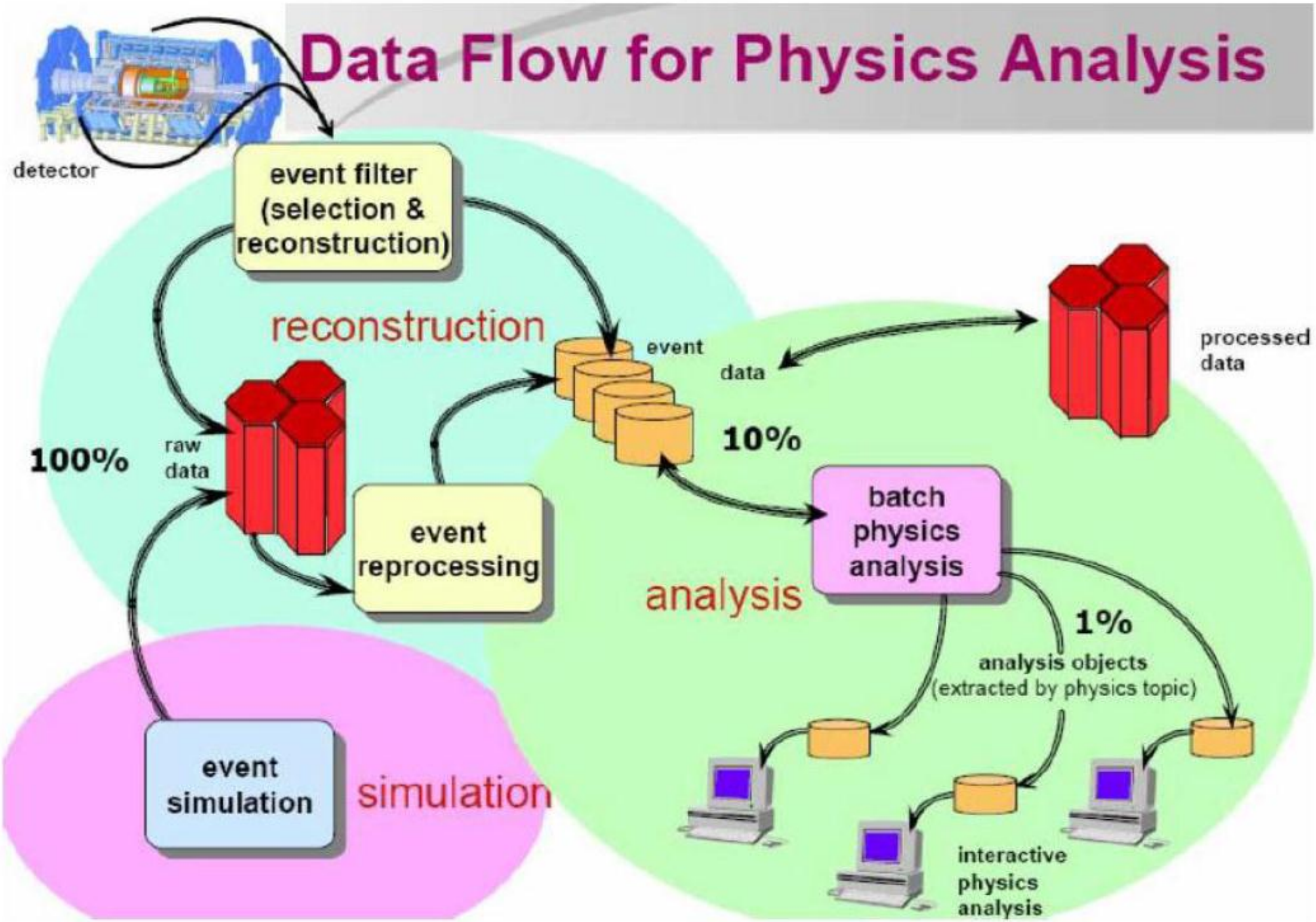
- **RAW data to Physics**
  - **The road from collisions to physics publications**

- **From RAW data to Standard Model particles**
  - **About measuring properties of the final particles created from proton-proton collisions**

- **From Standard Model particles to measurements and searches**
  - **About how we analys data using ingredients we have constructed**

Large fraction of slides from A. Sfyrla lectures at CERN Summer School 2018

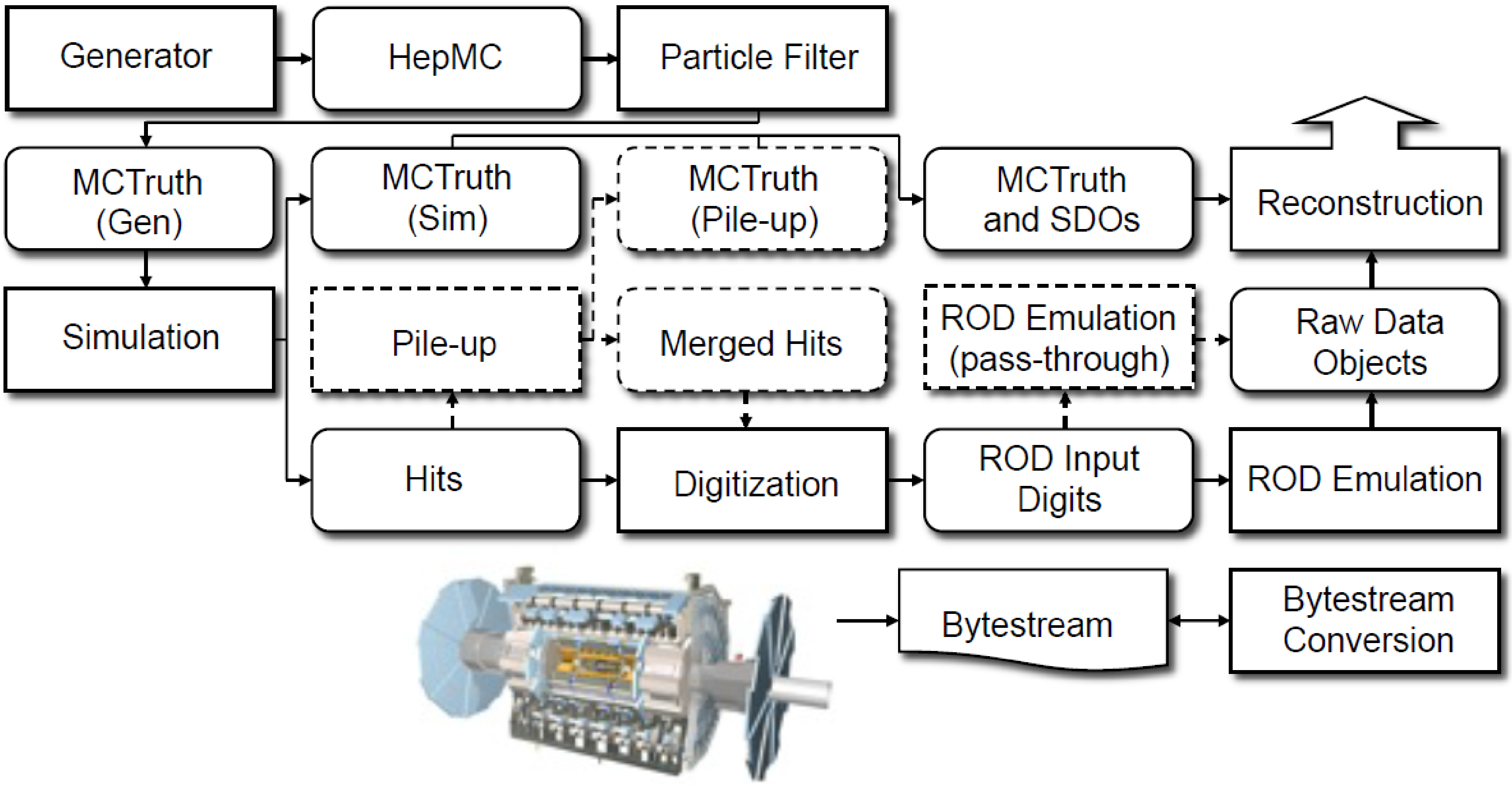
Prof. dr hab. Elżbieta Richter-Wąs


Data Flow for Physics Analysis
detector
event filter (selection & reconstruction)
reconstruction
event data
processed data
100%
raw data
10%
event reprocessing
batch physics analysis
analysis
1%
analysis objects (extracted by physics topic)
event simulation
simulation
interactive physics analysis

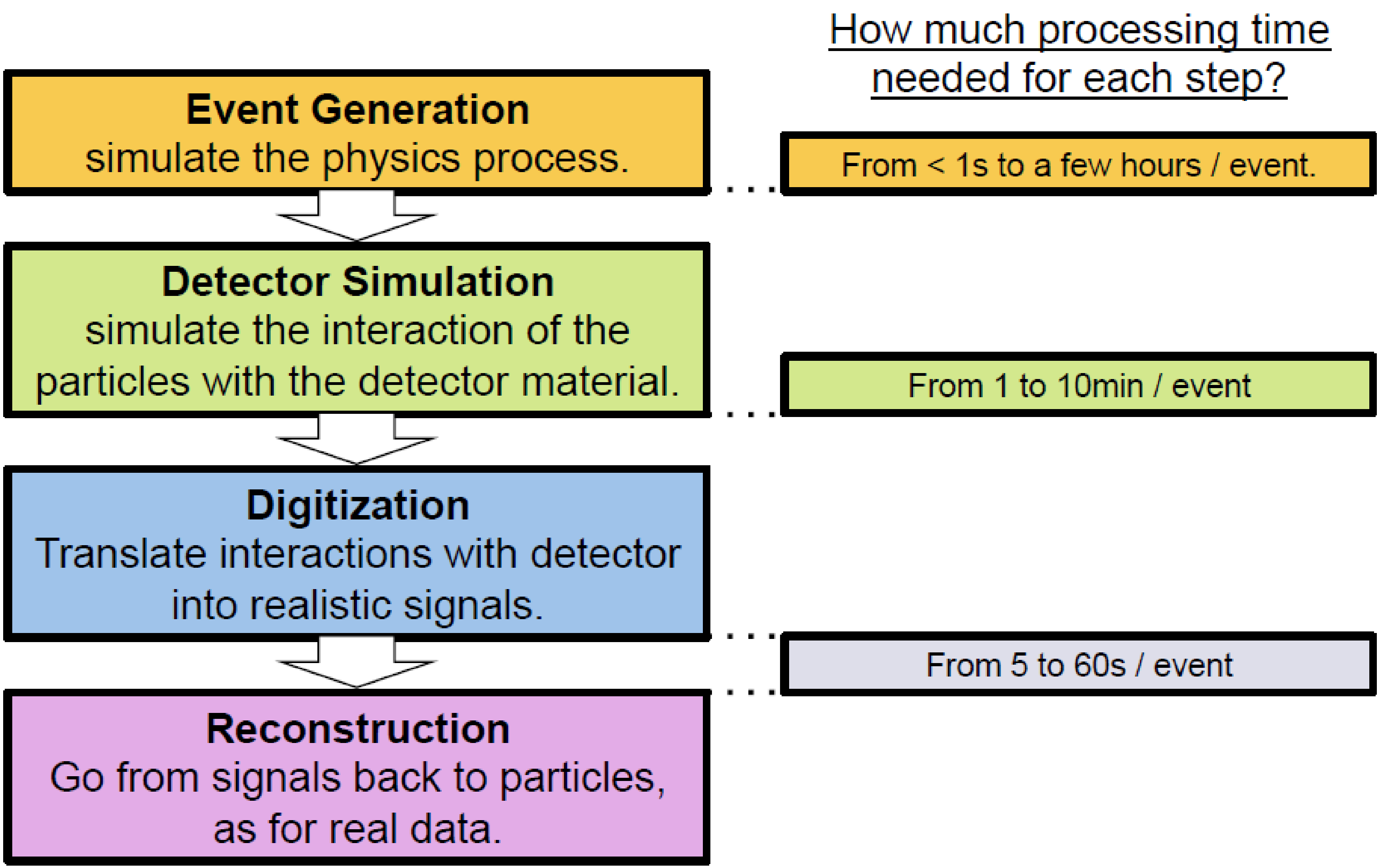
Monte Carlo simulation – why?

- **We only build one detector.**
  - How do we compromise physics due to detector design?
  - How would a different detector design affect measurements?
  - How does the detector behave to radiation?
- **In the detectors we only measure voltages, currents, times.**
  - It's an *interpretation* to say that such-and-such particle caused such-and-such signature in the detector.
  - Simulating the detector behavior we correct for inefficiencies, inaccuracies, unknowns.
- **We need a theory to tell us what we expect and to compare our data against.**
- **A good simulation is the way to demonstrate to the world that we understand the detectors and the physics we are studying.**

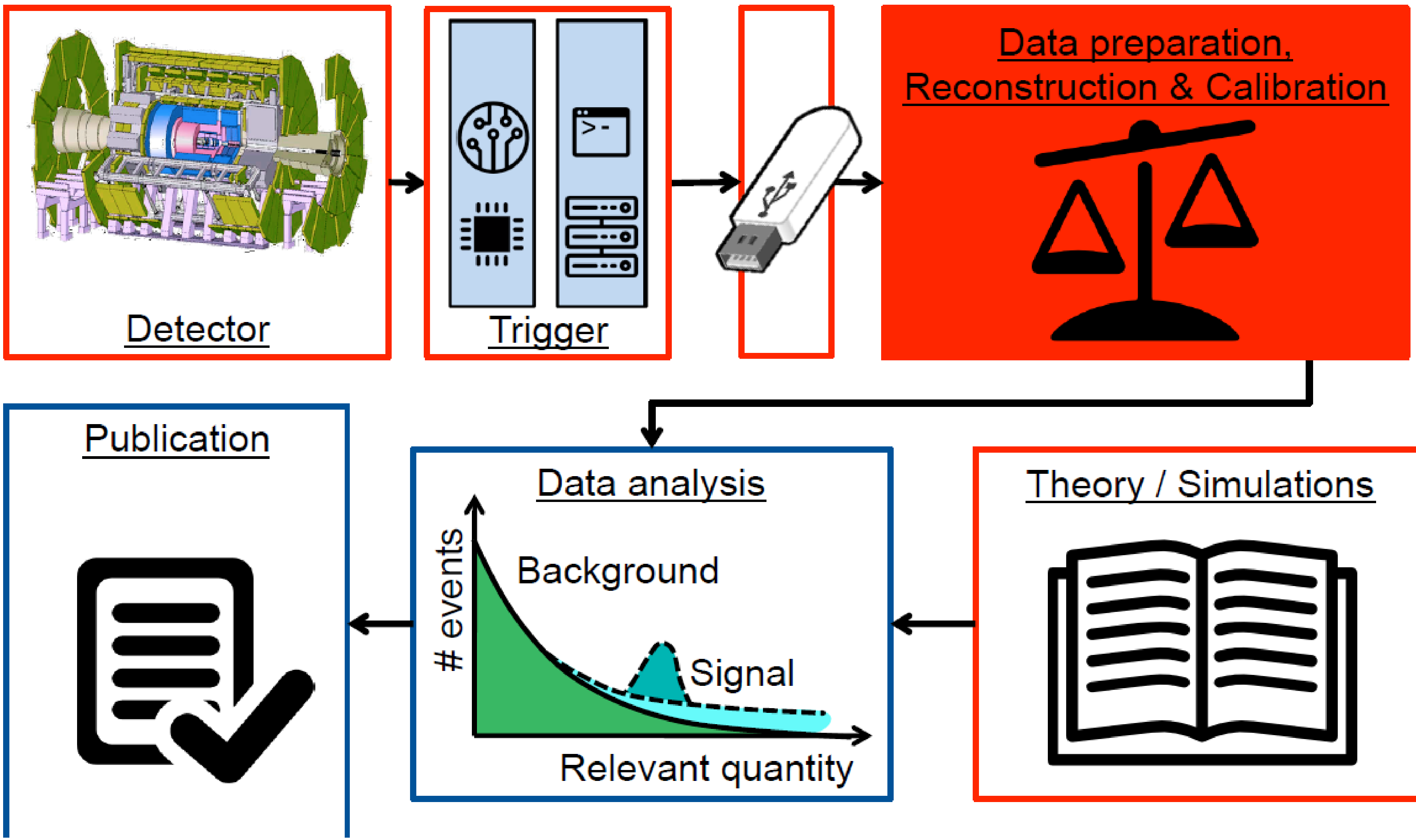
LHC simulation chain



Monte Carlo production chain



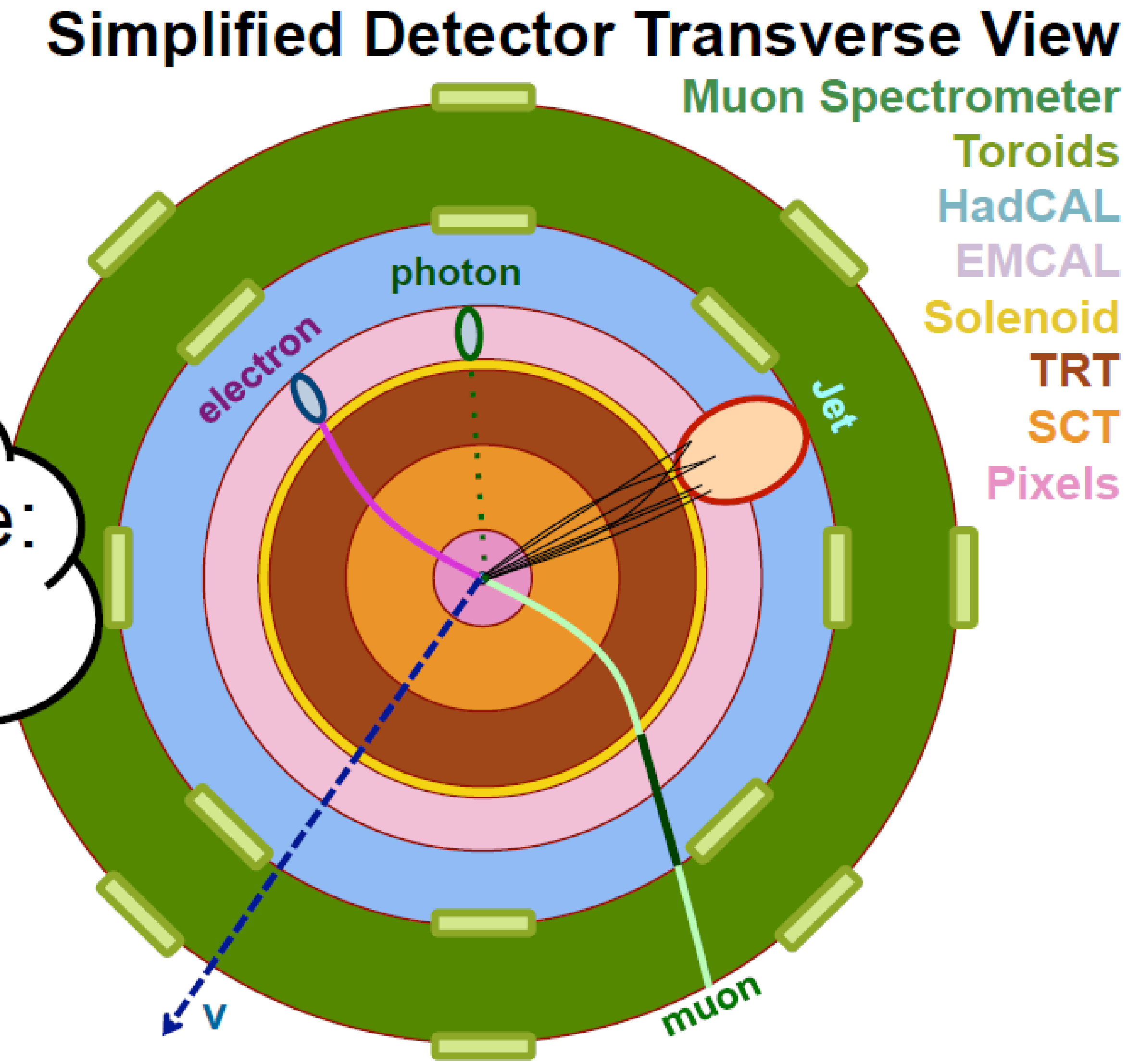
An event’s lifetime



What do we reconstruct?

Tracks and **Clusters**

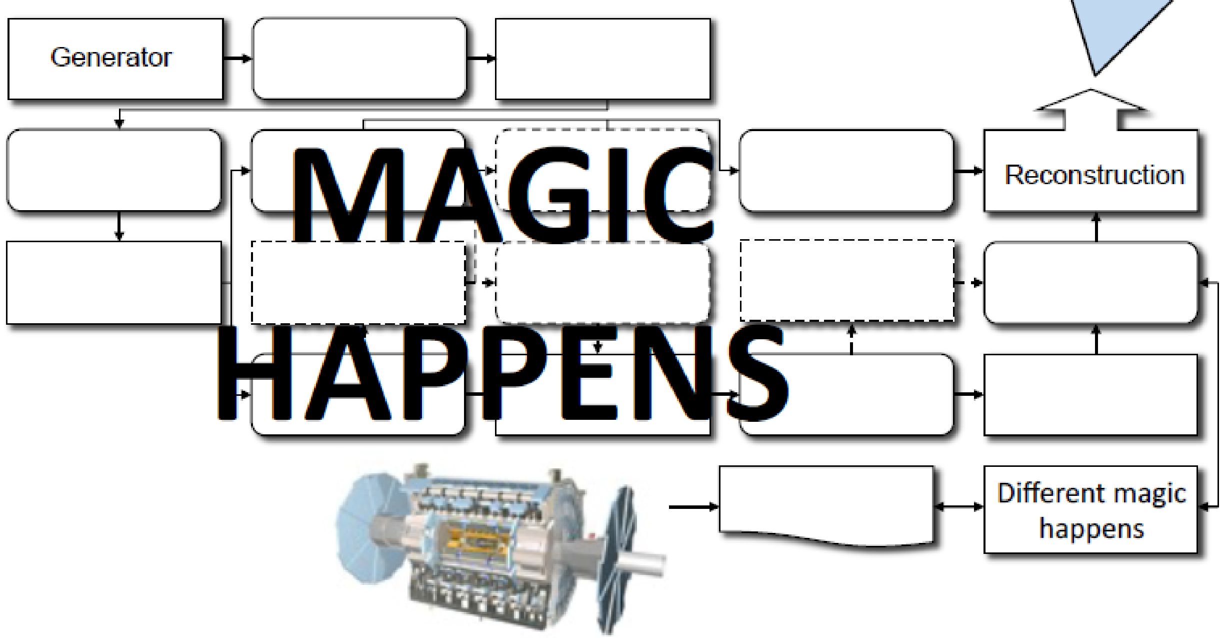
Combining those:
"**objects**"
("particles")



Reconstruction - figures of merit

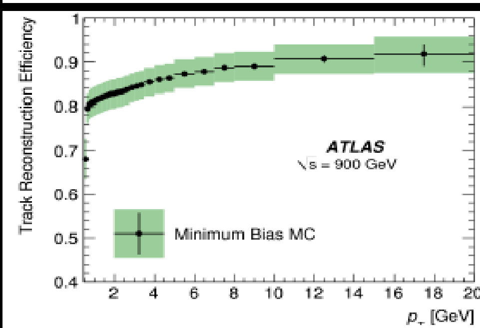
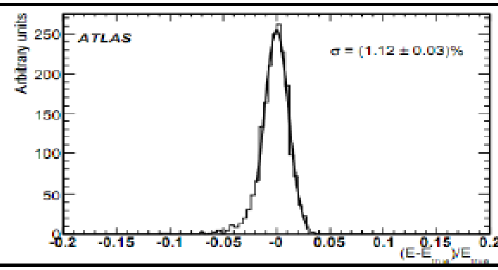
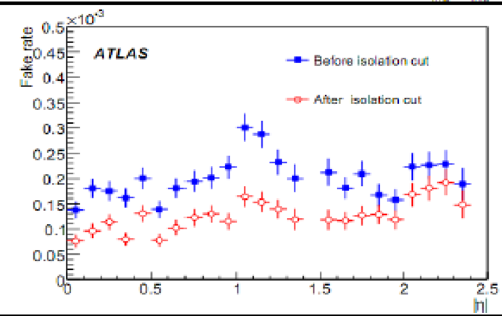
"True" quantities, i.e. quantities at MC generator level

"Reconstructed" quantities, i.e. quantities after having run detector simulation, digitization and reconstruction



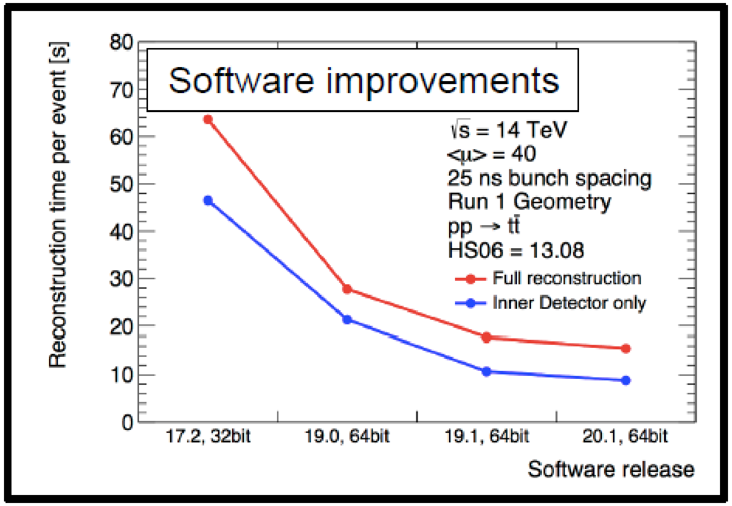
Reconstruction - figures of merit

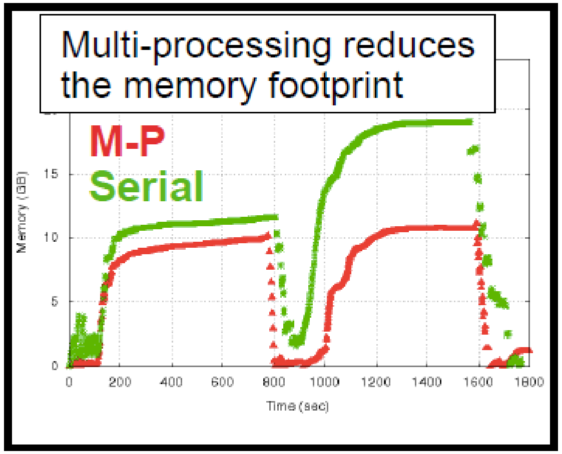
“true” quantity:
quantity at MC generator level.

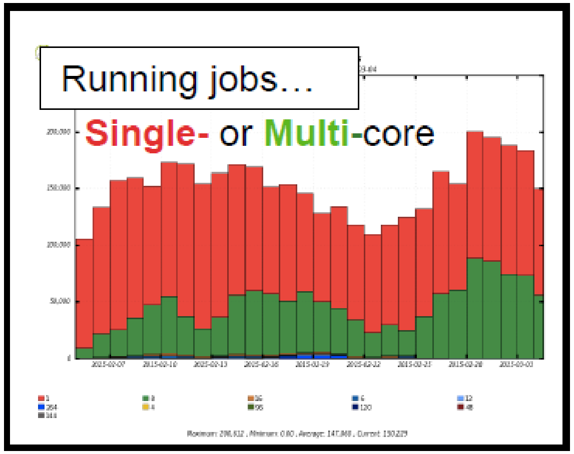
	Definition	Example		Needs be:
Efficiency	how often do we reconstruct the object	tracking efficiency = (number of reconstructed tracks) / (number of true tracks)		High
Resolution	how accurately do we reconstruct the quantity	energy resolution = (measured energy – true energy) / (true energy)		Good
Fake rate	how often we reconstruct a different object as the object we are interested in	a jet faking an electron, fake rate = (Number of jets reconstructed as an electron) / (Number of jets)		Low

Reconstruction - goals

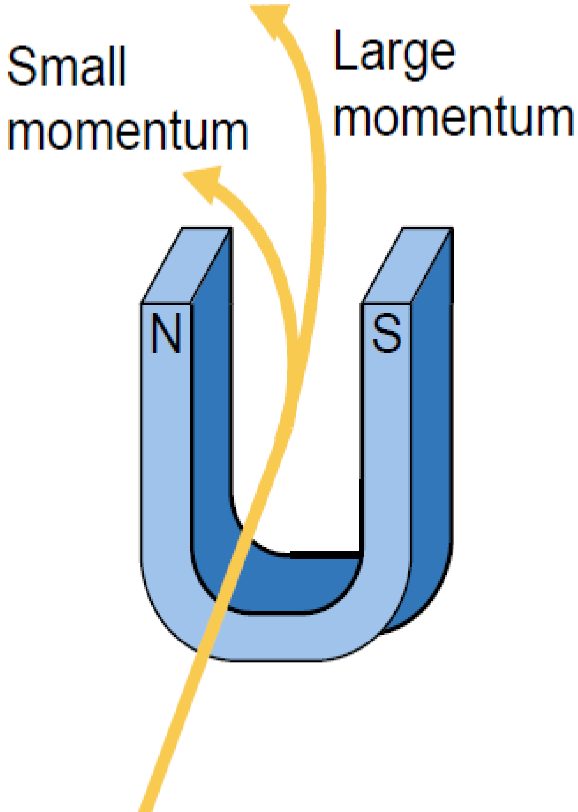
- **High efficiency.**
- **Good resolution.**
- **Low fake rate.**
- **Robust against detector problems and data-taking conditions:**
  - Noise.
  - Dead regions of the detector.
  - Increased pile-up.
- **Computing-friendly.** →
  - CPU time per event.
  - Memory use.

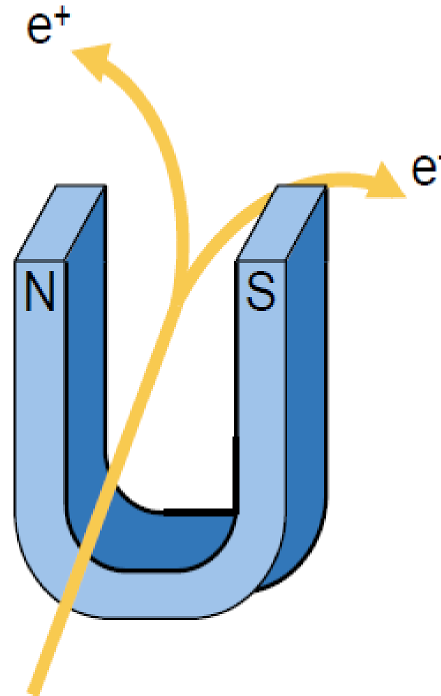






Why do we need magnetic field?

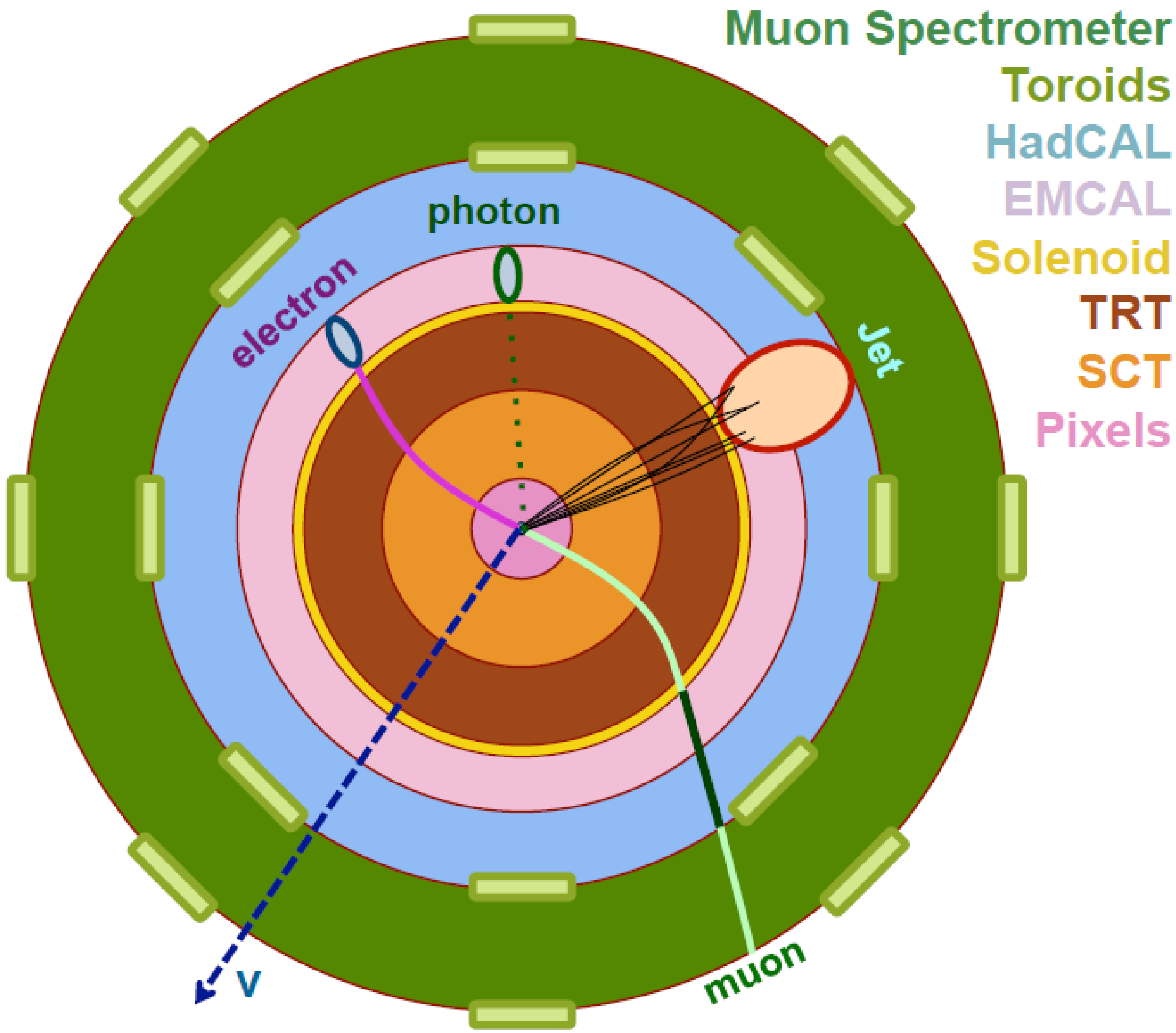




What do we reconstruct?

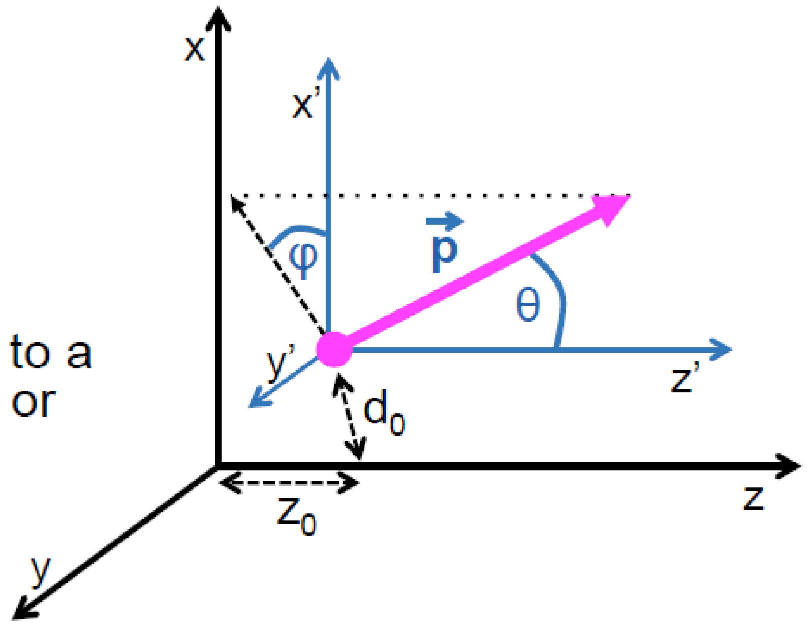
Tracks and Clusters

Simplified Detector Transverse View



Tracking in a nutshell

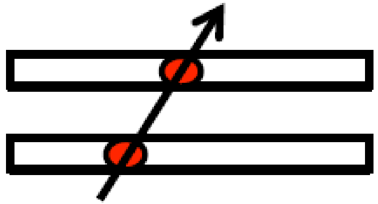
- **A track represents a measurement of a charged particle that leaves a trajectory as it passes through the detector.**
- **For a track we measure:**
  - Its momentum;
  - It's direction;
  - Its charge;
  - Its "perigee": the closest point to a reference line, transverse (d_0) or longitudinal (z_0).



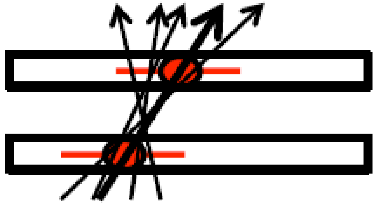
- **Tracks are key ingredients of most of particle reconstruction.**

Tracking in a nutshell: track fitting

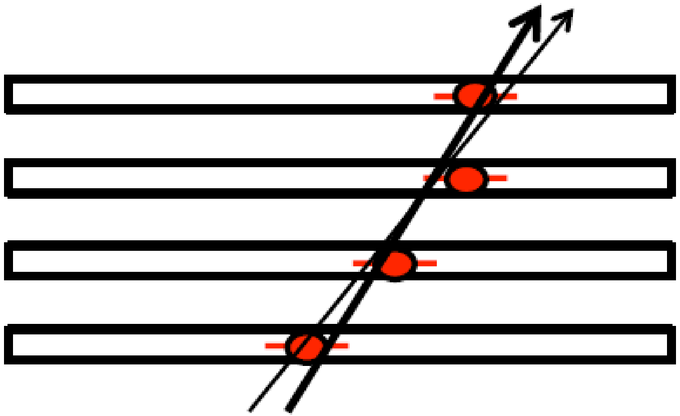
- **Perfect measurement – ideal**



- **Imperfect measurement – reality**



- **Small errors and more points help to constrain the possibilities**



- **Quantitatively:**
  - Parameterize the track;
  - Find parameters by Least-Squares-Minimization;
  - Obtain also uncertainties on the track parameters.

Tracking in a nutshell: track fitting

- **For a track we measure:**
  - Its momentum;
  - It's direction;
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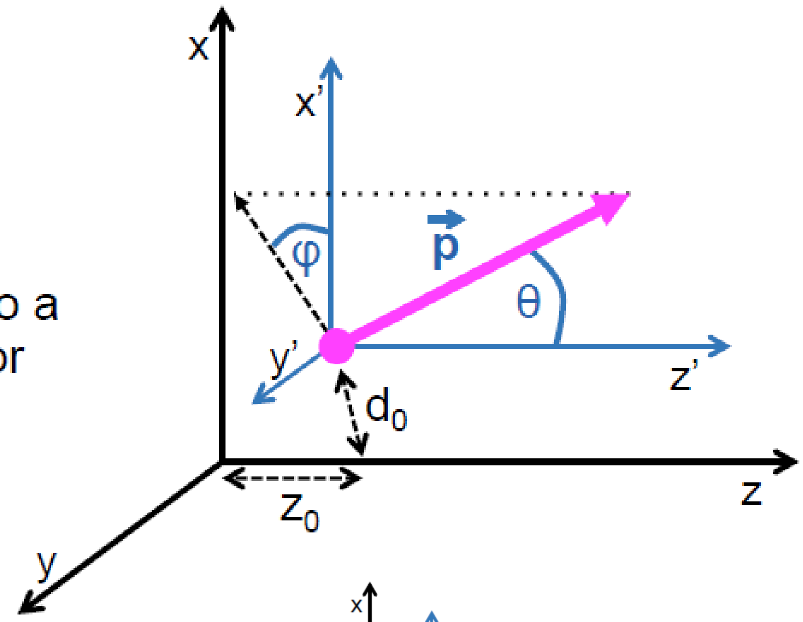
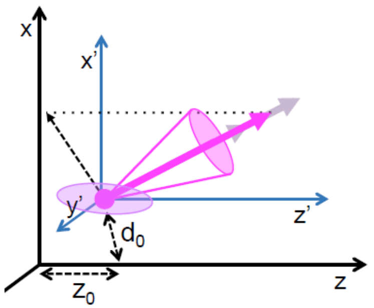


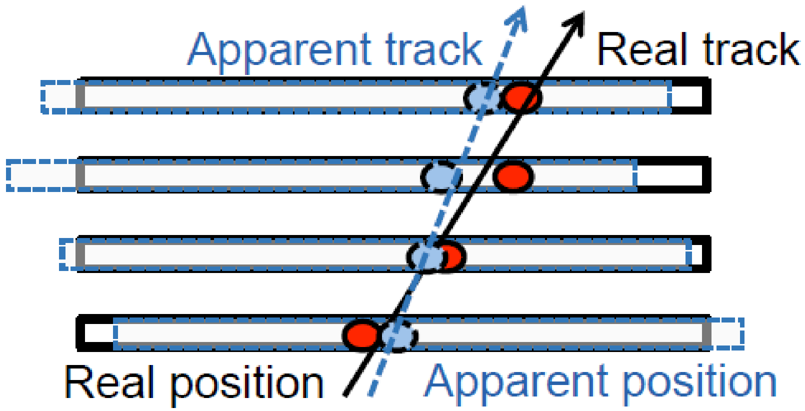
- **Small uncertainties are required.**
  - δd0 is O(10μm) and δθ O(0.1mrad).
  - Allows separation of tracks that come from different particle decays (which can be separated at the order of mm).



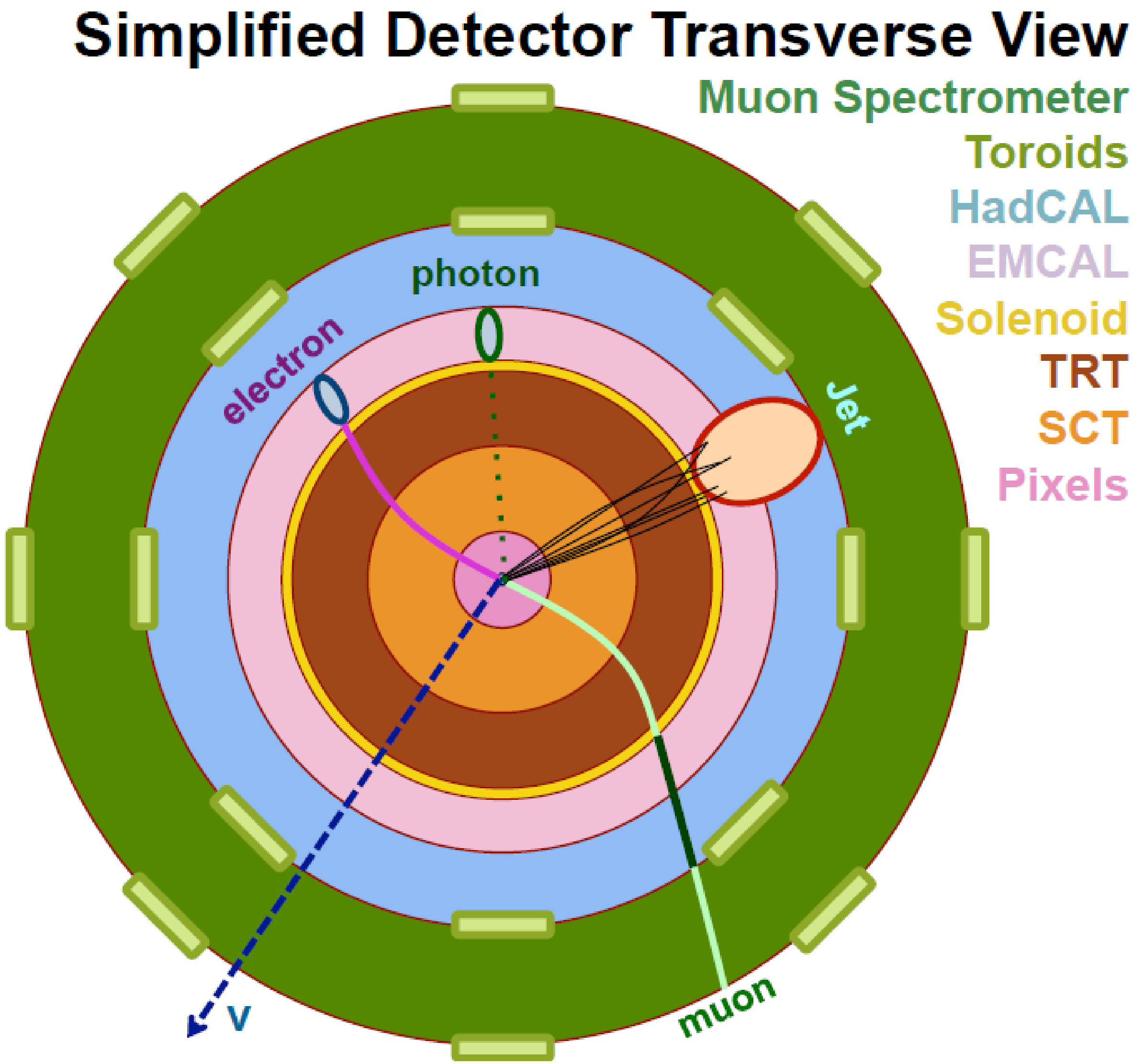
Tracking in a nutshell: the uncertainties

- **Presence of Material**
  - Coulomb scattering off the core of atoms
  - Energy loss due to ionization
  - Bremsstrahlung
  - Hadronic interaction

- **Misalignment**
  - Detector elements not positions in space with perfect accuracy.
  - Alignment corrections derived from data and applied in track reconstruction.

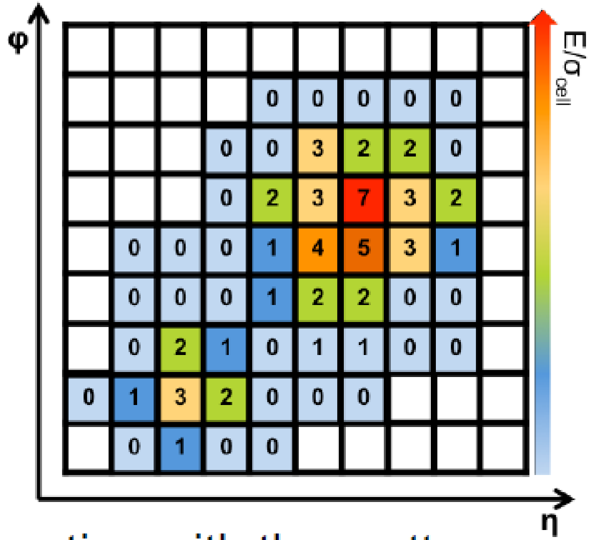


What do we reconstruct?



Clustering in a nutshell

- **Reconstruct energy deposited in the calorimeter by charged or neutral particles; electrons, photons and jets.**
- **For a cluster we measure:**
  - The energy;
  - The position of the deposit;
  - The direction of the incident particles;

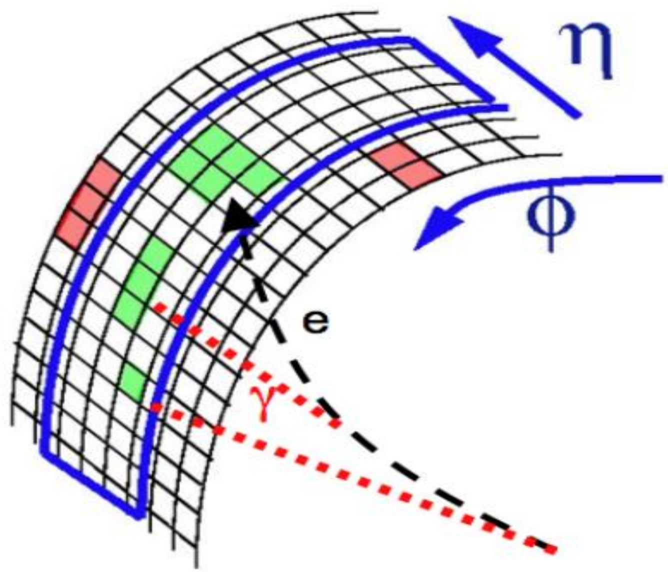


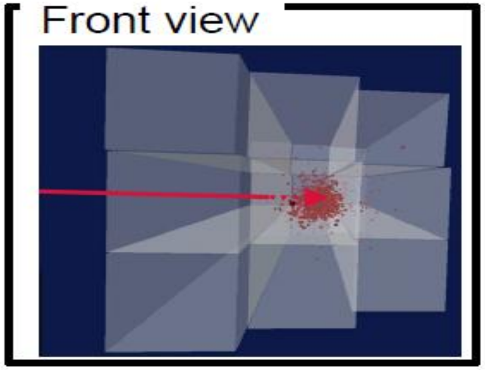
- **Calorimeters are segmented in cells.**
  - Typically a shower created by a particle interacting with the matter extends over several cells.
- **Various clustering algorithms, e.g.:**
  - **Sliding window**. Sum cells within a fixed-size rectangular window.
  - **Topo-clustering**. Start with a seed cell and iteratively add to the cluster the neighbor of a cell already in the cluster.

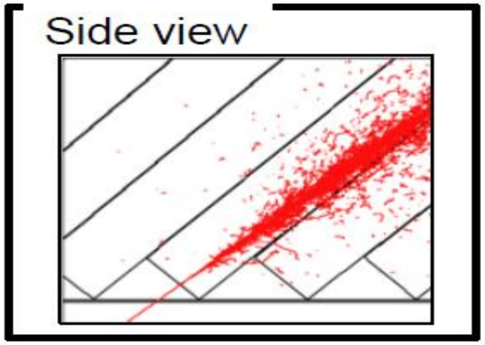
Cluster finding – an example

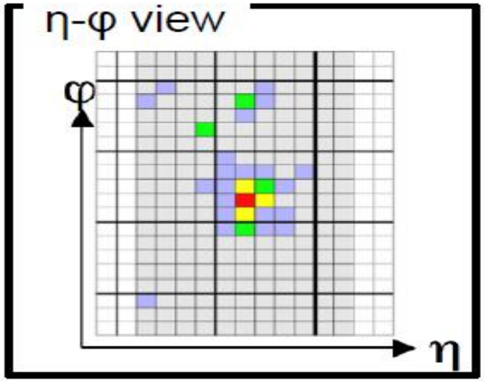
CMS crystal calorimeter – ECAL clusters

◎ electron energy in central crystal ~80%, in 5x5 matrix around it ~96%.

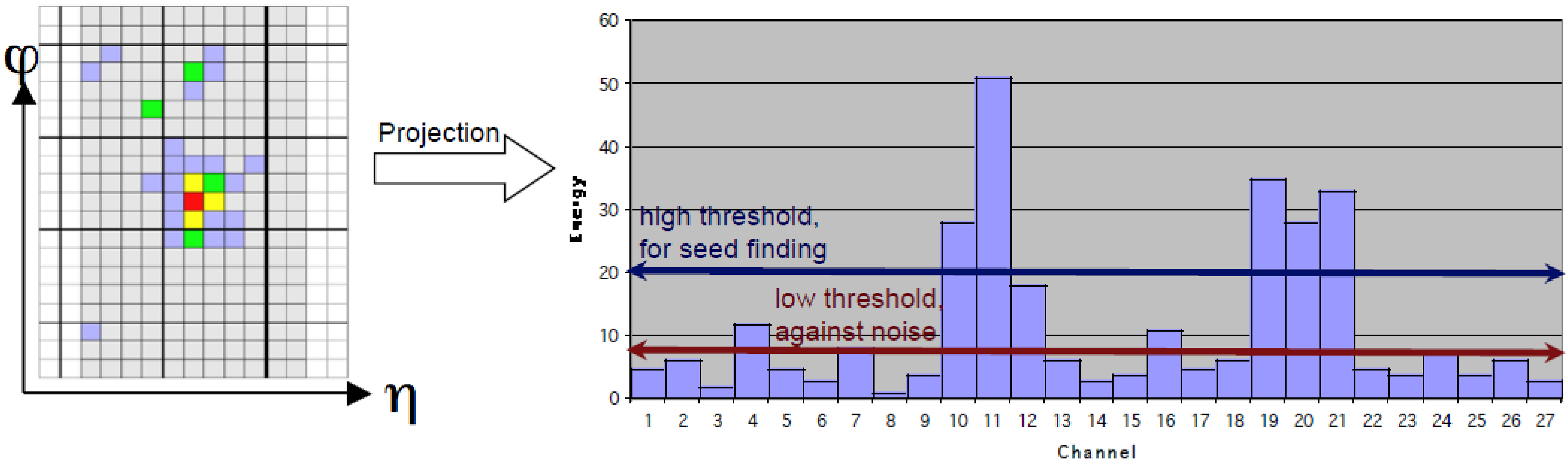








Cluster finding – an example

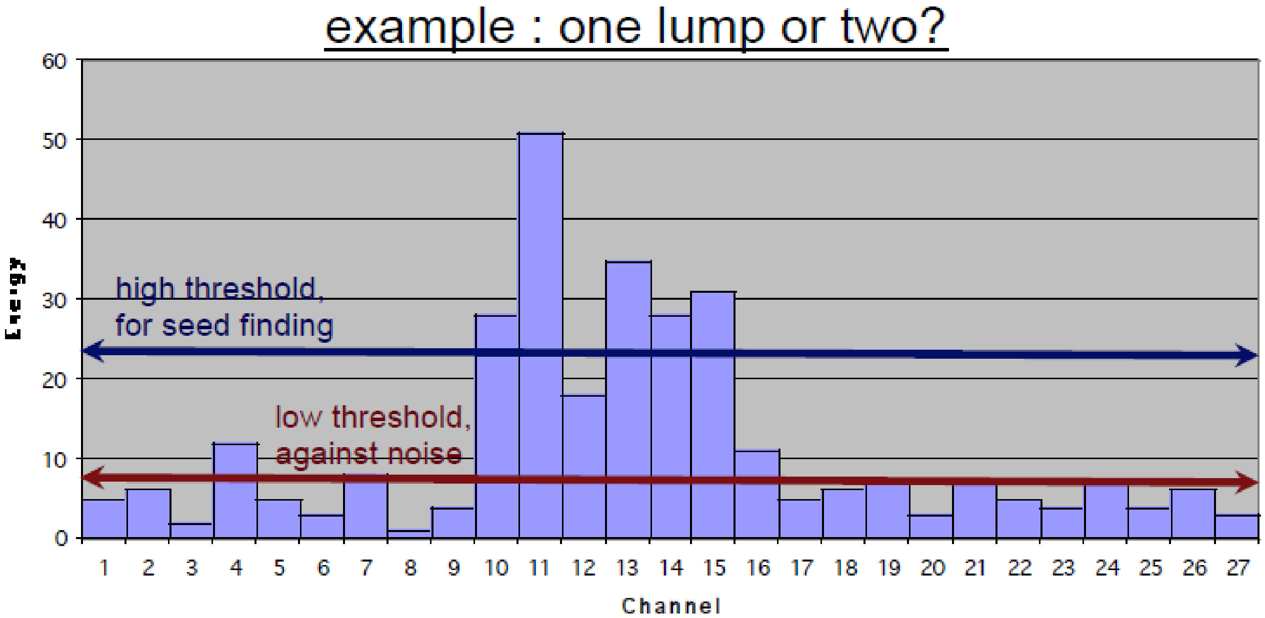


Simple example of an algorithm

- Scan for seed crystals = local energy maximum above a defined seed threshold
- Starting from the seed position, adjacent crystals are examined, scanning first in φ and then in η
- Along each scan line, crystals are added to the cluster if
    1. The crystal's energy is above the noise level (lower threshold)
    2. The crystal has not been assigned to another cluster already

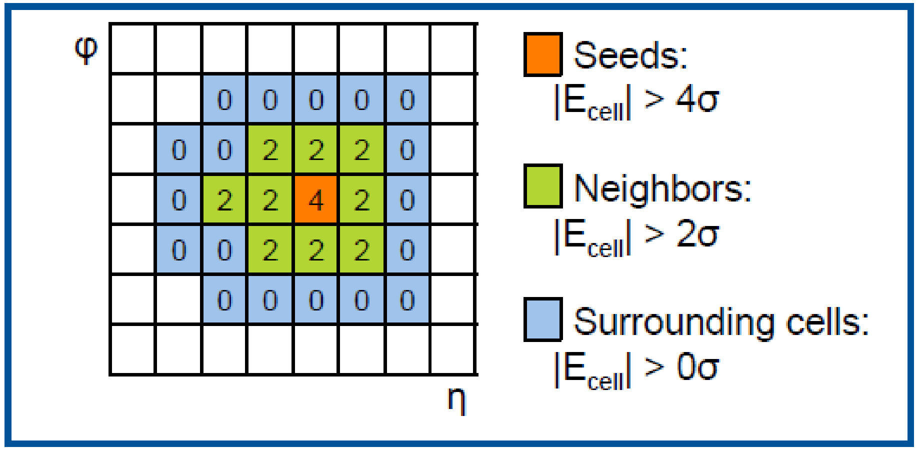
Cluster finding – difficulties

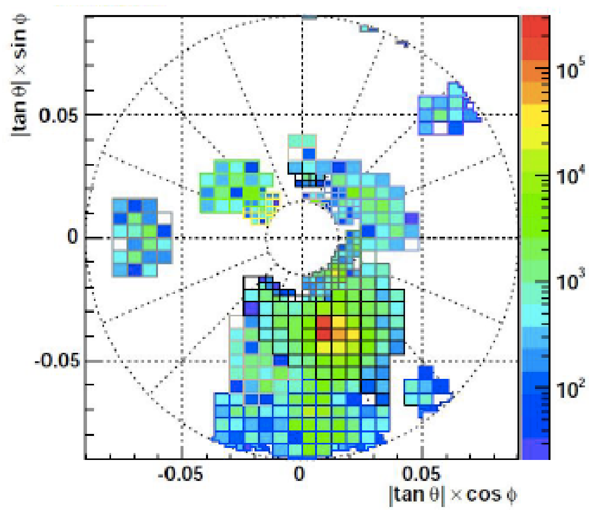
- **Careful tuning of thresholds needed.**
  - needs usually learning phase;
  - adapt to noise conditions;
  - too low : pick up too much unwanted energy;
  - too high : loose too much of “real” energy. Corrections/Calibrations will be larger.



Cluster finding – topological clustering

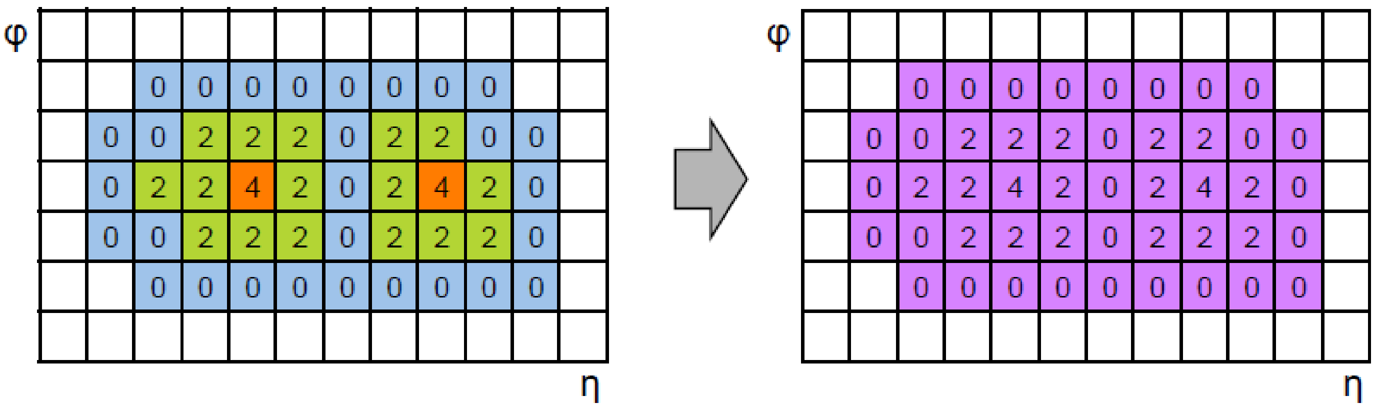
“Topological” clusters, i.e. “blobs” of energy inside the detector.



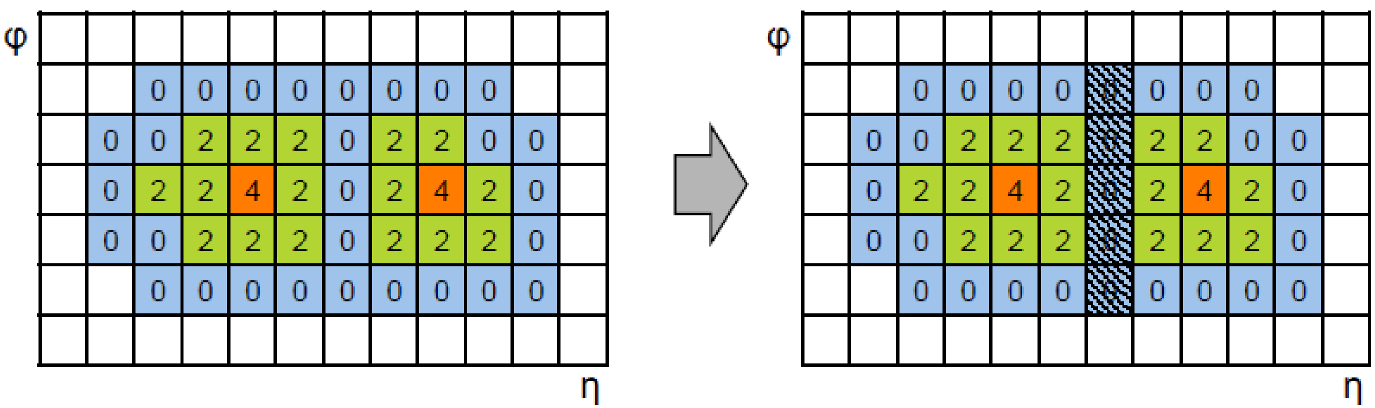


Cluster finding – merging and splitting

- If clusters have common neighboring cells, they are merged according to the basic algorithm.



- Clusters are split if more than one local maxima.



For common cells, a weight is applied to share them (shaded cells).

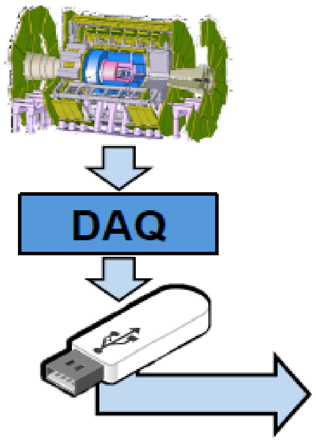
Cluster calibration

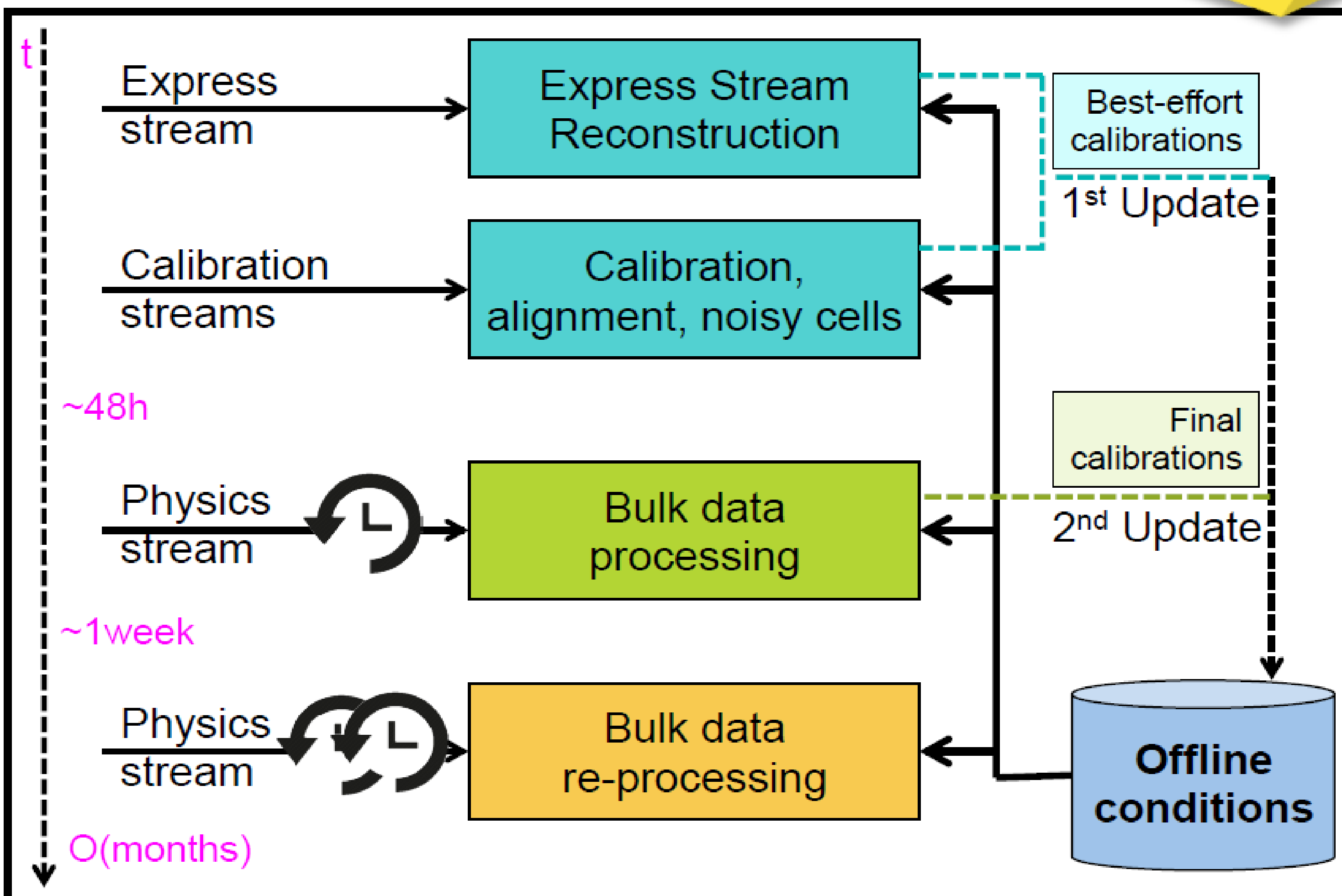
Possible energy measurements:

- **Non-calibrated clusters: sum energy using baseline cell-level detector calibration.**
  - That's NOT the true energy of the particle that originated the cluster.
- **Local calibration: apply weights to correct for:**
  - the different **calorimeter response** on an EM (e.g. π^0) or a hadronic (e.g. $\pi^{\pm}$) deposition.
  - the low energetic deposits, lost in the tails of the shower (**"out-of-cluster"** corrections, derived from simulation).
  - the presence of **dead material**, i.e. material without a read-out device, where energy is lost.
- **Corrections are complex functions of the energy and the position of the cluster and other parameters defining the cluster shapes.**

Reminder!

THE EVENT AT TIER0

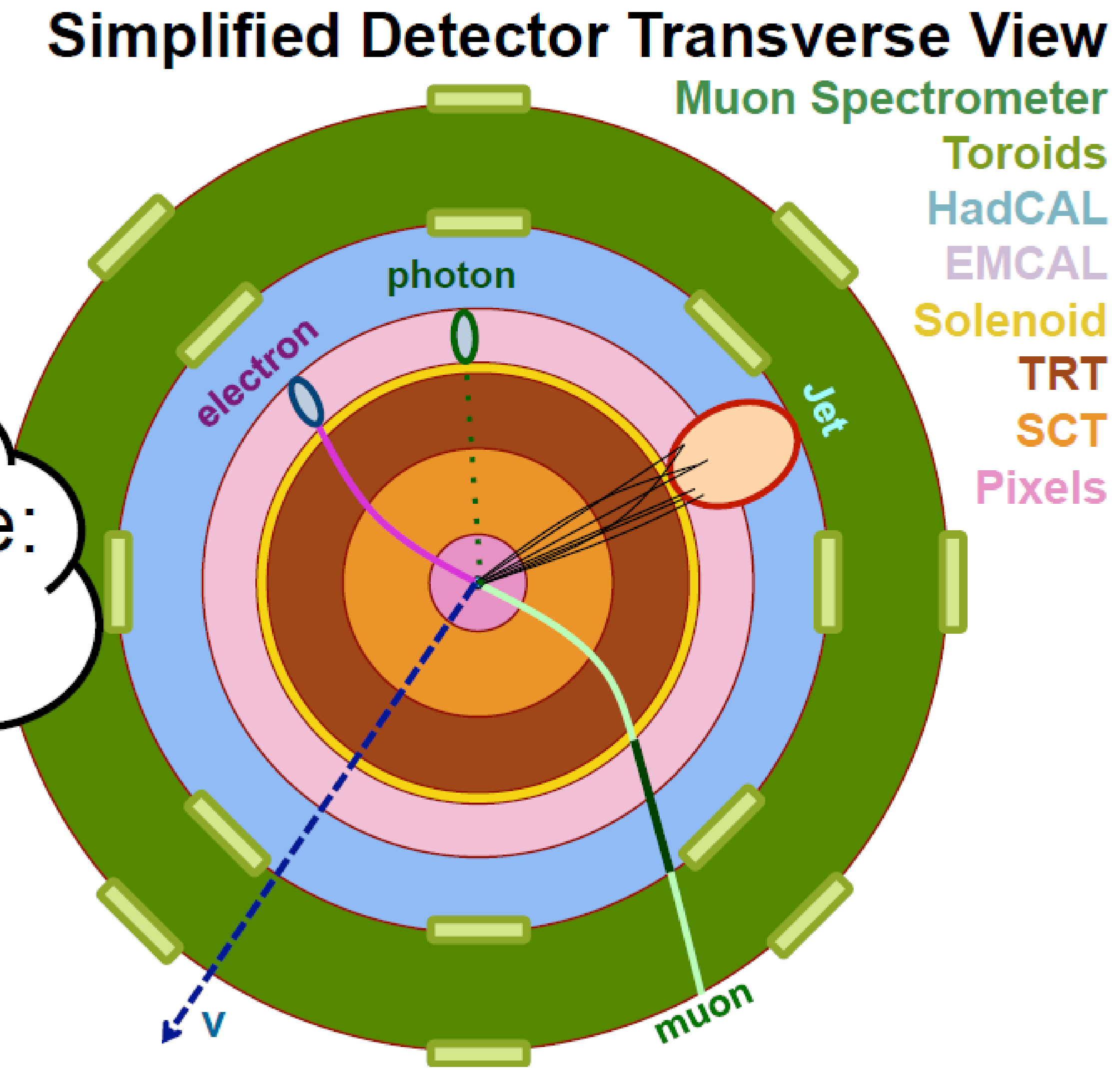




What do we reconstruct?

Tracks and Clusters

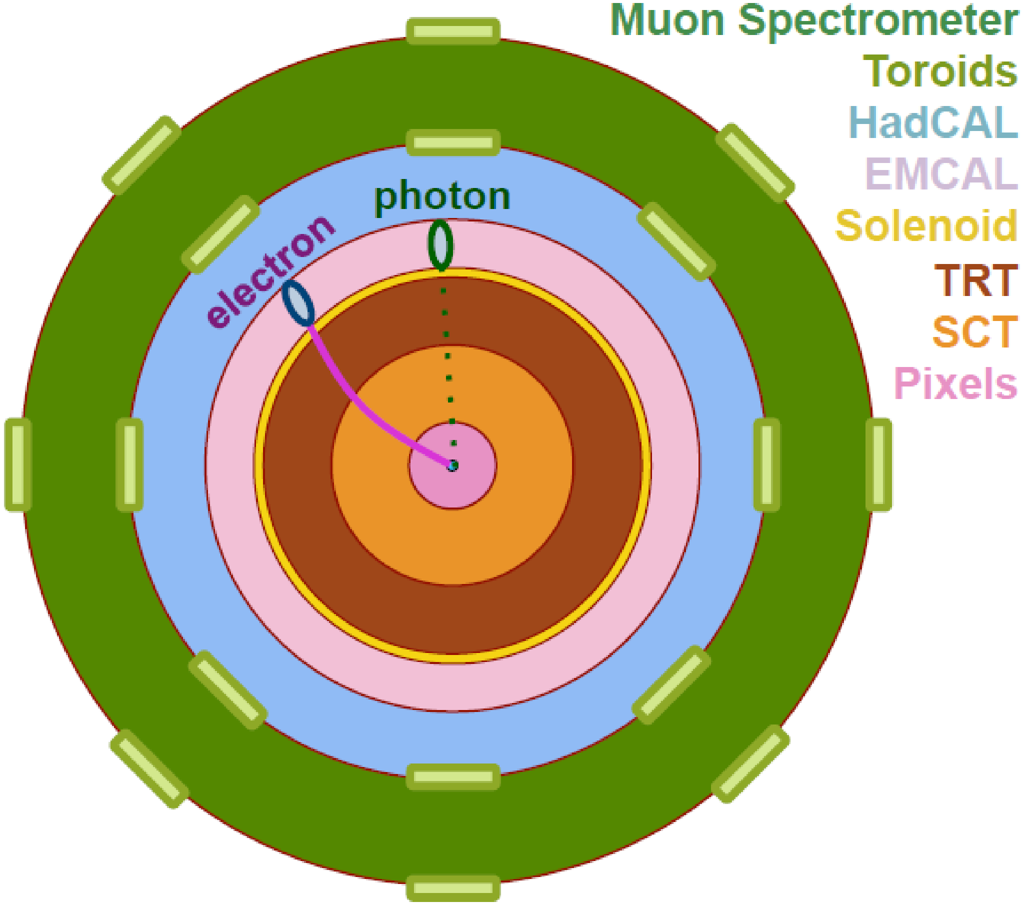
Combining those: “**objects**” (“particles”)



Electrons and photons

- **Final Electron momentum measurement can come from tracking or calorimeter information (or a combination of both).**
  - Often have a final calibration to give the best electron energy.
- **Often want "isolated electrons".**
  - Require little calorimeter energy or tracks in the region around the electron.

Simplified Detector Transverse View



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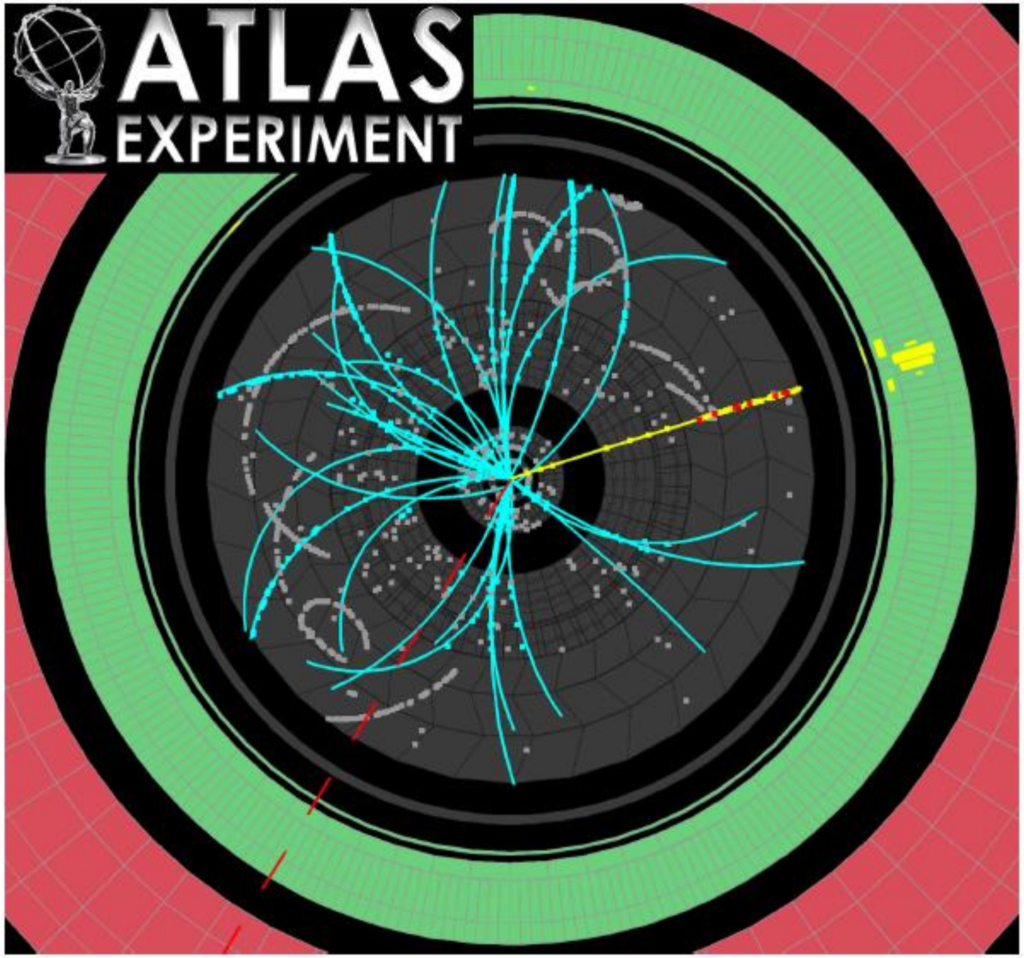
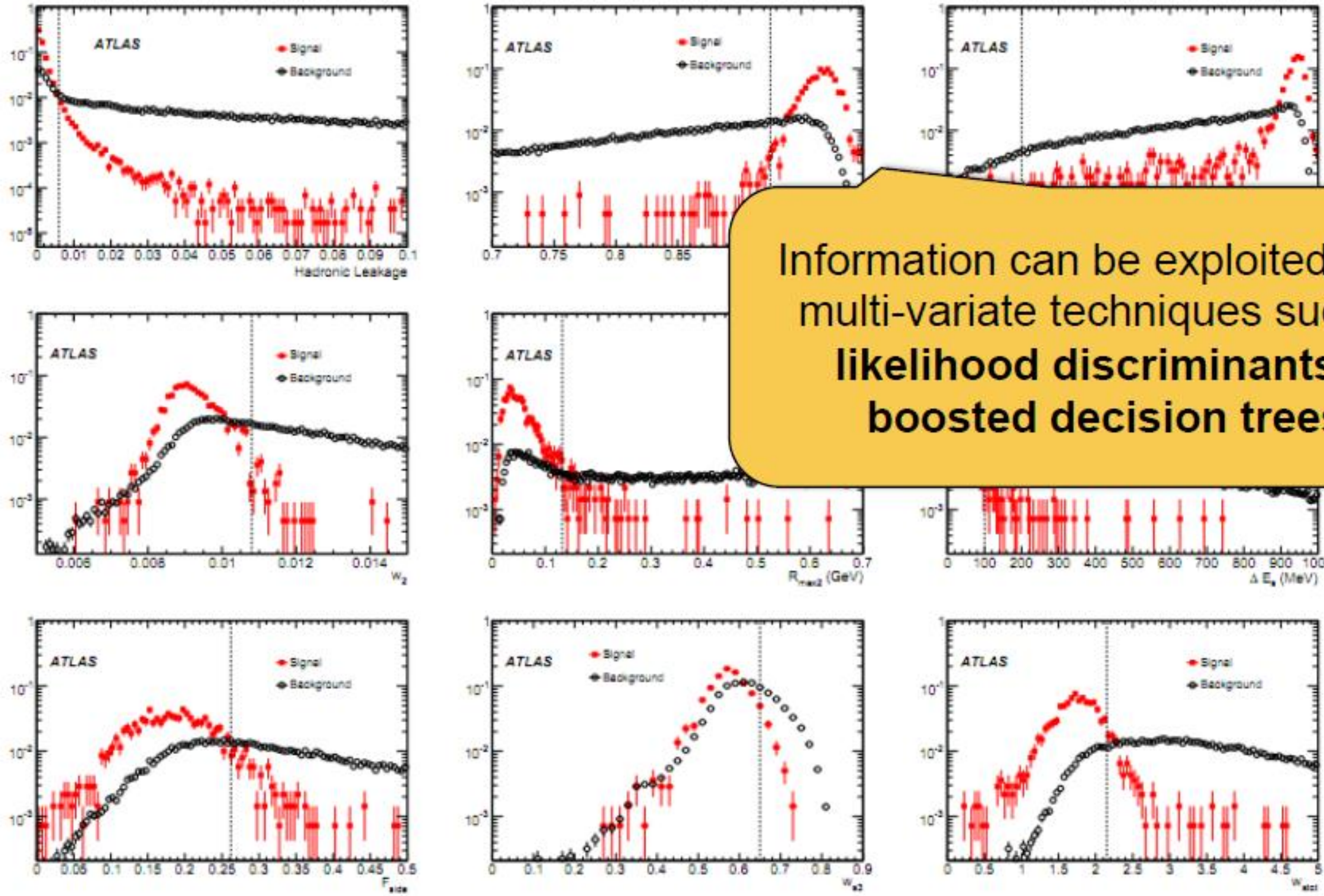


Electrons and photons (backgrounds)

- Hadronic jets leave energy in the calorimeter which can fake electrons or photons.
- Usually a Jet produces energy in the hadronic calorimeter as well as the electromagnetic calorimeter.
- Usually the calorimeter cluster is much wider for jets than for electrons/photons.
- So it should be “easy” to separate electrons from jets.
- However have many thousands more jets than electrons, so need the rate of jets faking an electron to be very small $\sim 10^{-4}$.
- Need complex identification algorithms to give the rejection whilst keeping a high efficiency.

Electrons and photons (backgrounds)

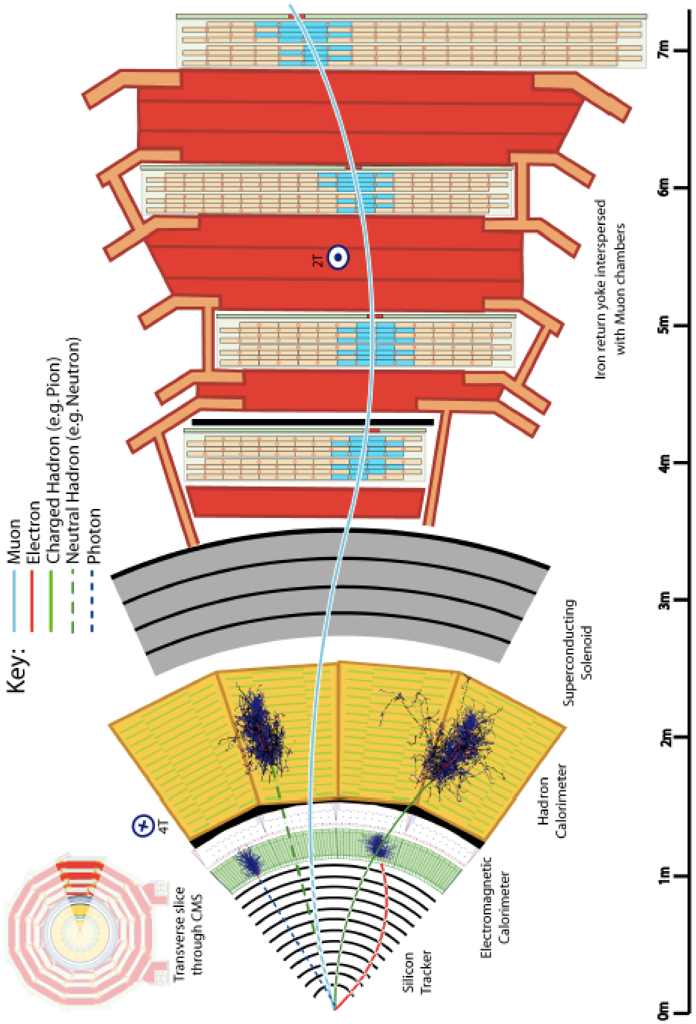


Information can be exploited using multi-variate techniques such as **likelihood discriminants** or **boosted decision trees**.

Example of different calorimeter shower shape variables used to distinguish electron showers from jets in ATLAS

Muons

- **Combine the muon segments found in the muon detector with tracks from the tracking detector**
- **Momentum of muon determined from bending due to magnetic field in tracker and in muon system**
  - Combine measurements to get best resolution
  - Need an accurate map of the magnetic field in the reconstruction software
  - Alignment of the muon detectors also very important to get best momentum resolution



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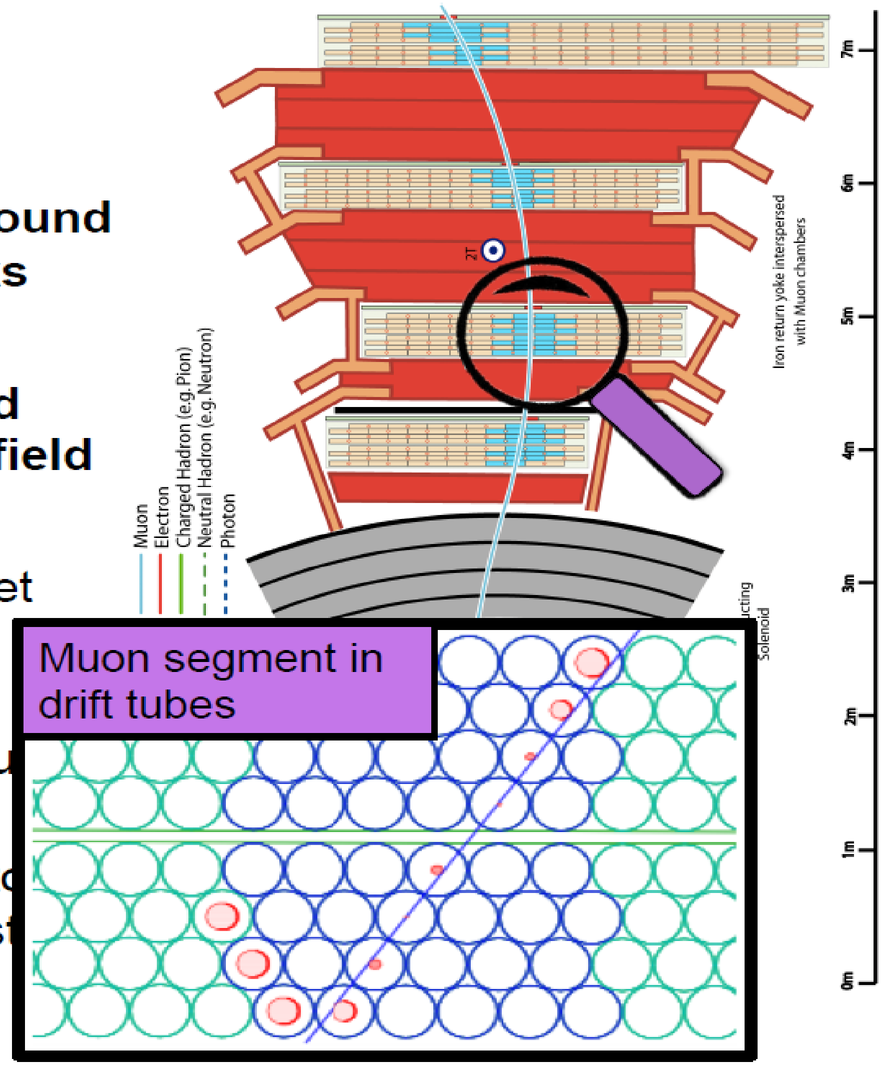
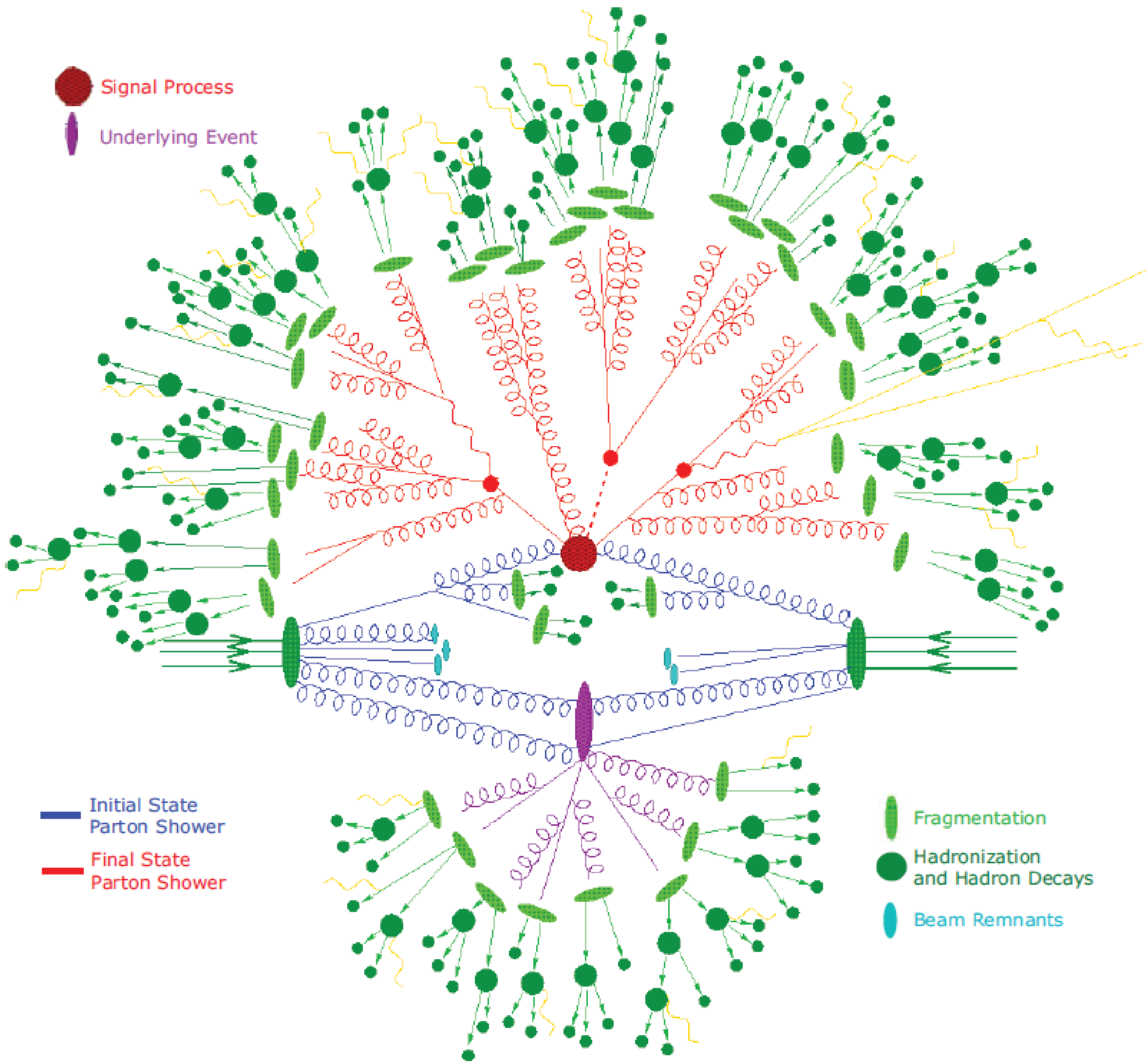
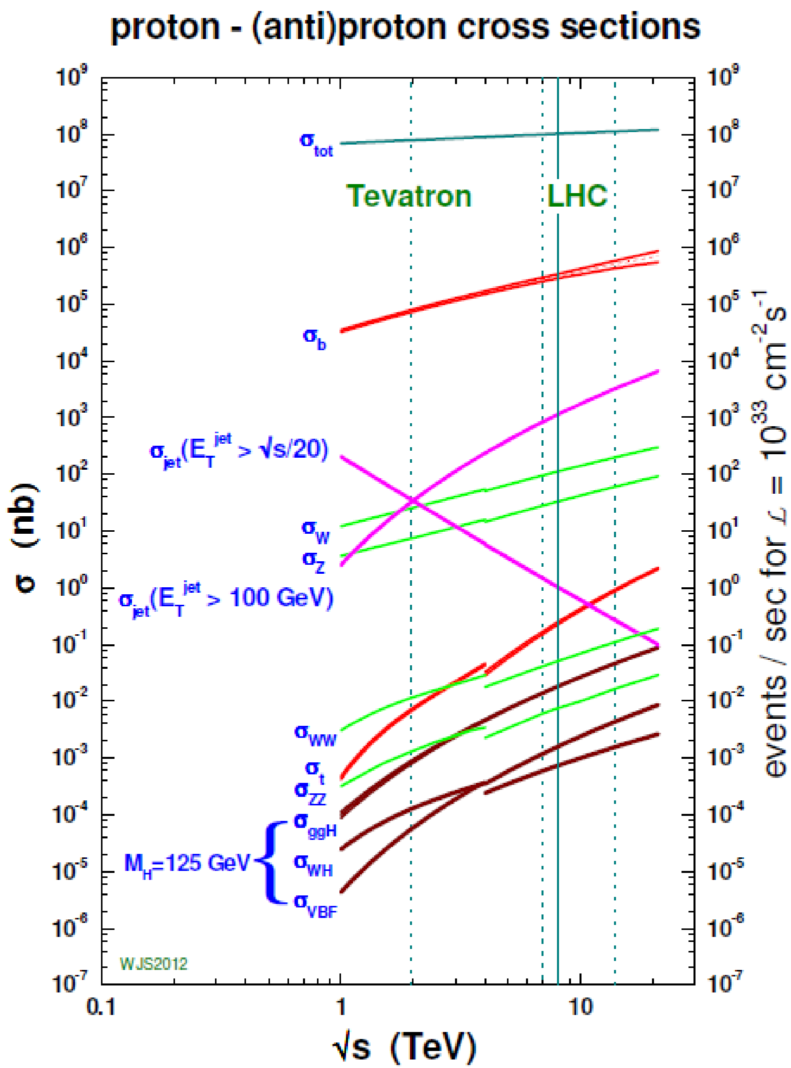


Jets


Signal Process
Underlying Event
Initial State Parton Shower
Final State Parton Shower
Fragmentation
Hadronization and Hadron Decays
Beam Remnants

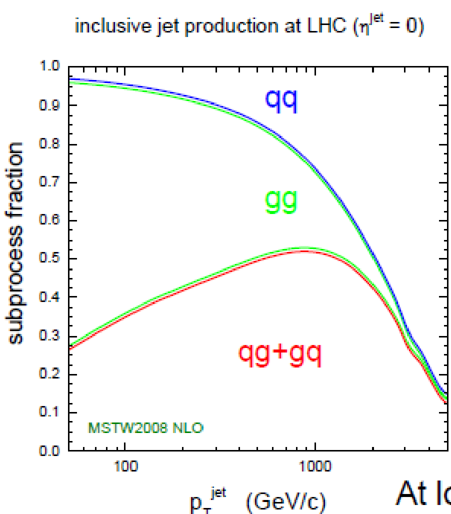
Standard Model processes



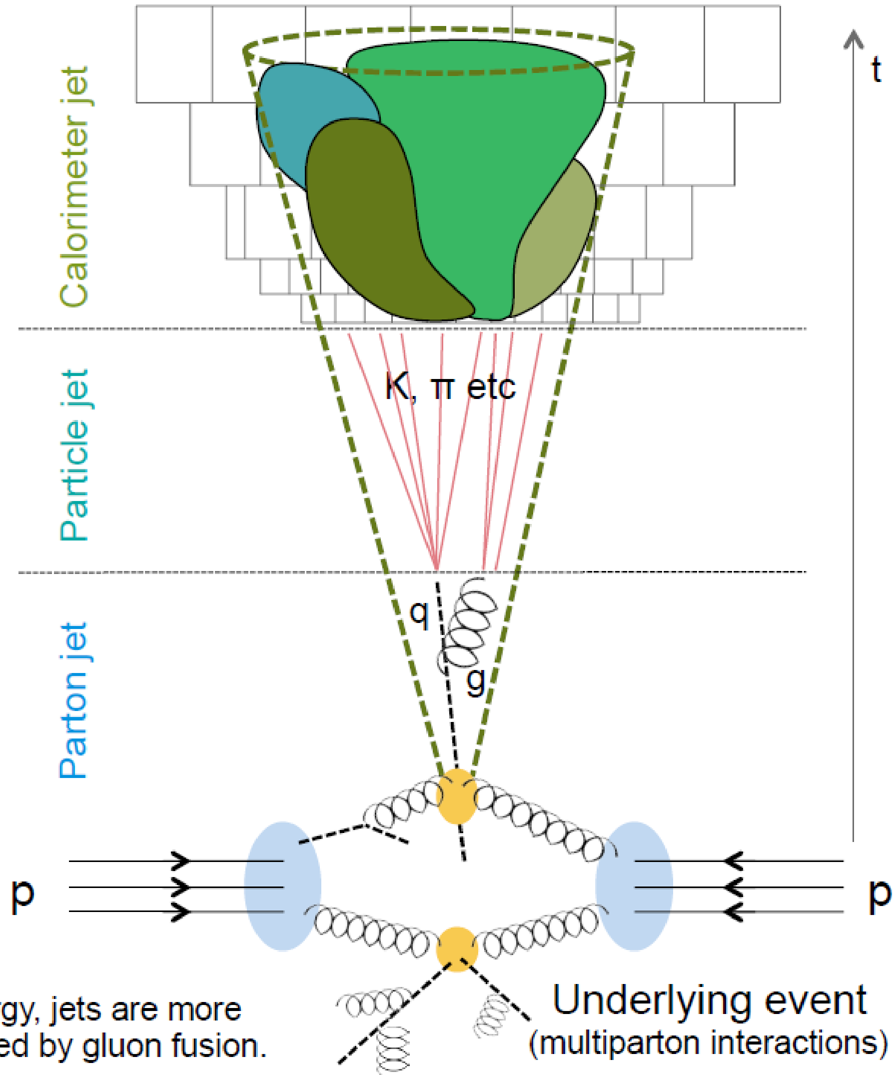
Jets are produced:

- by fragmentation of gluons and (light) quarks in QCD scattering.
- by decays of heavy Standard Model particles, e.g. W & Z.
- in association with particle production in Vector Boson Fusion, e.g. Higgs.
- in decays of beyond the Standard Model particles, e.g. in SUSY.

Jets

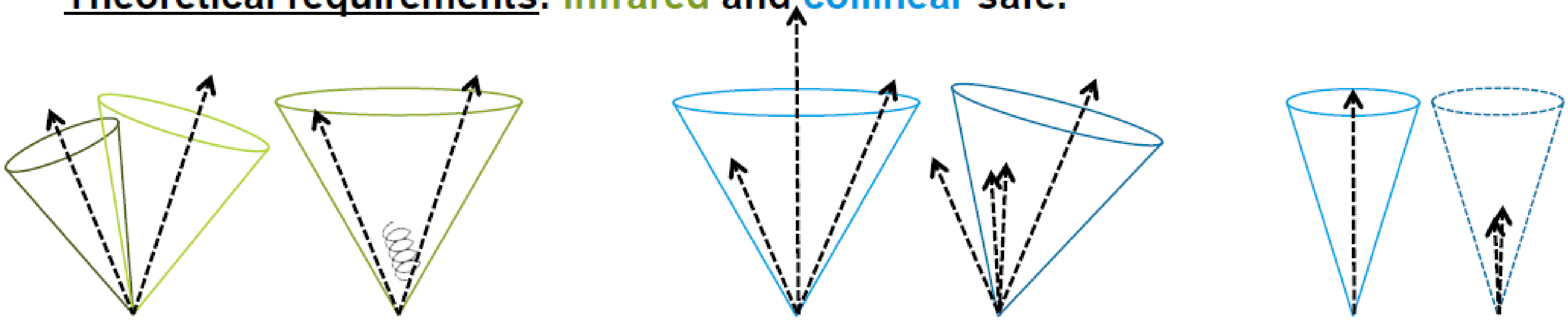


At low energy, jets are more likely produced by gluon fusion.



Jet algorithms

Theoretical requirements: infrared and collinear safe.



Soft gluon radiation should not merge jets

Final jet should not depend on the ordering of the seeds…

…and on signal split in two possibly below threshold

Experimental requirements: detector technology & environment independent, easily implementable.

Insignificant effects of detector
- Noise
- Dead material
- Cracks

Stability with
- Luminosity
- Pile-up
- Physics process

Fully specified
Fast

Jet algorithm commonly used at the LHC: 'anti-k_t'. A 'recursive recombination' algorithm. Starts from (topo-)clusters. Hard stuff clusters with nearest neighbor. Various cone sizes (standard R=0.4/0.5, "fat" R=1.0).

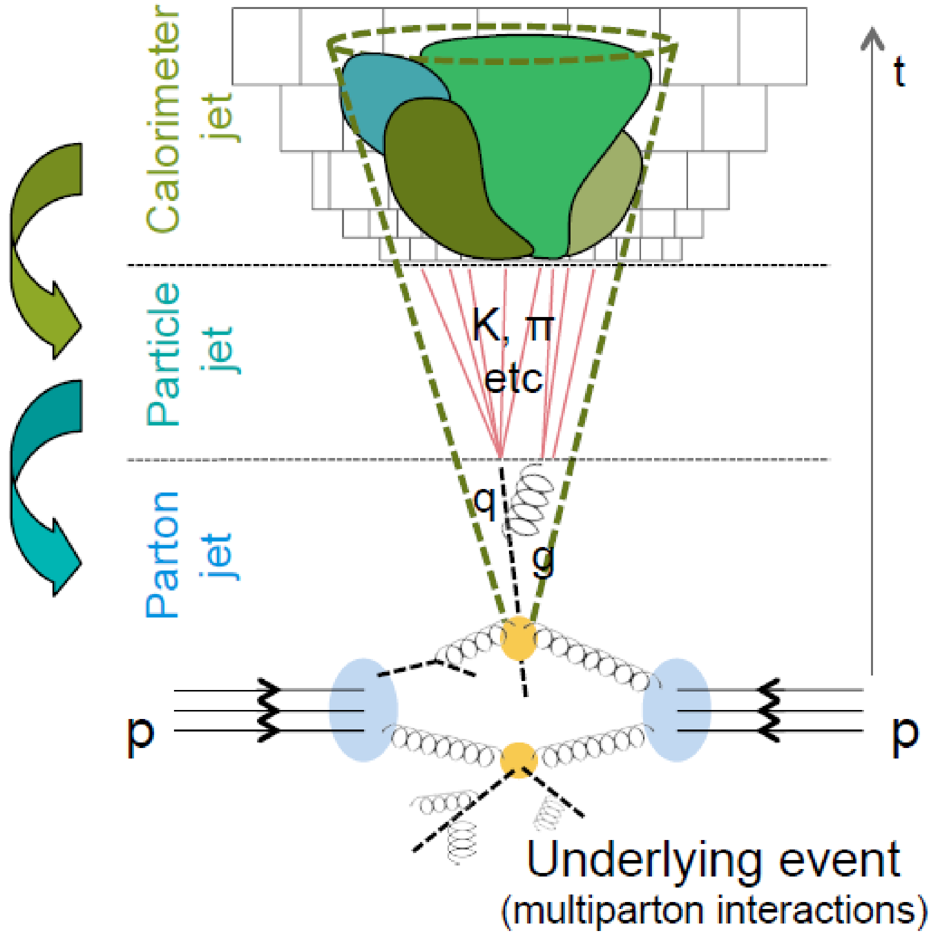
Jet calibration

Correct the energy and position measurement and the resolution.

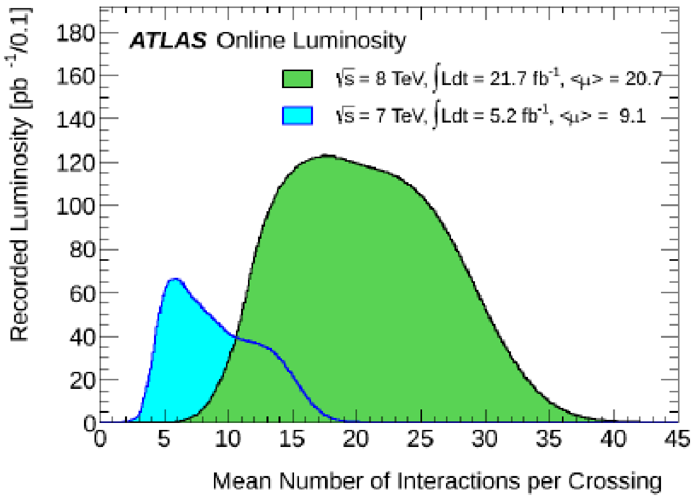
Account for:

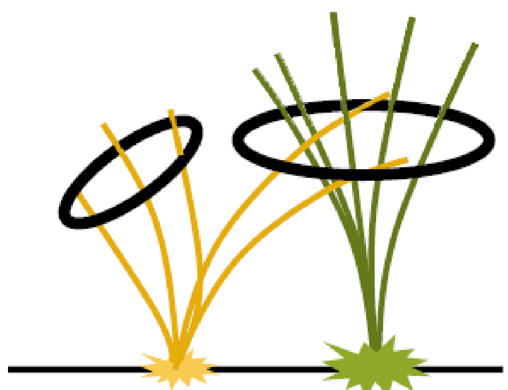
<u>Instrumental effects</u>
Detector inefficiencies
'Pile-up'
Electronic noise
Clustering, noise suppression
Dead material losses
Detector response
Algorithm efficiency

<u>Physics effects</u>
Algorithm efficiency
'Pile-up'
'Underlying event'



Jets & pile-up

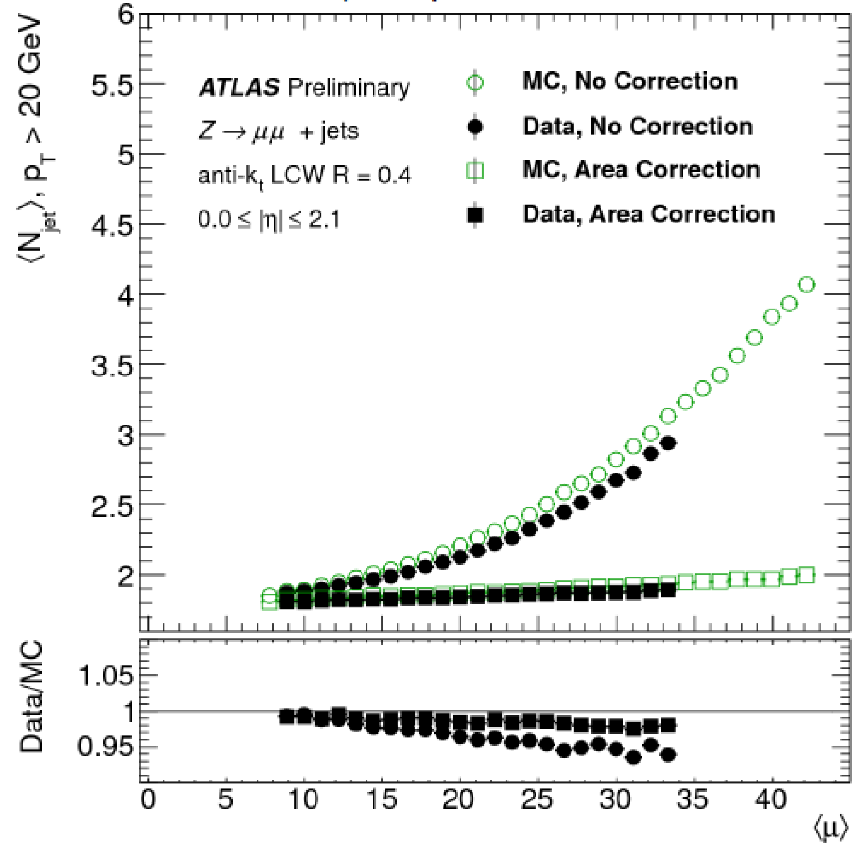




Multiple interactions from pile-up

'Jet-areas' corrections

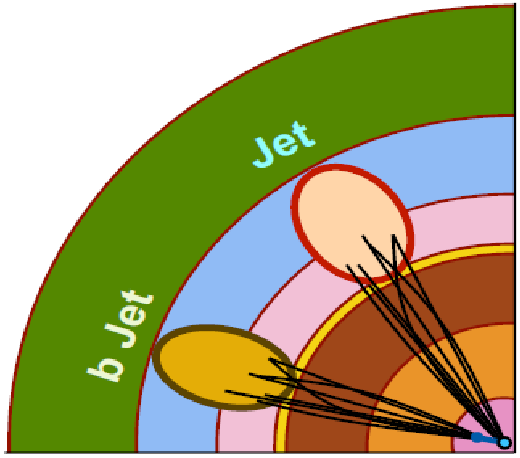
Inspired by arXiv:0707.1378

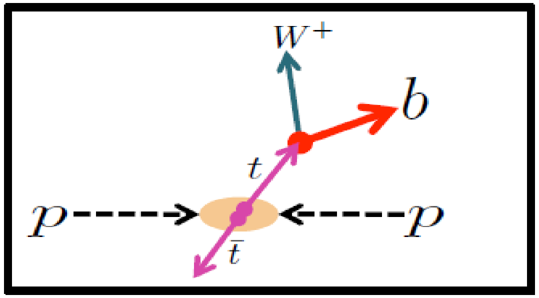


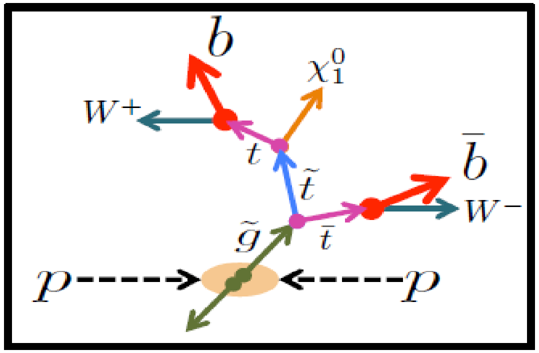
b-jets

- b-quarks have a lifetime of ~ 10^{-12} s.
- They travel a small distance (fraction of mm) before decaying.
- A "**displaced vertex**" creates a distinct jet, so b-jets can be tagged (**b-tagged**).
- b-tagging uses sophisticated algorithms, mostly **multi-variate**.

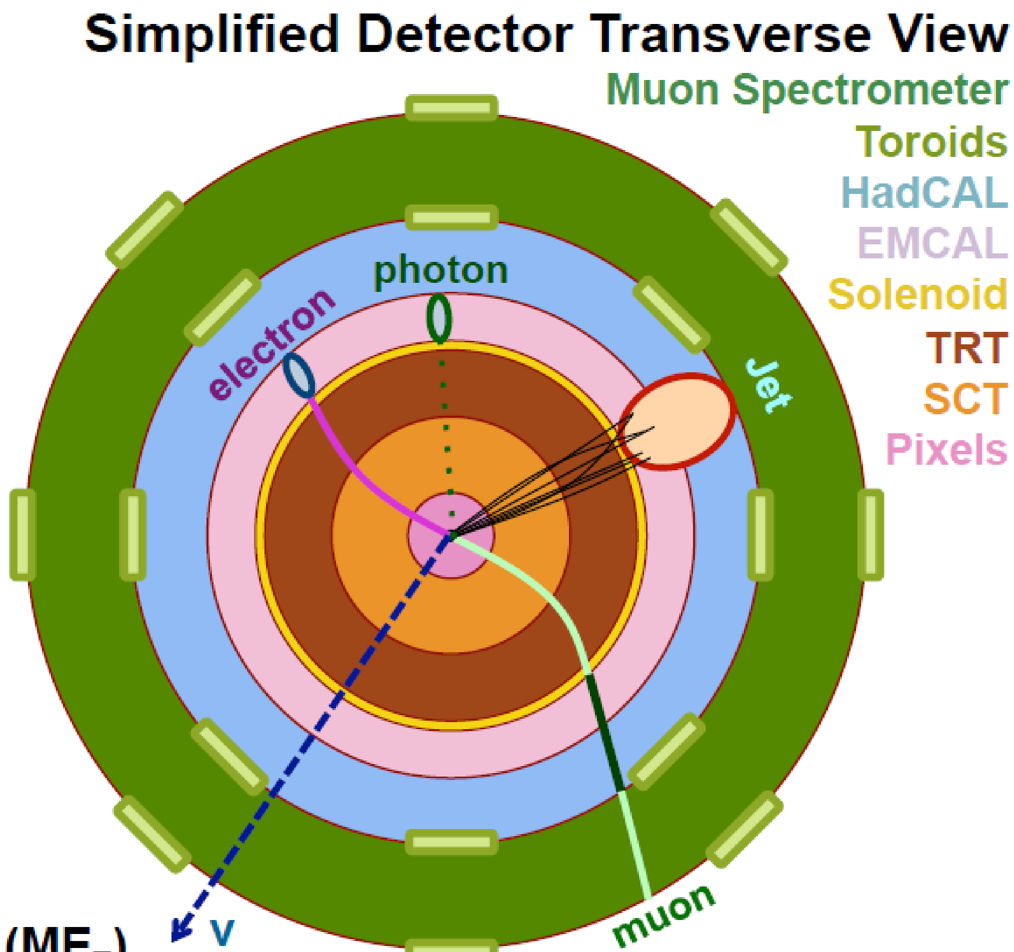
- b-jets create distinct final states, important for both **Standard Model measurements** and **searches for New Physics**.







Missing transverse momentum



In the transverse plane:

$$\sum \vec{p}_T = 0$$

Missing Transverse Momentum (ME_T)

Missing transverse momentum

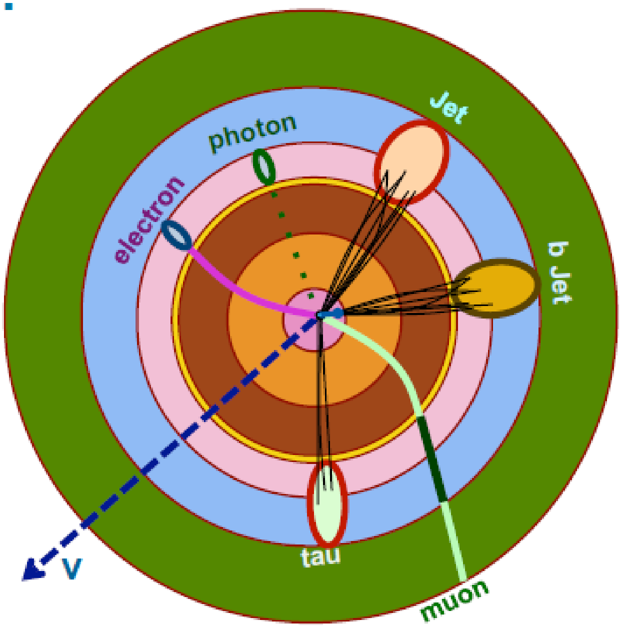
Impossible to measure particles that don't interact in the detector.

➲ Instead, measure everything else & require momentum conservation in the transverse plane.

- ◎ Sensitive to pile-up and detector problems.

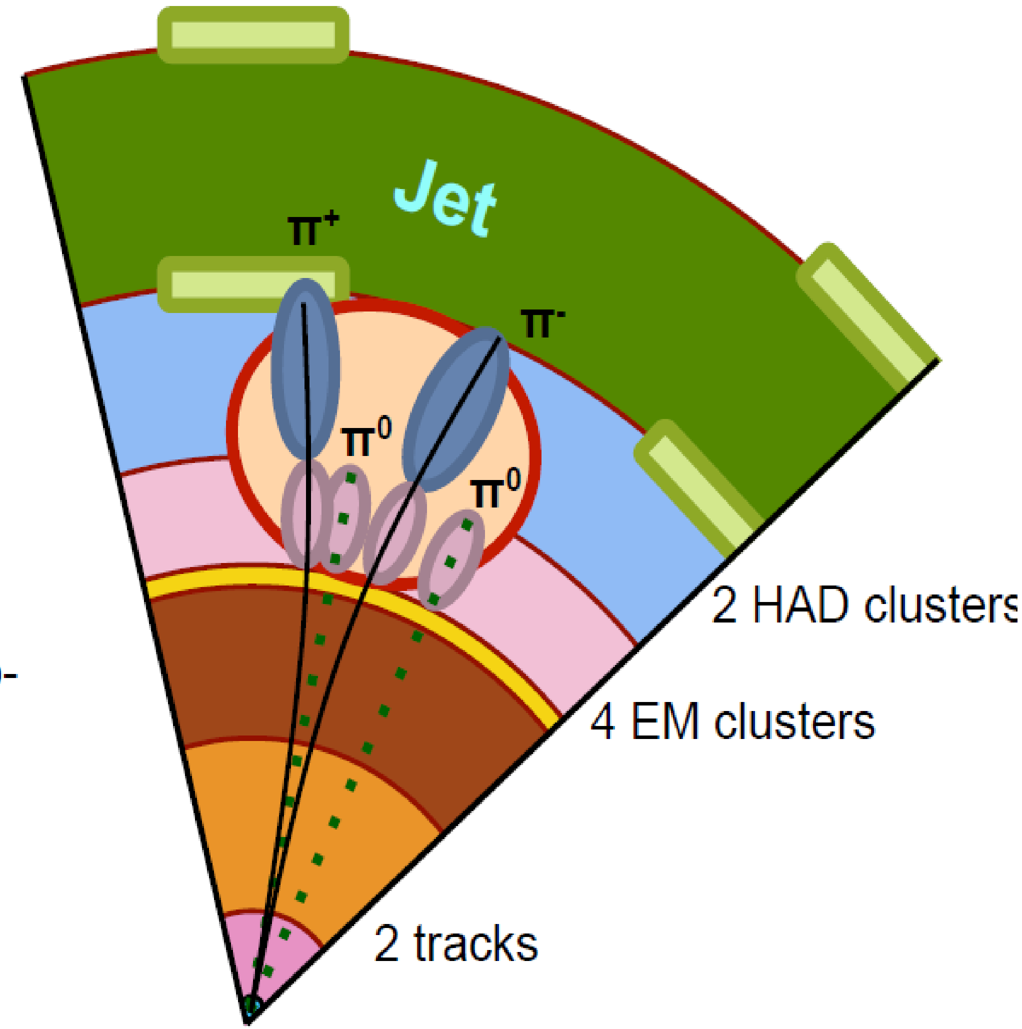
Only as good as its inputs.

- ◎ Use calibrated physics objects: electrons, photons, muons, taus, jets.
- ◎ Add remaining soft energy.



Particle flow

- "Flow of particles" through the detector.
- Reconstruct and identify all particles, photons, electrons, pions, …
- Use best combination of all sub-detectors for measuring the properties of the particles.
- First used at LEP (ALEPH) and then at the LHC (CMS).

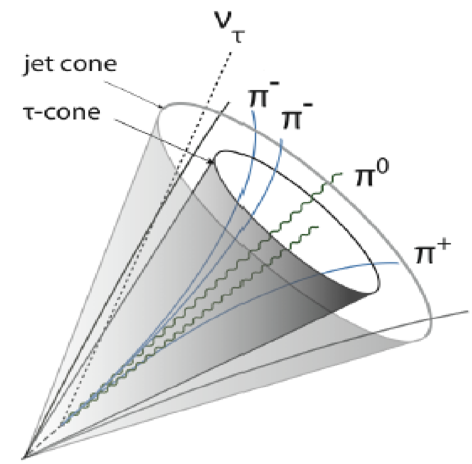


Reconstructing particles

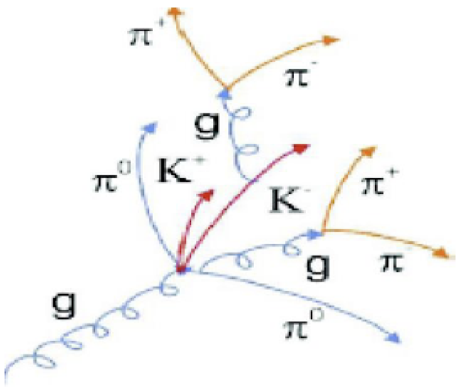
Tau Decay Mode			B.R.
Leptonic		$\tau^{\pm} \rightarrow e^{\pm} + \nu + \nu$	17.8%
		$\tau^{\pm} \rightarrow \mu^{\pm} + \nu + \nu$	17.4%
Hadronic	1-prong	$\tau^{\pm} \rightarrow \pi^{\pm} + \nu$	11%
		$\tau^{\pm} \rightarrow \pi^{\pm} + \nu + n\pi^{0}$	35%
	3-prong	$\tau^{\pm} \rightarrow 3\pi^{\pm} + \nu$	9%
		$\tau^{\pm} \rightarrow 3\pi^{\pm} + \nu + n\pi^{0}$	5%
Other			~5%

- Hadronic tau reconstruction extremely challenging.
- Using **multi-variate** techniques based on track multiplicity and shower shapes.

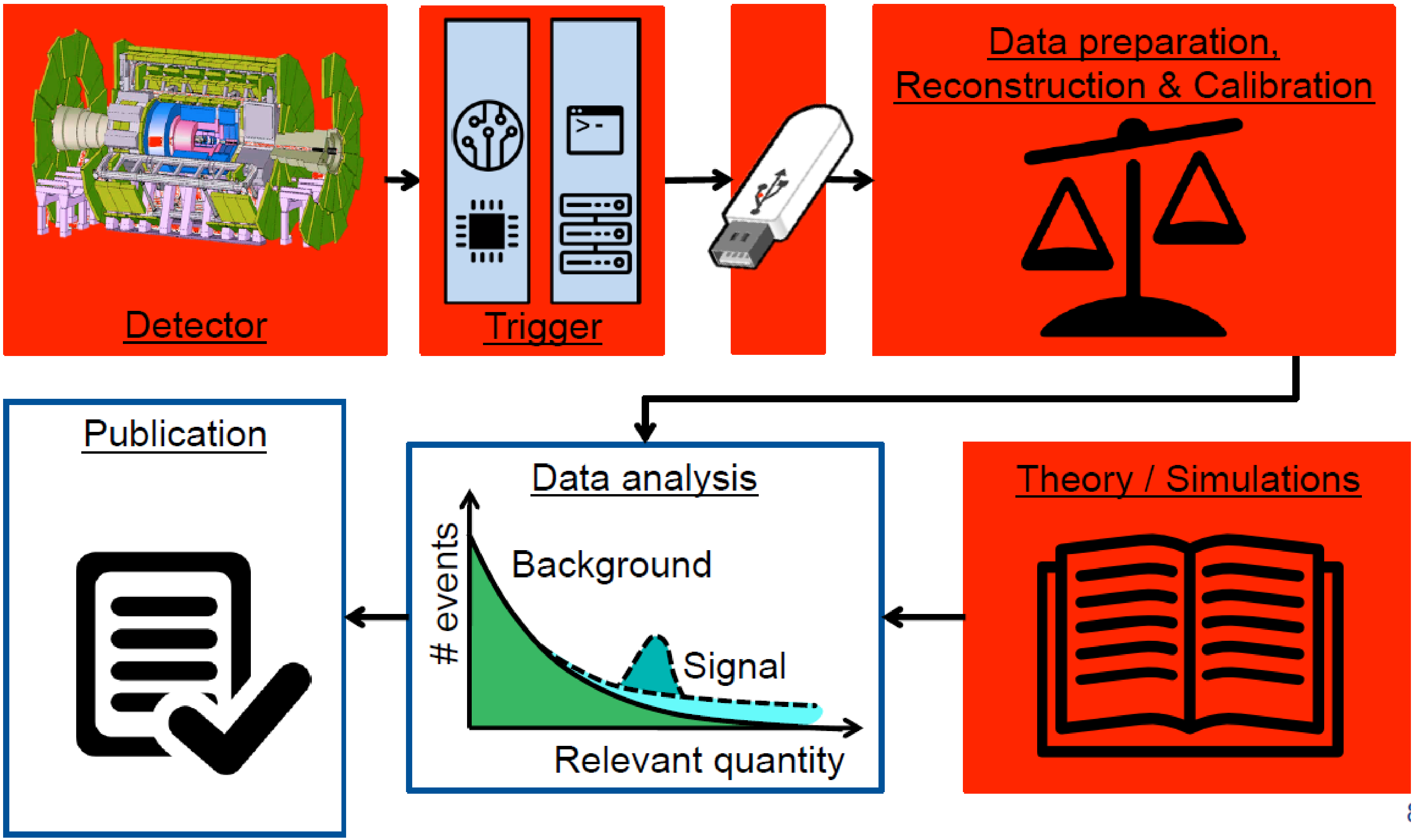
A tau jet (signal)...



...vs. a QCD jet (background)

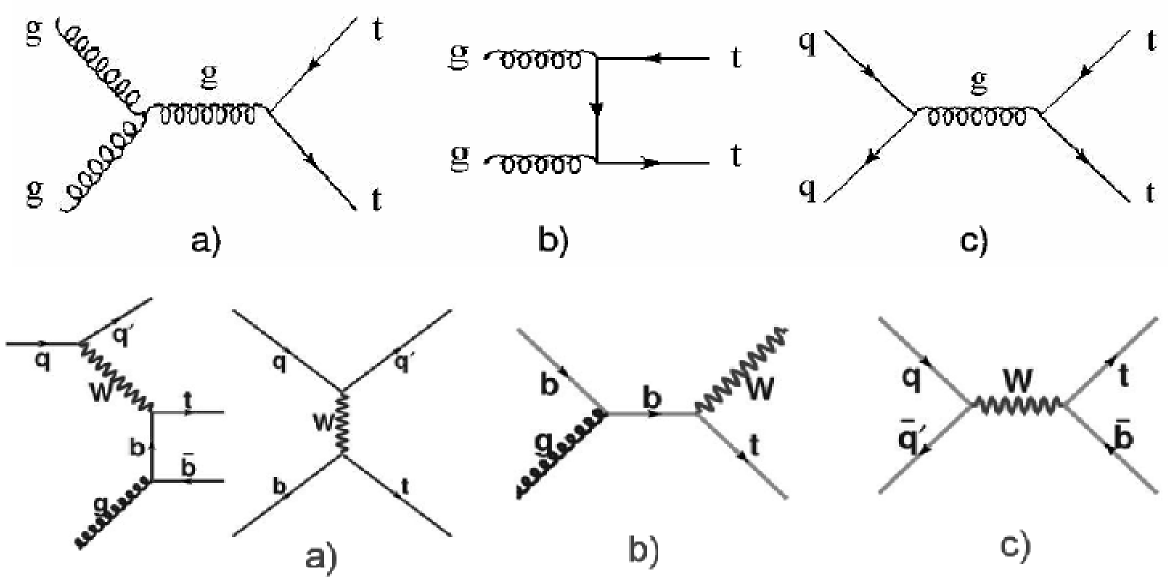


An event's lifetime

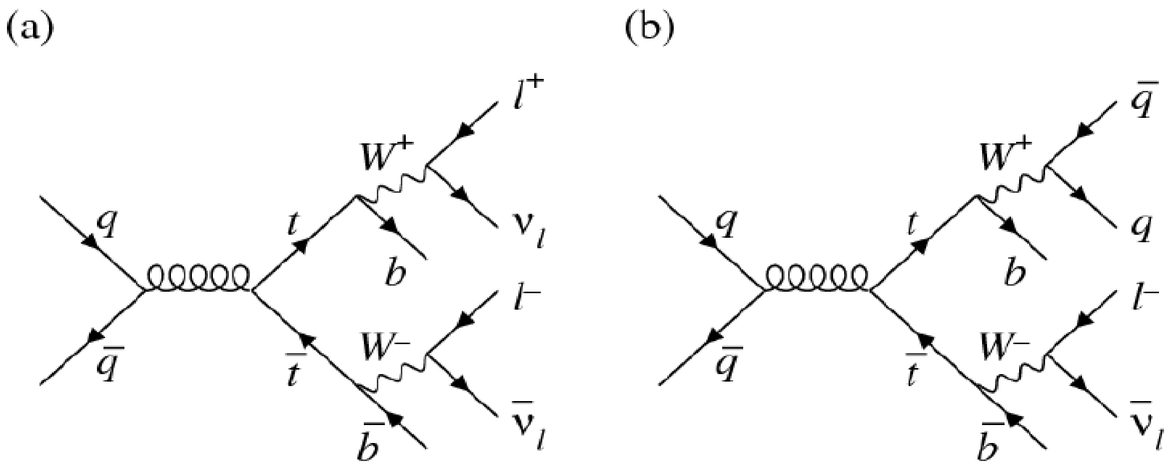


SPARE SLIDES

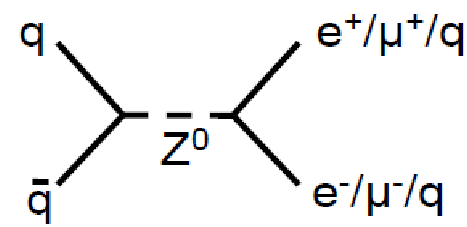
t,W,Z



Diagrams from http://arxiv.org/pdf/1201.5844.pdf



Diagrams from http://arxiv.org/pdf/1004.1181.pdf



Measuring particles

- Particles are characterized by
  - ✓ Mass [Unit: eV/c^2 or eV]
  - ✓ Charge [Unit: e]
  - ✓ Energy [Unit: eV]
  - ✓ Momentum [Unit: eV/c or eV]
  - ✓ (+ spin, lifetime, …)

Particle identification via measurement of:

e.g. (E, p, Q) or (p, β, Q)
(p, m, Q) ...

- … and move at relativistic speed

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\ell = \frac{\ell_0}{\gamma}$$ length contraption

$$t = t_0\gamma$$ time dilatation

$$E^2 = \vec{p}^2c^2 + m^2c^4$$

$$E = m\gamma c^2 = mc^2 + E_{\text{kin}}$$

$$\vec{\beta} = \frac{\vec{p}c}{E} \qquad \vec{p} = m\gamma\vec{\beta}c$$

Relativistic kinematics in a nutschell

$$E^2 = \vec{p}^2 + m^2$$

$$\ell = \frac{\ell_0}{\gamma}$$

$$E = m\gamma$$

$$t = t_0\gamma$$

$$\vec{p} = m\gamma\vec{\beta}$$

$$\vec{\beta} = \frac{\vec{p}}{E}$$

Relativistic kinematics in a nutschell

Center of mass energy

- In the center of mass frame the total momentum is 0
- In laboratory frame center of mass energy can be computed as:

$$E_{\text{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

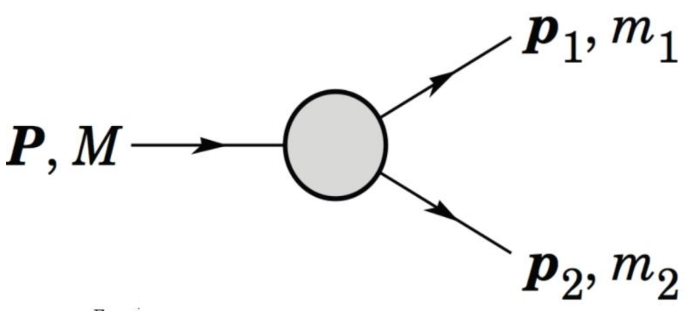
Hint: it can be computed as the "length" of the total four-momentum, that is invariant:

$$p = (E, \vec{p}) \qquad \sqrt{p \cdot p}$$

What is the "length" of a the four-momentum of a particle?

Kinematics

2-bodies decays



$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M}$$

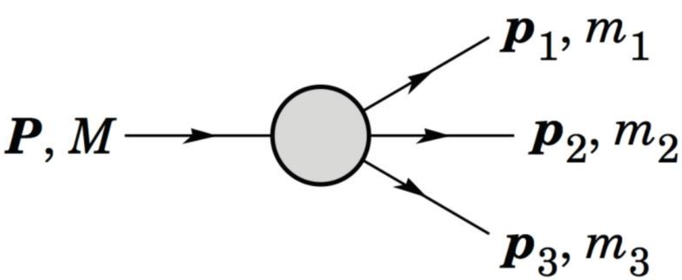
$$|\boldsymbol{p}_1| = |\boldsymbol{p}_2|$$

$$= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M}$$

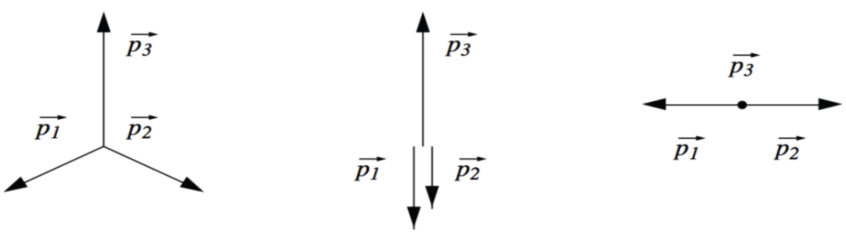
Invariant mass

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

3-bodies decays



$$|\boldsymbol{p}_3| = \frac{\left[\left(M^2 - (m_{12} + m_3)^2\right)\left(M^2 - (m_{12} - m_3)^2\right)\right]^{1/2}}{2M}$$



(a) (b) (c)

$\max(|\vec{p}_3|)$ $\quad (m_{12})_{min} = m_1 + m_2$

$\min(|\vec{p}_3|)$ $\quad (m_{12})_{max} = M - m_3$

A real example: pion decays

pion decays at rest

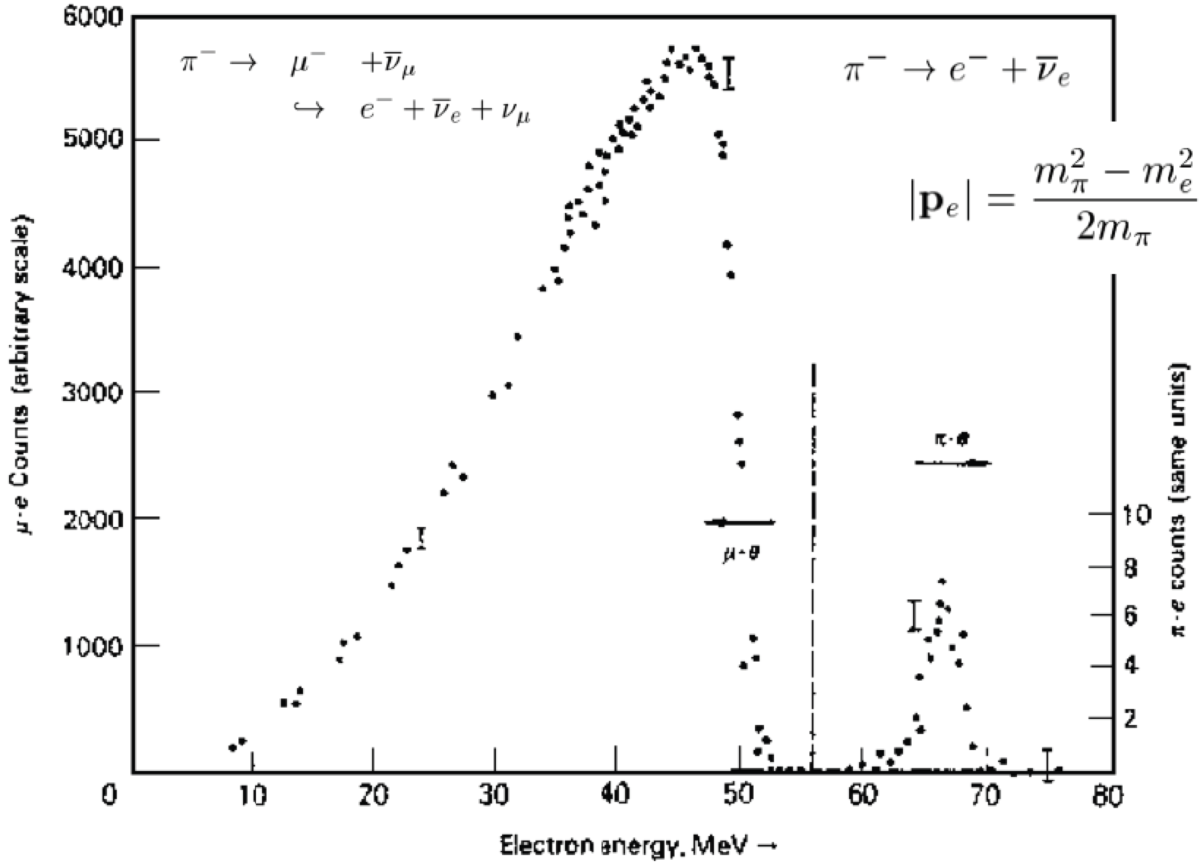
$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}c \simeq 30\,\mathrm{MeV/c}$$

in most cases muon decays at rest

$$|\mathbf{p}_e|_{max} = \frac{m_\mu^2 - m_e^2}{2m_\mu}c \simeq 52\,\mathrm{MeV/c}$$

$$|\mathbf{p}_e|_{min} = 0$$

$$m_\nu = 0.$$



$$|\mathbf{p}_e| = \frac{m_\pi^2 - m_e^2}{2m_\pi}c \simeq 70\,\mathrm{MeV/c}$$

HEP, SI and „natural” units

Quantity	HEP units	SI units
length	1 fm	10^{-15} m
charge	e	$1.602 \cdot 10^{-19}$ C
energy	1 GeV	1.602×10^{-10} J
mass	1 GeV/c^2	1.78×10^{-27} kg
$\hbar = h/2$	6.588×10^{-25} GeV s	1.055×10^{-34} Js
c	2.988×10^{23} fm/s	2.988×10^{8} m/s
$\hbar c$	197 MeV fm	…
	"natural" units ($\hbar = c = 1$)	
mass	1 GeV	
length	1 GeV^{-1} = 0.1973 fm	
time	1 GeV^{-1} = 6.59×10^{-25} s	