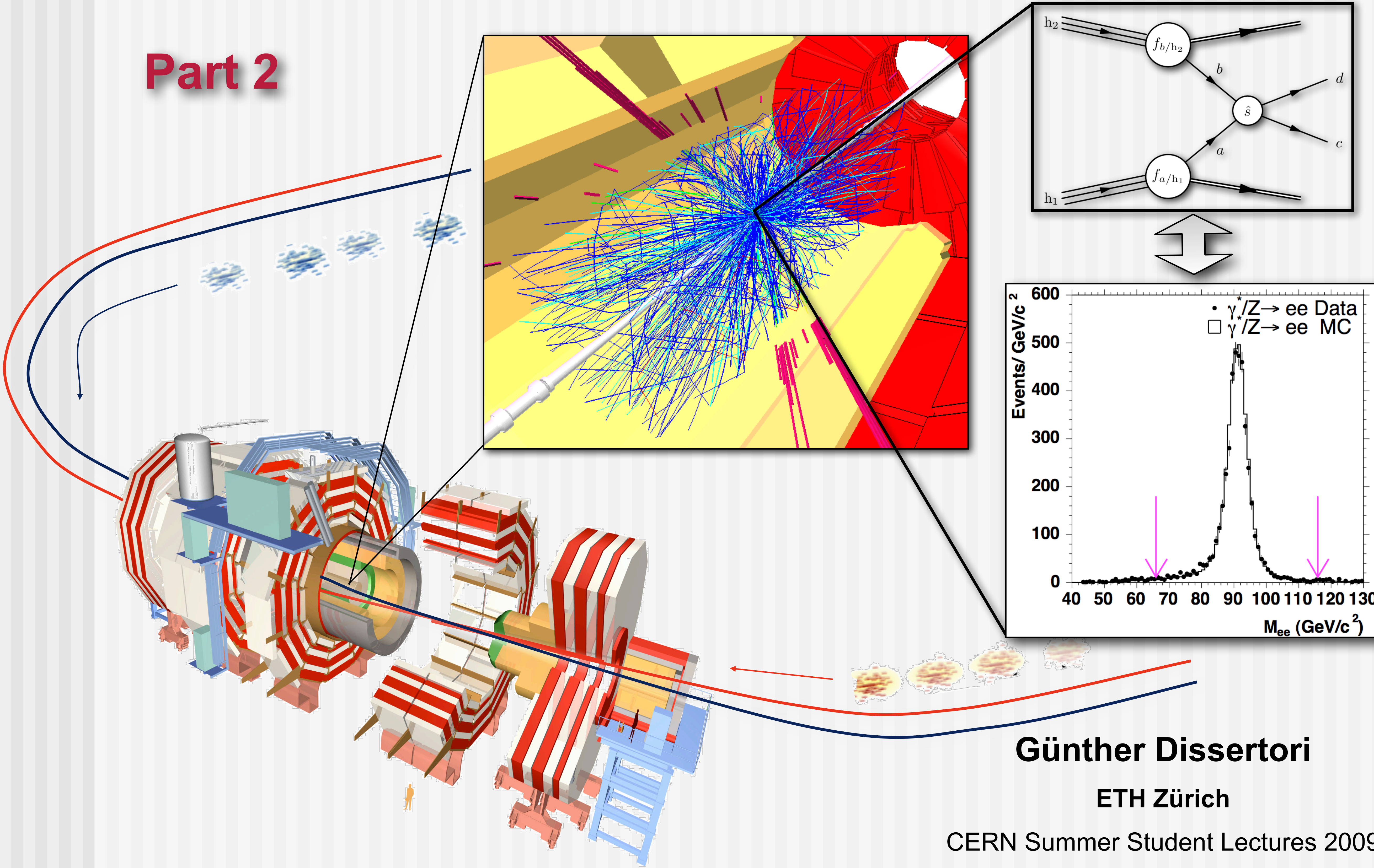
From Raw Data to Physics Results

Part 2



Günther Dissertori

ETH Zürich

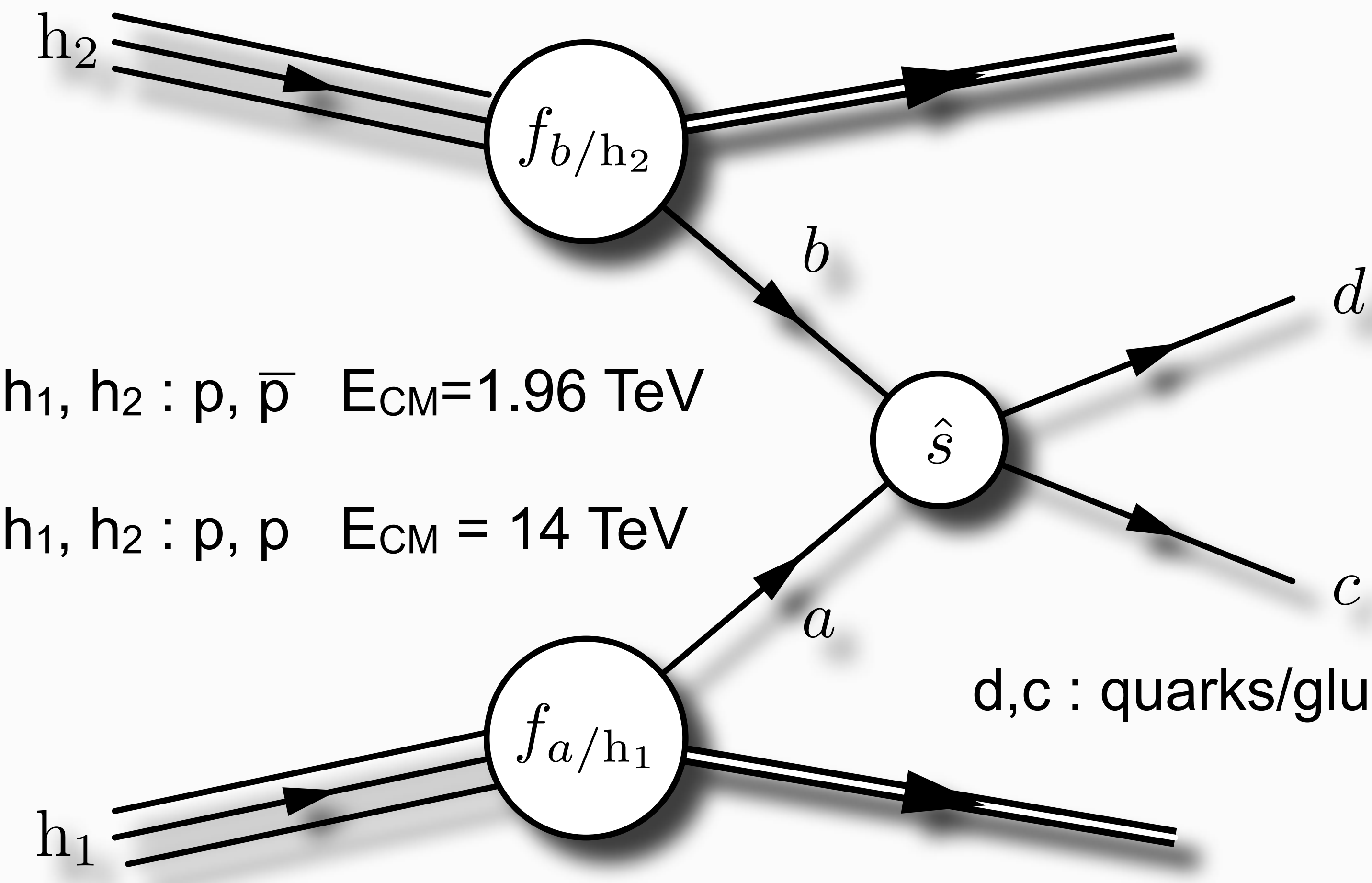
CERN Summer Student Lectures 2009

A "more complicated" example

"The greater the obstacle, the more glory in overcoming it." (Moliere)

JET production at hadron colliders

- at the Tevatron, or in the future at the LHC



h_1, h_2 : p, $\bar{p}$ E_{CM}=1.96 TeV

h_1, h_2 : p, p E_{CM} = 14 TeV

d,c : quarks/gluons

see also lecture by B. Heinemann

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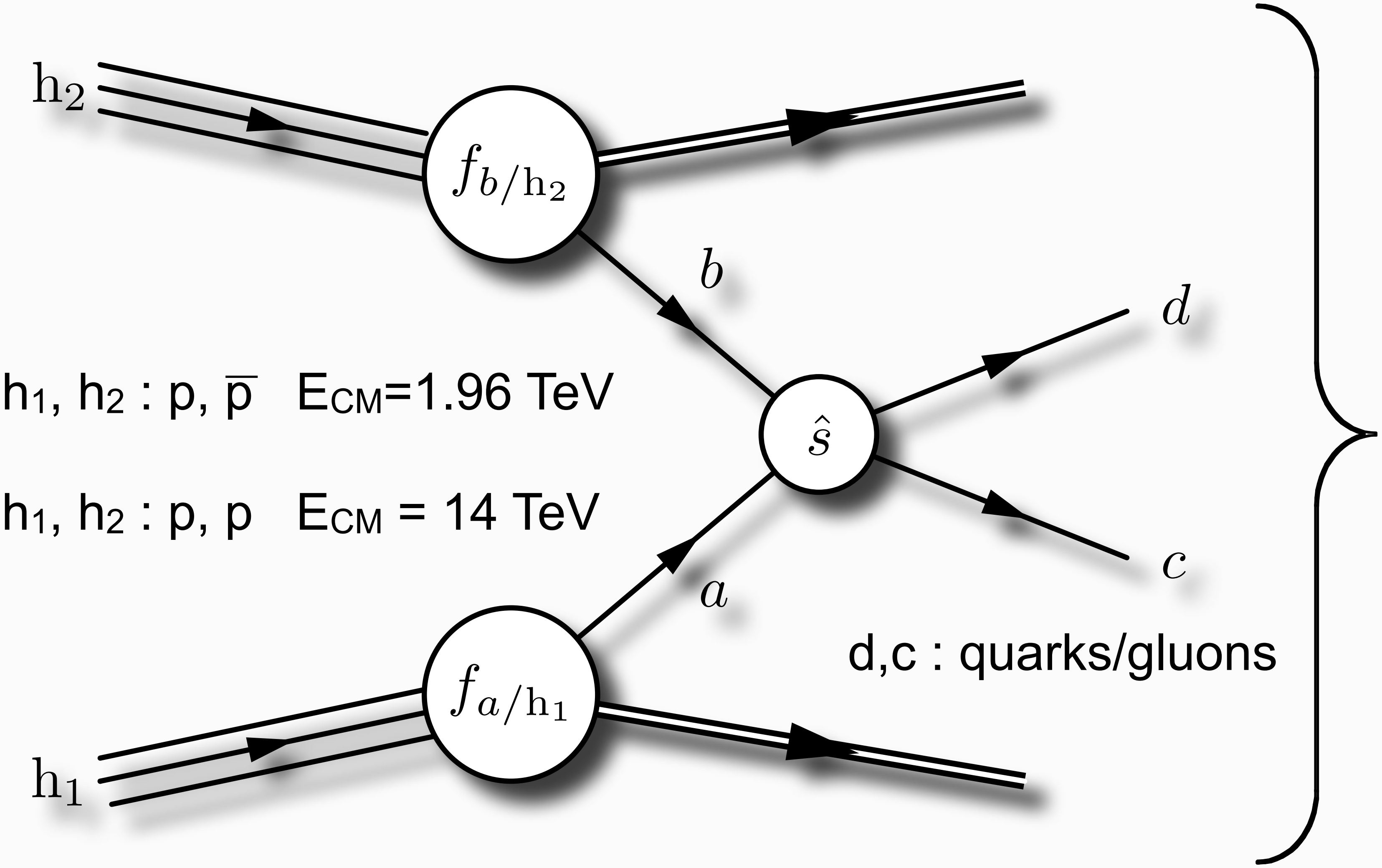

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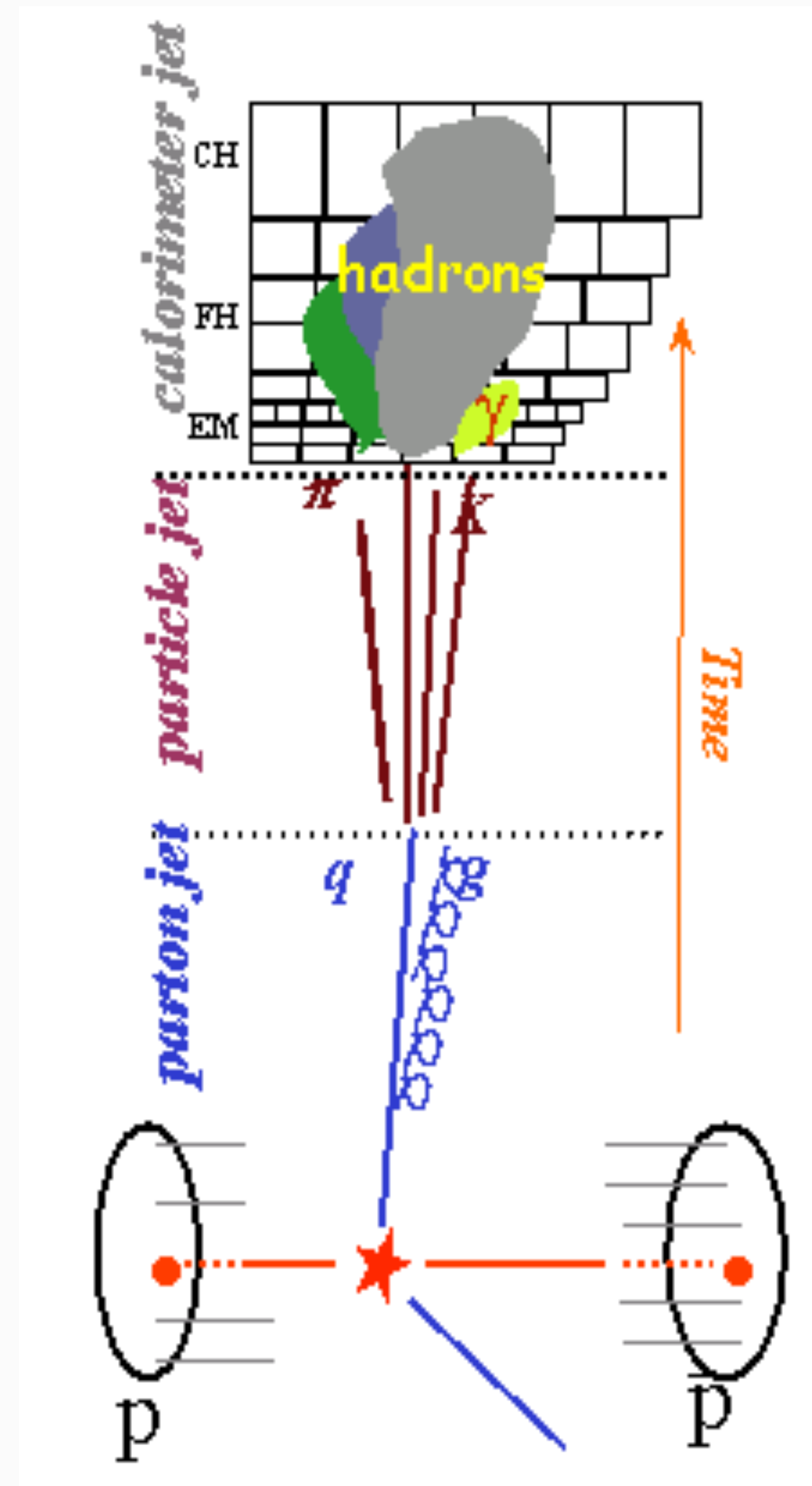

JET production at hadron colliders

ETH Institute for Particle Physics

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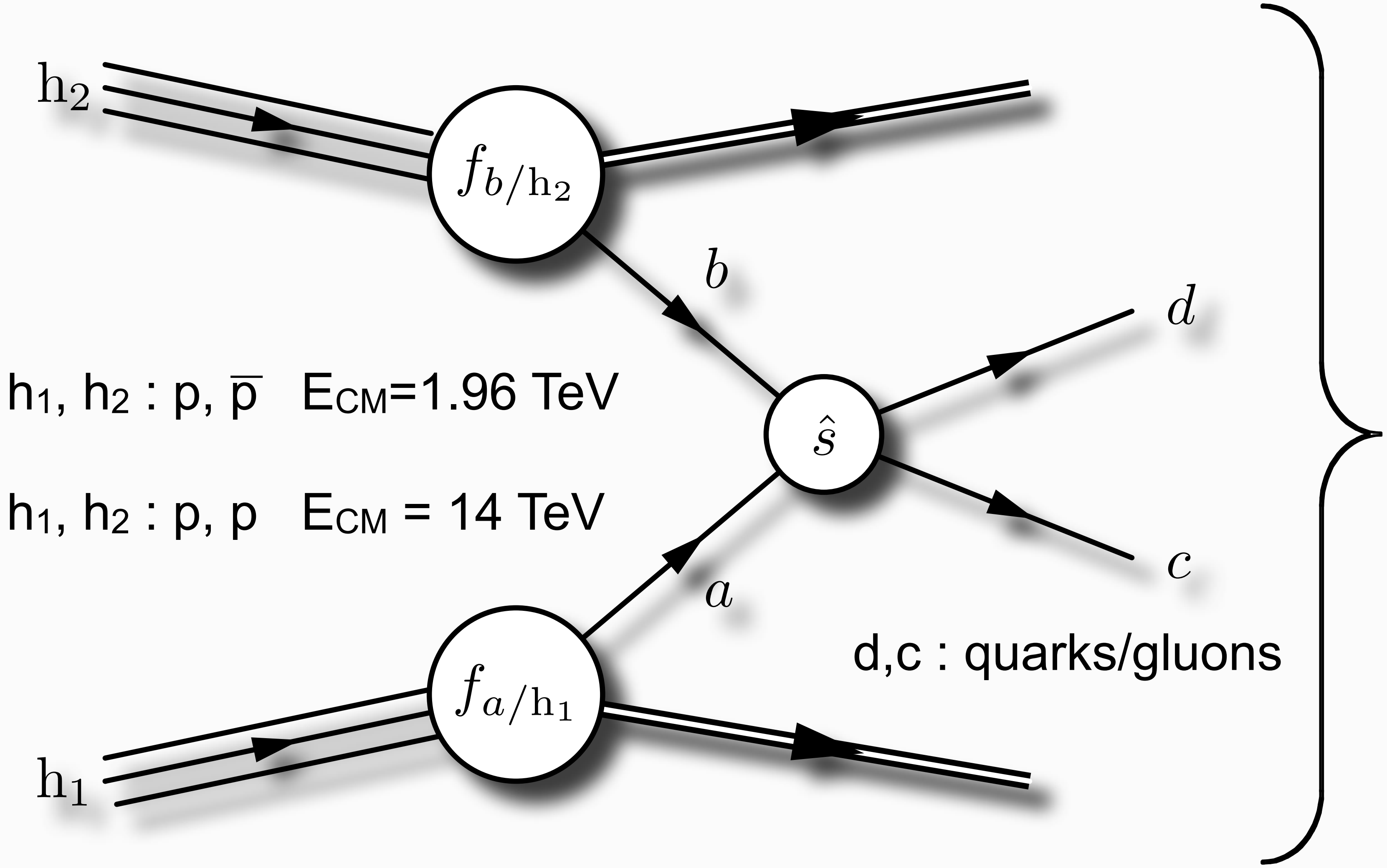

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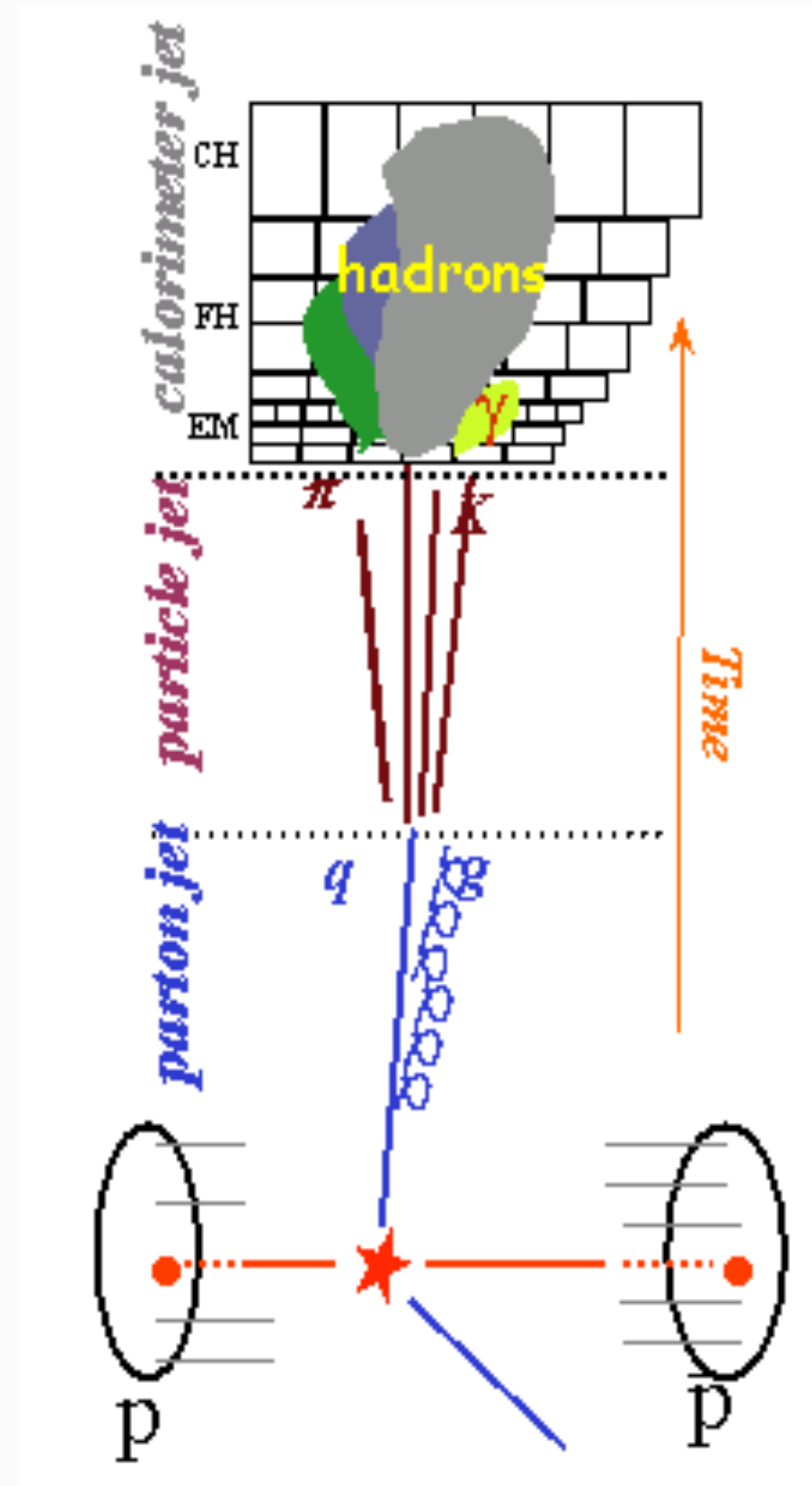

Goal

- measure probability that quarks/gluons are produced with a certain energy, at a certain angle
- Problem : do not observe quarks and gluons directly, only hadrons, which appear collimated into **jets**
- Reconstruct tracks and/or energy clusters in the calorimeter

What do we have to measure?

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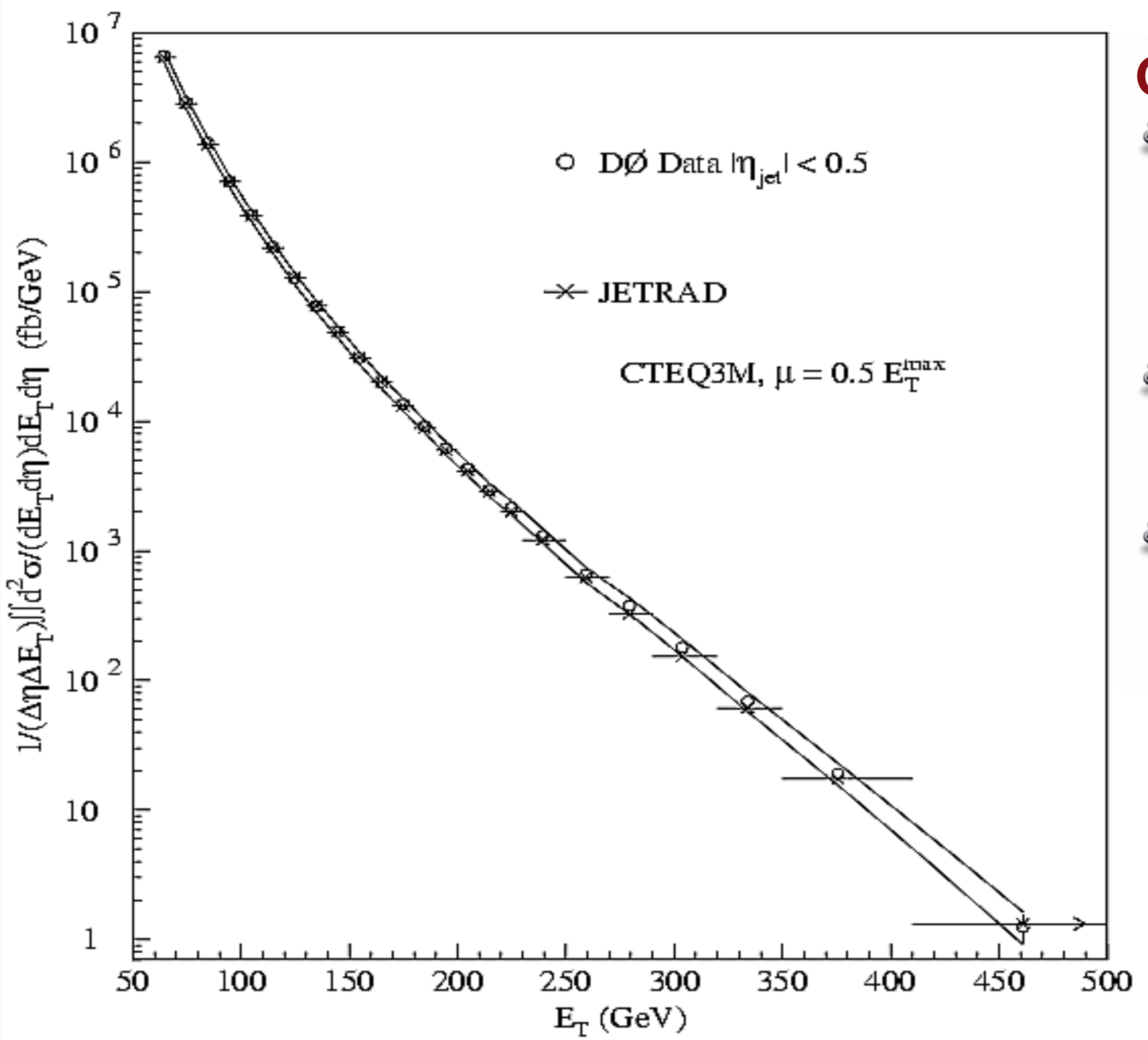

Goal

- measure cross section (probability) that jets are produced with a certain transverse energy E_T, within a certain rapidity range
- Test of perturbative QCD, over many orders of magnitude!
- Look at very high energy tail, new physics could show up there in form of excess (eg. sub-structure of quarks?)

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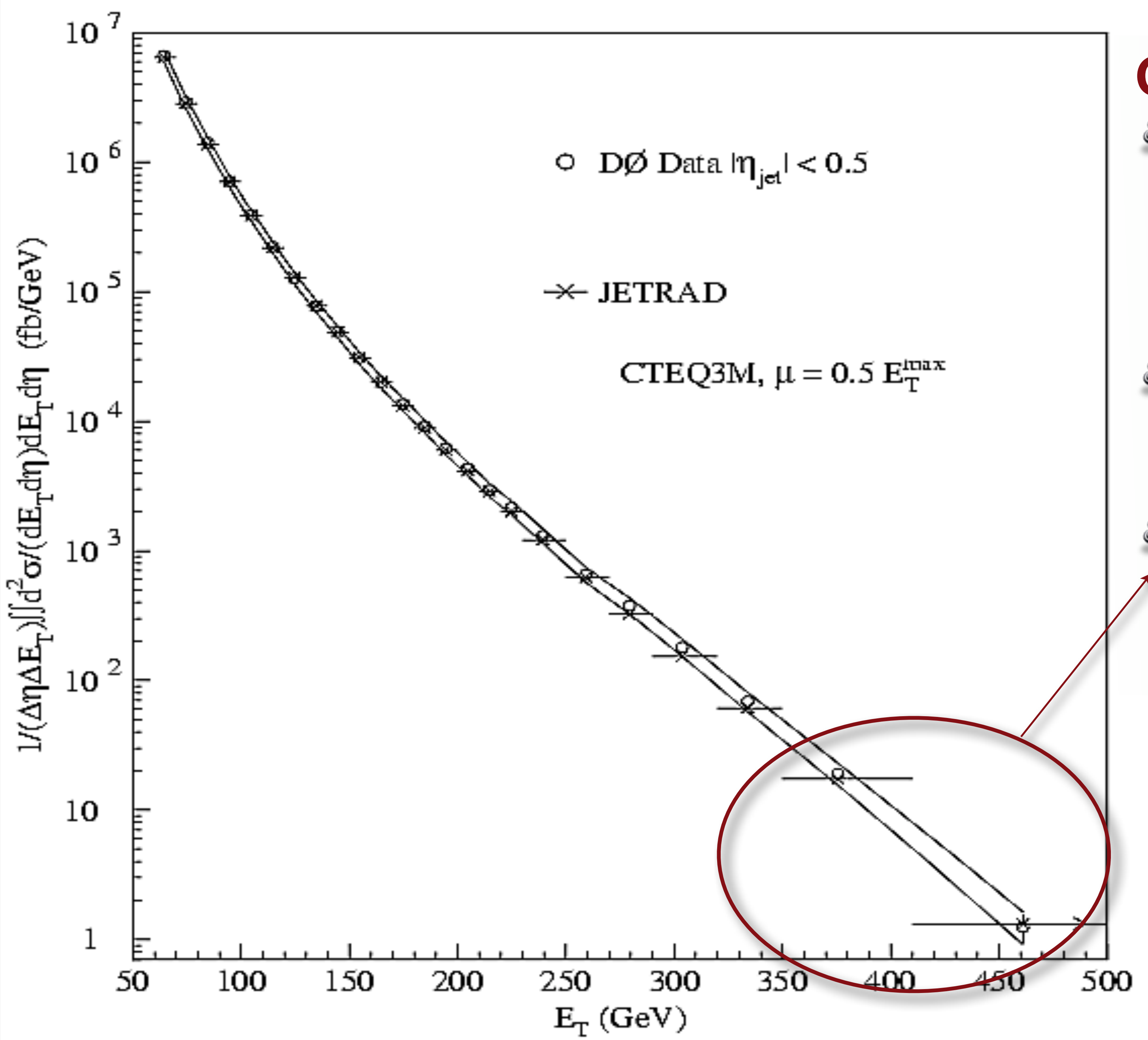

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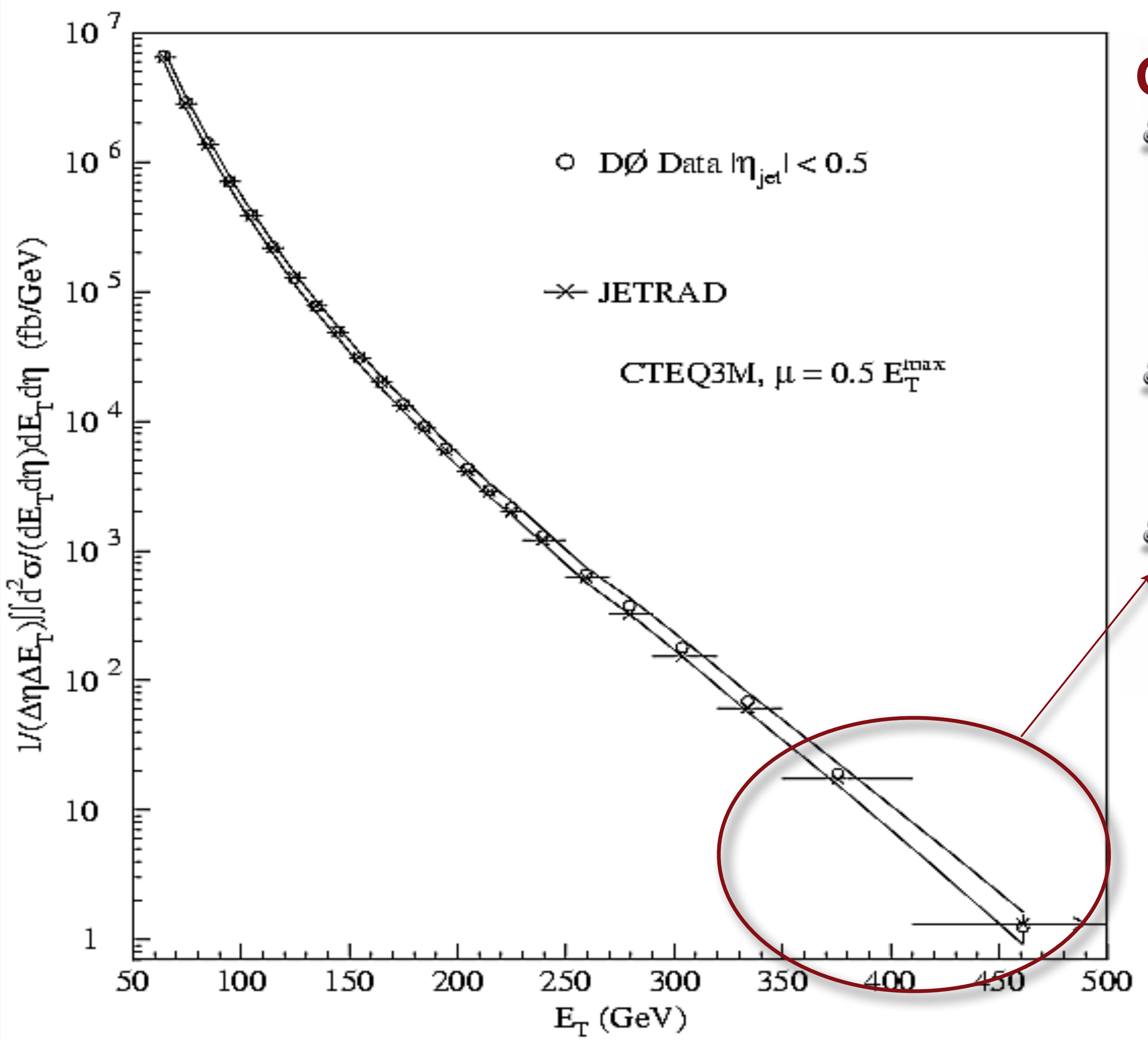

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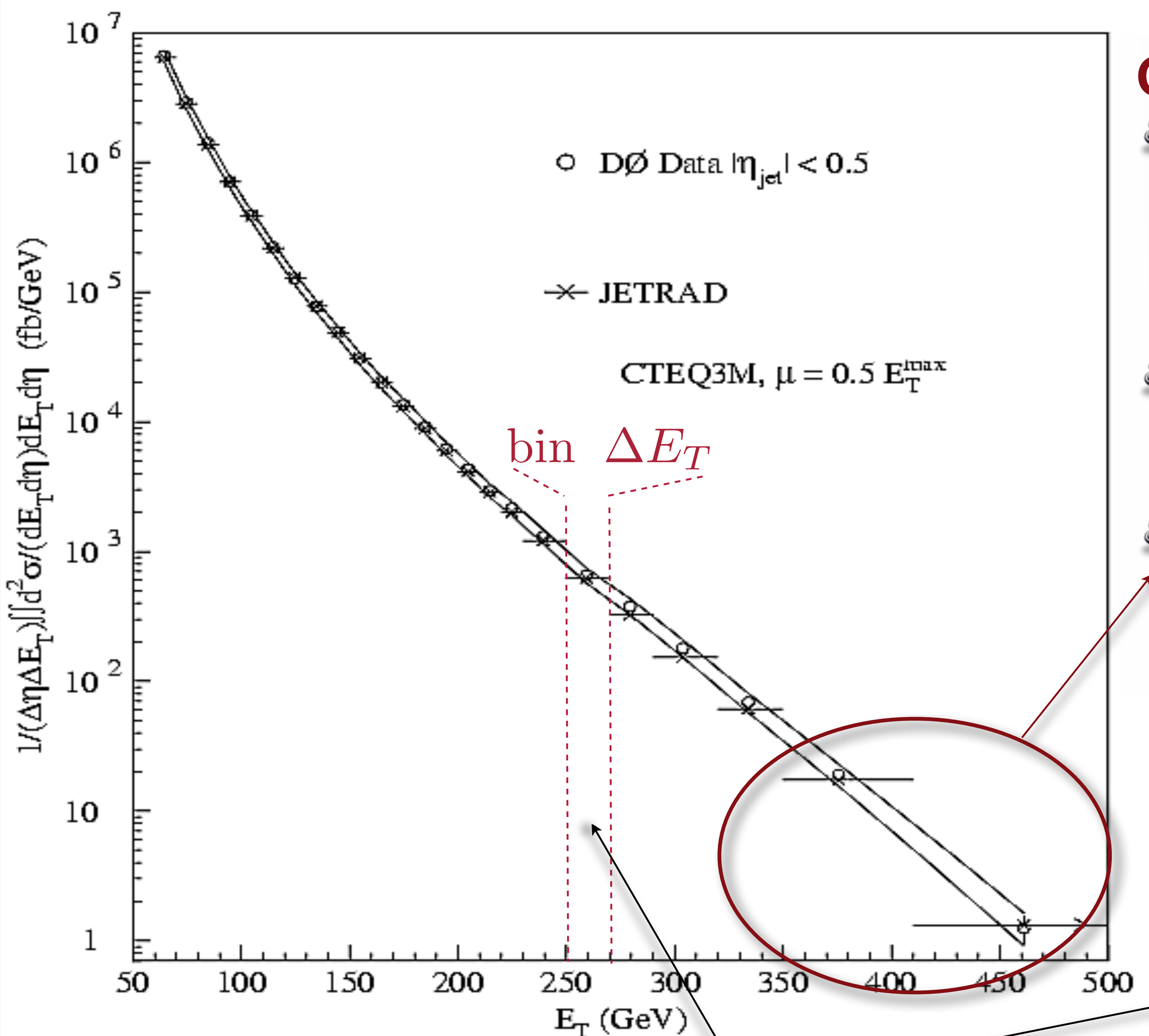

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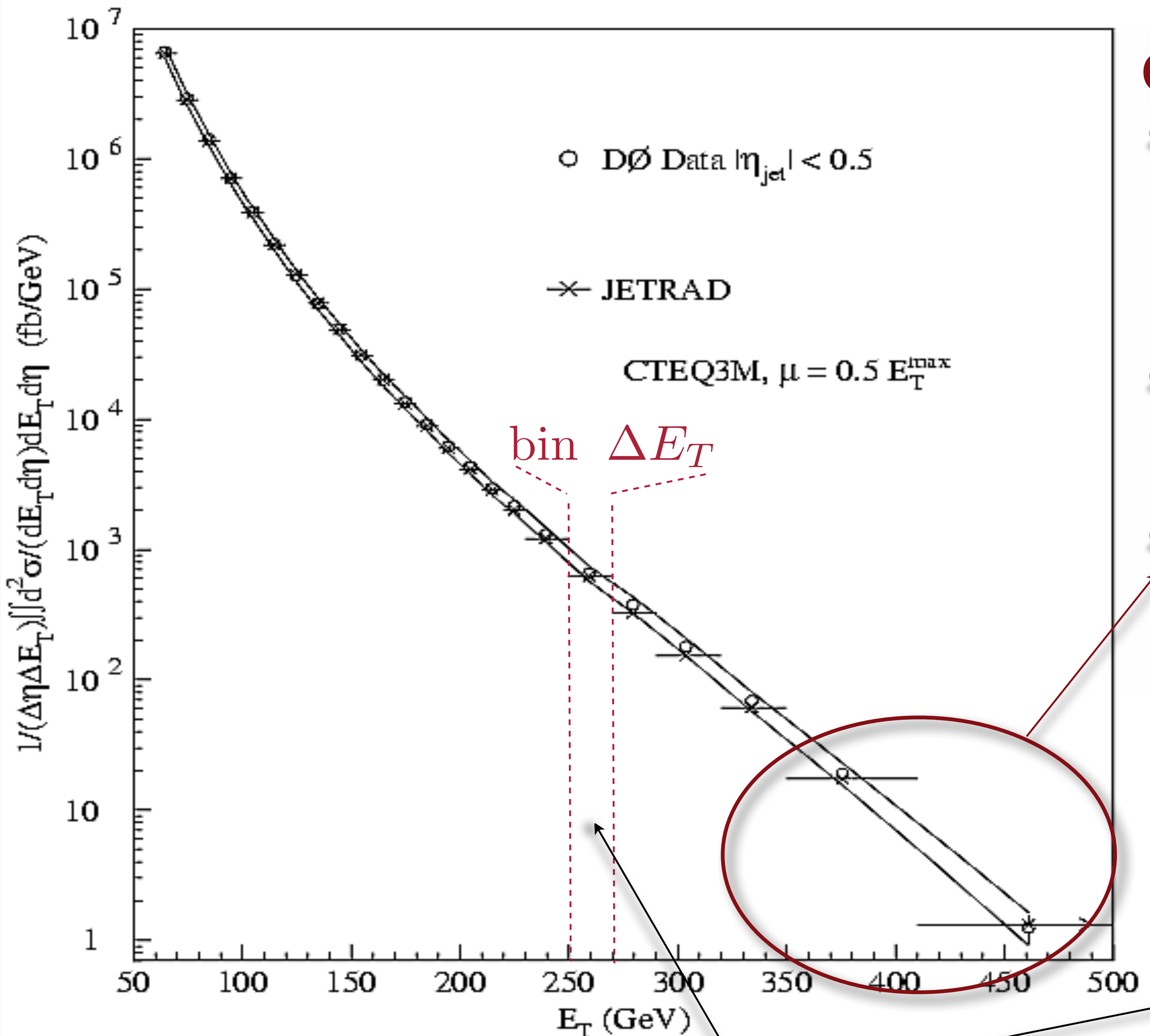

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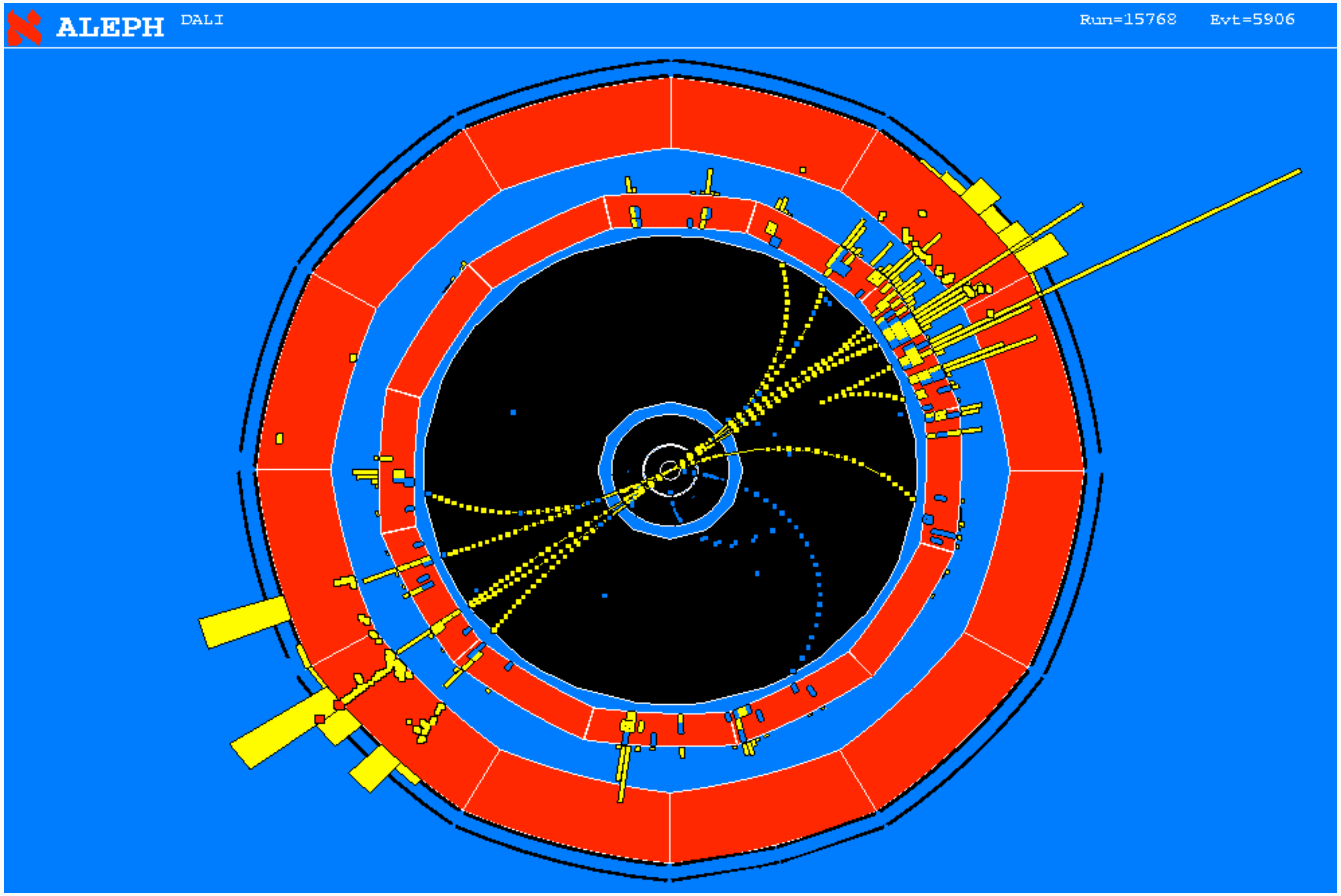
efficiency to reconstruct jets

integrated accelerator luminosity

What is a jet?



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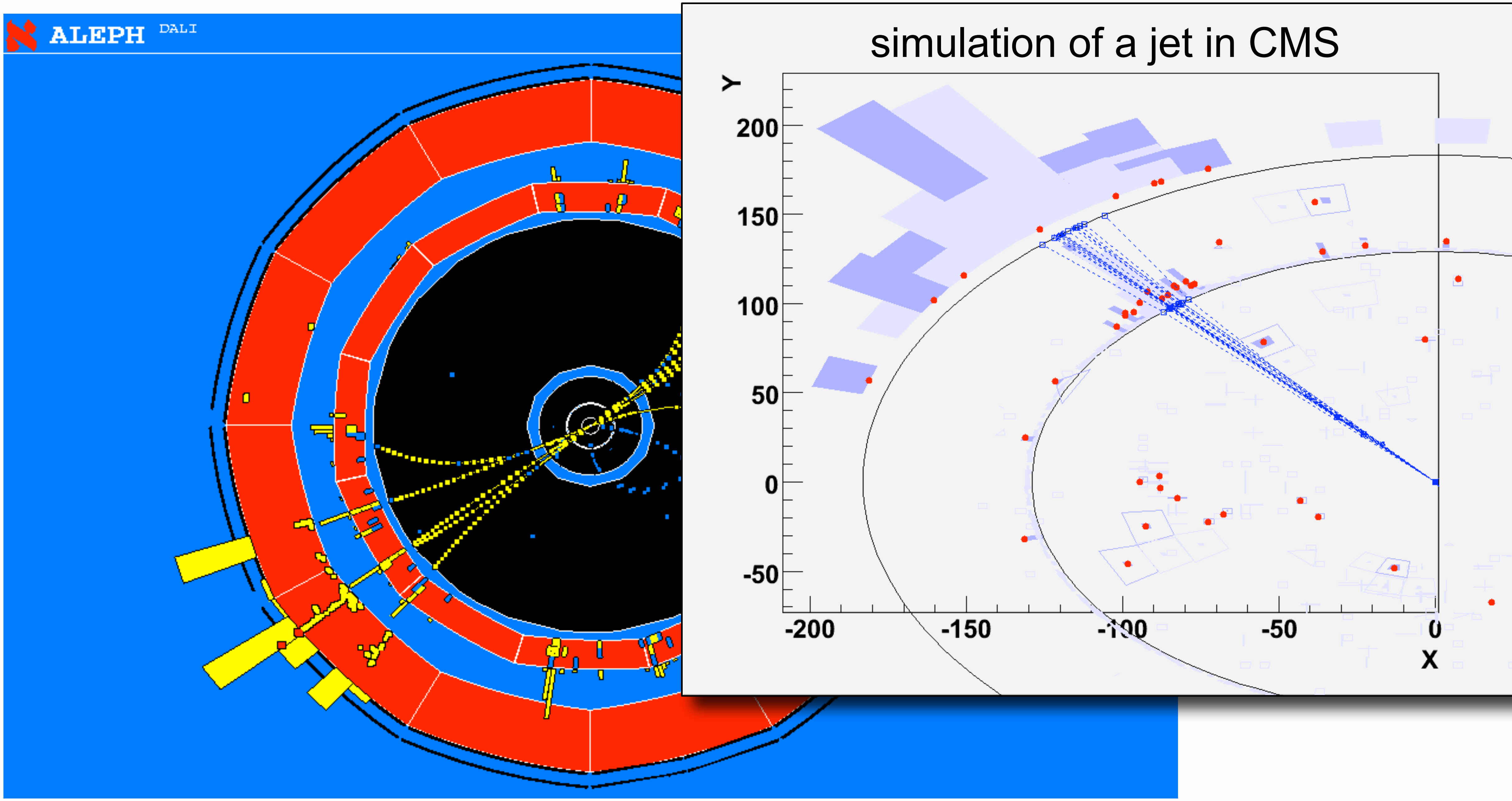

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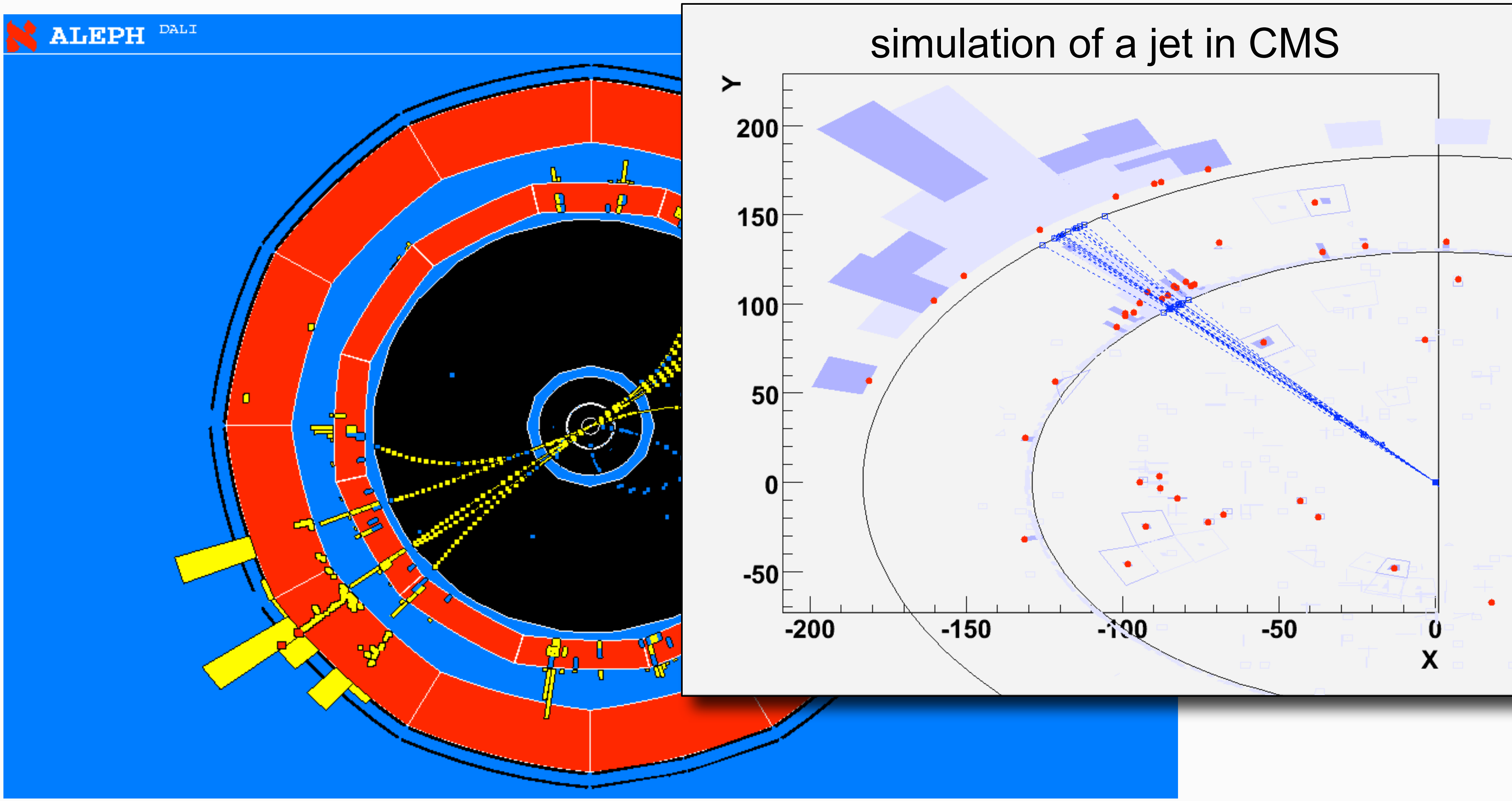
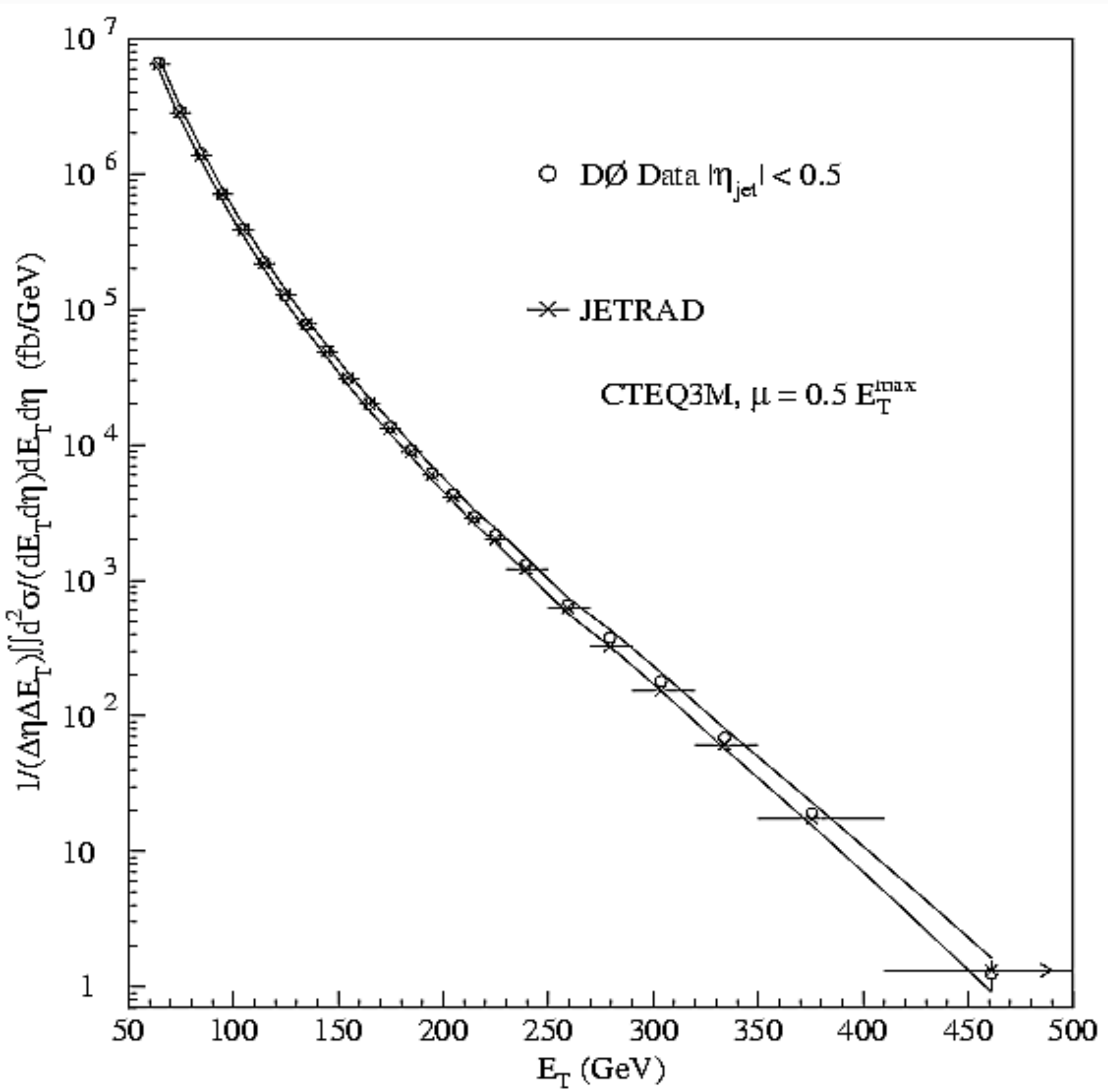


“cluster/spray of particles (tracks, calorimeter deposits) or flow of energy in a restricted angular region”

- clear : need some algorithmic definition. See later..

Problem 1 : Energy scale

- Question : how well do we know the energy calibration?
- Critical because of very steeply falling spectrum!



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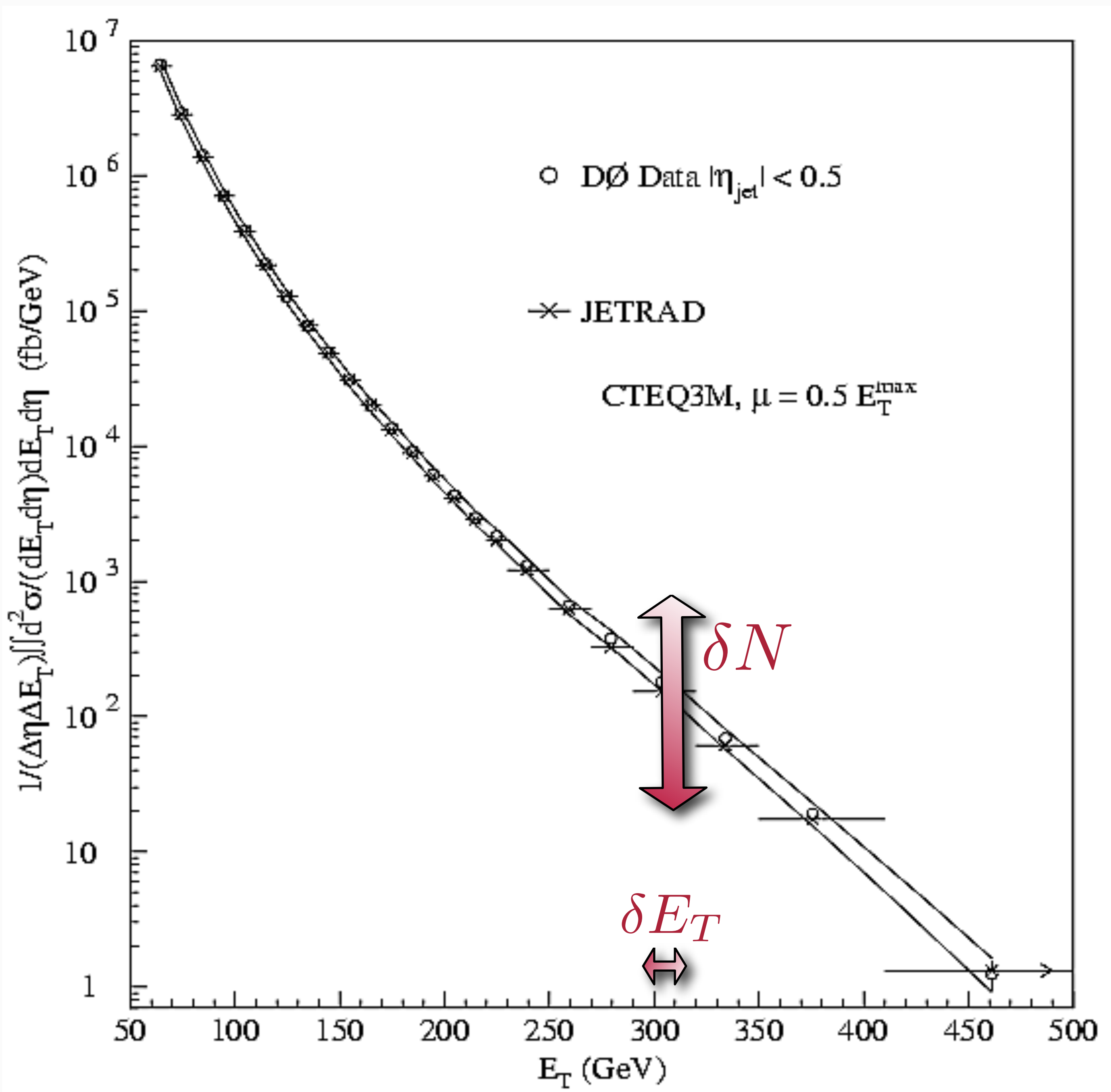

$$\frac{d^2\sigma}{dE_T d\eta} \approx \text{const} \cdot E_T^{\ -6}$$

relative uncertainties

$$\frac{\delta N}{N} \approx 6 \cdot \frac{\delta E_T}{E_T}$$

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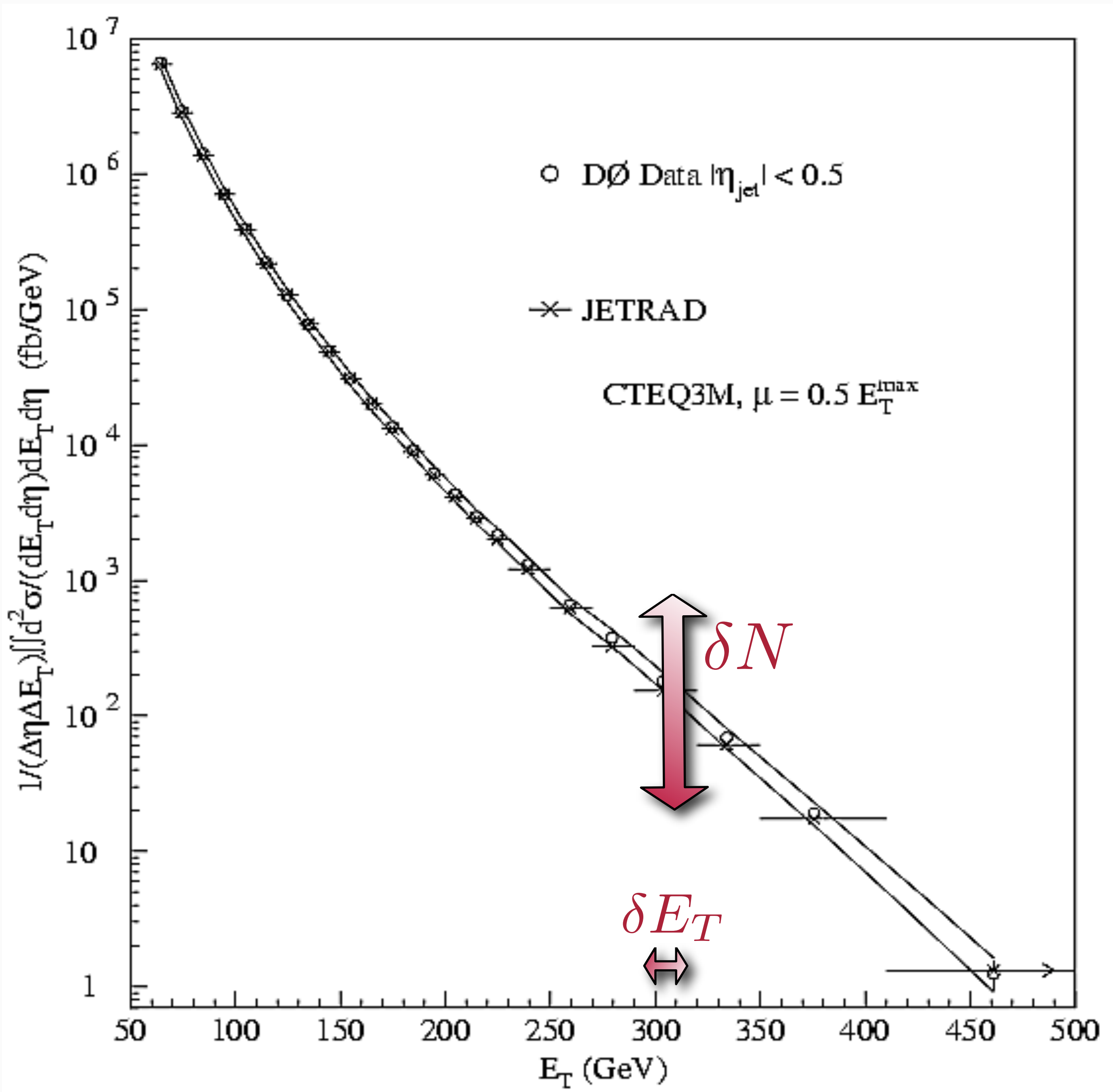

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so beware:

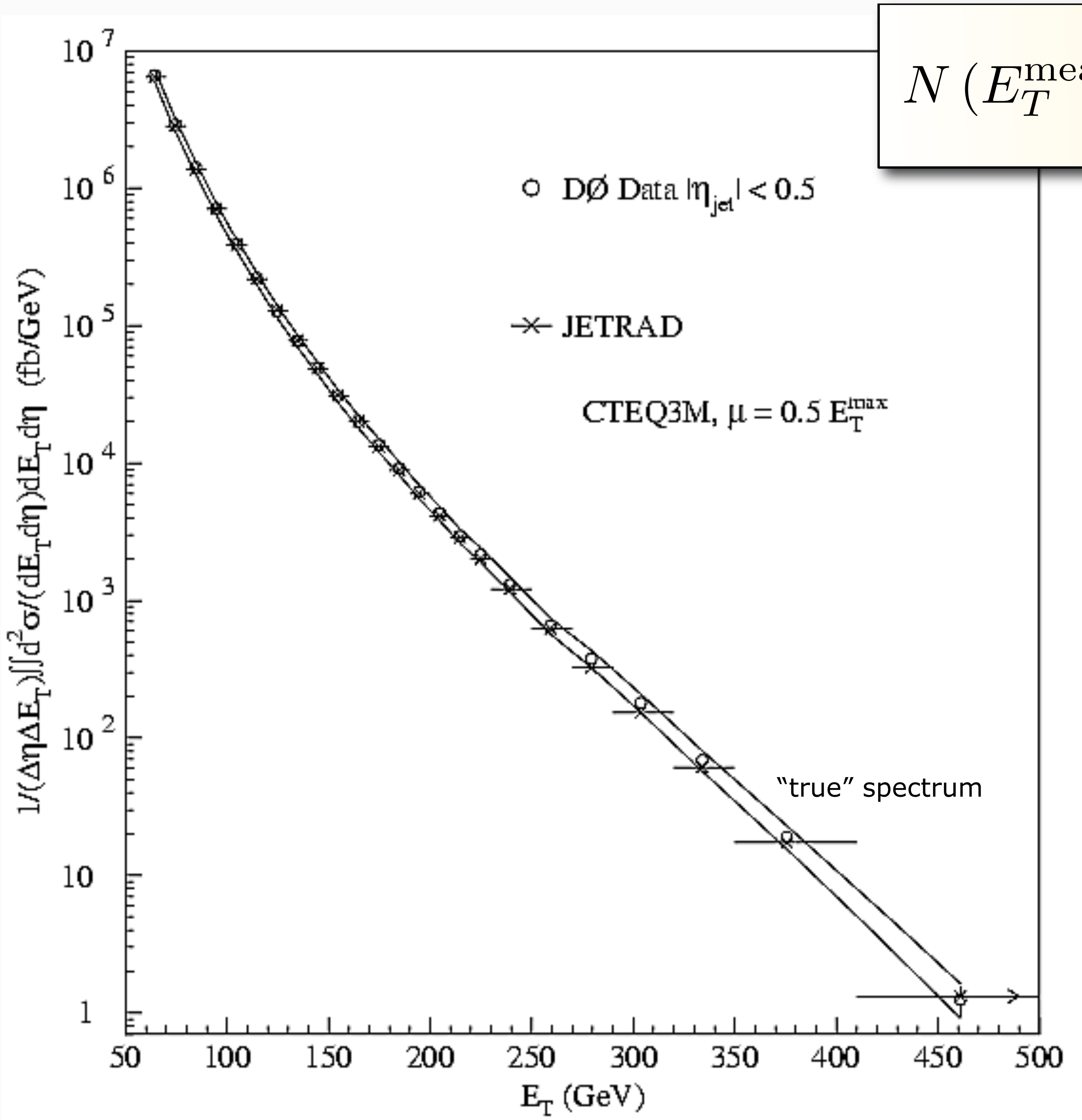
eg. an uncertainty of **5%** on absolute energy scale (calibration)

➔ an uncertainty of **30%** (!) on the measured cross section

Problem 2 : Energy resolution

- The energy resolution can distorts the spectrum
- Again : Critical because of very steeply falling spectrum!

$$N\left(E_T^{\mathrm{meas}}\right) = \int_0^\infty N\left(E_T^{\mathrm{true}}\right) \cdot \mathrm{Resol}\left(E_T^{\mathrm{meas}}, E_T^{\mathrm{true}}\right) \mathrm{d}E_T^{\mathrm{true}}$$



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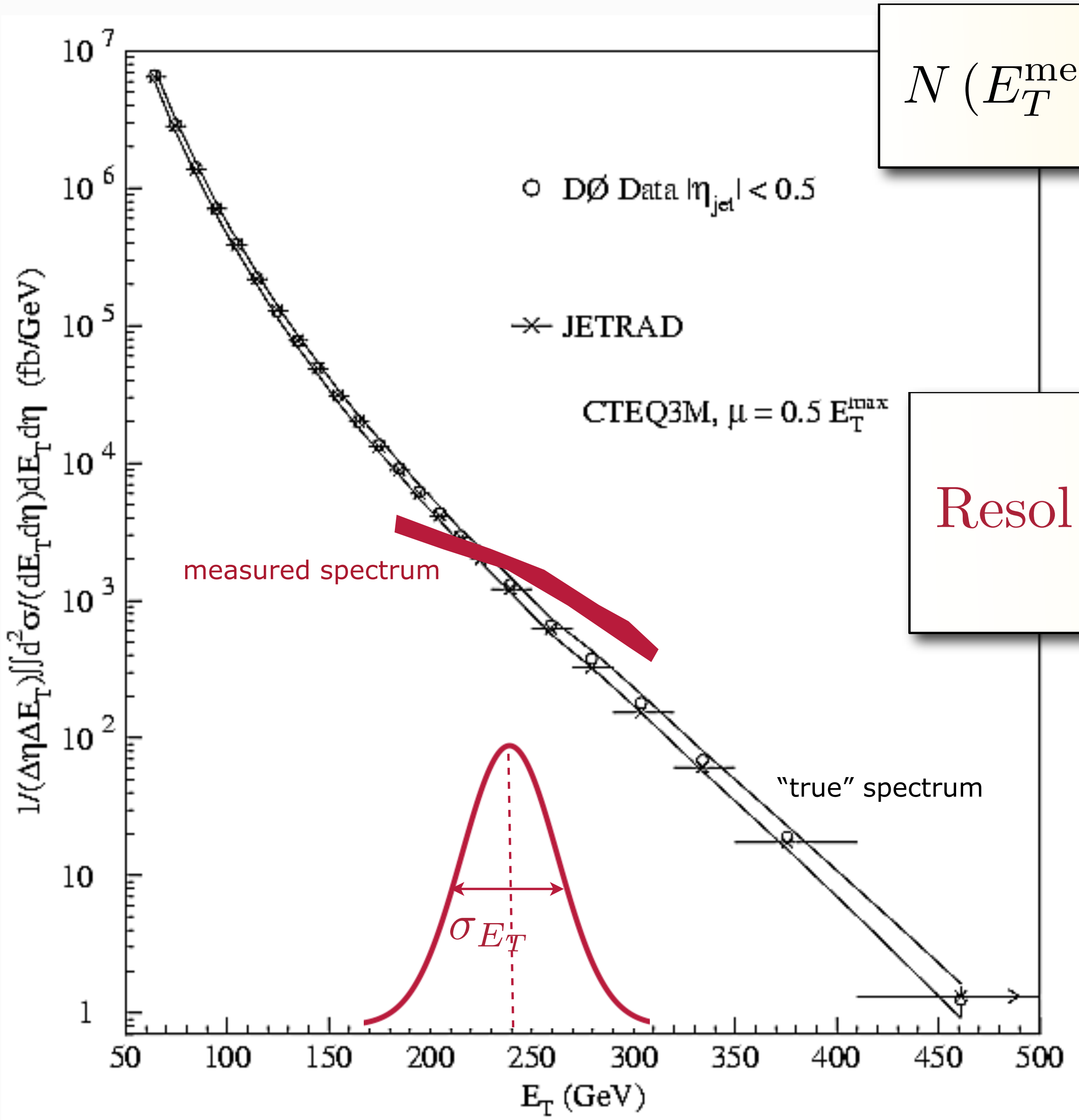
eg. Gaussian resolution function

$$\mathrm{Resol}\left(E_T^{\mathrm{meas}}, E_T^{\mathrm{true}}\right) \propto \exp\left[-\frac{\left(E_T^{\mathrm{meas}} - E_T^{\mathrm{true}}\right)^2}{\sigma_{E_T}^2}\right]$$



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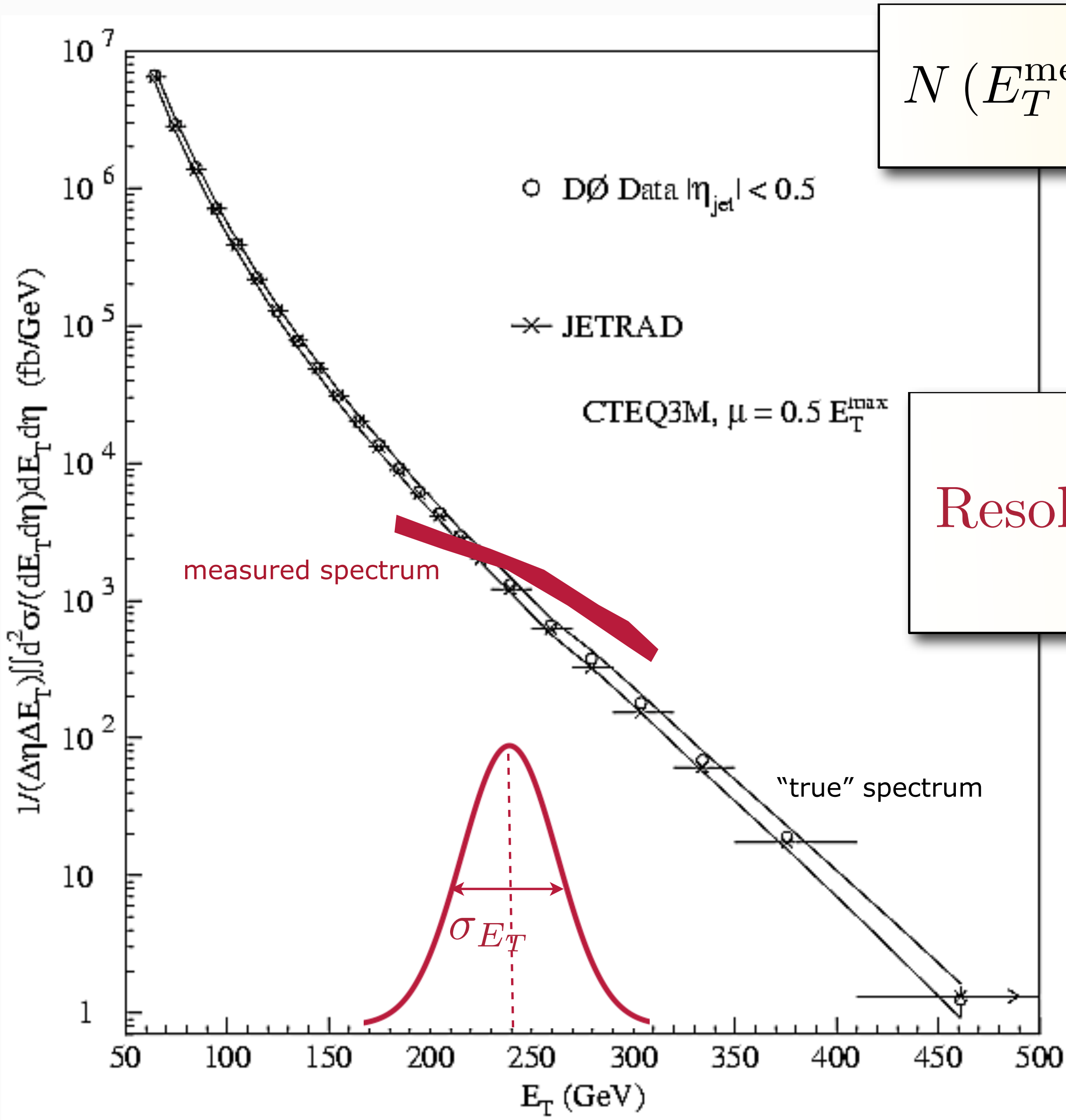

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so beware:

A bad energy resolution can distort the true spectrum

➔ have to determine the energy resolution

➔ have to "unfold" the measured spectrum

➔ problem is minimized if bin width ~ σ_{E_T}

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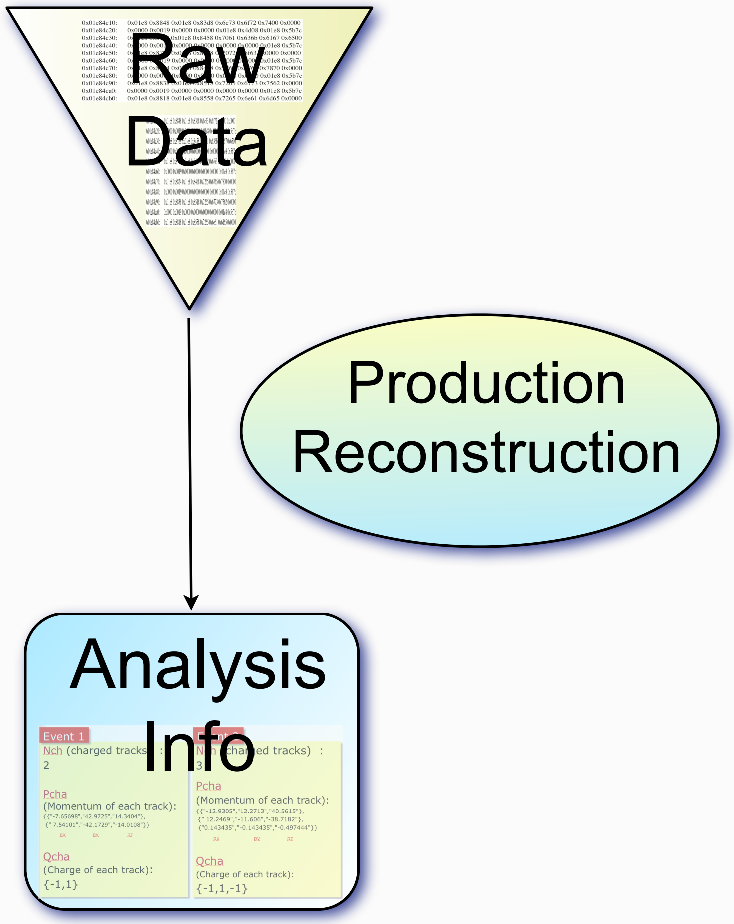
  - determine parameters, eg. by fitting the prediction to the data

How is all this done in practice?

"The only place you'll find SUCCESS before WORK is in the dictionary" (May B. Smith)

The process in practice

- The reconstruction step is usually done in common
  - “Tracks”, “particle ID”, “calorimeter towers” etc are general concepts, not analysis-specific. Common algorithms make it easier to understand how well they work
  - “very coordinated” data access



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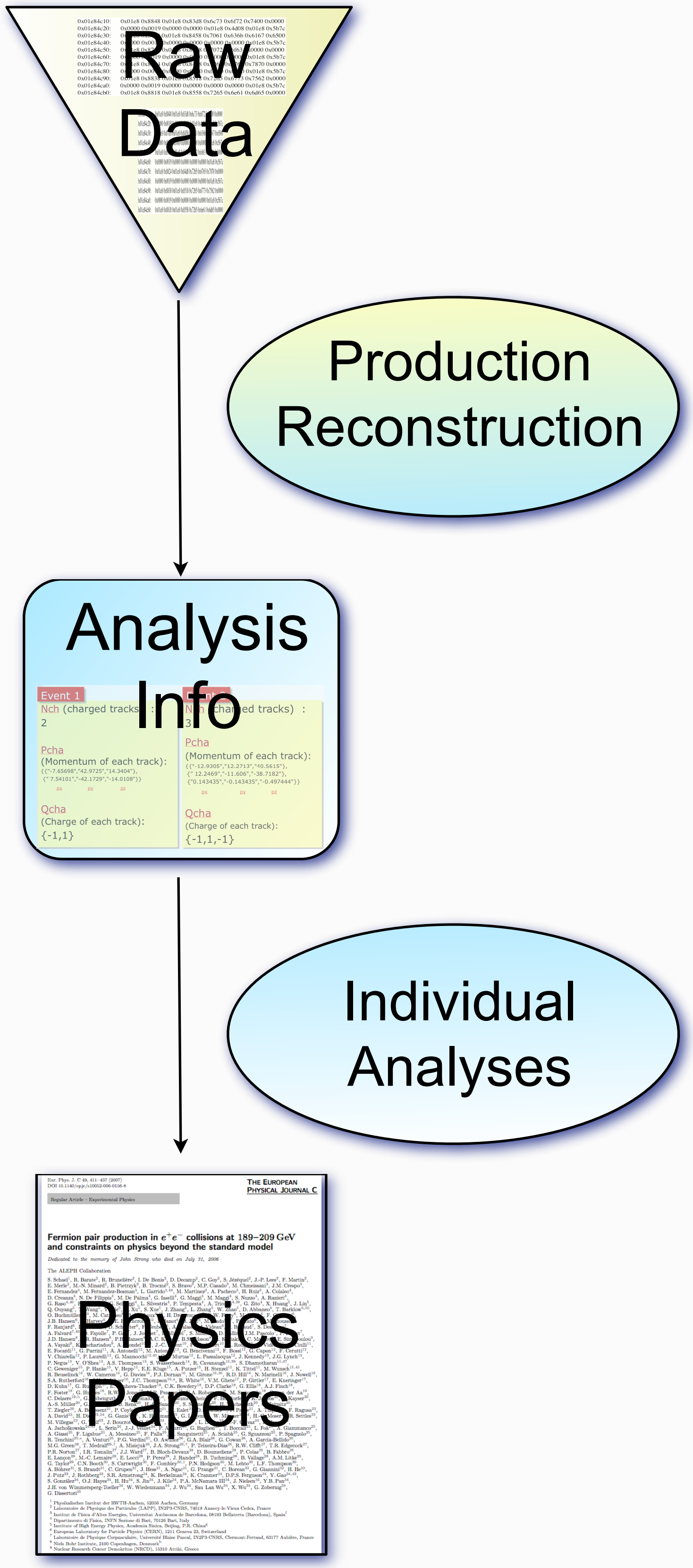
  - Many different measurements being done at once
  - Small groups working on topics they are interested in
  - Many different time scales for these efforts
  - "chaotic" data access



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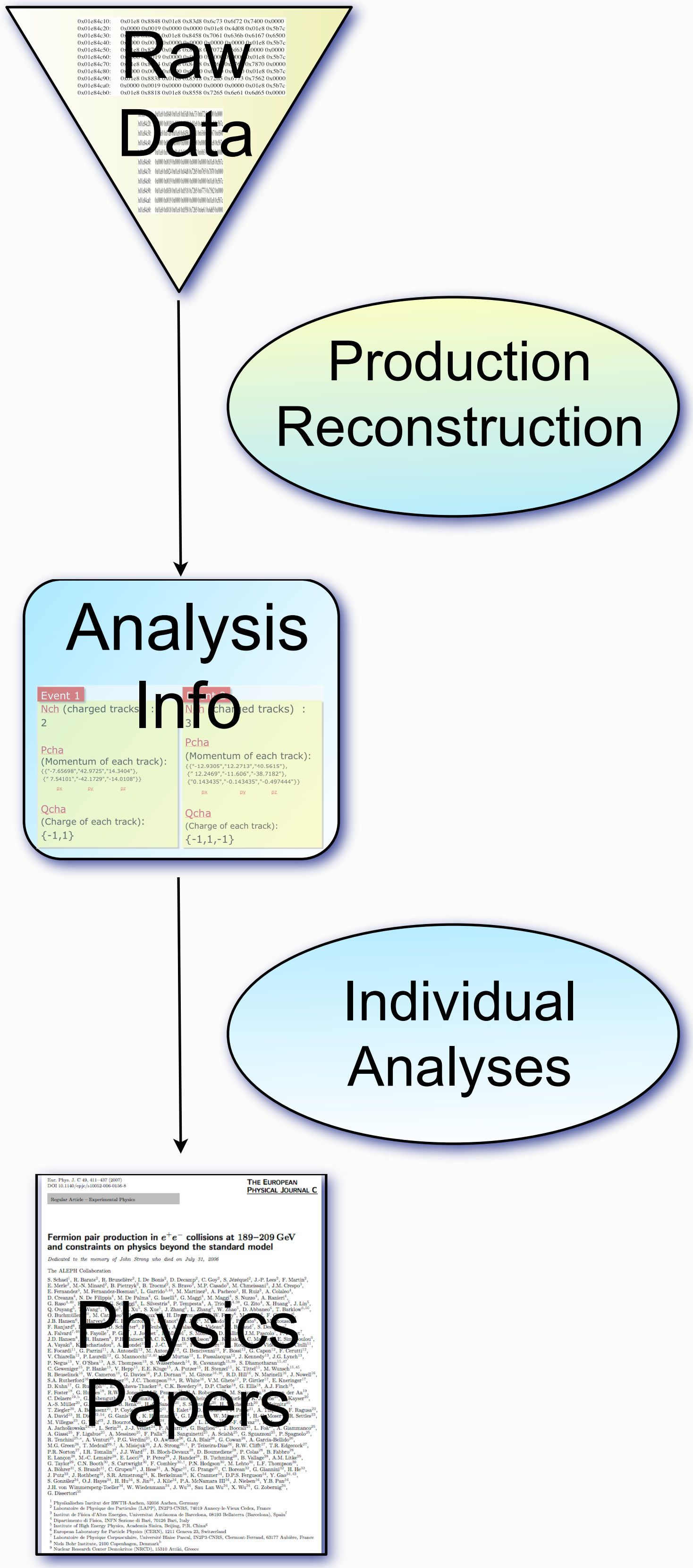
- Collaborations build offline computing systems to handle all this



Track finding

Why does tracking need to be done well?

- Determine how many charged particles were created in an event
- Measure their momentum
  - direction, magnitude
  - combine these to look for decays of particles with known masses
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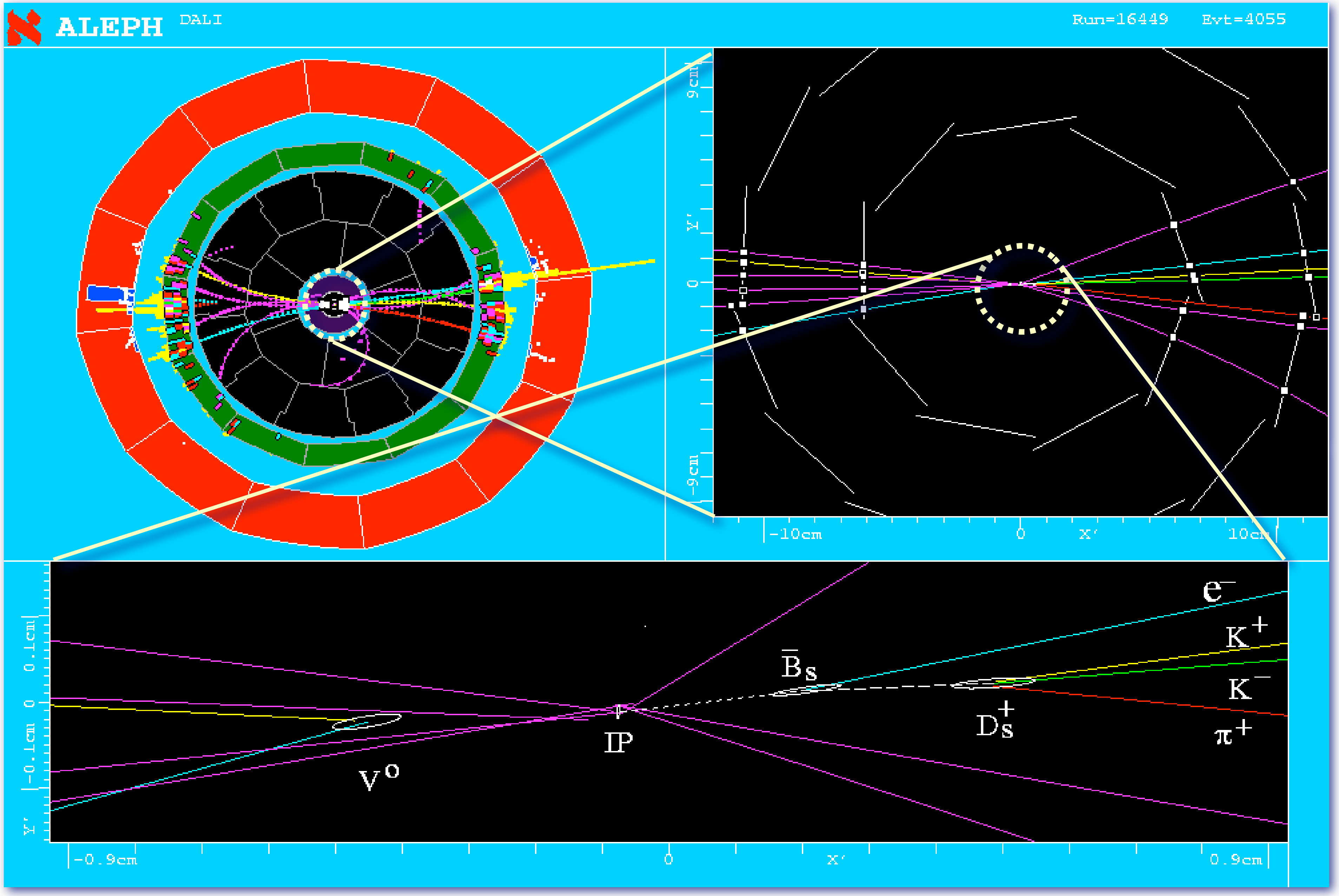
  - only final stable particles are visible
- Measure spatial trajectories
  - combine to look for separated vertices, indicating particles with long lifetimes



Track Fitting

- 1D straight line fit as simple case
- Two perfect measurements
  - away from interaction point
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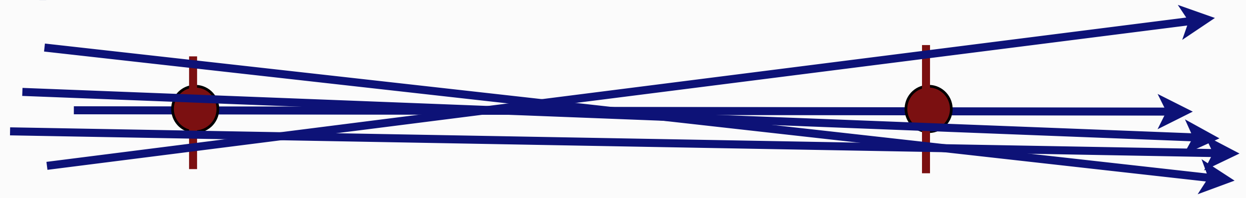

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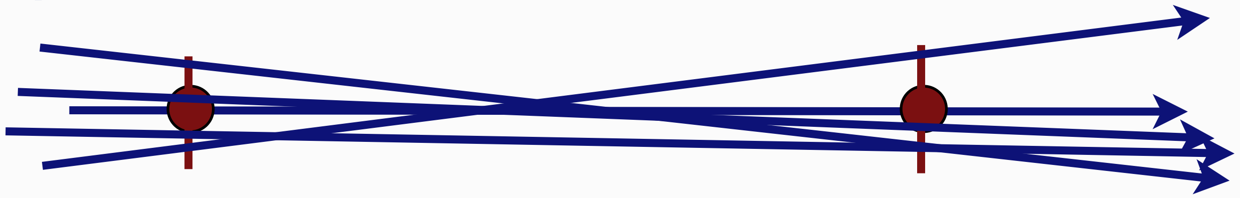

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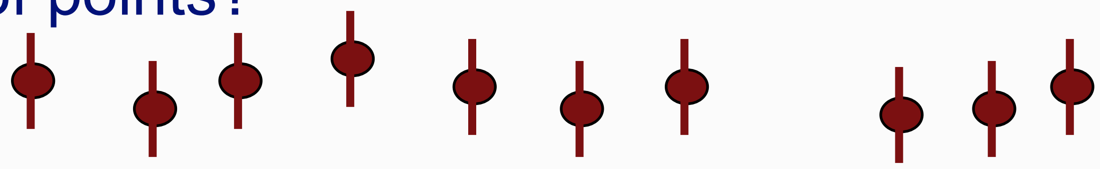
  But how to find the best point from a large set of points?



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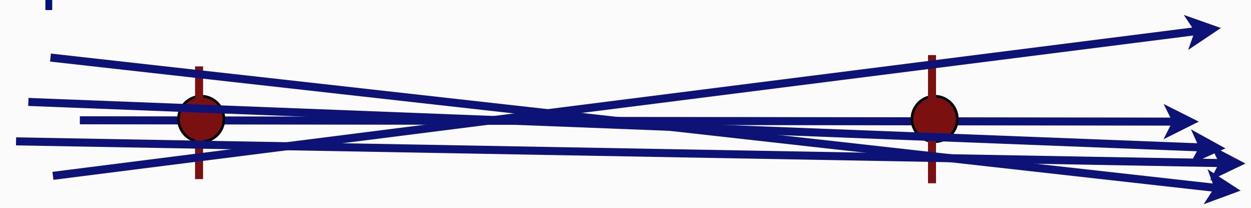

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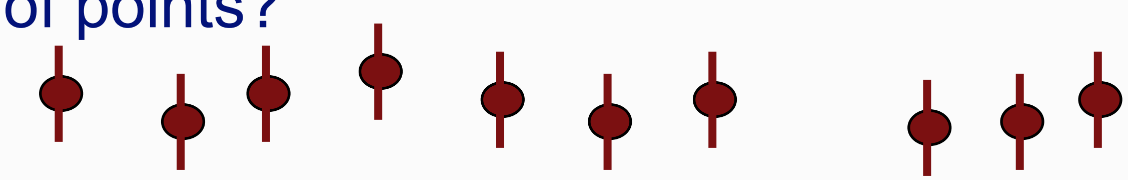

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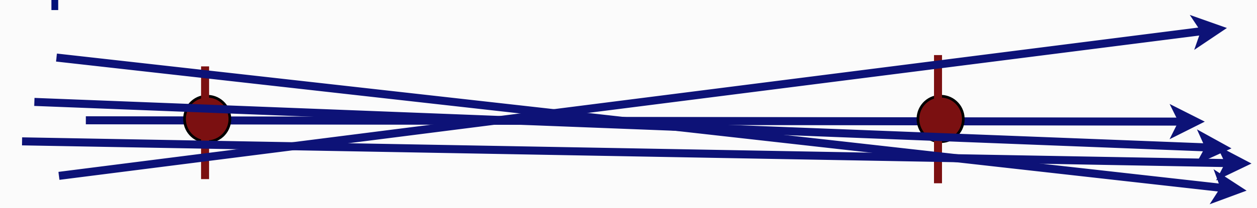

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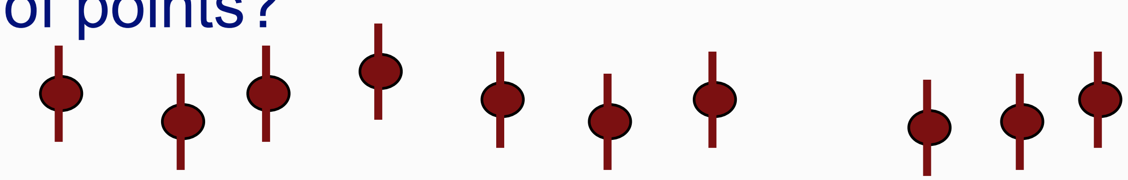

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predicted track position at i^{th} hit

position of i^{th} hit

  - Find track parameters by Least-Squares-Minimization

$$\boxed{\chi^2 = \sum_{i=1}^{n_{\text{hits}}} \frac{(y_i - y(x_i))^2}{\sigma_i^2}}$$

uncertainty of i^{th} measurement

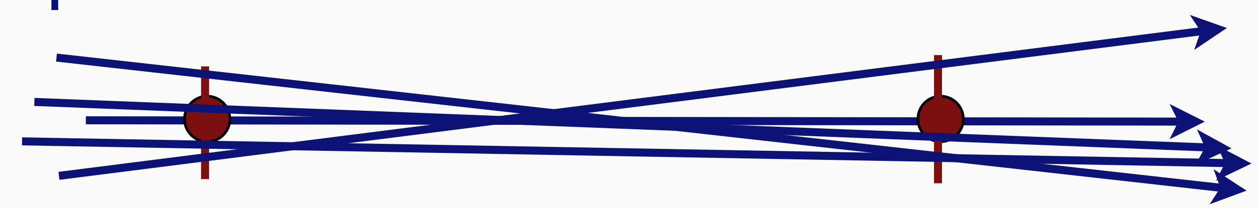
see also lecture by G. Cowan

Track Fitting

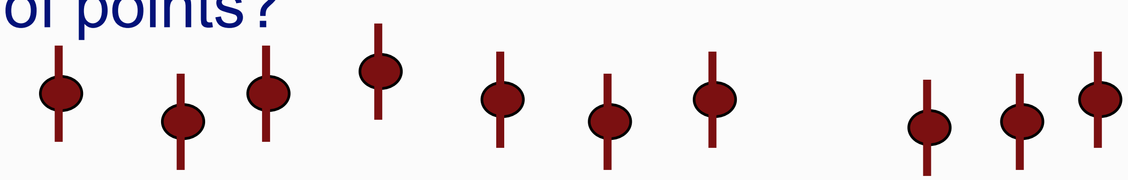
ETH Institute for Particle Physics

- 1D straight line fit as simple case
- Two perfect measurements
  - away from interaction point
  - no measurement uncertainty
  - just draw a straight line through them and extrapolate

- Imperfect measurements give less precise results
  - the farther you extrapolate, the less you know



- Smaller errors and more points help to constrain the possibilities. But how to find the best point from a large set of points?



- Quantitatively
  - parameterize a track:
  - In case of straight line $\boxed{y(x) = \theta\, x + d}$ or, eg., helix in case of magnetic field present
  - Find track parameters by Least-Squares-Minimization
  - Obtain also uncertainties on track parameters

$\delta\theta \qquad \delta d$

position of i^{th} hit

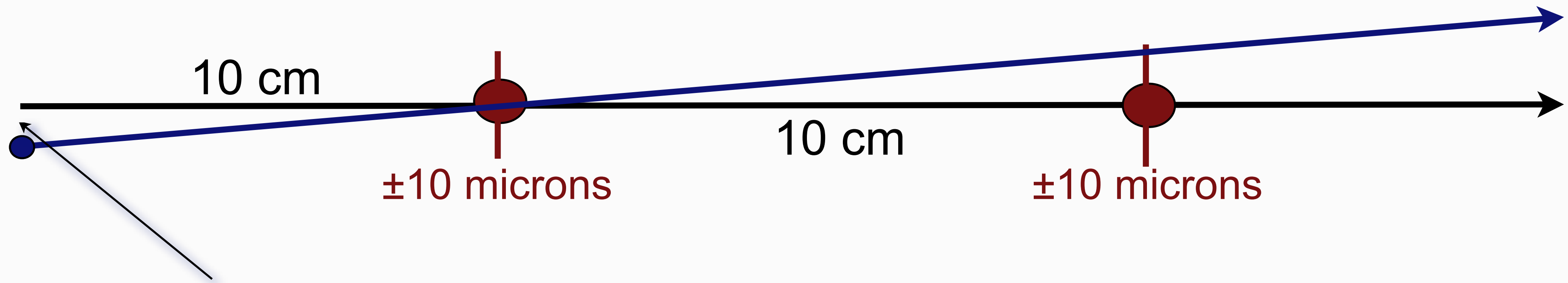
predicted track position at i^{th} hit

$$\boxed{\chi^2 = \sum_{i=1}^{n_{\text{hits}}} \frac{(y_i - y(x_i))^2}{\sigma_i^2}}$$

uncertainty of i^{th} measurement

see also lecture by G. Cowan

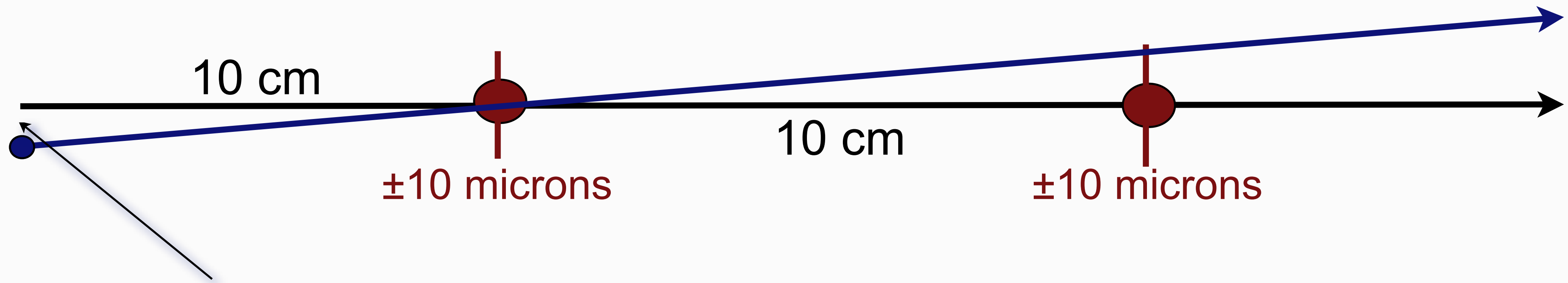
“Typical” size of errors



- Error δd on position is about ±10 microns
- Error $\delta\Theta$ on angle is about ±0.1 milliradians (±0.002 degrees)
- Satisfyingly small errors
  - allows separation of tracks that come from different particle decays (which can be separated at the order of mm)

- However
  - we “see” particles by interaction with a detector (=material)

“Typical” size of errors



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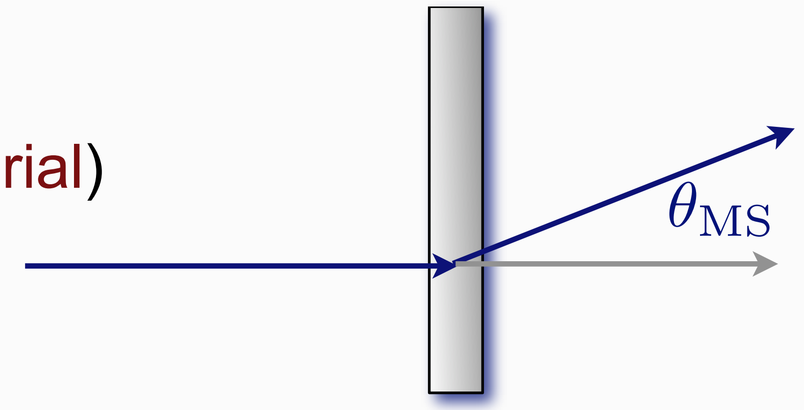

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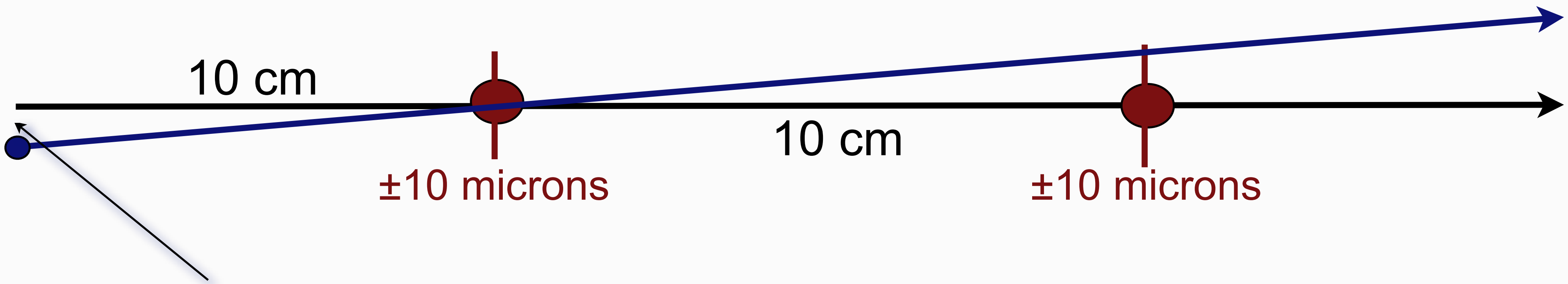

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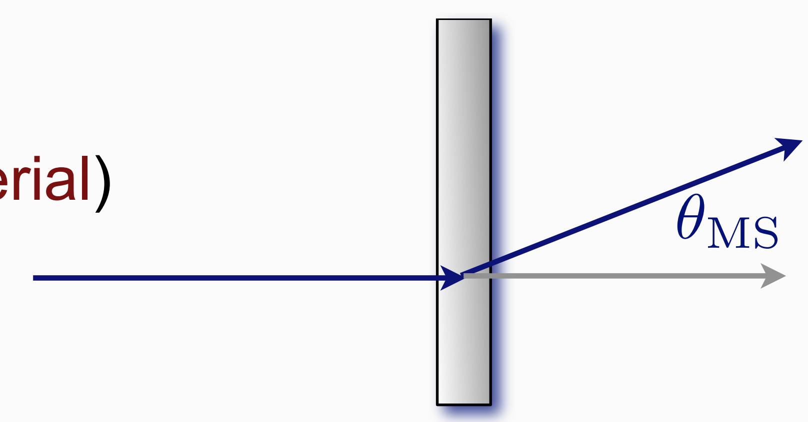
- Satisfyingly small errors
  - allows separation of tracks that come from different particle decays (which can be separated at the order of mm)

- However
  - we “see” particles by interaction with a detector (=material)
  - interaction leads to : energy loss, change in direction
  - This is **Multiple Scattering**
    - Charged particles passing through matter “scatter” by a random angle



$$\sqrt{\langle\theta^2_{\mathrm{MS}}\rangle} = \frac{15\,\mathrm{MeV}/c}{\beta p}\sqrt{\frac{\mathrm{thickness}}{X_{\mathrm{rad}}}}$$

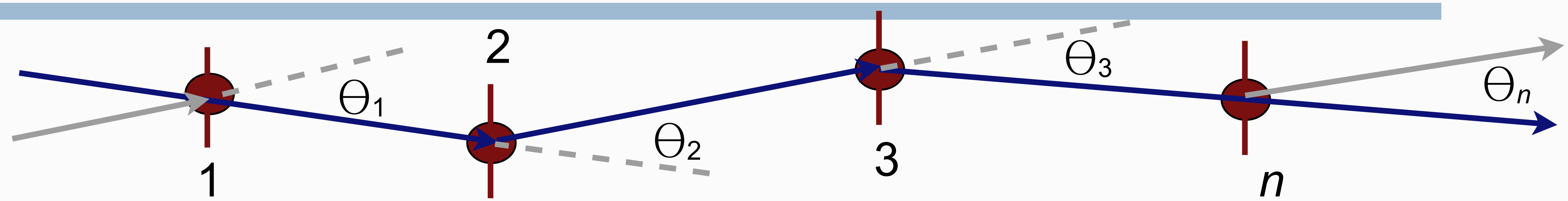
examples:

300 micron Si : RMS = 0.9 mrad / βp

1 mm Be : RMS = 0.8 mrad / βp

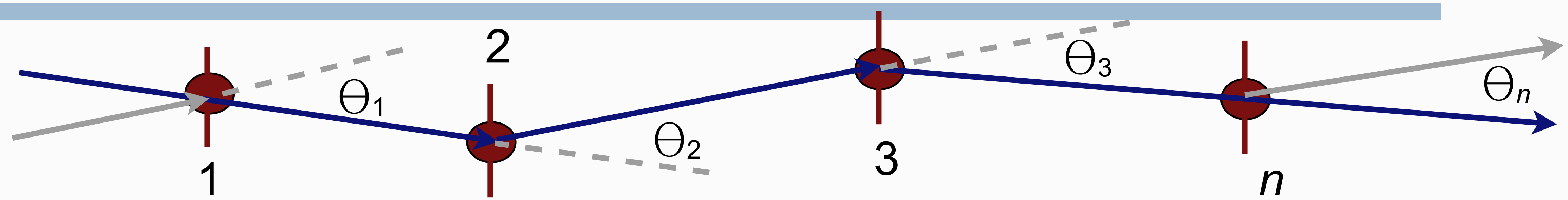
➔ leads to additional position errors

Kalman filter



- So? Could extend track parameterization to take this into account
  - *n* additional parameters $y(x) = d + \theta\, x + \Theta(x - x_1)\theta_1(x - x_1) + \Theta(x - x_2)\theta_1(x - x_2) + \cdots$
- and include the multiple scattering information into the Least-Squares (*n* equations, *n* unknowns)
  - For large *n*, computing time grows like O(n^3), quickly un-practicable

Kalman filter



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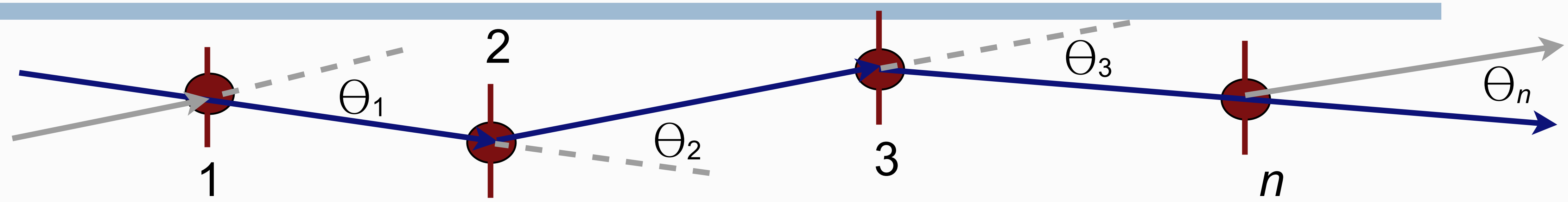

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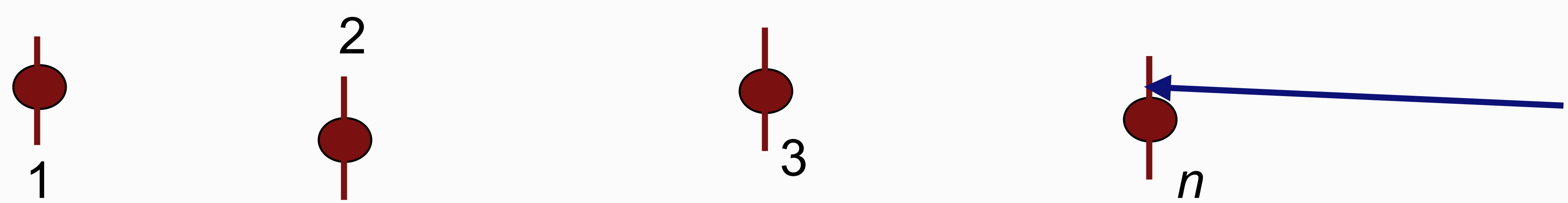

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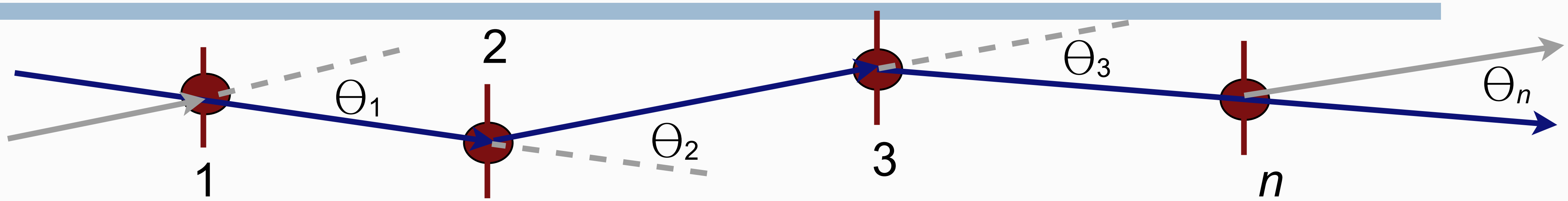

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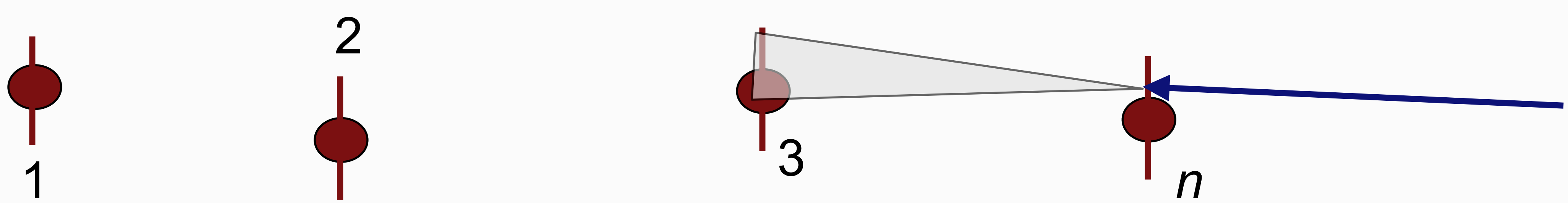

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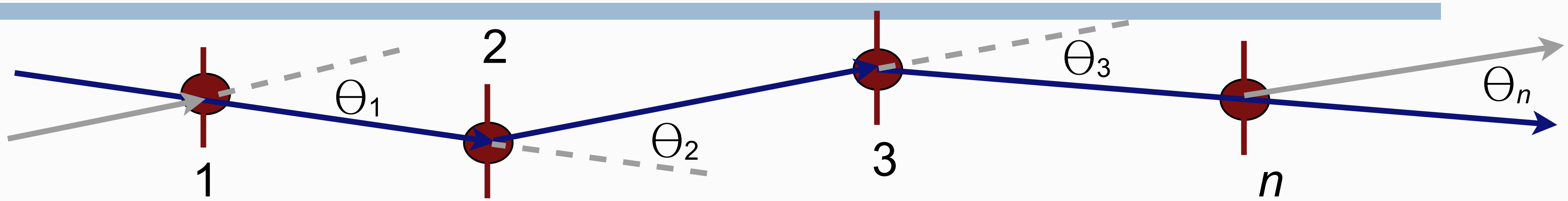

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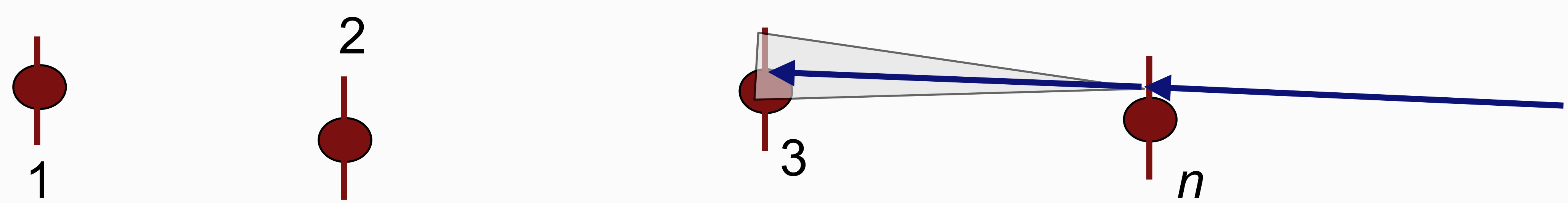

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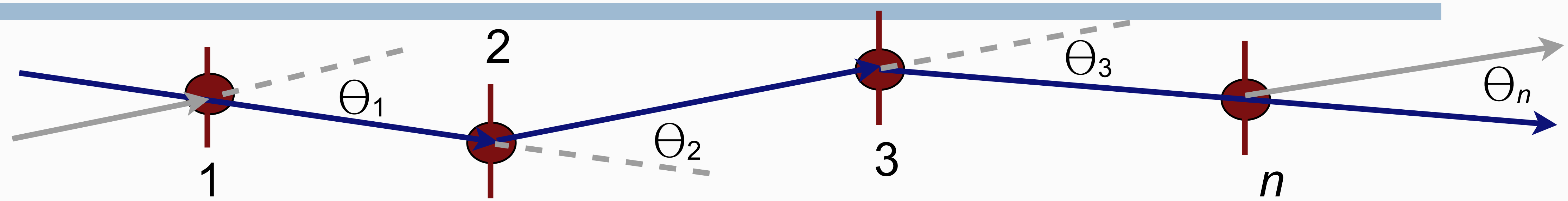

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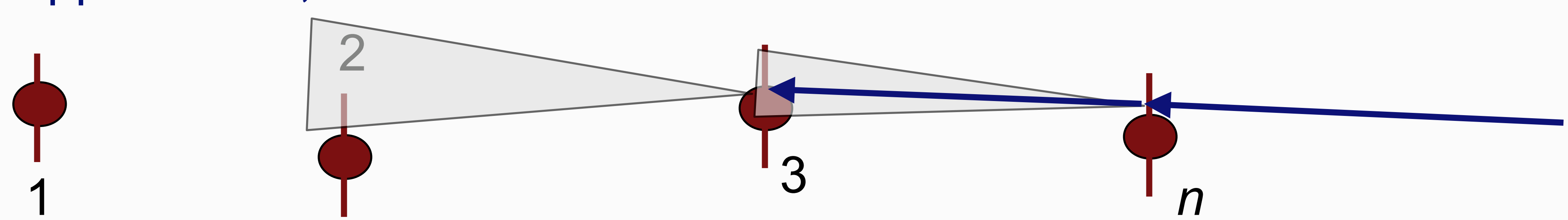

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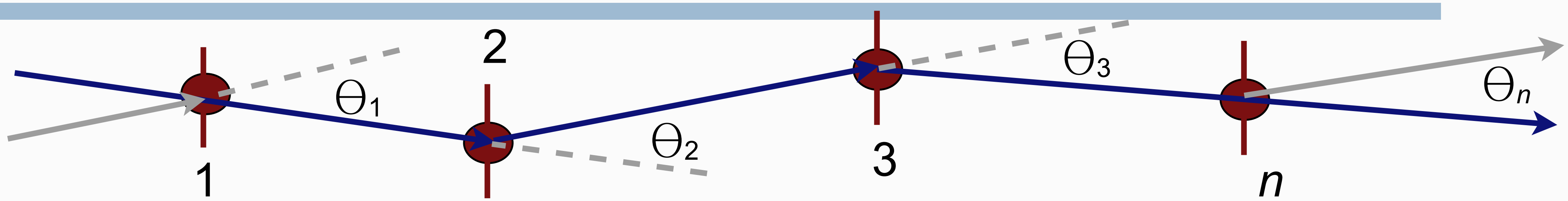

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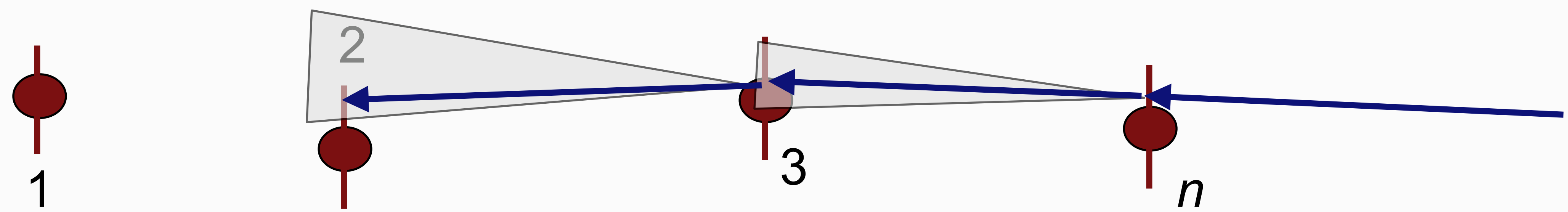

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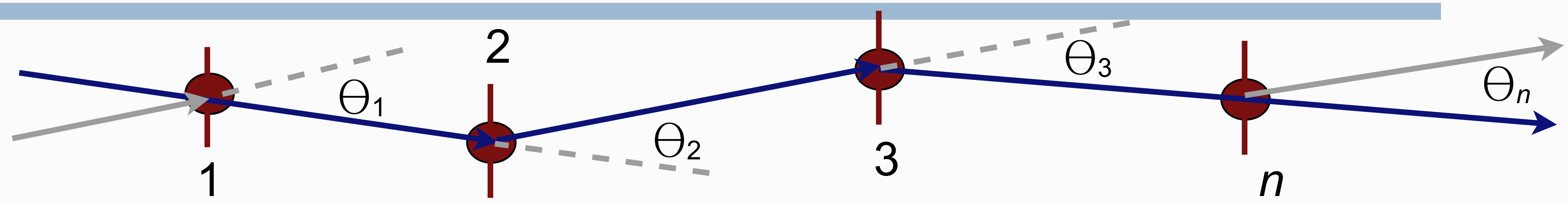

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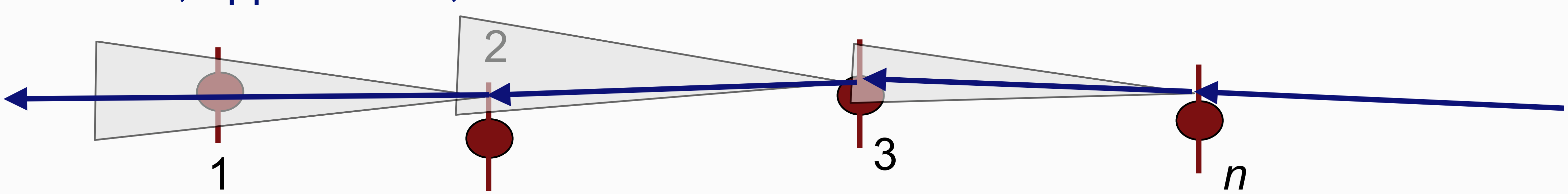

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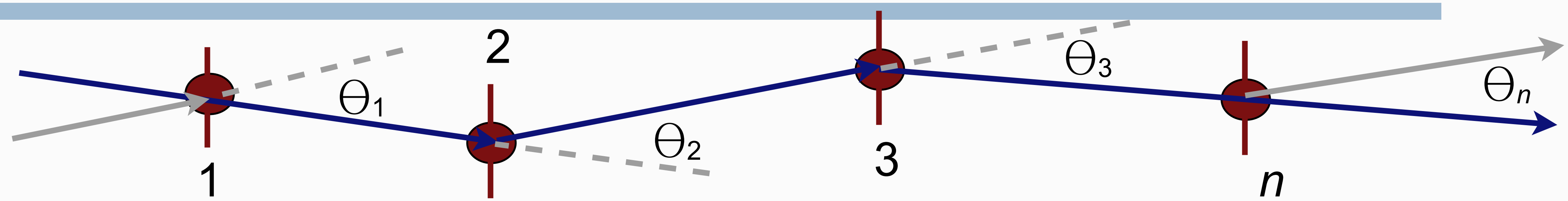

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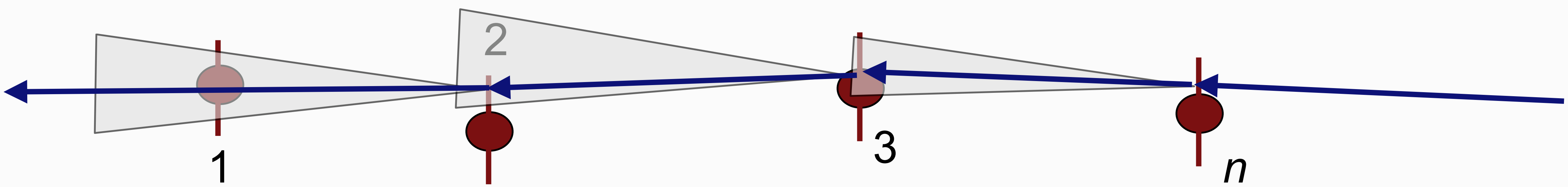
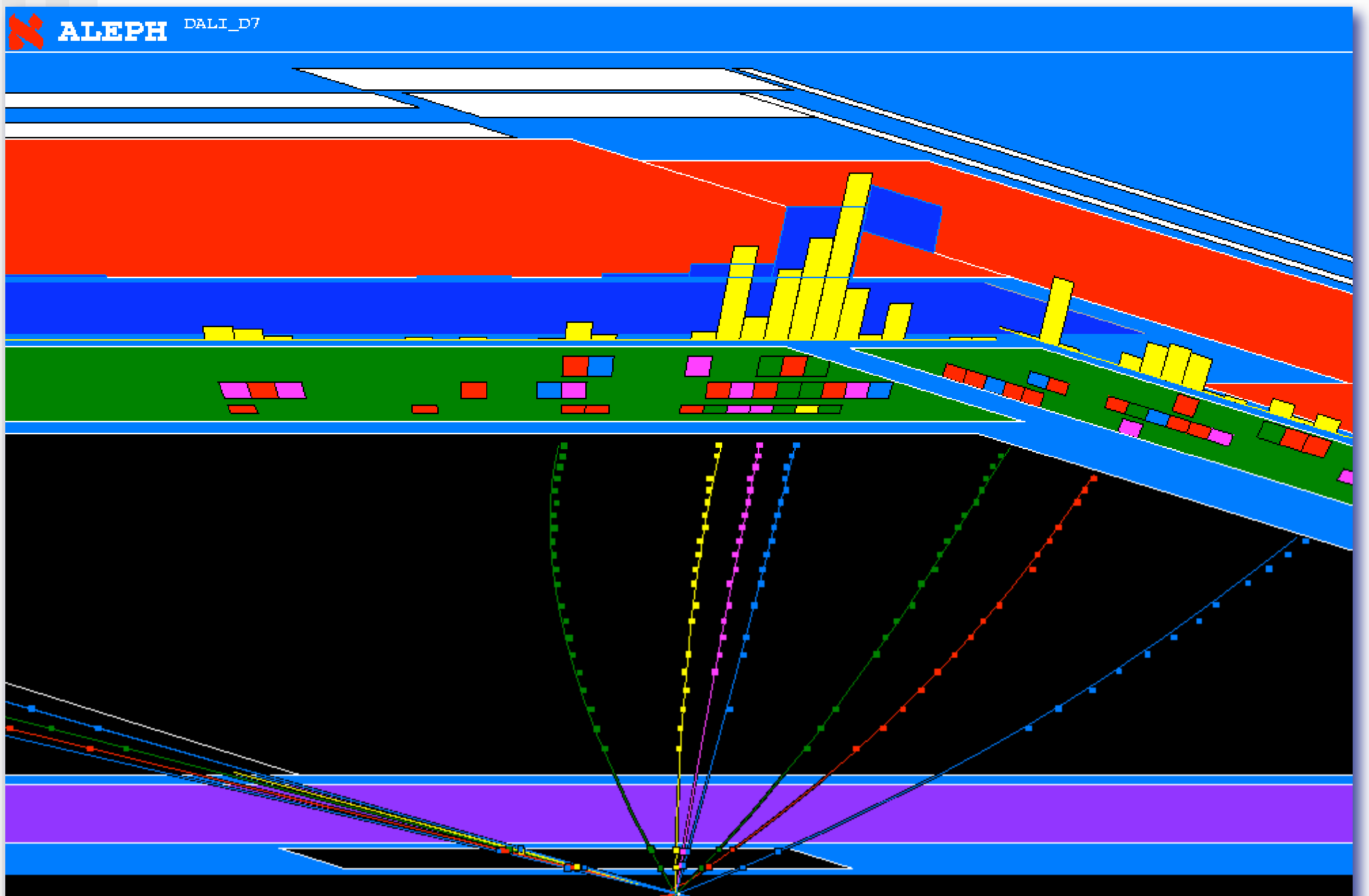


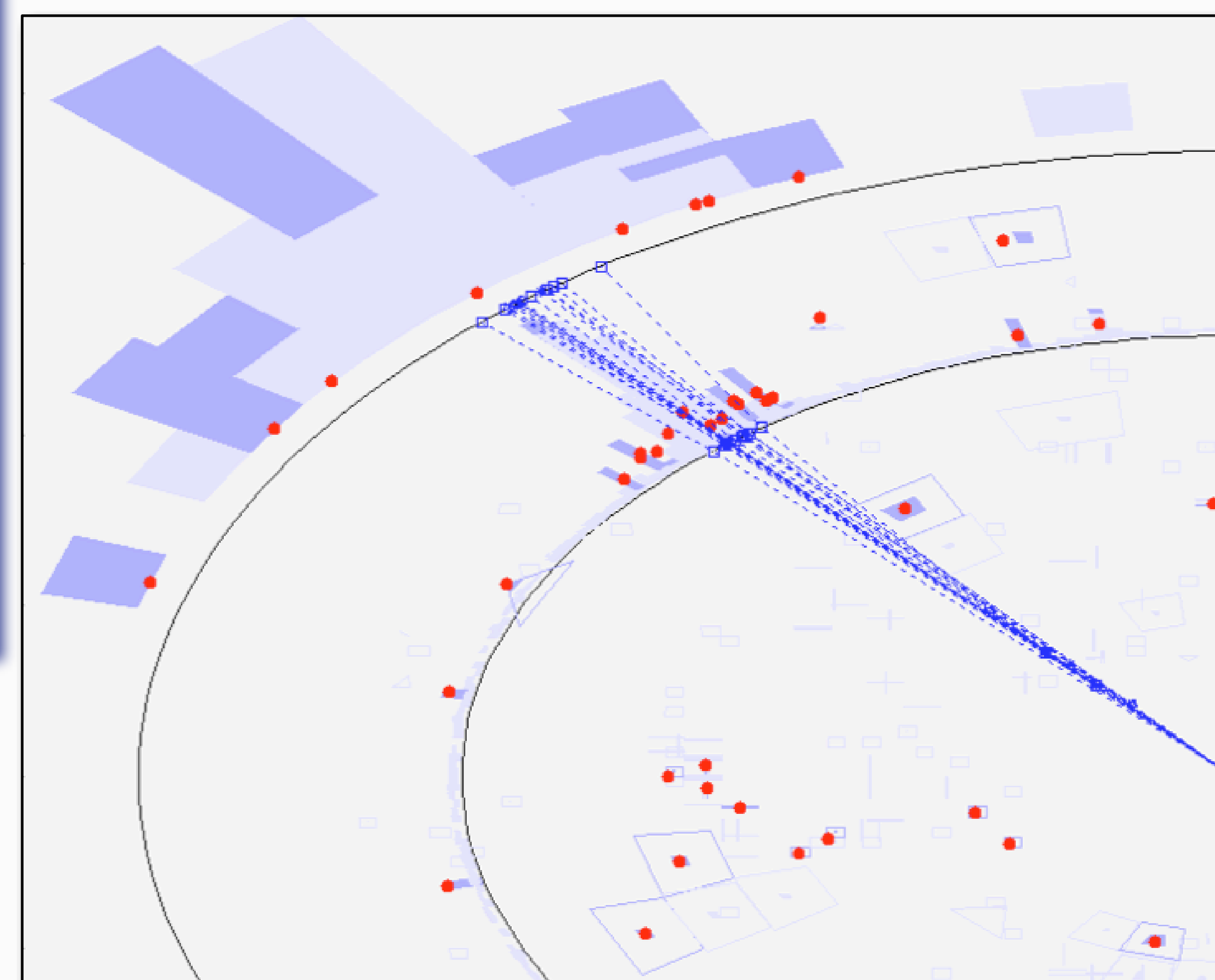
  - leads to O(*n*) computations!
  - in each step, make extrapolation to next layer, using information from current track parameters, expected scattering error, and measurement at next layer
  - Needs a starting estimate (seed) and may need some iterations, smoothing
  - This method is based on theory of the **Kalman Filter**

Calorimeter energy reconstruction

Goals

- Reconstruct energy deposited by charged and neutral particles
- Determine position of deposit, direction of incident particles
- Be insensitive to noise and “un-wanted” (un-correlated) energy





- and obtain the best possible resolution!

Clusters of energy

- Calorimeters are segmented in cells
- Typically a shower extends over several cells
  - Useful to reconstruct precisely the impact point from the “center-of-gravity” of the deposits in the various cells

Clusters of energy

ETH Institute for Particle Physics

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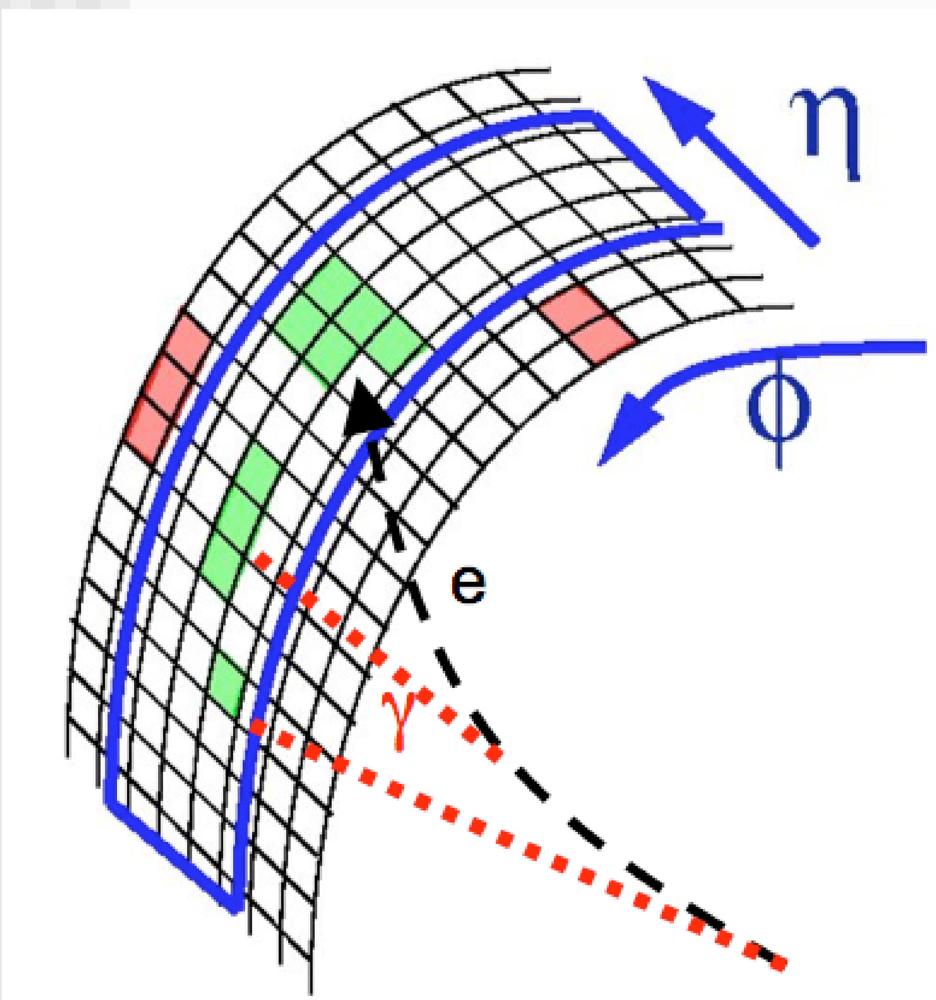
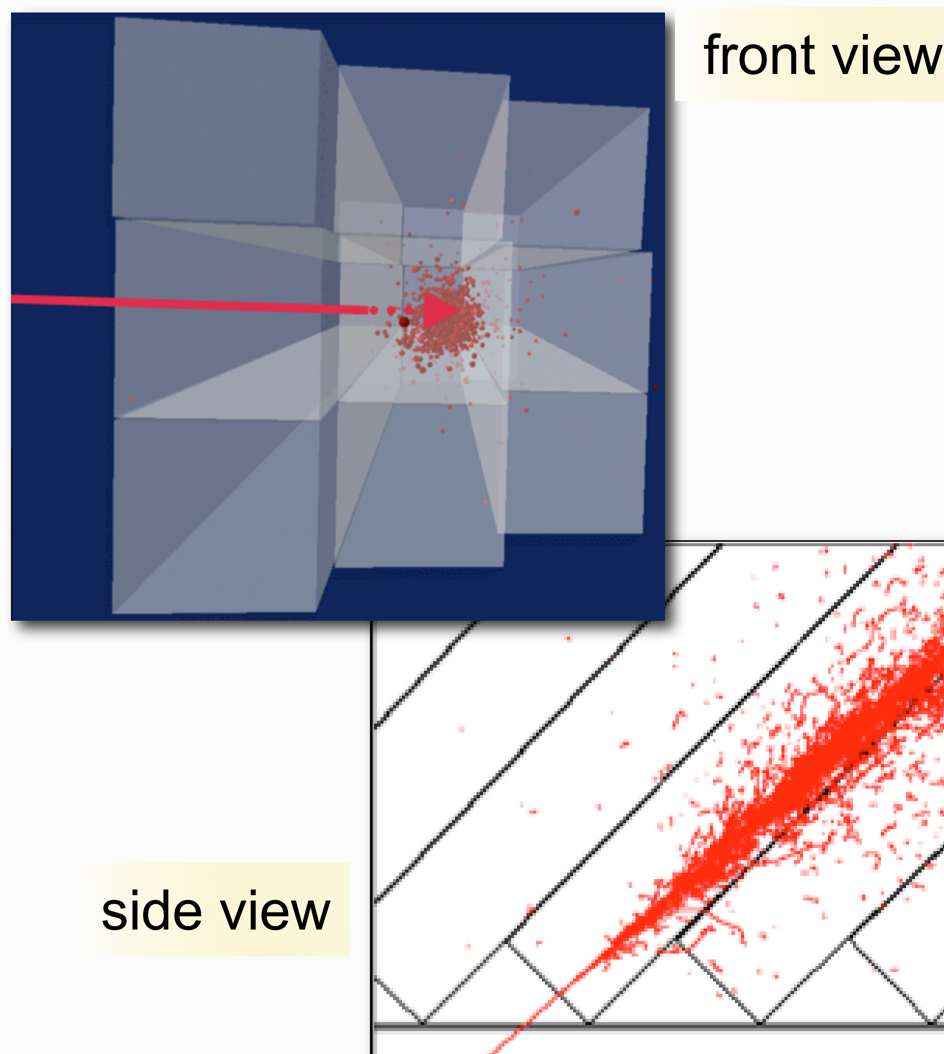
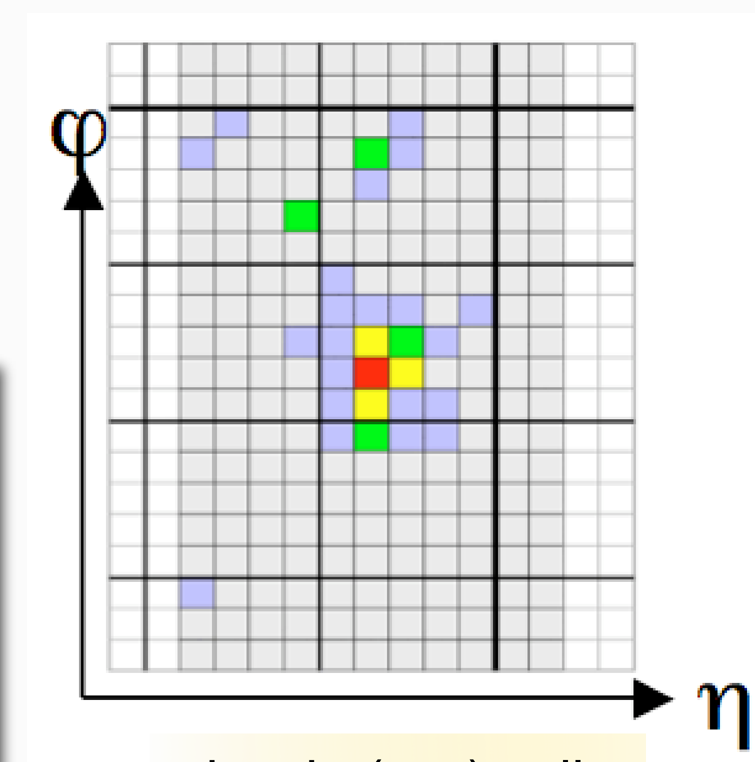
- Example CMS Crystal Calorimeter:
  - electron energy in central crystal ~ 80 %, in 5x5 matrix around it ~ 96 %





front view

side view

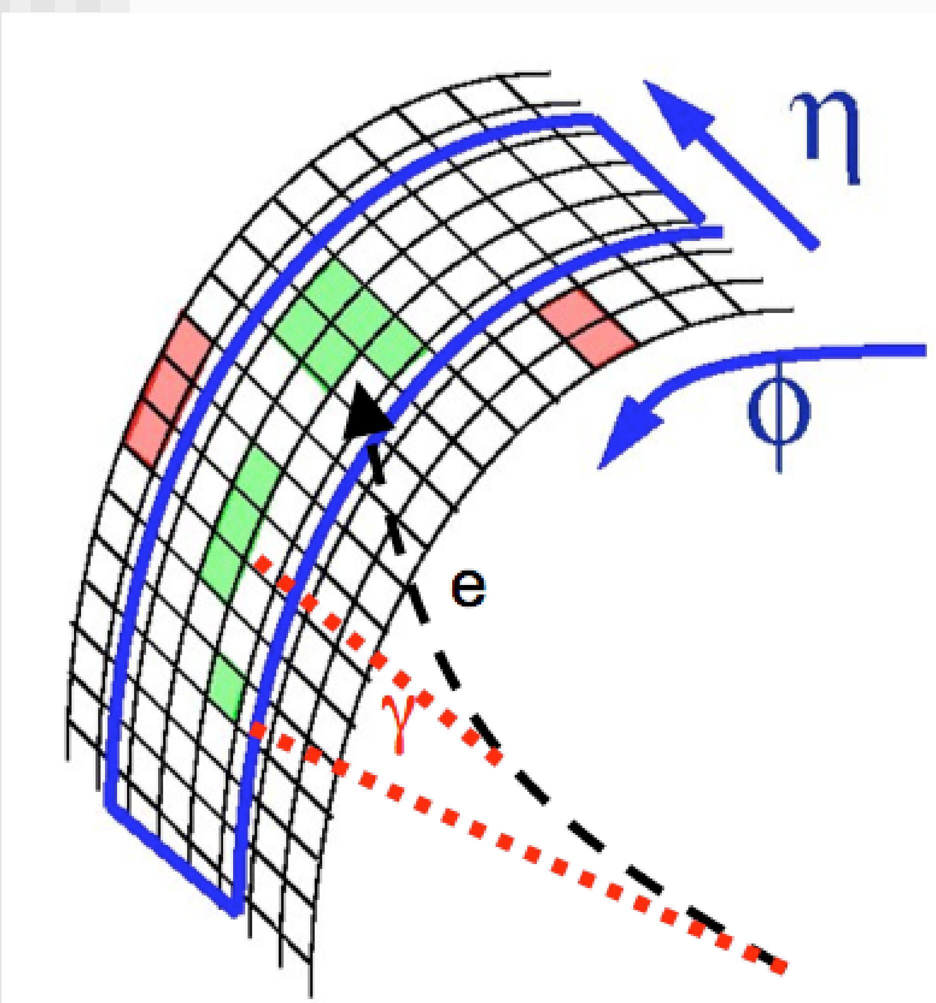


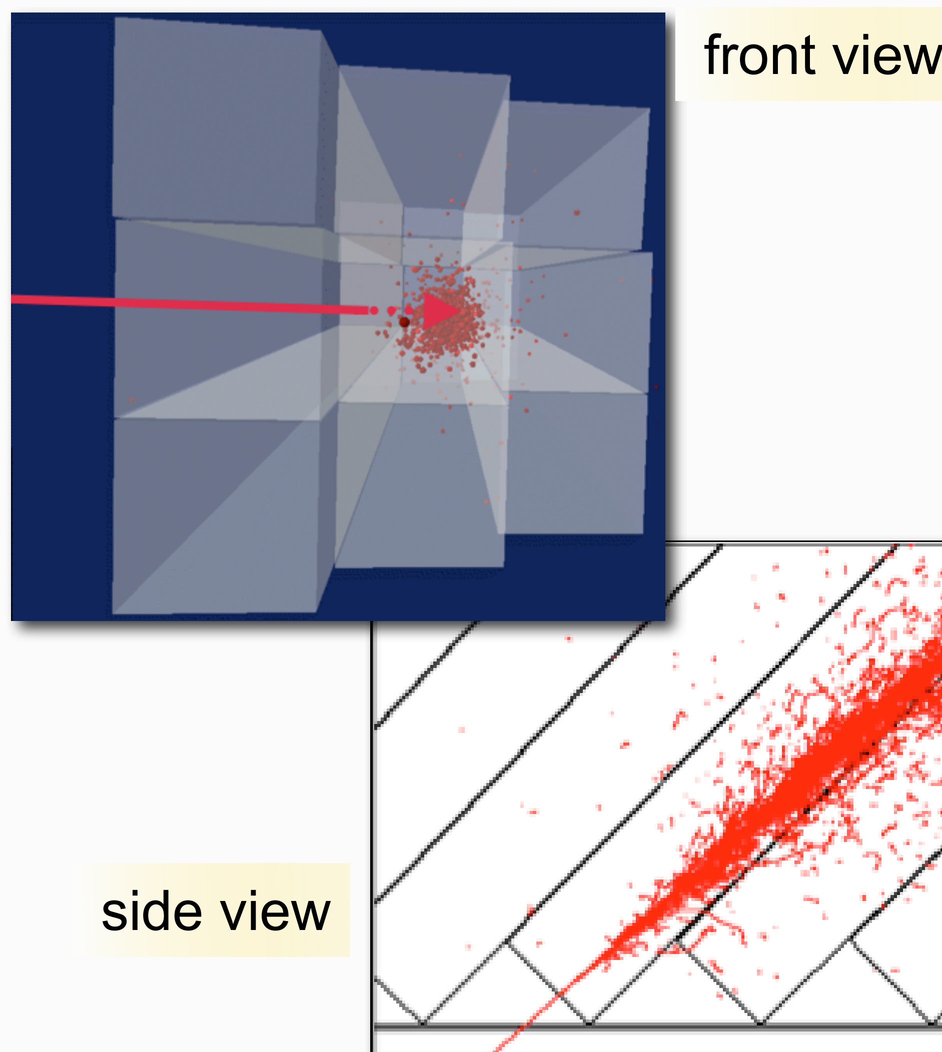
view in (φ,η) cells

Clusters of energy

ETH Institute for Particle Physics

- Calorimeters are segmented in cells
- Typically a shower extends over several cells
  - Useful to reconstruct precisely the impact point from the “center-of-gravity” of the deposits in the various cells
- Example CMS Crystal Calorimeter:
  - electron energy in central crystal ~ 80 %, in 5x5 matrix around it ~ 96 %
- So task is : identify these clusters and reconstruct the energy they contain





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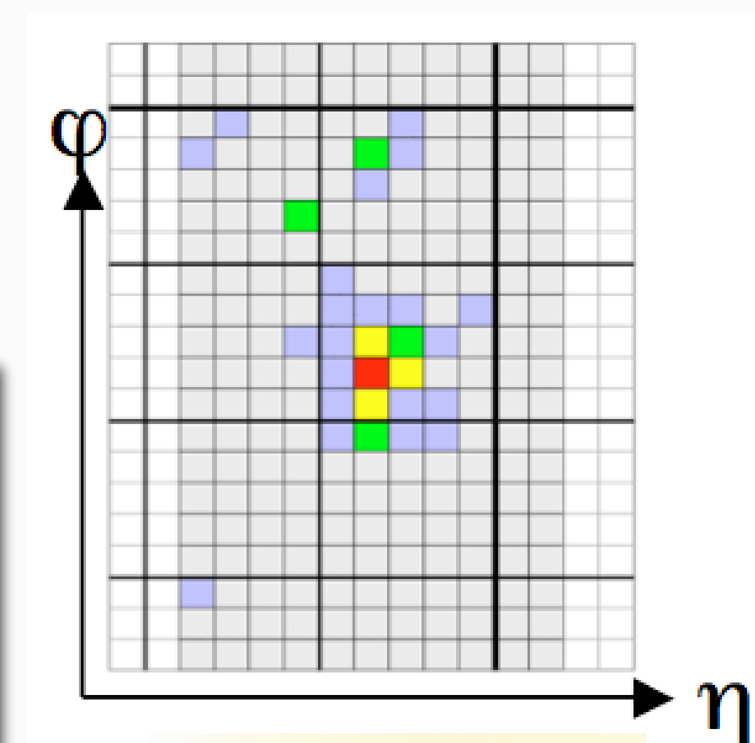

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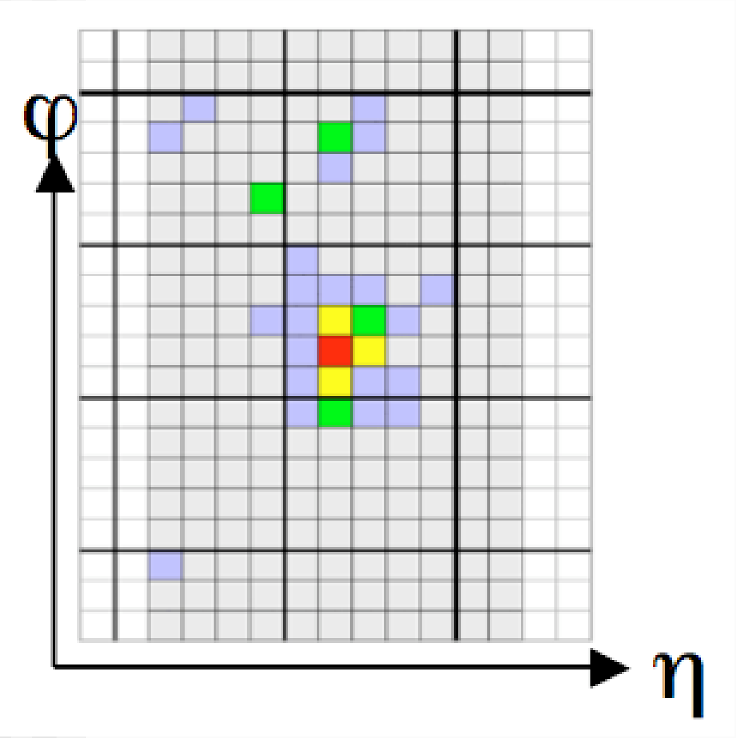
Cluster Finding

- Clusters of energy in a calorimeter are due to the original particles
  - Clustering algorithm groups individual channel energies
  - Don’t want to miss any; don’t want to pick up fakes



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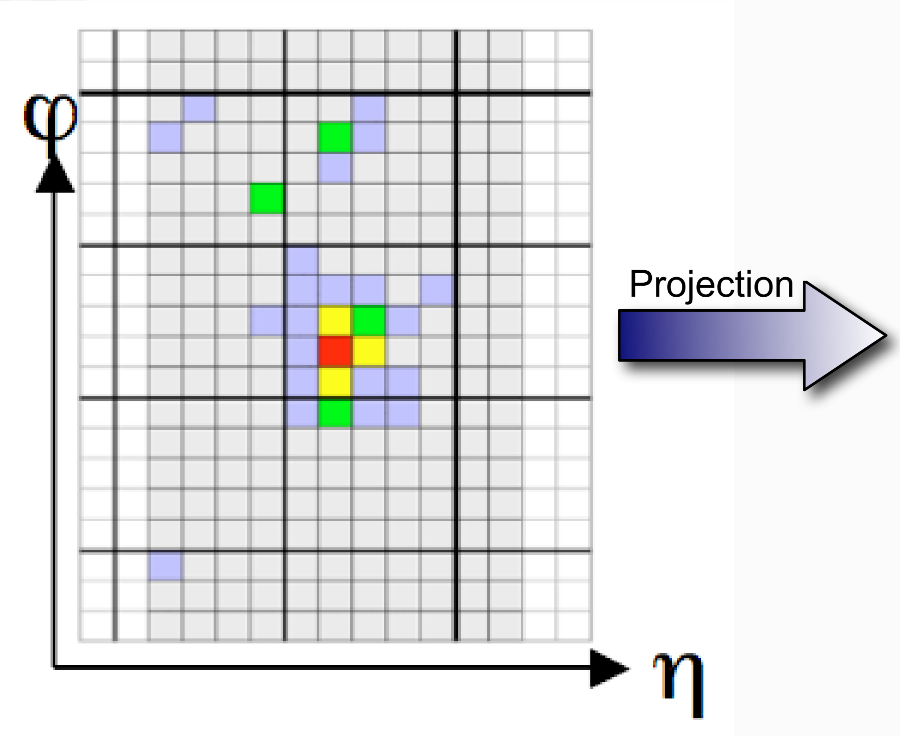

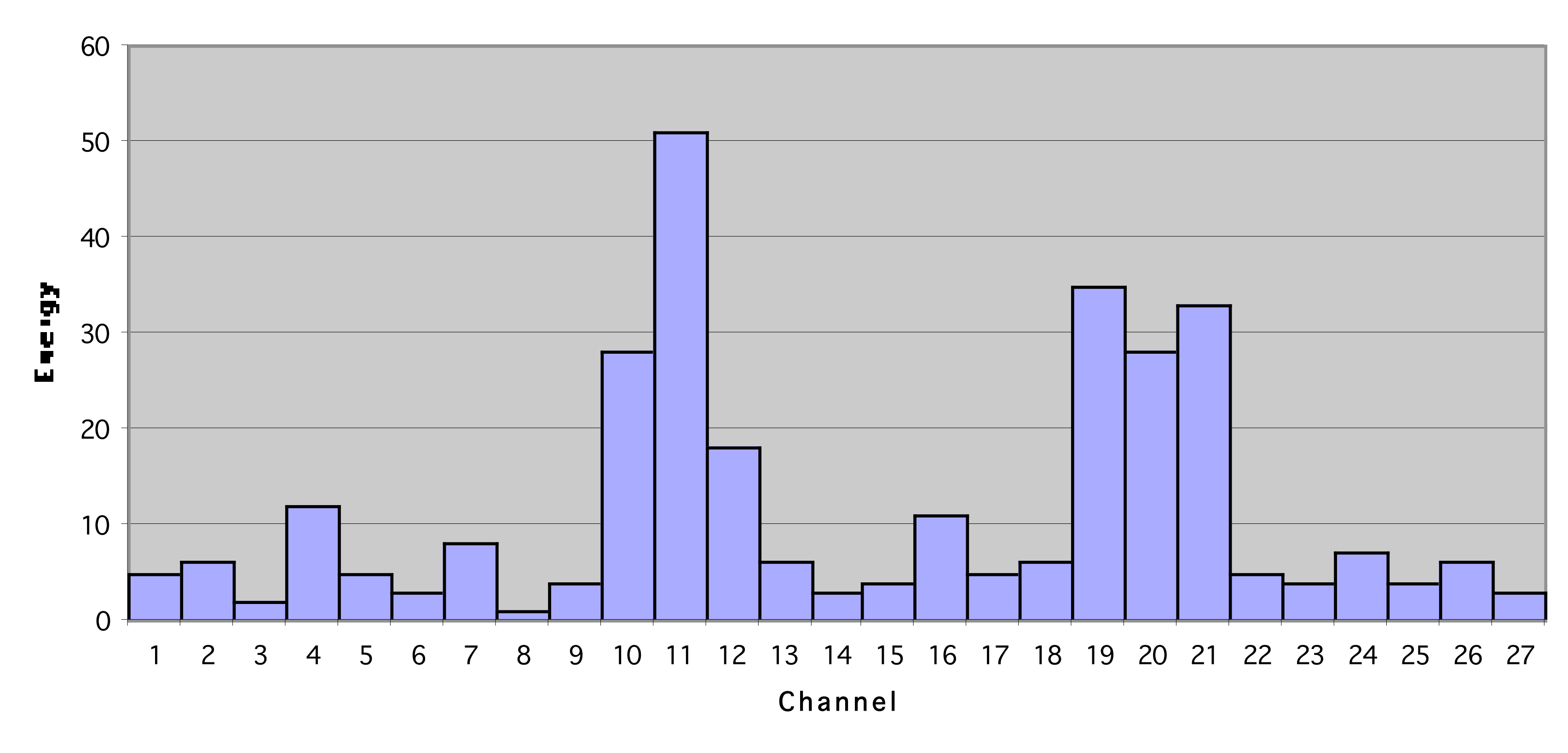

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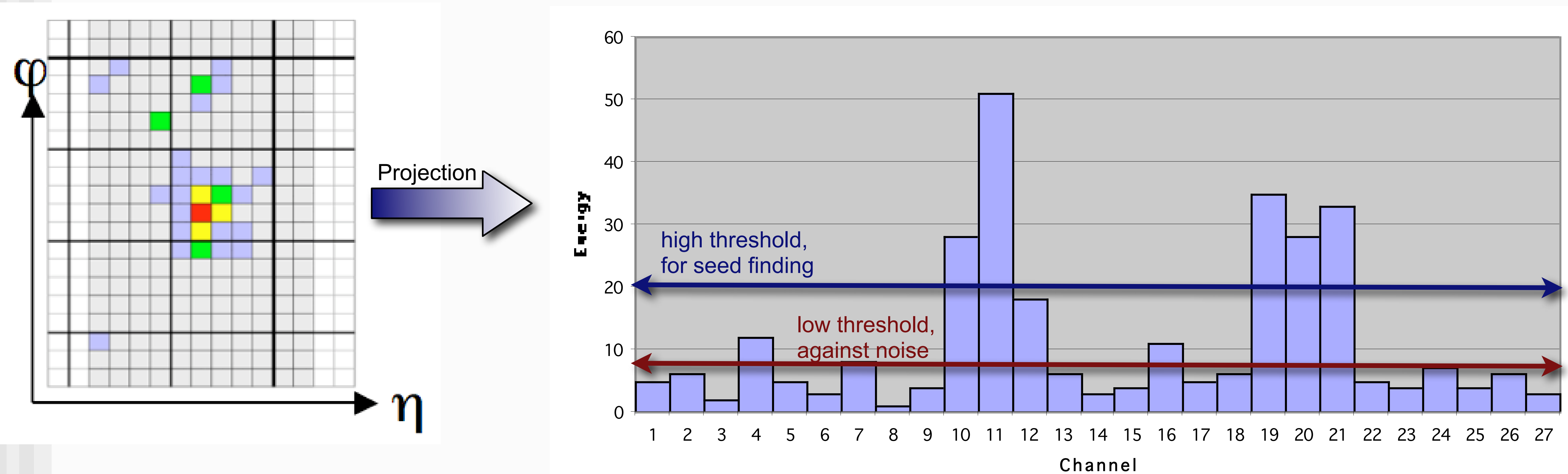


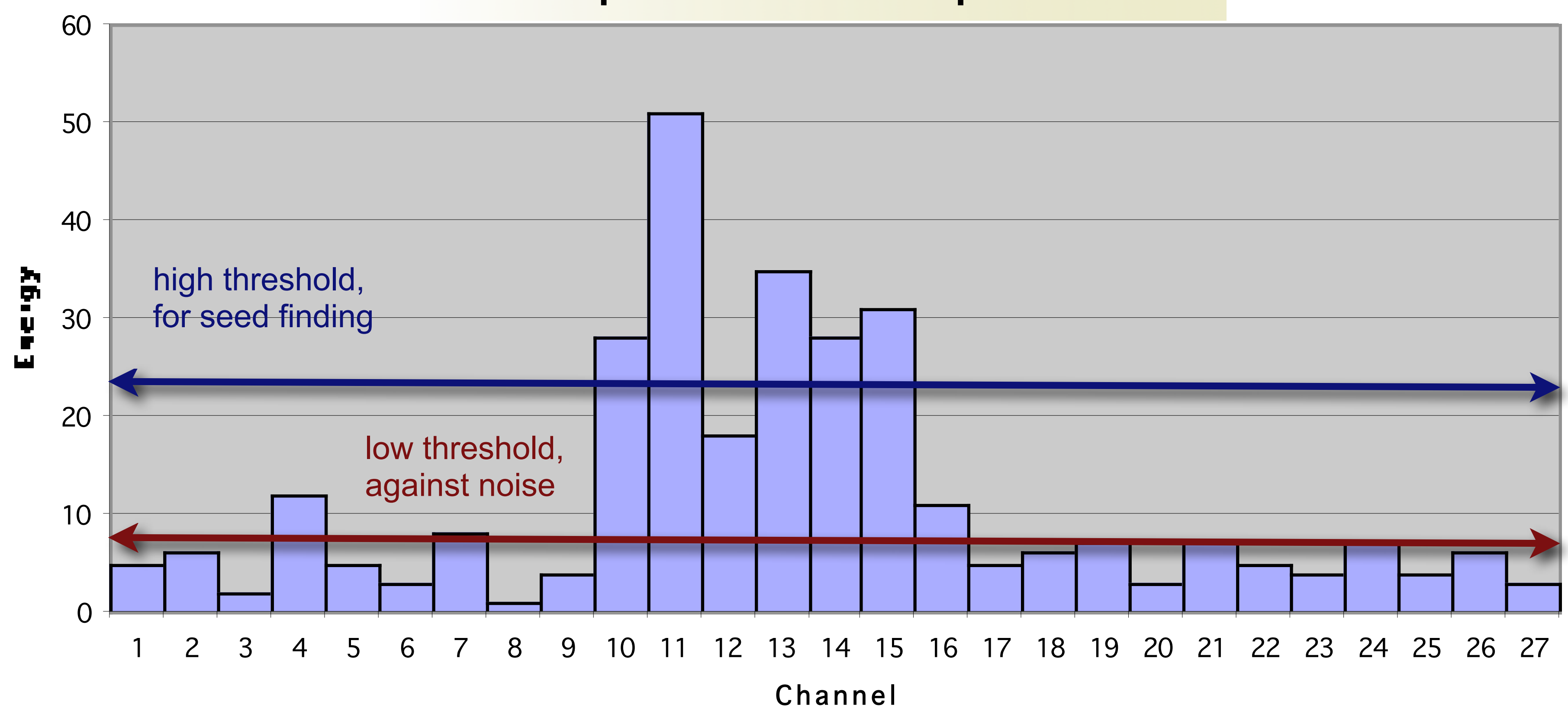
Simple example of an algorithm

- 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
  3. The previous crystal added (in the same direction) has higher energy

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
- Sometimes several clustering stages, in order separate or combine nearby clusters

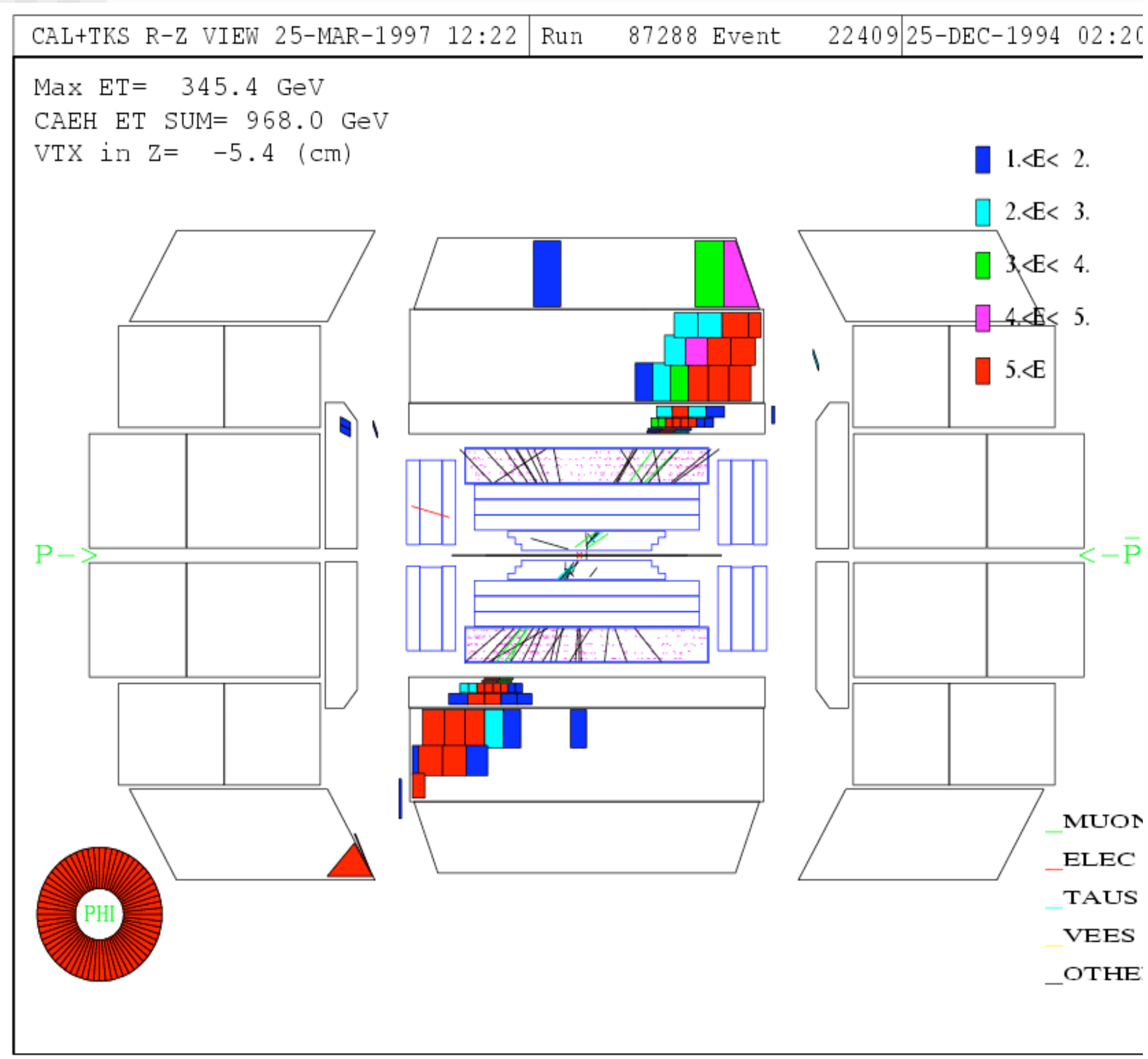
example : one lump or two?

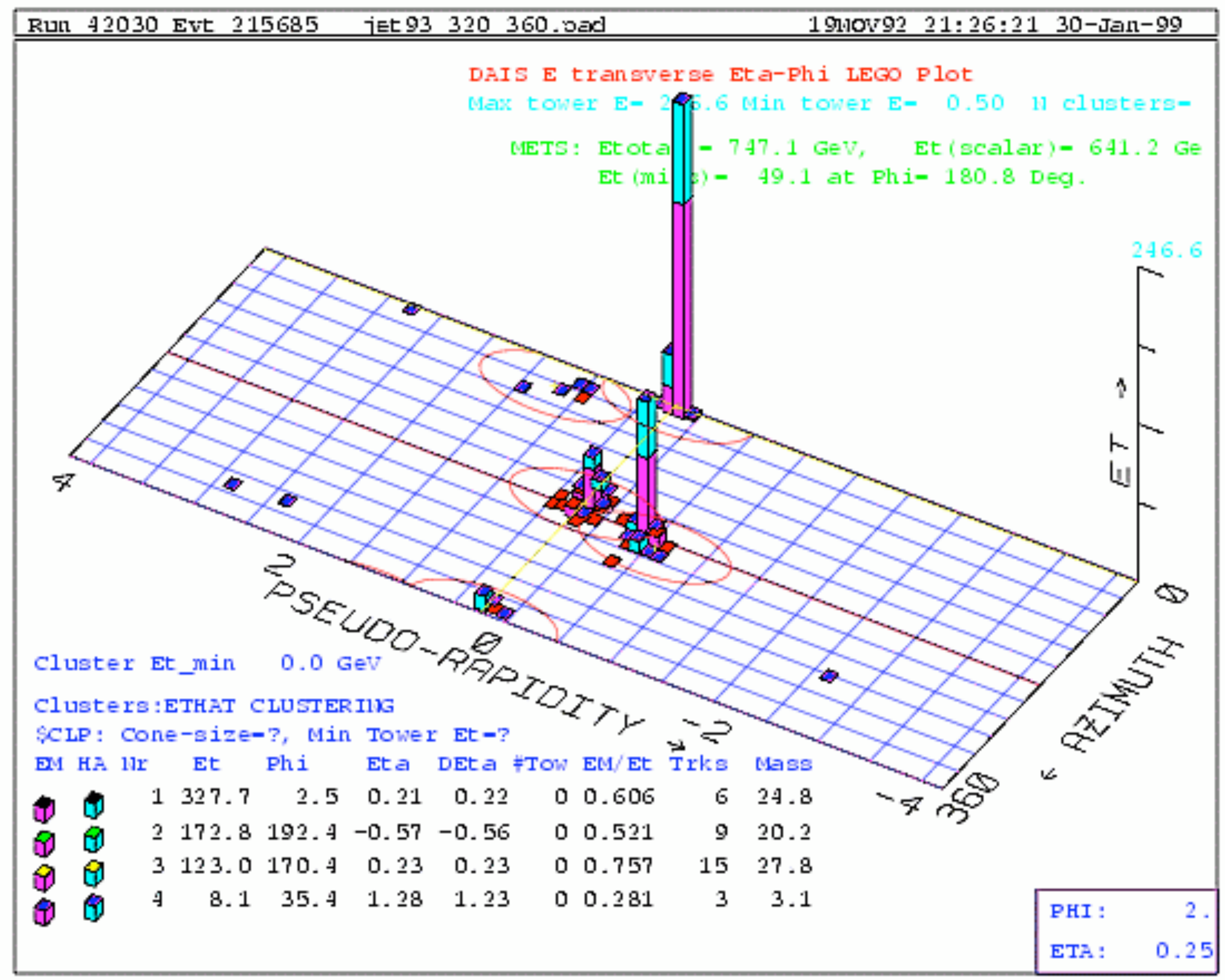


Jet Algorithms

Jets in Hadron Collider Detectors

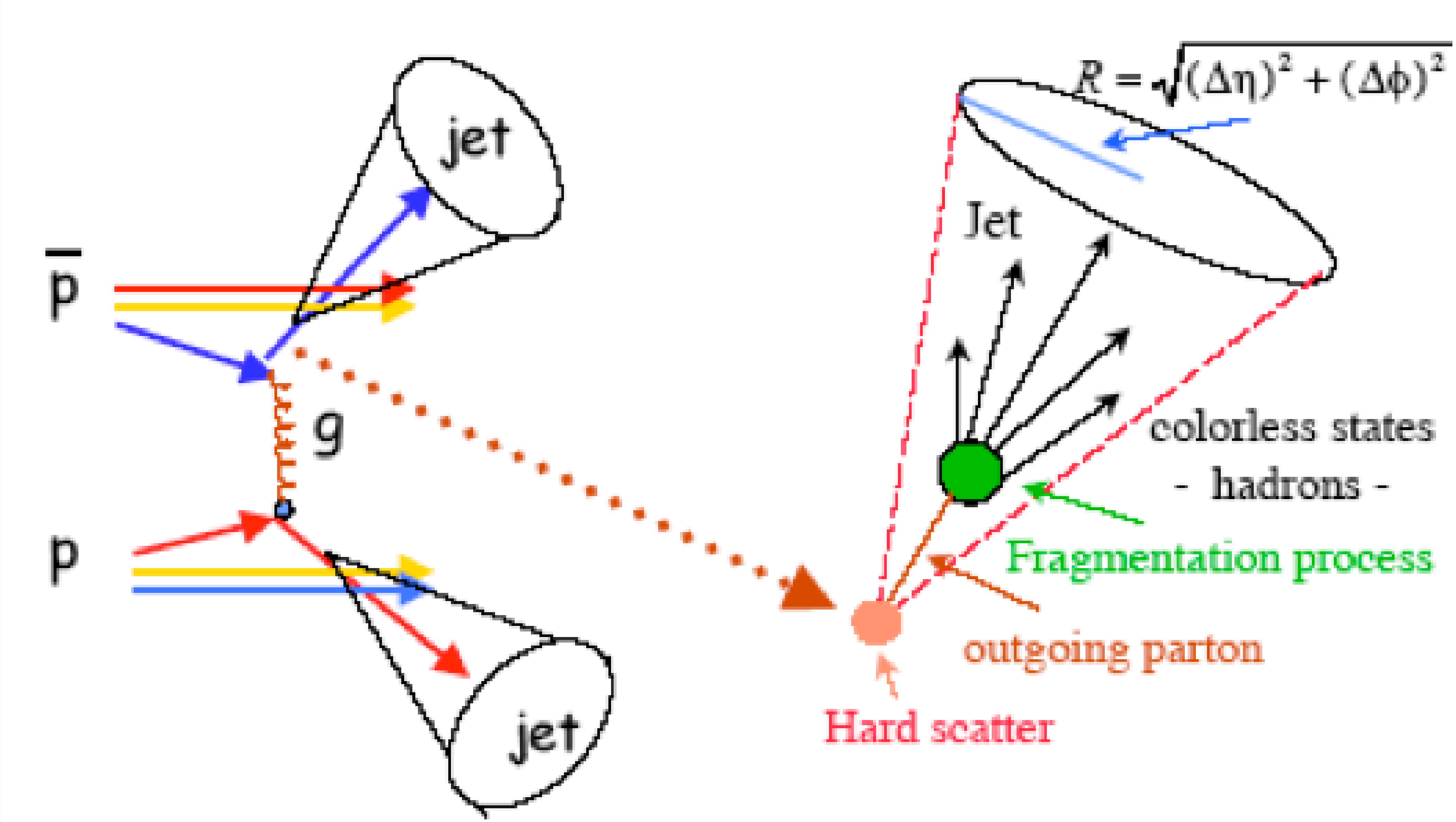
Jets in DØ CDF





- Introducing a cone prescription seems "natural"...
- But how to make it more quantitative?
  - don't want people "guessing" at whether there are 2,3, ... jets

Cones...



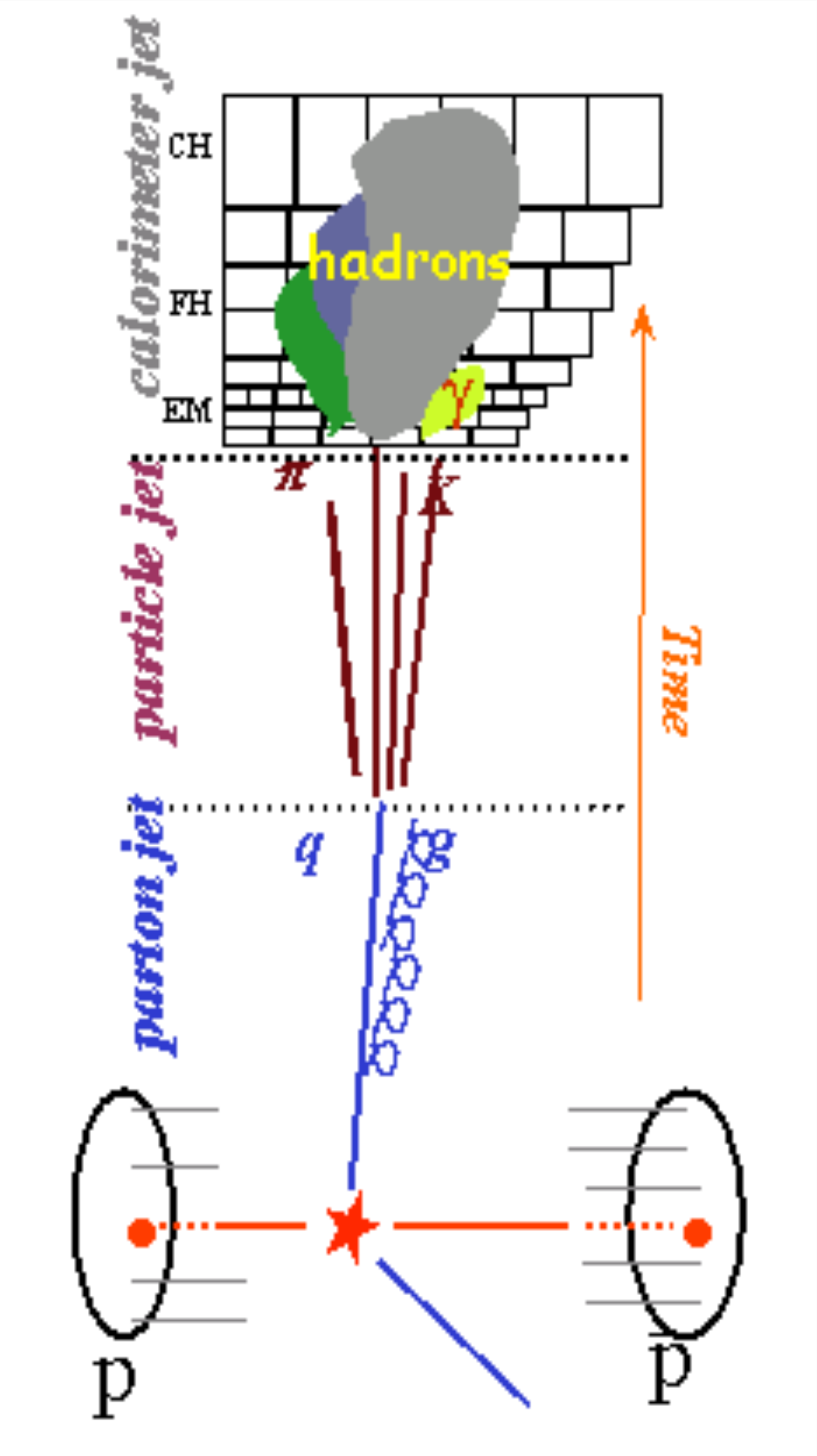
The natural (?) definition of a jet in a hadron collider environment

from J. Huston, CTEQ summer school 2004

Requirements

ETH Institute for Particle Physics

- Applicable at all levels
  - partons, stable particles
    - for theoretical calculations
  - measured objects (calorimeter objects, tracks, etc)
  - and always find the same jet



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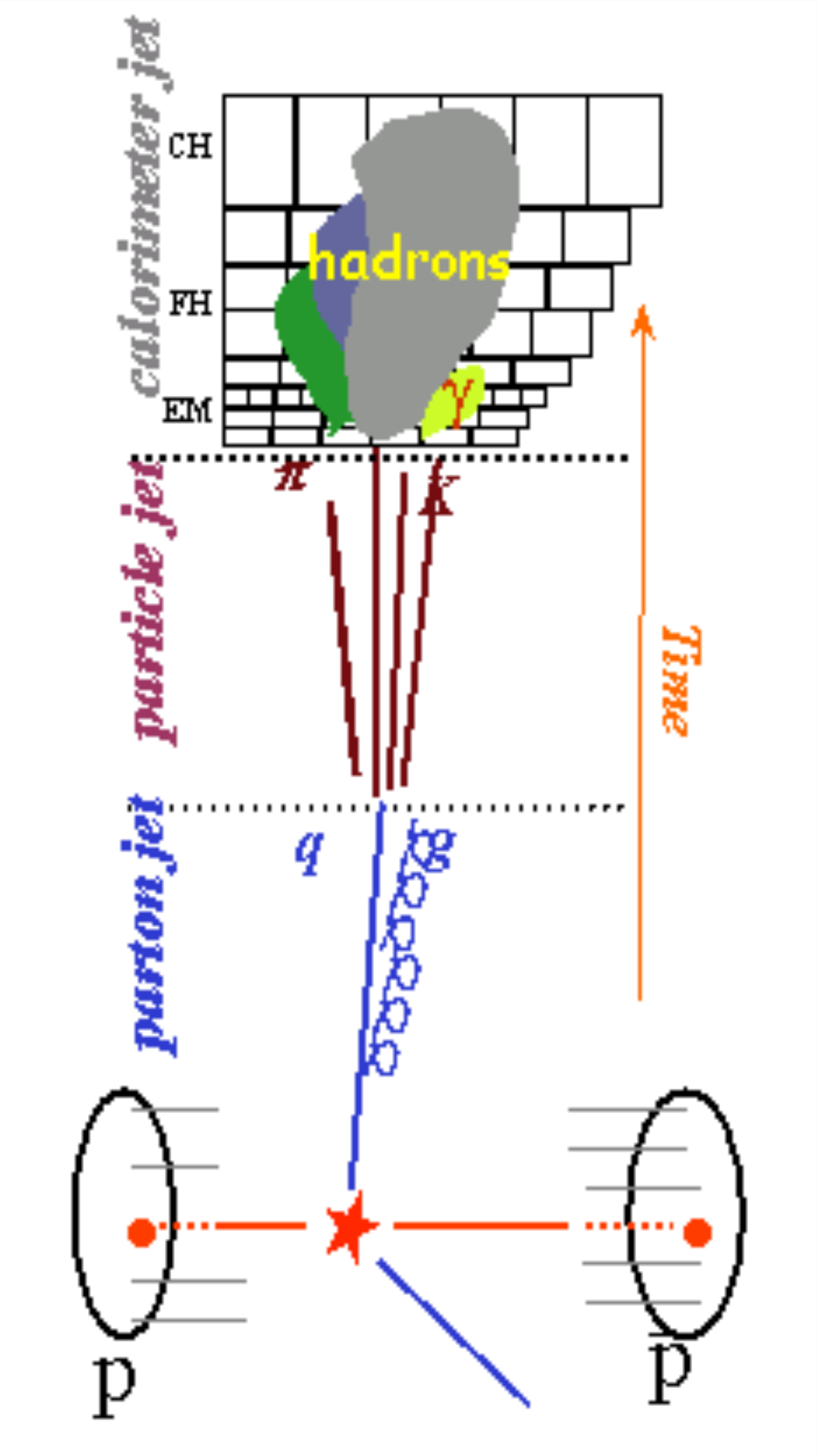
- Independent of the very details of the detector
  - example : granularity of the calorimeter, energy response,...



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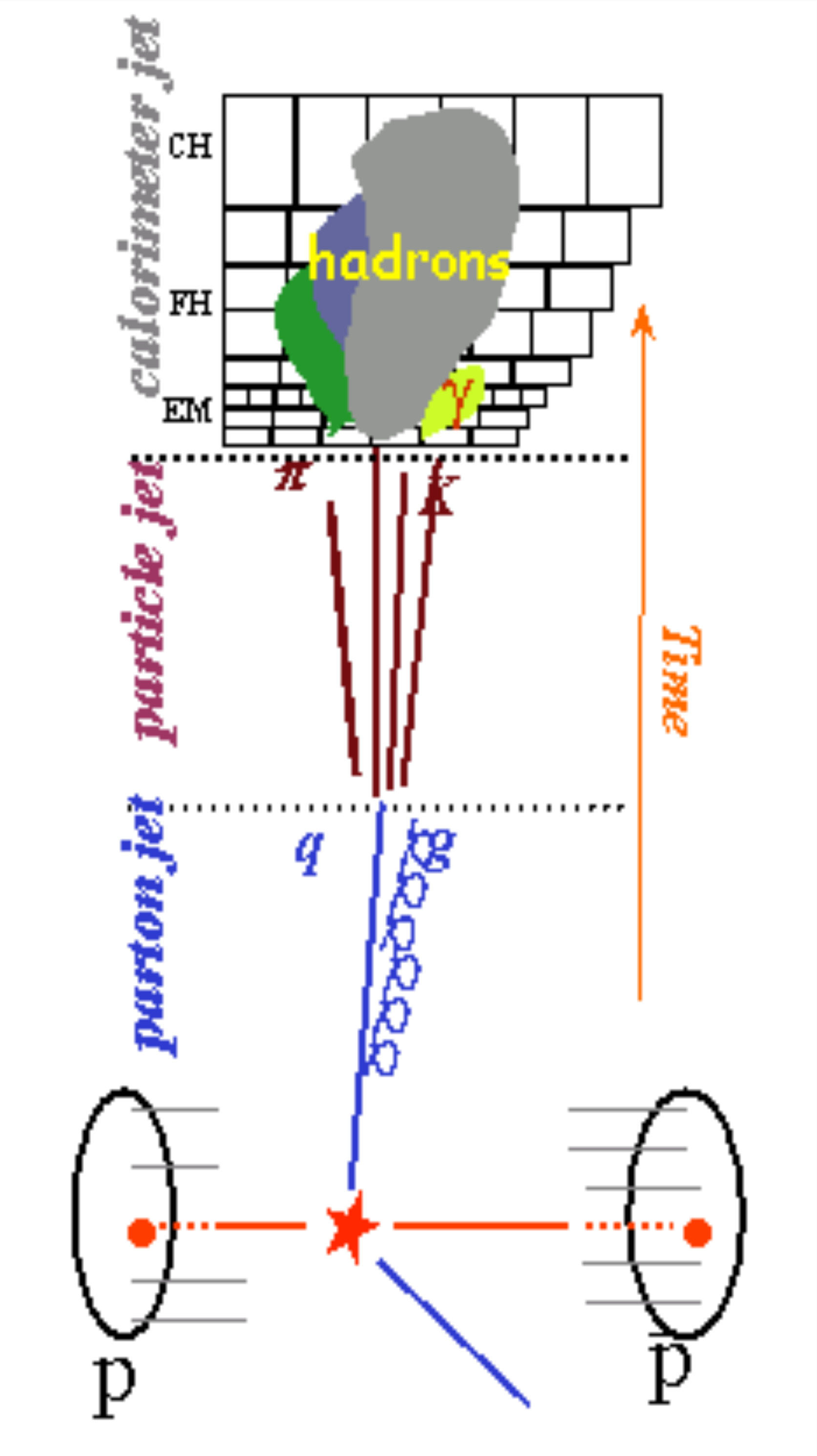
- Easy to implement !



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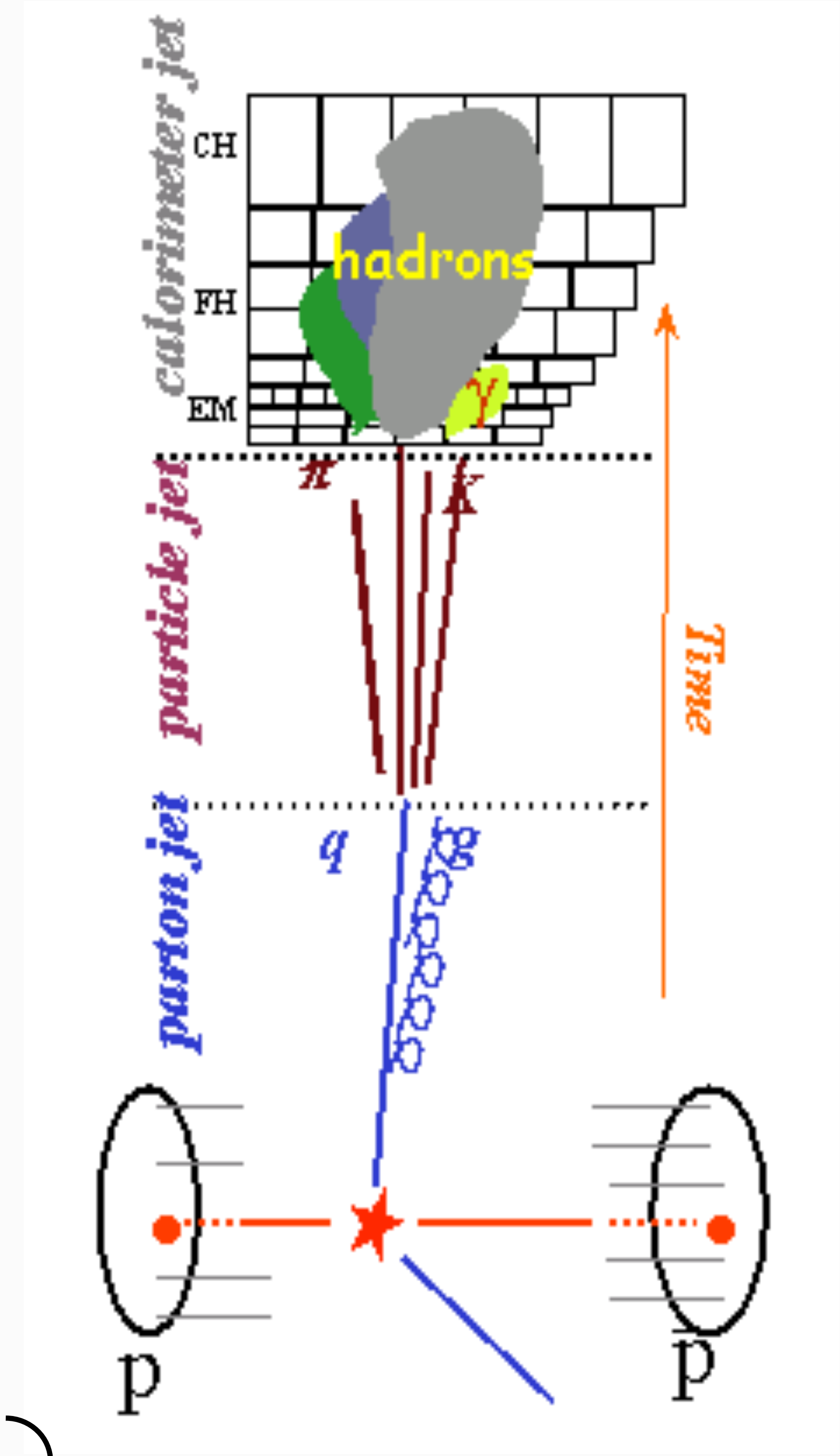
- Independent of the very details of the detector
  - example : granularity of the calorimeter, energy response,...

- Easy to implement !

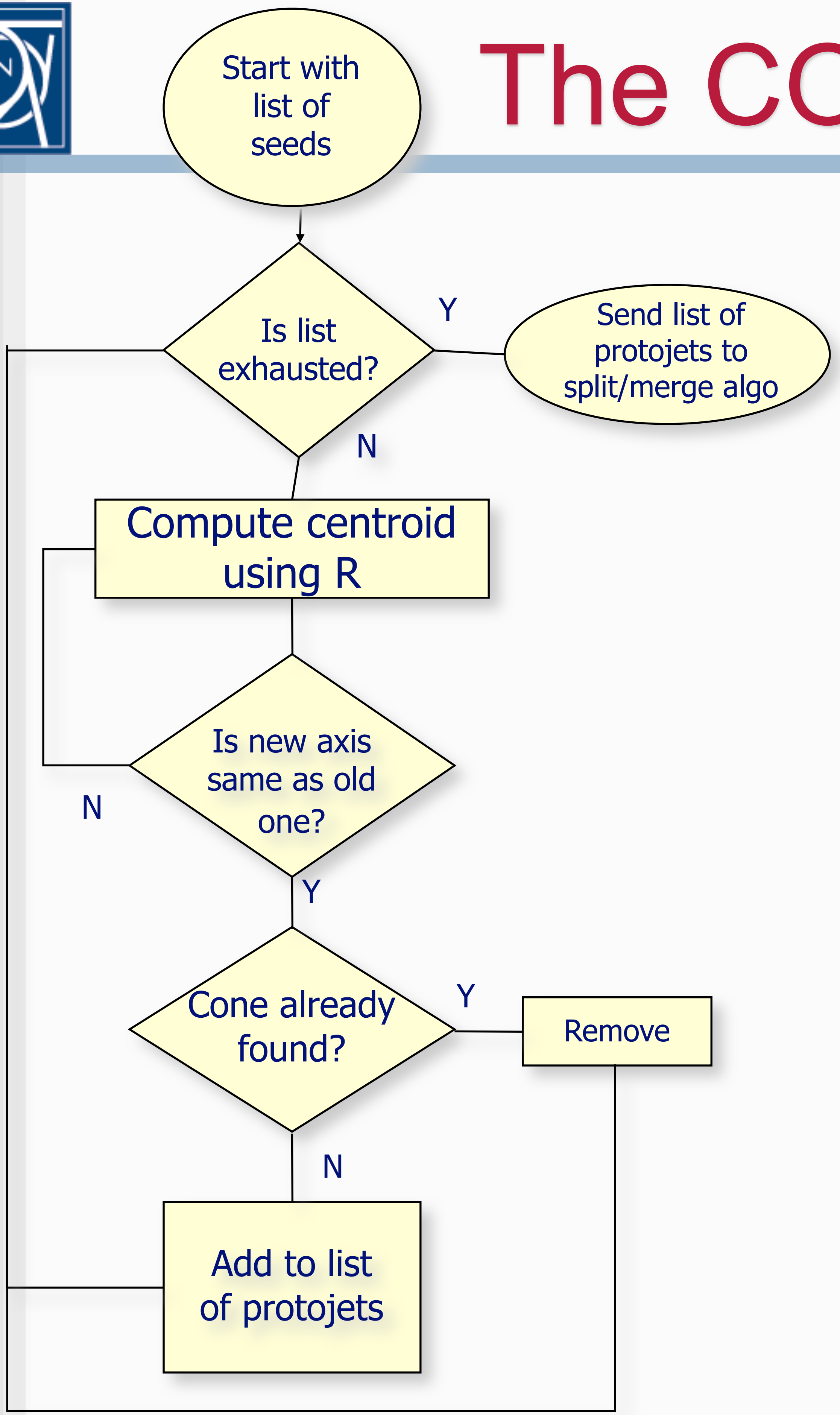
- Close correspondence between

$$P_{\text{parton}} \longleftrightarrow P_{\text{jet}}$$

(Energy Momentum angle)



The CONE algorithm



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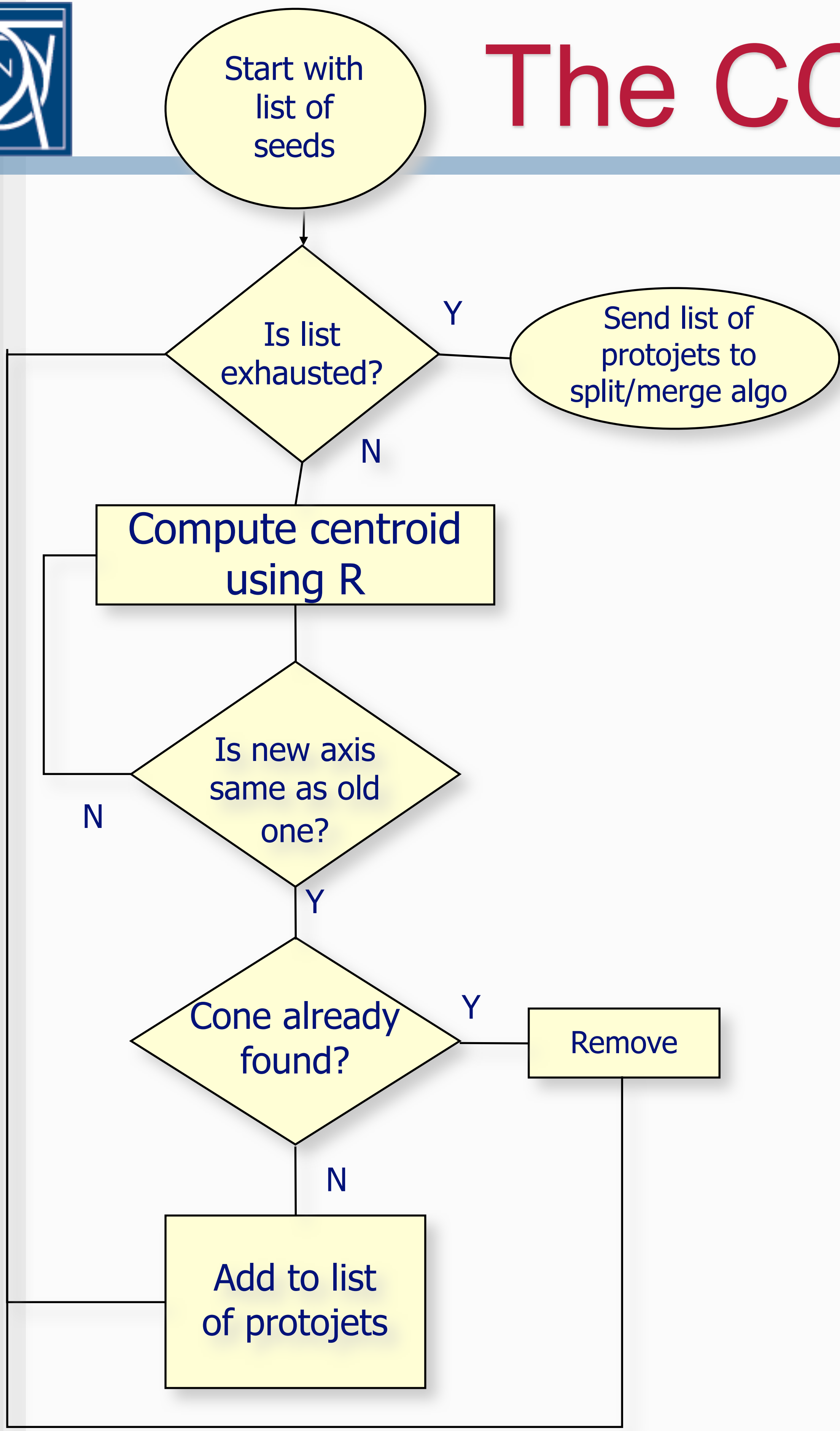

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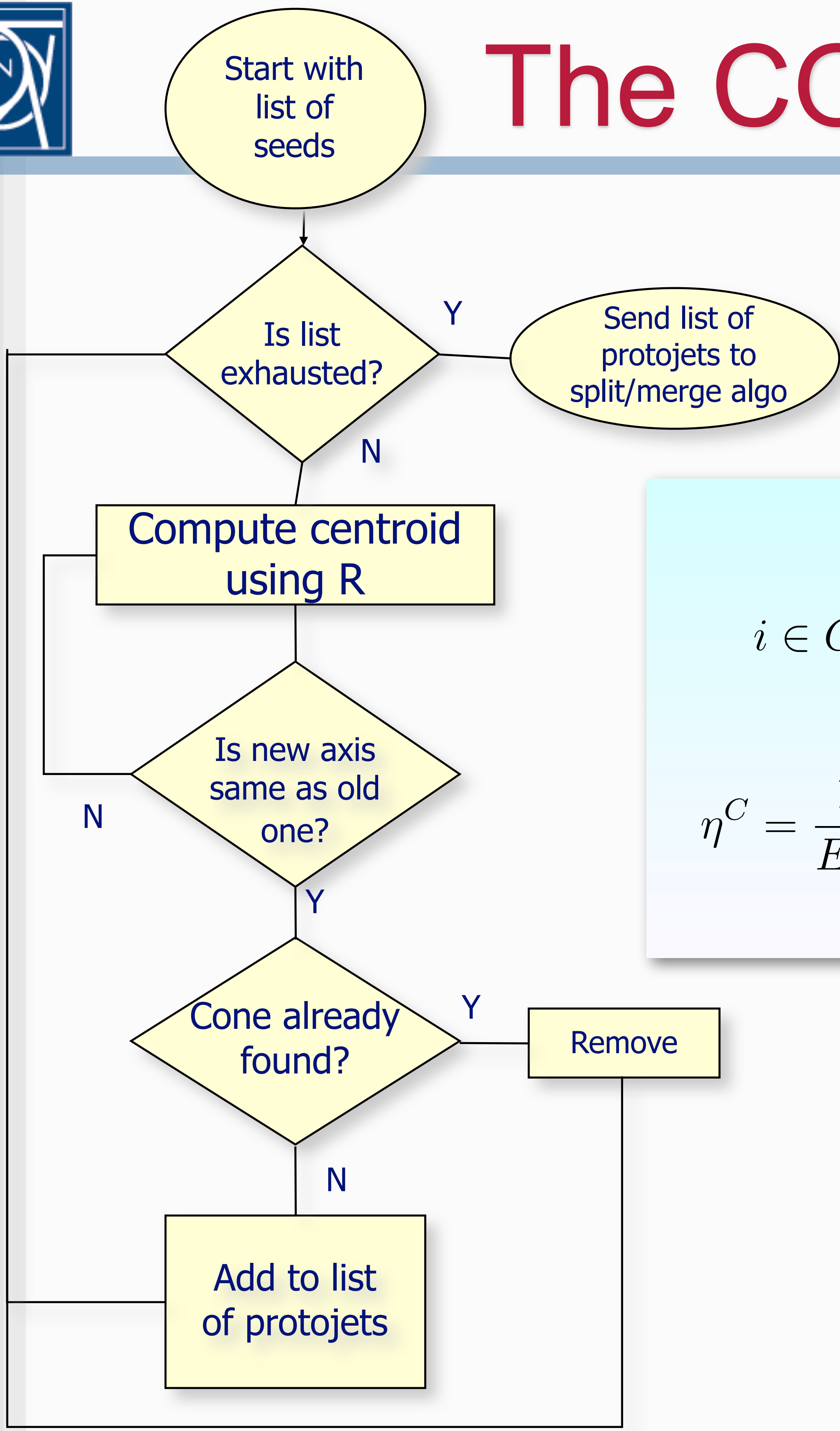

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Centroid (one possible def) :

$$i \in C \quad : \quad \sqrt{(\eta^i - \eta^C)^2 + (\Phi^i - \Phi^C)^2} \leq R \quad \text{cone radius}$$

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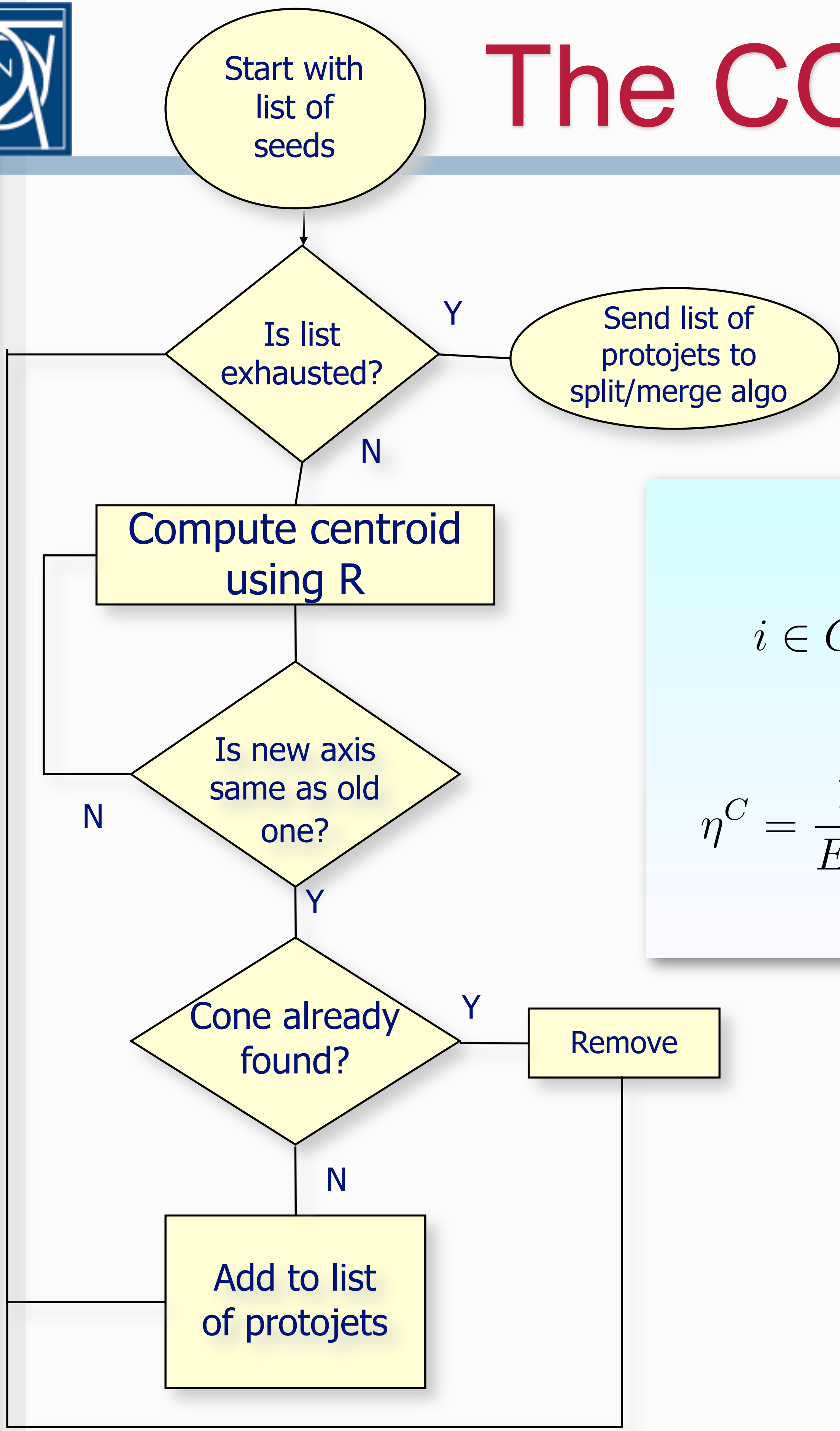

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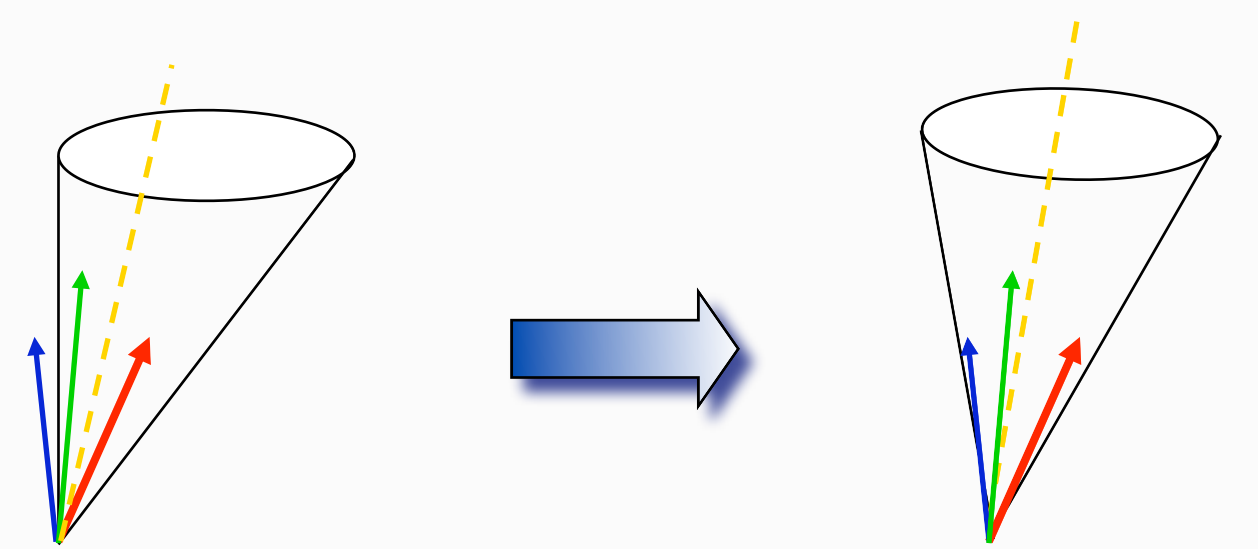
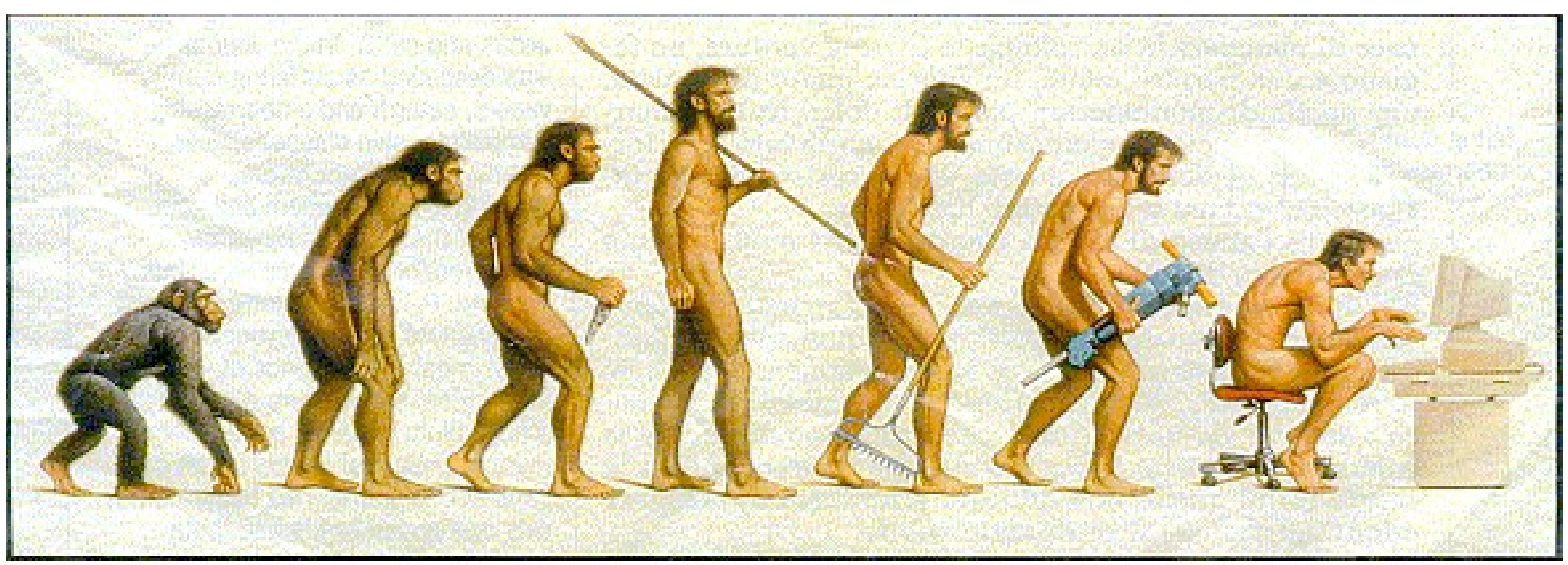


The computing behind all this



Somewhere, something went terribly wrong

Some numbers

- Examples from CMS, estimates
  - Rate of events streaming out from High-Level Trigger farm ~150 Hz
  - each event has a size of the order of 200 kByte

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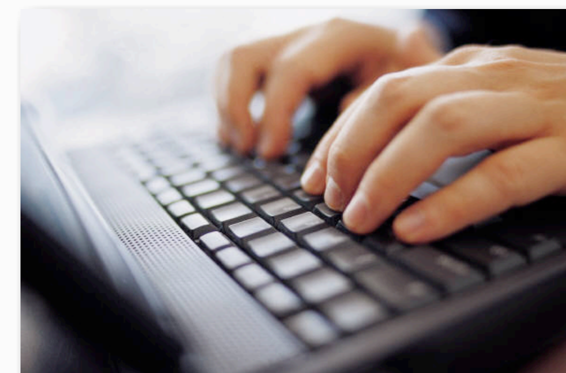

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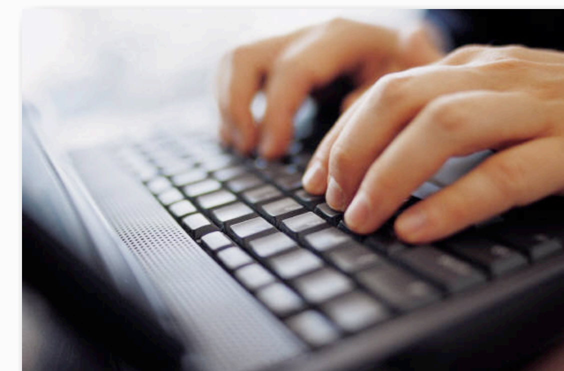

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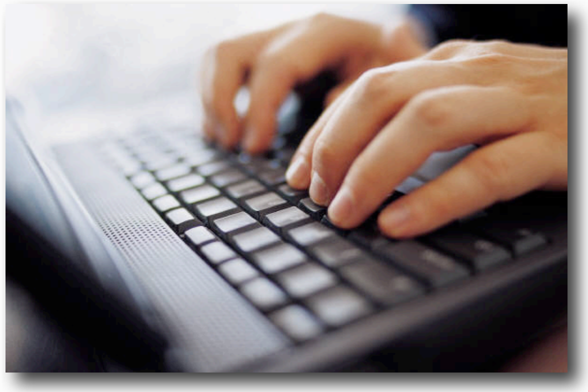

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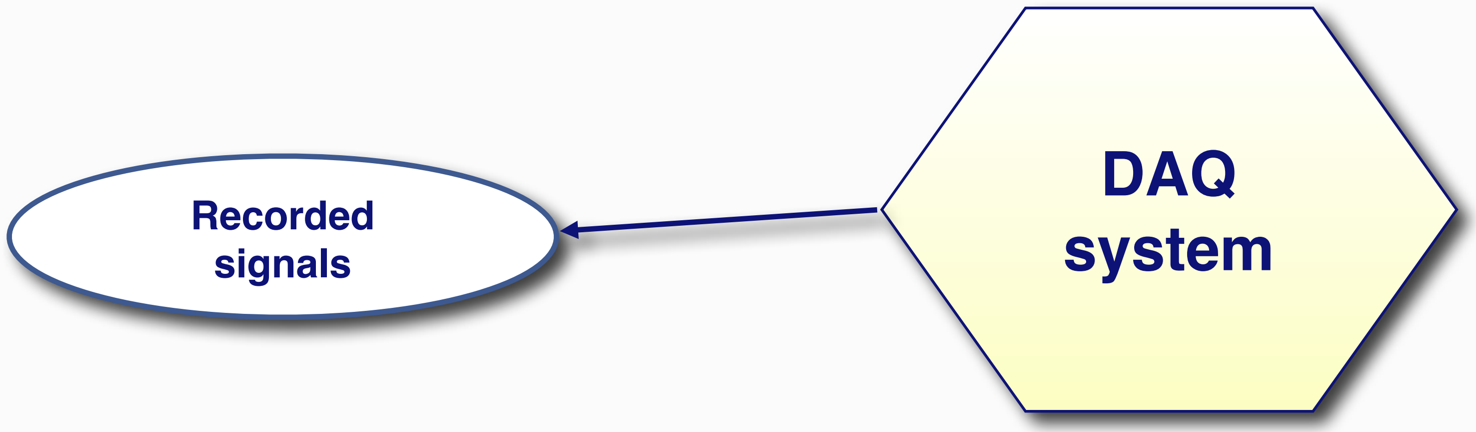
- Now : ~2 million lines of code (reconstruction and simulation)

RECO flow



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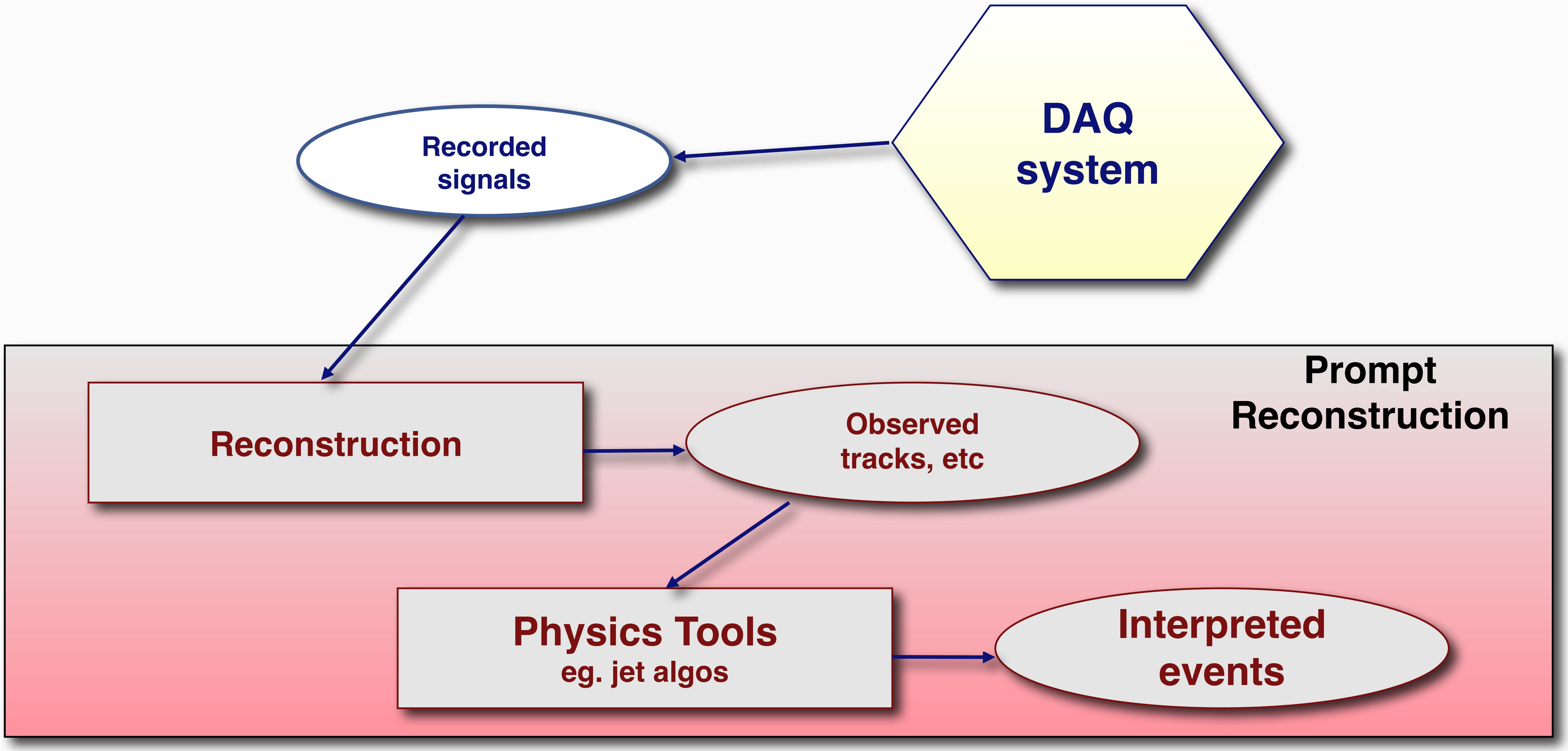
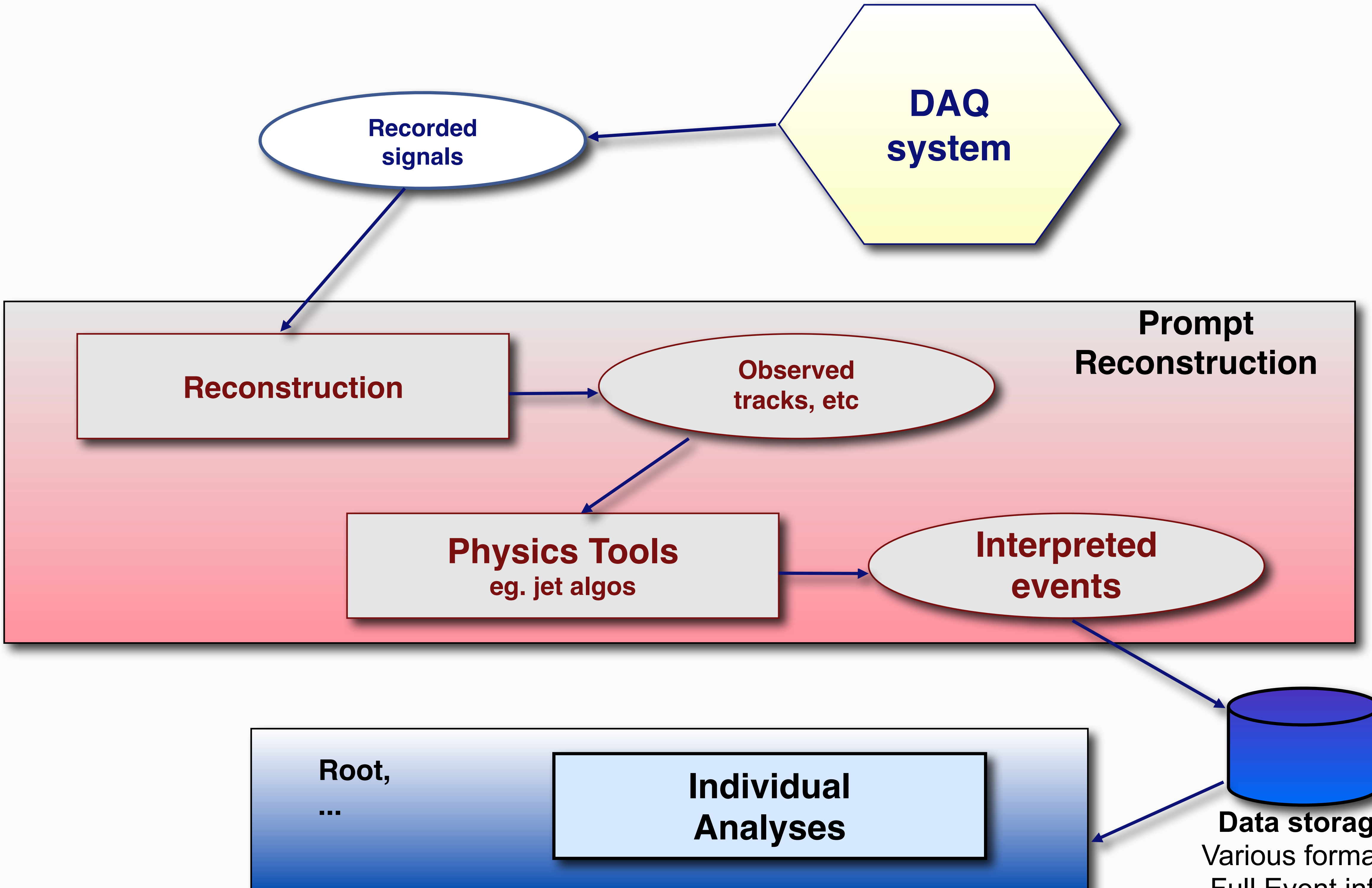
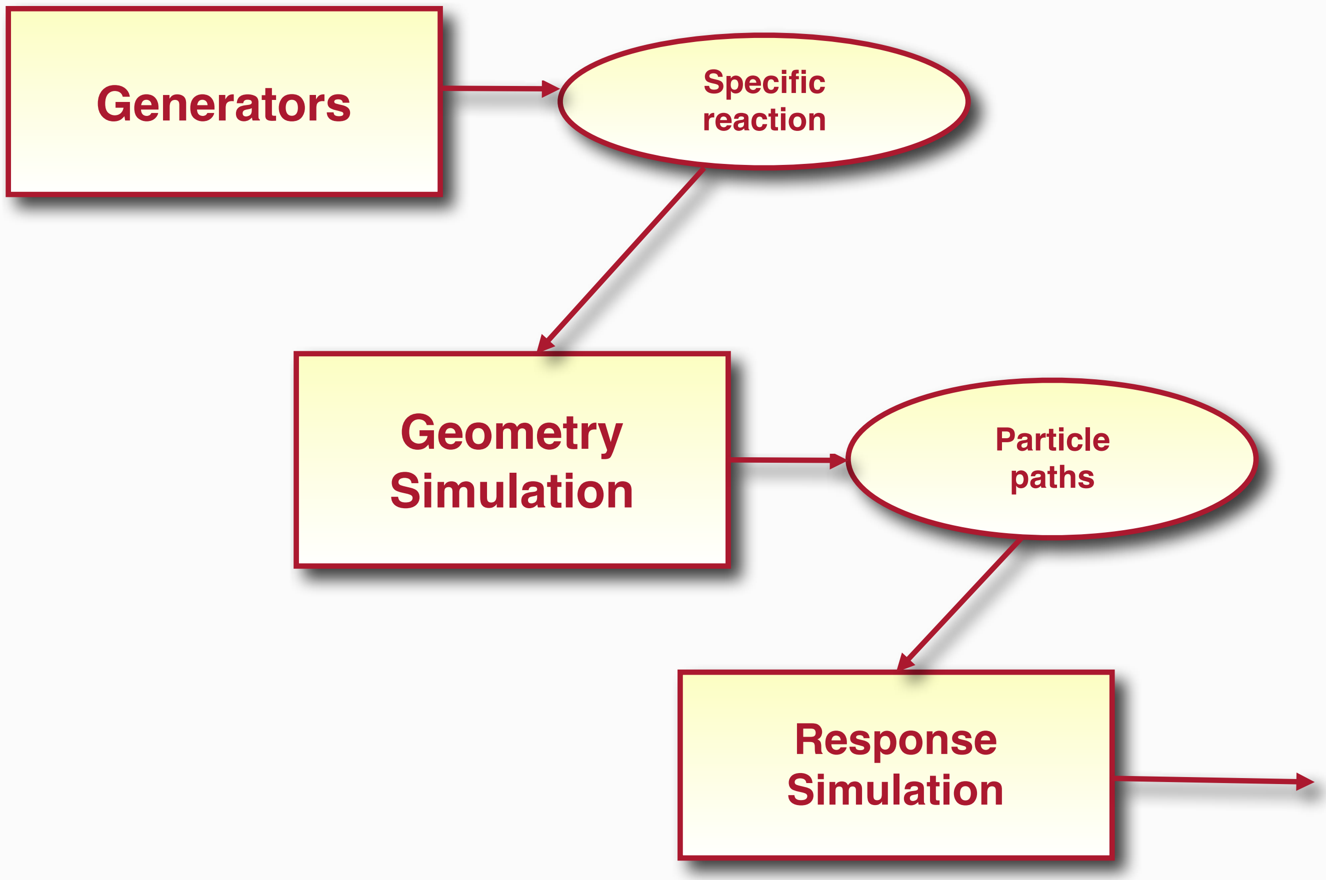

DAQ system
Recorded signals
Prompt Reconstruction
Reconstruction
Observed tracks, etc
Physics Tools
eg. jet algos
Interpreted events

RECO flow



Data storage
Various formats:
Full Event info,
only RECO info,
reduced/selected RECO info

Flow of simulated data



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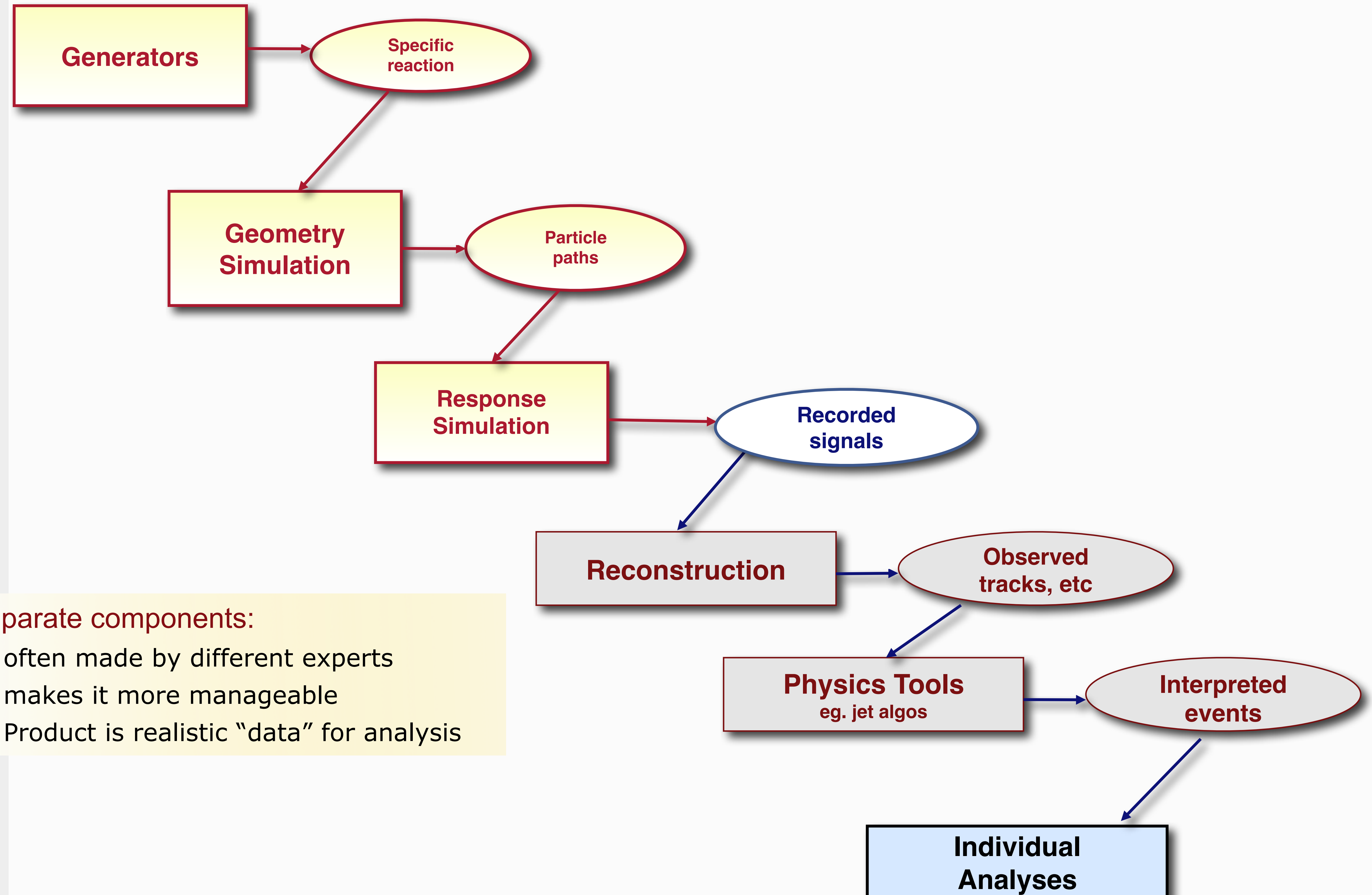

Separate components:

- often made by different experts
- makes it more manageable
- Product is realistic “data” for analysis

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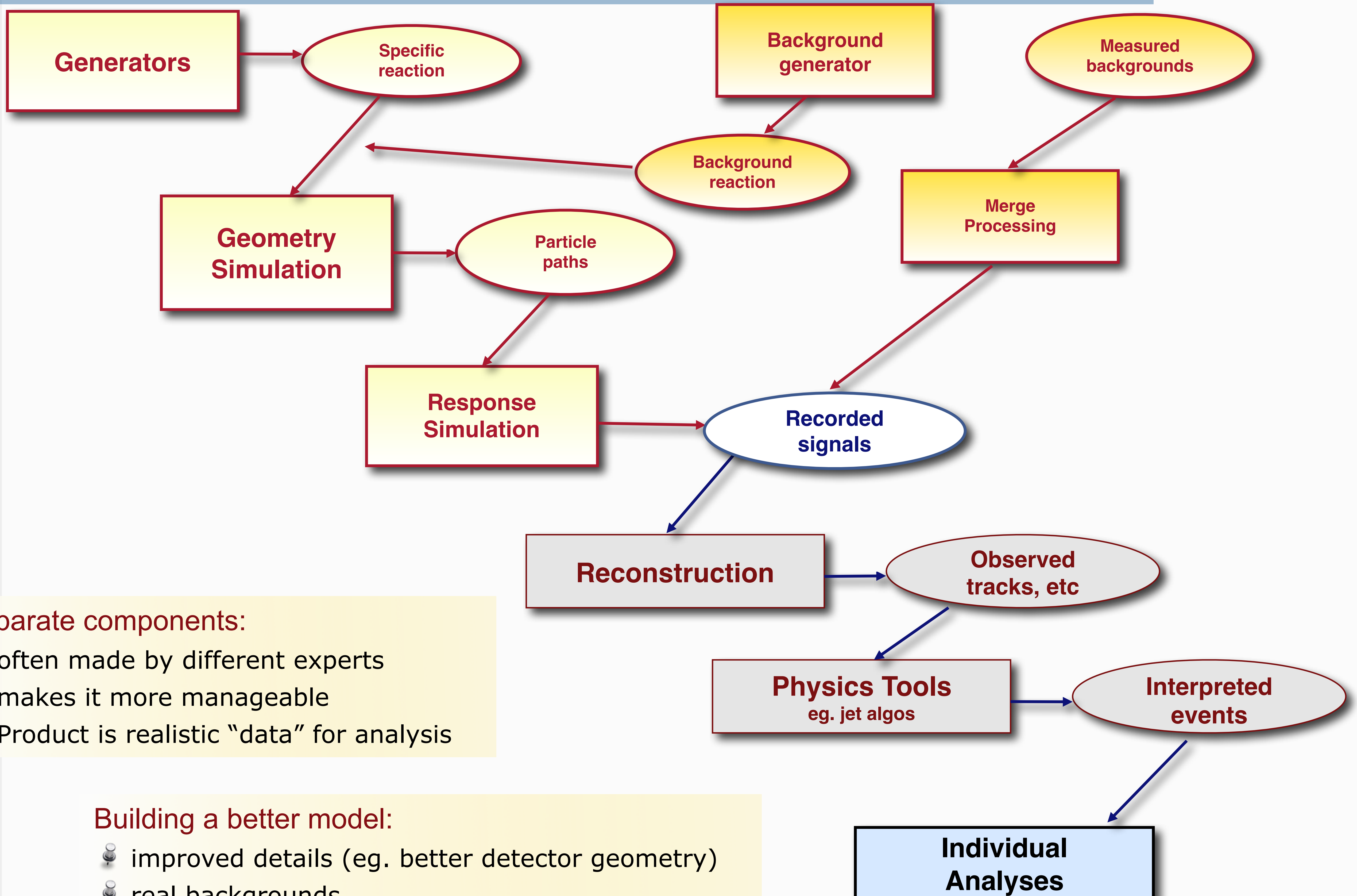

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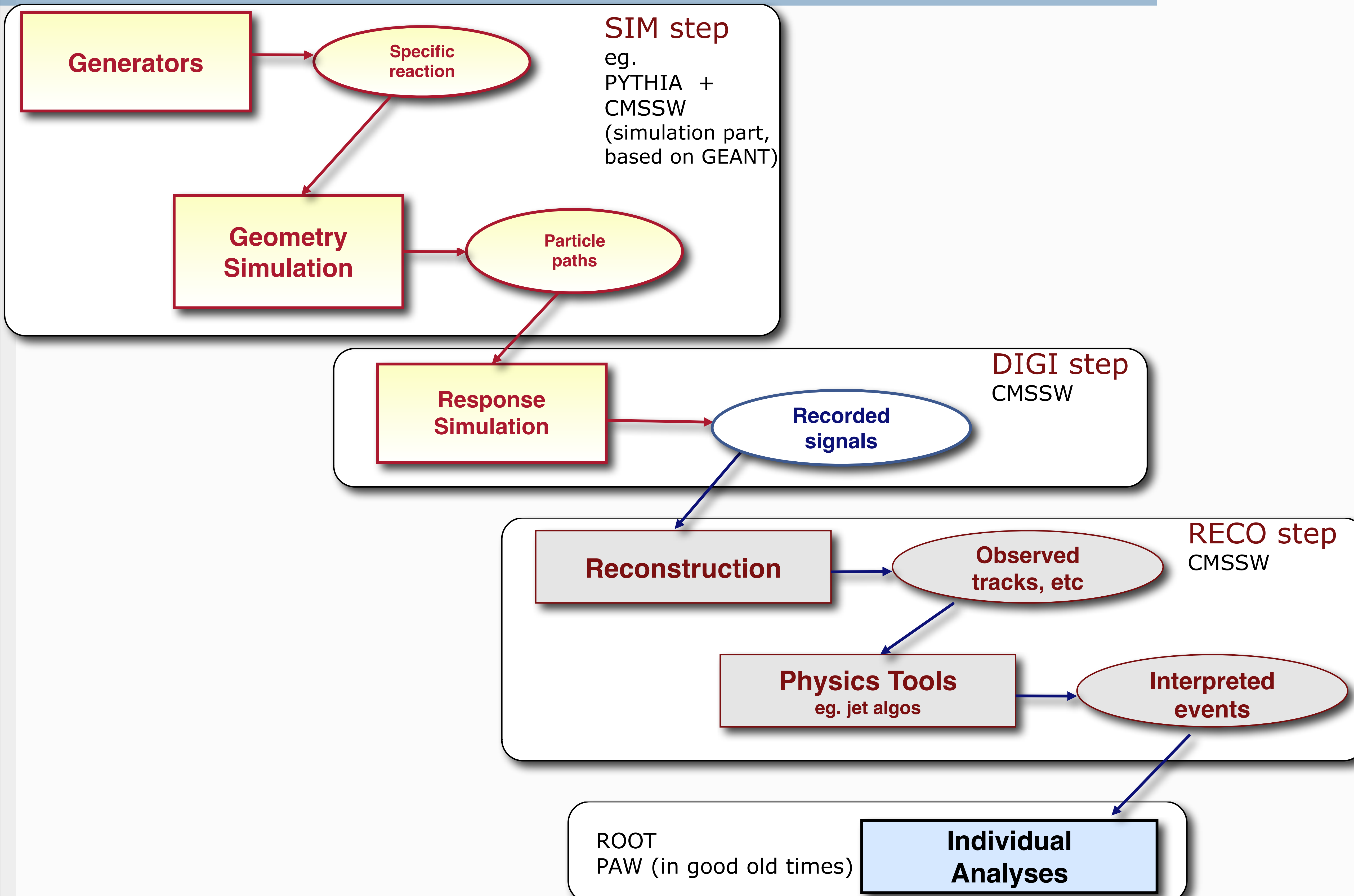
Building a better model:

- improved details (eg. better detector geometry)
- real backgrounds

Partitioning production systems



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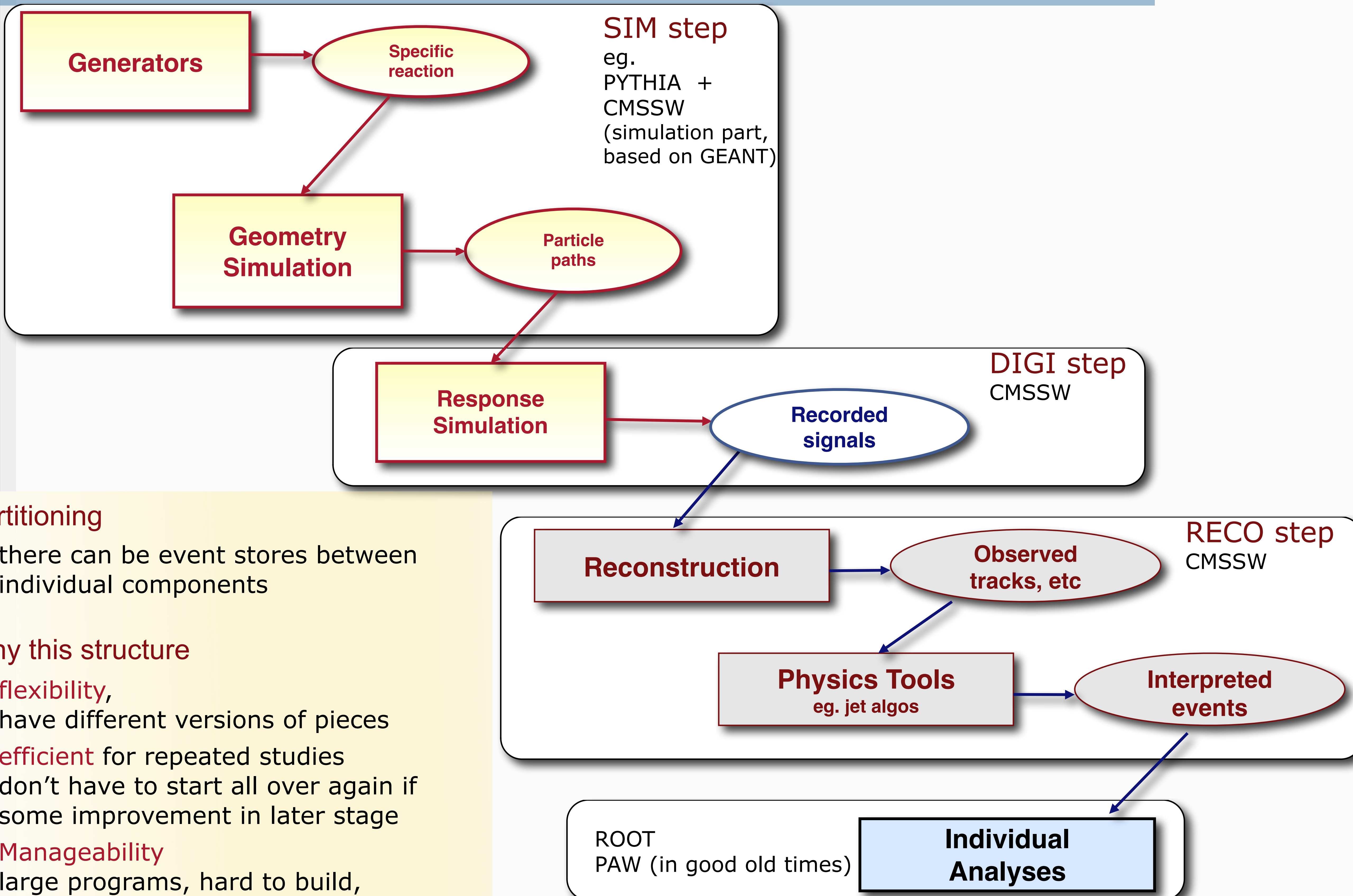

Partitioning

- there can be event stores between individual components

Why this structure

- flexibility,
  have different versions of pieces
- efficient for repeated studies
  don't have to start all over again if some improvement in later stage
- Manageability
  large programs, hard to build, understand, debug, maintain, ...

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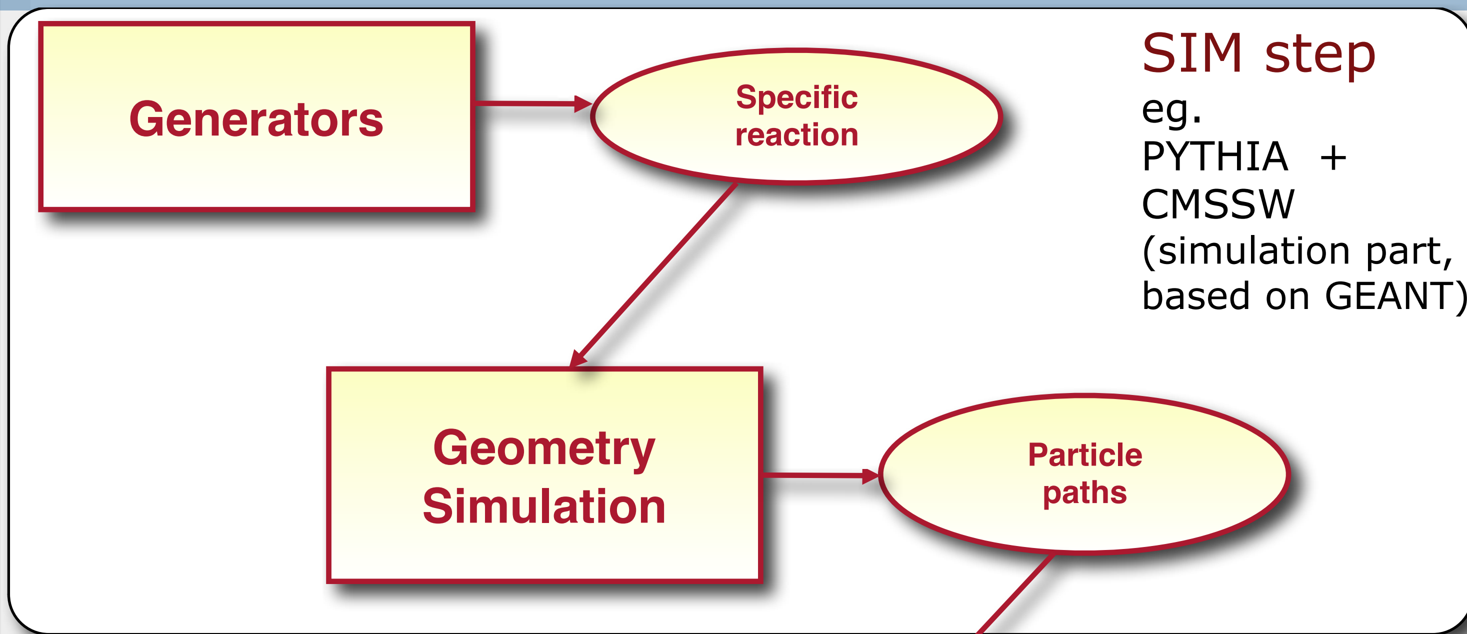

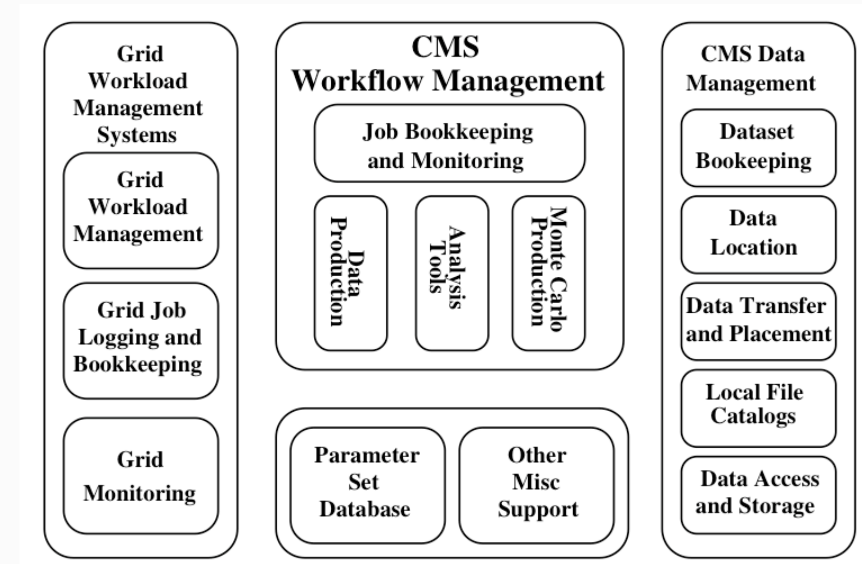

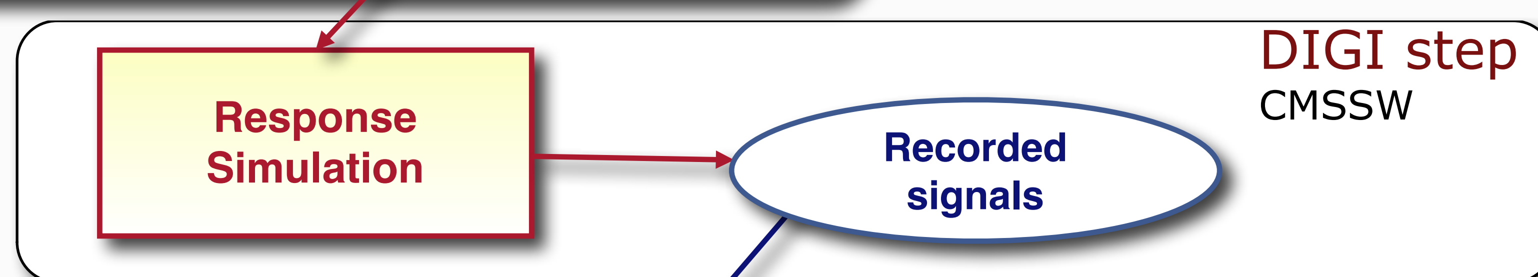

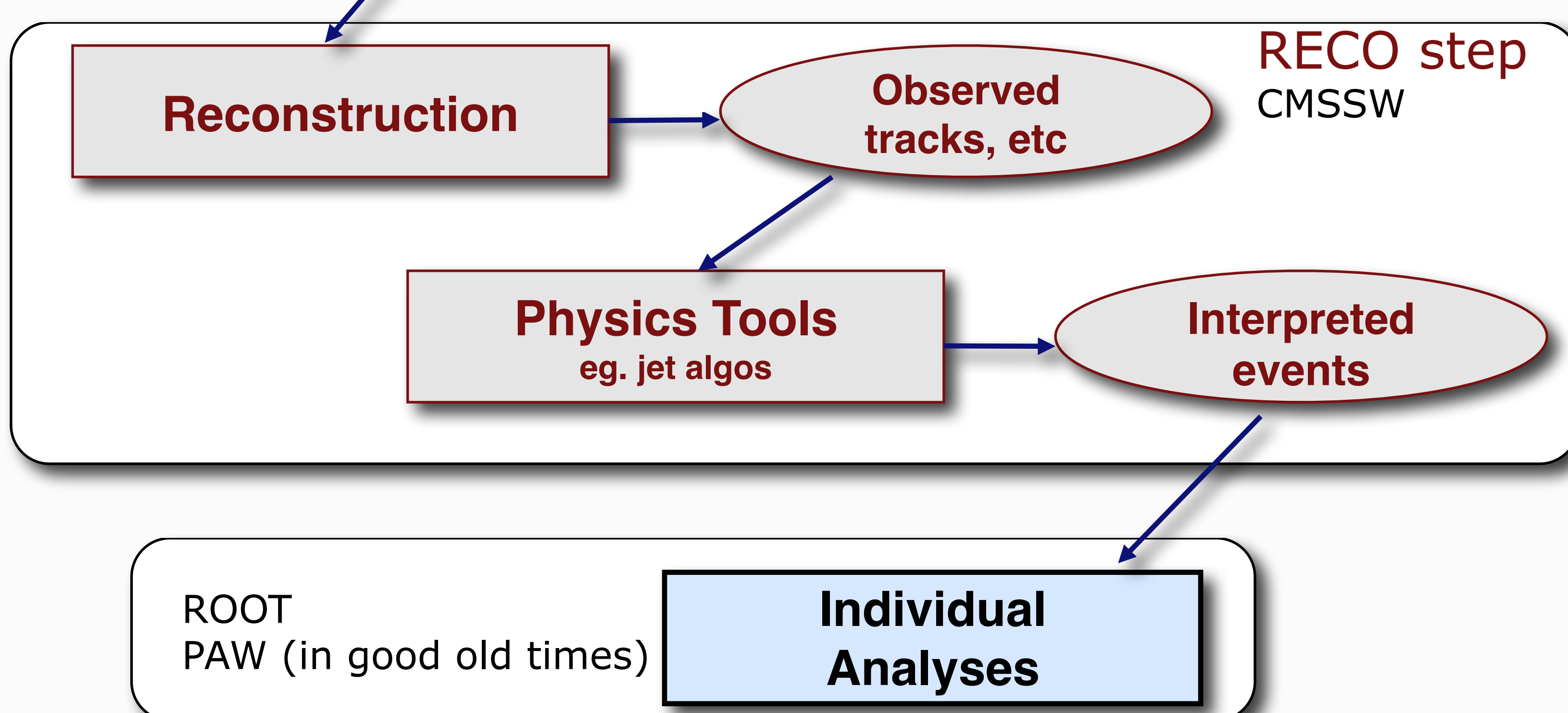

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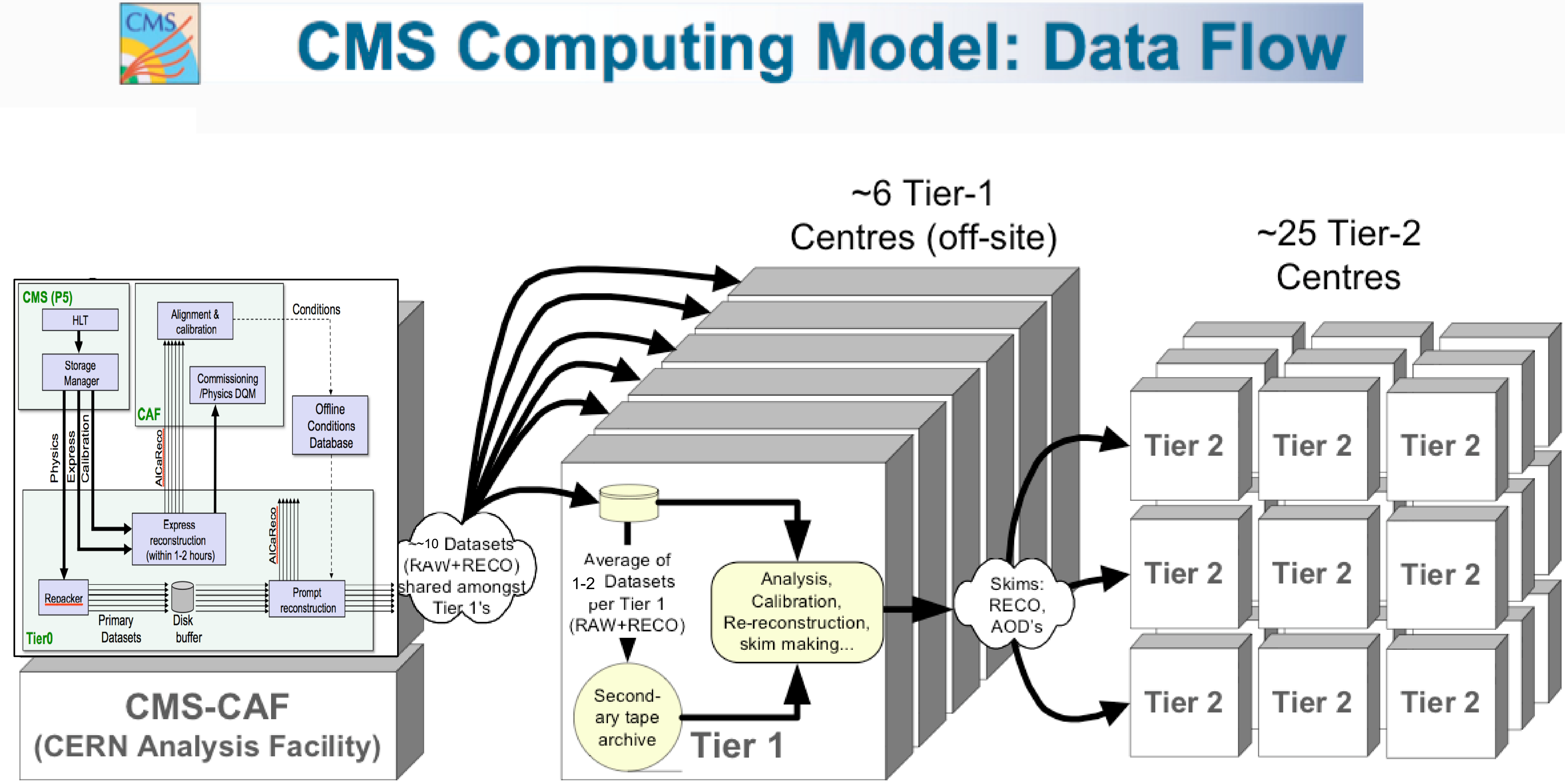

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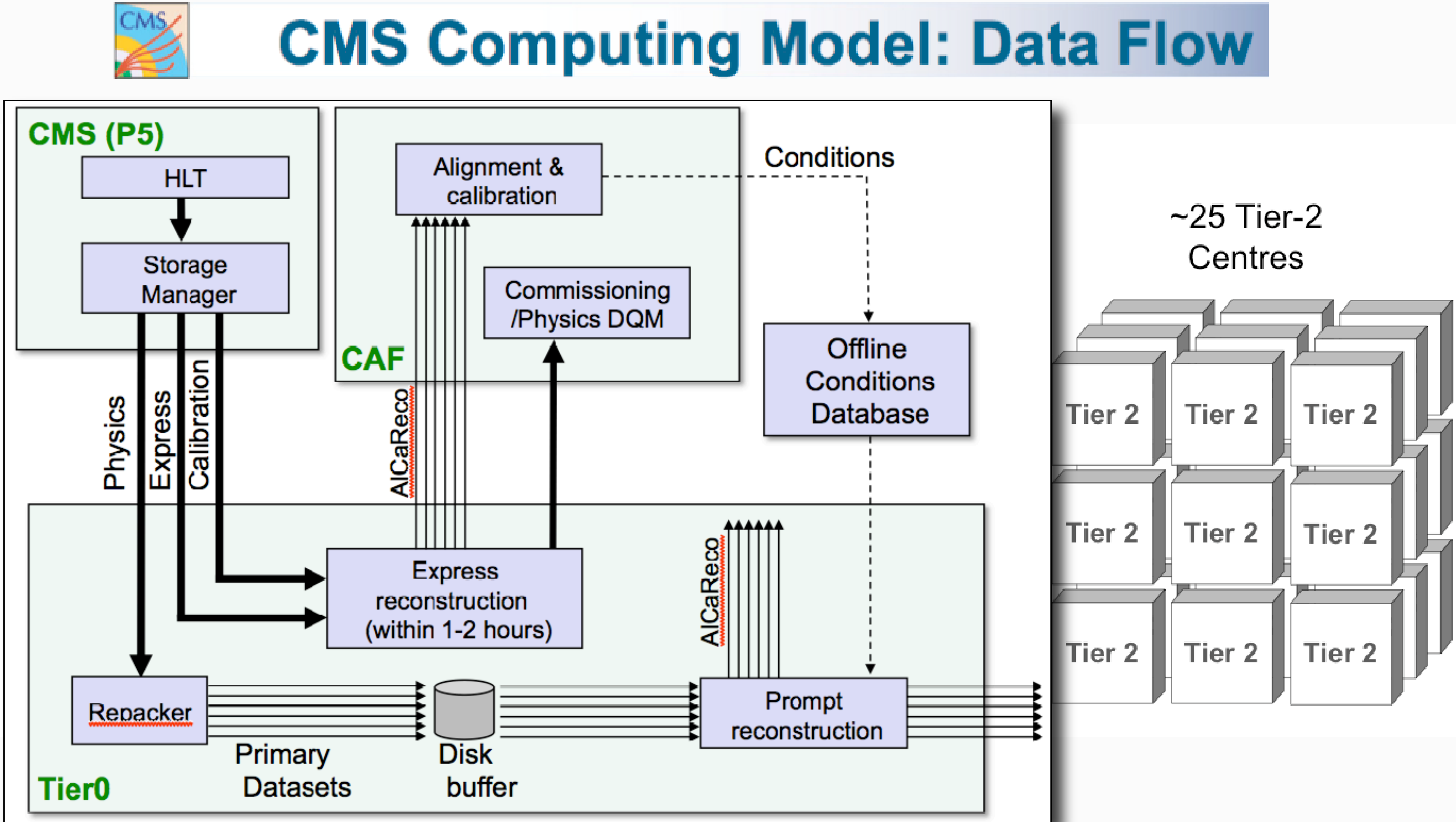

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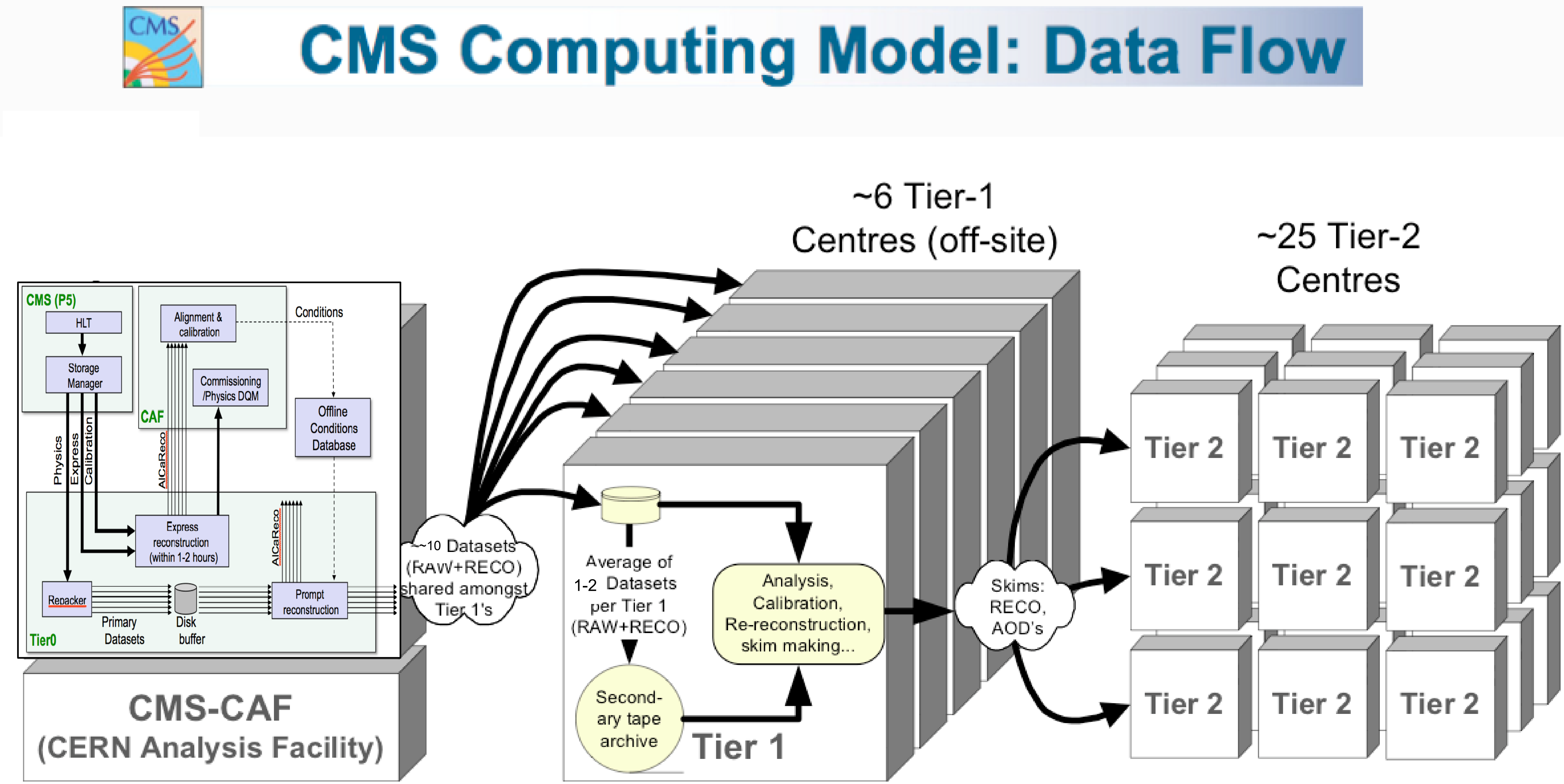

Summary

"Doing something ordinary is a waste of time" (Madonna)

What wasn't covered

- Details on track fitting, Kalman filters
- Secondary Vertex finding
- Alignment
- Particle Identification
- Calibration techniques, "in-situ" methods
- Particle/Energy flow
- Trigger menus, their studies
- more details on parameter fitting,
  eg. lifetime and mass measurements
- how to estimate systematic errors
- Databases, persistent data storage
- Programming languages in use (F77, C, C++, JAVA, ...)
- .....

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  is how we get from raw data to physics papers

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